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– GESAMP –

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No. 34 1990

Review of potentially harmful substances. Nutrients.

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NOTES

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DEFINITION OF MARINE POLLUTION BY GESAMP

"Pollution means the introduction by man, directly or indirectly, of substances or energy into the marine environment (including estuaries) which results in such deleterious effects as harm to living resources, hazards to human health, hindrance to marine activities including fishing, impairment of quality for use of sea water and reduction of amenities".

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PREAMBLE

A core group meeting was convened at Unesco Headquarters, Paris, 14-17 September 1987. The meeting was attended by Dr. J. Portmann (Chairman, UK), Dr. R. Elmgren (Sweden), Dr. I. Koike (Japan), Dr. L.D. Mee (IAEA), Dr. M.A. Saad (Egypt) and Dr. J. Stirn (Yugoslavia). Dr. A. McIntyre (Chairman of GESAMP Working Group 26 on the State of the Health of the Ocean) attended part of the meeting as observer. Dr. P. Bjornsen acted as meeting secretary.

The Chairman opened the meeting at 09.30 hrs. on 14 September, welcomed the participants and noted the particular relevance of this work to the ongoing review of the state of the health of the ocean. The meeting was further welcomed by Dr. G. Kullenberg, Unesco Technical Secretary for GESAMP, who referred to the XVII Session of GESAMP where it had been decided that Unesco becomes the lead agency for Working Group 13 with Dr. J. Portmann as Chairman of the Group. He stated that the meeting was supported by UNEP, FAO, IOC and Unesco. He also stressed the need for a solid progress report to the next session of GESAMP, which may lead to the formation of a separate Working Group on the eutrophication problems if so required.

Dr. Mario Ruivo, Secretary of IOC, also welcomed the participants emphasizing the gravity of the eutrophication problem in some of the IOC programmes such as GIPME (Global Investigation of Pollution in the Marine Environment) and OSLR (Ocean Science on Living Resources).

I. INTRODUCTION

The main purpose of this report is to assess the extent to which increases in the availability of nutrients due to anthropogenic activities affect plant production in the sea and the consequences this may have upon man's interests and the environment. Nutrients in this context can be defined as those substances which are required for growth of primary producers such as benthic algae, aquatic vascular plans and phytoplankton all of which are autotrophic organisms using light as their energy source. This process of primary production also involves nutrients being taken up mainly from the surrounding water and the use of energy carriers and enzymes leading to the production of a sufficient increase in cell material to induce cell division. The major nutrients in a marine context are compounds of nitrogen and phosphorus and, to a lesser extent, silicate. Because the inputs of nitrogen and phosphorus compounds are known to have been particulary affected by anthropogenic activity, the report focusses particularly on these.

It is, however, worth noting that a wide variety of elements, e.g. iron, manganese, zinc, copper and cobalt, are also known to be essential for the process of algal production to proceed, as these elements are incorporated into organic molecules which enter into photosynthesis reactions. It has also been shown that at least some algal species require the presence of organic compounds such as Vitamin B^{12}, thiamine and biotin. Little is known about the general availability and dynamics of such substances in the sea and whether or not they may exert limiting or stimulatory influences under natural conditions. The possible role of such trace organics as chelating agents which might affect availability of trace elements or as growth factors, is a matter which requires further study.

The Cause for Concern and Definition of Key Terms

Where large inputs of nutrients have been made to freshwater lakes, there have been concomitant increases in the concentrations of nutrients present and changes have taken place in algal species composition and productivity including the appearances of intense algal blooms and deleterious effects on the lake ecosystems. For many years it was argued that this was simply an acceleration of the natural ageing process of a lake ecosystem and it was suggested that no parallel could exist in the more dynamic marine environment. It also seemed to be true that, being a vastly larger environment, the sea would be more than capable of absorbing nutrient inputs. However, in recent years, considerable attention has been paid to the apparently increased frequency of occurrence of exceptional algal blooms[1] and the scale of such events in temporal, geographical and biomass

[1] Exceptional blooms in this context are those which are noticeable, particularly to the general public, directly or indirectly through their effects. They may, in fact, be common, even more or less regular events and many have been noted in historical records. They merit the term exceptional purely on account of their noticeability through their colour, foam production, toxicity etc.

production terms. The attention has come about due to concern over the consequences of such events and has led to the recognition that they are often associated with increased nutrient inputs and in turn that some of the effects do not necessarily involve exceptional blooms but merely changes in species of plants which may be either planktonic (i.e. free floating unicellular plants at the base of the marine food chain) or fixed algal species commonly known as sea-weeds, benthic unicellular microalgae or benthic vascular plants such as sea grasses.

Thus, there is now ample reason to believe that the increase in inputs of nutrients to the sea has given rise to similar changes to those observed in freshwater lakes. Indeed, there is a growing body of evidence that widespread environmental quality changes including effects on the productivity of the sea actually do occur.

The term often used to describe these effects is eutrophication. However, this term is understood in almost as many different ways as the frequency with which it is used. For the purposes of this report the term eutrophication is used simply to mean "enhanced nourishment" and refers to the stimulation of aquatic plant growth by mineral nutrients, particularly the combined forms of phosphorus or nitrogen. This may occur naturally, e.g. as a result of upwelling or seasonal run-off from land in association with rainfall cycles such as monsoons and may, if it occurs over long time scales, allow the ecosystem of the affected area to adapt. Alternatively, it may be anthropogenically induced and involve relatively large changes in nutrient inputs over comparatively short time scales.

Thus in the sense used here, eutrophication need not necessarily imply undesirable consequences and may actually be considered desirable in certain situations e.g. nutrient increases in the photic layers associated with OTEC plants and used for mariculture projects. It will certainly span a large range of effects, from ones of limited and acceptable (even desirable) impact to those with increasingly serious undesirable consequences, ultimately reaching a point at which the environment in question would be described as degraded. This critical level of eutrophication will vary from situation to situation. For example, on a coral reef it may be the point at which macroalgae blanket the coral substrate, or as in the naturally oligotrophic[2] Mediterranean Sea, the occurrence of algal blooms which discolour the normally clear blue water. At the other end of the continuum, in the more turbid and naturally productive waters of the North Sea, it may be the point at which oxygen replenishment capacity is exceeded by the rate at which bacteria use oxygen in the degradation of organic matter produced by primary production.

Whilst the preceding paragraphs go into some detail as to the meaning of the term eutrophication, the important issue is the actual effects the nutrient enrichment can have on the marine environment and the extent to which these are regarded as harmful i.e. constitute pollution. Thus the report seeks to assess the extent to which increases in the availability of nitrogen and phosphorus nutrients due to anthropogenic

[2] An oligotrophic environment represents the opposite end of the spectrum of nutrient availability and is one which is naturally poor in nutrients and in which primary productivity is normally low.

activities affects either the rate of primary production or the composition of the species involved in primary production, and the extent to which the effects are adverse.

II. FORMS OF NUTRIENTS IN CHEMICAL TERMS. GENERAL DISCUSSION ON THE CONCEPT OF MOST LIMITING NUTRIENTS

There is an abundant literature on the natural forms of nutrients in the marine environment and their utilisability by primary producers, and it is not the purpose of this report to review the subject or to give comprehensive details. However, the following simple description of the basic principles may assist the reader. For further details of the subject see for example Cushing and Walsh (1976) for information on nutrient cycles, Raymont (1980) for information on nutrients in relation to primary production and levels in the environment and Morris (1980) for details of the ecology of phytoplankton.

The rate of primary production of new organic matter in the marine environment is generally limited either by nutrient availability or by one of two physical factors: light intensity and temperature. Even in the latter case the final maximum size of the crop is, however, usually limited by the availability of either combined phosphorus or nitrogen. As has already been mentioned, other micronutrients may, under certain circumstances also be important in this respect. The actual growth rate will be a function of more complex biological factors such as grazing pressure and the presence of a seed population of the species concerned. The stability of the water column will also influence both the level of production and whether the full maximum potential crop yield is achieved.

In natural as well as moderately polluted coastal sea water, phosphorus usually appears in the following forms: particulate, colloidal, inorganic phosphate and dissolved organic. Orthophosphate is the form preferred by unicellular algae, but on the basis of results obtained through algal monocultures, an ability to utilize other forms such as polyphosphates and organic phosphorus, seems to be widespread.

Whilst under certain circumstances phosphorus can be the limiting nutrient in the sea i.e. its availability is exhausted and the production rate is determined by remineralization processes, it is generally agreed that combined inorganic nitrogen is usually the most limiting nutrient in the sea. The principal forms of inorganic nitrogen in the marine environment are dissolved molecular nitrogen, which is usable by blue-green algae (cyanobacteria), nitrate, nitrite and ammonia; organic forms of nitrogen also occur in both particulate and dissolved forms, for example as urea and amino acids.

The chemistry of nitrogen in the sea is quite complex and no well-balanced nitrogen budget has yet been produced for the world ocean. In its most oxidized combined form, nitrogen exists as the nitrate ion and this constitutes the most important reservoir of combined nitrogen in the deep ocean. In highly productive marine ecosystems, phytoplankton production is usually driven by the availability of nitrate, although actual uptake is primarily of ammonia. In less productive systems, however, ammonia may be the more important form. This probably reflects dependence on nitrogen regeneration within such ecosystems i.e. dependence on direct recycling. Phytoplankton are also able to utilize other forms of nitrogen, notably nitrite, urea and some amino acids, particularly where more readily assimilable forms have become exhausted.

Nitrogen nutrients are introduced to the sea by terrestrial weathering and plant decomposition, oceanic mixing processes, regeneration from decomposing marine primary and secondary producers (in the water column and sediments) and by air-sea exchange processes (including dry deposition and rainfall). Human activities may influence all of these processes. The most common land-based sources of nutrients arise from domestic wastes (principally sewage and detergents), agricultural run-off (either of fertilizers or through increased erosion and weathering), animal wastes from intensive livestock units (industrial farming), industrial effluents and atmospheric discharges from fuel combustion and agriculture. These sources supply nitrogen and phosphorus in a wide variety of chemical forms, not all of which are immediately taken up by marine plants but require further remineralization by heterotrophic processes. Depending on the composition of the discharge, a wide geographic area may thus become nutrient enriched.

It is important to point out from the outset of this discussion that there is no simple, direct relationship between the growth of a plant population and the amount of nutrients added to a given system. In shallow waters, nutrients initially incorporated into the biomass may be rapidly regenerated, either in the water column or on the water/sediment interface. Either way, they are then available for reincorporation into the growing population. The cycle may be repeated for tens or hundreds of times before the nutrients eventually escape from the system (to the deep sea or the atmosphere) or become buried in the sediments. The ecological impact of a given nutrient source will thus vary with the depth and flushing characteristics of the receiving water body.

III. SITUATION REGARDING OPEN SHELF SEAS/OCEAN AREAS

About 99% of the phosphate (and probably nitrate) reaching the euphotic zone of the open ocean originates from the deep ocean from whence it is transported by oceanic mixing processes (Broecker, 1974). The remaining 1% is of continental origin and is washed into the sea by rivers (though most of this is quickly removed by primary producers in coastal seas and estuaries). The annual production of the world's phosphate mines would be equivalent to about 5% of that which reaches the euphotic zone of the world ocean (were it to be dumped at sea). The equivalent for anthropogenic nitrate (from the chemical industry and fuel combustion) would be a mere 3% (Broecker, op. cit.). From these figures, it is obvious that, whatever their impact in coastal areas, the effect of the present anthropogenic discharge of nutrients to the sea will have little effect on the fertility of the open ocean.

The position regarding the effect of nutrient enrichment on open shelf seas is somewhat different to that in the open ocean. As the experiences described in Section IV for the North Sea and coastal margins of the USA show, there are certainly cases of nutrient enrichment and consequent changes in algal productivity in shelf sea waters. However, where these occur, the area affected is either relatively small or is hydrographically confined, as in the eastern North Sea, by current systems which prevent mixing offshore. Thus depending on what is meant by open shelf waters, it may be argued that the open waters away from the immediate coastal zones are not presently affected. Indeed, they are unlikely to be effected due to the dilution afforded by the water volume involved and the general transport to and from the ocean systems.

It is worthwhile reflecting on the factors which bring about natural eutrophication of some open-ocean areas and also on the level of natural variability which makes an open-ocean nutrient baseline difficult to achieve. Since most of the nutrients in the euphotic zone of the open ocean are supplied from the deep ocean, oceanic mixing processes must be the key to the fertility of these areas. This is largely true for the tropical ocean, though temperature and light are modulating factors in temperate and polar seas. The central areas of the major oceanic gyres are characterized by a relatively deep permanent pycnocline which provide an effective barrier for the eddy diffusion of nutrients to the euphotic zone. Wind stress vorticity tends to pile up warm surface water in the centre of the gyres (see Gill, 1982). These areas are the most unproductive regions of the world ocean (see the charts of Koblentz-Mishke et al., 1970 for example). Towards the outer edges of the gyres, the pycnocline is somewhat shallower and relatively less energy is required to mix nutrient-rich water into the euphotic zone. Ocean margins are thus intrinsically more fertile than the centre of the gyres.

In order for a phytoplankton bloom to occur, a seed population should exist. This factor is particularly important in coastal upwelling regions where some sinking cells may fall into subsurface waters which are carried to the surface by the upwelling process (see, for example Dugdale 1976). The overall process conveys biological stability to the system. This does not happen in some oceanic upwelling systems such as the equatorial Pacific (Thomas, 1979) where upwelled nutrients may become dispersed over a wide area before a sufficiently stable phytoplankton population can develop to incorporate them. Sporadic mixing or upwelling events followed by the development of a shallow and stable pycnocline, may result in an exceptional plankton bloom. On the other hand, a small but continuous flux of nutrients across a relatively stable pycnocline at the bottom of the euphotic zone may result in a stable deep maximum of highly pigmented micro-or picoplankton (see Fasham et al., 1985).

For most tropical or sub-tropical open-ocean areas, this gradual eddy diffusion of nutrients through the pycnocline (coupled with the efficient recycling of bound nutrients) would appear to be the principal mechanism of fertilization of the euphotic zone (see for example, King and Devol, 1979), though in the case of nitrogen, as much as 10% of the requirements may be met by dinitrogen fixation (Carpenter, 1983). In surface and near-surface waters of the least productive tropical oceans (the central North Pacific ocean for example), both oxidized combined nitrogen and phosphorus are often depleted to below the detection limits of usual colorimetric analytical procedures (Sharp et al., 1980). Seasonal variations in the pycnocline depth and gradient become increasingly important as a function of latitude. Intense spring blooms frequently occur at high latitudes (Heinrich, 1962). In such areas, low temperatures and poor light intensities limit new primary production in winter and frequent storms from autumn to early spring provide considerable mixing energy for fertilizing the surface waters.

Plankton productivity in the ocean is generally (but not always) limited by the availability of combined inorganic nitrogen. In temperate oceans the predominant form of this nutrient is nitrate, formed by the bacterial oxidation of organic nitrogen or mixed into the euphotic zone from deeper waters. This is not always the case in more oligotrophic environments, particulary in the tropics, where experiments with N-15 labelled nutrients have revealed that ammonium is more rapidly taken up than nitrate (Dugdale 1976). This observation suggests that nitrogen recycling is particularly efficient in these environments. In coastal upwelling systems, very intense blooms of diatoms occasionally exhaust dissolved silicate supplies and the bloom may become silicate limited (see Dugdale 1976). Some cases of phosphate limitation have also been reported.

The basic overall geochemical balance of nitrogen nutrients is still poorly quantified, partly as a result of the diverse oxidation states and chemical forms of this element in the sea (which complicates the analytical chemistry and makes fluxes difficult to evaluate). The role of air-sea exchange is particularly poorly understood and rain and dry deposition may represent a significant anthropogenically modified source of nitrogen to some oceanic areas. There is increasing evidence of the importance of nitrogen fixation (see Carpenter, 1983) and denitrification, both in sediments (for example, Billen 1978) and in some oceanic water columns (for example, Codispoti and Christensen 1985).

In the open ocean the flux of dissolved nutrients through the euphotic zone is mainly determined by physical driving forces and constraints. The physical forcing of the system varies, not only on a seasonal basis, but also on a much longer time scale. The best documented evidence of this comes from measurements made in the Pacific during the El Nino - Southern Oscillation (ENSO) events which occur irregularly about every seven years (TO-AN, 1983-87). The triggering mechanism for these events is not yet known but they result in a temporary reversal of the usual east-west atmospheric pressure gradient across the southern Pacific ocean and a consequent relaxation of dominant trade winds at the eastern margin of the ocean. Upwelling along the eastern Pacific coast decreases or virtually ceases and the warming of the ocean surface further reinforces the pycnocline. Nutrient concentrations quickly diminish to oligotrophic levels as do primary and secondary production.

On an even longer term, there is sedimentary evidence of relatively large changes in nutrient fluxes in the past as a result of climatic changes on a global scale (see Broecker, 1974; Rau _et al._, 1987). This obviously leads to the present day issue of anthropogenically induced climatic changes. If events such as ENSO can be triggered by some, as yet, unknown mechanism, what will be the effect of a gradual (though small) warming of the ocean surface resulting from the increase of atmospheric CO_2 as a result of man's use of fossil fuels? Furthermore, if there is anthropogenically induced damage to the earth's atmospheric ozone layer leading to an increase of ultraviolet radiation flux to the ocean (Anon, 1987), will this increase the surface photoinhibition of primary production in the ocean? These indirect mechanisms may be of far greater consequence to global oceanic nutrient fluxes and the food chain than that which would be caused by the diffuse discharge of nutrient-rich wastes to the open ocean. There is also concern as to our present lack of knowledge and understanding of the inter-relationship between world climatic events and marine productivity cycles.

IV. REVIEW OF EXPERIENCES FROM DIFFERENT REGIONS OF THE WORLD'S SEAS

This review is not intended to be exhaustive; it draws primarily on the experience of those directly concerned in preparing the review and its purpose is to provide examples of the nature of the problem and to illustrate the geographical scale over which it is encountered. Many other examples could be provided but they would not significantly extend understanding of the problem or alter the main conclusions.

IV.1 THE BALTIC SEA

The semi-enclosed Baltic Sea has shown clear symptoms of nutrient enrichment in recent decades (Melvasalo et al. 1981; Larsson 1986; Lassig 1987). The Baltic is one of the largest brackish water areas in the world, 373,000 km^2, including the Belt Sea and the Sound (Fig. 1). In the Baltic proper a primary halocline at about 70m depth separates a low salinity surface layer from a semi-stagnant deep water (Ehlin 1981). Low oxygen concentrations below the halocline were measured already before the turn of the century, but in the last few decades concentrations have decreased even further, and long periods of hydrogen sulphide formation have characterized the deep water (Lauiainen et al. 1987). Changes in mixing and water exchange cannot explain this deterioration, which must be due to increased oxygen consumption in Baltic halocline and below halocline waters (Shaffer 1979). Since good measurements were begun, 1950's for phosphate, 1968 for inorganic combined nitrogen forms, concentrations of both nitrogen and phosphorus have increased in the Baltic water column, as an average for the inorganic forms by a factor of 2-3 in the winter surface water. The Baltic nutrient load is estimated to have increased 4 times above background for nitrogen and 8 times for phosphorus; more than (Table 1) sufficient to explain the increase in concentrations (Maksimova 1982; Larsson et al. 1985; Helcom 1987a, 1987b) the calculations differ somewhat but in principle imply the same conclusions). Most of the phosphorus added is neither exported nor accumulated in the water column and must, therefore, end up in the sediment, whereas most of the added nitrogen is thought to be removed from biological cycling by denitrification to dinitrogen (Larsson et al., 1985; Rönner 1985).

In spite of such major changes in nutrient load and concentrations, only few data indicative of increased primary production or changed phytoplankton composition exist (See Kononen and Niemi 1984; Larsson 1986; Wulff et al. 1986). There are some indications also of increased zooplankton biomass (Wulff et al. 1986), increased growth of zooplankton feeding fish and macrobenthic biomass above the halocline (Cederwall and Elmgren 1980; Zmudzinski et al. 1987). A more than tenfold increase in the Baltic Seas fish catches in this century is likely to be only partly an

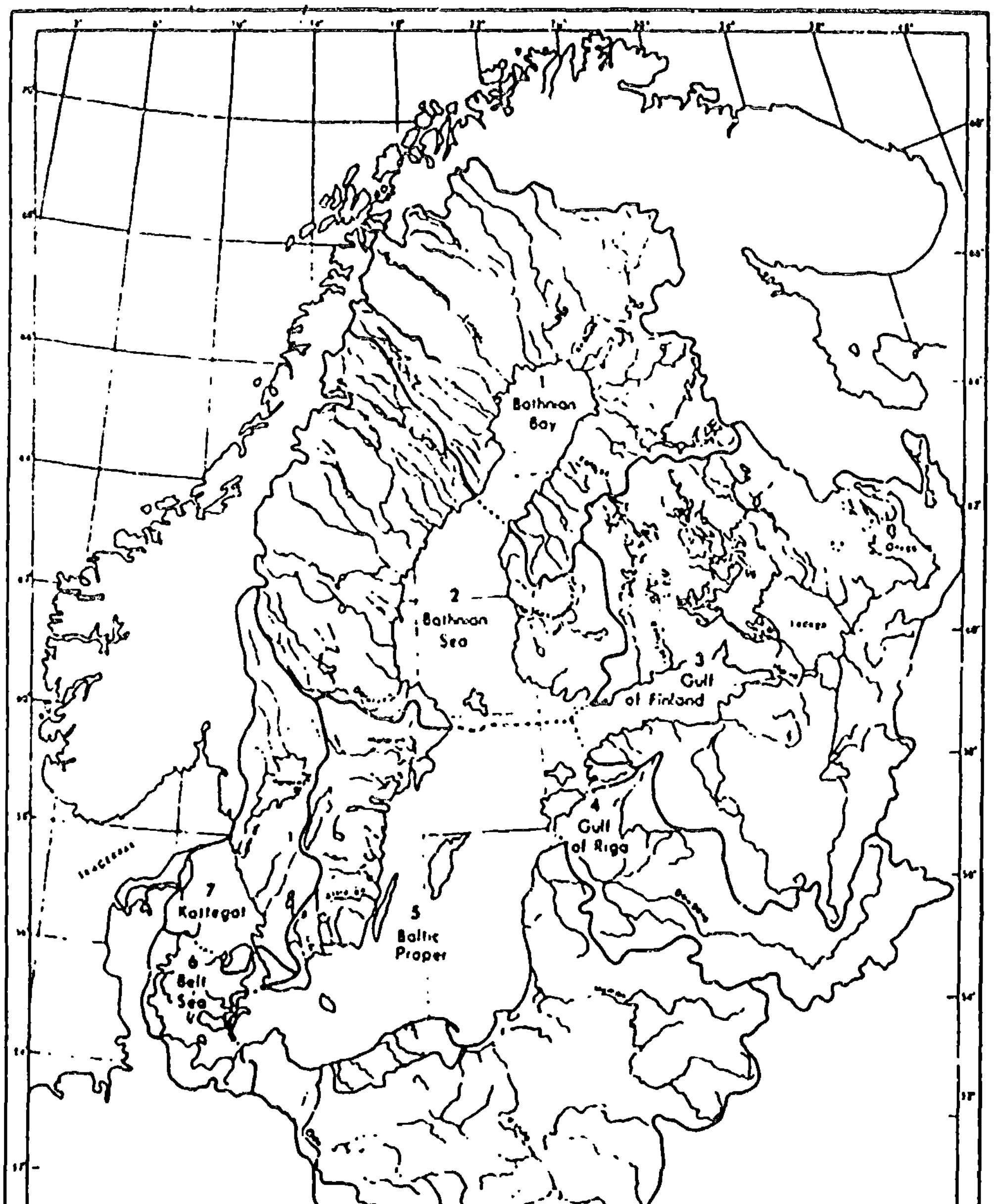


Fig. 1. Drainage basin and subregions of the Baltic Sea and its transition area (Falkenmark and Mikulski, 1974). Boundaries between Baltic Sea subregions (dashed lines). Boundaries between the corresponding drainage basins (thick lines).

Table 1. Baltic water balance (after sources in Ehlin 1981).

	Area, 1000 km²	Volume, 1000 km³	Maximum depth, m	Volume below 100m, 1000 km³
Bothnian Bay	36	1.5	147	0.01
Bothnian Sea	79	4.9	301	0.5
Gulf of Finland	29	1.1	123	<0.001
Gulf of Riga	18	0.4	51	0
Baltic proper	210	13.0	459	1.2
Total Baltic Sea (inside Danish straits)	373	20.9	459	1.7

Table 2. Areas and volumes of the Baltic Sea. After Ehlin et al. (1974) and U. Ehlin and G. Zachrisson, pers comm.

effect of eutrophication with elimination of competing seals and more efficient exploitation accounting for most of the increase.

Remedial action in the Baltic must seek to reduce the loads of both nitrogen and phosphorus, since nitrogen is normally the most limiting nutrient, whilst a surplus of phosphate will trigger large summer blooms of nitrogen-fixing, potentially toxic cyanobacteria. The appropriate action needs to be tailored closely to the situation in the area directly affected while taking the general Baltic situation into account.

IV.2 THE NORTH SEA AND KATTEGAT

The North Sea (including the Skagerrak) is a shelf sea with an area of 575,000 km^2 and a mean depth of 70m. A belt of water of reduced salinity moving anti-clockwise along the coasts of England, Belgium, the Netherlands, Germany and Denmark, receives fresh water and nutrient input on the way. In this water, clear symptoms of eutrophication have been registered in the last two decades. Calculations suggest that due to increased riverine (7 x for P, 4 x for N) and atmospheric loads (especially for N), the average nutrient concentrations in the waters along the Wadden Sea coastline may have doubled compared to background conditions (Gerlach 1987). Increases may have been even larger in in-shore areas of the Wadden Sea (De Jonge and Postma 1974). Unique long-term data series from Helgoland, covering 1962-1984 confirm that concentrations of both nitrogen and phosphorus nutrients have actually increased in association with the increased inputs from the Elbe (FRG 1986). Data from the same Helgoland station also indicate an annual average of a four fold increase in phytoplankton biomass accompanied by a change in composition from diatoms to flagellates (Radach and Berg in press, quoted from Gerlach 1987). However, at a station just a little further offshore not affected by the coastal water stream no such increases have been demonstrated.

In the Wadden Sea area, primary production has practically doubled. Macrobenthos, in the coastal zone areas not affected by oxygen deficiency has increased in biomass and become dominated by opportunistic species. In some areas of the German Bight and off the Danish West Coast, major fish and macrobenthos kills due to oxygen deficiency have occurred repeatedly in recent years (1981, 1982 and 1983) following large *Ceratium* blooms (Duursma et al. 1987). The North Sea has long been one of the world's most productive fishing area, but no link has been established between quality and quantity of catches and eutrophication of the coastal zone despite attempts to do so (Tiews et al. 1985).

Although nutrient measurements have been made on waters taken all over the North Sea, these have usually been undertaken on an intermittent basis and there is a remarkable lack of data which can be considered either of reliable enough quality or of long enough duration to permit confident assessment of the extent of change in nutrient concentrations in other parts of the North Sea. What data are available suggest that these other parts have been relatively unaffected. When inputs from land-based sources and the atmosphere are considered in relation to the mass of nutrients flowing through the area from the North Atlantic and the English Channel this is not surprising (see Table 2). Indeed it is the fact that the Rhine and the Elbe inputs flow close to the coast that makes their impact so effective.

Table 2

Inputs of nutrients to the North Sea all sources (tonnes/yr)

	Nitrogen	Phosphorus
River Inputs[1]	1,000,000	76,000
Direct Discharges[1]	95,000	25,000
Atmosphere[1]	400,000	N/A
North Atlantic Water)[2]) English Channel Water)	2,400,000	500,000

1. Ex Dept of Environment UK 1987
2. Ex Fed. Rep. Germany 1986

The Kattegat is the shallow sea area connecting the Baltic and the North Sea, and is thus affected by the eutrophication of both these areas by means of the water exchange, as well as by increased nutrient loads from land and by atmosphere (an estimated 6 times for N and 10 times for P above background, ICES 1987).

During the spring, the high outflow of low salinity Baltic Water and the warming of the surface layers through solar heating lead to stratification which is further enhanced during the warmer part of the year, when the thermo- and haloclines coincide. In recent years, the thin coastal layer of colder, high salinity water below the pycnocline has frequently become depleted in oxygen, with resultant kills of macrobenthos. The avoidance of the affected area by fish has been commercially important, as has the probable effect on the stocks of large crustaceans such as lobsters (virtually exterminated in the S.E. Kattegat) and Norway lobster (considerable mortality in 1985 and 1986). Remedial action planned in Sweden and Denmark is directed at both the nitrogen and phosphorus loads. Nitrogen is the most limiting nutrient in the Kattegat except near large nutrient discharges with a high N/P ration, such as some rivers in agricultural districts.

IV.3 THE MEDITERRANEAN SEA

Euphotic layers of the major part of the Mediterranean Sea have unusually poor natural supplies of nutrients, typical concentrations being below 0.05 mol. liter^{-1} P-PO_4 and 0.5 mol.liter^{-1} N-NO_3, hence it is known as one of the most oligotrophic regions of the World Ocean. Except for some areas, the Mediterranean shelf is rather narrow and land-borne nutrient inputs are generally very modest except in a few northern areas. Therefore, a widespread offshore eutrophication is unlikely ever to appear, except in the areas directly affected by discharges from rivers most of which are quite polluted.

In fact, two such areas already show indications of a large-scale anthropogenic eutrophication: Golfe de Lion (Bellan-Santini and Levean, 1987) and the Northern Adriactic (Gilmartin and Revelante, 1983; Degobbis et al., 1979; Stirn et al., 1974). The last presents an example of fast developing processes that clearly have a destabilising effect on both ecosystems and the economy (fisheries and tourism). A combination of river-borne and densely scattered point-sources supply this shallow area with unusually high levels of nutrients as shown in Table 3. In response, the productivity as a rule rises quite steadily all over the area (Fig. 2) but with the maximum rise in the western coastal zone (Emiglia Romagna) which, in the summer season, is affected by persistent heavy blooms such as "red tides" which cause anoxic conditions (Figs. 3 and 4) and mass mortalities of fish and benthic invertebrates. Under particular hydrological and weather conditions, summer blooms such as the catastrophic "red tide" of 1977, extend all over the North Adriatic and, there seems to be an increase in the frequency of these phenomena and a consequent decrease in oxygen levels. The decomposition of residual organic matter following the catastrophic "red tide" of 1977 which decreased oxygen saturation which had previously never dropped below 80°%, to as little as 17% (comparison of all measured data between 1911-1973). As a consequence, mass mortalities of

Table 3: Typical[1] concentrations of essential nutrients in euphotic layers along the median of the Adriatic Sea and in characteristic areas of the eutrophied North Adriatic.

AREAS	Concentrations in µmol.dm^{-3}		
	$P\text{-}PO_4$	$N\text{-}NO_3$	$N\text{-}NH_4$
Southern Bassin[2] (extremely oligotrophic)	0.03	1.0	0.5
Mid-Adriatic[2] (oligotrophic)	0.05	0.5	0.5
North Adriatic:			
Central-E waters[3] (moderately eutrophic)	0.12	1.5	1.0
NW-waters[3] (eutrophic)	0.30	5.0	>1.0
W-waters[4] (hipertrophic)	>0.15	>8.0	>2.0

1 = mean values measured during 1970-80; minima as appearing during picks and terminal phases of phytoplankton blooms excluded.

2 = data from Vučak & Škrivanić & Štirn (1982)

3 = data from Franco (1983) and Gilmartin & Revelante (1983)

4 = data from Chiaudani (1983)

Note: Concentrations within the plumes of the Po and a number of other alpine rivers as well asinshore all along the NW Adriatic are greatly exceeding the above levels: up to 1 µmol.dm^{-3} $P\text{-}PO_4$ and 50 µmol.dm^{-3} of total dissolved inorganic nitrogen.

Fig. 2 Schematic presentation of typical
North Adriatic circulation (Stirn,1969)

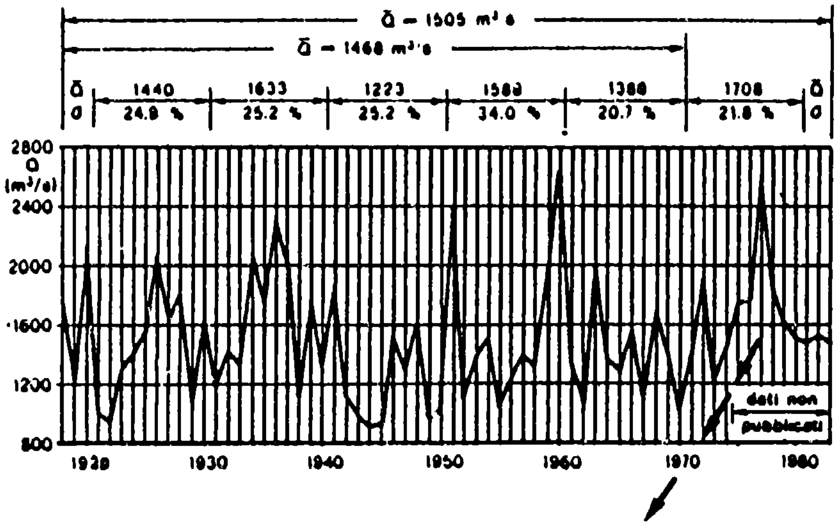
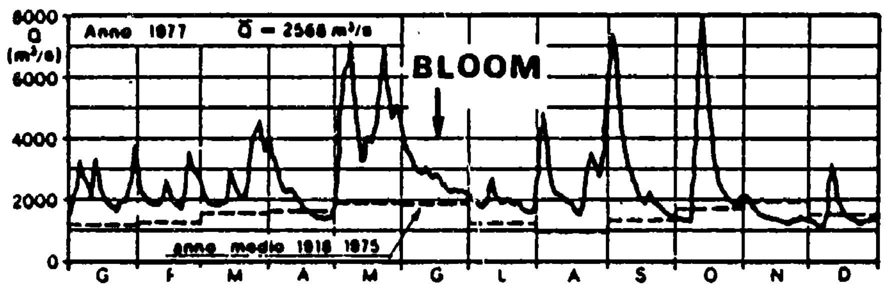


Fig. 3



River Po discharges during 1918-1983 and monthly discharges during 1977 (Grego&Mioni, 1985).

<u>Note</u>: Catastrophic bloom was in June 1977.

Fig. 4

benthic fauna have occurred (Stafanon and Boldrin, 1982).

In addition an increasing number of lagoons, semi-enclosed bays and maritime ports are subject to inputs of nutrients at levels that induce heavy eutrophication and associated adverse effects, the most drastic example being the Lake of Tunis (Unesco 1984, Stirn 1968). This shallow $48km^2$ lagoon receives sewage of 0.5 million population equivalents that result in massive additions of nutrients (median levels in mol.liter^{-1}: 2-8 $P\text{-}PO_4$, 4-16 $N\text{-}NH_4$ and 2-12 $N\text{-}NO_3$) and extremely high standing crops of phytoplankton (50-400 g.liter^{-1} of chlorophyll-a, up to 5-10^7 cells liter^{-1}) and of macroalgae, mainly Ulva (w.w. biomass 0.5-5.0 kg.m^{-2}). In spite of intensive consumption of this plant material, mainly by herbivorous reef-forming polychaete worms, there is a substantial surplus of dead organic matter which decomposes during the summer seasons and takes up all available oxygen. The resulting anoxia causes mass mortality of fish and less tolerant invertebrates.

Coastal Mediterranean Waters of Egypt

Along the coast of Egypt are several relatively enclosed sea water areas that receive considerable amounts of untreated sewage discharges. They are El-Mex Bight, Eastern Harbour, Western Harbour of Alexandria (Fig. 5) and Abu-Kir Bay (Fig 6). Information for the first and last were taken from El-Nady (1981), for the second from Saad et al., (in press) and for the third from Hemeda (1982).

In El-Mex Bight, the concentration of phosphate is higher in the inshore than in the offshore waters, the highest phosphate values are found off the drainage water discharge. The annual average phosphate concentration is 1.3 g-at liter^{-1}. Silicate concentrations are higher in the coastal waters and decrease seawards, they are also higher in the surface than in the bottom waters, giving an annual mean value of 35.5 g-at liter^{-1}.

In Abu-Kir Bay, the main source of phosphate is mostly from allochthonous origin, giving a maximum of 2.5 g-at liter^{-1}. The inshore waters always contain the highest silicate content compared with the offshore waters (maximum value 133 g-at liter^{-1}). The main silicate supply is the discharge from Lake Edku.

The BOD_5 value of the wastes discharged into the Eastern Harbour is equivalent to 5 tonnes of oxygen day (Tech. Report 1978). Eutrophication in this semi-closed area increased to the point where it became unsuitable for recreation and fishing. Depletion of dissolved oxygen and liberation of H_2S occurs at the eastern side, due to the limited exchange of its water with the open sea. The maximum values of nutrients amounted to 8.12, 21.0, 42.0, 1.08 and 44.7 g at liter^{-1} for NH_3, NO_2, NO_3, PO_4 and SiO_3, respectively. The surface nitrate and phosphate values in spring and summer, were lower than the bottom values, in autumn and winter the reverse applies.

In the Western Harbour, dissolved oxygen is depleted in summer and H_2S is liberated. The maximum average phosphate value and the minimum average oxygen concentrations are found near waste-outfalls. The annual

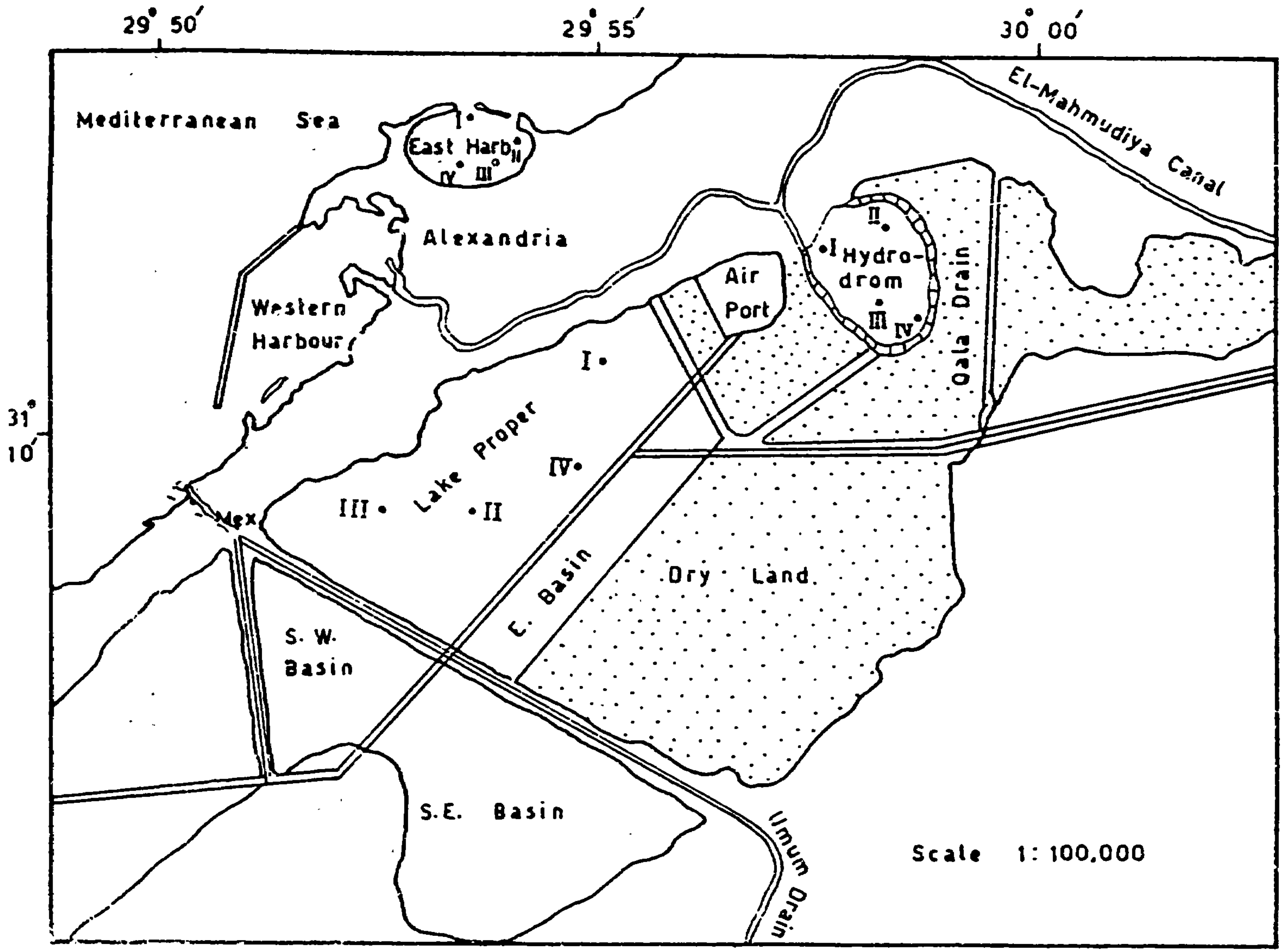
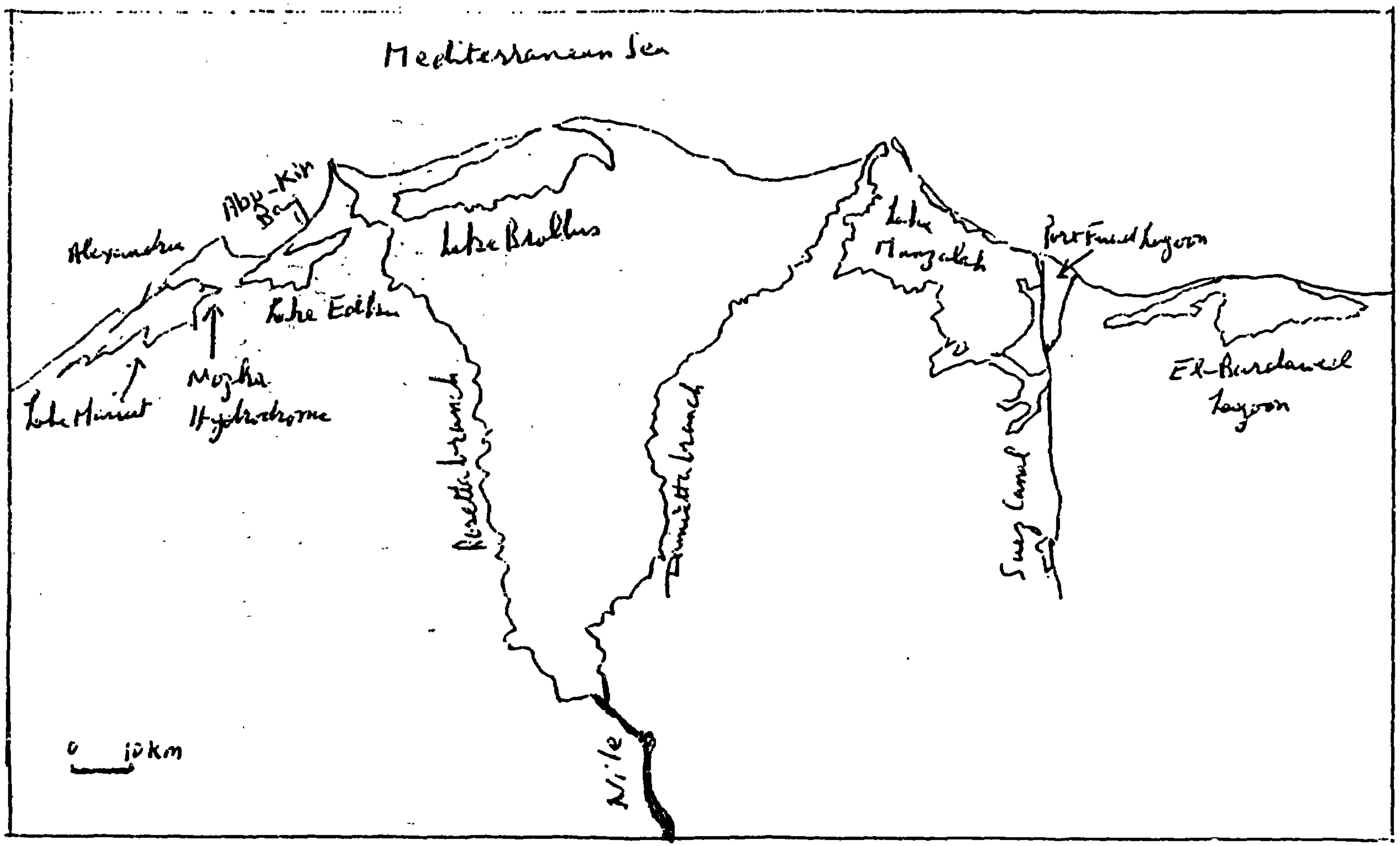

29° 50′
29° 55′
30° 00′
31° 10′
Mediterranean Sea
East Harb
Alexandria
Western Harbour
El-Mahmudiya Canal
Hydro-drom
Air Port
Qala Drain
Lake Proper
Mex
E. Basin
Dry Land
S. W. Basin
S.E. Basin
Umum Drain
Scale 1: 100,000

Fig. 5

Fig. 6


Mediterranean Sea
Abu-Kir Bay
Alexandria
Lake Brollus
Lake Edku
Lake Mariut
Mozha Hydrodrome
Rosetta Branch
Damietta Branch
Lake Manzalah
Port Fuad Lagoon
Suez Canal
El-Bardawil Lagoon
Nile
0 10km

average values of nutrients are 2.5, 0.66, 0.57 and 17.9 g-at liter^{-1} for NO_3, NO_2, PO_4 and SiO_3, respectively.

Experiences from selected brackish water lagoons (Egyptian Delta Lakes) and the Nile Estuaries

The coastal delta lakes in Egypt, as well as the Nile estuaries (Fig. 7) are important land-based sources of nutrient inputs to the southern Mediterranean. They receive huge amounts of drainage waters and the lakes are connected to the Mediterranean with narrow channels, except Lake Mariut, whose water is pumped to the sea.

Several investigations on nutrients and eutrophication have been made on Lake Mariut through the last three decades (Wahby, 1961; Aleem and Sammaan, 1969; Saad, 1973; Wahby et al., 1978; Saad, 1980; Ahdy, 1982; Wahby and Abdel-Moniem, 1983; Saad et al., 1984, Saad, 1985 and El-Rayis and Saad, 1986). Due to the influence of acute pollution (domestic and industrial wastes and agricultural run-off) the phosphate concentrations in Lake Mariut are several times higher than those in the other Egyptian lakes. The total nitrogen load transported to this lake is also very high. In Lake Mariut, the eastern heavily polluted part has abnormal higher levels of phosphate and nitrogen salts. The connection of Lake Edku, Lake Brollus and Lake Manzalah to the sea creates special environmental conditions near their point of connection. The concentrations of nutrients in these lakes are mainly controlled by fluctuations in the drainage waters and domestic waste discharging into them. The nutrient enriched lake waters discharging into the sea increases the productivity of the sea water. Investigations of nutrients on Lake Edku were carried out by Elster and Vollenweider, 1961; Sammaan, 1974; Saad, 1978 a, b; Soliman, 1983. Those on Lake Brollus were made by Darrag, 1974 and El-Sherief, 1983, and on Lake Manzalah by El-Wakeel and Wahby, 1970 and Abdel-Moati, 1985.

The Nile divides into Rosetta and Damietta branches with the delta between (Fig. 7). The summer of 1964 was the last normal discharge of the flood Nile water into the Mediterranean. The sudden cessation of this annual discharge of such a huge amount of river water (about 40 km^3) by the completion of the Aswan High Dam was followed by drastic changes in hydrography and biological economy of the south-eastern area of the Levantine Sea from Alexandria to Beirut (Halim et al., 1967). Since the completion of the High Dam and the creation of Lake Nasser, conditions in and around the two Nile estuaries have changed greatly. The amounts of the Nile water discharged into the Mediterranean have been greatly reduced and are now restricted to Rosetta branch. Its outflow is controlled by a barrage which allows the release of 6% of the silt-free flood water. The the sea-fisheries have been dramatically affected, dropping to about 25% of their previous value (Halim et al., 1974). However, nutrient inputs to the Mediterranean coastal waters in front of Egypt from land-based sources have increased in recent years following the progressive increase in population. This condition might ultimately be beneficial for the biological economy of these waters. Information on nutrients in the Nile branches have been published by Saad and Abbas (1985) and Halim et al. 1974 on the Rosetta branch and Abdel-Moati (1981) on the Damietta branch.

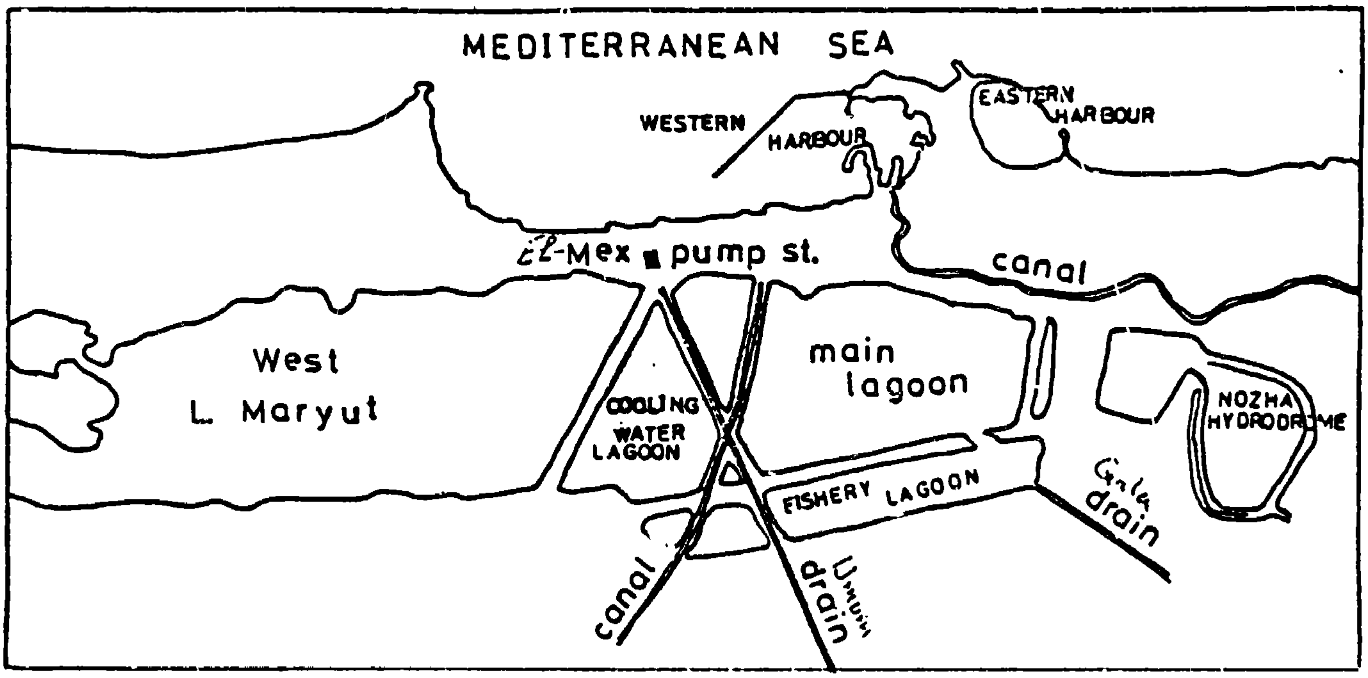

MEDITERRANEAN SEA
WESTERN
HARBOUR
EASTERN
HARBOUR
El-Mex pump st.
canal
West
L. Maryut
main
lagoon
COOLING
WATER
LAGOON
NOZHA
HYDRODROME
FISHERY LAGOON
drain
canal
drain

Fig. 7

IV.4 THE RED SEA AND THE GULF OF ADEN

The Gulf of Aden, except for the Bay of Tadjurah (Djibouti), is generally typical of the naturally eutrophic ecosystem that extends all over the Northern Arabian Sea. Due to monsoon-driven upwelling and general circulation the euphotic layers are almost steadily supplied with extraordinary high nutrient concentrations and consequently phytoplankton biomass is very high (typical yearly range 0.4 - 0.6 g. $liter^{-1}$ of chlorophyll-a. Therefore, the amounts of nutrients added to this environment from existing and expected anthropogenic sources will have a negligible effect except in some semi-enclosed areas affected by sewage discharges, such as in the Inner Bay of Aden and the surroundings of Djibouti.

Conditions in the Red Sea are entirely different, except at its southern end where bioproductivity is relatively high due to the influence of inflowing waters from the Gulf of Aden. The Red Sea is a typical oligotrophic tropical ecosystem with a very poor supply of nutrients. The whole ecosystem and the communities of "vulnerable"[3] coastal habitats in particular, are adapted to function at a climax state only in oligotrophic conditions, thus even modest rates of allochtonous enrichment lead to regressive modifications in the structure and ecosystem functions. For this reason the relatively modest sewage inputs from Eilat, Aqaba, Jeddah, Hodeidah and Massawa induce quite harmful effects within the local coastal environment generally, and particularly remarkable destructions of coral assemblages. Specific to the region, and quite rarely observed elsewhere, is the pollution via fallout of phosphate mineral dust in surroundings of the loading terminals in Aqaba that triggers a variety of pollution effects including eutrophication and subsequent harmful ecological processes (Abu-Hilal, 1985; Walker and Ormond,1982); most affected are the coral assemblages and to some extent the seagrass beds and mangroves too, are most affected.

Eutrophication adversely affects the growth and reproduction of corals and regressively modifies the structure of whole coral communities. Blooming phytoplankton drastically increase the content of suspended matter and hence the sedimentation rates of both, living and dead algal material, leading to the negative effects mentioned above. Turbidity reduces light penetration required for algal symbionts and photophilic coral species. Even slight increases in nutrient concentrations may be damaging, since the coral community shows tight recycling of nutrients and any potential overloading may affect corals by altering calcification rates, energy balance, susceptibility to disease and possible overgrowth by competitors (Antonius 1985; Doty 1969; Fishelson 1973; Johannes 1972, Marangos et al., 1985, Mergner 1981; Mitchell and Chet 1975, Tomascik and Sanders 1985-87; Walker and Ormond 1982). The most destructive consequence of the eutrophied environments seems to be the overgrowth of coral substrata by epilithic algal films and by macroalgae, mainly filamentous green and blue green forms.

Degradation or losses of the above mentioned, "vulnerable

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3 Coral reefs, mangroves, tidal flats etc. (Ormond 1985)

habitats" lead sooner or later to negative economic effects such as:

- Indirect reductions of living resources, including commercial stocks, that depend upon the above habitats as feeding, resting or breeding grounds and as nursery areas;

- Reduction of aesthetic values, important either for tourist development or for existing tourist industry.

IV.5 JAPAN

Eutrophication of nearshore environments around Japan has become a serious problem in terms of coastal fisheries as well as the preservation of the marine environment in the last 20 to 30 years. For example, the occurrence of red tides (200-300 times/year) has been reported frequently in the last 10 years in the Seto Inland Sea. These have caused great damage to the mari-culture of juvenile yellow tail jack (Okaichi and Itami, 1985). The eutrophication has mainly been attributed to increases in the nitrogen and phosphorus inputs from land-sources. In 1972 the inflow and outflow of nitrogen in Japan were estimated to be 3.5×10^6 ton and 3.2×10^6 ton, respectively, and those of phosphorus were 5.3×10^5 ton and 1.1×10^5 ton, respectively (Nakanish and Ukira 1978). About 80% of the phosphorus inflow was derived from agriculture or food use, such as import of fertilizers and grain, and for nitrogen about half was also related to agriculture and food use, the other half being attributed to nitrogen fixation for industrial purposes. Those figures strongly suggest that outflow of nitrogen and phosphorus have increased dramatically during the last 100 years, because before that most of the nitrogen and phosphorus was recycled within the country.

Japan has a population of about 120 million, 60% of which lives in central and western parts of the Pacific coast, which includes the Tokyo metropolitan area with a population of about 30 million. (Fig. 8). Most of the industries in Japan are also located on the Pacific coast. Tokyo Bay, Ise Bay, some parts of the Seto Inland Sea, and other embayments are now recognized as being in a serious stage of eutrophication. Table 4 summarizes the nitrogen and phosphorus load to Tokyo Bay and other coastal areas, together with information of the geography of the surrounding (Nakanisha and Ukita, 1985). The Nutrient load on Tokyo Bay is extremely heavy, considering the area of its watershed and the concentrations of inflowed nitrogen and phosphorus. More than half of the nutrients flowing into Tokyo Bay originate from domestic waste reflecting the population density of the metropolitan area (ca. 2200 Km^{-2}). In fact, as Table 4 shows, nutrient input from human activities represent the predominant fraction of the total influx in all the areas listed, although each area has different characteristics in nutrient sources.

Corresponding to the high load of nutrients to the coastal waters, the expansion of coastal eutrophication is demonstrated by the detailed survey of chlorophyll-a concentrations and phytoplankton cell numbers (Iizuka, 1985a,1985b). More than 100 g^{-1} of chlorophyll-a concentrations was recorded at 28 locations (42% of total survey), with the highest value of chlorophyll-a (3600 g^{-1}) reported in Tokyo Bay, dominated by _Prorocentrum triestinum_ (Dinophyceae). Like Tokyo Bay, red tide flagellate

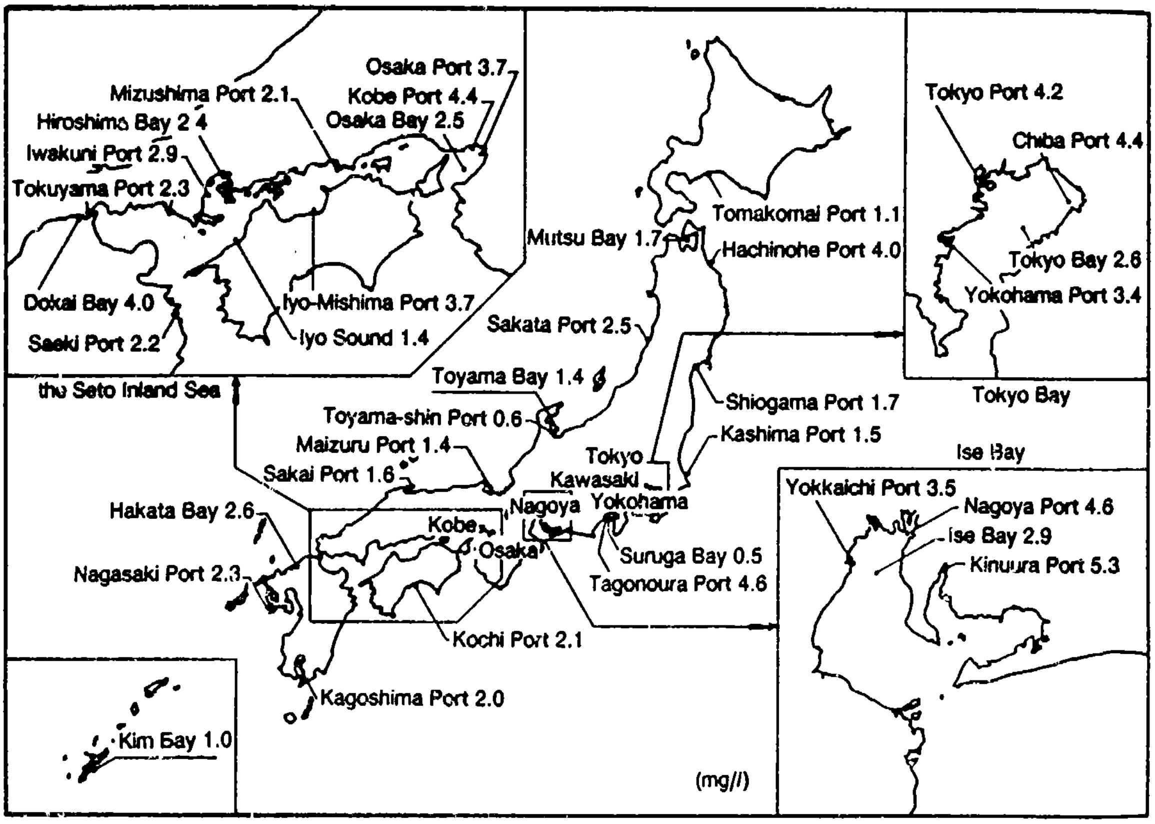


Figure 1. Average chemical oxygen demand (COD), a common pollution indicator, for the main bays and ports of Japan in 1984.

Fig. 8

Table 4. Nitrogen and phosphorus load in polluted embayments and inland sea in Japan.

Area	Tokyo Bay	Ise Bay	Seto Inland Sea
Geography			
Watershed area ($\times 10^6 m^2$)	8300	20659	42919
Volume ($\times 10^6 m^3$)	54000	46000	830000
Surface area ($\times 10^6 m^2$)	1400	1738	?2000
Averaged water depth (m)	38.6	20.0	37.7
Inflow water ($10^6 m^3$/y)	15330	41245	74460
Nitrogen load			
Total (kg/day)	342300	206700	493000
Per watershed(kg/km^2/y)	15053	3652	4193
Per bay volume (g/ m^3/y)	2.31	1.64	0.245
Per inflow (g/m^3)	8.15	1.83	2.42
Phosphorus load			
Total (kg/day)	41000	27500	49200
Per watershed (kg/km^2/y)	1803	486	418
Per bay volume (g/m^3/y)	0.277	0.218	0.0245
Per inflow (g/m^3)	0.975	0.243	0.241
Origin of nutreint load (%)			
Domestic waste			
nitrogen	54.0	33.6	37.5
phosphorus	60.0	35.6	41.9
Agricultural & industrial waste			
nitrogen	27.6	31.9	54.3
phosphorus	22.9	34.6	40.6
Natural drainage			
nitrogen	18.4[1)]	34.5[1)]	8.2
phosphorus	17.1[1)]	29.8[1)]	17.5

[1)] include argicultural drainage.

such as Heterosigma and Gymnodinium are often dominant species in high chlorophyll-a waters, which form aggregates at the water surface during the day time are often the dominant species in high chlorophyl-a waters. In such waters the maximum recorded chlorophyll-a content was 157 g liter^{-1}. Surveys based on cell numbers gave a similar trend e.g., 10^8 liter^{-1} cells were commonly observed in flagellates dominated waters, with 10^{-7} liter^{-1} cells in diatom dominated waters. If this is compared with data collected about 20 years ago, more than one order magnitude of increase in cell numbers is commonly apparent, except for the northern parts and the coast of the Japan Sea (Iizuka, 1963).

Most of the toxic phytoplankton observed in Japan belong to red tide forming dinoflagellates, such as certain species of Gonyaulax, Dinophysis and Protogonyaulax. Occurrence of these toxic phytoplankton has been reported from the various coastal embayments of mainly Pacific coast (Fukuyo, 1985; Fukuyo and Ishimaru, 1986). Among them, Protogonyaulax catanella is observed in many locations on the coast of Japan. Circumstantial evidence strongly suggests that increased frequency of intoxication of bivalves is closely correlated with the eutrophication of Japanese coastal embayments, i.e. stimulation of toxic phytoplankton growth (Takeuchi 1985). Ecological and physiological studies of these toxic phytoplankton to specify the growth factors and the mechanism of toxin formation are now in progress in both laboratory cultures and field observation (Ishimaru, 1985, Ogata et al. 1987).

Extensive studies towards understanding and improving the polluted coastal environments of Japan, including detailed monitoring of water and sediment qualities and biogeochemical cycle of inflowed nutrients, have been carried out. In the case of Tokyo Bay, more than 90% of the nitrogen input is estimated to be transported to the outer coast with an average retention time of ca. 40 days (Table 5). Nitrogen cycling such as assimilation of inorganic nitrogen and mineralization of organic nitrogen, within the bay is quite rapid, especially in the summer when biological activities are stimulated by the increase of both temperature and light intensity (Hattori et al., 1983). Based on the data on nitrogen uptake, ammonia regeneration and their ambient concentrations, the average retention time of inorganic nitrogen in the surface water might be less than several hours in the summer. This means that during its 40 days residence in the bay, nitrogen enters the cycles of assimilation and mineralization more than 100 times.

Growth limiting nutrients in terms of size of standing crop are usually nitrogen in the coastal marine environment. However, in relation to phytoplankton growth rate in the coastal waters, nitrogen is not the limiting factor in all cases. A detailed survey of C/N/P ratio in the phytoplankton population of Tokyo Bay suggests growth rate is limited neither by nitrogen nor by phosphorus even in summer time (Miyata and Hattori, 1986). Simultaneous occurrence of nutrient consumption and production through food webs in surface waters can partially explain these situations.

IV.6 HAWAII

Coral reef communities are generally recognized as being among the most sensitive ecosystems in relation to the potential effects of anthropogenically induced environmental changes. In their natural

Table 5. Nitrogen budget in Tokyo Bay (from Hattori et al, 1983)

1) Total amount (water column)		1.3×10^4 Tons
2) Inflow		
	River, etc.	1.1×10^5 Tons/year
	Precipitation	$6-10 \times 10^3$
	Nitrogen fixation	6×10^1
3) Outflow		
	Denitrification	2.2×10^3 Tons/year
	Sedimentation	4.9×10^3
	Outside of the bay	9.9×10^4
4) Average turnover time		0.12 Year

undisturbed state they are relatively poor in nutrient sources, consequently the addition of external nutrient supplies e.g. from sewage or increased agricultural activity and land run-off can have a major impact, as has been seen in several parts of the world.

One such example is Kaneohe Bay in Hawaii. This semi-enclosed bay is on the north east coast of Oahu and has a watershed bounded by steep mountains on the landward boundary and a barrier reef across the bay mouth. Prior to 1939 the land use was mainly rural agriculture and coral communities flourished in the protection of the barrier reef on the lagoon slopes. After 1939, the area was used for military purposes and parts of the bay were dredged and others filled in, the area was generally developed and the population grew markedly. As the population grew, sewage discharges directly to the bay grew in number and volume and in 1963 several large sewage outfalls were constructed in the south east Bay.

By 1965 some changes had become apparent in the nature of the ecosystem of the bay (Maragos, 1972). The coral community was in decline in the south lagoon and in the middle lagoon the green algae Dictyosphaera cavernosa was producing spectacular growth and smothering the coral. In the north west the reef corals were however still abundant and remained largely unaffected. The changes were attributed to the sewage discharges and it was decided that a long sea outfall should be constructed to divert the sewage out of the bay and directly into the deep ocean. This was completed and fully operational by mid 1978.

Some changes were apparent within a year or so of the diversion (Smith, et al., 1981) and it was already apparent that the progress of deterioration had been halted and some signs of recovery were detectable. In 1983 a major resurvey was conducted using techniques and sites similar to those used in the earlier pre-diversion surveys. These showed remarkable recovery of some coral species in the southern and middle lagoon and continued flourishing communities in the north. Dictyosphaera algae had greatly declined in the areas previously affected although there had been some development of the species in the northern sector (Maragos et al., 1985).

It is clear from the investigations that all the inorganic nitrogen and most of the phosphorus in the sewage was being utilised before it was eventually transported out of the bay. This added source of nutrient was acting as a major nutrient subsidy (nitrogen limiting) but once the source was removed recovering was fairly rapid although not complete due to the fact that some species are long-lived and take time to recolonise and regenerate (Smith et al., 1981).

IV.7 THE GULF OF MEXICO - WESTERN CARIBBEAN

In general, nutrient concentrations in the euphotic zone of the open Caribbean are rather low. Reactive inorganic nitrogen concentrations are particularly low and in some areas up to 40% of the nitrogen budget may be satisfied by nitrogen fixation. Along the western boundary of the Caribbean (Cuba, Mexico, Belize, Honduras, Nicaragua), there are some of the most extensive areas of coral reefs and sea-grasses in the world. The lack of major population centres or industrial activities along these coasts minimizes the risk of serious anthropogenically induced eutrophication which would otherwise represent a serious threat to these communities.

In the Gulf of Mexico, however, the situation is quite different. The Gulf receives very large river inputs from the Mississippi, and numerous rivers draining a major part of Mexico and Guatemala (R. Bravo, R. Panuco, R. Paploapan, R. Coatzacoalcos, R. Usumacinta). In these areas there is indirect evidence of major perturbations on the northwestern continental shelf and conclusive evidence of eutrophication in estuaries, lagoons and bays where major urban and industrial centres are located. Perhaps the most severe and best studies cases are those of the ports of Houston-Galveston, Coatzacoalcos and Havana.

The problem of Havana Bay was the subject of a major UNDP supported project concluded in 1984. The bay (area 5.2 km^2) is virtually anoxic with areas having negligible oxygen concentrations throughout the entire water column. It receives most of the city's drainage (a total of 1.05 x 10^5 kg BOD_5/day) and about 30 tons of total hydrocarbons/day, mostly from local industry. The small tidal range of the Caribbean and the narrow harbour entrance leads to a flushing time of about 6 days for the bay. This slow flushing and the high organic discharges coupled with additional organic matter derived as a result of eutrophication, have resulted in sediments with up to 45% organic matter. The case of the outflow from the Houston ship canal is somewhat similar. In the case of Coatzacoalcos, the river of the same name distributes its organic load and nutrients from the port and associated industries over a somewhat larger area, spreading the contamination but diluting some of the more chronic effects.

Although in many cases the eutrophication itself is not the principal problem it gives rise to a chemical environment with a low oxidative capacity and a large particulate flux of organic matter which favours the retention of associated contaminants such as trace metals (as sulphides) or lipophilic chlorinated hydrocarbons and thus exacerbates the pollution of the local environment. The large particulate organic load of the sediments and water column may also provide a favourable medium for the pathogenic bacteria associated with major urban sewage discharges.

IV.8 USA WATERS

As with other parts of the world, nutrient inputs to certain areas of USA coastal waters have increased markedly and there are numerous examples of changes in phytoplankton growth rates, dominant species and general ecological structure that may be attributable to the increased nutrient loads. From the detailed investigations that have been undertaken on nutrient loading of coastal waters it is clear that most estuaries, bays and indeed open coastal waters receive very substantial amounts of nutrients. In many cases the nutrient loading is actually greater than that encountered on intesively managed agricultural fields (Kelly & Levin, 1986). In this context it must also be recognized that the inputs are not evenly spread but are concentrated at the point of entry of a river, land drain, sewer pipe etc., and actually affect even more acutely a local area within an estuary.

Experimental evidence supports the theory that enrichment can increase production rates and alter the biological community in both water and sediments (Kelly *et al.*, 1985). However, the overall secondary productivity, e.g. of filter feeding species such as clams, does not appear to increase more than a little (Doering et al., 1986). Investigations into the fate of the nutrient inputs suggest that the scale of areas affected is expanding, thus many estuaries and bays that were thought of initially as traps for nutrients can now be seen to be at least partially open systems. This loss of nutrients to more open waters must be looked at in two ways. Firstly it provides evidence suggesting that recovery of a seriously affected area might be possible. Secondly, it suggests a potential for other wider areas to be affected if the input continues long enough, unless the nutrient is truly 'lost' to shelf sediments. This latter possibility indicates a need for a much greater understanding of the relationship between nutrient loads and internal recycling patterns.

Experience in general from investigations of eutrophication effects in the USA suggests that these are not necessarily most obvious in, and certainly are not confined to, the primary production step of the food chain i.e. phytoplankton, macro-algae and sea-grass production. More subtle but equally important, perhaps more so in relation to "pollution" effects, might be changes in species composition, changes in fish yield or the creation of conditions that favour species that either cause human health problems or species that act as vectors of human disease (Harwell et al., 1987).

V. ENVIRONMENTAL CHANGES DUE TO EUTROPHICATION AND THEIR EFFECTS ON MAN'S INTEREST

As the foregoing examples indicate, there is now ample evidence from a wide variety of situations around the world that addition of nutrients to the marine environment can affect phytoplankton production and in turn lead to other adverse effects. All of the affected environments have a common characteristic that of restricted water exchange with the open sea; they range in scale however, from small to large bays, lagoons or inlets to entire enclosed seas, as in the case of the Baltic. The extent of effect which is considered adverse or critical varies markedly, from area to area and ranges from reduced transparency of the water column in the naturally clear waters of the oligotrophic region via the occurrence of oxygen deficient bottom waters as a result of the decay of collapsed blooms to the almost perennial benthic oxygen deficiency over tens of thousands of square kilometers of the Baltic Sea.

The following paragraphs give some of the symptoms of eutrophication and are graded in an approximate order of progression of the development of the phenomenon. It will be noted that features such as increases in organic matter and the development of oxygen deficiency are not unique to eutrophication. They are just as likely to be caused by additions of organic matter from terrestrial sources with or without interference by man. Care must, therefore, be taken in the attribution of cause and effect.

It should also be taken into account that effects of eutrophication, particularly in coastal areas might interact (synergistically or antagonistically) with other impacts of human activity on the marine environment. Most of the possible interaction will be of an adverse nature. Thus disposal of organic material will obviously increase oxygen demand in addition to the secondary effects of eutrophication.

Enrichment might change survival of pathogenic bacteria discharged by domestic sewage. Several ecotoxins, especially insecticides, are known to affect crustacean zooplankton even in sub-ppb concentrations, and a reduction in predatory control of phytoplankton could enhance a stimulation of phytoplankton growth caused by nutrient enrichment. In shallow waters, the capability of benthic filter feeders to control phytoplankton stocks might analogously be reduced by stress from different pollutants. A better understanding of the dynamic function of marine ecosystems is required to evaluate the significance of such interactions.

In many areas, especially those which are oligotrophic or in which phytoplankton production is seasonally limited by nutrient supply, the first signs of the effects of additional nutrient availability will be enhanced phytoplankton activity. This may discolour the water, increase its turbidity and reduce light penetration. These effects may be transient but at unusual times of the year, or they may be of longer lasting duration.

As a consequence of reduced light penetration the zone in which fixed macroalgae can flourish may be reduced, resulting in either a restricted habitat or a total loss of that habitat. Sea grasses may no longer be able to survive and again a habitat may be lost. Conversely macroalgae may increase especially in inter-tidal areas where thick mats of green algae (particularly of Ulva lactuca) may appear and similar algal blankets have been encountered in coral reef areas. It is worth noting that fixed algae and aquatic vascular plants compete for essentially the same nutrients as phytoplankton. Thus, if phytoplankton production leads to demise of the algae more phytoplankton production may result.

With the increased phytoplankton production and availability of nitrogen or phosphorus based nutrients, changes in species composition may occur. This frequently seems to involve a reduction in the numbers of diatoms and an increase in various flagellate types. Often the species which become dominant appear to be less effectively used in the marine food chain and species diversity is reduced.

Although the evidence is equivocal there appears to be a circumstantial link between the increased availability of nutrients and at least the density and scale, if not the occurrence of certain species of algal blooms which are characterized by large amounts of mucous, e.g. Phaeocystis. These can cause interference with fishing operations, through the fouling of gear, and unsightly and smelly foams on beaches (Lancelot et al. 1987).

A number of phytoplankton species produce substances which may be toxic to man or animals or to fish species or birds. Blooms of both toxic and non-toxic algal species are known to occur in open waters where anthropogenic influences are unlikely. Here, the underlying cause of the blooms can usually be traced to local oceanographic conditions that supplement nutrient depleted surface waters with nutrient rich bottom water. In relatively enclosed coastal areas, there appears to be an increase in the number of blooms occurring and it has been suggested that this increase may be caused by anthropogenic nutrient inputs to coastal embayments. The extent to which this suggestion is valid is unclear but there is not evidence from Japan that the incidence of toxins in bivalves has been increased by nutrient inputs to coastal embayments (Takeuchi, 1985).

As primary productivity is increased the rain out of organic matter from dying primary and secondary producers is enhanced and the sediments become enriched with organic carbon and phosphates. This is likely to lead initially to enrichment of benthic animals in terms of both species, numbers and diversity. As organic enrichment of the bottom sediments progresses, species diversity will suffer and, if the conditions become so overloaded that anoxia occurs, near total loss of benthic animals may result.

This latter phase may be associated with severe depletion of oxygen levels in the water, especially in the deeper bottom waters. Thus the water column species diversity and density may also be depressed. Although prior to this phase the water column species composition may be enriched, due to the greater availability of food, this enrichment will often be characterized by smaller species which graze directly on the primary or secondary producers. The food chain may thus be shortened and the large species favoured by man as food may decline in numbers.

The risk of oxygen depletion and anoxia occurring is likely to be greater in the warmer regions of the world due to the more rapid rate of degradation of the organic matter and the fact that dissolved oxygen levels are naturally lower.

As the coastal margins become increasingly adversely affected and habitats are either lost or drastically altered, there may be consequent indirect effects on fisheries for species which are dependent for part of their lives on coastal areas e.g. as nursery or spawning areas, e.g mullet, penaeid, shrimp, flat fish. However, such events are not entirely predictable since the species may be flexible enough to cope with the stress e.g. as have the cod in the Baltic (Elmgren pers. comm.).

Finally it should be recognized that break points in the spectrum of eutrophication are usually sudden and the precise timing not easily predictable, especially in the early phases though some guidelines are possible. Figure 9 illustrates in a schematic way the interdependence of many of the events and lists some of the effects on man's interests. Since it is the impact on these which will most readily be noticed and acted upon rather than subtle changes in species composition, it is worth setting these out in brief detail. The effects can be broadly grouped according to the GESAMP definition of pollution.

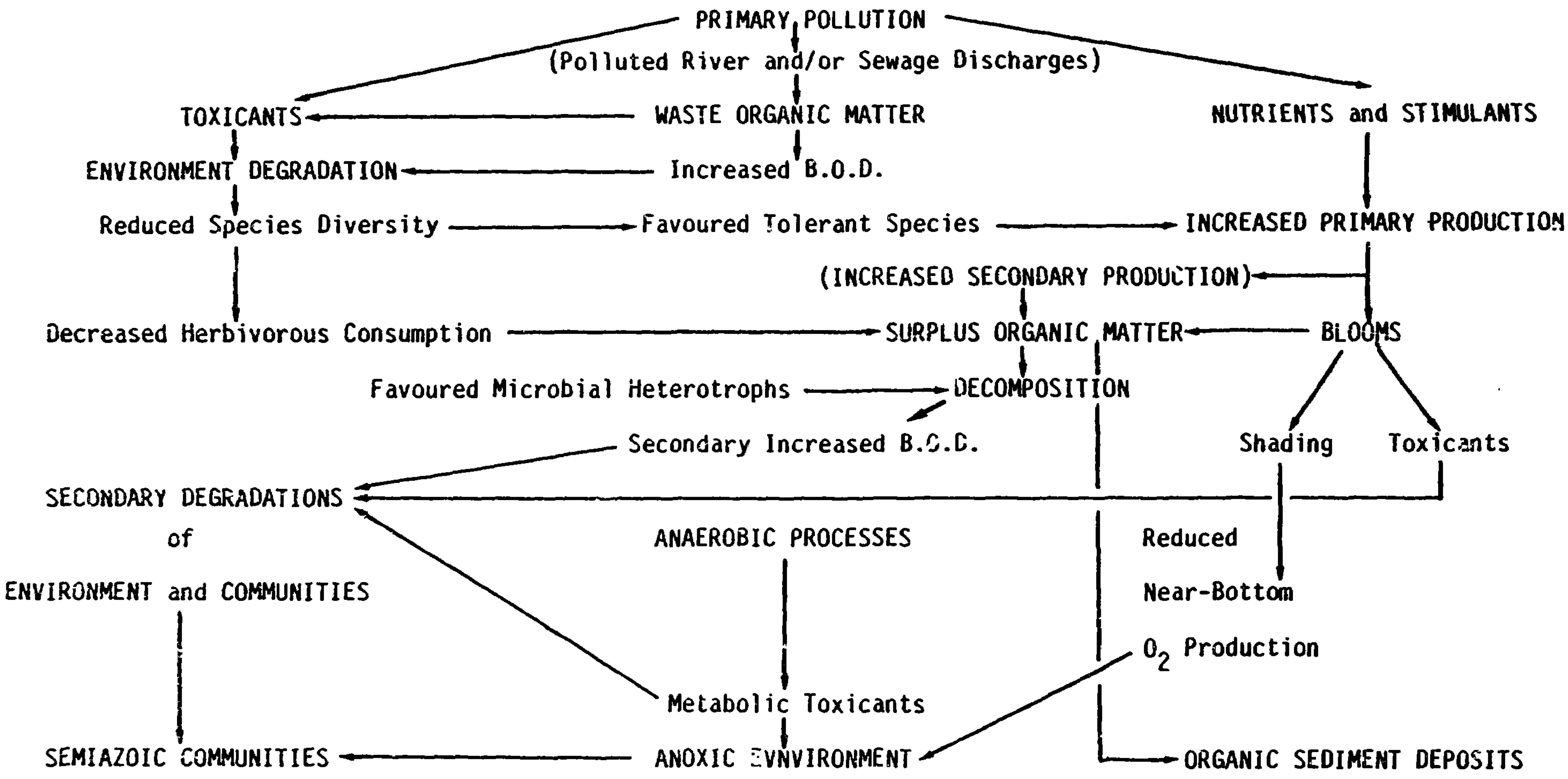
<u>Impact on Fisheries</u>

Initially the increase in primary production may be used to advantage by secondary producers and yields of fish or shellfish may actually increase. In some case, as has happened in the Adriatic, it may become possible to culture or harvest fatter suspension feeding bivalves such as oysters or mussels.

However, as habitats become changed or lost fish and shellfish production is likely to be reduced, either in overall terms or in species diversity terms, usually with consequent loss of income to commercial fishermen, and decrease in the attractiveness of the area to sport or

SCHEMATIC PRESENTATION OF EUTROPHICATION PROCESSES

(Modified from Štirn, 1971)



leisure fishermen.

If oxygen depletion occurs egg or larval survival may be affected and occasional stock recruitment failures may result. As benthic populations suffer there will be an attendant loss of food supply and, unless the fish species can adapt to other food sources as has happened with Baltic Cod, certain fish species may disappear. Finally, if deoxygenation events become large scale, fish may be directly killed.

Impact on Amenities

In naturally oligotrophic waters tourism is often a major source of economic well being. Among the main attractions of such areas are swimming and diving in the normally clear waters. Eutrophication may cause discolouration of the waters rendering them far less attractive, as has happened in the Mediterranean off Emilgia-Romana (Unesco, in press). Coral reefs may be affected and the previously abundant fish species disappear with consequent deterioration in the appeal of the area to sport fishermen and divers.

Blooms of phytoplanktonic algae may give rise to unsightly foams on beaches or to smelly decaying mats of stranded cells in the intertidal zone. Fixed algae may flourish but in the event of storms be washed up on beaches in large quantities only to decay in smelling piles. Increasingly, shallow lagoons in coastal areas are becoming eutrophic and anoxic giving rise to sulphide smells - the Lake of Tunis being one example.

Impact on Other Legitimate Interests

It is increasingly recognized that the natural diversity and character of the environment is something which merits active conservation for its own sake as well as its potential value as an amenity. This interest is clearly adversely impacted if man causes eutrophication of large areas.

Impact on Man's Health

As has clearly been mentioned, there is some evidence that blooms of certain species of algae, which are toxic to man, animals, fish or birds, may be more frequent in areas subjected to anthropogenically increased inputs of nutrients. A thorough review of the effects on human health which can arise as a consequence of direct or indirect contact with certain types of phytoplankton blooms is contained in a WHO Environmental Health Criteria Document (WHO, 1985). In view of this and the equivocal nature of the cause and effect evidence, it would be inappropriate to go into great detail as to the variety of effects, the nature of the species which cause them or the chemical nature of the toxins concerned. The three main toxic syndromes currently recognized in man do, however, merit a brief mention.

Paralytic Shellfish Poisoning (PSP)

PSP is caused by a variable (according to species and incident) range of related neurotoxins of which the best studied is saxitoxin. These toxins are concentrated by marine bivalves which remain unaffected by them.

Human consumption of the bivalves results in intoxication, with respiratory paralysis and death in the most severe cases. About 11 species from three genera (Gonyaulax, Pyrodinium and Gymnodinium) are known to produce PSP. PSP producing species are naturally endemic to some areas, notably the Pacific coast of Alaska, Canada and the USA and strict controls are maintained on bivalve harvesting. In other areas, events are sporadic and controls often do not exist (Mee et al. 1986).

Neurotoxic Shellfish Poisoning (NSP)

NSP is normally associated with the dinoflagellate Gymnodinium breve (= Ptychodiscus brevis), common along the coast of Florida and in the Gulf of Mexico. NSP includes potent icthyotoxins which cause spectacular fish kills. Though direct human fatalities have not been reported, on shore winds sometimes carry toxic cells to coastal settlements causing widespread human respiratory distress and skin irritation requiring hospitalization in the worst cases. Blooms of P. brevis have been particularly severe in Texas and Mexico in 1986-87 causing widespread public concern. The popular press in these countries has related the events to domestic and industrial pollution but there appears to be no firm scientific evidence of such a relation.

Diarrhoeic Shellfish Poisoning (DSP)

DSP is associated with species from two genera, Dinophysis and Prorocentrum. This is a recently described phenomenon recorded in Europe, South America and Japan. Toxins are concentrated by marine bivalves and cause diarrhoea in humans consuming them. There is, as yet, little information on the ecology of the causative dinoflagellates.

Toxic Blue-green Algal Blooms

Blooms of toxic blue-green algae are a common problem of eutrophic freshwater lakes, and have long been a feature of enclosed brackish lagoons of the Southern Baltic coastline. Their (sublethal) effects on man have long been known as "Haff disease" (Birger et al. 1973), and domestic animals have occasionally died from drinking the water. Recently, summer blooms of the nitrogen-fixing cyanobacterium Nodularian Spuamigena in the open Baltic have killed dogs, after the blooms have been concentrated along the shoreline by the wind (Edler 1986). Similar blooms have been recorded also in brackish inlets in Australia and may thus be expected also in other eutrophic nitrogen-limited brackish areas with sufficiently high summer temperatures (above 16-18°C).

VI. STRATEGIES FOR ASSESSMENT OF AND RESEARCH ON EUTROPHICATION EFFECTS (MONITORING, MODELLING, EFFECTS STUDIES)

The experiences presented in this report, suggesting that eutrophication is an expanding and common problem influenced by human in marine areas affected by human activity but with limited water exchange, emphasize the need for a widely applied monitoring system. This need is all the greater due to a marked lack of good quality long-time series data relevant to the problem.

The fundamental decision to be made is whether to select a few simple key parameters measured at many stations and on many occasions or to aim for a large set of parameters measured at a few selected stations. The latter approach provides a better chance of the data being interpretable in a biological context, while the former approach takes into account the fluctuations and spatial heterogeneity of the marine environment. For instance simple measurements of Secchi depth and oxygen concentration above the sediment would allow a description of the extent and duration of blooms and benthic anoxia, which are central aspects of eutrophication effects. The use of remote sensing of surface pigment concentration and moored buoys continuously transmitting data are promising tools for a closer monitoring of the variability of eutrophication effects, but with a limited potential for a wider regional application at present. Whichever strategy is chosen, a basic set of oceanographic physical data allowing an understanding of general current patterns and stratification is compulsory.

As eutrophication is primarily a stimulation of flux rates in the ecosystem, direct monitoring of these is likely to be more fruitful than monitoring of pool sizes, which are only secondarily affected by eutrophication. On the other hand, the measurement of flux rates often implies methodological problems (e.g. incubation effects) which can hardly be taken into account within a routine monitoring.

As a further distinction, some parameters such as phytoplankton biomass or production, reflect the instantaneous situation, while others e.g. benthic species composition give a more integrated picture. Clearly monitoring of parameters that are liable to change rapidly will involve rather frequent sampling and/or measurement. However, such monitoring is also likely to yield results which will more rapidly reveal responses to changes in environmental conditions than a programme which relies on more integrative parameters. Thus the choice of parameters will be governed to some extent by the desired time resolution of the programme.

Whichever approach is adopted two guiding principles should be observed. Firstly, resources for monitoring are likely to be limited and it is preferable to deploy this monitoring within a given set of parameters thoroughly at a few stations, perhaps using buoys as bases for continous records rather than monitoring inadequately (infrequently or few parameters) at many stations over a wide area. Secondly, the methods used in the monitoring programme should be common at least to the region in question. An example is the series of Reference Methods for Marine Pollution Studies published by the UNEP Regional Seas Programme Activity Centre. If it proves impossible for all participants to use a single method, very careful intercalibration should be undertaken of all methods used.

The following list of proposed parameters for monitoring of eutrophication effects includes flux rates and pool sizes, instantaneous and integrative parameters and finally represent different levels of sophistication and instrumentation requirements.

1. One of the first signs of eutrophication may be an increase in or longer periods of turbidity; the simplicity of the Secchi disc measurement makes it a valuable tool in area where a contribution

to turbidity by resuspension of sediments or seasonal variation in suspended sediments from riverine or other sources can be excluded. On a slightly more sophisticated level, measurements of turbidity using a turbidity meter can be used in addition to or instead of the Secchi disc measurement. Records of the colour of the water using a standard reference such as the Forel system may also provide useful data.

2. Long-term measurements of the dissolved oxygen content of the water and especially the deeper water, will provide useful data. If oxygen probes (electrodes) are used care must be taken to ensure they are correctly calibrated for the salinity in question and that the membrane is kept clean but intact.

3. Nutrient levels (particularly N, P and Si). It should be noted that concentrations of dissolved inorganic nutrients usually become depleted during growth seasons due to uptake by phytoplankton, except in very eutrophic environments. Therefore, it might be appropriate either to focus on winter concentrations or to measure total concentrations (including dissolved, organic and particulate forms).

4. Some record of phytoplankton density will be necessary and measurements of chlorophyll-a using a simple spectrophotometer will provide useful data, especially if supplemented by biovolume measurements made using a microscope.

5. In shallow areas if turbidity is increased, the ability of macrophytes to flourish may be affected; simple records of the distribution of benthic macrophytes (and vascular plants) in terms of percentage area covered and depth limits will provide a useful indication of any such effects.

6. A time series of measurements of primary productivity may provide some useful indications of changes in this index over time. This may be measured <u>in situ</u> or as potential production using an incubator using either the oxygen technique or with greater sensitivity, the C-14 method.

7. It will be necessary to have records of the species composition of the phytoplankton, at least to the extent that the dominant species during bloom events are recorded.

8. Information on the history of sediment characteristics can be extremely valuable as these are likely to be changed by organic enrichment. In its simplest form this may amount merely to a record of the depth of the aerobic layer. If good quality deep cores are available, measurements may be made of plant pigments (by solvent extraction) as a means of recording changes in extent and type of past phytoplankton sedimentation.

9. The organic carbon content of the sediments may change and this can be established by a variety of total organic carbon analysis techniques with various levels of sophistication. It should be remembered in this context, however, that increased primary

productivity is only one source of enhancement of sediment organic carbon, among e.g. sewage, food processing effluents, pulp and paper, effluents, etc. (This also applies to 8 above).

10. Assessment of the composition and density of the benthic fauna is a useful indicator of change in benthic conditions that may be attributable to eutrophication. It has the advantage of needing to be undertaken at relatively infrequent intervals and can be conducted at various levels of detail of identification. (Changes may also occur naturally or for other man-induced reasons).

11. Sedimentation rate measured over relatively short-time scales either using traps or integratively using the distribution of a radio tracer such as Pb-210 may be useful in undisturbed sediments in areas of steady sediment accumulation. However, this too can be affected by other anthropogenic activities.

12 Although some of the methods involved are relatively complicated, measurement of heterotrophic activity appears to offer some promise as an alternative or addition to primary production measurement. Its advantage is that it is light independent and less liable to variation due to the buffering effect of the DOC (dissolved organic carbon) pool. Three possible means of assessing heterotrophic activity are oxygen respiration, tritium labelled thymidine incorporation and exoproteolytic enzyme activity; the latter two methods offer greater sensitivity and the last mentioned involves a relatively simple colour change assessment.

13. Finally, remote sensing either by aircraft or balloons or by satellite imagery can be a remarkably sensitive means of acquiring data over large sea areas. It is, however, essential to establish the ground truth of the data by actual measurements at sea and it must be noted that at present, 1987, no satellite is available which offers suitable facilities to the scientific community in general.

Modelling Studies

Modelling studies are important primarily as a means of checking the consistency of our perceived understanding of a set of complex, interrelated problems. If modelling efforts are repeatedly successful in describing recorded events, they may later be used, with caution, as predictive instruments. In limnology, the simple semi-empirical approach of Vollenweider (e.g. 1982) has been found to be of considerable predictive value for phosphorus-limited lakes. It relates phosphorus load, scaled for lake hydraulic retention time, to various ecosystem responses, such as average chlorophyll content, peak chlorophyll content, hypolimnetic oxygen consumption, and even fish production (Rast et al. 1983). Much more complex lake models have been developed, but so far seem, at best, to do only as well as the simpler Vollenweider approach.

The Vollenweider approach cannot be simply applied to marine eutrophication, since it is based on the assumption of one mixed reactor, and on the simple inflow-outflow condition of lakes. Furthermore, nitrogen which is of central importance in marine eutrophication, has a much more complicated biogeochemical cycle than phosphorus, involving several oxidation states, denitrification and nitrogen fixation.

This suggests that rather more complicated approaches than that of Vollenweider, with greater emphasis on hydrodynamics and including more biological realism in the description of the nitrogen cycle, and perhaps dealing with two limiting nutrients (N and P - perhaps even Si in some cases), will be needed for analyzing marine eutrophication. The range in nutrient loads and resulting concentration is also greater in lakes than in most coastal marine habitats, making nutrient load the dominant structure variable for lakes. But lakes with similar P-loads may still vary in biological response by more than an order of magnitude, due to differences in the composition of the higher trophic levels (fish) of their biological community. Understanding such "top-down" ecosystem controls, requires much more biological knowledge than the Vollenweider approach and cannot yet be done even though there is evidence of its importance (McQueen et al. 1986) quantitatively for lakes. The fish productivity of marine areas is general 5-10 higher than for freshwater system of similar primary productivity (Nixon et al. 1986) making it highly likely that such "top-down" control is even more important in the sea than in lakes. So far, it has been little studied, perhaps because manipulating the composition of the fish community is much less realistic as a management option in the sea (see Riemann and Sondergaard 1986).

Thus, in studies of marine eutrophication, modelling at present is likely to be more of a necessary analytical method, than an accurate predictive instrument. This may gradually change in the future as investigation advances our understanding.

VII. REMEDIAL ACTIONS

In coastal waters which are widely open to the sea, particularly when human settlements are small and/or scattered, there is in principle no risk of a considerable anthropogenic eutrophication, provided that the sewage and similar effluents are adequately disposed and dispersed away from the immediate inshore zones. Disposal of mechanically pretreated effluents via submarine pipelines with diffuser outlets at an appropriate distance from the shore and in a depth below the themocline, wherever applicable, can be proposed as an adequate control measure, and the most economic one. Useful, relevant engineering information is available in the UNEP/WHO manual "Waste Discharges into Marine Environment", Pergamon Press, Oxford; 1982, 422p.

However, it should be stressed that this strategy of course does not apply to stagnant marine environments such as lagoons, semi-enclosed bays and inlets and many types of estuaries whose receiving capacity is very restricted.

In of coastal waters where of water exchange with the open sea is rather limited and where the integration of nutrient inputs via sewage, agriculture, industry and the natural load, carried by rivers, ecosystem receiving capacities can be exceeded. In such circumstances the strategy of direct discharge is obviously not a solution. In this case, it is of crucial importance to reduce levels of nutrients, entering the coastal sea wherever this is feasible; unfortunately, even so a substantial part of loads that cannot be at present controlled by technical measures will contribute to the enrichment of the coastal sea. From an engineering and management stand point this means very definite and advanced treatment of any substantial effluents discharged into rivers and of those from larger settlements and industries along the shores, plus significant improvements in utilization of agricultural fertilizers. Such projects require large funds to cover the capital and running costs and it would be a pity to use them, perhaps badly, without a significant effect. It is, therefore, very important that the measures taken are appropriate to the problem and its cause. For example, as was seen in previous chapters, for some areas of concern, it is still not known which are the limiting nutrients but in treatment technology and pertinent costs, it makes quite a difference if phosphorus or nitrogen is to be eliminated from effluents. While in some cases, the removal of phosphorus may be beneficial and sufficient, in most cases, a reduction of the nitrogen discharge is likely to be needed. It cannot be overemphasized that specific research and assessment is needed before decisions are taken.

VIII. SUMMARY

1. In order for phytoplankton growth to occur, nutrients must be present. The elements most commonly considered essential are the combined forms of phosphorus and nitrogen, but it is increasingly apparent that the presence or absence of other substances, albeit in trace amounts, may limit growth in some circumstances. It is also now generally recognized that if the readily available inorganic forms of nitrogen and phosphorus are exhausted, phytoplankton can continue to grow by utilizing internal reserves and/or other forms of nitrogen and phosphorus.

2. Blooms of phytoplankton occur when conditions favour rapid growth. Other factors, apart from nutrient availability, are important in this respect, light, temperature and water column stability being especially so. In temperate waters, the spring bloom of phytoplankton is a normal feature of the marine productivity cycle. In equatorial regions seasonal variation in production is much less marked. Areas in which upwelling of nutrient rich deep water occurs are markedly more productive, in both plankton and fish population terms, then adjacent regions.

3. Inputs to the marine environment of nitrogen and phosphorus have increased, mainly as a consequence of wide scale use of fertilizers, the adoption of intensive animal husbandry techniques, the discharge of sewage and industrial waste water, and at least in some areas, nitrogen oxide emissions to the atmosphere from combustion processes.

4. In some coastal waters and enclosed seas, increased inputs of nitrogen and phosphorus compounds have led to clearly detectable increases in the concentrations of such compounds in the water. The areas so affected are numerous and geographically widespread.

A common feature of all the areas so affected is a limited water exchange with the open sea. There is no evidence of such increases in open-shelf sea waters or open ocean areas and there seems little likelihood that this could occur in the foreseeable future.

5. There is evidence that in the marine environment, changes in phytoplankton species composition occur, inter-alia as a result of long-term climatic changes. It is also clear that phytoplankton blooms have always occurred. Some blooms of phytoplankton can cause problems and none of these seem to be new although, as a result of increased understanding or changes in public perception, their formal identification or classification may be new. For example deoxygenation, the production of toxins and the discolouration of sea water and, in certain cases, the production of unsightly foams are all matters readily appreciated now by most persons, at least in the developed part of the world.

6. In recent years, there have been more frequent reports of phytoblankton blooms of certain causing problems phytoplankton, especially in enclosed sea areas. There are also suggestions that algal blooms in general tend to last longer and be of greater scale in some areas than in the past and that they occur at unusual times of the year. To some extent, this probably reflects a greater awareness of the attendant problems. However, there is strong evidence from the worst affected areas, which are as far apart as Japan and the coastal inlets of the eastern North Sea, that some of the reports reflect genuine increases in both scale and frequency.

7. There is evidence that these increases in algal production are linked to the increases in inputs to those areas of nitrogen and phosphorus nutrients. Other changes have been noted which may also be linked to the availability of these additional nutrients in the affected areas, e.g. a tendency for a shift in the dominant phytoplankton species to forms which may be of less value in the overall marine food chain.

8. The main concern from a human health stand point in relation to changes in phytoplankton blooms is the fact that certain species give rise to toxins which are accumulated by filter-feeding molluscs such as mussels, clams and oysters and cause poisoning in man. Three syndromes recognized in this context are PSP, DSP and NSP. Blue-green algal blooms may also be toxic and cause illness in man and the death of animals.

9. Some blooms of toxic phytoplankton are almost certainly natural events. However, whilst such blooms occur in areas which are unlikely to be affected by added nutrients, there is some evidence from Japan, that in areas which are subject to major nutrient inputs, there is an increased frequency of blooms of species which give rise to PSP, DSP, NSP etc.

10. Certain phytoplankton blooms are associated with kills of fish and benthic fauna either through deoxygenation or because of secretion of substances which are either toxic or clogging. As with other

phytoplankton blooms, some of these events are almost certainly not associated with anthropogenically increased nutrient inputs. However, the increasing frequency of such events in association with fish farming in enclosed bays or inlets, i.e. areas in which amounts of nutrients are added to waters with restricted water exchange, suggests that there may well be a cause and effect relationship in such circumstances.

11. In the Baltic the cause for concern stems at least as much from the tendency for nutrients (especially phosphorus) to accumulate in the bottom waters and sediments, and from the increasing volume of deoxygenated deep water which arises as the plankton decay. Whilst this is in part a reflection of the slow and intermittent deep water turn over in the Baltic, it may well occur in other enclosed areas with high entrance sills, e.g. the Black Sea. On a smaller scale, it is certainly a potential problem in fjord-like inlets (with sills), and has been observed in areas such as Oslofjord and some Danish coastal areas.

12. In many areas of the world which are potentially threatened by eutrophication, there is a need for a marked improvement in observational monitoring efforts in order to establish time series data on which to base identification of eutrophication events or trends.

13. It is possible, on the basis of experience in areas which are recognizably eutrophied, to identify the types of changes which characterize the progressive stages of eutrophication from early onset to criticality, and these are listed in section VI of this report. Some of these parameters can be measured using relatively simple techniques and can assist in the avoidance of serious environmental consequences if remedial action is taken at a sufficiently early stage. Modelling of marine eutrophication is at a relatively early stage but is potentially useful for predicting certain events and the consequences of remedial action.

14. There is ample evidence, from action taken in local situations as widely separated as Japan, Hawaii and the Baltic Sea, that is possible to control the eutrophication process and improve environmental quality by reducing the scale of nutrient inputs to an affected area. The extent of reduction required and the time taken for the environment to recover will depend both on the degree of eutrophication and the characteristics of the area. In some cases, it may be sufficient to discharge the effluent further offshore in an area of better water exchange. In others removal of some of the nutrient load will be necessary. The reduction of the phosphorus inputs via sewage is relatively easy and inexpensive to achieve and may lead to a phosphorus limited system where excess nitrogen sources are available. Whilst this may prove adequate in some cases, in most the removal of nitrogen will also be necessary. Where the main source of nutrients is agriculture, reduction of both nitrogen and phosphorus inputs may be necessary and may require substantial changes in the use of fertilizers in agriculture and the adequate treatment or disposal of animal wastes from intensive animal husbandry units.

15. Whilst some of the effects of eutrophication are quite dramatic, it is extremely difficult to state with certainty that the occurrence of any one feature, or even a series of similar incidents over several successive years, is not a perfectly natural event. The marine environment is known to show marked but ill-understood short-term fluctuations and even less well understood long-term changes. By its very nature, eutrophication is simply an extreme form of a natural event and it does not help that, although there are common features, the early symptoms appear to vary in their occurrence from area to area. It can, therefore, be extremely difficult to identify the early stages of eutrophication with the desired scientific exactitude. Consequently, it may be hard to persuade the policy makers and pollution prevention authorities to take remedial or preventative action.

16. However, since eutrophication seems to occur only in areas with restricted water exchange, it is possible, on a local scale, to identify areas which may be at risk. Thus, for example, any lagoon, inlet, fjord or enclosed bay which receives anthropogenically enhanced nutrient inputs is liable to show signs of eutrophication in time. If the area is naturally oligotrophic, these symptoms are likely to be apparent with relatively smaller total additions than would be the case in an area of naturally high productivity/nutrient availability. More difficult to predict is the impact on large geographical areas which receive their nutrient additions from many sources, each of which individually might not be significant but which together may have a cumulative effect on a large area e.g. Baltic Sea and the eastern North Sea coastal water.

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