Non-rotating Gravity Currents. Rotating Gravity Currents. Tides. Upper Ocean Mixing Processes.

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EUTROPHICATION

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Introduction

Eutrophication is the enrichment of the environment with nutrients and the concomitant production of undesirable effects, while the presence of excess nutrients *per se* is merely regarded as hypernutrification. In more detail eutrophication is

> the process of nutrient enrichment (usually by nitrogen and phosphorus) in aquatic ecosystems such that the productivity of the system ceases to be limited by the availability of nutrients. It occurs naturally over geological time, but may be accelerated by human activities (e.g. sewage disposal or land drainage).
>
> (Oxford English Dictionary)

Anthropogenic nutrient enrichment is important when naturally productive estuarine and coastal systems receive nutrients from 'point sources', e.g. as outfall discharges of industrial plants and sewage treatment works, or human-influenced 'diffuse sources', such as runoff from an agricultural catchment. Whereas point source discharges are relatively easy to control, with an appropriate technology, diffuse and atmospheric sources are more difficult and require a change in agricultural and technical practice.

Coastal and estuarine areas with tide-associated accumulation mechanisms for seaborne suspended

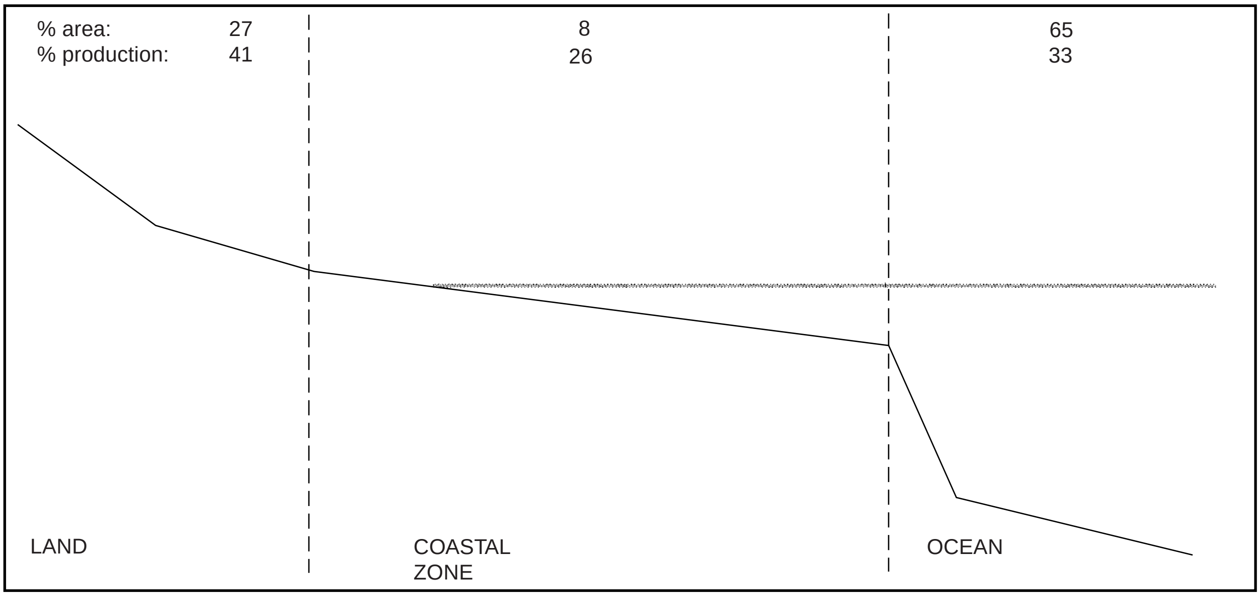

Figure 1 Indication of importance to primary production of different types of area (land, ocean, and shallow coastal seas and its fringes). (Redrawn after LOICZ, 1993. Report no. 25, Science Plan, Stockholm.)

matter are organically productive by nature and represent some of the world's most productive environments. This is the result of the freshwater outflow, and biogeochemical cycling within the estuarine systems and adjacent shallow coastal seas. About 28% of the total global primary production takes place here, while the surface area of these systems covers only 8% of the Earth's surface (**Figure 1**) and as such the effects of eutrophication are most manifest in the coastal zone, including estuaries, areas which are the focus of this chapter. As indicated below, there is generally a good qualitative understanding of the processes operating, but the quantitative influence on the ecological processes and the changes in community structure are still not well understood. Within the available field studies attention has been focused on long data series, because time-series with a length of less than 10 years have to be considered as too narrow a window of time relative to natural meteorological and climatic fluctuations influencing the ecosystem.

Table 1 Recent and 'prehistoric' loadings of some systems by nitrogen and phosphorus and the resultant annual primary production of these systems

System: period/year	*N influx ($mmol\ m^{-2}\ a^{-1}$)*	*P influx ($mmol\ m^{-2}\ a^{-1}$)*	*Mean annual nitrogen concentration in system ($\mu mol\ l^{-1}$)*	*Mean annual phosphorus concentration in system ($\mu mol\ l^{-1}$)*	*Annual primary production ($g\ C\ m^{-2}\ a^{-1}$)*
River Rhine and River Ems					
'background' situation			45 ± 25 (tN)	1.8 ± 0.8 (tP)	
English Channel					
'background' situation			5.5 ± 0.5 (winter NO_3)	0.45 ± 0.05 (winter DIP)	
North Sea					
'background' situation			9.1 ± 3.1 (NO_3) (near coast)	0.57 ± 0.13 (DIP) (near coast)	
Dutch western Wadden Sea					
'background' situation			13 ± 6 (tN) *c.* 4 (DIN)	0.8 ± 0.3 (tP) *c.* 0.3 (DIP)	< 50
Ems estuary	(rivers)	(rivers)	(for salinity gradient)	(for salinity gradient)	
'background' situation	315 (tN)	16 (tP)	10–45 (tN)	0.7–1.8 (tP)	
early 1980s	3850 (tN)	90 (tP)			
early 1990s	3850 (tN)	50 (tP)			
Baltic Sea					
'background' situation	57 (tN)	0.8 (tP)			80–105
(*c.* 1900)	(rivers + AD + fix)	(rivers + AD)			135
early 1980s	230 (tN) (rivers + AD + fix)	6.7 (tP) (rivers + AD)			
Narragansett Bay					
'prehistoric' situation	18–76 (DIN) (rivers + AD) 270–330 (DIN) (+ sea input)	~ 1 (DIP) (rivers + AD) 61 (DIP) (+ sea input)			130
'recent' (1990s)	1445 (DIN) (rivers + AD) 1725 (DIN) (+ sea input)	73 (DIP) (rivers + AD) 140 (DIP) (+ sea input)			290
Long Island Sound					
1952	—	—			
early 1980s	1040 (tN)	70 (tP)			*c.* 200
	(rivers + AD)	(rivers + AD)			300
Chesapeake Bay	290–2140 (DIN)	30 (DIP)			400–600
mid-1980s	1430 (tN)	40 (tP)			

tN, total nitrogen; tP, total phosphorus; DIN, dissolved inorganic deposition nitrogen; DIP, dissolved inorganic phosphorus; AD, atmospheric deposition; fix, nitrogen fixation.

Nutrient inputs are required for the natural functioning of aquatic systems. Eutrophication merely indicates that the system cannot cope with the available inputs. This chapter focuses on the causes and mechanisms of eutrophication as well as the consequences. It gives examples varying from eutrophication caused by freshwater inflow to that caused mainly by atmospheric inputs and nutrient import from the sea instead of land and atmosphere. It will be shown that increased organic enrichment may lead to dystrophication, the modification of bacterial activity leading ultimately to anoxia. Despite this, certain areas with low hydrodynamic energy conditions, such as lagoons, part of the estuaries and enclosed seas, can be considered as naturally organically enriched and thus require little additional material to make them eutrophic. In contrast, there are also naturally oligotrophic areas which drain poor upland areas and receive little organic matter.

The symptoms of eutrophication as a response to nutrient enrichment differ greatly, due mainly to differences in the physical characteristics of the different systems receiving this 'excess' organic matter and nutrients. For example, the mixing state (stratification or not) of the receiving body of water and the residence time (or flushing time) of the fresh water and its nutrients in the system determine the intensity of a particular symptom and thereby the sensitivity of systems to eutrophication events or symptoms. For example, in the UK, the susceptibility of waters to enrichment and adverse effects caused by nutrients is interpreted according to their ability as high natural dispersing areas (HNDA). In general, this reflects the waters' assimilative capacity, i.e. capacity to dilute, degrade, and assimilate nutrients without adverse consequences.

Historical Background

Several attempts have been made to determine either the nutrient loads to coastal zones during the 'pre-development period' (i.e. before widespread human development) or to determine the 'natural background' concentrations of nutrients. These assessments are important, as they may improve our understanding of the way eutrophication in the past may have changed and in the future will change aquatic systems. The term 'natural' is regarded here as those levels present before the large-scale production and use of artificial fertilizers and detergents started. It also covers the period just prior to the start of chemical monitoring

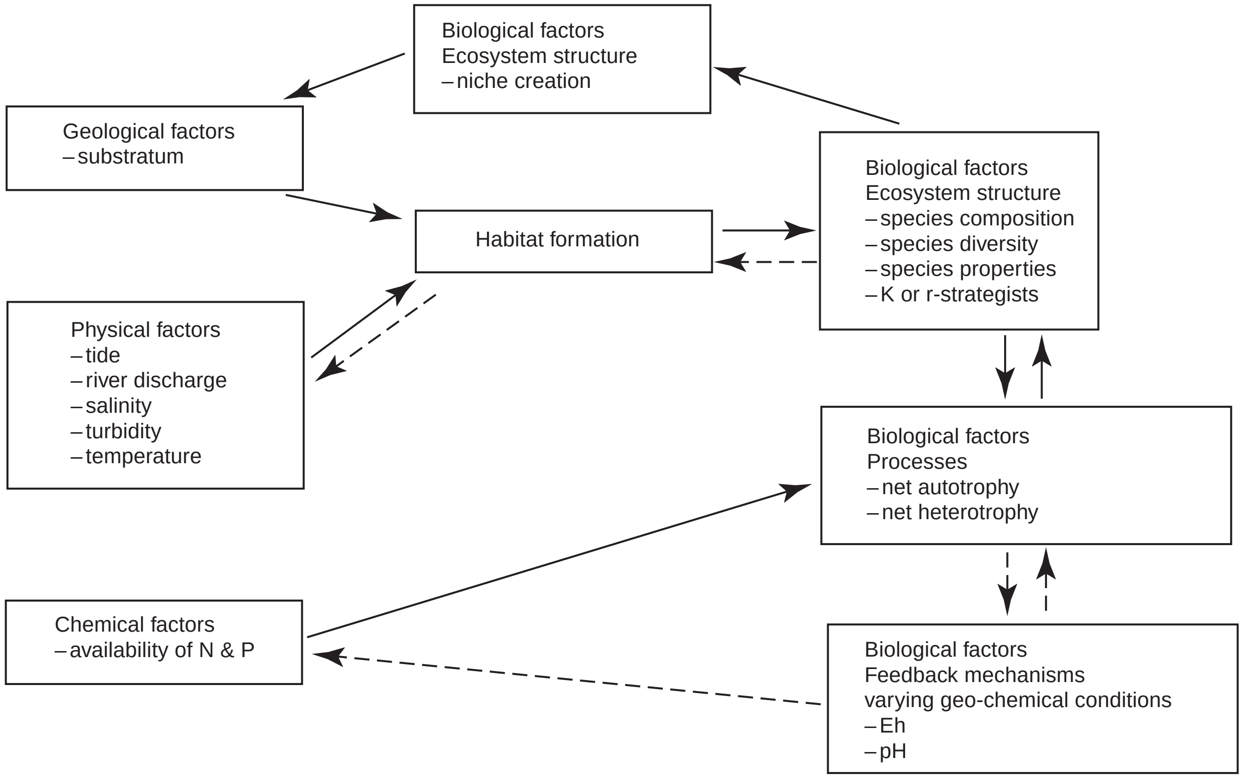

Figure 2 Operating forcing variables in the development of estuarine and marine biological communities.

of the aquatic environment. For example, the greatest increase in nutrient loads to the Dutch coast and the Wadden Sea occurred after the early 1950s, due to the introduction of artificial fertilizers and detergents.

Available data for Narragansett Bay (USA) suggest that the system presumably was nitrogen limited in the past and that the total dissolved inorganic nitrogen (DIN) input has increased five-fold, while that of dissolved inorganic phosphorus (DIP) has increased two-fold (**Table 1**). During that period the nutrient input from the sea is assumed to have been more important than the supply from the drainage basin, a feature that in the early 1950s has also been postulated for European waters.

Natural background concentrations for some Dutch and German rivers as well as the Wadden Sea are given in **Table 1**. The values represent the situation before the introduction of the artificial fertilizers and detergents. The 4- to 50-fold increase in the values in fresh waters and coastal waters is clear.

Structuring Elements and Processes

In addition to the inputs, the mechanisms and processes which influence the fate and effects of excess nutrient inputs will be considered. In coastal systems, eutrophication will influence not only the nutrient-related processes of the system but will also affect structural elements of the ecosystem (**Figure 2**).

Structuring Elements

The physical and chemical characteristics mainly create the basic habitat conditions and niches of the marine system to be colonized with organisms. These conditions also determine colonization rate, which is dependent on the organisms' tolerances to environmental variables.

Processes

Many nutrient transformation processes occur in estuaries, as they have the appropriate conditions. Estuaries can be considered as reactor vessels with a continuous inflow of components from the sea, the river, and the atmosphere and an outflow of compounds to the sea, the atmosphere, and the bottom sediments after undergoing certain transformations within the estuary (**Figure 3**). The important process elements are import, transformation, retention, and export of substances related to organic carbon and nutrients. Part of the transformation processes is illustrated in **Figure 4**. All these processes dictate that estuaries should be considered as both sources and sinks of organic matter and nutrients.

Output

Several processes contribute significantly to the prevention of eutrophication symptoms. Active bacterial removal of nitrogen may occur under favorable conditions due to the conversion of nitrogen compounds into nitrogen gas. These conditions are the spatial change from anoxic and hypoxic and oxygenated conditions. Phosphorus may be removed

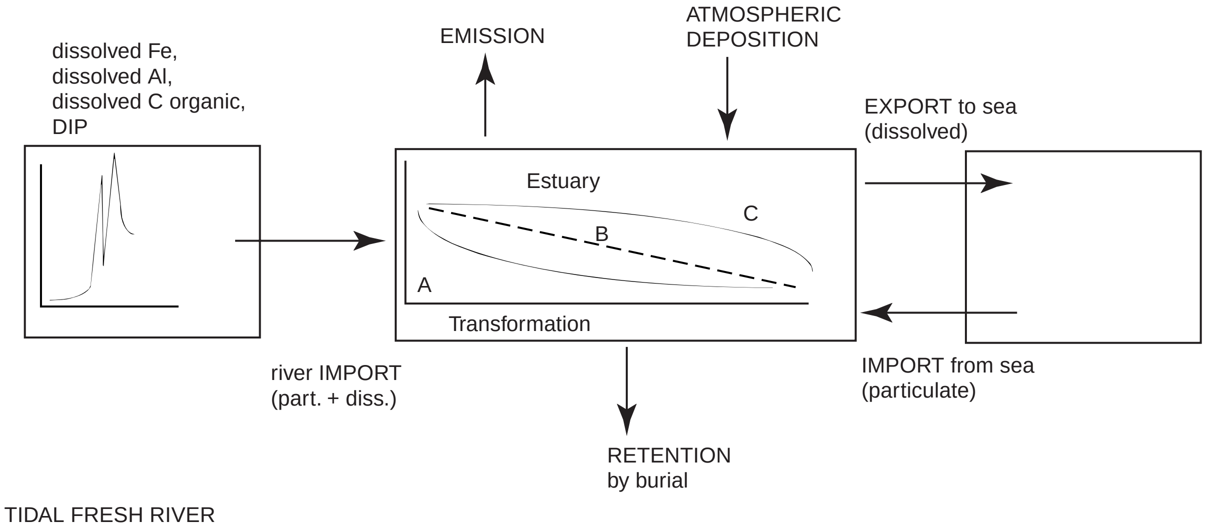

Figure 3 Box model showing fluxes, gradients, and processes in the freshwater tidal river, the estuary, and the coastal zone of the sea; part. = particulate; diss. = dissolved.

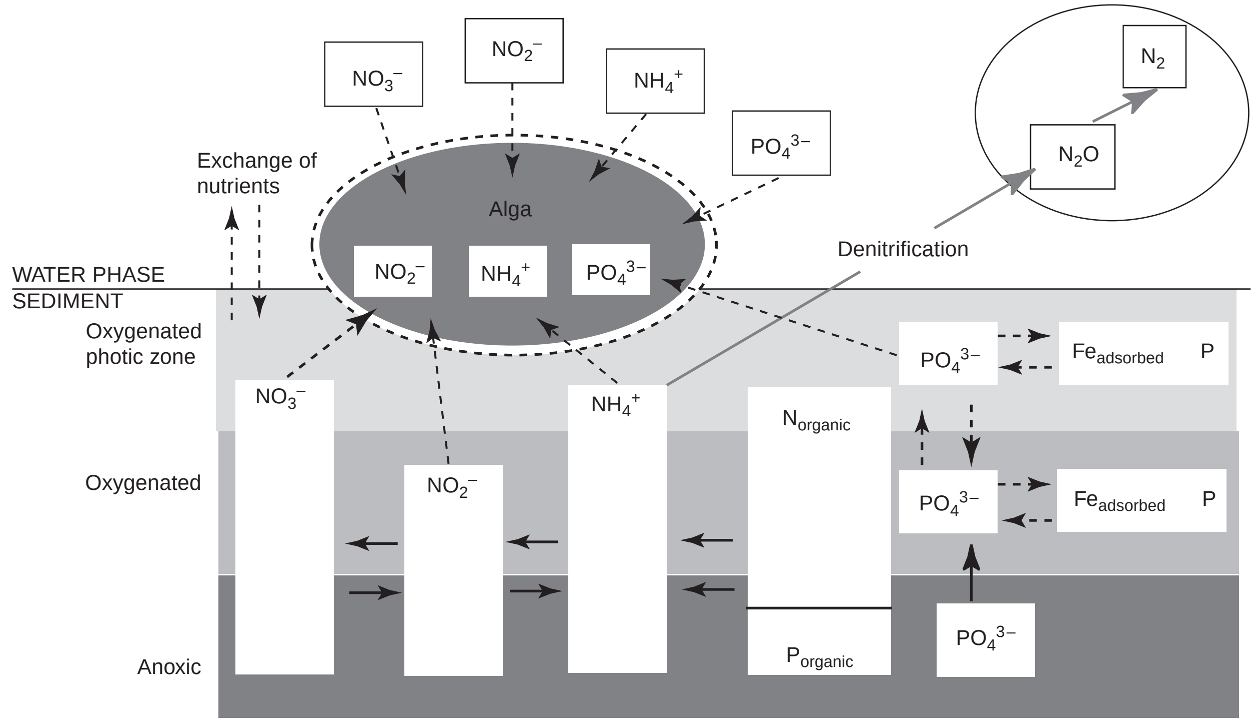

Figure 4 Schematic representation of conversion processes of nitrogen and phosphorus. Dashed lines represent assimilation, full lines represent biotic conversion (mainly microbial), and dotted lines represent geochemical equilibria. (Modified after Wiltshire, 1992 and van Beusekom & de Jonge, 1998 and references therein.)

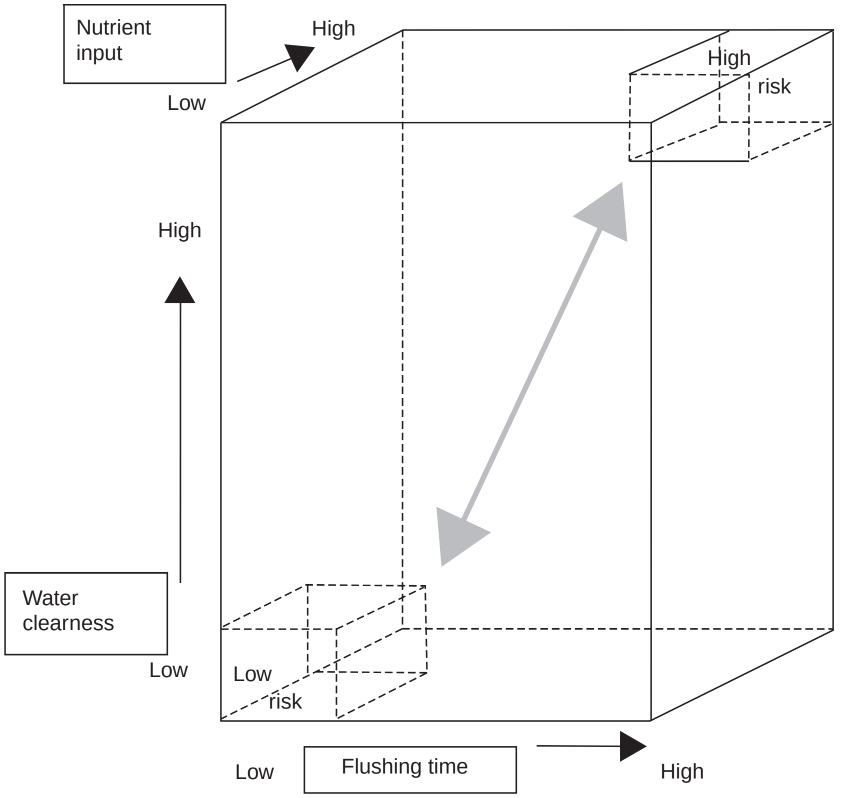

Figure 5 A 3-D classification scheme of eutrophication risk of estuaries based on flushing time, turbidity, and nutrient input.

from the system due to either transport to the open sea or the permanent burial of apatites, for example.

There is a wide variation in bacterial processes enhancing the transformation of nutrients. The intensity of the several conversion processes is partly related to the differences in the dimensions of these systems and factors such as tidal range (energy) and freshwater inflow (flushing time of fresh water, residence time of fresh or sea water and turnover time of the basin water) and related important determinants such as turbidity.

The most important factors in the expression of eutrophication are: flushing time (f_τ), the turbidity (gradient) expressed as light extinction coefficient (k_z), and the input and concentration gradient of the nutrients N, P, and Si. The combination of mainly these three factors determines whether an estuarine system has a low or high risk of producing eutrophication symptoms (**Figure 5**).

The longer the flushing time then the more vulnerable the system is to nutrient enrichment, as the primary producers have a greater period available to utilize the excess nutrients. If the flushing time is shorter than the mean growth rate of the algae (areas with high dispersion capacity), flushing of the population will occur and thus prevent the symptoms within the system, although transport to the open sea will increase. Hence, if algal blooming does not occur within the estuary it may develop in the lowest reaches of the system or even just outside the system in the sea.

Case Studies Indicating Trends and Symptoms

In determining any response, it is necessary to describe the natural situation and its spatial and temporal variability, the change from that natural system, and the significance and cause of that change. As described above, it may be difficult to assess anthropogenic nutrient enrichment against a background of the natural variability in nutrient influxes and turnover and its impact on the productivity of the ecosystem under consideration. The greatest problem is to make a clear distinction between the two and to assess the contribution of

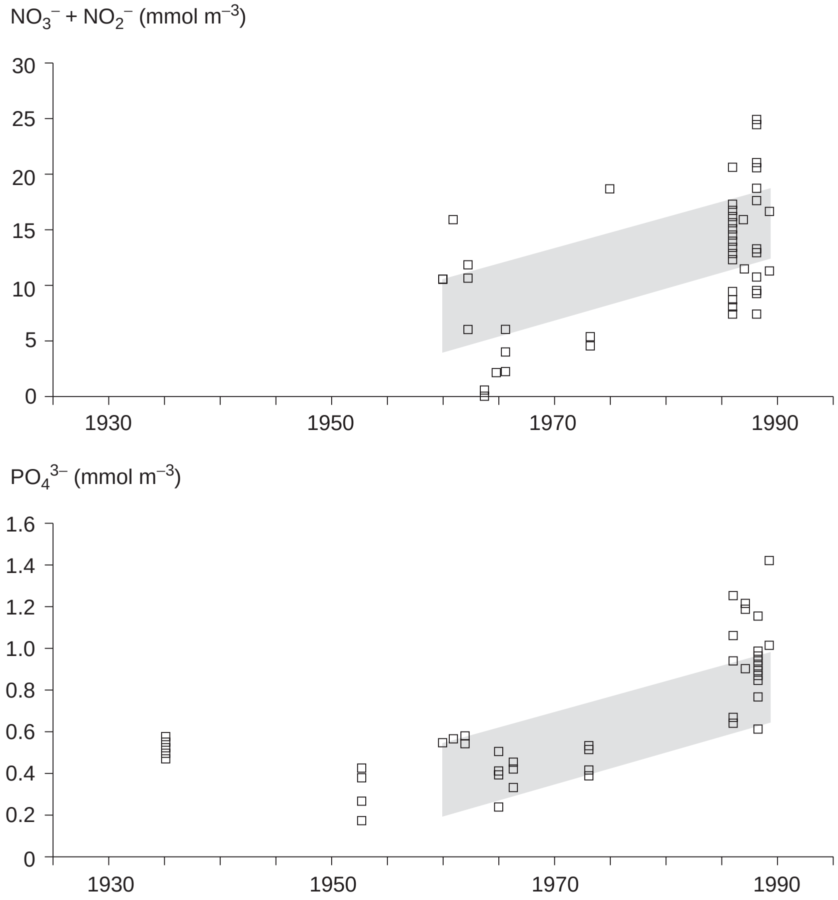

Figure 6 Winter concentrations of DIN and DIP in the central part of the Strait of Dover showing a two-fold increase in DIN and a three-fold increase in DIP. (Reproduced with permission from de Jonge, 1997.)

natural variation and of human activities to the nutrient enrichment and its symptoms in any system. Despite this, there are several case studies which illustrate the main features, as described below.

Forcing Variable 1: Riverine Inputs and Concentrations of Nutrients

There are many scattered data available on input values and concentrations of nutrients, but there are much less consistent long-term data series. Comparisons of historical and present data for the North Sea and Wadden Sea indicate that large-scale variability in inputs (**Figure 6**; inflowing Atlantic water) and large increases in inputs (**Figure 7**; inputs from rivers) resulted in an increased productivity. An analysis of the river, estuarine and coastal dynamics and an understanding of the processes, especially in the near-coastal dynamics, showed that there may be a time delay inherent in the system and that the

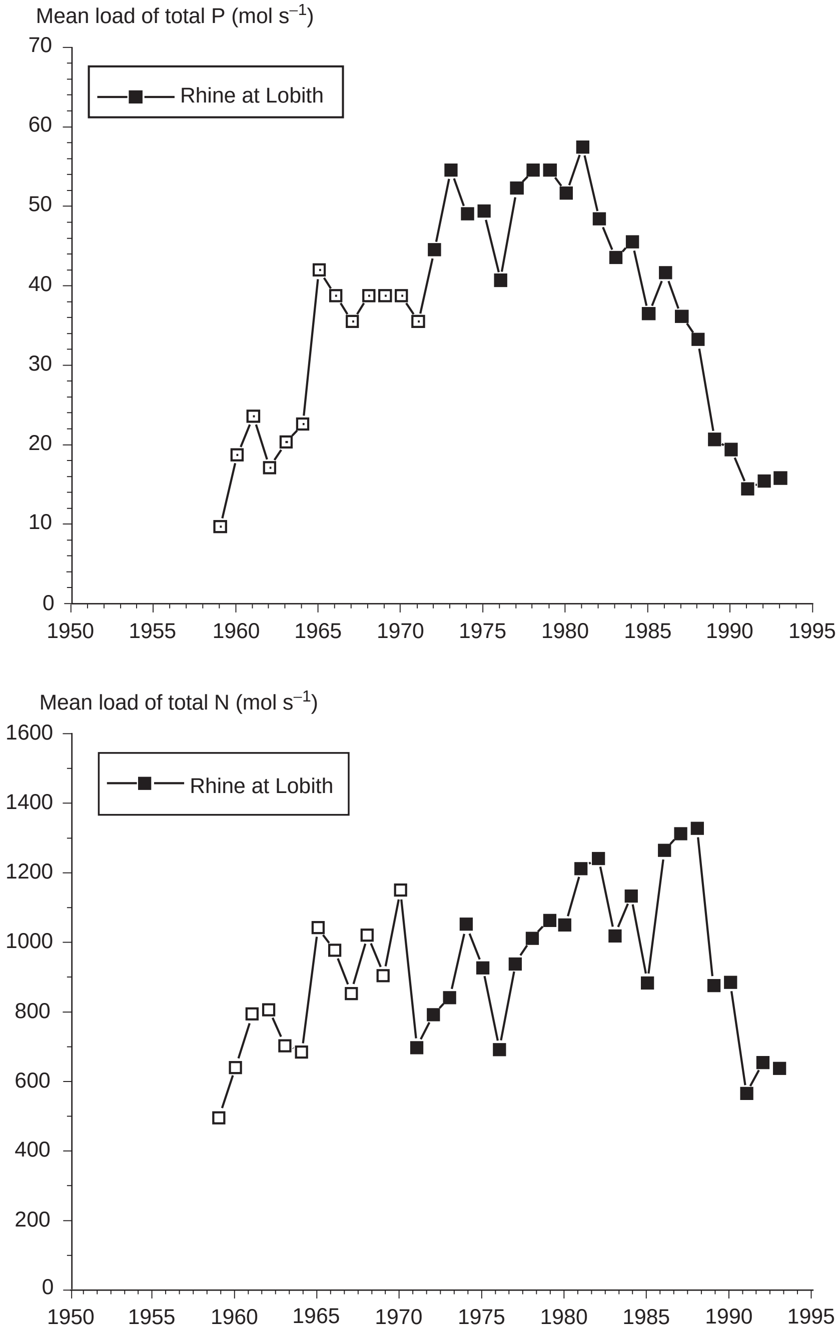

Figure 7 Development of the loads in total phosphorus and total nitrogen as measured on the border between Germany and The Netherlands. (Data from Rijkswaterstaat.)

coast may respond later than the estuary. It is of note that detailed and systematic monitoring was required to detect these trends. Consequently, international agreements (the Oslo and Paris Conventions and European Commission Directives) were designed to control these trends. The measures were effective and thus the remediation may be a model for systems elsewhere (cf. **Figure 2**).

The changes reported include an increase of surface algal blooms (**Figure 8**), a major sudden change in plankton composition from diatoms to small flagellates, and an increase in the area with elevated nitrogen and phosphorus concentrations (**Figure 9**) and oxygen deficiency (**Figure 10**). There are well-defined positive relationships between riverborne nutrients and the long-term variation in primary and secondary production in the western Dutch Wadden Sea (**Figure 11**). However, the processes and responses are complicated by inputs from the North Sea, including the inflowing Atlantic water (**Figures 6** and **12**) and meteorological conditions. This is important as it emphasizes the need to consider all aspects when reduction measures have been undertaken.

Forcing Variable 2: Size of Receiving Area

The Baltic Sea is typical of many semi-enclosed seas with nutrient loadings. Although the four- to

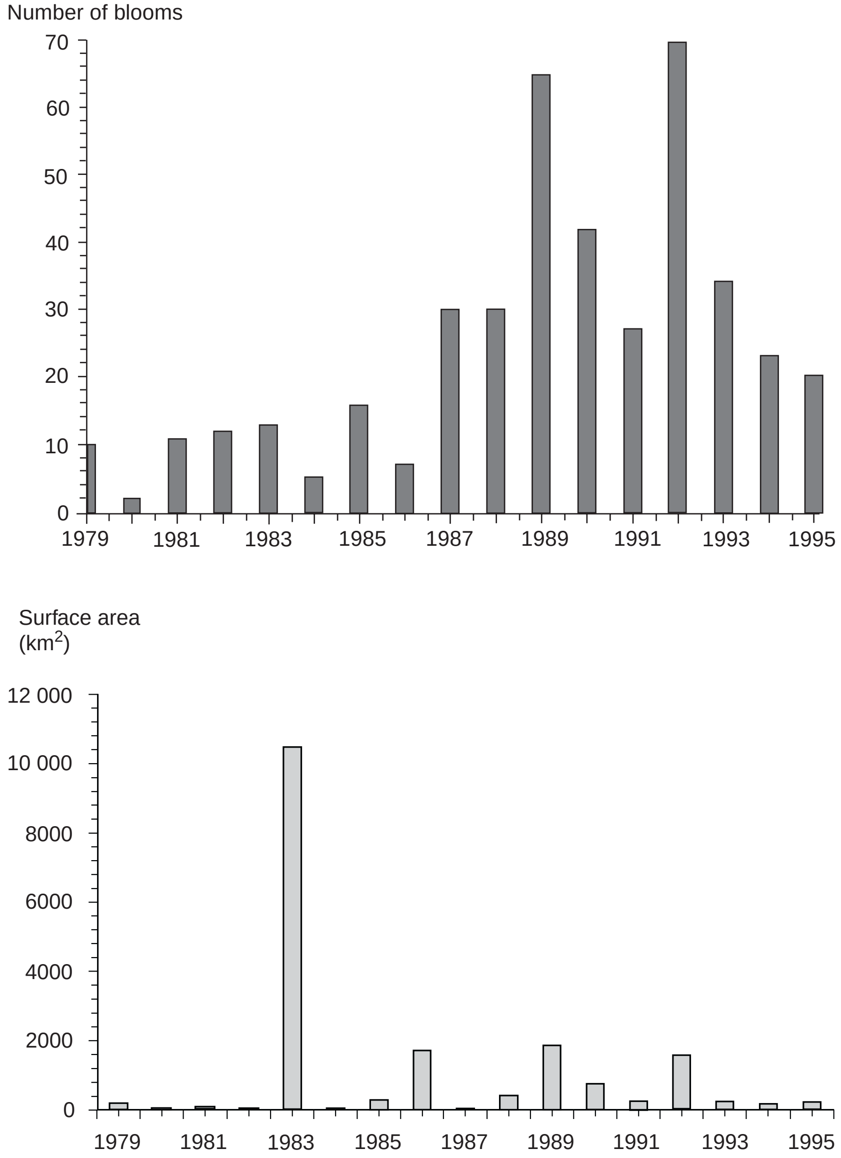

Figure 8 Surface algal blooms observed during Dutch airborne surveys over the period 1979–1995 (after Zevenboom 1993, 1998). (A) Frequency per annum; (B) surface area in km^2 per annum.

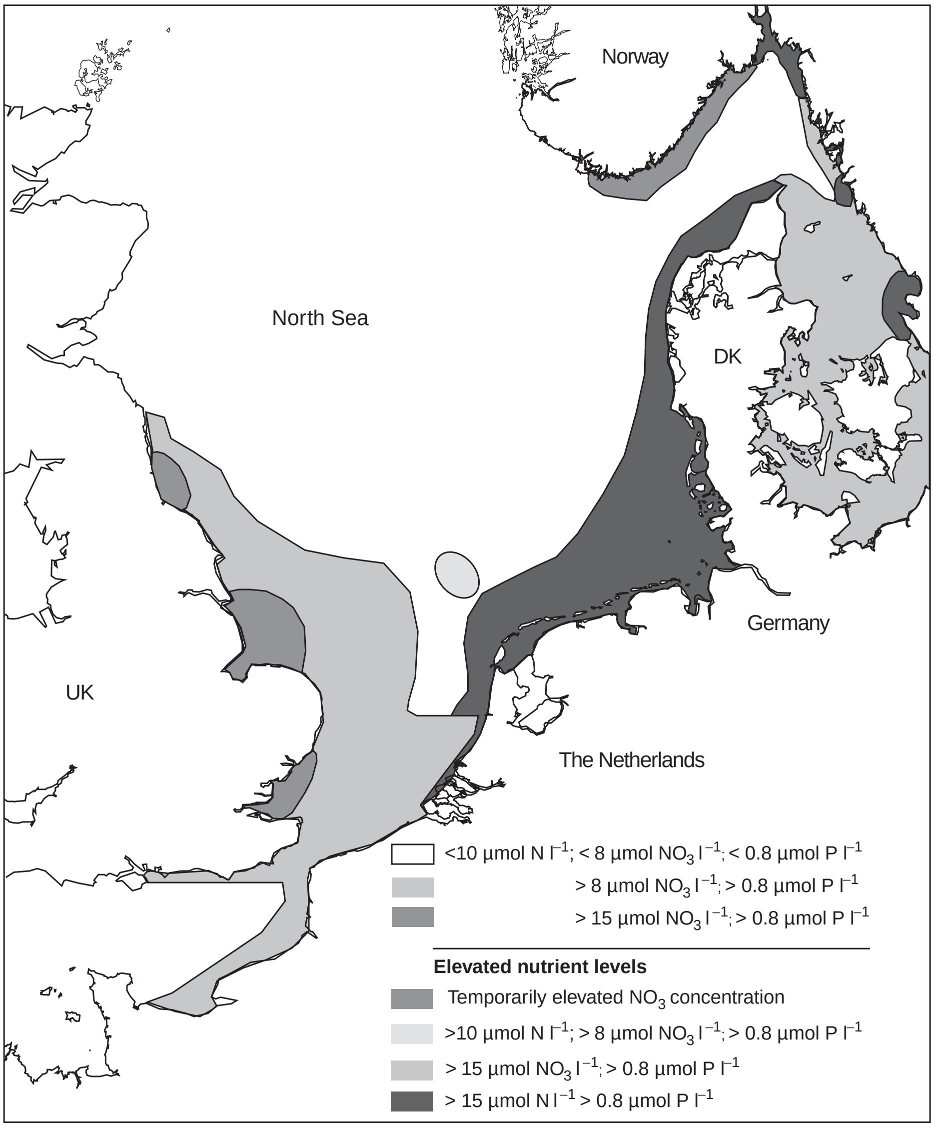

Figure 9 Elevated nutrient levels in North Sea waters (data from OSPAR 1992). The background levels have been agreed to be 10 µmol l^{-1} DIN and 0.6 µmol l^{-1} DIP (from Zevenboom 1988, 1993).

eight-fold increased nutrient loads only changed the primary production by 30–70%, the permanent anoxic layer of the Baltic increased from 19 000 to near 80 000 km^2 (nearly the entire hypolimnion) as the result of the eutrophication (**Figure 13**). This produced a dramatic structural decline in population size of two important prey species (the large isopod *Saduria entomon* and the snake blenny *Lumpenus lampetraeformis*), which in turn greatly influenced the local cod populations. The increased density of algal mats reduced the development of herring eggs, possibly by exudate production and the large hypoxic areas adversely affected the development of cod eggs. Thus nutrient enrichment in the Baltic greatly damaged some essential parts of the food web and the ecosystem structure.

In additon, more localized eutrophication of the inner Baltic occurs due to fish farming (**Figure 14**), which accounts for over 35% and 55% of the total local nitrogen and phosphorus inputs respectively. It was concluded that phosphorus was the most important determinant, e.g. leading to a strongly reduced N/P ratio. This nutrient enrichment produced an increase in the primary production and an increase in turbidity which negatively affected the macrophyte populations and stimulated the blooming of cyanobacteria. The loss of five benthic crustaceans has been observed, while a gain of four was reported, of which two were polychaetes (*Polydora*

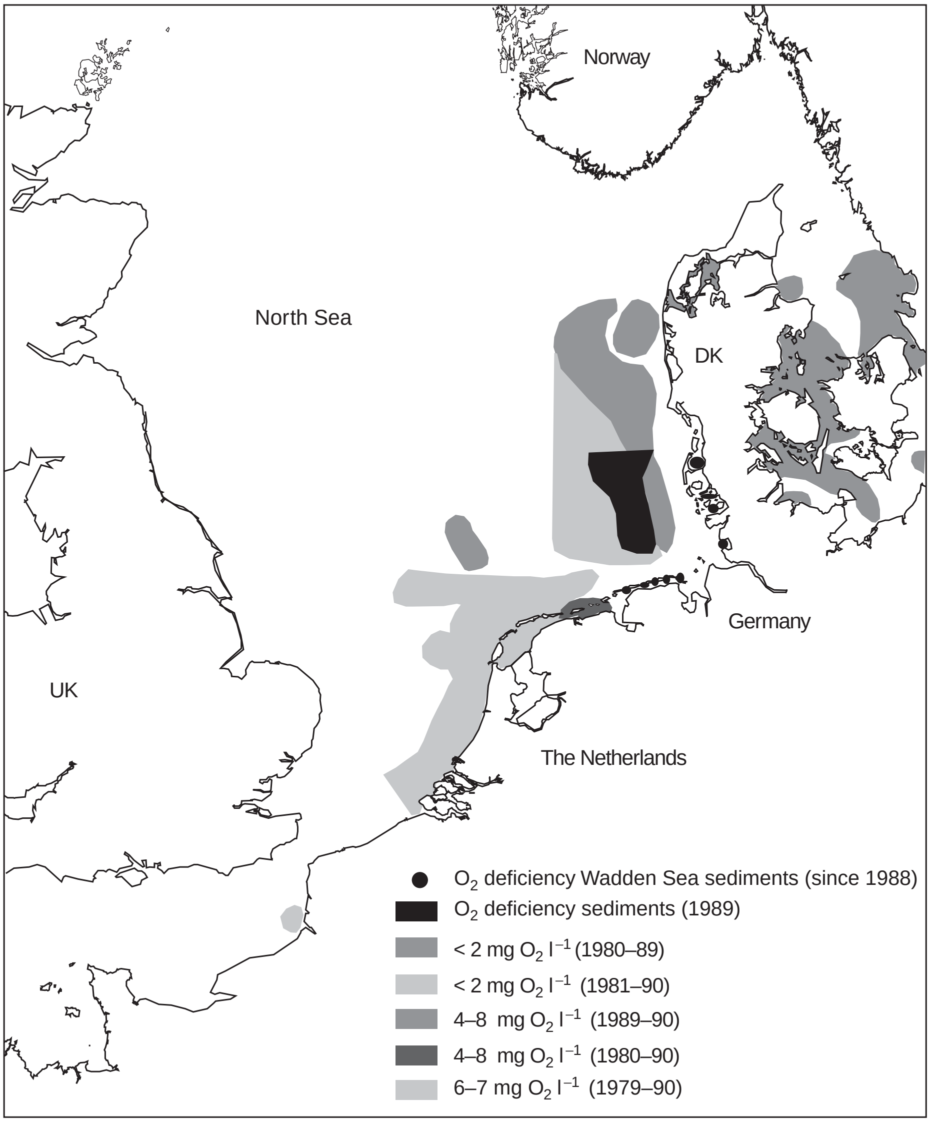

Figure 10 North Sea areas with oxygen deficiency. (Data after OSPAR, 1992; Zevenboom, 1993.)

redeki, *Marenzelleria viridis*) new to the area. Furthermore, the macrobenthos showed a structural change from suspension feeders to deposit feeders. Finally, the extensive bloom of the microalga *Chrysochromulina* in the late 1980s in the outer Baltic apparently developed in response to nutrient build-up on the eastern North Sea and contributed to the hypoxia and eutrophic symptoms.

Forcing Variable 3: Peak Loadings and Changing Ratios in Nutrient Fractions

In Chesapeake Bay (USA; north Atlantic west coast) (**Figure 15**), the total phosphorus concentrations decreased with time, but nitrogen had maximum concentrations in the mid-1980s and the DIN concentrations doubled in the oligohaline zone of the bay. Significant increases were detected in surface chlorophyll-a data between 1950 and 1970 in all the regions of the bay and there has been a significant long-term increase in the DIN/DIP ratios since the 1960s in much of the bay. This ratio was generally above the Redfield ratio of 16 (necessary for optimal plant growth) in all regions in winter and spring, but in summer and autumn the values were below the Redfield ratio in the main part of the bay, suggesting N limitation. Potentially limiting concentrations of reactive silicate and DIP often occurred in the mesohaline to polyhaline bay.

Forcing Variable 4: River Basin Alterations

Alterations in the lower part of the Rhine river basin have led to a decrease in the flushing time of the

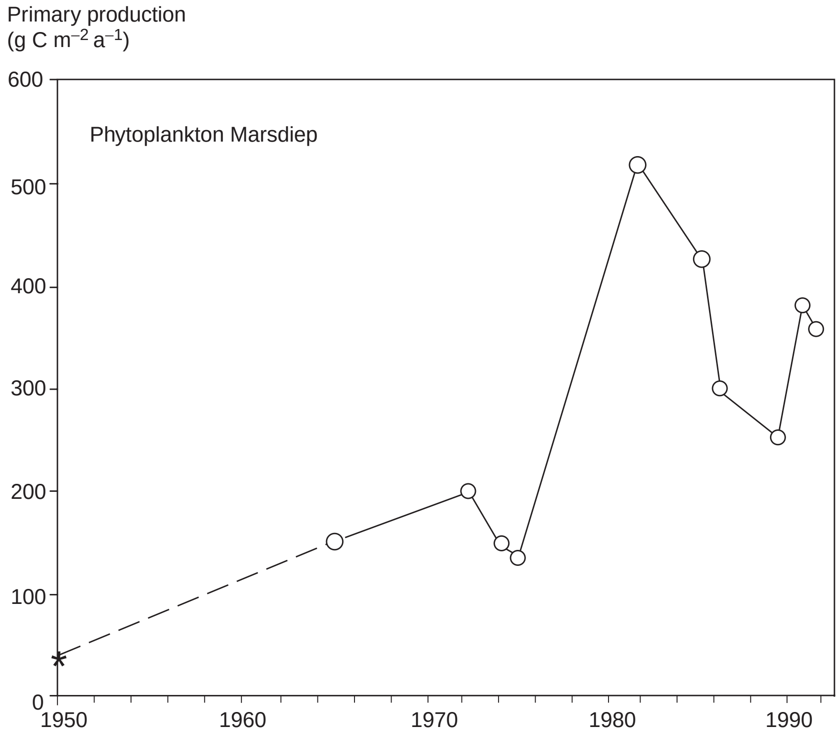

Figure 11 Time-series of available values on primary production in the western Dutch Wadden Sea, as reviewed by de Jonge *et al*. 1996 (with permission).

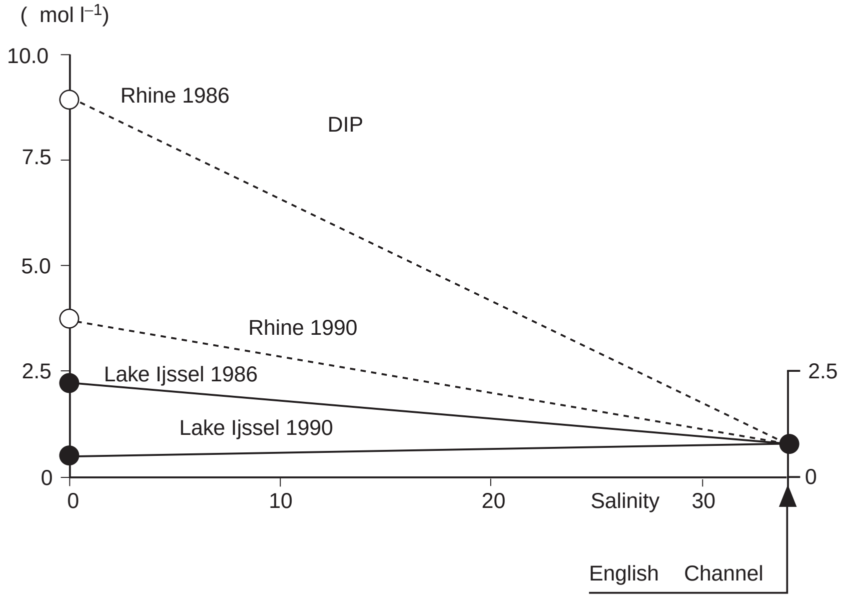

Figure 12 Mixing diagram of DIP for the years 1986 and 1990 when nutrient concentrations in river water declined after having increased for decades. The strong and structural (cf. also main river Rhine values in **Figure 13**) decrease in DIP values over a short time period is remarkable. Also the conclusion that in 1990 the DIP values of fresh water in Lake Ijsselmeer were lower than the values in the Strait of Dover/English Channel (which has consequences for the primary production potential of coastal waters in the southern Bight of the North Sea and coastal policy plans and management plans is striking. (Reproduced with permission from de Jonge, 1997.)

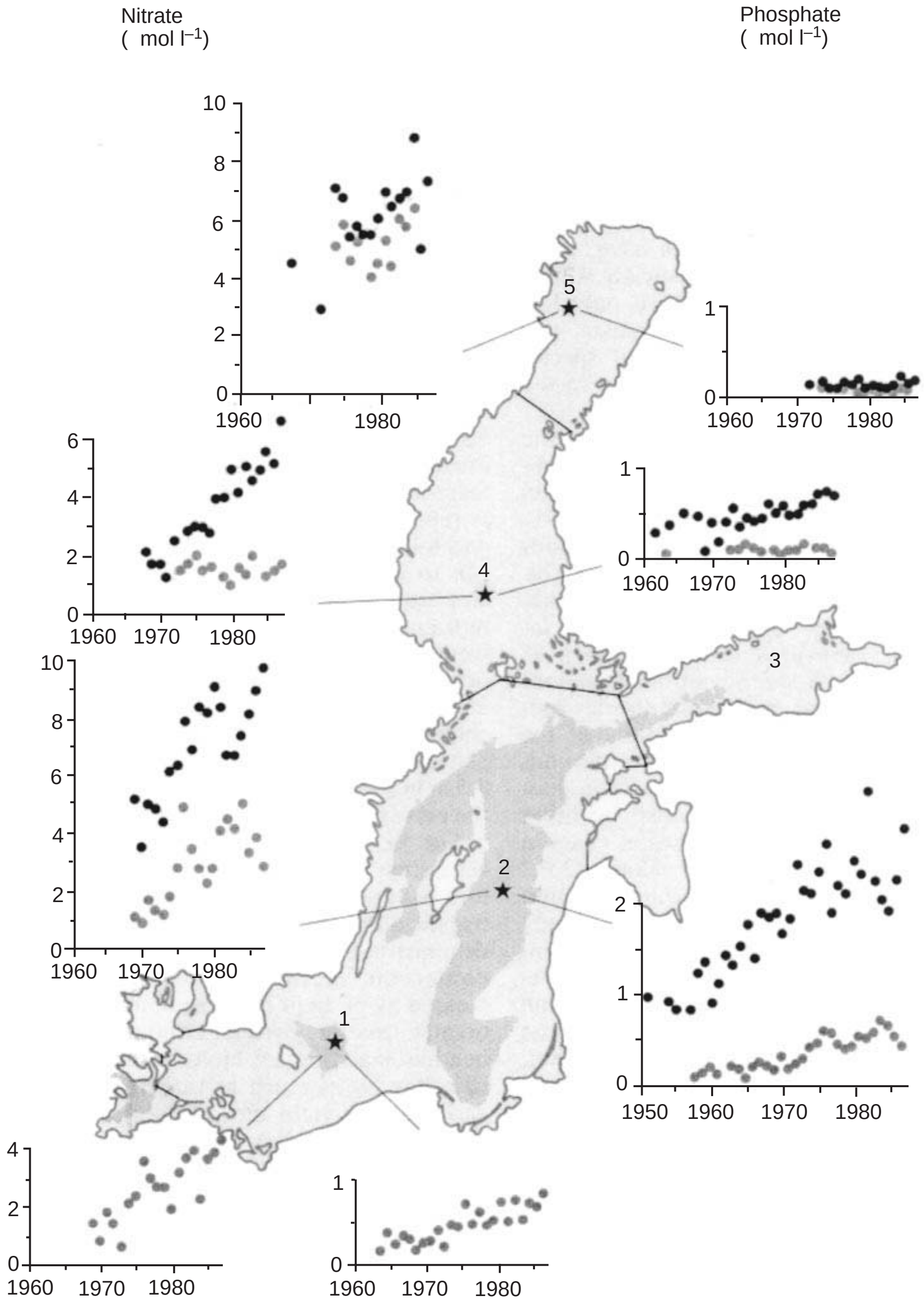

Figure 13 Map of the Baltic Sea with hypoxic and anoxic areas in (1) Arkona Basin, (2) the Gotland Sea, and (3) Gulf of Finland. Further trends in nitrate (left panels) and phosphate (right panels) in surface waters in winter (gray) and at 100 m depth (black). (Reproduced with permission from Elmgren, 1989.)

system and concurrent relative increase in the discharge of nutrient loads to the Dutch Wadden Sea.

Eutrophication in Florida Bay (**Figure 16**) possibly produced a large-scale seagrass die off (4000 ha of *Thalassia testudinum* and *Halodule wrightii* disappeared between 1987 and 1988), followed by increased phytoplankton abundance, sponge mortality, and a perceived decline in fisheries. This very large change in the health of the system followed major engineering works to the Everglades area and reflected changes in the nutrient concentrations, the nutrient pool, the chlorophyll levels, and turbidity. The preliminary nutrient budget for the bay assumes a large oceanic and atmospheric input of N and P to the bay, although the denitrification

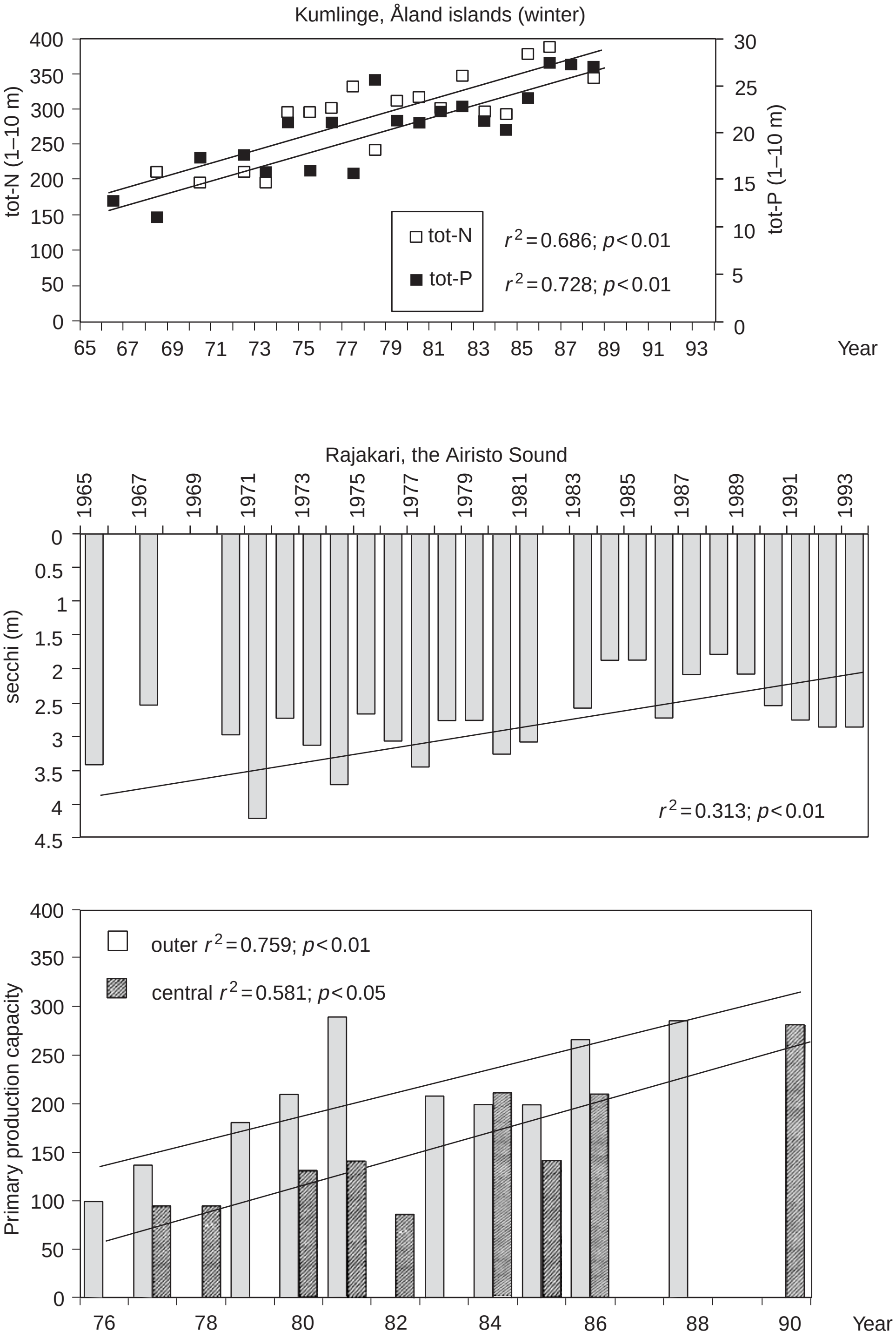

Figure 14 Development of nutrient levels in the open outer archipelago region (Baltic part of Finland) over the period 1963–93, the increase in turbidity over the period 1965–93, and the consequent increase in primary production capacity over the period 1976–90. (Reproduced with permission from Bonsdorff *et al*., 1997.)

rates are unknown. The cause(s) of the seagrass mortality in 1987 is still unknown. Although not mentioned, synergistic effects (where eutrophication effects are exacerbated by other pollutants) are also expected in urbanized and developed areas. Furthermore, the change in primary producers in this area reflected vascular plants operating as k-strategists under stress and replaced by more opportunistic algae like phytoplankton species.

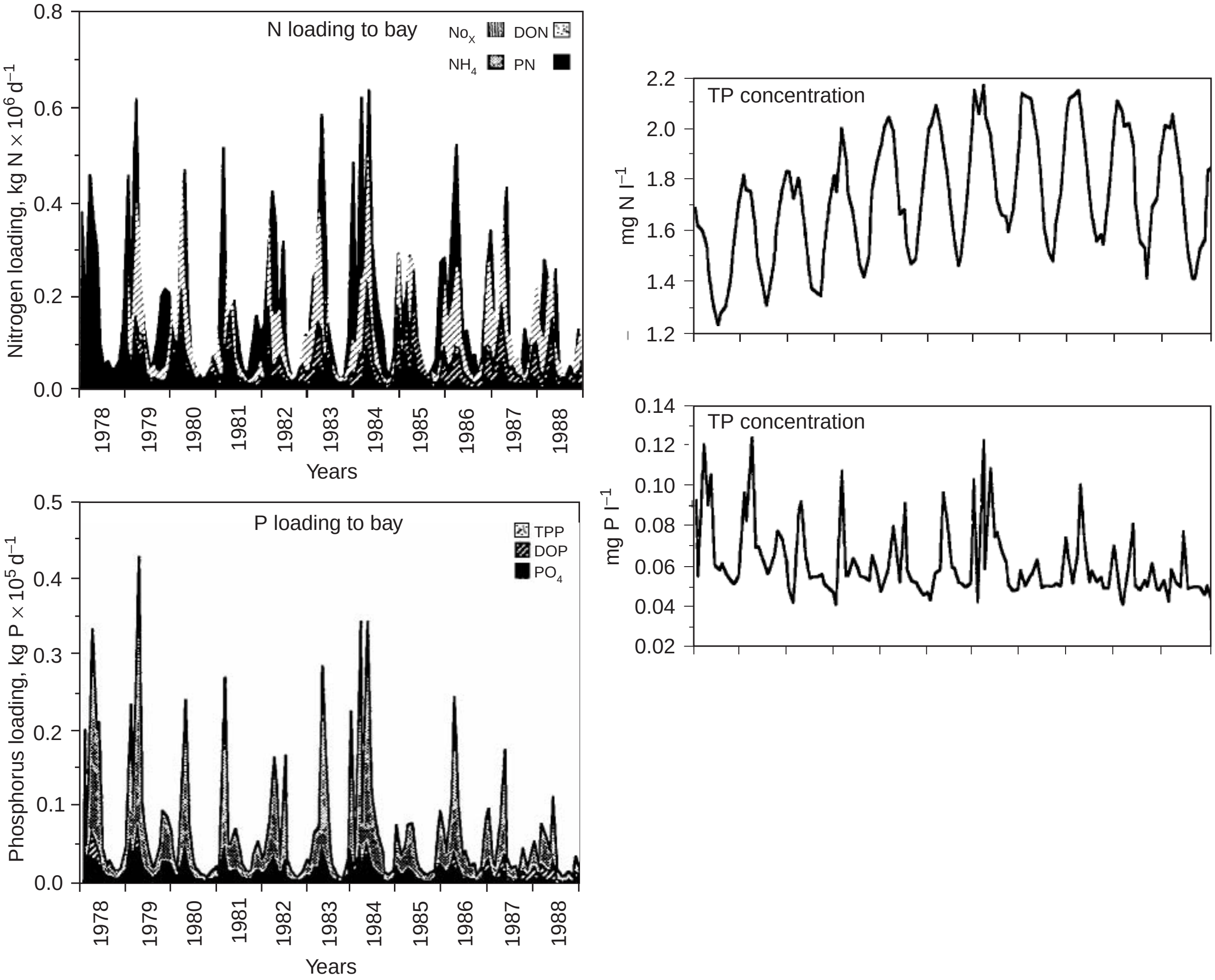

Figure 15 Record of monthly averaged nitrogen and phosphorus inputs to the mainstem of Chesapeake Bay and the monthly average values of total nitrogen and total phosphorus measured at the fall-line of the Susquehanna River (original data from Summers 1989). (Reproduced with permission from Boynton *et al.*, 1995.)

Forcing Variable 5: Stratification

The Peel-Harvey estuarine system (South Pacific west coast of Australia) receives a high nutrient loading but has a phosphorus release during stratification-induced anoxia from the bottom sediments. This is after a clear loading of the estuary and the subsequent development of dense populations of microphytobenthos which is responsible for the nutrient storage. This release (**Figure 17**) contributed to the changes in macroalgal community structure and increased turbidity due to algal blooms. Remedial measures are now in place to reduce inputs and remove the adverse symptoms.

Forcing Variable 6: Hydrographic Regime (Residence Time and Turbity)

The creation of red tides (noxious, toxic, and nuisance microalgal blooms) in Tolo Harbor (Hong Kong) resulted from large urban nutrient inputs, a water residence time of 16–42 days, and a low turbidity which led to the phytoplankton producing dense populations. Diatoms decreased in abundance from 80–90% to 53% in 1982–85, dinoflagellates increased concurrently with red tides (**Figure 18**) and chlorophyll-a levels also increased significantly. Oxygen depletion occurred due to nutrient loadings and the local development of phytoplankton in combination with reduced water exchange (long flushing time), features associated with a low-energy eutrophic environment. In addition, the area is degraded after heavy pollution by heavy metals and organic contaminants. In other systems (e.g. Southampton Water, UK) regular blooms of the nuisance ciliate with a symbiotic red alga, *Mesodinium rubrum*, is the result of increased nutrients, high organic matter, relatively long residence time, and turbid waters.

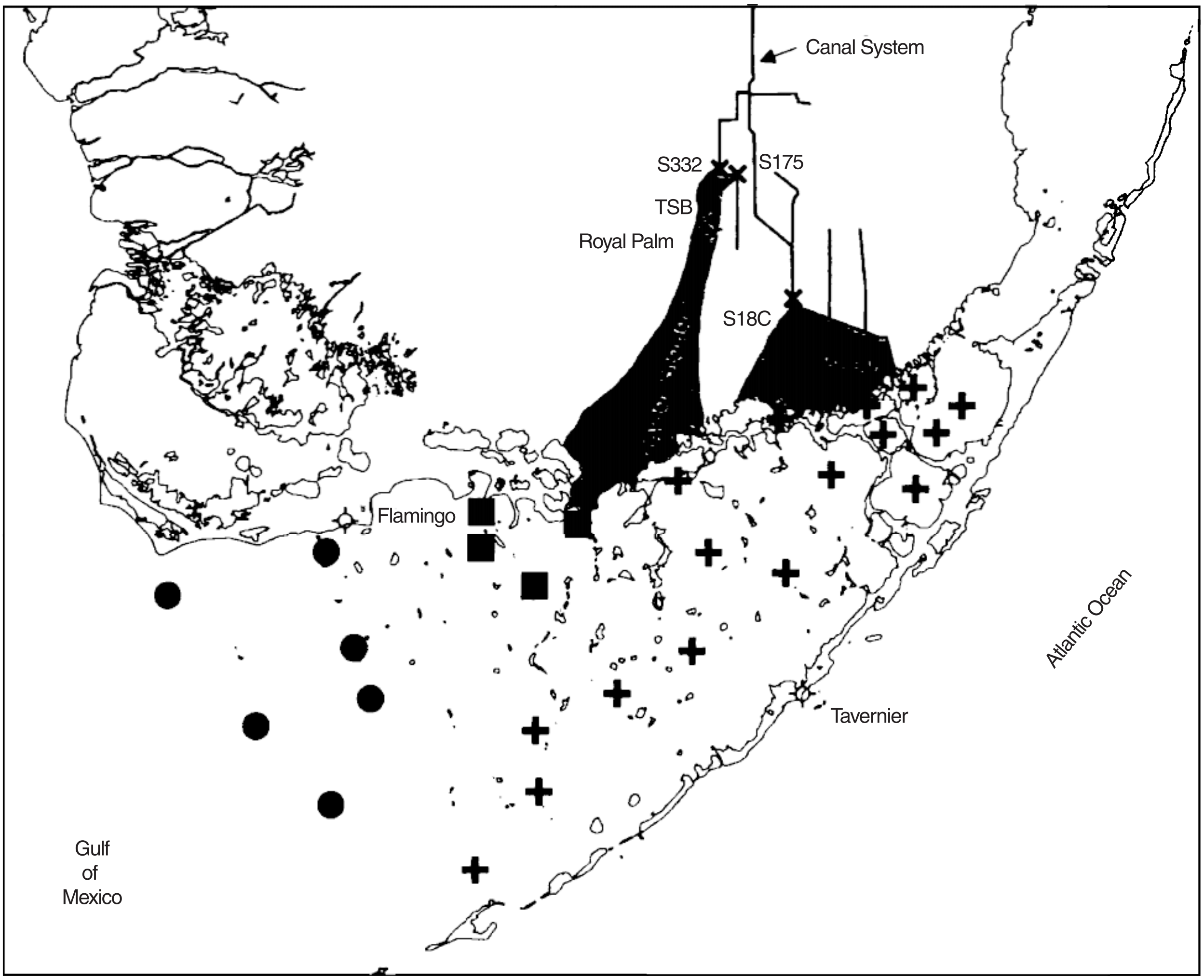

Figure 16 Map of Florida Bay with three zones of similar influence as a result of a cluster analysis on mean and SD of five principal component scores. Stations are labeled as eastern bay (+), central bay (■), and western bay (●). (Reproduced with permission from Boyer *et al.*, 1999.)

Conceptual Model of Effects

There have been few studies assessing all possible effects of nutrient enrichment but it is possible through the many different case studies to create a conceptual model of the main effects. **Figure 19** gives a descriptive overview on functional groups of plants and animals and at differing levels of biological organization, thus mainly at the process level.

'Hot Spots' and Remedial Measures

With regard to eutrophication, 'hot spots' may be those being hypernutrified, such as estuaries (e.g. the Ythan, Scotland) or those areas showing regular symptoms of eutrophication, e.g. the Baltic Sea. Other good examples are the near absence of beaver dams in the USA today, and the absence of large natural wetlands as a result of reclamation in many low-lying countries. In the past these natural obstacles as beaver dams and large wetlands favored the retention of nutrients resulting in lower more 'near' natural loads of coastal systems. It is clear that restoration of river systems or the rehabilitation of the integrity of entire river systems in combination with the application of best possible techniques is the best remedial measure to implement, coupled with river basin and catchment management.

In general 'hot spots' are all close to intensive land use (agriculture and urbanized areas), with poor waste water treatment and no removal of P and N. Increasing development is usually accompanied by greater waste treatment, for example, European Directives require better treatment de-

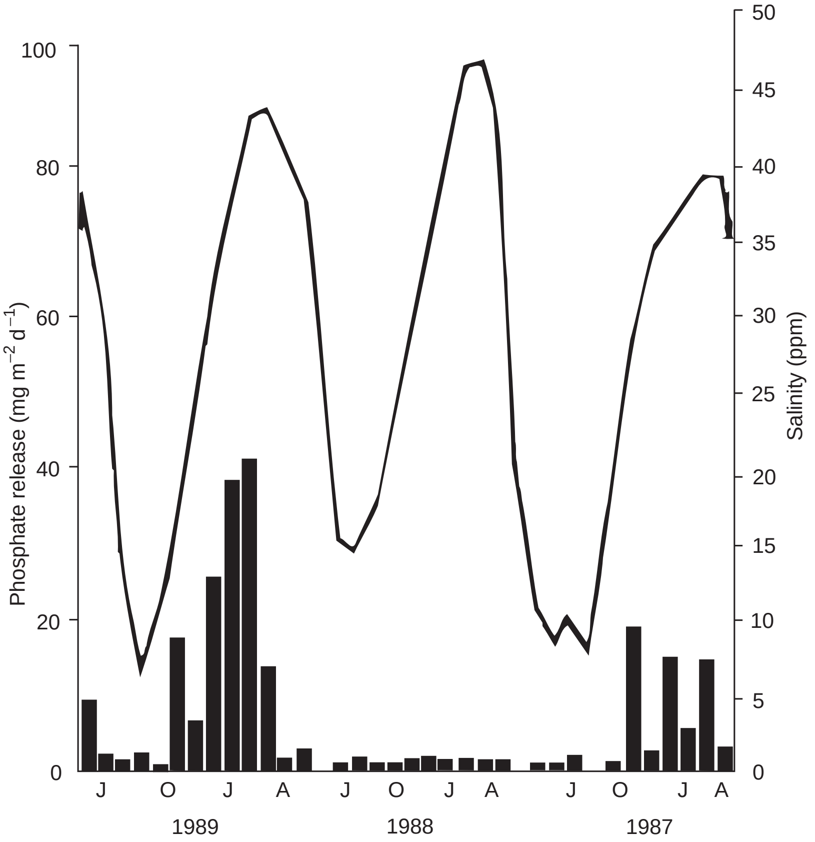

Figure 17 Release of phosphorus from the sediments of Harvey estuary. The data are release rates, recorded under standard conditions in the laboratory, for cores removed from the same site in the estuary at different times of year. The background line shows the estuarine salinity at the time. (Reproduced with permission from McComb, 1995.)

pending on the local population and the ability of receiving waters to assimilate waste. However, it is axiomatic that sewage treatment removes organic matter but, unless nutrient stripping is installed, which is expensive, it may fail to remove, or hardly remove nutrients. Similarly, the creation of nitrate vulnerable areas requiring fertilizer control, as within the EU Nitrates Directive, will reduce inputs. However, the fact that ground water may retain nutrients for many years, even decades in the case of aquifers, will dictate that the results of remediation will not be apparent for a while.

Areas requiring attention include populated regions, agricultural lands, and low-energy areas (Baltic Sea with Åland Islands, German Bight in the North Sea, Long Island Sound, Chesapeake Bay), i.e. mainly the large estuarine systems as well as developing countries with no or hardly any

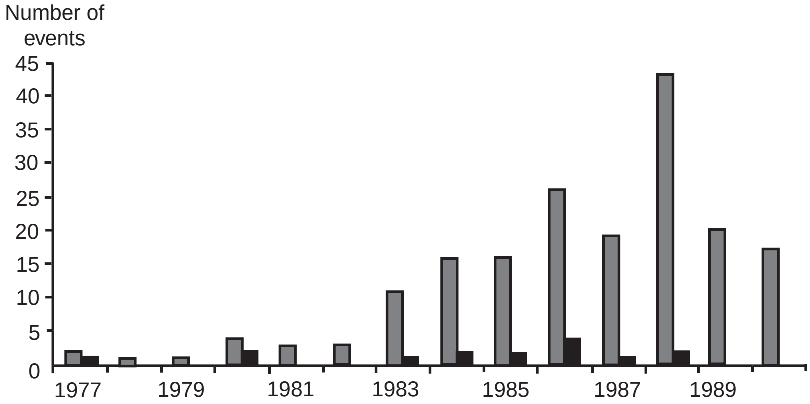

Figure 18 Red tides and associated fish kills in Tolo Harbor. (Reproduced with permission from Hodgkiss and Yim, 1995.)

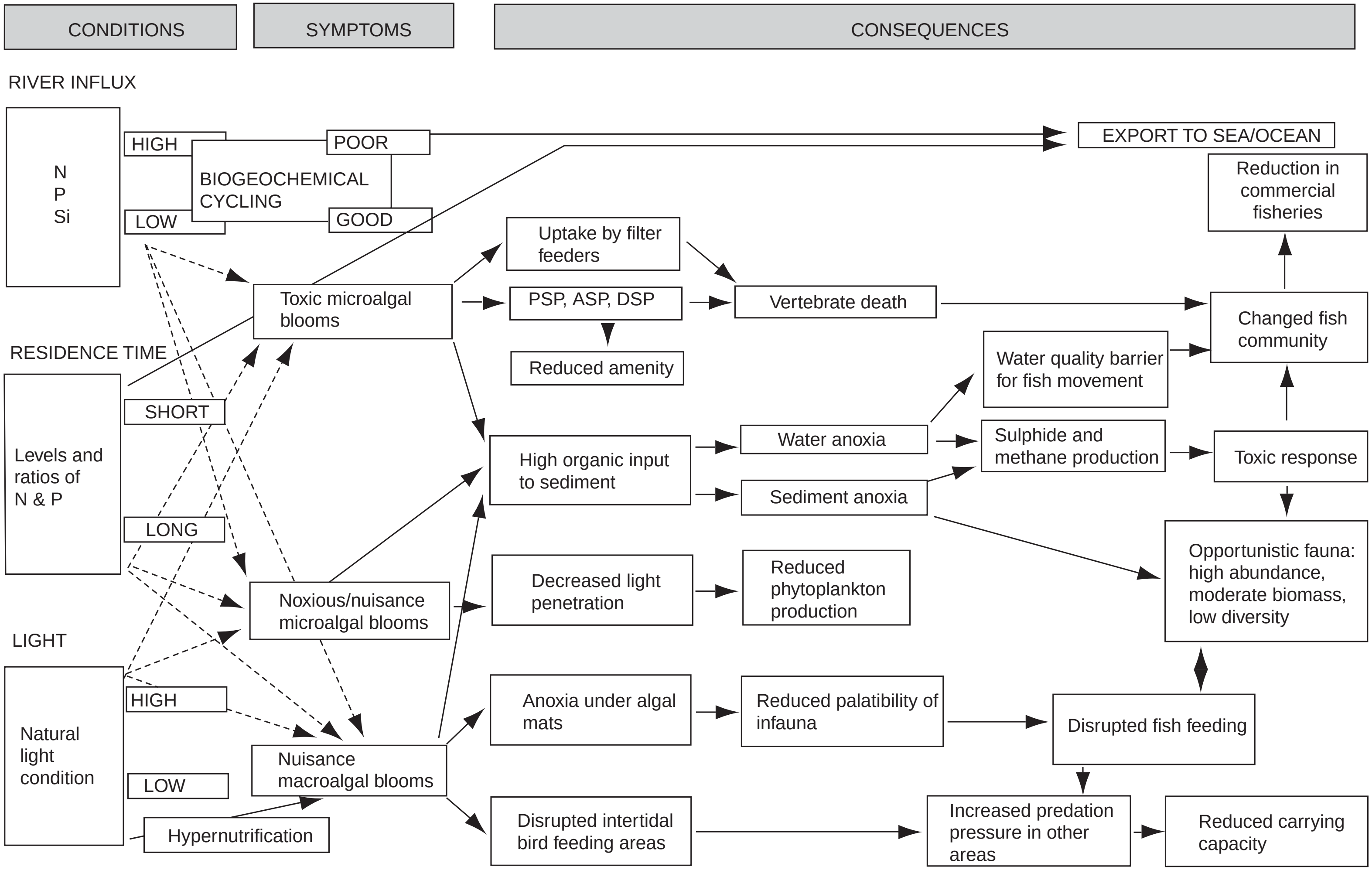

Figure 19 Overview of potential effects of nutrient enrichment in combination with turbidity conditions and residence time of water in an estuarine area.

wastewater treatment. Anthropogenic eutrophication must be addressed, especially further improvement of wastewater treatment and technical processes to reduce the emissions of nutrients and related (NO_x) compounds to the atmosphere.

Despite increasing knowledge, most countries show the same history when focusing on eutrophication. The fact that the information given above suggests a reduction in the emission of nutrients should be interpreted with caution, because differences in nutrient ratios in combination with changes in concentrations may lead to the development of undesirable micro- and macro-algae. For example, Sweden's reduction policy, which focused on phosphorus, failed as phosphorus became depleted along the coasts but not in the central part of the Baltic Sea where it was supplied in excess from anoxic deep water – thus maintaining the near-surface algal blooms. Given the action plans adopted by developed nations to further reduce nutrient loads, it can be argued that in the near future, eutrophication will be caused by sea water that has been enriched with nutrients for decades instead of fresh water. This is due to the expectation that the present nutrient policy on 'diffuse sources' and the increasing application of modern, sophisticated wastewater treatment plants will further diminish the freshwater loads. However, the atmospheric deposition of nitrogen as well as phosphorus (in dust) will become increasingly important due to many nutrient sources resulting from land use (burning of fossil carbon, fields, and forests).

The process of nitrogen fixation of increasing future importance as a mechanism during low nutrient conditions to compensate for the remedial measures taken by the different governments. This expectation means a well-balanced reduction in nutrient loads to prevent noxious blooms. It also means continuing to pay attention to eutrophication in all its aspects. At the moment nitrogen fixation is probably a small N-source as is the case in most nutrient-rich estuarine systems. However, some species have developed the ability to cope with very low nitrogen concentrations under conditions where just enough is provided by nitrogen fixation. Further global reduction in nitrogen emissions is required to protect the environment. It is possible that the problem due to N fixation will be apparent when reduction in phosphorus loads have been taken as far as possible.

The most important 'hot spot' on this planet is the rapidly growing world population. The big question and challenge is how to offer every individual 'sustainable' living conditions while at the same time maintaining the integrity of our aquatic systems. This marked increase in population size is the main cause of the most common and most severe environmental problem of today and tomorrow.

See also

Carbon Cycle. Coastal Circulation Models. Harmful Phytoplankton Blooms. Marine Silica Cycle. Nitrogen Cycle. Phosphorous Cycle. Primary Production Distribution. Primary Production Processes. Regional and Shelf Sea Models. River Inputs. Tides. Trapped Particulate Flux.

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EVAPORATION AND HUMIDITY

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Introduction

Evaporation from the sea and humidity in the air above the surface are two important and related aspects of the phenomena of air–sea interaction. In fact, most subsections of the subject of air–sea interaction are related to evaporation. The processes that control the flux of water vapor from sea to air are similar to those for momentum and sensible heat; in many contexts, the energy transfer associated with evaporation, the latent heat flux, is of greatest interest. The latter is simply the internal energy carried from the sea to the air during evaporation by water molecules. The profile of water vapor content is logarithmic in the outer layer, from a few centimeters to approximately 30 m above the sea, as it is for wind speed and air temperature under neutrally stratified conditions. The molecular transfer rate of water vapor in air is slow and controls the flux only in the lowest millimeter. Turbulent eddies dominate the vertical exchange beyond this laminar layer. Modifications to the efficiency of the turbulent transfer occur due to positive and negative buoyancy forces. The relative importance of mechanical shear-generated turbulence and density-driven (buoyancy) fluxes was formulated in the 1940s, the Monin-Obukhov theory, and the field developed rapidly into the 1960s. New technologies, such as the sonic anemometer and Lyman-alpha hygrometer, were developed, which allowed direct measurements of turbulent fluxes. Furthermore, several collaborative international field experiments were undertaken. A famous one is the ‘Kansas’ experiment, whose data were used to formulate modern versions of the ‘flux profile’ relations, i.e., the relationship between the profile in the atmosphere of a variable such as humidity, and the associated turbulent flux of water vapor and its dependence on atmospheric stratification.

The density of air depends both on its temperature and on the concentration of water vapor. Recent improvements in measurement techniques and the ability to measure and correct for the motion of a ship or aircraft in three dimensions have allowed more direct measurements of evaporation over the ocean. The fundamentals of turbulent transfer in the atmosphere will not be discussed here, only the special situations that are of interest for evaporation and humidity. As the water molecules leave the sea, they remove heat and leave behind an increase in the concentration of sea salts. Evaporation, therefore, changes the density of salt water, which has consequences for water mass formation and general oceanic circulation.

This article will focus on how humidity varies in the atmosphere, on the processes of evaporation, and how it is modified by the other phenomena discussed under the heading of air–sea interaction. All processes occurring at the air–sea interface interact and modify each other, so that none are simple and linear and most result in feedback on the phenomenon itself. The role of wind, temperature, humidity, wave breaking, spray, and bubbles will be broached and some fundamental concepts and equations presented. Methods of direct measurements and estimation using *in situ* mean measurements and satellite measurements will be discussed. Subjects requiring further research are also explored.

History/Definitions and Nomenclature

Many ways of measuring and defining the quantity of the invisible gas, water vapor, in the air have developed over the years. The common ones have