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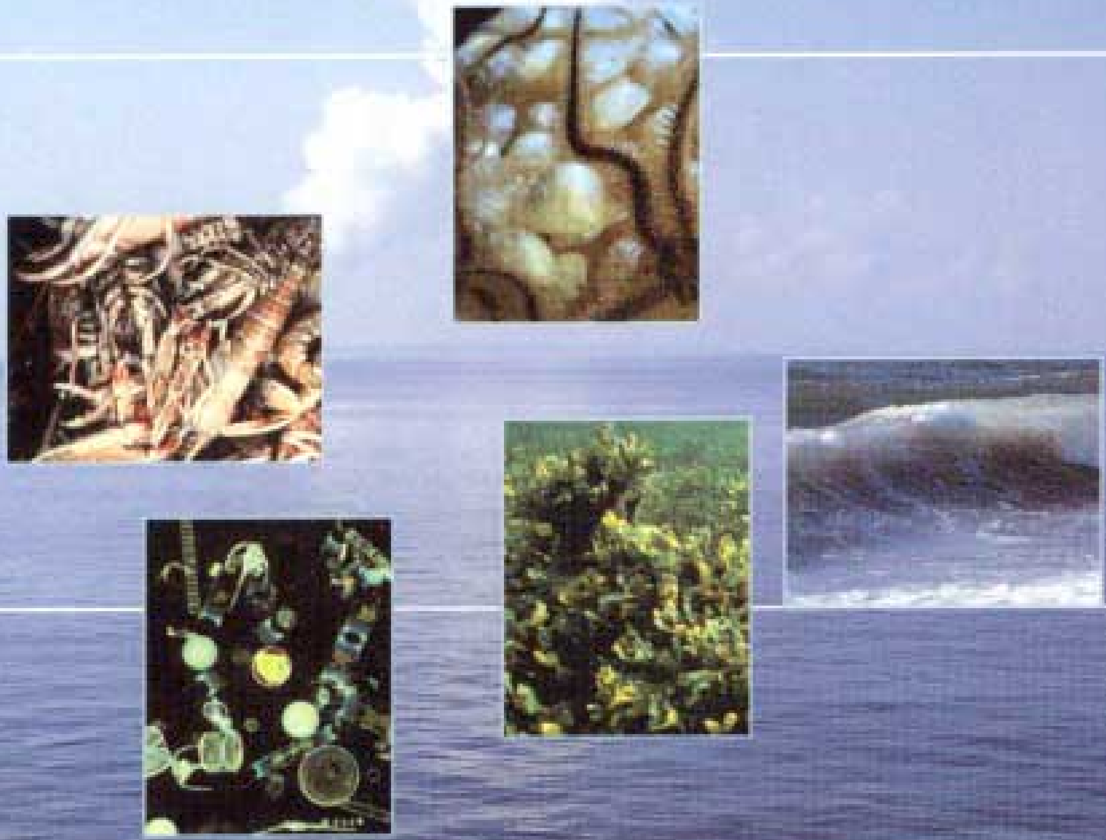
The Danish Marine Environment: Has Action Improved its State?



Ministry of Environment and Energy, Denmark
Danish Environmental Protection Agency

Miljø- og Energiministeriet **Miljø**styrelsen

The Danish Marine Environment: Has Action Improved its State?

Lars Gejl/Biofoto

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The Danish Marine Environment: Has Action Improved its State?

Conclusions and perspectives of the Marine Research Programme HAV90

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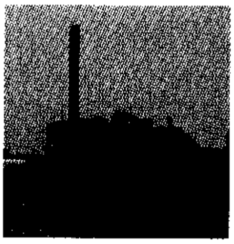

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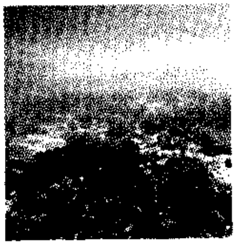

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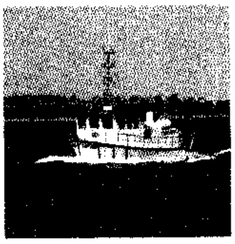

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Foreword

The Marine Research Programme 1990 – commonly referred to as HAV90 - has now been concluded. This report attempts to comply with an evident desire for the new knowledge acquired under the programme to be summarized and presented.

The report provides a generalized summary of the most important findings of HAV90 with regards to input, transport and turnover of nutrients in Danish marine waters.

Based on this summary and the results of the marine monitoring programme, the impact of the Action Plan on the Aquatic Environment on our marine waters has been assessed.

In addition, the report assesses the significance of HAV90 for future monitoring of the environmental state of Danish marine waters.

It is the authors' wish to reach as broad a public as possible and the report is therefore written in a manner which will hopefully enable it to be read by persons with no other qualification than a general interest in the Danish marine environment.

A steering committee participated in the discussion of the content of the report, and in several cases also participated in preparing the manuscript. The members of the steering committee were as follows:

Jørn Kirkegaard,
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1 Introduction

The 1987 Action Plan on the Aquatic Environment included setting up a research programme entitled Marine Research Programme 1990, popularly called HAV90. The research programme, which ran during the period 1988-94, aimed to strengthen the foundation for making decisions in the future administration of Danish coastal and marine waters, as well as to strengthen Danish environmental research in general.

The objective was to enhance our knowledge of the environmental impact of nutrient loading of the marine waters as well as our general knowledge of the marine ecosystems in order to document the effects of the implemented reductions in nutrient loading.

In addition, the results of the programme were to be used to improve the monitoring programme established under the Action Plan on the Aquatic Environment. When the Nationwide Monitoring Programme was set up in 1989 and revised in 1992, it was acknowledged that an optimal monitoring programme for the inner Danish marine waters could not be established before completion of HAV90, when the results could be analysed with a view to their use in the monitoring programme.

At the time the Action Plan on the Aquatic Environment was adopted in 1987, knowledge about the transport and turnover of nutrients in the Danish aquatic environment was insufficient and there was consequently an inadequate basis for documenting the effects of the various interventional measures adopted to combat eutrophication and oxygen deficit. This report therefore attempts to answer two questions:

- What significant new knowledge has been gained under HAV90, particularly with regard to the input, transport and turnover of nutrients and the significance of these factors for oxygen conditions in the inner Danish marine waters.
- To what extent can the knowledge obtained be utilized in connection with monitoring of Danish marine waters.

We provide a general description of the relationships between nutrient loading, production and turnover in the Danish marine waters. The effects of the Action Plan on the Aquatic Environment on the state of the marine environment are described on the basis of the results of HAV90 studies and of monitoring activities undertaken in connection with the Nationwide Monitoring Programme under the Action Plan on the Aquatic Environment. In addition, an assessment is made of what impact actual fulfilment of the reduction targets stipulated in the Action Plan on the Aquatic Environment will have on the environmental state of Danish marine waters.

Chapter 2 provides an overview of the contribution made by the HAV90 programme to answering of a number of questions of an environmental or administrative nature. The chapter summarizes the contribution of the HAV90 projects to an assessment of the impact of the Action Plan on the Aquatic Environment, as well as how HAV90 has strengthened the general scientific basis for making decisions.

Chapter 3 describes the historical background for implementation of the Action Plan on the Aquatic Environment, the Nationwide Monitoring Programme and the Marine Research Programme 1990.

Chapters 4 and 5 describe the most important scientific knowledge attained under HAV90. Chapter 4 focuses on nutrient loading of the inner Danish marine waters from the land, the atmos-

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phere and from adjoining marine waters. The knowledge gained about the transport, retention and removal of nutrients in the marine environment is examined.

Chapter 5 concerns the effect of the nutrients input to Danish marine waters. The significance of nutrients and physical processes (hydrographic conditions) for primary production is described. Nutrient and organic matter turnover in the water column and in the sediment is examined, as is their significance for oxygen conditions in the marine environment.

Chapter 6 assesses how the results of HAV90 can be incorporated into a revision of the Nationwide Monitoring Programme under the Action Plan on the Aquatic Environment. The background for the monitoring programme is sketched out and the information value of the individual programme areas that comprise the present monitoring programme is evaluated on the basis of knowledge gained under HAV90. Finally, a number of proposals are made for adjusting the existing monitoring programme and suggestions for new programme areas are discussed.

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2 HAV90: Conclusions and perspectives

To improve the environmental condition of Danish marine waters it is necessary to reduce nutrient loading from the land, particularly, nitrogen runoff from fields and nitrogen deposition from the atmosphere, which derives from agriculture, traffic and power production. It is important to acknowledge that eutrophication of the marine environment is also a transboundary problem, and one whose effective solution requires international cooperation.

In 1987, the Danish Parliament adopted the Action Plan on the Aquatic Environment to reduce Danish nutrient inputs to the aquatic environment from sewage works, industry and agriculture by 50% for nitrogen and 80% for phosphorus.

In connection with the Action Plan, it was decided to establish the Marine Research Programme 1990 - commonly referred to as HAV90 - with the aim of strengthening Danish research on the marine environment in general and thereby the foundation for future administration of Danish marine waters. A further objective was to provide knowledge for use in assessing the impact of the Action Plan on the Aquatic Environment. Finally, HAV90 was also intended to provide information that could be used in evaluating the results of the Nationwide Monitoring Programme for marine waters set up under the Action Plan on the Aquatic Environment.

2.1 Impact of the Action Plan on the Aquatic Environment

HAV90 has improved our knowledge of a large number of processes in Danish coastal waters. However, it has rarely been possible to demonstrate direct effects of the Action Plan on the Aquatic Environment during the short lifetime of HAV90, among other reasons because many of the interventional measures were not implemented until the final phase of the programme, and because it will take several years before the impact of the Action Plan becomes apparent in the marine environment. Moreover, it is beyond the scope of HAV90 to assess the value of the monitoring programme implemented under the Action Plan. However, in combination with the results of the Nationwide Monitoring Programme set up under the Action Plan, the results of HAV90 provide a good foundation for assessing the impact of the Action Plan on Danish marine waters.

Eutrophication

Eutrophication is enhanced input of nutrients leading to changes in biological structure and turnover. In the case of marine waters, the effects of eutrophication include changes in the species composition of phytoplankton, enhanced growth of annual macroalgae, shading-out of the perennial benthic vegetation, changes in the species composition of the benthic invertebrates, etc. An accompanying effect can be low oxygen concentrations in the bottom water that further affect the fish, benthic invertebrates and plants. Total oxygen depletion can result in the release of hydrogen sulphide from the sediment, causing extensive death of organisms associated with the sea floor. As only a few species can survive these extreme conditions, and as it takes time for plants and animals to recolonize damaged areas, eutrophication results in an impoverished biological community.

2.1.1 Estuarine fjords and shallow coastal waters

The Danish coastal waters are markedly affected by high nutrient loading. In many places, changes have been detected in biological conditions as a result of increased nutrient concentrations. This is particularly so in the Danish estuarine fjords, which show clear signs of eutrophication (see accompanying box).

The main human contribution to nutrient loading of Danish estuarine fjords derives from Danish arable land. The effect of this riverine loading is greatest where there is least exchange with the open sea, i.e. the effect is greatest in the innermost part of the fjords. The neighbouring countries contribute to loading of the open marine waters, thereby increasing the nutrient concentration of the water exchanged between the open marine waters and Danish fjords. In several Danish estuarine fjords, however, this contribution is of less importance than the local Danish contribution (Figure 2.1).

Only few HAV90 projects have directly attempted to document the effects of reduced nutrient loading. On the other hand, though, many HAV90 projects have investigated central processes in nutrient turnover, and the results obtained can be used when assessing the possible effects of the Action Plan on the Aquatic Environment. Hence the actual effects of the Action Plan are mainly revealed in the results of the monitoring of the marine waters undertaken by the county authorities and the National Environmental Research Institute. These results are reported annually by the Counties, the National Environmental Research Institute and the Danish Environmental Protection Agency.

The upgrading and expansion of sewage works undertaken since the end of the 1980s as a step in the Action Plan on the Aquatic Environment has led to a marked reduction in nutrient loading of coastal waters from point sources.

Phosphorus loading from point sources used to account for most of the phosphorus input to Danish coastal waters, and the effects of reduced loading have been detectable as falling phosphorus concentrations in many estuarine fjords and coastal waters.

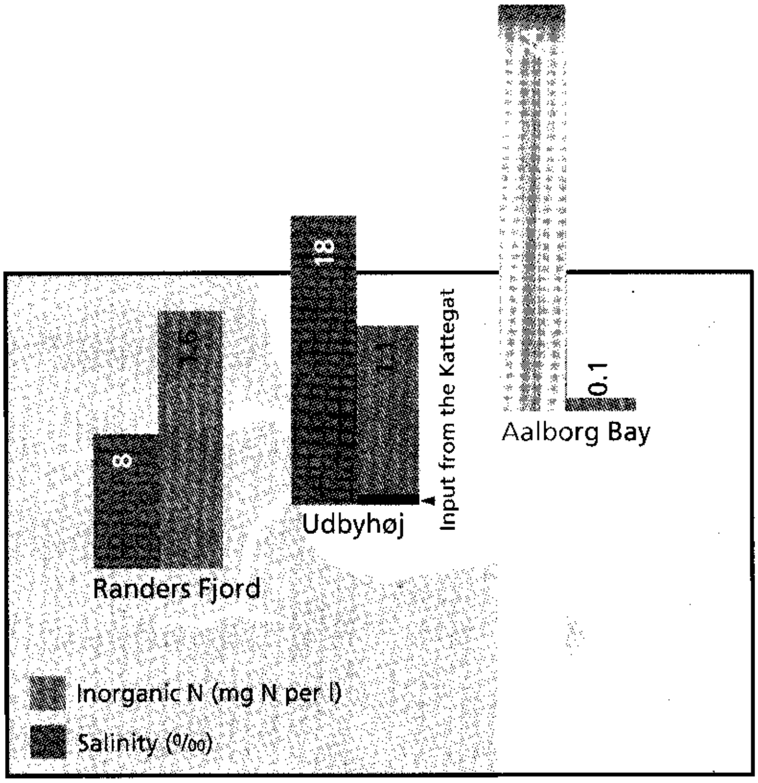

Figure 2.1

Mean annual concentration of inorganic nitrogen from Randers Fjord to the western Kattegat (1991-94: Data from Århus County). The amount of inorganic nitrogen flowing into the fjord from the Kattegat is calculated from salinity measurements at the stations. The figure illustrates that the nitrogen content of the fjord is almost solely determined by the local input.

The interventional measures stipulated in the Action Plan on the Aquatic Environment to reduce phosphorus loading have had positive effects locally and primary production in several fjords is now limited by phosphorus availability in spring and early summer. A reduction in phytoplankton biomass has thus been seen in parts of Limfjorden and Mariager Fjord which appears to be due to the reduced input of phosphorus. The general reduction in phosphorus loading of coastal waters has not led to a general improvement in the environmental state of these areas, however.

Point-source nitrogen loading has also declined correspondingly. However, nitrogen loading of Danish fjords mainly derives from diffuse sources by leaching from arable land, and that contribution has not been reduced as much as stipulated in the Action Plan on the Aquatic Environment.

When corrected for freshwater runoff, nitrogen loading from diffuse sources proves not to have decreased significantly since initiation of the Action Plan. Similarly, nitrogen loading from the atmosphere - which derives from com-

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bustion processes and volatilization from agricultural land - has not fallen either.

As precipitation and runoff were low during the period 1991-93, there was a reduction in nitrogen runoff compared with the average for the 1980s. However, the length of the period and the reduction in loading were too limited for a marked decrease in planktonic algal biomass to be detectable in the coastal waters as a whole. Moreover, neither has any evidence been detected of an unambiguous increase in the density and depth distribution of the benthic vegetation; in a few areas, macroalgae and eelgrass have been detected at greater depths than before, but the depth distribution of the benthic vegetation is reduced in other areas. Similarly, the development in benthic fauna and oxygen conditions in recent years does not indicate any systematic improvement in environmental conditions.

Nevertheless, results of HAV90 research projects and the Nationwide Monitoring Programme clearly indicate that a significant reduction in nitrogen loading will result in less phytoplankton and hence better light penetration of the water and improved living conditions for benthic plants and animals.

Accumulated pools of nutrients in the sediment of affected fjords and coastal waters can considerably delay improvements in the state of the environment for many years, however.

It is therefore natural to question whether the environmental state of the coastal waters will improve sufficiently if the reduction targets stipulated in the Action Plan on the Aquatic Environment are met, i.e. 50% for nitrogen loading and 80% for phosphorus loading from agriculture, sewage works and individual industrial outfalls.

A 50% reduction in nitrogen loading from the land would not yield a 50% reduction in the nitrogen concentration in our estuarine fjords and coastal waters due to exchange with the open sea and input from the atmosphere.

In general, the relative reduction in nutrient concentrations is least in areas with high water exchange. However, these are also the areas that are least affected by eutrophication. In fjords and enclosed coastal waters where loading is high and water exchange low, the nitrogen concentrations will typically be reduced by 20-40% if loading from land is reduced by 50% (Borum, 1996). Such marked reductions in the nitrogen concentration will have a direct effect on the amount of phytoplankton and hence on the whole biological system.

The rate at which the environmental state of the coastal waters is restored depends on the amount of nutrients retained in the sediment, water exchange, and the colonization speed of the biological organisms. The studies undertaken in Kertinge Nor (a shallow cove) have shown that retained pools of nutrients in the sediment contribute to maintaining a poor environmental state for many years following a reduction in loading. In areas with high water exchange, it is expected that the influence of retained nutrients will dissipate within a shorter time horizon (e.g. 5-10 years).

Biological changes can take a long time as slowly growing species of benthic plants and animals have first to re-establish new colonies. However, experience indicates that changes in biological structure can help improve the environmental conditions and thereby shorten the transitional period to reach a new state. It is well documented that it can take many years before the condition of lakes is affected by a reduction in phosphorus loading. In the case of marine waters, in contrast, it can be expected that a reduction in loading, especially of nitrogen, will relatively rapidly initiate improvement in the state of the shallow coastal waters, and that a new balance could reasonably be expected to be attained within a period of approximately 10 years.

2.1.2 Open marine waters

The open parts of the inner Danish marine waters are also affected by nutrient loading. The winter concentration of inorganic nitrogen was considerably lower in the 1950s than is the case today, and phytoplankton production was therefore also considerably lower. Decomposition of sedimented phytoplankton and other organic particles did not previously give rise to widespread occurrence of oxygen deficit. The average winter concentration of nitrogen in the inner Danish marine waters has generally been increasing since the end of the 1960s (see for example, Frier and Christensen, 1991). Nationwide data indicate that nitrogen concentrations in the inner Danish marine waters were very high in 1993/94. The surface water nitrate concentration in the Kattegat and the northern part of the Belt Sea in winter 1993/94 was thus 40% and 70% higher, respectively, than the average for the 8 preceding years. Nitrogen concentrations in the surface water of the Kattegat and the Belt Seas are often higher than that in the inflowing water from the Baltic Sea and from the Skagerrak (see also Figure 4.16). The higher concentrations are due in part to local input from the land (freshwater runoff from Denmark and Sweden) and deposition from the atmosphere, and in part to mixing of the surface water and bottom water in the southern Kattegat and in the Belt Sea. The concentration of phosphorus has decreased in the northern and eastern Kattegat in recent years. Apart from these examples, there are no other signs that the Action Plan on the Aquatic Environment has led to a reduction in the phosphorus concentrations of the open parts of the Danish marine waters (Dahl et al., 1995).

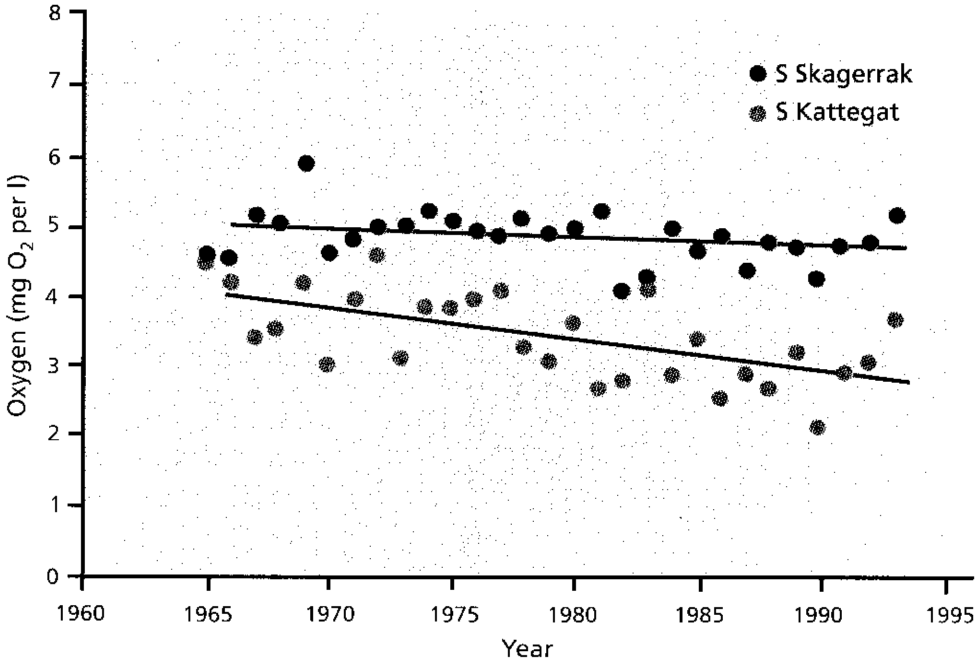
The increased concentrations of nutrients in the open parts of the Danish marine waters have in some areas more than doubled phytoplankton production until the 1980s. In the period 1954-60, phytoplankton production in the Kattegat comprised approximately 70 g carbon per m^2 per year, while that for the period 1984-93 was approximately 190-230 g carbon per m^2 per year (Richardson and Heilmann, 1995).

Production has been high for many years now. Since 1975, it has not been possible to demonstrate a clear trend in either primary production, biomass or species composition of the phytoplankton in the inner Danish marine waters (Agger et al., 1994). The increased oxygen consumption in connection with the decomposition of the increased biomass has resulted in very low oxygen concentrations in the bottom water, and there is no indication that this will change in the near future (Figure 2.2).

In the Skagerrak and in the northern Kattegat, where the water is very deep and water exchange is good, benthic faunal growth enhanced during the 1970s and 1980s, the biomass there having increased in line with the input of nutrients. The increase in biomass is an eutrophication effect explained by

Figure 2.2

Mean oxygen concentration under the pycnocline in the southern Skagerrak and in the southern Kattegat in August to October over the period 1965-93 (from HAV90, Report 59).



the fact that the input of nutrients gives rise to enhanced production of phytoplankton which, on sedimenting out, increase the food resource for the benthic invertebrates. In contrast, the benthic faunal biomass is generally low in areas that are regularly subjected to oxygen deficit (for example the southern Kattegat), and the benthic invertebrates in such areas are mainly represented by young, small individuals.

Model calculations undertaken as part of the HAV90 programme show that a reduction in nitrogen input to the Danish marine waters will have a positive effect on the oxygen concentration of the bottom water. While the Action Plan on the Aquatic Environment will contribute to that development, it will not be possible to attain optimal oxygen conditions through the Action Plan alone. The model calculations show that acceptable oxygen conditions can be attained in the majority of the open parts of the inner Danish marine waters through implementation of the internationally adopted reductions in nutrient discharges together with the Action Plan for Sustainable Agricultural Development, and through further reductions in emissions to the atmosphere.

The overall conclusion, then, is that realization of the reduction targets stipulated in the Action Plan on the Aquatic Environment will lead to improvements in the environmental state of Danish estuarine fjords and other enclosed coastal waters, but that significant improvements in the open marine waters will also require reductions in nutrient inputs from neighbouring countries and a reduction in Danish atmospheric inputs.

2.2 HAV90 and the scientific foundation for decision making

In connection with the administration of the Danish marine environment, questions are regularly raised among politicians, experts, interest organizations and the public concerning the causes and nature of the eutrophication problems, as well as concerning decisions on initiatives to improve the environmental state of the sea, including a reduction in nutrient and organic matter loading. Several of these questions were formulated and discussed in connection with two Consensus Conferences, and one of the tasks of the HAV90 programme has been to answer these questions.

In this section, the results of HAV90 are examined in relation to these questions.

The scientific foundation is examined in more detail in Chapters 4 and 5.

2.2.1 The relative importance of the various sources of nutrient loading

What is the relative importance of the various sources of nutrient input to the open marine waters? Is production in marine waters limited by nitrogen or phosphorus?

Nutrients in the open parts of the marine waters derive from the land, the atmosphere and the adjoining marine waters. The value of Danish efforts to reduce loading from the land has to be evaluated on the basis of the inputs from elsewhere.

Since the 1991 Consensus Conference on the Aquatic Environment, our knowledge of water and nutrient transport across the open boundaries of the Kattegat at the Skagerrak and the Baltic Sea/Belt Sea has not improved to any great extent.

Analyses of inorganic nutrients carried out in the 1990s do not indicate that the input of inorganic nitrogen from the Skagerrak has changed since the 1980s. In contrast, though, the input of inorganic phosphorus from the Belt Sea to the Kattegat seems to have fallen somewhat (National Environmental Research Institute, unpublished observation), apparently as a result of a fall in local input from Denmark and Germany.

HAV90 has provided new knowledge about the bioavailability of the organically bound nutrients transported to the Kattegat from the Skagerrak and the Baltic Sea. If the concentration of biologically available nitrogen in the inflowing water was reduced by 20%, there would be a corresponding reduction in input to the Kattegat of approx. 50,000 tonnes per year. Marked improvement in environmental conditions in the open parts of the Kattegat is therefore dependent on a reduction in nitrogen input from both local sources and sources that discharge into the Belt Sea and the North Sea (including the Jutland Coastal Current).

HAV90 has confirmed previous assumptions about the atmospheric input of nutrients, and has provided a detailed geographical and temporal description of atmospheric loading. The relative importance of the atmospheric contribution to total loading can thereby be assessed with satisfactory certainty. As with many other marine waters near land in the industrialized world, deposition from the atmosphere accounts for 30-40% of total nitrogen input to the Kattegat.

The nitrogen:phosphorus ratio in the inputs to the estuarine fjords and coastal waters is often higher than the ratio in the algae (7:1 on a weight basis and 16:1 on a molar basis), and the systems could therefore be expected to be phosphorus-limited. Nitrogen loss by denitrification (conversion of nitrate to gaseous nitrogen) is considerably higher in the fjords than in the open marine waters, however. The molar ratio between available nitrogen and phosphorus in the water rapidly falls below 16:1 (7:1 by weight) moving towards the open sea, and several studies undertaken in coastal waters indicate that nitrogen is the most important limiting nutrient for plant growth and biomass. This is supported by studies of the nutrient content of phytoplankton and macrophytes, by the relationship between the total nutrient concentration and phytoplankton biomass, and by bioassays involving addition of nutrients. However, phosphorus limitation can occur in certain areas, in which case, though, mainly in the early growth season.

It is regularly claimed from various sides that blue-green algae in the marine environment can overcome nitrogen limitation by taking up nitrogen from the air, and that the Action Plan on the Aquatic Environment's reduction targets for nitrogen loading are therefore worthless. It should be emphasized, though, that with a single exception (Århus Bight in 1975), significant amounts of nitrogen-fixing algae have never been found in the Kattegat. HAV90 has shown that the reduction targets in the Action Plan are appropriate for both phosphorus (especially with regard to inland waters and certain estuarine fjords) and nitrogen (especially with regard to the marine waters).

2.2.2 Eutrophication of coastal waters

Is there a direct and documented coupling between nutrient loading, environmental state and eutrophication effects in our estuarine fjords and other coastal waters? Does reducing loading from Denmark have any effect or are our efforts overshadowed by inputs from adjoining marine waters? What influence do climatic factors have on the effects of eutrophication in our coastal waters?

The nutrients input to our fjords and other enclosed coastal marine waters mainly derive from the Danish land mass, the import of "foreign" loading through water exchange with the open marine waters generally being of lesser significance in these areas.

There is a direct relationship between riverine loading and the concentration of nutrients in the fjords, a relationship which can be precisely modelled in areas where the water exchange is known. HAV90 describes a corresponding simple, good relationship between nutrient concentration, phytoplankton biomass, light conditions in the water column and the distribution of benthic vegetation. There is thus a clear coupling between nutrient input, nutrient concentration and primary production, and hence the basic factors affecting biological state.

The HAV90 programme has significantly improved our knowledge of the importance of filter-feeding benthic macroinvertebrates for the regulation of phytoplankton, of the input of organic matter from the water column to the sediment via aggregation of phytoplankton, and of the turnover of the organic matter in the sediment. It has been shown that mussels are able to completely regulate the development of the phytoplankton and are thereby of decisive importance for the composition of organic matter production. Interannual variation in the occurrence of benthic macroinvertebrates as a result of episodes of oxygen deficit is thus a major cause of the extreme interannual fluctuations seen in the environmental state of our coastal waters.

HAV90 has also improved our knowledge of oxygen dynamics in coastal waters. It has become clear that oxygen turnover in the fjords and coastal waters is far more dynamic and complicated than is the case in the open marine waters.

We have obtained a better understanding of the variation in and regulation of nutrient and organic matter turnover and its importance for oxygen dynamics in fjords and coastal waters, but we still lack the knowledge to be able to predict and forecast the development in oxygen conditions based on a knowledge of loading, meteorology and hydrography. The oxygen concentration is subject to very great temporal and geographical variation, and oxygen deficit in coastal waters is primarily caused by high local oxygen consumption.

HAV90 also indicates, though, that certain hydrographic conditions can cause sudden episodes of oxygen deficit as a result of the inflow of hypoxic bottom water from other areas.

Weather conditions can affect nutrient and organic matter input to the coastal waters via precipitation and riverine runoff, but can also have a decisive influence on the state of the coastal waters through variations in temperature and wind conditions.

Long-lasting ice cover or high summer temperatures together with periods of weak wind increase the frequency of stratification of the water masses and thereby the risk of oxygen deficit and death of benthic macroinvertebrates. Both local and global weather conditions can therefore have a great influence on when and to what degree the eutrophication problems are expressed. One can say that unfavourable weather conditions promote the unfavourable effects of enhanced nutrient input.

Even though there are still significant holes in our knowledge of the variation in the state of the coastal waters, there is no doubt about the general causative relationships between sources, inputs, concentrations and environmental state. There is absolutely no doubt that a marked reduction in nutrient loading from the land will considerably improve the state of the coastal waters.

2.2.3 Eutrophication of open marine waters

What regulates nutrient and organic matter turnover in the open marine waters? Are episodes of oxygen deficit in the Kattegat and the Belt Sea the result of nutrient loading, or is oxygen deficit caused by meteorological conditions? How are the benthic macrophyte communities affected by increased nutrient loading and episodes of oxygen deficit?

Primary production of planktonic algae in the Kattegat has doubled since the mid 1950s in accordance with increased nutrient loading, especially with nitrogen. HAV90 has considerably improved our knowledge of the depth distribution and fate of the primary production, as well as the significance of the individual groups of organisms and their regulatory effect in the open water bodies.

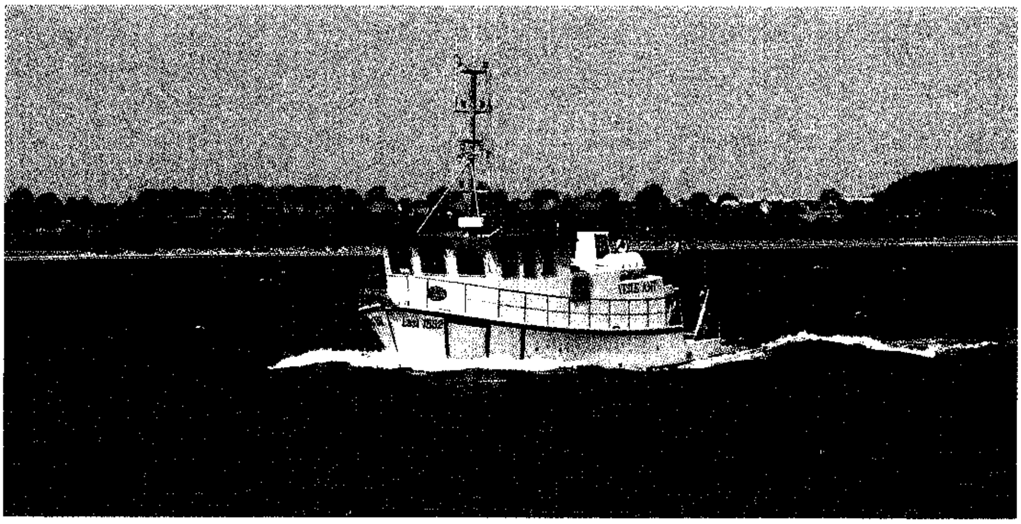
The oxygen concentration of the water is the net result of total oxygen input and total oxygen consumption. Oxygen input to the bottom water in the open marine waters is primarily determined by the meteorological conditions, while oxygen consumption is primarily determined by metabolism of the produced organic matter, and hence is markedly correlated to nutrient levels. The general increase in the frequency and extent of episodes of oxygen deficit over the last 15 years must thus be seen as the result of a general increase in organic matter sedimentation (and implicitly, increased organic matter production and nutrient loading), while the reduction in oxygen concentration seen in individual years will primarily be determined by the actual meteorological conditions.

Under the HAV90 programme it has also been shown that a considerable part of annual production sinks to the bottom (62 g carbon per m^2 in the southern Kattegat and 118 g carbon per m^2 in Århus Bight), where it decomposes below the pycnocline with resultant consumption of oxygen.

Model calculations have shown that oxygen input to the Kattegat bottom water takes place through input of water from the Skagerrak and by mixing with overlying oxygen-rich surface water. The model calculations also show that oxygen input in the critical period during summer and the early autumn is primarily controlled by the meteorological conditions (wind), while oxygen consumption is primarily determined by the amount of organic matter sedimenting out.

The benthic macroinvertebrate communities in the open Danish marine waters are exposed to both positive and negative effects of eutrophication: Increased sedimentation of organic matter can enhance production and biomass because the communities are generally considered to be food-limited, while frequent falls in the oxygen concentration can stress the animals and under certain circumstances eradicate whole populations.

However, the reported effects of eutrophication on the benthic macroinvertebrate communities are almost



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entirely based on studies in which the measurements of oxygen concentration and sampling of benthic fauna rarely coincide in time and space. This considerably reduces our knowledge of the causal relationship to the variation in the presence of benthic macroinvertebrates - a topic that is otherwise extremely important to elucidate, not least because the benthic macroinvertebrates are an important food resource for a number of commercially important fish (e.g. cod and plaice).

2.2.4 Nutrient removal in coastal waters

How great is the loss of nitrogen and phosphorus during transport from the land to the open sea via the coastal waters (nature's self-purification capacity)? Will there be a self-augmenting effect such that loss will be relatively greater when the state of the coastal waters has improved due to a reduction in loading?

Part of the nutrients input from the land will either be deposited in the sediment or transformed during transport through the fjords and the coastal waters. The total load therefore diminishes in size by the time it reaches the open sea. HAV90 has contributed important new knowledge about this topic, especially in the case of nitrogen removal by denitrification, which has been thoroughly described.

We now have a far broader knowledge of the nitrogen and phosphorus removal per unit area in different systems, and we know that this removal is greatest in areas with a high nutrient content. The relative removal in relation to loading is only known in the case of more enclosed coastal waters for which actual mass balances have been established on the basis of water exchange calculations. Despite the large removal rates, considerable amounts of nitrogen and phosphorus pass through the coastal waters to the open sea. Nature's self-purification capacity is thus insufficient to remove the excess nutrients within the time horizon of residence in the coastal waters, and hence the natural balance between (and the availability of) nitrogen and phosphorus does not re-establish.

It has been proposed that the removal of excess nitrogen will take place increasingly effectively as the state of the coastal waters improves following a reduction in loading, i.e. there is supposed to be a self-augmenting effect that will benefit the environmental state of both the coastal waters and the open marine waters. While both self-augmenting and stabilizing mechanisms have been found during the experimental research on removal processes, we are still unsure how the total loss of nutrients in the coastal zone will change with decreasing loading.

2.2.5 HAV90 and monitoring of the marine environment

The current monitoring programme under the Action Plan on the Aquatic Environment covers virtually all our coastal and marine waters with the exception of the open parts of the North Sea and the Skagerrak. The location of the stations has enabled comprehensive charting of both physical, chemical and biological conditions in the inner Danish marine waters.

The existing monitoring programme should be updated, however, such that future monitoring takes account of the new knowledge of the effects of nutrients in the sea, including that gained in connection with HAV90.

Among other things, it has become clear that there is a great need for a critical analysis of the objective of and need for the monitoring programme. In addition, there is a need for a clear description of the monitoring programme's strategy and organization, including the duties and responsibilities of the participating institutions, just as quality assurance and appropriate storage of data have to be clarified. Finally, there is a great need for a critical analysis of the methods employed, the geographical location of the sampling stations, and the frequency with which the samples are collected.

The HAV90 programme and the monitoring programme have led to the collection of a vast amount of data and have considerably improved our knowledge. A critical examination of this data and knowledge should be one of the foundations of any efforts to optimize the monitoring programme.

The monitoring should be adjusted to the conditions that control and dominate the environmental state of the area in question. In practice, this means that the monitoring of shallow water areas should concentrate on environmental conditions and effects associated with the sea floor, while monitoring at the deeper stations should concentrate on environmental conditions and effects in the open water bodies, as well as the effects of primary production on mineral cycling within the sediment.

The present monitoring of the marine environment is described in Chapter 6, which also gives examples of how the knowledge attained under HAV90 can be incorporated when adjusting the individual parameters or when new parameters are to supplement the existing monitoring programme.

By way of example, HAV90 has provided new knowledge of the geographical coverage of sampling stations, of sampling frequency, of hydrographic conditions, of measurement of primary production, of analysis of plankton communities, of the value of nutrient analyses, of the spatial and temporal distribution of oxygen deficit, and of turnover of nutrients and organic matter in sediments. The new knowledge in these areas should be utilized when assessing and adjusting the monitoring programme.

In conclusion, it should be noted that the international monitoring programmes in many cases contribute useful information about the state of Danish marine waters, especially as regards the open marine waters. In order to ensure optimal exploitation of data, a future monitoring programme should be coordinated with the international programmes. The Danish obligations in connection with the international programmes should therefore be incorporated in the future national monitoring programme.

3 Background for the Action Plan on the Aquatic Environment

Biofoto

At a total cost of approximately USD 1,800 million, the Action Plan on the Aquatic Environment represents one of the largest Danish investments in the environment. Adoption of the Action Plan was necessitated by the increasing frequency and extent of oxygen deficit in the Danish marine waters up through the 1970s and 1980s.

3.1 Origin and scope of the Action Plan on the Aquatic Environment

In autumn 1981, the Minister for the Environment submitted a report to Parliament pointing out the serious threats that were facing the quality of both groundwater and surface water. In January 1984, the Danish EPA published a report on oxygen deficit and fish mortality in 1981 (Danish EPA, 1984a), and in March 1984 the Agency published estimates for organic matter, nitrogen and phosphorus loading of the inner Danish marine waters from the land (Danish EPA, 1984b).

On the basis of these reports, the so-called NPo report (N: nitrogen, P: phosphorus, and o: organic matter) was published in August 1984. This contained an overall description of the environmental impact of the discharge of nitrogen, phosphorus and organic matter. In extension thereof, Parliament adopted the NPo Action Plan on 31 May 1985. This stipulated a number of interventional measures to reduce discharges of nutrients from agriculture, freshwater fish farms and sewage works.

In October 1986, episodes of oxygen deficit struck again in the Kattegat and became the subject of considerable media attention. This, together with pressure from environmental organizations, brought the problem to the forefront of the political agenda.

A few months later, on 31 January 1987, the government put forward the "Action Plan Against Pollution of the Danish Aquatic Environment with Nutrients", commonly referred to as the Action Plan on the Aquatic Environment.

This short and intense decision-making process is notable given that nutrient pollution and the oxygen deficit problem had already been pointed out several years earlier in a number of reports and action plans.

Adoption of the Action Plan meant that the implementation of environmental policy measures aimed at the aquatic environment accelerated. As events started to pick up speed from October 1986, there thus arose demands for more drastic measures and shorter deadlines that those stipulated in the NPo Action Plan.

The Action Plan on the Aquatic Environment stipulates that total discharges of nitrogen and phosphorus from agriculture, individual industrial outfalls and municipal sewage works have to be reduced by 50% and 80% percent, respectively. According to the plan, total nitrogen discharge from these three sectors has to be reduced from a total of

Action Plan on the Aquatic Environment

"Action Plan Against Pollution of the Danish Aquatic Environment with Nutrients", commonly referred to as the "Action Plan on the Aquatic Environment" was put forward by the Danish government in 1987. The Action Plan encompasses a large number of interventional measures directed at sewage treatment, storage of animal fertilizer and reductions in agricultural discharges of nitrogen and phosphorus to the environment. According to the Action Plan, total discharge of nitrogen from agriculture, municipal sewage works and individual industrial outfalls has to be reduced by 50% from a total of 290,000 tonnes per year in 1987 to around 145,000 tonnes per year in 1993. Similarly, phosphorus discharge has to be reduced by 80% from a total of approx. 12,000 tonnes per year to 2,200 tonnes per year.

Nationwide Monitoring Programme under the Action Plan on the Aquatic Environment

The purpose of the programme is to describe the environmental state of the groundwater, springs, watercourses, lakes and the sea, and to document the effects of the interventional measures and investments implemented with a view to reducing discharges to the aquatic environment. Monitoring of the marine environment is primarily directed at the inner Danish marine waters and is to a large extent based on investigations of the chemical and biological conditions in the open water bodies, as well as on investigations of the benthic flora and fauna.

290,000 tonnes per year to around 145,000 tonnes per year, while phosphorus discharges have to be reduced from approx. 12,000 tonnes per year to 2,200 tonnes per year.

The deadline for attaining these reductions was originally three years. However, as the target was difficult to reach within the original deadline, it was extended to 1 January 1993 (cf. "Report on the Action Plan on the Aquatic Environment" given by the Environment and Planning Commission on 30 April 1987).

The Action Plan on the Aquatic Environment only addresses part of the nutrient and organic matter inputs to the inland and marine water bodies. Thus, no reduction targets are specified for freshwater fish farms and marine fish farms. It has instead been decided that the discharge regulations are to be tightened. Similarly, the interventional measures stipulated in the Action Plan do not cover loading from stormwater outfalls and sparsely built-up areas.

With regard to loading from the atmosphere, it was decided (a) to reduce agricultural emissions of ammonia, (b) to draw up a plan for reducing power station emissions of nitrogen oxides (NO_x) and (c) to introduce American norms for limiting pollution from vehicle exhaust fumes.

When stipulating the Action Plan on the Aquatic Environment's requirements for the reductions in discharges, there was considerable disagreement as to the actual magnitude of discharges. Similarly, there was also uncertainty about what impact the interventional measures adopted would have if the reduction targets were fulfilled. It was therefore decided to implement a nationwide monitoring programme, as well as a marine research programme and a waste water research programme. Together, these programmes were to evaluate the effect of the investments and interventional measures made under the Action Plan.


Peter Bondo Christensen/NERI

3.2 Questions arising from the Consensus Conferences on the aquatic environment

The Action Plan on the Aquatic Environment was adopted during a time of heated discussion on the aquatic environment, there being considerable disagreement about the magnitude of nutrient loading and what interventional measures would be most effective from the point of view of environmental economics.

At the request of the prime minister and at very short notice, the then Council for Research Policy and Planning arranged a Consensus Conference in April 1987 aimed at reviewing existing knowledge on the subject and evaluating the technical and economic conditions for improving the aquatic environment. The 1987 Consensus Conference addressed the following questions:

- How great are the inputs and outputs of nitrogen and phosphorus in the Danish aquatic environment, and with what degree of certainty can they be determined?
- What is the significance of nitrogen and phosphorus loading from Danish sources for the environmental quality of our inland waters, estuarine fjords and the sea around Denmark?
- How long will it take before we can expect significant improvements in environmental quality, and how will this be detectable?
- What environmental criteria can be used as the basis for deciding upon the extent of the interventional measures necessary?

Runoff from arable land was identified as the most important source of nitrogen pollution, while phosphorus pollution mainly derived from industry and municipal sewage works. In addition, it was established that it will take some time for a positive effect of the interventions to become detectable because of the nutrient pools already accumulated in the soil and water. The 1987 Consensus Conference concluded that the great uncertainty about the magnitude of the inputs, especially those from the adjoining marine waters and the atmosphere, made it uncertain how great an effect the planned interventions would have on oxygen conditions in the open sea. Implementation of a differentiated intervention package and strategy was recommended, in particular emphasizing better utilization of animal fertilizer and better phosphorus stripping of sewage works effluent.

The objective of the 1991 Consensus Conference was to take stock of current scientific knowledge about nitrogen, phosphorus and organic matter in the soil and the aquatic environment. In continuation hereof, it was also the objective to evaluate what would happen if the reduction targets were sharpened further or realized by other means than those stipulated in the Action Plan on the Aquatic Environment.

The questions addressed by the 1991 Consensus Conference included:

- What significance has denitrification for nitrogen removal in various types of wetlands and water bodies?
- How much nitrogen is discharged to Danish terrestrial and marine waters from the atmosphere?
- How great are the inputs and outputs of nitrogen and phosphorus to and from the Kattegat and the Belt Sea,

and what is the temporal variation?
- What effect will implementation of the Action Plan on the Aquatic Environment have on the environmental state of Danish estuarine fjords, and what is the time frame for expected improvements?
- What effect will implementation of the Action Plan on the Aquatic Environment have on the environmental state of the Belt Sea and the Kattegat, and what is the time frame for expected improvements?

The Consensus Conference concluded that the interventional measures stipulated in the Action Plan had improved water quality in many watercourses and certain lakes, but that there had been no detectable improvements in the sea. The view was that the marine environment in the coastal waters would improve if the requirements of the Action Plan were fulfilled, but that improvement in the open sea would require corresponding interventional measures in other countries, as well as a reduction in loading from the atmosphere.

It was also established that the data were insufficient to assess the state of and changes in the marine environment of the coastal waters as well as the relative importance of the various sources for the input of nitrogen and phosphorus. In extension hereof, it was concluded that the knowledge then available was an inadequate basis for either sharpening or relaxing the requirements stipulated in the Action Plan on the Aquatic Environment.

3.3 The Marine Research Programme 1990

In the mid 1980s, analysis and evaluation of Danish marine research revealed that although it had considerable potential, the research was spread over many fields and numerous small institutions. As a consequence, important research areas lacked scientific depth, and research into many of the fundamental processes in the sea had not been undertaken with a strength and rate that fulfilled society's need for new knowledge. One example was research in eutrophication, including the production and mineralization of organic matter in our marine waters.

A debate consequently arose about Danish marine research which underlined the need for closer and more extensive cooperation between the universities and the Danish EPA's institutions of that time. Joint discussions resulted in agreement that the cooperation would benefit from being strengthened through a joint effort aimed at elucidating the significance of the increasing eutrophication of the Danish marine waters and utilizing the information gained to predict the effects of pollution-limiting interventional measures.

The major joint effort to enhance our knowledge of marine processes was given the name Marine Research Programme 1990, commonly referred to as HAV90. When the Action Plan on the Aquatic Environment was adopted, USD 15 million was concomitantly set aside for the implementation of HAV90.

3.3.1 Programme areas under HAV90

The research projects under HAV90 were to focus on:

- Improving our understanding of physical processes, chemical processes and biological effects
- Developing models to describe water and nutrient transport and nutrient turnover in Danish marine waters and adjoining waters
- Developing models to describe physical and biological processes in coastal and front zones
- Measuring physical processes, chemical processes and biological effects through intensive field and laboratory measurements
- Developing methods and equipment for *in situ* measurements
- Statistical analysis of historical data

The projects were grouped under four main programme areas: 1) Nutrient and organic matter turnover and transport in coastal waters, including the impact of loading on them; 2) Nutrient and organic matter turnover in the open water bodies; 3) The role of the sediment in nutrient and organic matter turnover; 4) The significance of meteorological processes for eutrophication.

The projects in the first programme area emphasized studies of transport mechanisms and turnover in relation to loading, including an understanding of the current environmental state of the coastal waters.

The activities in the second programme area concentrated on projects aiming at quantifying horizontal and vertical transport of nutrients and their effects on production and biological structure in the open water bodies.

The research on the role of sediment in nutrient and organic matter turnover aimed to elucidate a number of relationships between organic matter production in the open water bodies and oxygen consumption in the sediment, as well as to determine which processes regulate the oxygen balance in the sediment and the biogeochemical processes in marine sediments.

The research on the significance of meteorological processes for eutrophication focused on atmospheric processes, particle deposition and modelling of nutrient deposition on the sea.

3.3.2 Results of HAV90

About 70 projects have been wholly or partly financed through HAV90. The majority of these projects have been reported in a series of Danish EPA reports entitled "Havforskning fra Miljøstyrelsen" (Marine Research from the Danish EPA). Each of these reports includes an English summary.

In the period 1989-94, a total of 39 PhD students received their degrees through HAV90 and a further 70 or so students completed MSc degrees.

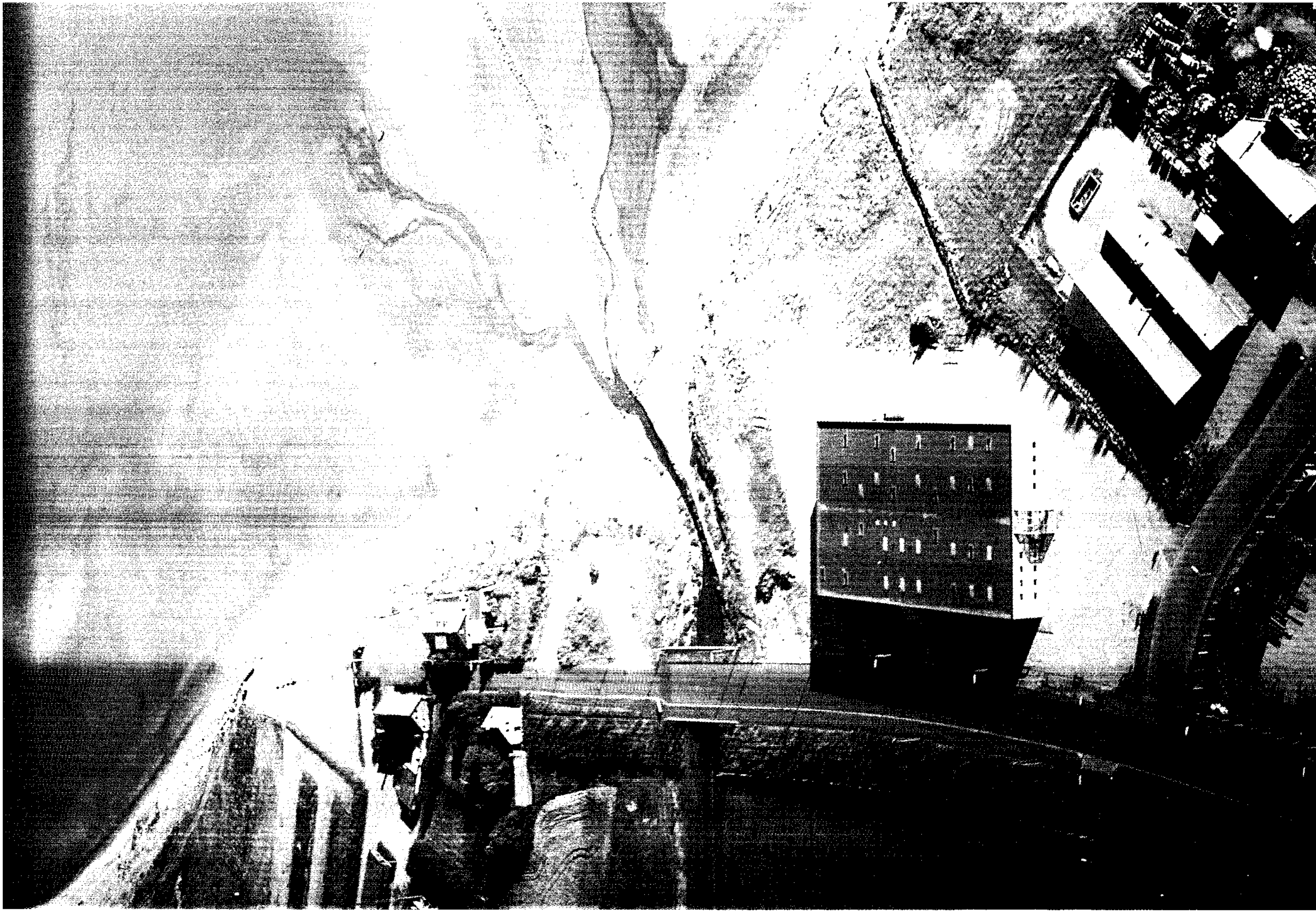
Approximately 250 scientific papers have already been published in international journals, and by the end of 1997, a further 40 articles will have been published as a result of HAV90 projects.

As part of the HAV90 programme, the Danish EPA and the EU Commission jointly held an international symposium from 13-16 October 1993 entitled "Nutrient Dynamics in Coastal and Estuarine Environments". The symposium was attended by approximately 240 scientists from around the world.

Finally, a national seminar was held on 29-30 November 1993 for persons occupied with administering and monitoring the Danish marine environment. At the seminar, a broad selection of HAV90 projects were presented, the emphasis though being on results of importance for the general understanding of biological conditions and nutrient turnover in Danish marine waters.

The objective of HAV90 was also to stimulate inter-institutional and hence interdisciplinary cooperation between universities, consultancy firms and sector research institutes, as well as internationalization of Danish marine research.

The intention was to provide USD 15 million in financial support to marine research over a five-year period. The direct support was subsequently reduced to just over USD 11 million during the programme period. Even though the financial injection only represented a moderate expenditure compared with many other scientific research programmes or with other countries' expenditure in this area, HAV90 considerably stimulated the initiation of interdisciplinary cooperation, the education of new scientists during the course of the programme, and the accumulation of new knowledge on the marine environment (HAV90, Report 60).



4 Nutrient loading and transport

The Danish marine waters receive nutrients from the land, the air and from adjoining marine waters. The inputs from the land derive either from direct point-source discharges to the marine water or via discharge to watercourses and lakes, from where the nutrients are transported onwards to the coastal waters.

In order to be able to evaluate the relative importance of the individual sources for eutrophication of the aquatic environment and their relationship to the politically determined reduction targets, it is necessary to know the size of the contribution from the individual sources and understand how these can change during transport from the source to the open sea.

4.1 Nutrient sources and loading of the marine environment

The increase in nutrient loading of the marine environment originates from the land. Some of the land-based sources are encompassed by the Action Plan on the Aquatic Environment, the objective of which was to reduce nutrient loading by various interventional measures.

The significance of the various sources differs when one compares the innermost parts of the estuarine fjords, the coastal waters, the inner Danish marine waters and the Danish marine waters as a whole.

4.1.1 Sources of nutrient loading from the land

Nutrients from the land can be roughly divided into point sources and diffuse sources. In this context, the point sources encompass discharges from sewage works, individual industrial outfalls, sparsely built-up areas, stormwater outfalls, freshwater fish farms and marine fish farms. Point sources of emissions to the air encompass power stations, combined heat and power stations, district heating plants, industrial enterprises, etc.

Diffuse sources encompass runoff from rural areas (fields, forests and other types of landscape), with runoff from agricultural land being the dominant diffuse source. Diffuse inputs to the air mainly encompass emissions from traffic and ammonia volatilization from agriculture.

Discharges from the various sources are assessed annually by the Nationwide Monitoring Programme under the Action Plan on the Aquatic Environment (see for example, Danish EPA, 1995 and 1996).

Discharges from municipal sewage works have fallen markedly since the adoption of the Action Plan on the Aquatic Environment, and there is no doubt that once those sewage works granted exemption from the compliance deadline have been upgraded, the reduction targets stipulated for sewage works discharges will be met.

Just over half of the total discharge from municipal sewage works is discharged directly to the sea, which is also the case for the majority of the individual industrial discharges. The reduction targets for discharges from individual industrial outfalls have long been met and these discharges seem presently to lie at a stable level.

The discharges from freshwater fish farms have been falling since the adoption of the Action Plan on the Aquatic Environment, and are presently considered to have attained a stable level.

Svend Tougaard/Biofoto

Table 4.1

Nitrogen, phosphorus and organic matter loading from point sources and diffuse sources in 1994. Organic matter is measured as biological oxygen demand over 5 days (BOD_5) (Suhr, 1994; Henriksen et al., 1995; Danish Environmental Protection Agency, 1995).

	Nitrogen (tonnes)	Phosphorus (tonnes)	Organic matter (tonnes)
Municipal sewage works	10,200	1,600	10,200
Individual industrial outfalls	2,700	300	25,700
Sparsely built-up areas	1,200	300	4,600
Stormwater outfalls	370	90	900
Freshwater fish farms	1,400	300	3,500
Marine fish farms	300	30	not calculated
NO_x emissions	280,000	not calculated	not calculated
NH_x emissions	115,000	not calculated	not calculated
Diffuse loading from rural areas	260,000[a]	not calculated	not calculated

[a] For practical reasons, diffuse loading from rural areas cannot be calculated precisely, but it is estimated that leaching from arable land in 1994 was of the same magnitude as when the Action Plan on the Aquatic Environment started (Danish Environmental Protection Agency, 1995). It is believed that half of the nutrients lost by diffuse loading reach the groundwater while the remainder reach the surface waters.

In contrast, discharges from marine and terrestrial saltwater fish farms have not changed since the adoption of the Action Plan on the Aquatic Environment.

Similarly, there has been no marked change in discharges from sparsely built-up areas, which seem to remain at the same level as at the start of the Action Plan.

Discharges from stormwater outfalls were also roughly the same in 1994 as at the time the Action Plan was adopted.

At the national level, runoff from rural areas accounts for much of total nutrient loading of the inland and marine waters. At the time the Action Plan was adopted, nitrogen loss to the groundwater, inland waters and marine waters from agriculture was estimated at approx. 260,000 tonnes per year. In the latest status report on the aquatic environment (Danish EPA, 1995), it is estimated that leaching of nitrogen from arable land is at the same level as when the Action Plan on the Aquatic Environment came into force in 1987.

Total Danish atmospheric emissions of NO_x (nitrogen oxides) amount to approx. 280,000 tonnes nitrogen per year (Table 4.1), of which 70% derives from power and heat production and from traffic. In comparison, atmospheric emissions of ammonia from Danish sources are estimated at approx. 115,000 tonnes nitrogen per year (Henriksen et al., 1995).

As the various nitrogen compounds are deposited differently on the sea, the magnitude of emissions does not reflect the size of atmospheric inputs of nitrogen compounds to the sea (see Section 4.3).

4.1.2 Total nutrient loading of Danish marine waters from the land

The sources of nutrients and organic matter and their transport pathways to Danish marine waters are outlined in Figure 4.1. Annual nutrient inputs to Danish marine waters are calculated regularly in the annual reports of the Nationwide Monitoring Programme.

As a result of the efforts made under the Action Plan on the Aquatic Environment to upgrade the sewage works, there has been a decrease in direct discharges to the sea from sewage works, individual industrial outfalls, stormwater outfalls and sparsely built-up areas. Thus in the period 1989-94,

Table 4.2

Trend in total nitrogen loading from land to the total combined Danish marine waters over the period 1989-94 (Danish Environmental Protection Agency, 1995). Input from watercourses only encompasses input from Danish watercourses, just as direct discharges only encompass Danish land-based sources (sewage works, industry and sparsely built-up areas) discharging directly to marine areas. In contrast, the figure for atmospheric deposition encompasses both national and international sources. Atmospheric deposition was calculated for 1994 on the basis of 1990 emission data and 1994 meteorological data but taking into account geographical variation in deposition (cf. Skov et al., 1995). In calculating total deposition, the area of the total combined Danish marine waters was assumed to be 96,538 km^2. The deposition figures for the remaining years are placed in parentheses as their exact magnitude has not been calculated.

Year	Nitrogen (tonnes)			
	Water-courses	Direct discharges	Atmospheric deposition	Total
1989	61,900	16,700	(118,900)	197,500
1990	97,000	14,900	(118,900)	230,800
1991	78,500	13,500	(118,900)	210,900
1992	91,700	12,500	(118,900)	223,100
1993	98,200	9,800	(118,900)	226,900
1994	119,100	9,400	118,900	247,400

direct loading of the marine waters fell from approx. 17,000 tonnes nitrogen per year to approx. 9,000 tonnes, and from approx. 4,000 tonnes phosphorus per year to approx. 1,600 tonnes, corresponding to a decrease of 45% and 60%, respectively (Table 4.2 and 4.3). Point-source discharges of organic matter to marine waters have decreased from approx. 73,000 tonnes in 1989 to approx. 34,000 tonnes in 1994 (Danish EPA 1995).

Nitrogen transport to the sea via Danish watercourses amounted to approx. 119,000 tonnes in 1994, and during the period 1989-94 varied between 62,000 and 119,000 tonnes nitrogen per year (Table 4.2). Total nitrogen loading of Danish marine waters from the land was therefore largely unchanged during the period 1989-94, the variation seen being attributable to interannual variation in precipitation and runoff.

Phosphorus transport to the sea via Danish watercourses amounted to approx. 3,000 tonnes per year, and is not equally dependent on meteorological conditions (Table 4.3). The total phosphorus loading of the sea has fallen from a starting level of approx. 8,000 tonnes per year in 1989 to approx. 5,700 tonnes per year in 1994 due to the decrease in direct point-source discharges resulting from improved treatment of sewage (Table 4.3).

Some of the nutrients input to Danish marine waters are deposited from the

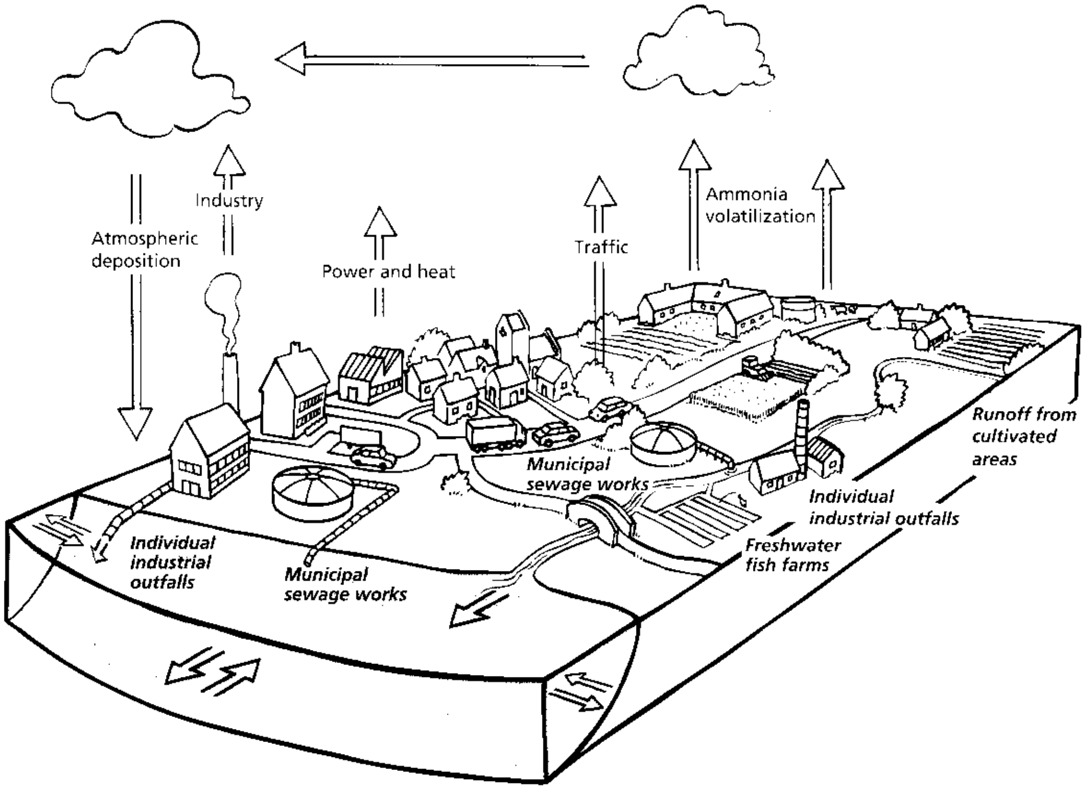


Figure 4.1

Sources and transport pathways for nutrient loading of Danish marine waters. Sources named in italics are encompassed by the Action Plan on the Aquatic Environment and are calculated under the Nationwide Monitoring Programme. The blue arrows indicate the transport pathways.

atmosphere, partly with the precipitation (wet deposition) and partly directly by dry deposition (particle fallout). The most important airborne nitrogen compounds are ammonia compounds (NH_3), which are mainly produced in connection with livestock farming, and nitrogen oxides (NO_x), which are mainly produced as nitrogen monoxide (NO) by combustion processes (see Section 4.3 for a more detailed examination of atmospheric deposition).

It is estimated that annual atmospheric inputs to Danish marine waters amount to 1.2 tonnes nitrogen per km^2 (corresponding to 12 kg nitrogen per ha per year) and 12 kg phosphorus per km^2. As the total area of Danish marine waters is 96,538 km^2, total annual nutrient atmospheric inputs of nitrogen and phosphorus to Danish marine waters amount to about 119,000 tonnes and 1,160 tonnes, respectively.

The large contribution of atmospheric inputs to total loading of Danish marine waters (Tables 4.2 and 4.3) is due to the large area of Danish marine waters as a whole, which include a large segment of

Table 4.3

Trend in total phosphorus loading from the land to the total combined Danish marine waters over the period 1989-94 (Danish Environmental Protection Agency, 1995). Input from watercourses only encompasses input from Danish watercourses, just as direct discharges only encompass Danish land-based sources (sewage works, industry and sparsely built-up areas) discharging directly to marine areas. In contrast, the figure for atmospheric deposition encompasses both national and international sources and was calculated assuming a constant deposition rate of 12 kg phosphorus per km^2 per year and an area 96,538 km^2 for the total combined Danish marine waters.

Year	Phosphorus (tonnes)			
	Water-courses	Direct discharges	Atmospheric deposition	Total
1989	2,860	3,970	1,160	7,990
1990	3,570	3,100	1,160	7,830
1991	2,330	2,500	1,160	5,990
1992	1,960	2,050	1,160	5,170
1993	2,040	1,600	1,160	4,800
1994	2,960	1,570	1,160	5,690

Figure 4.2

Map of Danish marine waters. By "the total combined Danish marine waters" is understood all Danish marine waters, whereas by "the inner Danish marine waters" is understood the marine waters delimited in the north by the boundary between the Skagerrak and the Kattegat and in the south by the Drogden Sill (the Øresund) and the Darss Sill (the Baltic Sea) (Map and research: Jonathan Wyse, Topaz Design and Thorkild Aarup).

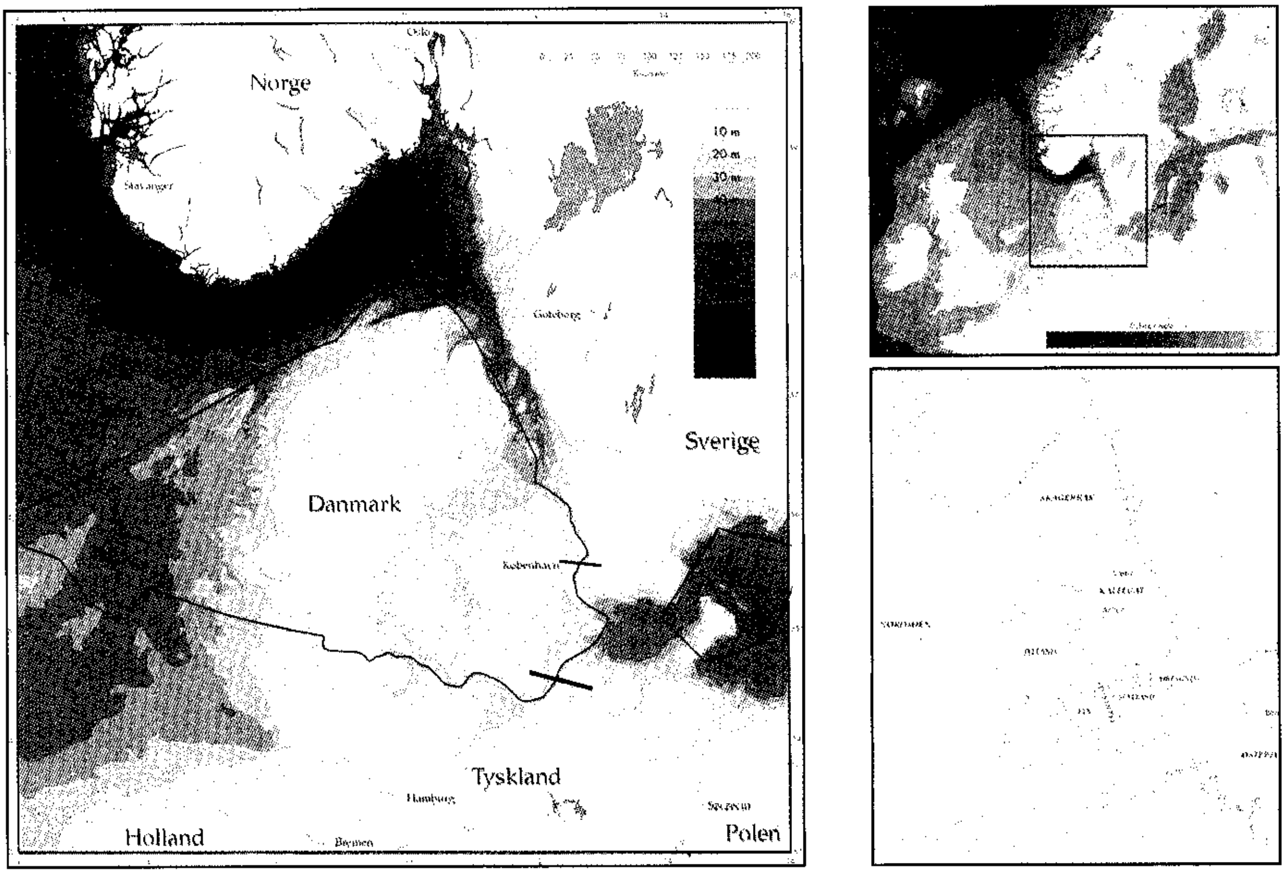


Table 4.4

Total estimated nitrogen loading of inner Danish marine waters (Total N in tonnes) from Danish, Swedish and German watercourses and point sources. The estimates are based partly on data from the Danish Environmental Protection Agency (1991, 1992, 1993 and 1996), OSPAR (1994, 1995 and 1996; unpublished working papers), the Baltic Marine Environment Protection Commission (1993), Ærtebjerg et al. (1993), and Charlotte Carlsson, 1996 (personal communication).

Year	Inner Danish marine waters				Kattegat alone		
	Total	Denmark	Sweden	Germany	Total	Denmark	Sweden
1990	128,000	78,000	40,000	10,000	66,000	33,000	33,000
1991	111,000	63,000	39,000	9,000	61,000	29,000	32,000
1992	122,000	70,000	43,000	9,000	69,000	34,000	35,000
1993	120,000	75,000	36,000	9,000	61,000	32,000	29,000
1994	147,000	89,000	48,000	10,000	83,000	43,000	40,000

the North Sea. A considerable part of atmospheric loading therefore derives from international sources (Figure 4.2). In contrast, the contribution from watercourses and direct discharges is usually the dominant terrestrial source of nutrient input to the inner Danish marine waters (see Section 4.1.3).

As can be seen, there is considerable difference between the magnitude of nutrient discharge from land-based sources (Table 4.1) and the nutrient input to the sea (Tables 4.2 and 4.3). Among other reasons, this is because up to 50% of the nitrogen loss from agriculture enters the groundwater, with only the remainder being lost to the surface water. In addition, part of the nutrients entering the watercourses and lakes is retained or lost during transport to the sea.

4.1.3 Nutrient loading of inner marine waters from the land

As nutrient loading most often causes special problems in the inner Danish marine waters, it is relevant to calculate loading of these marine waters separately (Tables 4.4 and 4.5). The calculations for the inner Danish marine waters (see Figure 4.2) encompass:

- Danish inputs between the Skagerrak boundary in the north and the Drogden Sill and Darss Sill in the south
- Swedish inputs between the Skagerrak boundary in the north and the Drogden Sill in the south
- German inputs west of the Darss Sill
- Atmospheric deposition between the Skagerrak boundary in the north and the Drogden Sill and Darss Sill in the south.

Total land-based nitrogen loading of the inner Danish marine waters from Denmark, Sweden and Germany has not changed since 1990 (Table 4.4). The extraordinary great input to the inner Danish marine waters in 1994 of 147,000 tonnes nitrogen is due to the very high runoff from land, especially in January, March, September and December. Runoff in 1994 was thus the highest recorded in more than 50 years. In the case of the Kattegat alone, the Swedish share of land-based nitrogen loading was of the same magnitude as loading from Denmark.

Nitrogen loading of the Kattegat and the inner Danish marine waters from the land (watercourses and direct sources) is 1.5-3 times greater than nitrogen loading from the atmosphere. As a rule of thumb, 80-85% of the nitrogen transported in the watercourses derives from agriculture. Local Danish sources thus play a decisive role for loading of the Danish estuarine fjords.

Deposition of inorganic nitrogen from the atmosphere on the inner Danish marine waters is calculated to be

Table 4.5

Total estimated phosphorus loading of inner Danish marine waters (Total P in tonnes, rounded off to the nearest 10) from Danish, Swedish and German watercourses and point sources. The estimates are based on data from the Danish Environmental Protection Agency (1991, 1992, 1993 and 1996), OSPAR (1994, 1995 and 1996, unpublished working papers), the Baltic Marine Environment Protection Commission (1993), Ærtebjerg et al. (1993), and Charlotte Carlsson, 1996 (personal communication).

Year	Inner Danish marine waters				Kattegat alone		
	Total	Denmark	Sweden	Germany	Total	Denmark	Sweden
1990	7,170	4,850	1,690	630	2,300	1,100	1,200
1991	5,000	3,330	1,100	600	1,930	1,030	900
1992	4,200	2,830	870	500	1,520	920	700
1993	3,720	2,620	740	400	1,470	850	620
1994	4,870	3,190	1,080	600	2,170	1,240	930

around 52,000 tonnes per year assuming a constant deposition of 1.2 tonnes nitrogen per km^2 per year and a total area for the inner Danish marine waters of 43,030 km^2. Of this, approx. 27,000 tonnes fall on the Kattegat. Ammonia compounds typically account for 60% of the total nitrogen deposition, while the remainder stems from nitrogen oxides. Nitrogen deposition from the atmosphere is thus also a significant source of nitrogen input to the inner Danish marine waters. Moreover, the airborne nitrogen is input to the surface layer of the water column in a form that is directly utilizable by the primary producers (see Section 4.5).

Atmospheric deposition of phosphorus on the inner Danish marine waters comprises approx. 520 tonnes per year, of which around 270 tonnes fall over the Kattegat. Deposition of phosphorus from the atmosphere is therefore of minor significance (Table 4.5). The magnitude of air-borne phosphorus loading is uncertain, however, and may be locally high.

4.2 Nutrient transport and retention in coastal waters

As described above, large quantities of nutrients are transported to the estuarine fjords and coastal waters via watercourses. Only part of these nutrients is transported onwards to the open marine waters, however. The remainder is temporarily or permanently retained in the coastal waters through deposition in the sediment, incorporation in organisms or complete removal from the aquatic environment (primarily removal of nitrogen by denitrification; see Section 4.2.2). The coastal waters thereby function as a filter between the land and the open sea.

Factors such as water retention time, depth and stratification of the water column can considerably influence both nitrogen and phosphorus removal in coastal waters. Similarly, the fate of the nutrients is considerably influenced by the biological components that regulate nutrient and organic matter turnover and affect the physical and chemical conditions in the water column and the sediment. With respect to nutrient removal in fjords and coastal waters, the most important questions are: How great is the permanent storage and removal of nutrients in relation to total input to the coastal waters? What is the significance of temporary retention for eutrophication of the open marine waters and what changes will occur in retention and removal when loading of the coastal waters is reduced, for example as a result of the Action Plan on the Aquatic Environment?

4.2.1 Retention

Nutrients input to coastal waters can be temporarily retained through incorporation in the benthic vegetation or deposition in the sediment. For example, the eelgrass and filamentous algal populations in Kertinge Nor bind up to 3 g nitrogen per m^2 and 0.4 g phosphorus per m^2 during the course of the growth season (HAV90, Report 43). Correspondingly, it has been found that nitrogen binding by the benthic microalgae in Knebel Vig is of the same magnitude (HAV90, Report 46).

The bound nutrients are thus unavailable to the phytoplankton throughout the spring and summer period. However, the nutrients are released again upon mineralization of the plant biomass, and can thereafter be incorporated into plankton and/or transported to the open marine waters.

It is difficult to determine what significance this temporary retention in the benthic vegetation has for eutrophication of the open marine waters, but as the retention primarily occurs in the summer, when loading from the land is low, one could expect that it will have a significant impact on the state of the coastal waters. In contrast, the effect on total transport of nutrients from the land to the open sea will be less.

The sediment permanently contains pools of nutrients, both in soluble inorganic form and as particle-bound nutrients. It is only the dissolved nutrients that are released to the water column (HAV90, Report 16), and particle-bound nutrients have therefore first to be converted to a soluble form before they can be released.

Inorganic nitrogen is primarily present in the sediment in the form of ammonium, which can bind (adsorb) to clay particles and organic matter. The sediment's binding capacity for ammonium is often high, but as binding is weak, it can easily be released to the water column.

Sediment binding of ammonium thus only slightly delays release of the ammonium pool, and one can therefore expect ammonium retention to have only a minor effect on transport to the open sea.

In contrast, the sediment can effectively retain phosphorus, and hence delay or reduce the release of phosphorus. Inorganic phosphorus binds to calcium and to oxidized iron (ferric iron; Fe^{3+}) in the sediment. The calcium-bound phosphorus becomes permanently buried in the sediment, whereas the iron-bound phosphorus is released when the oxidized iron is reduced to ferrous iron (Fe^{2+}) (HAV90, Reports 17 and 43). It is therefore the sediment pool of oxidized iron that comprises a buffer that can delay the release of phosphorus and hence the phosphorus transport to the open sea. The buffering capacity ceases once the pool of oxidized iron is used up (see Section 5.6.2). The temporary phosphorus retention in the sediment of coastal waters probably has an impact on the environmental state of the coastal waters themselves.

Through mineralization of organic matter in the sediment, mobile sediment pools of nutrients can be released over a number of years. Thus for many years following a reduction in nutrient loading, the sediment will act as a significant source of nutrient input to the local nutrient balance. This so-called internal loading is known to be able to maintain lakes in an eutrophic state for many years following cessation of loading from the land. There is justified hope that internal loading will abate more rapidly in the estuarine fjords than in the large lakes as water exchange is often much quicker in the coastal waters. Depletion of the sediment nitrogen and phosphorus pools following a reduction in external loading has been recorded in, for example, Kertinge Nor. Based on the size of the mobile nitrogen and phosphorus pools in the sediment, internal loading in Kertinge Nor should decrease markedly within approx. 10 years (HAV90, Report 43).

4.2.2 Removal

Permanent removal of nitrogen from the aquatic environment takes place through denitrification, whereby nitrate is reduced to free gaseous nitrogen by a bacterial respiration process. The process requires anoxic conditions and therefore mainly occurs in the sediment (see Section 5.6.1).

The magnitude of denitrification depends on nitrate input to the anoxic layers in the sediment (HAV90, Report 50). Nitrate can either be transported down from the bottom water or produced by nitrification (oxidation of ammonium) in the oxygen-containing surface layer of the sediment. When the nitrification process is the nitrate source for denitrification, one refers to coupled nitrification-denitrification.

Nitrogen removal in the Danish coastal waters is generally greatest in the winter season. At that time, nitrate runoff from the land is greatest, and the nitrate in the bottom water is the most important source of nitrate for denitrification. At the same time, nitrification in the sediment is high because the oxygen conditions are good. In the summer season, the nitrate concentrations are normally relatively limited in the bottom water, and the magnitude of denitrification is therefore completely dependent on nitrification activity in the oxygen-containing part of the sediment, which is restricted to the upper few millimetres.

As part of the HAV90 programme, denitrification has been measured intensively in several different marine waters. Average annual denitrification varied between 1.4 tonnes nitrogen per km^2 (corresponding to 14 kg nitrogen per ha per year) in Århus Bight and 3.0 tonnes nitrogen per km^2 (corresponding to 30 kg nitrogen per ha per year) in Norsminde Fjord and Kertinge Nor/Kerteminde Fjord (HAV90, Report 50). The rather limited variation in the absolute magnitude of denitrification means that an extremely variable part of the nitrogen input to coastal waters will be removed by denitrification. In fjords with high nutrient input and rapid water exchange, only a few percent of the nitrogen load is removed by denitrification. In coastal waters with a low nitrogen input and a low water exchange, in contrast, over half of the nitrogen load might be removed (HAV90, Report 50). Rather than assuming that a fixed percentage of the nitrogen input to coastal waters is removed by denitrification (Seitzinger, 1988), it would be more correct to instead apply an average annual rate of approx. 2.0 tonnes nitrogen per km^2 (corresponding to 20 kg per ha) for all the inner Danish marine waters (HAV90, Report 50).

The relatively constant denitrification rates indicate that a change in nutrient inputs to coastal waters or in the composition of the biological organisms is only of minor significance for the removal rate. However, detailed process studies (HAV90, Report 50) have shown that the absolute removal is actually dependent on both nutrient loading and changes in the biological components, which are in turn affected by changes in loading.

When nutrient loading and the nitrogen concentrations are enhanced, denitrification will increase because the nitrate concentration in the bottom water increases in the winter season. Similarly, high mineralization will also increase denitrification if oxygen conditions in the bottom water remain good since denitrification is thereby stimulated (HAV90, Report 50). If oxygen conditions deteriorate, as often happens under the pycnocline when loading is high, coupled nitrification-denitrification will cease and the high mineralization rate will instead cause high release of ammonium from the sediment (Figure 4.3). In such cases, permanent nitrogen removal will primarily take place through storage of undegraded organic matter.

Theoretically, denitrification should remove an increasing part of the total nitrogen load if loading decreases. A number of factors influence this, however. When loading decreases, there is less nitrate available in the bottom water for denitrification. Moreover, as growth conditions improve for both benthic microalgae and larger benthic plants, a greater amount of nitrogen is taken up in the plants. The assimilated nitrogen

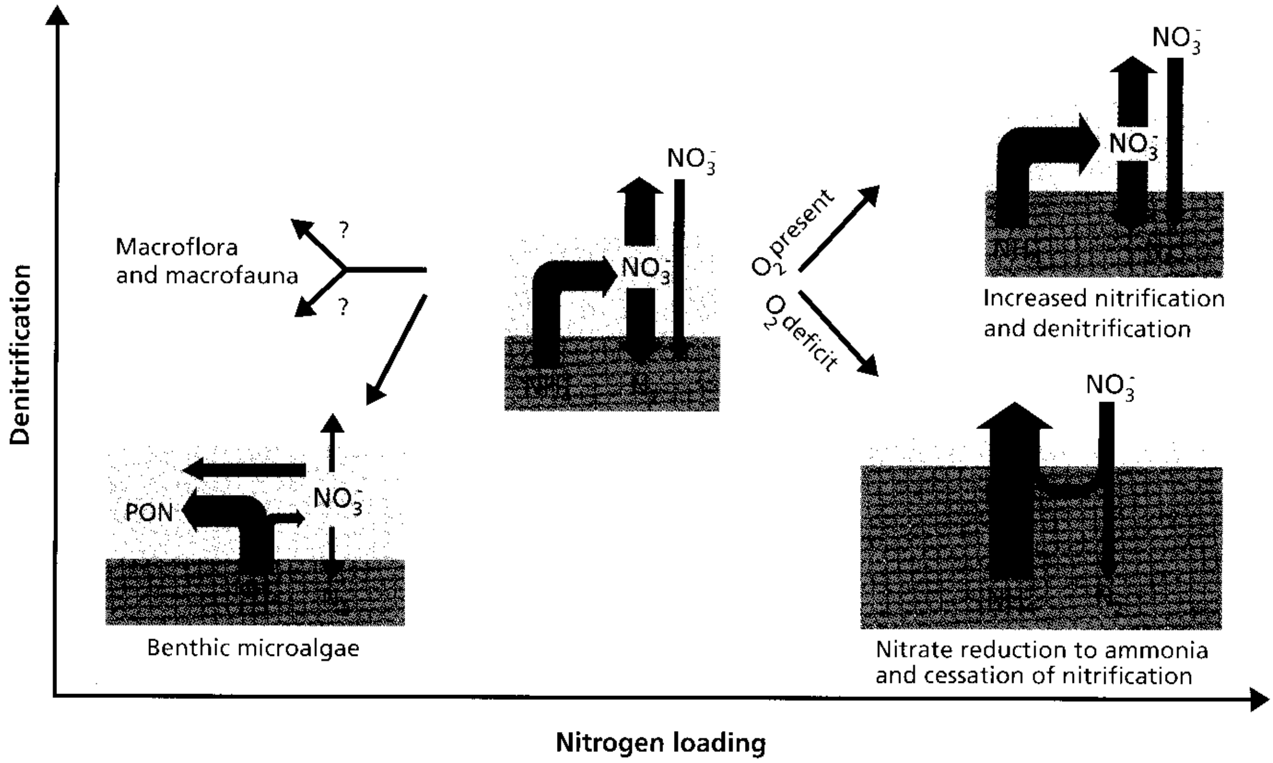


Figure 4.3

Nitrogen removal by denitrification under conditions of enhanced and reduced nitrogen loading. The centre panel illustrates the "normal situation", where denitrification is primarily coupled to effective nitrification of ammonium formed by mineralization processes in the sediment. The sediment is stable and oxygen conditions at the bottom are good. Under conditions of enhanced nitrogen loading, mineralization increases leading to an increase in ammonium release from the sediment. If oxygen conditions are good (upper right panel), nitrogen removal by denitrification increases. If oxygen conditions are poor (lower right panel), nitrification ceases and nitrate can be reduced to ammonium, the result being a lower denitrification rate. Under conditions of reduced nitrogen loading, light penetration of the water increases and small microalgae can colonize the sediment surface (lower left panel). When the nitrogen concentrations in the water are low, nitrogen uptake by the algae can out-compete denitrification. When loading is low, conditions also improve for animals and larger plants (upper left). Process studies undertaken as part of the HAV90 programme indicate that both factors can enhance denitrification (From HAV90, Report 50).

thereby becomes unavailable for the denitrification process. Well-developed communities of microalgae on the sediment surface can thus completely hinder denitrification (HAV90, Report 50). A reduction in nitrogen loading will also increase the number and distribution of benthic invertebrates. The animals in the sediment can stimulate the coupled nitrification-denitrification process by pumping oxygenated water down into the sediment (HAV90, Report 43).

An increased distribution of rooted macrophytes might also stimulate nitrogen removal through greater deposition of organic matter in the sediment and through oxygenation of the root zone, whereby the coupled nitrification-denitrification can be stimulated (Figure 4.3). The total effect on nitrogen removal of reduced nitrogen input and a change in the biological community is thus still unclear.

4.2.3 Deposition and resuspension

Net deposition of sediment only occurs in about one third of the inner Danish marine waters (Madsen and Larsen, 1986). In these areas sediment deposition typically amounts to 1.5 mm per year. Very great deposition (>10 mm per year) can occur in the northern Kattegat, however. In the case of the inner Danish marine waters as a whole, annual net deposition of nitrogen amounts to approx. 29,000 tonnes and that of phosphorus to approx. 9,000 tonnes. In the Kattegat alone, net deposition is approx. 21,000 tonnes nitrogen and 6,500 tonnes phosphorus.

The net deposition of sediment is determined by ^{210}Pb dating, which yields the average deposition, i.e. the amount of sediment that remains deposited in one spot. Sedimentation rates can also be measured by means of sediment traps, which are elongated tubes hung in the water column. Particles in the water will settle in the sediment traps, but the traps will typically contain contributions from both sedimentation and resuspension of sediment from the bottom. The traps therefore provide a measure of the gross sedimentation rate (HAV90, Reports 14 and 18). In shallow water depths, gross sedimentation is high as the bottom material is frequently resuspended because of the current or wave motion.

In shallow water depths, wave motion will cause frequent resuspension of bottom material. In the Danish estuarine fjords, waves typically develop with a wavelength of approx. 8 metres at a wind speed of 5 metres per second. The waves create forward and backward movements that reach down to a depth corresponding to half of the wavelength. Waves with a wavelength of 8 metres can therefore cause resuspension at depths under 4 metres. Studies in Roskilde Fjord (HAV90, Report 51) thus showed that the amount of resuspended matter in the water increased markedly at depths between 1-4 metres at wind speeds of more than 7 metres per second (Figure 4.4).

As a result of resuspension, there is considerable difference between measurements of net sedimentation and gross sedimentation. In Århus Bight, for example, the net sedimentation rate measured by ^{210}Pb dating was approx. 2.5 g dry weight per m^2 per day at water depths of around 15-16 m, while the gross sedimentation rate measured using sediment traps placed 0.3 m above the bottom varied between 30 and 500 g dry weight per m^2 per day (HAV90, Report 14).

The greatest resuspension events occur in periods with strong wind and great wave motion. Daily measurements

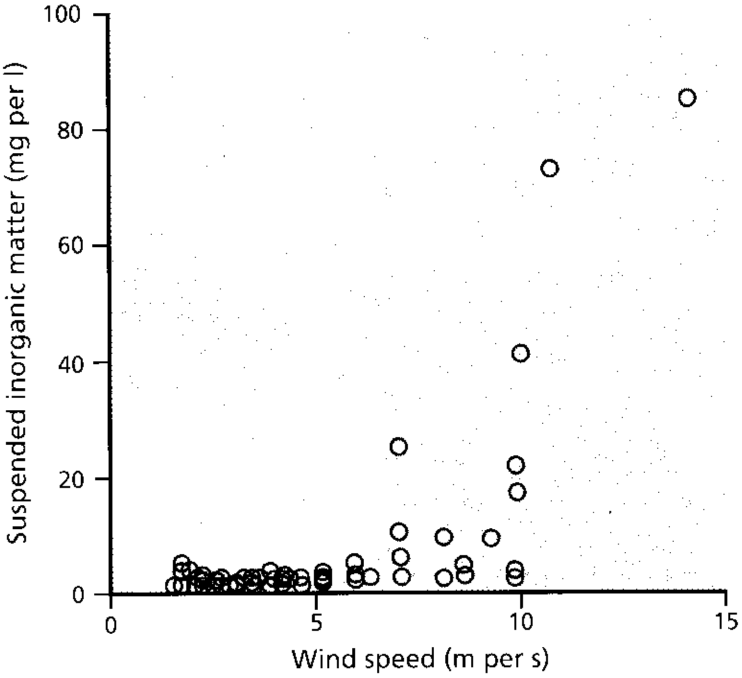


Figure 4.4

The amount of suspended inorganic matter in Roskilde Fjord measured at increasing wind speeds (from HAV90, Report 51).

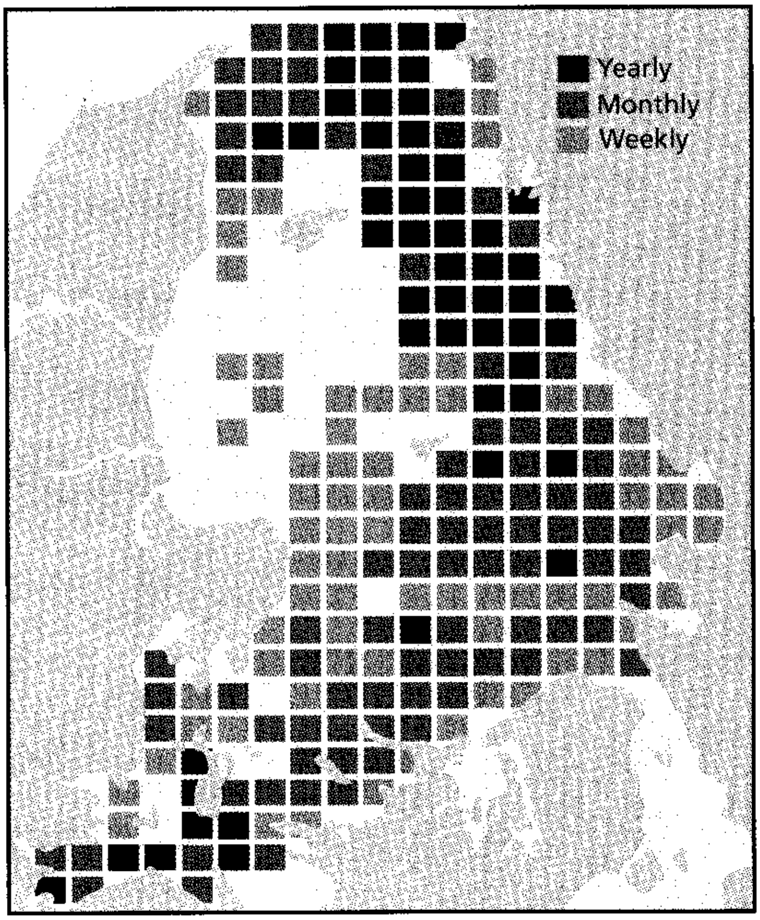


Figure 4.5

The frequency of wave-induced resuspension of bottom material in the Kattegat (from Floderus and Phil, 1989).

made in quiet periods revealed a positive relationship between current speed and gross sedimentation rate measured using sediment traps (HAV90, Report 18). If the traps are emptied every second week, however, a positive relationship is found between wave motion and gross sedimentation (HAV90, Report 14). Thus a single or a few days of strong wave motion can blur the effect of the current-induced resuspension.

The possibility for wave-induced resuspension in the open parts of the Kattegat largely depend on the water depth, resuspension events occurring more frequently than once per week in the shallow western areas (water depths less than 10 metres), and more rarely than once per year in the deepest, northeastern parts (water depths greater than 10 metres) (Figure 4.5).

The frequency with which resuspension occurs is reflected in the composition of the marine sediment. In the shallow areas of the Kattegat, the sediment is sandy with an average organic matter content of 2% (expressed in percent of the sediment's dry weight), a total nitrogen content of 0.04% and a total phosphorus content of 0.02%. At deeper depths (the northern Kattegat), the sediment is fine-grained with a high content of organic matter (7-10%), total nitrogen (0.2%) and total phosphorus (0.05%). The greatest deposition of nutrients thus occurs in areas where resuspension is least.

4.2.4 Coastal waters as filters

The coastal waters thus serve as a filter between the land and the open sea that removes part of the nutrients passing through. The actual significance of this filter function is still a matter of debate, however.

It is well documented that a considerable part of the nutrients discharged into watercourses and lakes is removed during transport to the coastal waters. The documentation is in the form of mass balances in which both the inputs and outputs have been determined with reasonable precision. This is possible for watercourses and lakes as the inlet (source) and outlet are reasonably clearly defined.

It is difficult to establish precise mass balances for coastal waters, however, in that the boundary to the open sea serves both as a source and as an outlet. Large quantities of water with relatively high concentrations of nutrients are thus transported both in and out of the coastal zone. The use of water exchange models can provide a reasonable measure of net transport of nutrients out of the fjords, and can thereby also determine the loss of nutrients (HAV90, Report 9). However, there is no sense in expressing such loss in percent of the riverine nutrient input as it is not possible to determine whether the removed nutrients originally derived from the land or from the open sea. If the loss is to be meaningfully expressed in percent of the input, inflow of nutrients from the open sea has to be included in the overall loading balance. An approximate balance can be established on the basis of a salt balance making a number of very rough assumptions. Comparison of data from various Danish and foreign coastal waters shows that removal of phosphorus and nitrogen varies from a few percent up to approximately 75% of the total input (Figure 4.6). This is in contrast to the literature claim that nitrogen removal in coastal waters generally amounts to 50% (Seitzinger, 1988). As mentioned above, nitrogen removal varies as a function of both physical and biological conditions.

The number of mass balances hitherto established for coastal waters is still too low for a detailed analysis of the influence of these factors on nutrient removal to be meaningful. Moreover, there has not yet been the opportunity to determine how mass balances for various coastal waters develop in the long term following a reduction in loading. The longest time series existing for Danish waters derive from Ringkjøbing Fjord and Mariager Fjord, where there has been a real reduction in phosphorus loading, but where nitrogen loading has only varied as a result of variations in the amount of precipitation and runoff. The data from these fjords lend no support to the theory of a self-augmenting effect with an enhanced relative removal of phosphorus (Borum, 1996).

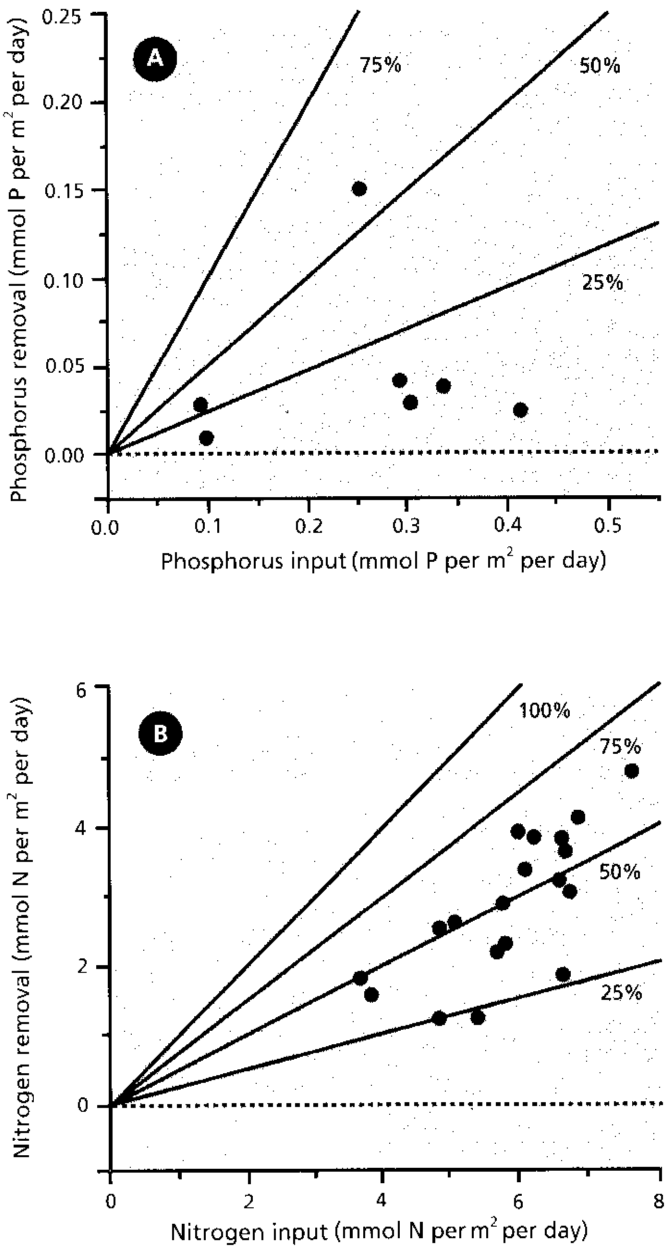


Figure 4.6

Loss of phosphorus (A) and nitrogen (B) from various coastal waters expressed in percent of the total input from the land and adjoining marine waters. Phosphorus is lost by deposition in the sediment whereas nitrogen is removed both by denitrification and by deposition in the sediment. It can clearly be seen that the percentage loss varies markedly from area to area (from Borum, 1996).

4.3 Atmospheric deposition of nutrients

In order to determine the input of nutrients from the atmosphere one can either carry out measurements at a number of characteristic places or estimate the sources and calculate how much reaches the Danish marine waters. Both methods have been employed and good correspondence has generally been found between the two measures of loading. The measurements are conducted in connection with the Nationwide Monitoring Programme under the Action Plan on the Aquatic Environment (e.g. Hovmand et al., 1992), while the calculations have been undertaken as part of the HAV90 programme, as has the comparison of the two methods (HAV90, Report 37). The fundamental processes behind the airborne transport of nitrogen compounds from sources to sea are described below in the manner in which they have been modelled in connection with HAV90 projects.

4.3.1 Transport, transformation and deposition

The most important airborne nitrogen compounds are ammonia compounds, NH_X, which primarily derive from livestock in the form of ammonia (NH_3), and nitrogen oxides (NO_X), which are primarily produced as nitrogen oxide (NO) in combustion processes.

The strength of the various sources varies with time. Thus the production of nitrogen oxide varies both with the season (heating) and the time of day and week (traffic). Ammonia emissions exhibit similar variations, being dependent on when animal fertilizer is spread on the fields and when volatilization is greatest (around midday). The temporal variation in the sources will consequently also differ in different areas.

When released from the sources, nitrogen compounds spread through the atmosphere while being chemically transformed in processes involving other substances in the air. At the same time, the atmosphere continually exchanges substances with the surface of the earth. The processes whereby substances are returned to the surface from the atmosphere are termed deposition. Thus it is deposition processes that are responsible for the input of the airborne nutrients to the surface of the sea.

The released substances are led away from the source by transport and diffusion. In this context, transport is understood to mean that the substances are lead away by the wind, the direction therefore being determined by the mean wind. Diffusion ensures that the original amount of the substance released is continually diluted and spread, because the wind constantly varies around its mean direction. In order to be able to describe atmospheric transport conditions, one has to have information about the mean wind and the diffusion characteristics of the atmosphere (HAV90, Report 21).

Once ammonia and nitrogen oxide have been released to the atmosphere, both substances undergo a number of chemical transformations in interaction with other substances in the atmosphere.

Ammonia particularly interacts with sulphuric acid and nitric acid, while the nitrogen oxides enter into photochemical reactions with ozone. Described very simply, sulphuric acid in the atmosphere converts ammonia to ammonium particles within a few hours.

Nitrogen oxides (NO, NO_2) enter into complicated and rapid reactions with ozone and other compounds, generally always ending up as nitrate particles after a few days. As chemical transformations take place continually in the atmosphere, deposition is usually determined for families of substances. This division is based on the compounds originally released from the source, for example the ammonia family and the nitrogen oxide family. The atmospheric reactions occur both as dry reactions and as wet reactions in water drops.

The actual deposition processes are normally divided in wet deposition and dry deposition. As the name implies, wet deposition involves rain, while dry deposition on a surface is a diffusion process that among other things depends on the nature of the surface (HAV90, Report 35). In the case of wet deposition, the substances are either incorporated during rain drop formation in the clouds, or they are directly washed out of the atmosphere by falling rain drops. Knowledge of the precipitation conditions is therefore of great significance in order to be able to estimate wet deposition. Our knowledge of precipitation conditions over the sea is rather limited, however, which is why an observation programme for the measurement of precipitation conditions over the Kattegat was initiated under HAV90. A description of these and other studies concerning wet deposition is given elsewhere (HAV90, Report 26).

4.3.2 Magnitude of deposition of nitrogen compounds

The magnitude of airborne nitrogen deposition can be determined by measuring deposition at selected locations and thereafter extrapolating to areal mean values on the basis of the measurements. There are problems with using this method, however, as there is some uncertainty connected with measurement accuracy when extrapolating deposition from measured values, and in extrapolating from specific measurement points to whole areas. Alternatively, one can - as was done in the HAV90 programme - establish models that encompass all the above mentioned processes. This enables one to model the transport from all source locations to marine waters and then use the model to directly calculate the areal mean value. The modelling method has the further advantage that it provides the possibility to evaluate the significance of specific sources by "fictively" changing them in the model. The modelling method also has its great uncertainties, however, as knowledge of both sources and processes is naturally limited. It is therefore pleasing that the two different methods yield reasonably similar results (Larsen et al., 1991; HAV90, Report 37). In fact, all present and previous estimates of nitrogen deposition on the Kattegat lie within plus or minus 20% of 1.2 tonnes nitrogen per km^2 per year.

Danish and foreign sources contribute differently to the various airborne nutri-

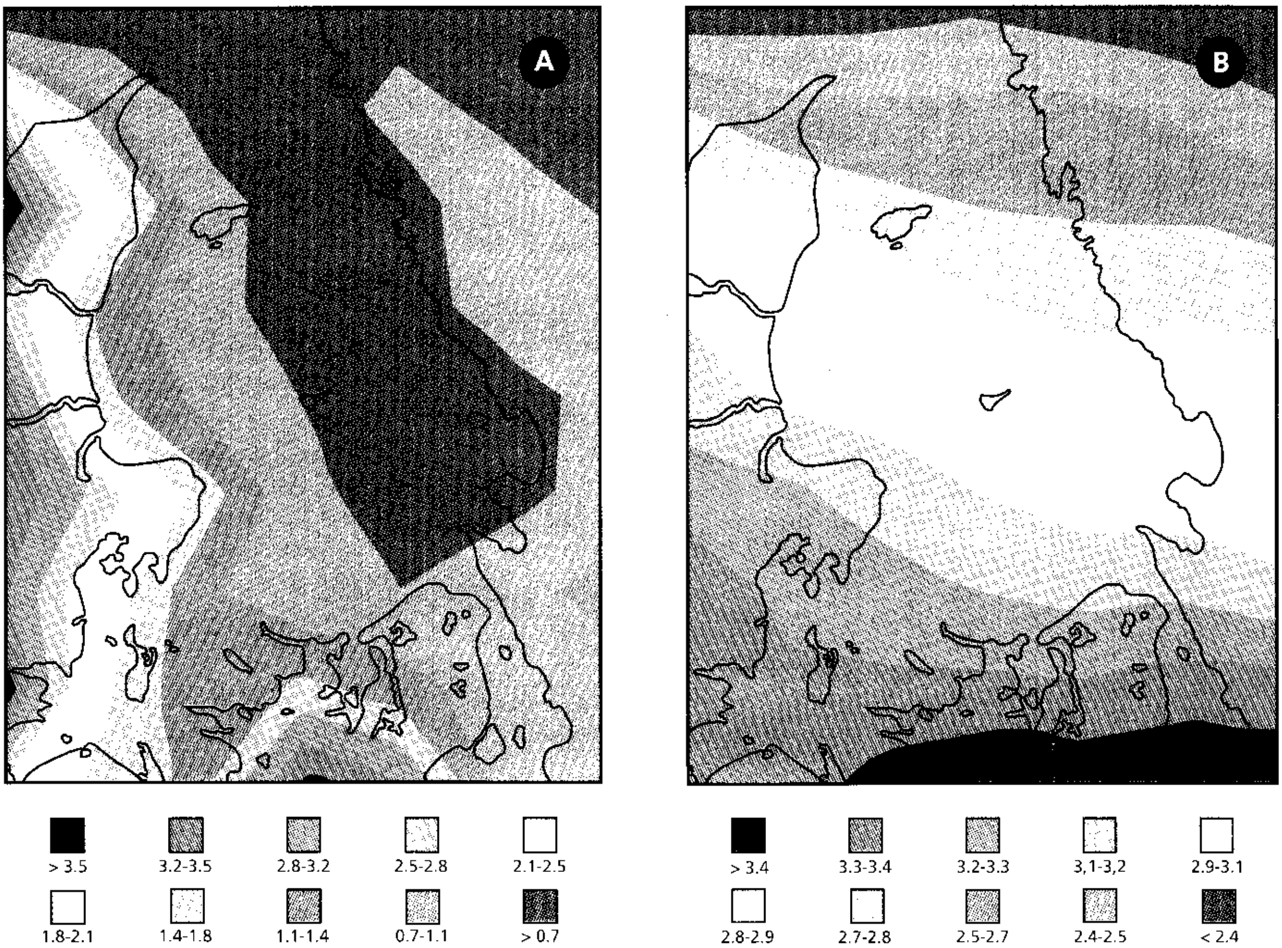


Figure 4.7

Model calculations of the mean annual concentration (ppb; parts per billion) in the air over Denmark of ammonia (A) and ammonium particles (B). It can be seen that the concentration of ammonia declines far more rapidly over water than does the concentration of ammonium particles. This is due to the higher conversion rate and deposition rate of ammonia (from HAV90, Report 37).

ents that are deposited on the Danish marine waters. For obvious reasons, the relative contribution of Danish sources is greatest in the case of substances having a short residence time in the atmosphere (see Table 4.1). Ammonia is deposited rapidly, while nitrogen oxide is only deposited slowly. Danish sources therefore account for approx. 80% of ammonia deposition on the Kattegat. The Danish share of total nitrogen deposition on the Kattegat is only approx. 20%, however, the remainder deriving from foreign sources. Considerable exchange of airborne nitrogen thus takes place between countries. As a consequence, a reduction in Danish sources of airborne nitrogen deposition will have only minor impact on the total loading of the inner Danish marine waters unless the good example set also induces other countries to reduce their atmospheric emissions of nitrogen.

By far the majority of airborne nitrogen derives from the land and the majority is also deposited close to land, deposition thereafter declining with increasing distance from land. The strength of this pattern varies from substance to substance in that some substances (e.g. ammonia) are rapidly converted in the atmosphere and equally rapidly deposited. In the case of such substances, the amount available for deposition declines rapidly with increasing distance from the local source area. Other substances such as ammonium and nitrate particles are only slowly transformed in the atmosphere and are also deposited slowly. Deposition of such substances therefore declines only slowly with increasing distance from the coast (HAV90, Report 37). This is illustrated in Figure 4.7.

Nearly all the atmospheric parameters, especially precipitation, exhibit considerable temporal and spatial variation, and deposition from the atmosphere will vary accordingly. Annual variation in deposition on the Kattegat in particular has therefore been studied very carefully both in the Nationwide Monitoring Programme and under the HAV90 programme (Hovmand et al., 1992;

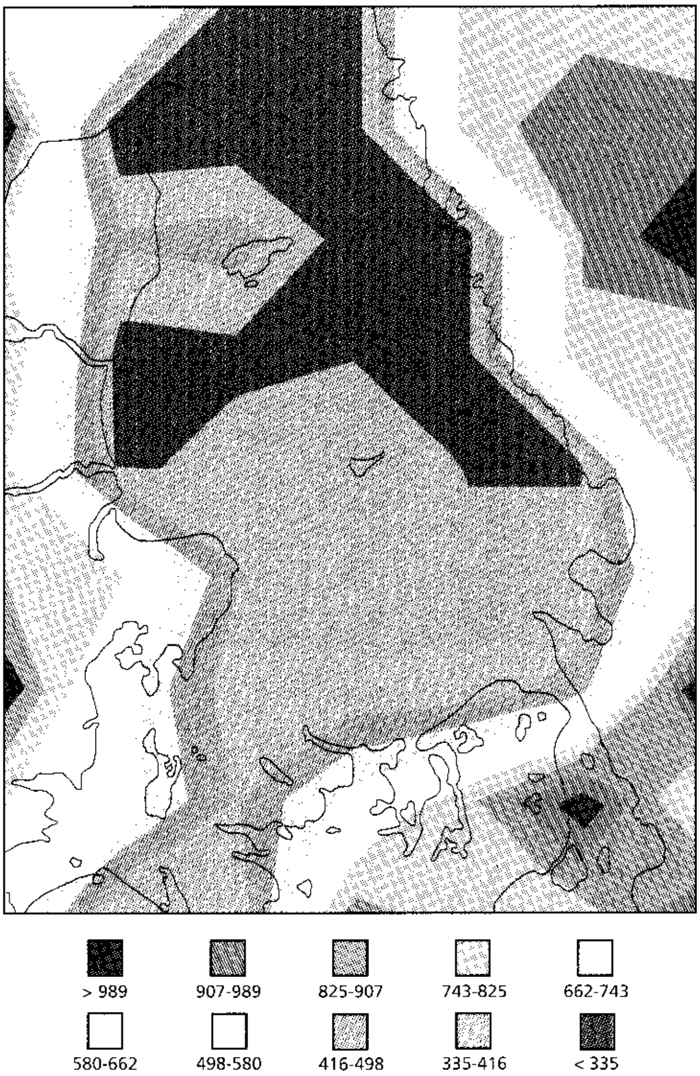


Figure 4.8

Model calculations of annual deposition of nitrogen oxides on Danish marine waters (kg nitrogen per km^2 per year). Nitrogen oxides account for approx. 40% of total nitrogen deposition on the Kattegat. The model has difficulty in describing the detailed conditions for narrow water bodies such as the Øresund (from HAV90, Report 37).

HAV90, Report 37). Deposition follows a clear pattern, with a maximum in the early spring, followed by a minimum in May, a maximum in summer and finally a minimum in December-January. Input from the atmosphere is thus high in the periods during which biological activity is high. The deposition rate varies by almost a factor two, and also varies from place to place and from year to year. Deposition can therefore also be expected to vary markedly from year to year, but this has not been investigated as intensively as the seasonal variation.

The most thoroughly determined figures for airborne transport to the sea are those for the Kattegat which, compared with other parts of the inner Danish marine waters (e.g. the Belt Sea), is an open, vast sea. As the other inner Danish marine waters are generally closer to Danish and foreign sources, deposition per unit area on these marine waters must be expected to be higher than that on the Kattegat. As stated in Section 4.1.3, airborne inputs of nitrogen to the Kattegat amount to approx. 1.2 tonnes nitrogen per km^2 per year. As the Belt Sea and the western Baltic Sea lie closer to land, deposition on these areas is a little higher per unit area (approx. 1.3 tonnes per km^2 per year (Hovmand et al., 1992)). Loading might be even greater close to the coasts. How much greater is uncertain, as measurements are not made near the coast and the calculation models do not have such fine details built into them. Figure 4.8 illustrates such horizontal differences for the deposition of members of the nitrogen oxide family of substances.

4.4 Hydrography and input from adjoining open marine waters

The hydrographic conditions in the open parts of the inner Danish marine waters are determined by Denmark's location between the North Sea, which has a high salinity, and the Baltic Sea, which has a low salinity. Nutrient input to the inner Danish marine waters is therefore determined by, among other things, the water transport over the boundaries of the North Sea and the Baltic Sea and the nutrient concentration in the water bodies.

4.4.1 Hydrography

Water exchange between the Baltic Sea and the North Sea through the inner Danish marine waters is closely coupled to wind conditions over Scandinavia. Expressed simply, one can say that when the wind blows from the west, water flows in over the boundary of the Skagerrak, and when strong wind blows from the west for a long time, water from the Skagerrak flows into the Baltic Sea too. The reverse is true when the wind blows from the east. Because the water flow depends on wind strength, wind direction and duration, periods of inflow and outflow alternate. As a con-

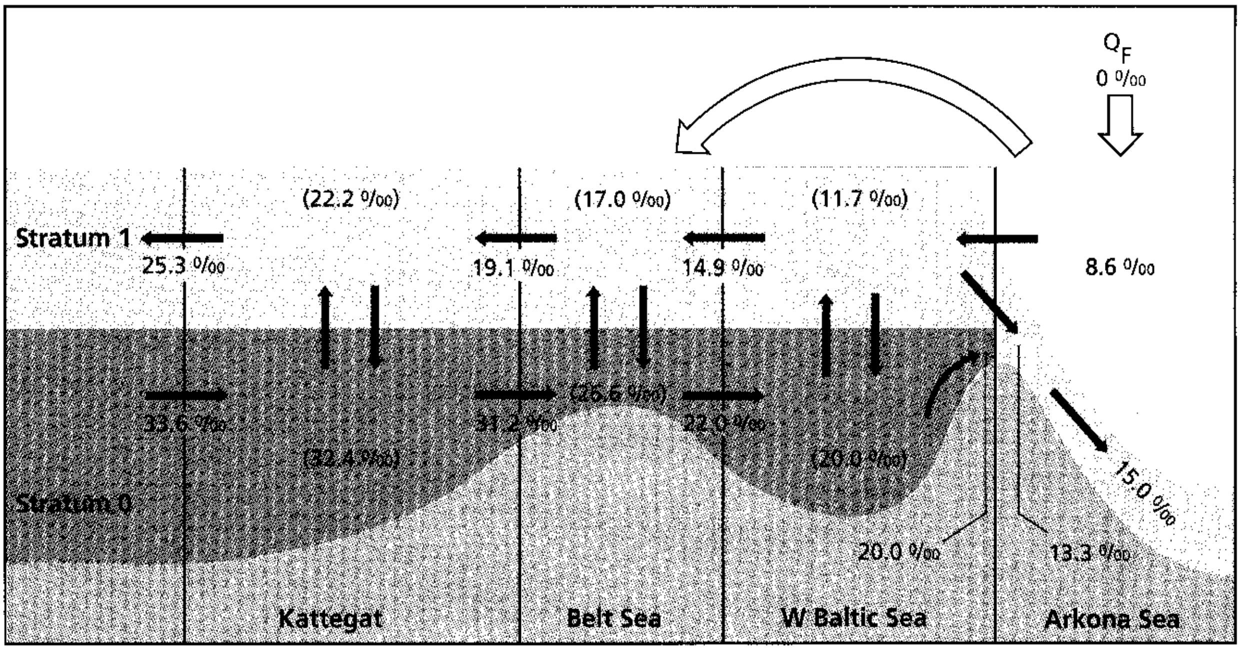


Figure 4.9

Cross-section through the inner Danish marine waters showing the mean direction of flow and the mean annual salinity in surface and bottom water of the different marine waters (from HAV90, Report 1).

sequence, transport of the nutrients carried along by the water flow is also very variable, and water exchange between the North Sea and the Baltic Sea means that there is both import and export of nutrients to and from the inner Danish marine waters.

Net transport of water from the Baltic Sea to the North Sea through the inner Danish marine waters amounts to approx. 470 km^3 per year. This corresponds to the total freshwater input from the rivers feeding into the Baltic Sea, precipitation and evaporation over the Baltic Sea being roughly equal (HAV90, Report 4). The outflow of low-salinity water is greatest in April-May, at which time the wind frequently blows from the east and the freshwater input to the Baltic Sea is greatest. Easterly winds lower the sea level in the Kattegat, but raise the sea level in the southwestern Baltic Sea. The difference in sea level drives the water flow towards the Kattegat. In contrast, the sea level in the Kattegat rises during periods of strong westerly wind as the water is pressed down into the Kattegat from the North Sea and the Skagerrak. In this situation the sea level lowers in the western part of the Baltic Sea.

During periods of strong outflow from the Baltic Sea, the low-salinity surface water can be clearly seen on infrared satellite images (HAV90, Report 3). The water follows the Swedish west coast as it curves to the right due to the earth's rotation (see Figure 5.3). The low-salinity Baltic Sea water lies in the Kattegat like a tongue above the high-salinity bottom water derived from the North Sea, and the two water masses are separated by a boundary layer, the pycnocline (see Section 5.2.2).

There is considerable horizontal variation in the Kattegat's hydrography, both north-south and east-west, among other things in connection with fronts described in Section 5.2.3. The salinity of the Kattegat's bottom water is usually fairly uniform at approx. 33‰, however (Figure 4.9). In contrast, the mean salinity of the surface water increases from approx. 18‰ in the south to approx. 33‰ in the north. This is due to entrainment of bottom water. Due to turbulence, considerable mixing takes place in the Great Belt, and the salinity of the surface water consequently varies between 8‰ and 26‰ while that of the bottom water varies between 16‰ and 32 ‰. At the boundary of the western Baltic Sea (the Drogden Sill), the Øresund is so shallow (7 metres) that the salinity of the water is largely the same throughout the whole water column. When the water flows out of the Baltic Sea, its salinity is 8-10‰, whereas that of the inflowing water is up to 30-32‰.

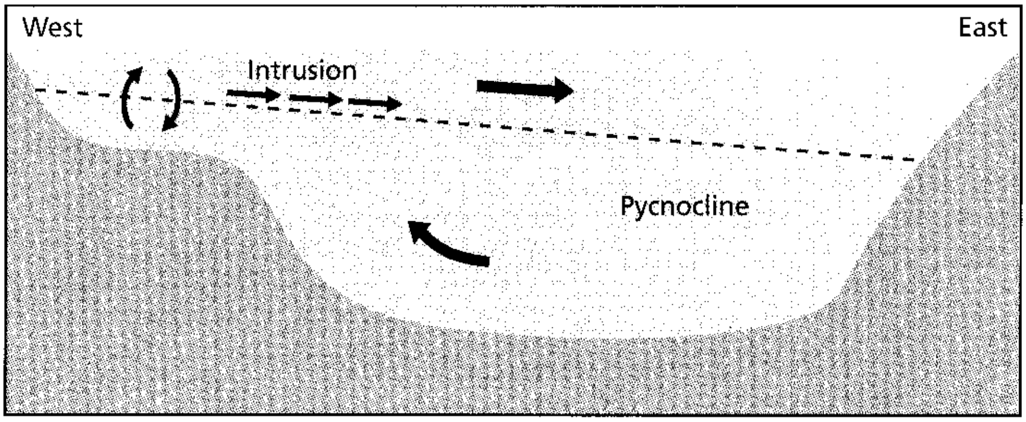


Figure 4.10

Diagram of the slope of the pycnocline across the Kattegat when the wind is westerly. Mixing across the pycnocline in shallow areas results in a density of the mixed water between that of the bottom water and that of the surface water.

When the wind is westerly, surface water is initially blown away from the east coast of Jutland and the sea level rises along the west coast of Sweden (Figure 4.10). The loss of surface water is replaced by water from greater depths being drawn in (and up) towards the coast, so-called upwelling. The pycnocline in the Kattegat thereby comes to slope across the Kattegat, lying higher in the west and deeper in the east (Figure 4.10). Upwelling can change the character of the surface water from one day to the next. Thus water sampled in the surface of shallow areas can represent surface water one day but bottom water another day, even though both samples are taken at the surface (Figure 4.11).

As the western Kattegat is shallow (approx. 10 metres), the pycnocline can "flood" the shallow areas. The high-lying pycnocline in the west can more easily be broken down by wind-induced mixing. This results in mixing of the nutrient-poor surface water and the nutrient-rich bottom water. Moreover, the nutrient content of the water can be further increased through resuspension of sediment in shallow areas. Mixing of the water yields a density somewhere between the initial density of the two water masses, and the mixed water mass therefore penetrates out into the Kattegat as a so-called intrusion layer lying just above the pycnocline (Figure 4.10). As nutrient availability is high in this water, new phytoplankton production

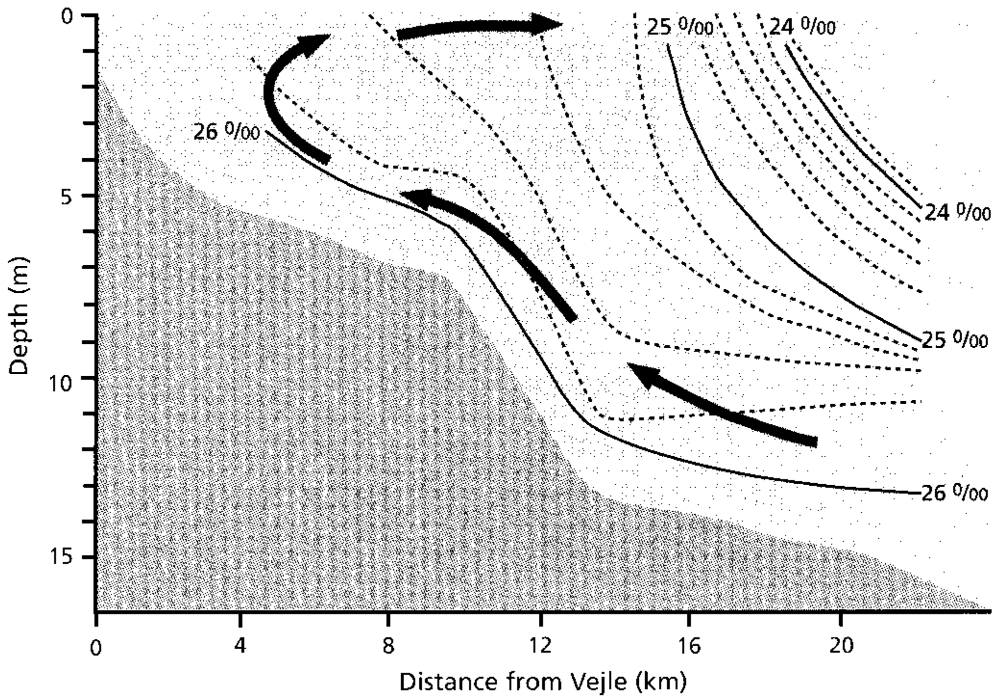


Figure 4.11

Salinity in Vejle Fjord on 21 September 1988 during upwelling. Note that the salinity at the surface is greatest innermost in the fjord (i.e. closest to Vejle). The arrows indicate the circulation pattern. The wind blew from the west at a speed of 4-5 metres per second (from HAV90, Report 4).

can arise in the intrusion layer (see Section 5.2.2).

The low water depth in many coastal waters and fjords means that salinity is roughly the same throughout the water column, and that stratification is mainly due to solar irradiation, which warms up the upper layer. Warming reduces the density of the surface water, resulting in stratification between the light water at the surface and the heavy water at the bottom. The stratification is not particularly marked and can easily be broken down by the wind, as has for example been shown in Roskilde Fjord (HAV90, Report 51). In the more open fjords and bays with greater water depths, the hydrographic conditions are to a greater extent determined by the general hydrography of the inner Danish marine waters, i.e. water exchange between the Baltic Sea and the North Sea.

The residence time of the water in the open parts of the inner Danish marine waters can vary considerably. The residence time for the bottom water is traditionally judged to be approximately 4 months. However, under HAV90 it has been found that the bottom water in the whole of the Kattegat can be renewed in 4 days (HAV90, Report 3). This took place in the form of density-driven inflow of water from the Skagerrak.

4.4.2 Inflow and outflow to and from the Baltic Sea and the Skagerrak

Flow across the boundaries of the Baltic Sea and the Skagerrak involves enormous quantities of water. Even though the concentration of nutrients is often low, transport of nutrients to the inner Danish marine waters across the boundaries during the course of a year is much greater that input from the land and the atmosphere. This is illustrated in Figure 4.12, which shows the significance of boundary transport in the overall balance established for the Kattegat.

Expressed in terms of the annual mean, there is a net input to the inner Danish marine waters from the Baltic Sea of approx. 122,000 tonnes nitrogen, while export to the Skagerrak is greater, namely approx. 173,000 tonnes. The inner Danish marine waters receive approx. 10,700 tonnes phosphorus from the Baltic Sea and export 6,600 tonnes to the Skagerrak.

As a result of the large amounts of total nitrogen and total phosphorus imported and exported across the boundaries to the other Danish marine waters, boundary transport is an important part of the overall balance. However, it is far from all the nutrients transported that are immediately available for biological production (see Section 4.5.3).

The calculated long-term mean outflow from the Baltic Sea of approx. 470 km^3 per year corresponds to 15,000 m^3 per second (Danish EPA, 1981). This outflow is subdivided in the ratio 7:3:1 between the Great Belt, the Øresund and the Little Belt. The outflow comprises a surface flow *into* the Danish marine waters of 38,000 m^3 per second and a bottom flow *out* of the inner Danish marine waters of 23,000 m^3 per second. In connection with the passage of low-pressure weather fronts, the flow can reach more than 100,000 m^3 per second. In such cases the flow is usually in the same direction in both the top and the bottom water. The nutrient content of the water in the Baltic Sea is generally 2 to 3-fold lower than that in the Kattegat (see Section 4.5.4).

Nitrogen transport across the Baltic Sea boundary has been calculated for the mean situation in the 1980s (HAV90, Report 29). Surface layer transport into the Belt Sea amounts to 177,000 tonnes total nitrogen, while bottom layer transport into the Baltic Sea from the Belt Sea amounts to 55,000 tonnes nitrogen. Net transport from the Baltic Sea thus amounts to approx. 122,000 tonnes nitrogen. As large amounts of nutrients are input to the Belt Sea (the southern parts of the inner Danish marine waters), transport from the Belt Sea to

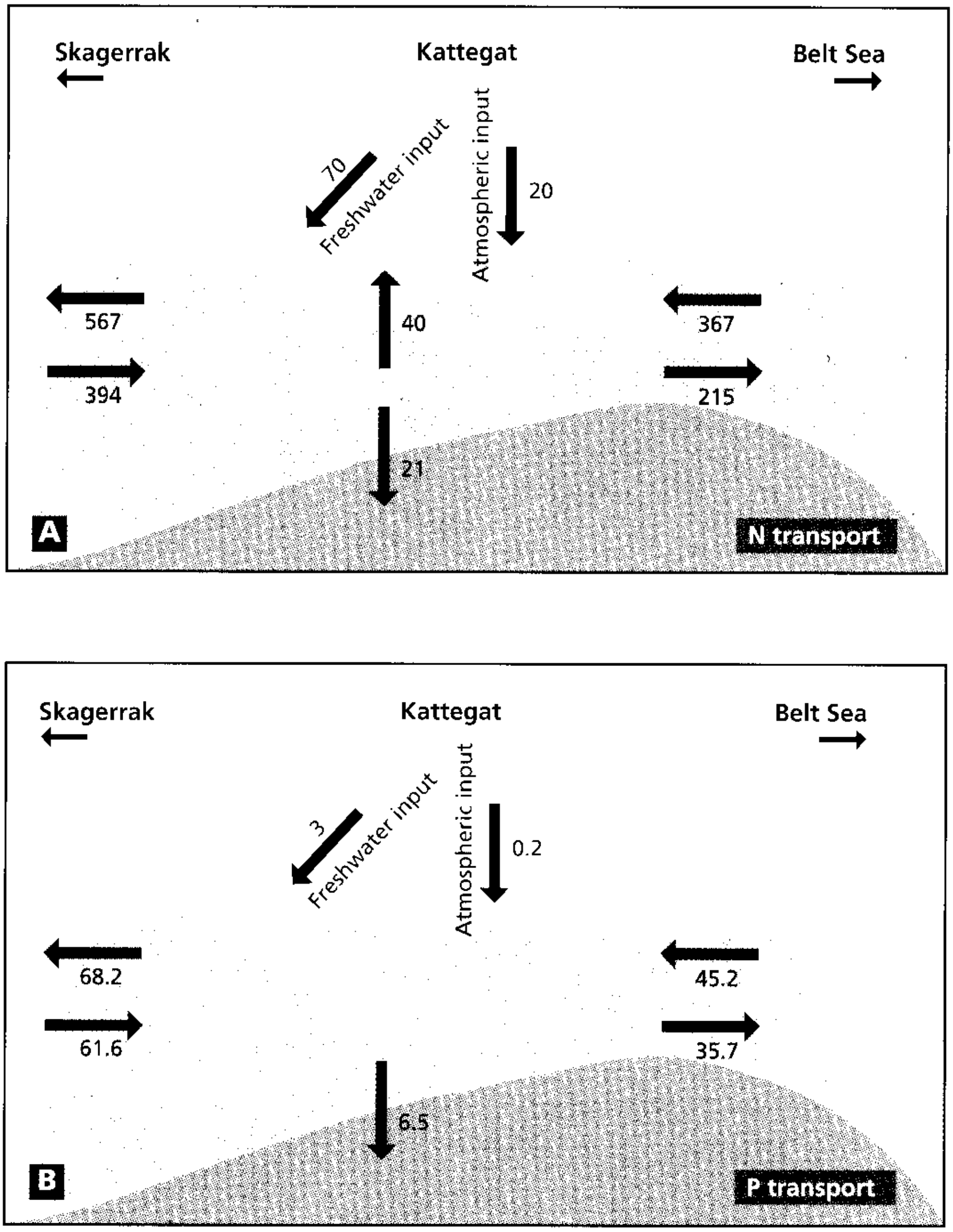


Figure 4.12

Diagram of the significance of boundary transport for the Kattegat's nutrient budget. The figures are given in 1,000 tonnes per year. A) Total nitrogen; B) Total phosphorus. Note that transport across the boundary towards the south does not represent direct transport to the Baltic Sea but transport over the boundary between the Kattegat and the southern parts of the inner Danish marine waters. Note also that boundary transport is large compared with both inputs from the land and the atmosphere and with deposition into the sediment (from HAV90, Report 29 and Ærtebjerg, personal communication).

and from the Kattegat is far greater. Transport from the Belt Sea to the Kattegat amounts to 367,000 tonnes nitrogen, while transport from the Kattegat to the Belt Sea amounts to 215,000 tonnes nitrogen (Figure 4.12).

Phosphorus transport has been calculated for the same mean situation by Ærtebjerg (personal communication). Surface layer transport into the inner Danish marine waters from the Baltic Sea amounts to 18,500 tonnes total phosphorus, while bottom layer transport from the inner Danish marine waters to the Baltic Sea amounts to 7,800 tonnes total phosphorus. Net transport into the inner Danish marine waters thus amounts to approx. 10,700 tonnes total phosphorus. If one focuses solely on the Kattegat, 45,000 tonnes phosphorus is transported from the Belt Sea into the Kattegat, while 35,700 tonnes phosphorus is transported in the opposite direction (Figure 4.12).

Water transport across the boundary of the Skagerrak is extremely variable. For example, the average inflow to the Kattegat from the Skagerrak amounts to 45,000 m^3 per second (approx. 30,000 m^3 per second in the summer and approx. 60,000 m^3 per second in the winter). Short-term variations (on a time scale of approx. 1 week) in connection with the passage of low-pressure weather fronts can increase inflow to 150-200,000 m^3 per second, which is 4,000-fold greater than discharge in the river Gudenå.

Surface layer transport of total nitrogen out of the Kattegat to the Skagerrak amounts to approx. 570,000 tonnes nitrogen per year, while bottom layer transport into the Kattegat amounts to approx. 390,000 tonnes nitrogen per year (Figure 4.12). Water exchange over the boundary thus results in net export of total nitrogen to the Skagerrak of approx. 173,000 tonnes nitrogen per year (calculated as the mean for the mid 1980s) (HAV90, Report 29).

Phosphorus transport from the Kattegat to the Skagerrak during the corresponding period has been calculated by Ærtebjerg (personal communication). Surface layer transport out of the inner Danish marine waters amounts to 68,200 tonnes phosphorus per year. Bottom layer transport into the Kattegat amounts to 61,600 tonnes phosphorus per year. The net result is that 6,600 tonnes phosphorus is exported from the inner Danish marine waters to the Skagerrak each year (Figure 4.12).

4.4.3 The Jutland Coastal Current

The Jutland Coastal Current has previously been defined as that area along the Jutland west coast where one can measure the effect of freshwater from the German rivers. Interest in the Jutland Coastal Current has focused on determining the magnitude of the resultant nutrient input to the inner Danish marine waters. When water from the German Bight penetrates into the Kattegat, this usually takes place at a depth of 10-25 metres, from where it can mix with both underlying and overlying water (HAV90, Reports 6 and 49) (Figure 4.13).

It is estimated that if all the nutrients input to the German Bight are utilized in the production of organic matter, and if all of this material ends up in the Kattegat via the Jutland Coastal Current, the oxygen demand for degrading this

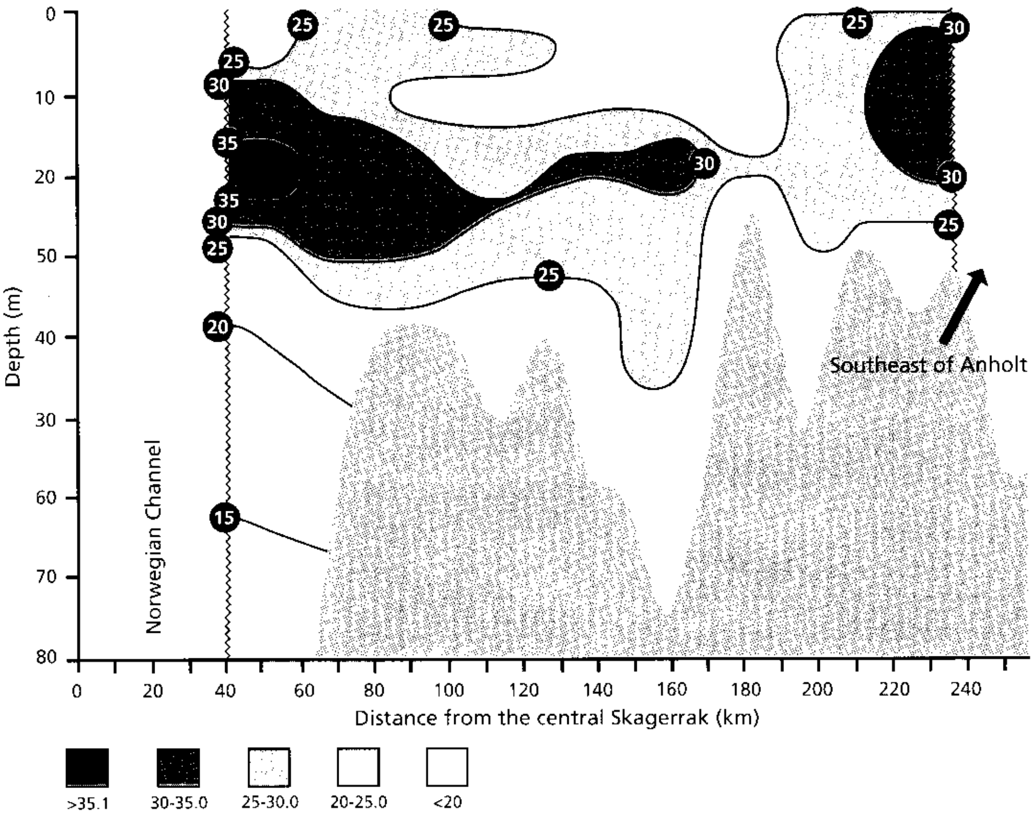


Figure 4.13

The percentage of water from the German Bight along a longitudinal transect from the central Skagerrak down through the Kattegat to Anholt (from HAV90, Report 49).

Lars Gejl/Biofoto

organic matter will correspond to twice the amount of oxygen contained in all the water in the Kattegat (HAV90, Report 6). In winter 1988-89, water from the Jutland Coastal Current comprised the majority of the water that flowed in from the Skagerrak to the Kattegat bottom water. The water had an enhanced nutrient content and the net result was the input of an additional 15,000 tonnes nitrogen to the Kattegat (Ærtebjerg, 1990).

A nutrient input from the German Bight of that magnitude is an exception, however. The Jutland Coastal Current does not normally input extra nutrients to the Skagerrak in the period December to May. In the remainder of the year from May to December, the concentration of nutrients in the Jutland Coastal Current by the time the water reaches the Skagerrak is seldom higher than the background concentration in the Skagerrak. Moreover, as part of the HAV90 programme, it has been shown that previous estimates of transport from the Jutland Coastal Current to the Kattegat bottom water is overestimated (HAV90, Report 49). The new estimates indicate that only approx. 10-20% of the Kattegat bottom water derives from the German Bight.

4.5 Availability of the nutrients input to Danish marine waters

Only a small part of the nutrients input to and present in the sea is available for biological production. Simple compounds such as inorganic nutrients can be immediately taken up by algae, while the availability of organically bound nutrients will vary with their chemical nature. Algae can utilize nitrogen in the form of simple compounds such as urea and amino acids, but these compounds normally only comprise a small part of the total amount of nitrogen in the sea. A considerable part of the dissolved organic compounds in the sea consists of humus derived from the land. The term humus encompasses a group of organic compounds with varying size and chemical characteristics. Humus is poorly degradable, however, and the availability of the humus-bound nutrients is therefore considered to be low.

4.5.1 Nutrients from the land

The input of nutrients from watercourses and point sources takes place in the form of inorganic compounds, especially nitrate (NO_3) and phosphate (PO_4), as well as in the form of organically bound nutrients (see Section 4.1). Among other things, the latter encompass nutrients that are bound in freshwater organisms (algae, larger plants and animals).

The annual input of nitrate and phosphate from the land to the Kattegat is determined on the basis of measurements at a number of watercourse monitoring stations. The monitoring stations are located as near to the outflow to the sea as technically possible from the monitoring point of view. In the case of watercourses lacking a monitoring station, calculated values are used. Discharges from the Danish sewage works and other point sources are almost solely (90%) in the form of nitrate and phosphate. According to the calculations, approx. 40-50,000 tonnes nitrate and 500-1,100 tonnes phosphate are discharged to the Kattegat each year from Denmark and Sweden (see also Tables 4.4 and 4.5).

4.5.2 Nutrients from the atmosphere

Atmospheric deposition of nitrogen on the surface of the sea takes place in the form of simple inorganic compounds belonging to the ammonia and nitrogen oxide families (Section 4.3), and are believed to be 100% available for plants in the sea (Pearl, 1995).

4.5.3 Nutrients from adjoining marine waters

The Skagerrak and the Baltic Sea are important sources of nutrient input to the inner Danish marine waters (see Section 4.4). However, there is great uncertainty about the biological availability of these nutrients. Studies undertaken as part of HAV90 based on chemical analyses and growth experiments with algal cultures in water collected from the Skagerrak and the western Baltic Sea show that the availability of dissolved organically bound nutrients does not differ between the two water bodies, and that the availability is markedly lower than previous estimates for water from the Skagerrak (HAV90, Report 40; Richardson and Ærtebjerg, 1991).

A large part of the nutrients that flow into the Kattegat with the bottom water from the Skagerrak is in the form of inorganic nutrients that are 100% available. In contrast, the majority of the nutrients that derive from the Baltic Sea are in an organically bound form and therefore less available to the algae. HAV90 studies have shown that 35-70% of the nitrogen and 60-70% of the phosphorus input with the Skagerrak water are available for algal growth. In the case of the water from the Baltic Sea, availability is generally lower: 15-35% of total nitrogen and 50-65% of total phosphorus is available for algal growth (HAV90, Report 40). The studies were undertaken with one single algal species, and the values must therefore be considered as minimum estimates.

The annual transport of biologically available nitrogen and phosphorus is illustrated in Figures 4.14 and 4.15. The inputs from watercourses and point sources encompass both Danish and Swedish inputs, which are the means for the period 1991-94.

The biologically available part of these sources is comprised of inorganic nutrient salts and a smaller amount of organically bound nutrients. This part was calculated on the basis of data for the biological oxygen demand of sewage effluent and watercourse water. The transport of biologically available nitrogen and phosphorus over the boundaries of the Skagerrak and the Belt Sea was calculated on the basis of data from the 1980s (see Section 4.4.2) and of studies undertaken under HAV90 (HAV90, Report 40).

The bottom water from the Skagerrak and the surface water from the Belt Sea are the main sources of biologically available nutrients to the Kattegat (Figure 4.14). Local inputs (watercourses, point sources, atmospheric deposition) comprises approx. 15% of the total input of biologically available nitrogen. As is apparent from Figure 4.14, the total input of biologically available nitrogen to the Kattegat exceeds the total output by approx. 100,000 tonnes. This difference may be attributable to loss by denitrification, deposition in the sediment or conversion to non-biologically available nitrogen compounds. Finally, part of the difference may be attributable to uncertainty in the calculation of boundary transport.

The input of biologically available nitrogen to the Kattegat from the Belt Sea derive in roughly equal proportions from the Baltic Sea proper and from local German and Danish inputs to the Belt Sea and the western Baltic Sea.

Figure 4.14

Budget for biologically available nitrogen in the Kattegat. The figures are expressed in 1,000 tonnes per year. The figure should be compared with Figure 4.12A, where inputs and outputs are expressed in terms of total nitrogen.

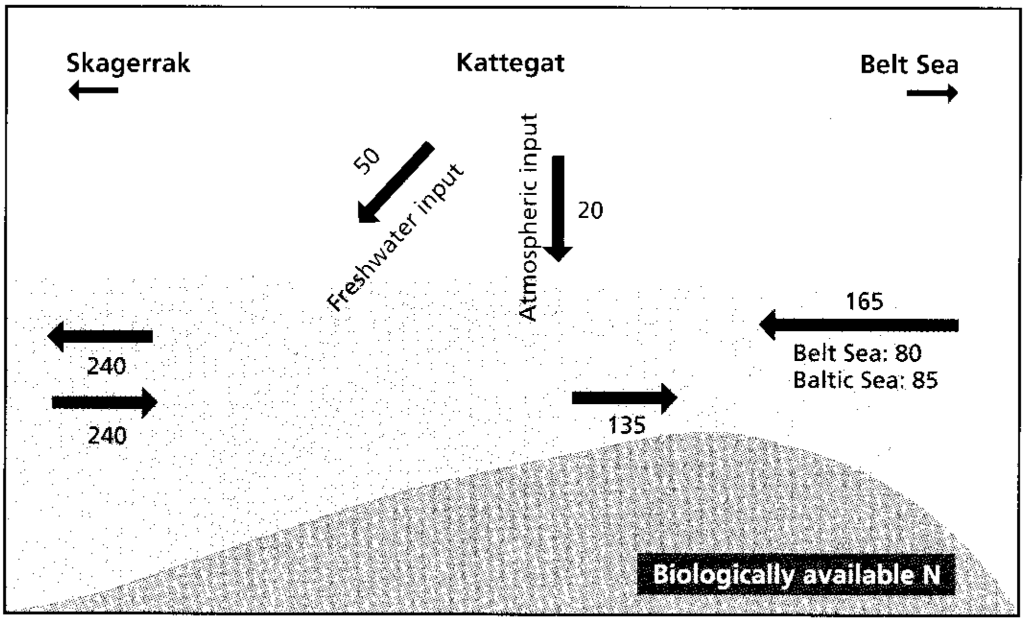
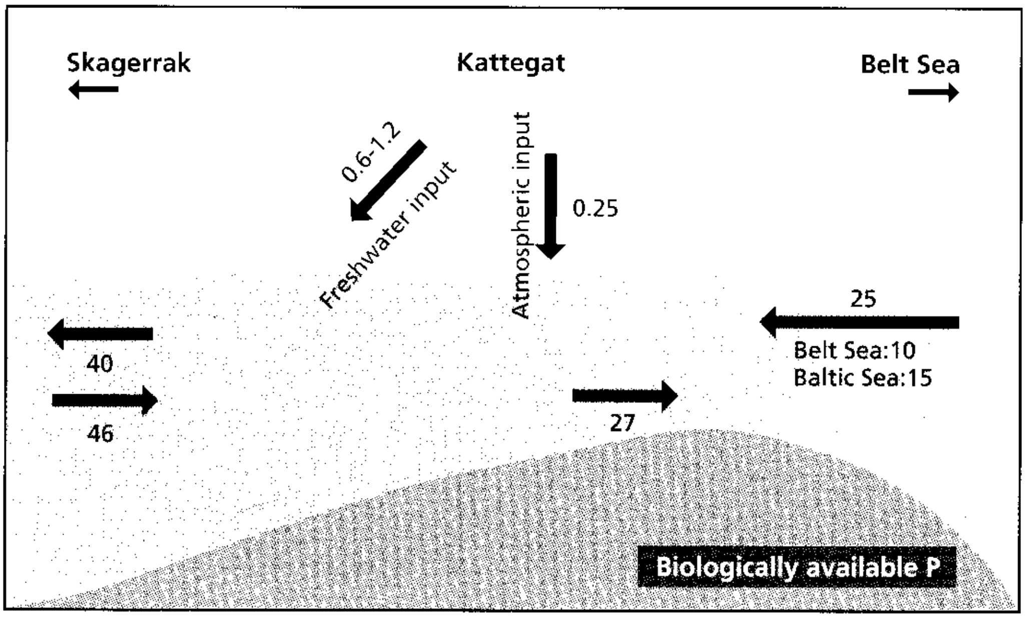


Figure 4.15

Budget for biologically available phosphorus in the Kattegat. The figures are expressed in 1,000 tonnes per year. The figure should be compared with Figure 4.12B, where inputs and outputs are expressed in terms of total phosphorus.



These local inputs increased markedly during the period 1950-75, while it is unknown to what extent inputs from the Skagerrak have increased during the same period. The inflowing water from the Skagerrak consists of a varying mixture of water from the Atlantic Ocean, the North Sea and the Jutland Coastal Current. If the concentration of biologically available nitrogen in the inflowing water has increased just 20% over the period 1950-75, it corresponds to an increase in input to the Kattegat of approx. 50,000 tonnes biologically available nitrogen per year. This underlines that marked improvements in environmental conditions in the open Kattegat can only be obtained through reductions in the local sources together with reductions in the sources that discharge into the Belt Sea and the North Sea (including the Jutland Coastal Current).

The significance of the transport from the Skagerrak and the Belt Sea is even more pronounced in the case of phosphorus in that the local sources only comprise around 1% of the total input of biologically available phosphorus to the Kattegat. Total input of biologically available phosphorus to the Kattegat exceeds output by 5,000 tonnes. This deficit may be attributable to loss by deposition in the sediment or conversion to non-biologically available phosphorus compounds, with part of the dif-

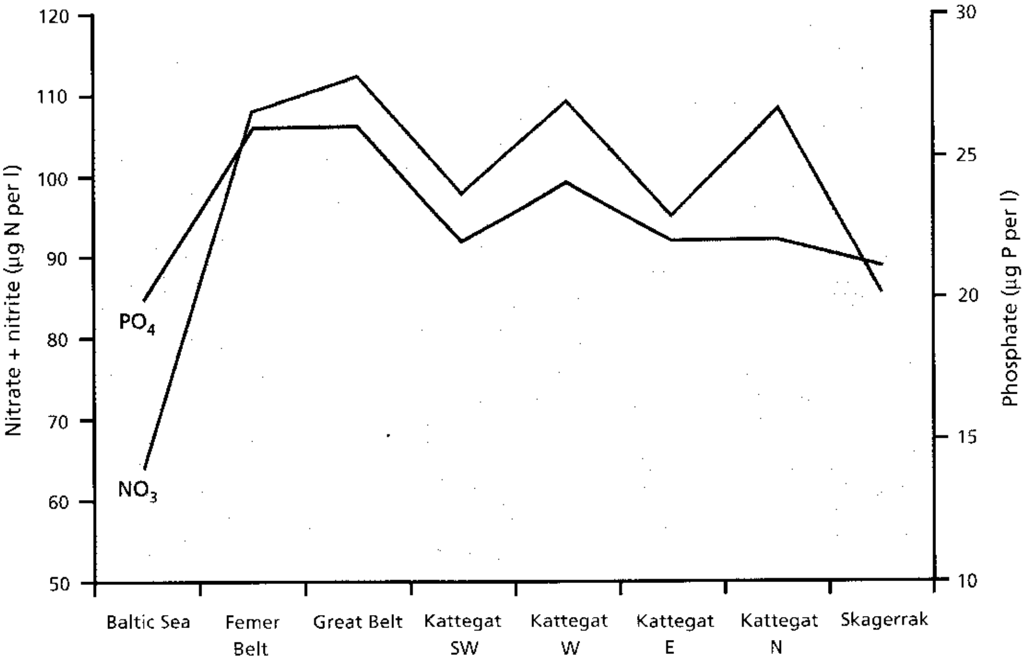


Figure 4.16

Winter concentrations of nitrogen (nitrate+nitrite) and phosphorus (phosphate) in the surface water (0-10 metres) in the inner Danish marine waters as well as in the Skagerrak (30-75 metres, ≥34‰) and the Baltic Sea (Arkona, 0-10 metres). The values represent the average of the winter concentrations (December-February) for the period 1985-94.

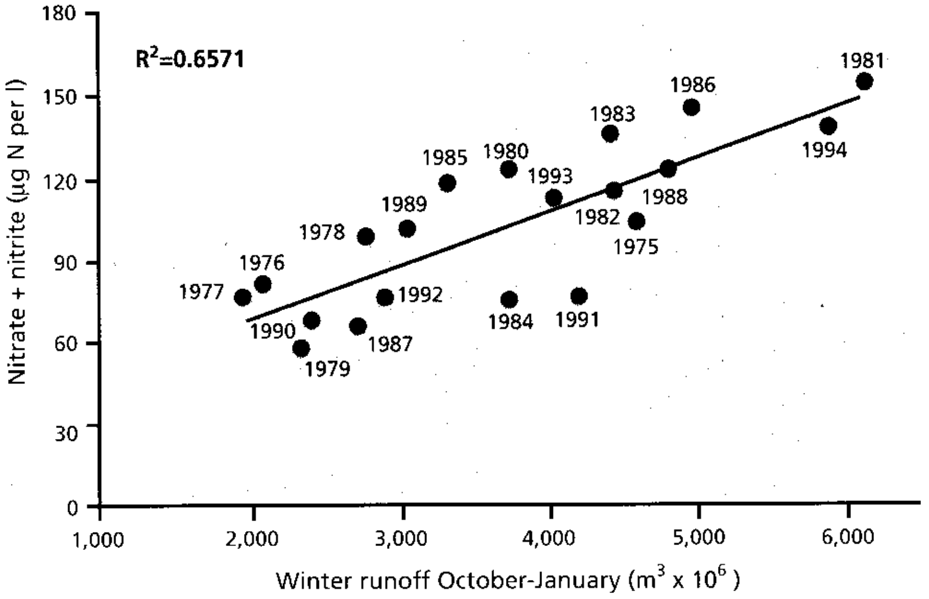


Figure 4.17

Average winter concentration of nitrogen (nitrate+nitrite) in the surface water (0-10 metres) in the southern Kattegat and the Great Belt as a function of winter runoff (October-January) from the Danish land mass to the Kattegat and the Belt Sea for the period 1985-94 (from Ærtebjerg, unpublished).

ferences being attributable to uncertainty in the calculation of boundary transport. Subject to reservation about these uncertainties, the budget indicates that there is a net import of biologically available phosphorus to the Belt Sea from the Kattegat (and originally from the Skagerrak). The local inputs to the Kattegat (watercourses and point sources) have halved during the period 1991-94 as a result of improved sewage treatment. Compared with the major transports over the sea boundaries, this reduction is virtually insignificant for the total loading of the Kattegat with biologically available phosphorus. A significant reduction in loading can only take place through reductions in the sources that discharge into the Baltic Sea, the Belt Sea and the North Sea.

The weight ratio between biologically available nitrogen and phosphorus in the total input to the Kattegat is 6.5:1, which is a little lower than the nitrogen:phosphorus weight ratio in the algae (which is normally 7:1). As the losses (estimated as imbalance in the nitrogen and phosphorus "budgets") are relatively greater for nitrogen than for phosphorus, everything indicates than primary production in the Kattegat is highly nitrogen-limited. Even minor reductions in nitrogen loading of the

Kattegat will therefore reduce primary production, thereby leading to improvement in the oxygen content of the bottom water (HAV90, Report 29).

4.6 Nutrient concentrations in the inner Danish marine waters

As mentioned earlier, the nutrient content of the water of the inner Danish marine waters is enhanced by inputs from Danish, Swedish and German terrestrial areas, as well as by deposition from the atmosphere. Nutrient concentrations are therefore enhanced in these waters compared with the concentrations in the adjoining marine waters, namely the Skagerrak and the Baltic Sea. In winter, when runoff is normally high and algal production has not yet started, the concentration of inorganic nutrients is maximal. In this period, the concentration of nitrate-nitrogen in the Kattegat is markedly higher than in the Baltic Sea (approx. 38%), and somewhat higher than in the water flowing in from the Skagerrak (approx. 17%) (Figure 4.16). The picture is the same for phosphorus, except that the excess concentrations in the Kattegat are more modest (11% higher than in the Baltic Sea and 7% higher than in the Skagerrak).

The winter concentration of nitrate in the inner Danish marine waters is coupled to the magnitude of runoff from the land (Figure 4.17). In very wet winters, for example 1986 and 1994, the excess concentration of nitrate in the inner Danish marine waters was therefore considerably higher than the average figures for the 10-year period 1985-94. High winter concentrations of nitrate-nitrogen means potentially greater algal production during the spring bloom in the inner Danish marine waters compared with that in the Skagerrak and the Baltic Sea.

Seasonal variation in nutrient concentration in open marine waters

The concentration of inorganic nutrients is determined by the rate of primary production, input, output and loss. In the winter, the input of nitrate is high because of runoff from the land, while the loss due to uptake by algae is low as algal production is light-limited. During the spring bloom, the nutrients are incorporated into phytoplankton production and the concentrations fall to very low levels in the surface water. Throughout the production period, nutrients input to the waters will be rapidly taken up by the algae and the concentration will remain low. This is the situation until the end of October-November, when algal production once again becomes light-limited and runoff from the land increases. The concentration of nitrate in the surface layer increases to maximal values, usually in the months December-February.

5 Nutrients, production and mineral cycling

The basis for life in the sea is the production of organic matter by plants, usually referred to as primary production. This production and the amount of organic matter that can be produced primarily depend on the amount and availability of inorganic nutrients and light. Primary production is generally greater in the coastal waters than in the open marine waters because of the higher nutrient content of the water (runoff from the land), better light conditions (low water depth) and close physical coupling between the sediment and the water column. The primary producers encompass perennial anchored macroalgae, rooted flowering plants, annual drifting or anchored macroalgae, benthic microalgae and phytoplankton. In open, deep marine waters (>20 metres), it is primarily the microscopic phytoplankton that account for the primary production since light attenuation by the water is usually so great that benthic plants cannot exist.

Physical processes, which set the general limits for biological production in the sea, are also an important determinant of production conditions. An obvious example is the phytoplankton spring bloom, which is closely coupled to solar radiation and stratification of the water column. On a smaller scale, physical processes are also of decisive significance for production conditions and biological structure in the sea. Thus wind and water current cause turbulence in the water, thereby breaking down concentration gradients around individuals or populations. They also affect the physical composition of the marine sediment, and thereby determine the types of organism that can live in and on the sediment.

The part of the organic production that sinks to the sediment is degraded via microbial food chains in the bottom water or by benthic invertebrates and bacteria in the marine sediment. This results in the release of nutrients which can be recycled to new primary production. Degradation of the organic matter involves the consumption of oxygen, and the greater the amount of organic matter that sinks to the sea floor, the greater the amount of oxygen required for degradation processes. High sedimentation of organic matter can therefore lead to oxygen deficit in the bottom water.

5.1 Phytoplankton production

Organic matter production by phytoplankton is the most important source of organic matter for all the higher marine life forms.

Through primary production, inorganic carbon (CO_2) is incorporated into the various marine plant forms as organically bound carbon using light as the energy source (photosynthesis).

5.1.1 Measurement of primary production

Primary production is traditionally measured using the ^{14}C technique, which was developed in Denmark at the beginning of the 1950s. Primary production is measured by following the uptake and incorporation of the radioactive isotope $^{14}CO_2$ into organic matter. Since the development of the ^{14}C technique, Danish scientists have led the way in the further development and use of the method. Moreover, measurement of phytoplankton primary produc-

Svend Tougaard/Biofoto

tion has been a part of Danish monitoring activities since 1974.

The method is not entirely problem-free, however, and it became clear as early as the mid 1970s that much of the primary production was not measured when using the traditional technique.

Studies under the HAV90 programme have attempted to clarify which processes are included in the measurements, and to evaluate the significance of the dissolved organic matter that is "lost" from the algae to the surroundings during photosynthesis (HAV90, Reports 5 and 55).

It was shown that measurements of total production (= production of particulate organic matter plus production of dissolved organic matter) generally exceed the traditionally determined particle-bound part of the production.

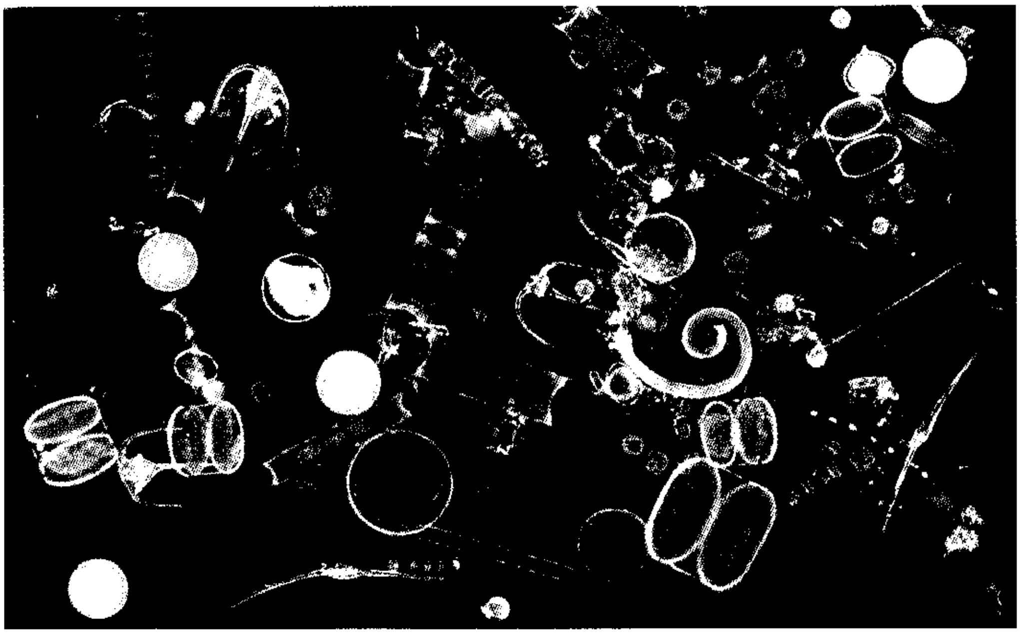
The difference between the two production measurements varied among sampling localities and also depended on whether natural algal communities or algal monocultures were used. Great deviation has been found in the same samples using the two methods, but the total production generally seems to exceed production of particulate organic matter by 10-20%.

Chlorophyll and primary production

Plants "trap" light energy for use in photosynthesis by pigments within the plants. Chlorophyll *a* is present in all plants, and is often the quantitatively most important pigment. In natural phytoplankton communities, there will be a more or less constant relationship between the concentration of chlorophyll *a* and phytoplankton biomass, and the latter is therefore usually determined by measurement of chlorophyll *a*. As a rule of thumb, one can use the conversion factor 40 between chlorophyll *a* and phytoplankton carbon (1 µg chlorophyll *a* = 40 µg carbon). Phytoplankton production of organic matter (primary production) is measured by incubating natural water in small flasks in which incorporation of the radioactive isotope $^{14}CO_2$ is followed over a short period of time.

5.1.2 Regulation of primary production

Phytoplankton primary production (PP) can be regulated at two levels, primary production being equivalent to the product of algal biomass (e.g. measured as the concentration of the pigment chlorophyll *a*) and the production per unit biomass (specific production PP/chlorophyll *a*), each of which is regulated by different regulatory mechanisms. Productivity is primarily determined by the availability of nutrients, light and temperature, while loss processes such as grazing and sedimentation solely affect the biomass. With a certain time lag, increased productivity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can also lead to an increased biomass in the summer if the loss remains constant or increases only slowly. In the Danish estuarine fjords and coastal waters, phytoplankton biomass varies between approx. 1 and 100 μg chlorophyll *a* per litre (corresponding to about 40-4,000 μg carbon per litre) (HAV90, Report 30, Figure 5.5), while the variation in phytoplankton primary production is generally far smaller, typically within a factor 10 (Agger et al., 1994). The reason is partly that the specific productivity is only slightly nutrient-limited. However, by far the main reason is that the production layer becomes increasingly thinner at high phytoplankton concentrations due to phytoplankton self-shading. The productivity or turnover in a given area will thus primarily vary with the annual variation in solar radiation and temperature, as shown for Kertinge Nor (Figure 5.1; HAV90, Report 45).

Essential nutrients

Plants need a number of elements in order to be able to form the organic compounds necessary for their growth, e.g. proteins. Nitrogen and phosphorus are the quantitatively most important nutrients, and are primarily taken up by the plants as inorganic salts. In the aquatic environment the concentrations of nitrogen and phosphorus are often low, which is why phytoplankton growth and biomass development are regulated by the availability of these nutrients. Silicon comprises a necessary component of diatoms, which are important primary producers, especially in the spring. The main source of silicon is silicates entering the marine environment with freshwater. In areas with little input of freshwater, diatom biomass can be limited by low silicon availability.

5.1.3 Phytoplankton annual production

Under the HAV90 programme, phytoplankton biomass determined using the ^{14}C technique was found to be 260 g carbon per m^2 in Århus Bight (HAV90, Report 59) and 290 g carbon per m^2 in the southeastern Kattegat (HAV90, Report 10). Both localities are so deep and light conditions at the bottom so poor that primary production by benthic plants can be excluded. The difference in production at the two localities hardly reflects a difference in water nutrient content between the localities, but is more likely due to difference in the number of samples and the duration of the measurement periods.

A large part of phytoplankton annual production occurs in the early spring. In the above mentioned cases, the phytoplankton spring bloom thus accounted for approx. 20% of annual production in 1989 (southeastern Kattegat) and 15% in 1990 (Århus Bight), even though the spring peak was very short.

By comparing with earlier measurements made at lightships, it has been found that phytoplankton production has increased approx. 23-fold in the Kattegat since the mid 1950s. Changed experimental and calculation methods can only explain a minor part of this increase, which must therefore be attributable to the build-up of a greater phytoplankton biomass and higher phytoplankton production as a result of enhanced input of nutrients (HAV90, Report 10).

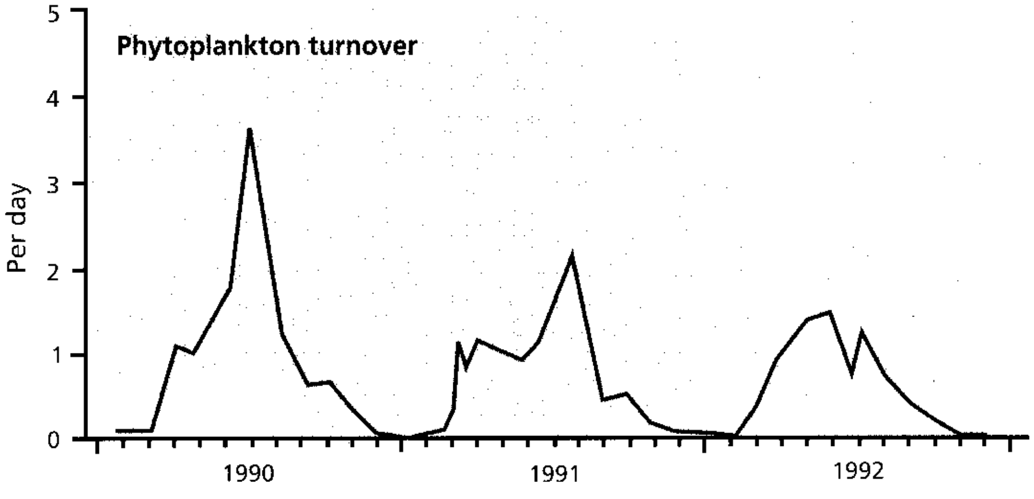


Figure 5.1

Productivity (primary production/biomass) of phytoplankton in Kertinge Nor calculated from the volume-specific primary production and phytoplankton biomass. As a good estimate, phytoplankton biomass can be calculated as 40 times the chlorophyll concentration (from HAV90, Report 45).

5.2 Coupling between physical conditions and production

In the open marine waters such as the Kattegat, primary production is closely coupled to the physical conditions in the water column. Stratification of the water column is of decisive significance for the primary production and for the fate of the organic matter produced. This is because stratification effectively limits the exchange of dissolved substances (e.g. nutrients and oxygen) between the water layers, but does not have the same degree of effect on sedimentation of particle-bound organic matter from the upper layer to the bottom.

5.2.1 The annual production cycle

In the classic description of the annual cycle of primary production, the phytoplankton spring bloom is initiated by formation of the pycnocline in the spring concomitant with increasing solar radiation. The concentration of nutrients is high during winter. However, photosynthesis cannot counterbalance respiration and the loss due to grazing and sedimentation at the low light intensity that the phytoplankton experience in the well-mixed water column in winter. Formation of the pycnocline and increasing solar radiation in the early spring is accompanied within weeks by phytoplankton blooms in the surface layer and a resultant high consumption of nutrients. Part of the spring bloom is consumed by planktonic animals, but the majority of the new biomass sinks through the pycnocline more or less intact, thereby removing nutrients from the surface layer.

A pycnocline divides the water into an upper (surface) and a lower (bottom) layer differing in density. As the pycnocline hinders mixing of the water, the nutrient and oxygen content of the two layers consequently also usually differ. The pycnocline is located where the change in the density of the water is greatest with depth. Stratification of the water column in the inner Danish marine waters is largely due to a difference in salinity between an upper low-salinity layer that derives from the Baltic Sea, and a lower high-salinity layer that derives from the North Sea. Solar radiation raises the temperature of the upper layer, thereby reducing its density, which contributes to the maintenance of stratification in the summer.

It is the salinity of the water that primarily determines its density, however, a 1‰ change in salinity (e.g. from 25‰ to 26‰) having roughly the same effect on density as a temperature increase of 6°C. During spring periods of high outflow from the Baltic Sea, the upper and lower layers of the Kattegat can differ in salinity by as much as 20‰. From the end of the spring bloom until October, when stratification of the water is most marked, the surface layer concentration of nutrients and phytoplankton (but not necessarily the magnitude of primary production) is generally low.

The plankton community is dominated by small forms adapted to low nutrient concentrations (HAV90, Report 11). The nutritional requirements of the algae are primarily met by recycled nutrients released upon mineralization by grazing planktonic animals. By comparing the primary production in the southeastern Kattegat with the winter concentration of nutrients and nutrient input in the productive period, it was found that nitrogen is recycled approx. 7-8 times before it sediments out in particle-bound form (HAV90, Report 10).

Ammonium is the most important algal nitrogen source throughout the summer, and the considerable recycling of nitrogen in the photic surface layers (i.e. the layers where there is sufficient light for photosynthesis) is in concert with the fact that ammonium is also the most important metabolic product from grazers and predators in the free water masses (HAV90, Report 10). Production of ammonium (and phosphate) thus takes place continuously in the surface layer, which makes it difficult to use the concentrations to determine which nutrient limits primary production at a given point in time. Despite the considerable recycling of nitrogen, production can only be maintained in the longer term if new nutrients are input to the water since loss will continually occur through sedimentation to the sea floor.

As discussed earlier, input of nutrients to the surface water takes place as runoff from the land via estuarine fjords, from adjoining marine waters (especially the Baltic Sea), by deposition from the atmosphere or from the nutrient-rich sediment via various mixing mechanisms between the layers. In stratified waters, some mixing occurs between the layers (entrainment), either by friction between the layers or by the action of the wind whereby some of the energy in the wind is transferred to the water.

In the Great Belt, the southward flow of bottom water is relatively strong. Friction between the bottom current and the surface layer causes turbulence which draws considerable amounts of surface water downwards into the bottom water. This downward transport of water is of the same magnitude as the upward transport of water. The process ensures continuous input of oxygen into the bottom water, and severe oxygen deficit therefore rarely occurs in the Great Belt.

In the Kattegat, where wind-induced mixing dominates, upward water transport is 4 times as great as downward water transport. This means that the salinity of the bottom water remains roughly unchanged from the Skagerrak to the Belt Sea, while the salinity in the surface layer increases from approx. 20‰ in the southern Kattegat to approx. 30‰ at the Skagerrak boundary. The poor mixing of oxygen-rich surface water into the bottom layers means that the effect of low oxygen concentrations in the bottom water of the Kattegat is far greater than for example in the Great Belt (HAV90, Report 1).

5.2.2 Phytoplankton blooms in the pycnocline

The pycnocline between the lighter, nutrient-poor surface water and the heavier, nutrient-rich bottom water often provides good growth conditions for phytoplankton with a low light requirement. The advantage for the algae is that they can utilize the nutrients from the bottom water and the weak light from above, while at the same time not being mixed out of the layer.

Studies in the southern Kattegat have shown that enhanced algal concentrations in the pycnocline are more or less permanent from the end of the spring bloom until late in the autumn (HAV90, Reports 10 and 33). Phytoplankton production in the pycnocline in the southeastern Kattegat in March, May and September 1992 accounted for 20-50% of the total primary production in the water column (HAV90, Report 33), and around 30% of annual production in 1989 (HAV90, Report 10).

Phytoplankton growth is based on nutrients input from the bottom water by vertical mixing processes or by advective input of nutrient-rich water with an intermediate density, which intrudes into the pycnocline (intrusion layer, see Section 4.4.1).

In some periods, the phytoplankton in the pycnocline might consist of just one or a few species able to exclude other phytoplankton and hinder grazing by the formation of toxins (HAV90, Report 28). This was the case during the *Chrysochromulina* bloom in 1988 (Nielsen et al., 1990; Kaas et al., 1992), but not in 1991 and 1992 (HAV90, Report 33).

Stratification of the water column in the inner Danish marine waters is partly broken down during the course of the autumn when the frequency of strong winds is higher. However, the energy that is transferred from the wind to the water is seldom sufficient to mix the whole water column. For example, the wind has to blow at 10 metres per second for almost 3 days for the transferred wind energy to be able to mix the whole water column in a typical autumn situation in Århus Bight (HAV90, Report 39).

Apart from direct wind-induced mixing, stratification is also weakened in autumn as a result of reduced outflow of water from the Baltic Sea. Moreover, the more frequent occurrence of long-lasting westerly winds presses water into the Kattegat from the north. The friction between this water flow and the bottom increases mixing of the water column. Breakdown of the stratification results in the influx of nutrients to the surface water from the bottom water. This can eventually lead to an autumn bloom of large phytoplankton.

Wind- and current-induced turbulence both lead to mixing of the water column. Calculations of mixing in the Great Belt over a 90-year period show that the contribution made by the current has been slowly declining while that made by the wind over the last 35 years has increased in the southern Kattegat (HAV90, Report 31). However, analyses of wind data for that period from the northern Kattegat do not reveal any major changes in the frequency of force 6 and 9 Beaufort winds (HAV90, Report 2).

Fronts

Fronts can be considered as vertical boundaries in the water masses. In the same way as fronts in the atmosphere separate cold and warm air masses, fronts in the sea separate water masses differing in nature, typically in density. In the southern Kattegat, fronts arise when water flows out through the Øresund and the Belt Seas. In the transitional zone between the Kattegat and the Skagerrak, a front forms between the stratified Kattegat water and the more salty, but less stratified Skagerrak water. Fronts often provide good conditions for phytoplankton growth.

5.2.3 Phytoplankton blooms in fronts

Areas in which the density of the surface water changes drastically in a horizontal direction are called fronts. These normally separate stratified water from more well-mixed water masses. Fronts arise, for example, as a result of tidal water (especially in the North Sea) and where the currents drive different water masses together, e.g. at the mouths of rivers and estuarine fjords. In the southern Kattegat, fronts arise when water flows through the Øresund and the Belt Seas. No appreciable mixing occurs through the Øresund and salinity there only increases from 8‰, which is the salinity of the surface water in the Baltic Sea, to approx. 10‰ when the water leaves the Øresund. This light water continues flowing northwards as a cur-

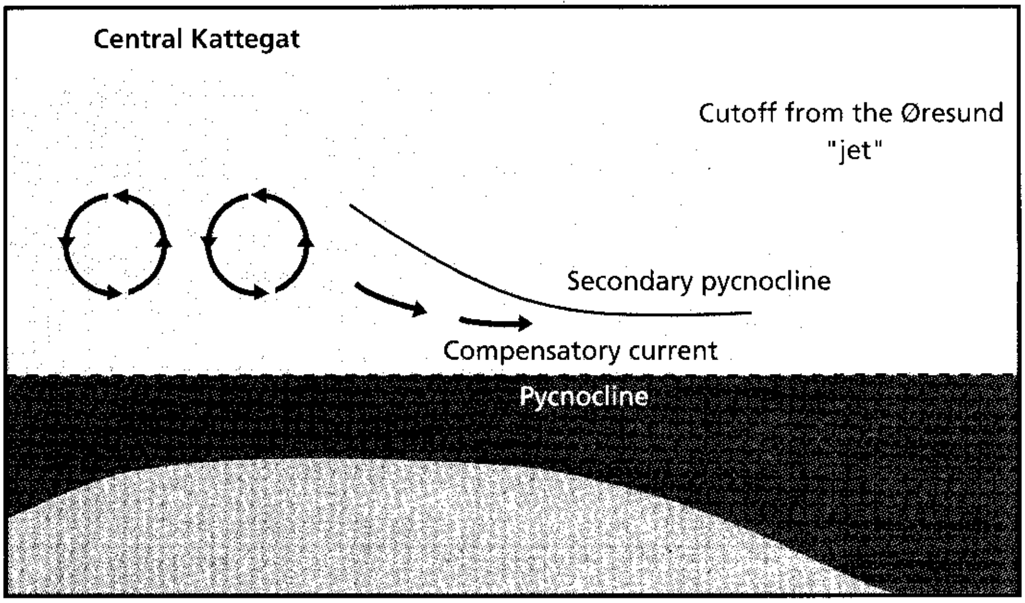


Figure 5.2

Compensatory current and secondary pycnocline. Following wind-induced mixing of the water in the central Kattegat, the water current will be enriched with nutrients and at the same time cause a secondary pycnocline to form. The compensatory current leads to high production in a thin layer in the centre of the water column. The nutrient-rich water from the central Kattegat is drawn back towards the fronts by the compensatory current. This thus occurs in the part of the water column that has sufficient light for phytoplankton production, and primary production can consequently be considerable in this layer (see Section 5.2.2 on phytoplankton blooms in the pycnocline). The layer is often only 1 metre thick and can therefore be difficult to identify. It is consequently difficult to collect representative samples from the layer in connection with a monitoring programme.

rent distinctly separated from the surface water in the Kattegat, which has a salinity of approx. 18‰. Due to the earth's rotation, the current in the Kattegat clings to the Swedish coast. In contrast, the Baltic Sea water that flows out through the Great Belt becomes intensively mixed with the bottom water in the Great Belt. As a result, the salinity here increases to between 14 and 20‰ in the outflowing water. The surface water continues as a less well-defined current out into the Kattegat, again separated from the surface water in the central Kattegat by a front.

Both satellite images and field measurements reveal the existence of isolated extrusions that have been severed from the fronts facing the central Kattegat, especially when the wind speed falls (HAV90, Reports 3 and 20). These evoke compensatory flow back towards the fronts at deeper depth, but above the normal pycnocline (Figure 5.2). This creates a secondary pycnocline above the general pycnocline, thereby rendering vertical mixing of the water even more difficult. There is no secondary pycnocline in the very central part of the Kattegat, though, and it is

Satellite image prepared by SMHI, Sweden

Figure 5.3

Satellite image of the Kattegat on 25 May 1987. In the transitional zone between the Kattegat and the Skagerrak, a front can be formed between the stratified Kattegat water and the more salty but less stratified Skagerrak water. In this front area, both the concentration of phytoplankton and phytoplankton production are enhanced compared with that in the marine waters outside the front (HAV90, Report 49). In all probability, the high production is due to upward transport of nutrients from the bottom water in the front area.

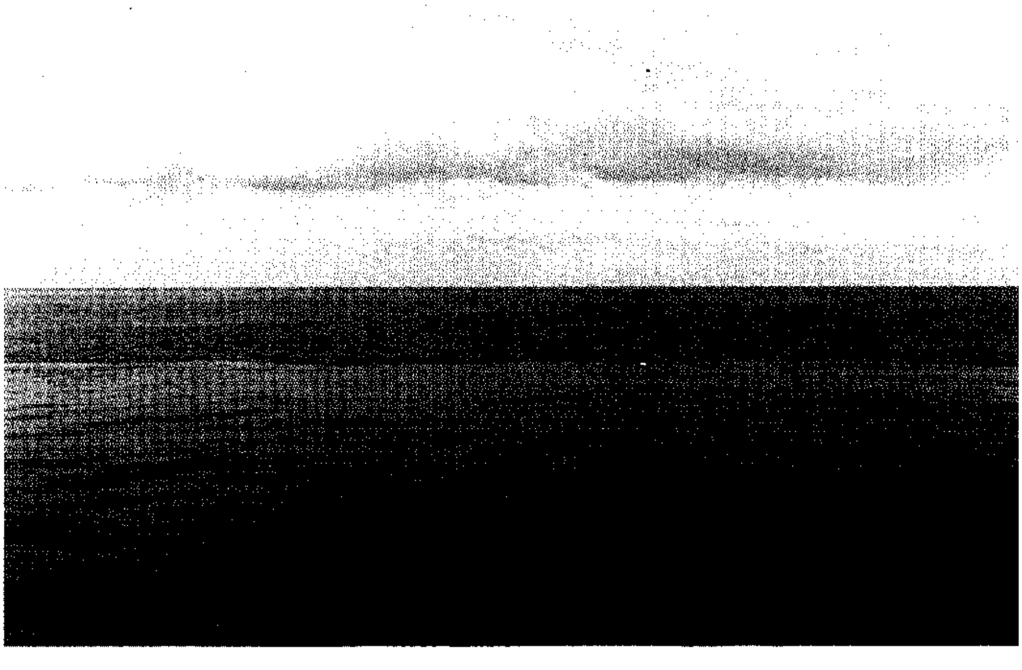


Photo: Frontgruppen

Figure 5.4

Photograph of the Skagerrak front taken in September 1992. In the photograph, the front is apparent as a difference in the roughness of the surface water across the front. A plastic bottle can be seen at the front. Many objects (plastic bags, sacks, sticks, tires, etc.) were observed in the area near the front. The existence of the front was confirmed by salinity profiles.

therefore only here that the wind can blend the nutrients up into the water above the general pycnocline. This is why it is only in the central parts of the Kattegat that significant phytoplankton growth takes place in the surface water in connection with periods of strong winds during summer.

The fronts are seldom located in the same place for very long. For example, the fronts that separate the outflowing water from the Øresund from the Kattegat water will move eastwards when the easterly wind drops and shifts to a westerly wind. A permanent monitoring station can therefore lie within a front one day and lie outside it the next day. This is important to bear in mind as the fronts separate water masses differing in chemical and biological characteristics.

5.3 Production and turnover of plankton biomass

Phytoplankton biomass in the Danish coastal waters is closely coupled to the availability of nitrogen. An increase in nitrogen input thus results in an increase in phytoplankton biomass. Part of this biomass can be metabolized in the water column through the pelagic food chains, while part of it will sediment out of the water column and be metabolized at the sea floor (benthic food chains). The number of pelagic grazers and the formation of aggregates (aggregation of algal cells) are some of the factors regulating the "fate" of the phytoplankton, i.e. whether they are metabolized in the water column or sink to the bottom.

5.3.1 Nutrient availability and plankton biomass

A comparative analysis of 162 data sets from Danish marine waters, including 120 data sets from estuarine fjords and coastal waters, revealed a close relationship between phytoplankton biomass (measured as chlorophyll *a*) and the

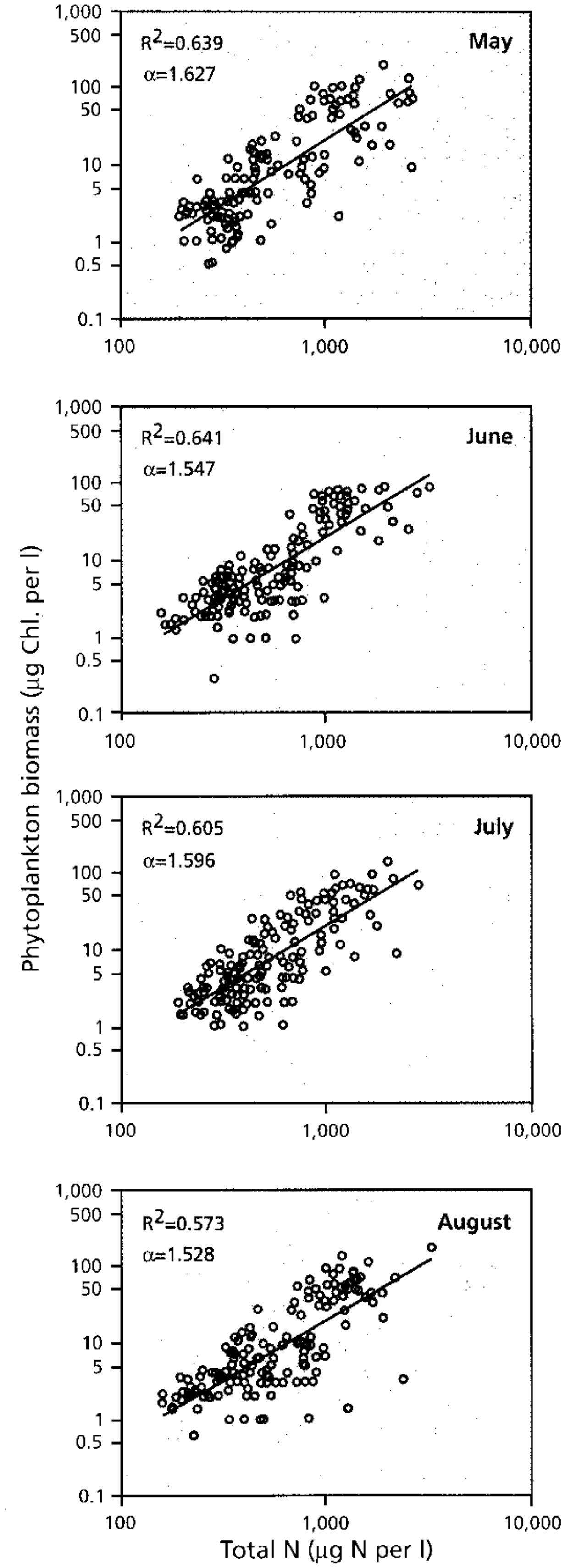


Figure 5.5

The relationship between phytoplankton biomass (measured as chlorophyll *a*) and concentration of total nitrogen at 120 different sampling stations in Danish estuarine fjords and coastal waters. Data is shown for the summer period (May-August) (from HAV90, Report 30).

nitrogen concentration in the water, while the relationship to the phosphorus concentration is considerably weaker (HAV90, Report 30). The relationship to nitrogen is most pronounced in the summer, when the concentration of total nitrogen is generally lowest due to the low runoff from the land and loss by denitrification (Figure 5.5).

The two variables in Figure 5.5 are not independent since the phytoplankton themselves contain nitrogen. However, as they typically only account for 5-15% of the total nitrogen, the relationship must be considered to be rather convincing. In the summer period, total nitrogen can explain approx. 60% of the variation in phytoplankton biomass (chlorophyll *a*), while the remainder has to be ascribed to differences in light conditions, the presence of varying numbers of benthic grazers etc. in the different water bodies. An important fact revealed by the relationships between total nitrogen and phytoplankton biomass (chlorophyll *a*) is that the slope exceeds 1 in the summer, i.e. that a given increase in total nitrogen predicts a relatively greater increase in phytoplankton biomass. The reason for this could be that grazing pressure is unable to keep up with the development in algal biomass when nutrient availability is high.

Based on the relationships shown in Figure 5.5, it can be predicted that reductions in the nitrogen availability (nitrogen input) in Danish estuarine fjords and coastal waters will generally lead to lower algal concentrations. The relationships also show that the reduction in algal biomass will be at least of the same magnitude as the reduction in nitrogen input, and probably even greater than the reduction in nitrogen input during summer.

5.3.2 Grazing of phytoplankton

Phytoplankton biomass is determined by the productivity (the biomass-specific primary production) and loss due to grazing or sedimentation out of the surface layer. The conditions for high phytoplankton biomass are high nutrient availability and low grazing. This situation occurs if development in the biomass of planktonic grazers (e.g. copepods) is unable to keep up with phytoplankton growth, or if the benthic filter feeders such as mussels are cut off from large parts of the water column due to stratification.

In contrast to macroalgae and eelgrass, direct grazing on phytoplankton is considerable. The organic matter can be metabolized through food chains in the free water masses (pelagic food chains) or, as is the case in many Danish coastal waters, via benthic filter feeders, e.g. mussels and tunicates.

In marine pelagic food chains, the size ratio between prey and predator organisms is approx. 1:10. The length of the food chains is therefore extremely dependent on the size of the algae that dominate the primary production. Large algae can be consumed by copepods, which in turn are eaten by larger organisms, e.g. fish larvae.

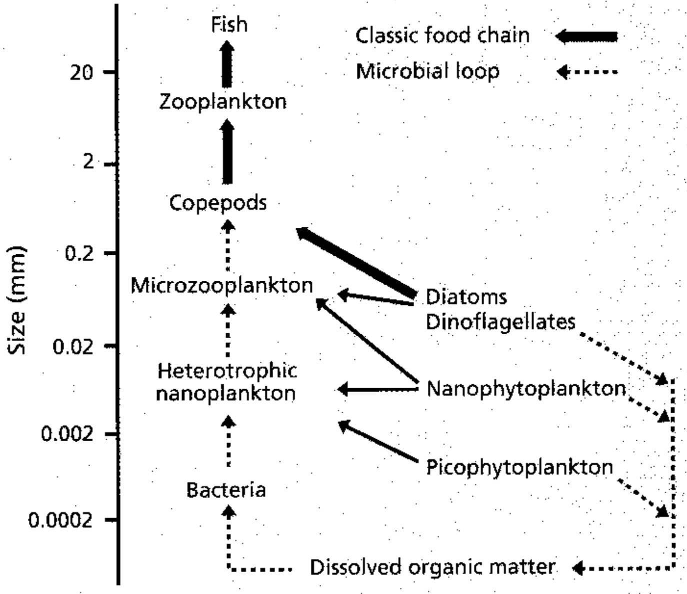
The transfer of organic matter through this classic, short grazing food chain is very effective and comprises the basis for considerable production of fish, for example around the banks in the North Sea. The development rate of copepods is markedly temperature-dependent, and there will often be a considerable delay between production and biomass accumulation.

When the nutrient content of sea water is low, it is often small algae or blue-green bacteria (blue-green algae) that account for primary production. The food chains tend to be long and the transfer of organic matter to the upper links in the chain is ineffective. Moreover, phytoplankton "lose" part of the fixed carbon to the surrounding water in the form of simple organic compounds that are the basis for bacterial growth. Via the microbial loop, a part of the carbon ends up in a size that can enter the grazing food chain, but the organic matter yield is poor.

In the Kattegat, the number of important grazers such as copepods is closely coupled to the temperature, while their food uptake and production is closely coupled to the density of large phytoplankton (HAV90, Report 10). Episodic blooms of large phytoplankton in the summer in connection with wind-induced mixing of nutrient-rich bottom water are effectively grazed by the large community of copepods. In contrast, algal blooms in the spring and autumn will generally sink out from the surface layer because the water temperature and hence copepod biomass are low at these times of the year. In 1989, the water temperature during the spring bloom was approx. 5°C, and hence considerably higher than normal. Accordingly, the copepods consumed approx. 12% of the spring bloom as compared with 5% normally (HAV90, Report 10). A consequence of "high" winter-spring temperatures can thus be that the nutrient loss by sedimentation of the spring bloom is reduced and that a greater part of the nutrients is retained in the surface layer (Smetacek and Pollehne, 1986). The "fate" of the spring bloom (grazing or sedimentation) will therefore vary from year to year. A characteristic biological element of shallow estuarine fjords and coastal waters is the benthic filter feeders such as mussels and tunicates. In shallow areas, a considerable part of algal production is channelized to the mussels, which can consequently build up a considerable biomass. In these areas, benthic grazing control of phytoplankton is theoretically possible even under very nutrient-rich conditions simply because of the animals' large biomass (Cloern, 1991). In the case of the outer parts of Roskilde Fjord, it has been calculated that populations of blue mussels and soft clams can filter the overlying water column from 1-10 times each day. The grazing potential is greatest at the most shallow stations (HAV90, Report 51). Accordingly, the concentration of phytoplankton and zooplankton clearly varies with the depth and the grazing potential.

Pelagic food chains

The background for the pelagic food chains is phytoplankton production of organic matter. If the production is dominated by large algae (diatoms and dinoflagellates), the food chain will be short (classic food chain). If the production is dominated by small algae or bacteria, the food chain will be long. Because of loss due to respiration in the many links, the transfer of organic matter to the upper links will be low in the long food chain.



The mussels effectively filter and consume phytoplankton and smaller zooplankton in the size range 2-200 µm (HAV90, Report 51). The prey:predator length ratio in this case ranges from 1:1,000 to 1:10,000, and is therefore far smaller than in the pelagic food chains in the free water masses. The transfer of organic matter in this short grazing food chain is extremely effective, a fact also exploited commercially in mussel fishery in several Danish estuarine fjords. As grazing by mussels is very efficient even on larger planktonic organisms, the presence of large populations of benthic filter feeders can reduce the significance of the pelagic grazing food chains. Thus not only can the mussels consume small copepods directly (HAV90, Report 51), but they are also considerably more effective than the copepods at filtering small phytoplankton.

A characteristic of many estuarine fjords is the low number of copepods, a phe-

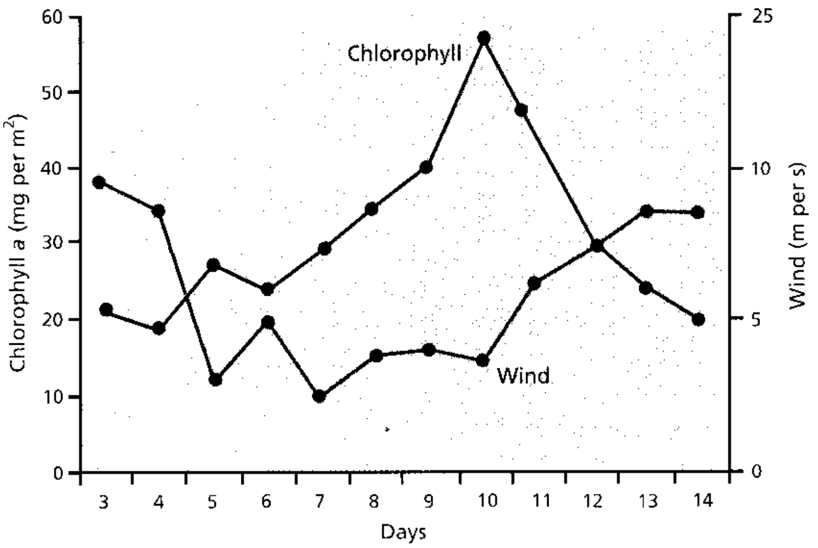


Figure 5.6

Temporal variation in wind speed and areal concentration of phytoplankton (measured as chlorophyll a) in Roskilde Fjord (depth 4.5 metres) over a 2-week period in March (from HAV90, Report 51).

nomenon commonly referred to as the "fjord effect". The reason for the low number of copepods in the fjords is far from clear, though.

In contrast to their competitors in the free water masses (e.g. the ciliates and copepods), the grazers among the benthic invertebrates are not completely surrounded by food, but have to filter the water layer closest to the bottom. If the water column is not well mixed, the concentration of phytoplankton will be low in the bottom layer of water as it is re-filtered many times. The growth of benthic grazers is therefore limited by poor food availability. Under such conditions, the influence of benthic grazers on the phytoplankton biomass will be minimal and in stratified water columns, phytoplankton productivity and biomass development will therefore be regulated by light, nutrients and pelagic grazing in the water column.

Studies in Roskilde Fjord revealed that phytoplankton biomass falls when the wind speed is high as a result of mixing of the water to deeper depths (HAV90, Report 51). During windy periods with a fully mixed water column, phytoplankton biomass fell markedly, primarily due to grazing by benthic mussels and secondarily to lower areal production caused by deteriorated light conditions (Figure 5.6).

A high level of benthic invertebrate grazing and variation in the mixing of the water masses can be causes of the characteristically great variations in the concentration of phytoplankton often seen in several of our estuarine fjords. In the majority of Danish coastal waters, the wind is the most important factor with respect to mixing of the water column. One can therefore expect that the variation in the number of phytoplankton will correlate with the frequency of wind events. For example, low-pressure fronts pass over the country at approx. 10-day intervals, and such events are reflected in the amount of phytoplankton.

In the Danish estuarine fjords and coastal waters, where tidal currents generally only make a minimal contribution to vertical mixing of the water, the mussel populations are extremely vulnerable to "abnormal" meteorological conditions such as long wind-still periods and longer periods of ice cover, which can lead to oxygen deficit at the sea floor. Under these conditions, whole populations can be decimated and grazing control by the benthic invertebrates will only re-establish slowly (Hedal, 1991).

5.3.3 Sedimentation of production

A considerable part of the organic matter produced in the upper illuminated surface layers sinks to the bottom, where it both provides the primary food resource for benthic invertebrates and the organic substrate for microbial food chains. The sedimented organic matter consists of living or dead phytoplankton and of organic matter that has been metabolized in the food chains in the water mass and which therefore lacks recognizable structures.

Living phytoplankton often settle out in the form of aggregates comprised of many cells. The formation of large aggregates with high sedimentation rates is described as one of the mechanisms behind the rapid sedimentation of the spring blooms (HAV90, Report 53), which is characteristic for temperate marine waters such as those in Denmark.

Aggregates can arise as a result of individual phytoplankton cells coming into physical contact with each other and subsequently sticking together. Repeated collisions eventually leads to the formation of large aggregates provided the adhesiveness of the cells is high. The critical conditions regulating aggregate formation are therefore the adhesiveness of the phytoplankton and the frequency of contact between them. Under natural conditions, contact frequency will mainly be determined by the extent of mixing in the water (and hence by the wind speed), as well as by the density in which the phytoplankton are present.

In laboratory studies it has been shown that stirring the water causes phytoplankton to form aggregates (HAV90, Report 53). The probability for aggregate formation varies greatly depending on the phytoplankton group and the nutritional status of the cells, albeit that an unambiguous predictable pattern cannot be demonstrated. A subsequent field study in Isefjorden showed that the temporal variation in the concentration of dominant diatoms during the spring bloom can be partly explained by the coagulation theory, which states that the sedimentation rate of large aggregates increases during windy periods, thereby reducing phytoplankton density in the water (HAV90, Report 53). The studies thus indicate a possible important mechanism for the transport of organic matter to the sea floor.

The sedimentation of organic carbon produced in the upper water layers in the southeastern Kattegat has been measured by means of sediment traps suspended in the water column. Sedimentation amounted to 62 g carbon per m^2 in March-October, thus comprising about 20% of the total organic matter production in the productive period (HAV90, Report 10). Using the same technique, sedimentation in Århus Bight was found to be 118 g carbon per m^2 per year, or approx. 45% of organic matter production (HAV90, Report 59). Both localities are characterized by considerable horizontal and vertical heterogeneity and presumably, significant horizontal transport of organic matter. It is therefore very uncertain whether all the material that collects in the suspended sediment traps is produced in the overlying water column or whether it to some extent also includes material resuspended from the sediment or material produced elsewhere. This underlines the fact that there will always be some uncertainty associated with drawing up organic matter budgets on an areal basis in the heterogeneous Danish coastal waters.

The seasonal variation in sedimentation in the southern Kattegat is characterized by a considerable input of intact diatoms during and following the spring bloom. During the rest of the year, organic matter input to the sea floor is dominated by organic matter metabolized in the pelagic food chains. In this period, the nitrogen content in the sedimented organic matter is low, which reflects selective retention of this nutrient in the pelagic food chains (HAV90, Report 10).

5.4 Benthic vegetation

An important biological element of coastal waters is the benthic vegetation, which consists of benthic microalgae on the sediment surface, rapidly growing annual macroalgae, large perennial brown algae and eelgrass. The benthic vegetation is an important producer of organic matter, which is then channelized onwards up the food chain to benthic invertebrates and fish.

Dense populations of benthic plants provide protection for fish fry and other animals, and safeguard the sediment against erosion and resuspension. The vegetation affects nutrient dynamics in the coastal waters and is of decisive significance for oxygen conditions in shallow waters. Furthermore, vegetated areas provide the basis for important pound net fishery, and the composition and distribution of the vegetation affects the recreational value of the areas.

S. E. Jørgensen/Biofoto

As with the phytoplankton, nutrient loading of the marine environment provokes a strong reaction from the benthic vegetation involving changes in species composition, abundance and distribution. When nutrient input increases, the populations of eelgrass and large perennial brown algae are partly or completely replaced by massive occurrences of rapidly growing annual macroalgae. Typical examples are the blooms seen in Køge Bay, where filamentous brown algae *(Ectocarpus sp.)* cause major problems. It is therefore important to be able to predict changes in the vegetation as a result of changes in human impact. This makes it imperative to posses a thorough knowledge of the factors and mechanisms that regulate the composition and distribution of the benthic vegetation, as well as the effects that benthic vegetation have on the general environmental state of coastal waters.

5.4.1 Composition of the benthic vegetation

The composition of the benthic vegetation is determined by a wide range of natural factors such as light, salinity, exposure, sediment type and grazing by benthic invertebrates. In addition, the various plant types and species are to a varying extent dependent on the nutrient content of the water. As with the phytoplankton in the open sea, it is particularly the amount of nitrogen that limits the plants' growth and biomass development (HAV90, Report 41).

A traditional belief, which has primarily been used to explain the competition between small and large phytoplankton in lakes and in the open sea, is that small algal species with thin thalli (leaf tissue) and hence a large surface area relative to their volume are very effective at taking up nutrients from the surroundings. Small algae should therefore be better adapted to water bodies with low nutrient concentrations than large species with thick thalli. However, studies conducted as part of the HAV90 programme have shown that even though it is correct that nutrient uptake per unit biomass is most rapid in macroalgae with thin thalli, it is the large, slowly growing algae with thick thalli that are the most successful in nutrient-poor waters (HAV90, Report 41). In the least eutrophic coastal waters, eelgrass and the perennial brown algae dominate the benthic vegetation, while the rapidly growing macroalgae with thin thalli first appear in large numbers when the nutrient availability increases.

Thus in contrast to the traditional belief, algal forms with thick thalli are better adapted to nutrient-poor conditions. In concert with this, a detailed analysis of the nutrient budgets of various macroalgae shows that the thicker, slowly growing algae are more easily able to meet their nutrient requirements for growth than the thin forms (HAV90, Report 41). Thick macroalgae have a low nutrient requirement that can be met by uptake from the water even at very low nutrient concentrations. Moreover, they are better able to store nutrients for hard times, and, finally, they are better able to recycle nutrients within the plants themselves. In contrast, the thin algal forms have a high nutrient requirement, and demand a continually high nutrient uptake from the water in order to be able to meet their nutrient requirements (HAV90, Report 41).

The presence of nutrient-demanding "weed" species of macroalgae that cause deterioration in the quality of the water in coastal waters varies from place to place. In Køge Bay, it is primarily the filamentous brown algae (belonging to the genera *Ectocarpus* and *Pilayella*) that cause problems, while in Odense Fjord, Kertinge Nor, Limfjorden and Roskilde Fjord, the main problem has been with blooms of fast-growing short-living algae (the genera *Ulva*, *Chaetomorpha* and *Cladophora*). In the marine waters off the southern coast of Funen, all of these forms just seem to succeed each other throughout the growth season (HAV90, Report 22). Differences in the sensitivity of the species to temperature and salinity and differences in their nutrient budgets can to some extent explain the varying success of the species in the different areas (HAV90, Report 41), although our knowledge is still inadequate to allow complete explanations or tenable predictions.

5.4.2 Distribution of the benthic vegetation

As with species composition of the benthic vegetation, the areal distribution of the benthic vegetation is also affected by variations in natural factors. Water depth, light conditions, exposure to waves and currents and the occurrence of suitable bottom substrata for anchorage decisively affect the plants' ability to colonize an area. While it is true that nutrient loading stimulates the occurrence of particularly nutrient-demanding macroalgae in shallow water, the total biomass and distribution of the benthic vegetation nevertheless falls because the depth distribution of the plants reduces due to reduced light penetration in the water column (HAV90, Report 30). As described in Section 5.3, the amount of phytoplankton increases with increasing concentrations of nitrogen in the water column. Light penetration consequently decreases due to the increased presence of plankton and suspended matter, thereby deteriorating growth conditions for the benthic vegetation in deeper water. Analysis of monitoring data from a number of Danish coastal waters reveals that the maximum depth distribution of the various plant forms can be described as a function of the average nitrogen content of the water during their growth season (Figure 5.7).

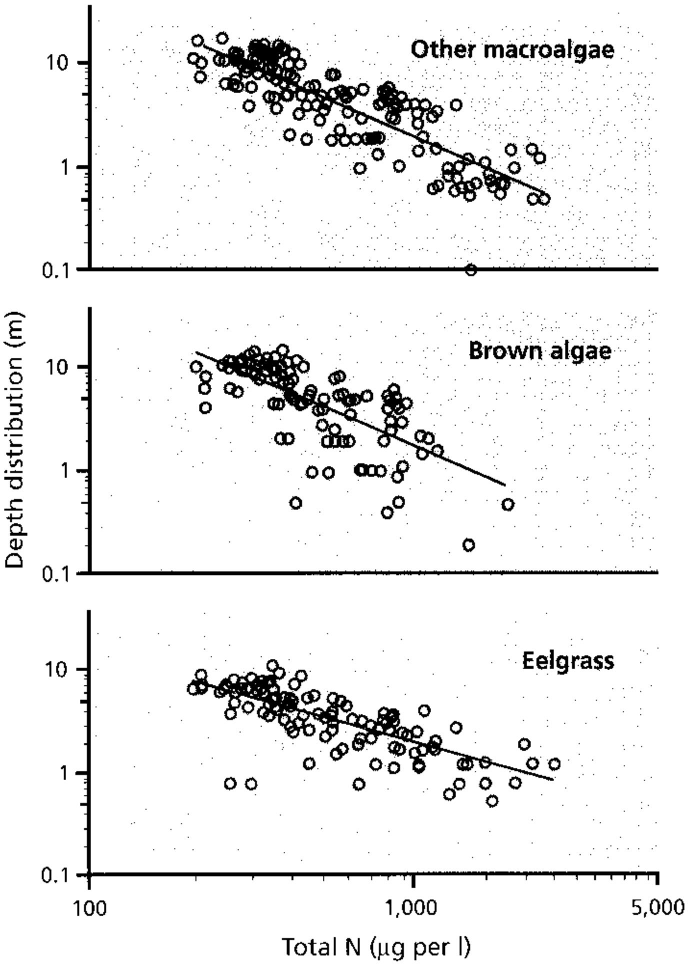


Figure 5.7

Relationship between the concentration of nitrogen and the depth distribution of eelgrass, perennial brown algae and other macroalgae. The data derive from numerous different Danish coastal waters and were collected at the beginning of the Nationwide Monitoring Programme.

The calculated average relationships provide a manageable measure of how the occurrence of benthic vegetation changes with changes in the nutrient content of the water. Due to local differences in exposure, the amount of suitable bottom substrate and regulation of the amount of phytoplankton, the data vary considerably around the slopes shown. Thus for any given area, precise assessment and prediction of the development in the depth distribution of the benthic vegetation in response to changed nutrient loading is subject to some uncertainty. The relationships are nevertheless well-suited as a management tool, especially because studies undertaken at the turn of the century (e.g. Petersen, 1893; Ostenfeldt, 1908; Rosenvinge, 1909) have provided us with good background data on the depth distribution of the benthic vegetation in a number of inner Danish marine waters. The former depth distribution is a good measure of nutrient conditions in the various marine waters before nutrient loading of the sea really started to accelerate. The relationships shown also indicate what nutrient levels we should aim at when reducing loading in order to achieve a desired condition with respect to the amount of phytoplankton and the distribution of benthic vegetation.

If the target stipulated in the Action Plan on the Aquatic Environment of a 50% reduction in nitrogen loading from agriculture, sewage works and individual industrial outfalls is fulfilled, this will typically reduce the nitrogen concentration by 40% in highly eutrophic, enclosed estuarine fjords, and by 20% in less eutrophic areas (Table 5.1). The amount of phytoplankton will fall correspondingly, and the depth distribution of the benthic vegetation will increase markedly. In certain areas, the effect on the areal distribution of the benthic vegetation will be far greater than the effect on the depth distribution because even small improvements in the plants' depth distribution will enable colonization of the whole of the sea floor in some shallow fjords. On the other hand, though, the example also indicates that the 50% reduction target for nitrogen loading stipulated in the Action Plan on the Aquatic Environment will not be sufficient to ensure restoration of a satisfactory environmental state in the worst affected areas.

5.4.3 Significance for the ecosystem

The benthic vegetation of coastal waters has a large biomass and areal production, and consequently affects the turnover and exchange of oxygen, organic matter and nutrients. The standing biomass of plants binds nutrients during the growth season, and thereby reduces nutrient availability for the phytoplankton. The location of the vegetation in the transitional zone between the water column and the sea floor, where nutrients are released through degradation of the organic matter, means that the plants can serve as a filter able to take up the nutrients before they reach the water column (HAV90, Reports 22 and 43).

Even in nutrient-poor areas, the benthic vegetation's areal production can far exceed phytoplankton production in severely affected areas. It is generally thought that the total primary production increases with increasing nutrient loading, and it has also been stated that eutrophication should therefore have a beneficial effect on the production of benthic invertebrates and fish. However, enhanced eutrophication of the coastal waters reduces the very productive communities of eelgrass and large brown algae, and hence the total production of organic carbon does not change very

Table 5.1

Examples of changes in phytoplankton biomass and benthic vegetation depth distribution following a reduction in the nitrogen concentration of coastal waters (as a result of the implementation of interventional measures to reduce nitrogen loading stipulated in the Action Plan on the Aquatic Environment). Calculated using empirical relationships formulated on the basis of monitoring data.

	Highly eutrophic areas			Weakly eutrophic areas		
	Before	After	Change (%)	Before	After	Change (%)
Total nitrogen (µg l^{-1})	1500.0	900.0	40%	400.0	320.0	20%
Phytoplankton biomass (µg chlorophyll *a* l^{-1})	17.8	10.3	42%	4.3	3.4	21%
Eelgrass depth distribution (m)	1.7	2.5	+47%	4.6	5.4	+17%
Brown algae depth distribution (m)	1.0	2.0	+100%	5.8	7.8	+34%

significantly, even though the production of phytoplankton and annual macroalgae increases (HAV90, Report 41). Eutrophication of the shallow coastal waters thus mainly results in changes in the quality of the organic matter produced, and not in the amount (Borum, 1996).

One can therefore say that enhanced nutrient loading of coastal waters causes production to shift from "beneficial" production of eelgrass and other rooted macrophytes that have a positive effect on environmental conditions, to "harmful" production of filamentous algae, epiphytes and phytoplankton that have a negative effect on environmental conditions. Among other things, the qualitative changes in coastal water production affects oxygen conditions, and oxygen deficit with resultant death of benthic invertebrates and fish can therefore often occur in even the shallow parts of our estuarine fjords (see Section 5.7.1). The shift from primary production based on slowly degradable perennial plants to one based on phytoplankton and rapidly metabolized annual macroalgae probably results in more fluctuating oxygen consumption in the water and sediment and greater temporal and spatial separation between oxygen production (through primary production) and oxygen consumption (through degradation). The enhanced number of phytoplankton, which are a better food resource for many benthic invertebrates than are the macrophytes, undoubtedly provides them with more food, but the marked fluctuations in oxygen conditions cause great mortality among the benthic invertebrates. It is therefore rather doubtful whether enhanced nutrient loading of shallow coastal waters leads to increased production of benthic invertebrates and fish.

5.5 Benthic invertebrates and fish

Input of organic matter from the photic surface layers comprises the food resource for the benthic invertebrates inhabiting the deeper water depths. The benthic faunal communities are generally considered to be food-limited and enhanced input of organic matter to the nutrient-rich deeper marine waters can be expected to lead to greater production at the sea floor. In areas where primary production is naturally high, e.g. at the Skagerrak front (HAV90, Report 49) both individual growth and benthic invertebrate community biomass are markedly higher than outside the front area (Josefson and Jensen, 1992a). It has previously been shown from studies in the Øresund that the growth of benthic invertebrates that feed off organic matter on the sediment surface (deposit feeders) is fully coupled to sedimentation of intact phytoplankton in the spring, while the growth of filter-feeding benthic invertebrates is maximal in the autumn (Christensen and Kanneworff, 1985). It would thus appear that the growth of deposit feeders is dependent on the nutritional quality of the organic matter input to the sea floor rather than the total amount of matter deposited.

The close relationship between the magnitude of production in the water column and benthic invertebrate growth and biomass has been shown both in the Baltic Sea and the North Sea, as well as in the Dutch part of the Wadden Sea. In recent decades, benthic invertebrate biomass in these areas has increased in step with increasing phytoplankton production caused by eutrophication (Beukema, 1991; Josefson et al., 1993). The studies thus indirectly document that a certain part of the enhanced primary production is channelized to the benthic invertebrates. It should be emphasized, though, that a positive relationship between nutrient input (primary production) and benthic invertebrate biomass has only been demonstrated in non-stratified marine waters or at places above the primary pycnocline (see Section 5.2.1).

Enhanced nutrient loading of strongly stratified marine waters such as the southern Kattegat has led to more frequent episodes of oxygen deficit that have had a very negative effect on the

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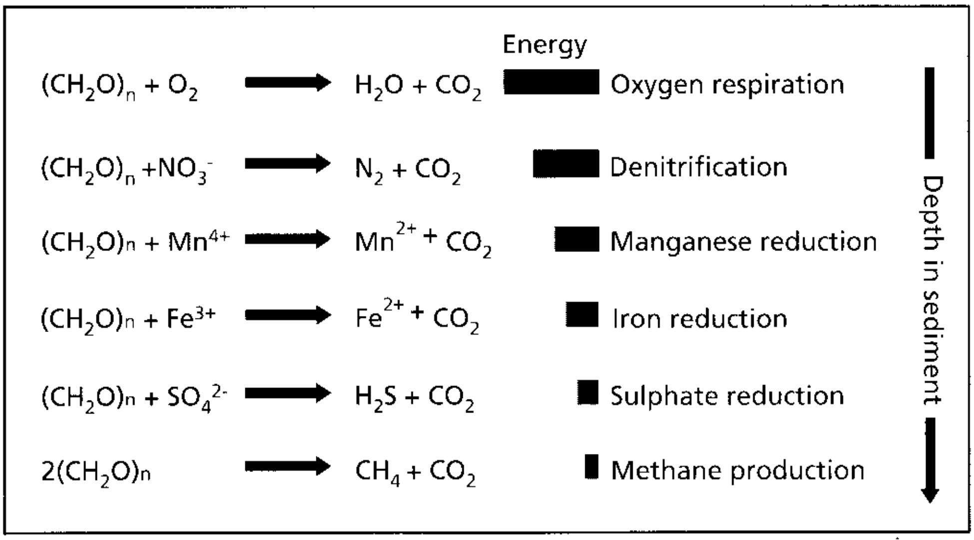
benthic invertebrate communities. Long periods of low oxygen concentrations in the bottom water can lead to mass mortality among benthic invertebrates. Most often, a low oxygen concentration will lead to the elimination of the most sensitive species of benthic invertebrates. In more rare cases, all the benthic invertebrates can be eradicated. Following severe episodes of oxygen deficit in the southern Kattegat and the western Baltic Sea (e.g. in 1981 and 1988; HAV90, Report 1), major changes were detected in the benthic fauna, with general reductions in the number of species and biomass as well as a shift towards smaller individuals (Josefson and Jensen, 1992b). The impact on the benthic fauna was greatest at the monitoring stations situated immediately under the pycnocline, where the oxygen pool in the bottom water was least and the oxygen deficit greatest.

Re-establishment of a varied benthic invertebrate community following episodes of severe oxygen deficit can take several years due to the long generation times of the different invertebrates. With repeated severe or mild episodes of oxygen deficit such as observed in the southern Kattegat through the 1980s, the benthic fauna will not be able to re-establish "equilibrium", but will continuously remain in a re-establishment phase characterized by young individuals and small species.

During the last 100 years, the Kattegat has supported extensive fishery of benthic fish such as cod and plaice. Since the beginning of the 1980s, however, this fishery has declined markedly, while the catch of dab has increased in the southern Kattegat. This trend is purportedly explained by changes in nursery areas for plaice, e.g. the occurrence of filamentous algae in shallow waters, stress as a result of the regular occurrence of oxygen deficit in the bottom water and changes in the food resource, all of which are the result of enhanced eutrophication. The preferred food of plaice is small mussels and crustaceans, while the dab mainly feeds on brittle-stars. A shift in the composition of the benthic fauna towards dominance by brittle-stars, such as has occurred over the last century, thus seems to be qualitatively in agreement with the change in the fish populations. However, a quantitative analysis of the composition of the benthic fauna and the possible food resource for benthic fish provided no proof that the flat fish are food-limited in the southern Kattegat (HAV90, Report 27).

5.6 Mineral cycling in the sediment

Organic matter input from the surface layer constitutes the food resource for the benthic food chains. It is therefore



Figur 5.8

Mineralization of organic matter in the sediment. The energy yield of the individual respiratory processes and the depth to which the various oxidants penetrate into the sediment determine the distribution of the processes in the sediment.

the amount and quality of this input that determines production and turnover at the sea floor. The organic matter that sinks down from the surface layer and the pycnocline is degraded (mineralized) in the bottom water or in the sediment. The nutrients thereby released are returned to the surface layer after a shorter or longer delay depending on the strength and duration of stratification. Once back in the surface layer, the nutrients can generate new primary production. Degradation of the organic matter ultimately involves the consumption of oxygen, no matter whether degradation takes place in the microbial food chains in the water or through benthic invertebrates and bacteria in the sediment.

5.6.1 Degradation of organic matter in the sediment

The benthic invertebrates metabolize some of the sedimented organic matter while degradation of the remainder takes place through countless microbial processes. Solid structures and organic macromolecules (structural carbohydrates, lipids, proteins, etc.) are degraded by hydrolytic enzymes secreted by bacteria, whereafter the smaller molecules can be taken up by the bacteria via their cell membrane.

Microbial respiration processes take place with the use of various oxidants. In coastal sediments, oxygen is transported only a few millimetres down into the sediment from the water column, and respiration based on oxygen therefore only takes place in the thin upper zone. As a result, over half of the organic matter input to the sediment is degraded deeper down in the sediment where oxygen is absent. Respiration processes that take place without the use of oxygen (anaerobic respiration processes) thereby become of great quantitative and qualitative significance for mineralization in the marine sediment.

The energy yield that the bacteria obtain from oxidizing the organic matter depends on the oxidant used. Thus respiration with oxygen gives the greatest yield, followed by respiration with nitrate, oxidized manganese, oxidized iron and finally, sulphate. The best oxidant will always be used up first, and this determines the depth distribution of the various respiratory processes.

The distribution of the processes is therefore generally vertical, as illustrated in Figure 5.8. Denitrification starts at depths where oxygen can no longer penetrate, followed by manganese reduction, iron reduction and sulphate reduction. At depths below the penetration depth of sulphate, degradation results in the production of methane. Methane production does not require an external oxidant as half of the organic carbon is oxidized to carbon dioxide at the cost of the other half, which is reduced to methane (fermentation).

The different respiratory processes can sometimes overlap in the sediment, an example being that significant sulphate reduction often takes place in the iron reduction zone. Similarly, the presence of bioturbating animals (i.e. animals that burrow in the sediment) can result in a more complex distribution of the processes.

Even though the oxidation of organic matter with oxygen yields the most energy and is the most well-known oxidation process (aerobic respiration), its quantitative significance for carbon turnover in marine sediments is unclear as it can be difficult to obtain reliable measurements of oxygen consumption by sediment. As was demonstrated under the HAV90 programme, oxygen uptake by the sediment depends on conditions such as the water current immediately above the sediment surface, the oxygen concentration of the bottom water, the surface area (the sediment's topography), and the number of bioturbating animals (HAV90, Report 57). Oxygen uptake by the sediment is therefore directly proportional to the surface area, and field measurements have shown that oxygen consumption measured in the field can be significantly higher than that measured in the laboratory. Aerobic respiration is estimated to account for 40-60% of annual total carbon turnover in marine sediments (HAV90, Reports 15 and 57).

Denitrification takes place in a very thin layer (a few millimetres thick) immediately below the oxidized surface layer (HAV90, Report 50). In marine waters, the process is of only limited importance for the oxidation of organic matter, only approx. 2% of total carbon mineralization taking place through denitrification in marine sediments (HAV90, Reports 16 and 59). On the other hand, though, the denitrification process is important for the nitrogen balance in marine systems as the process permanently removes nitrogen through the reduction of nitrate available for primary production to free nitrogen gas, which is released to the atmosphere (see Section 4.2.2).

The respiratory processes based on the reduction of manganese and iron are also generally of minor quantitative significance for carbon mineralization in coastal waters since a large part of the oxidized iron and manganese present here is reduced by reaction with hydrogen sulphide (see Section 5.7.2), and only a minor part is used for oxidation of carbon (HAV90, Reports 15 and 59).

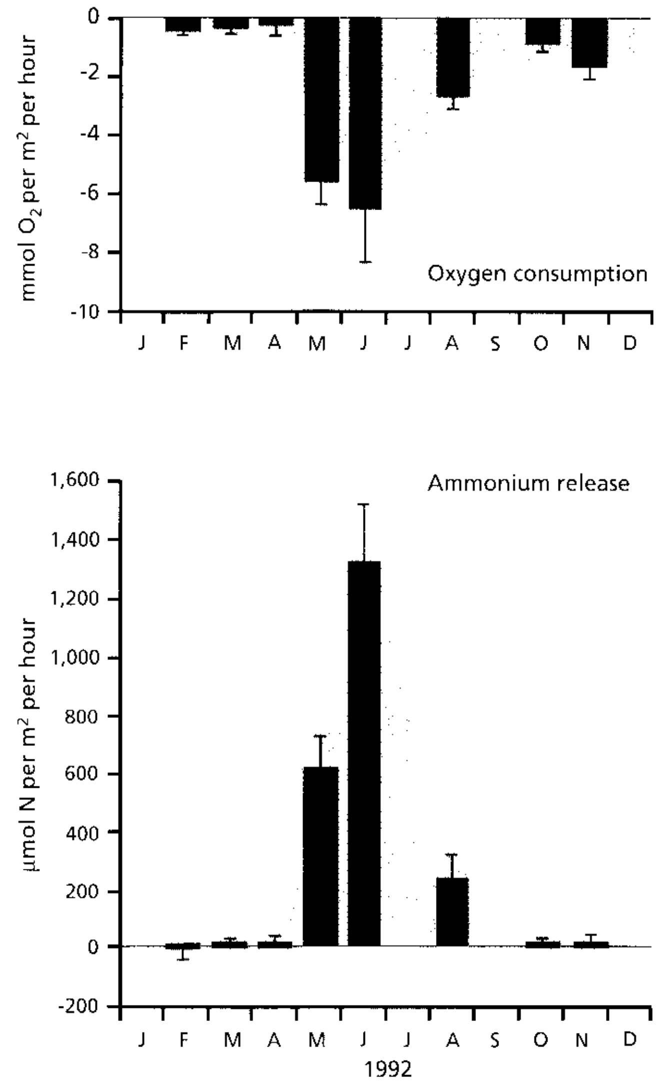
Energy yield is least with the anaerobic respiration process, sulphate reduction, yet the process is often the quantitatively most important in that 40-90% of the organic matter in marine sediments is oxidized by sulphate reduction. This is due to the very high sulphate concentration in the sea water, which is typically 150 times greater than the oxygen concentration. In Århus Bight, HAV90 studies showed that just under half of the annual carbon mineralization takes place through sulphate reduction (HAV90, Report 15). The process is particularly important from July to November, when oxygen penetration into the sediment is lowest (HAV90, Report 57) and when more than 75% of the total annual sulphate reduction takes place (HAV90, Report 15).

The zone where methane production takes place always lies under the sulphate-containing zone. In localities where turnover is high (high sedimentation of organic matter), methane production lies relatively close to the sediment surface, and in such cases methane bubbles form in the sediment. The zone with methane bubbles can be identified with seismic measuring equipment, and areas with high sedimentation and turnover are thus fairly easily registered (see Section 6.10).

5.6.2 Nutrient release from the sediment

Following mineralization, the nutrients in the sedimented organic matter can be released again from the sediment or permanently stored in the sediment, and hence removed from the nutrient cycle. After mineralization of the organic matter, the nitrogen-containing nutrients are released relatively rapidly from the sediment while the release of inorganic phosphorus (phosphate) can be delayed by up to several months.

As the sediment's ability to retain inorganic nitrogen is poor (see Section 4.2.1), the release of ammonium from sediments is closely coupled to mineralization of organic matter, which takes place throughout the whole growth season (HAV90, Reports 16 and 43). Ammonium release from the sediment is further enhanced when the oxygen content of the bottom water falls since oxidation of ammonium (nitrification) in the upper oxic sediment layers is suppressed (HAV90, Report 16). Ammonium release from the sediment is therefore often greatest during the summer and the late summer (Figure 5.9; HAV90, Report 43). The HAV90 programme has also shown that urea can be released from the sediments in quantitatively significant amounts. Urea is an organic nitrogen compound that can be directly utilized by the primary producers. The studies showed that the release of urea from the sediment in Århus Bight in 1990 was greater than ammonium release in the early spring, and on an annual basis was of the same order of magnitude as the total release of inorganic nitrogen (HAV90, Report 16). In the shallow and more eutrophic Kertinge Nor, however, urea release only amounted to approx. 10% of the total nitrogen release from the sediment (HAV90, Report 43). In Kertinge Nor, ammonium release from the sediment was approx. 10 times higher than ammonium release from the sediment in Århus Bight.

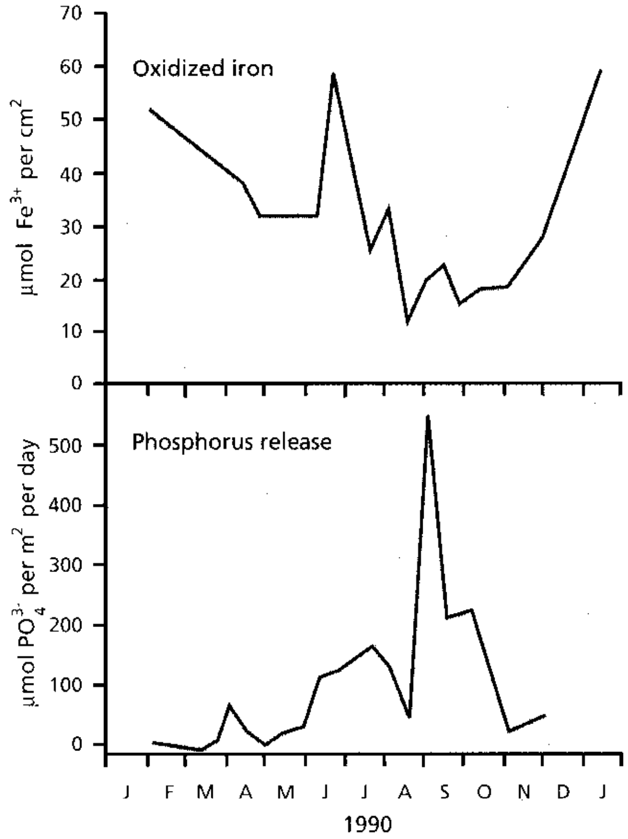


Figur 5.9

Seasonal variation in oxygen consumption and ammonium release from the sediment in Kertinge Nor. The release of ammonium is greatest in the summer, at which time the total mineralization of organic matter in the sediment is also greatest (from HAV90, Report 43).

Nitrogen can also be taken up by the sediment and the nitrogen flux, i.e. the exchange of nitrogen between the sediment and the water column is the net result of a number of complicated sediment processes involving nitrogen in one form or another (mineralization, assimilation, nitrification, denitrification). As primary production is nitrogen-limited in most marine waters (see Section 2.2.1), it is important to be able to determine the extent of any nitrogen release from the sediment as this nitrogen is immediately available for new primary production. In Århus Bight, the total nitrogen transport from the sediment to the water column comprised approx. 30% of the phytoplankton's annual nitrogen requirement (HAV90, Report 16). Other studies have shown that mineralization of nitrogen in sediment can contribute up to 80% of the primary producers' nitrogen requirement in areas with water depths between 5 and 50 metres. In Kertinge Nor, the release of inorganic nitrogen from the sediment accounted for approx. 80% of the total annual nitrogen load to the estuary in 1992 (HAV 90, Report 43). The examples show that it can be extremely important to take this "internal nitrogen loading" into account when evaluating the input of nutrients to primary production in marine waters.

During degradation, phosphorus bound to fresh organic matter (plant material) is released into the sediment where it can bind in many different ways. A large part is bound in non-metabolizable organic matter and as calcium phosphate, to which it remains bound, thereby becoming permanently buried in the sediment. Phosphorus also binds effectively to oxidized ferric iron (Fe^{3+}), and the iron-bound phosphorus pool is particularly interesting as phosphorus bound to oxidized iron is released again when the iron is reduced to ferrous iron (Fe^{2+}) (HAV90, Reports 17 and 43).



Figur 5.10

Relationship between the flux of phosphorus through the sediment surface and the sediment pool of oxidized iron (redrawn from HAV90, Reports 15 and 17).

The presence of the iron buffer in the sediment means that phosphorus release from the sediment becomes uncoupled from carbon mineralization in the sediment.

The sediment pool of oxidized iron varies considerably throughout the year. Typically, though, the oxidized iron is primarily reduced during the summer in reaction with hydrogen sulphide and as a consequence, the pool slowly diminishes during the summer (see Section 5.7.2). Phosphorus is therefore primarily released in the late summer and autumn, when the oxidized iron pool is lowest (Figure 5.10). Phosphorus release at this time of the year does not have any immediate effect on phytoplankton production as the latter is already limited by the availability of nitrogen and light. In more shallow water systems dominated by macroalgae and eelgrass, the pool of organically bound phosphorus can be greater than the pool of iron-bound phosphorus. In such cases, the above mentioned iron buffer is of less significance, and phosphorus is released evenly throughout the growth season in step with mineralization of the organic matter (HAV90, Report 43).

Phosphorus is mainly released as inorganic phosphate, which is directly utilizable as a nutrient for primary production. In Århus Bight, phosphate comprised 96% of the total annual phosphorus flux from the sediment in 1990, while the remaining 4% was dissolved organic phosphorus (HAV90, Report 17). The phosphate released from the sediment corresponded to 15-20% of the annual phosphorus uptake by the phytoplankton in Århus Bight (HAV90, Report 59). Phosphorus release from the shallow Kertinge Nor is extremely important, as evidenced by the fact that 70% of the total annual phosphorus load to the estuary in 1992 derived from internal release from the sediment (HAV90, Report 43).

5.7 Oxygen deficit

The oxygen content of the water is determined by the relationship between the input and consumption of oxygen. Oxygen is input to the water through exchange with the atmosphere and through photosynthesis by phytoplankton in the water column or plants on the sea floor. The input of oxygen to the part of the water column below the photic zone takes place solely through mixing with the surface layers or through horizontal water exchange. The consumption of oxygen takes place as respiration in the water column and in the sediment and through exchange with the atmosphere in cases where the water is oxygen-saturated.

Oxygen deficit

Oxygen deficit describes the situation when the oxygen content of the water (often the bottom water) falls to critically low levels. Environmental engineers traditionally operate with fixed limits for the oxygen concentration of 4 and 2 mg O_2 per litre. When the oxygen content falls below 4 mg O_2 per litre, many fish and benthic invertebrates are severely affected, and will attempt to flee. At concentrations under 2 mg O_2 per litre, long-term exposure will lead to the death of most animals unable to escape. A few species of benthic invertebrates can survive total oxygen deficit for short periods, however. In the worst cases, the anoxic conditions in the bottom water can lead to the release of hydrogen sulphide from the sediment, thereby causing extensive fish mortality.

5.7.1 Variation and areal distribution of oxygen deficit

One of the main effects of enhanced nitrogen loading of the inner Danish marine waters has been deterioration in oxygen conditions. Although oxygen deficit has always been a problem in the bottom water of stratified marine waters such as those in Denmark (Christiansen et al., 1993), the episodes have become more frequent since 1980 and the areas affected have become increasingly large.

The small water volume of shallow fjords and coastal waters results in large fluctuations in oxygen content. When primary production is high, oxygen oversaturation can occur in the water column during the daytime, while high respiration at night can lead to critically low oxygen concentrations in the water (HAV90, Report 51). A high benthic production may further result in heterogenous distribution of oxygen in the water column during light and dark periods (HAV90, Report 43). Periodic accumulation of organic matter on the sea floor and the presence of large organic matter pools such as those bound in eelgrass, macroalgae, benthic invertebrates, etc. render the estuarine fjords vulnerable to “abnormal” meteorological conditions, and episodes of oxygen deficit can occur within the space of a few hours (HAV90, Report 44). This often results in mass mortality of benthic organisms. Moreover, since recolonization only takes place very slowly in closed estuarine fjords, the effect of such episodes of oxygen deficit on the biological structure can last for several years. In areas with deeper water, there is less daily variation in oxygen concentration, and reduction in the oxygen content of the water is more gradual (HAV90, Report 1).

Stratification of the water column leads to regular episodes of oxygen deficit in the bottom water of the Kattegat. Moreover, oxygen deficit has even been seen in the North Sea, where there is only weak stratification in the summer.

More long-lasting stratification of the water column in the summer inhibits oxygen input to the bottom water. Thus for much of the year, oxygen is used from a limited and isolated oxygen pool in the bottom water. This can result in anoxic conditions at the sea floor in the late summer since the reduced oxygen input does not meet the oxygen demands of the benthic fauna and the microbial degraders.

Under the HAV90 programme a dynamic model has been established to describe the hydrological conditions in the inner Danish marine waters as well as the coupling between nitrogen and oxygen conditions (HAV90, Report 29). The model enables assessment of changes in oxygen conditions in the inner Danish marine waters in response to reductions in nitrogen loading.

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The model is used to describe various scenarios caused by various interventional measures. The first analysis is designated "1993", and the basis for this is full implementation of the interventional measures stipulated in the Action Plan on the Aquatic Environment with respect to nitrogen - interpreted here as a 50% reduction in nitrogen loading.

The designation "1996" refers to modelling based on implementation of both the Action Plan on the Aquatic Environment and a 50% reduction in nitrogen loading from the countries around the Baltic Sea and the North Sea (cf. the decisions of the Helsinki Commission and the 3rd North Sea Conference).

Finally, the designation "2000" refers to modelling based on implementation of the above mentioned measures as well as implementation of the Danish Action Plan for Sustainable Agricultural Development and an international 30% reduction in atmospheric emissions of nitrogen oxides.

Table 5.2

Minimum oxygen concentration measured in the bottom water of the inner Danish marine waters in 1993 together with the theoretical minimum concentration derived from the model calculations "1993", "1996" and "2000" (Anne Marie Rolev (personal communication), and HAV90, Report 29).

Marine area	1993	"1993"	"1996"	"2000"
	mg O_2 per l	Calculated theoretical mg O_2 per l		
Kattegat E	3.3	4.9	5.1	5.2
Kattegat SW	4.0	4.2	4.5	4.8
Øresund	3.2	2.7	3.8	4.1
Great Belt	3.6	3.9	4.1	4.4
Femer Belt	0.4	1.8	3.0	3.3

The analyses are performed on the basis of a hydrodynamic reference year, which covers the typical variation in the hydrodynamic conditions through the year. In addition, the mean loading during the 1980s is used as the reference level for the reductions in nutrient inputs. The results are only applicable for so-called normal years (i.e. a typical year with respect to precipitation, runoff, wind and water exchange).

The model calculates that full implementation of the Action Plan on the Aquatic Environment (the "1993" scenario) will increase the minimum oxygen concentration in the bottom water in autumn by around 0.6 mg O_2 per litre in relation to the period 1975-91. In normal years, the minimum oxygen concentrations will still be under 2 mg O_2 per litre in the Femer Belt and the Little Belt. According to the models, in a normal year oxygen concentrations exceeding 4 mg O_2 per litre will only be seen in the southern Kattegat and further north. The interventional measures in the "1996" scenario increase the average minimum concentration further (by 0.2 mg O_2 per litre in the Great Belt and the Kattegat, and 1.2 mg O_2 per litre in the Femer Belt, Table 5.2). With these measures, the oxygen concentration will no longer fall below 2 mg O_2 per litre in the Femer Belt in a normal year. However, the Little Belt will still be affected by severe oxygen deficit, and the Øresund and the Femer Belt will still experience oxygen concentrations lower than 4 mg O_2 per litre.

With the interventional measures in the "2000" scenario, only the Little Belt and the Femer Belt will still experience oxygen concentrations lower than 4 mg O_2 per litre. In the remaining parts of the Danish marine waters, the minimum oxygen concentration in a normal year will typically exceed 4 mg O_2 per litre.

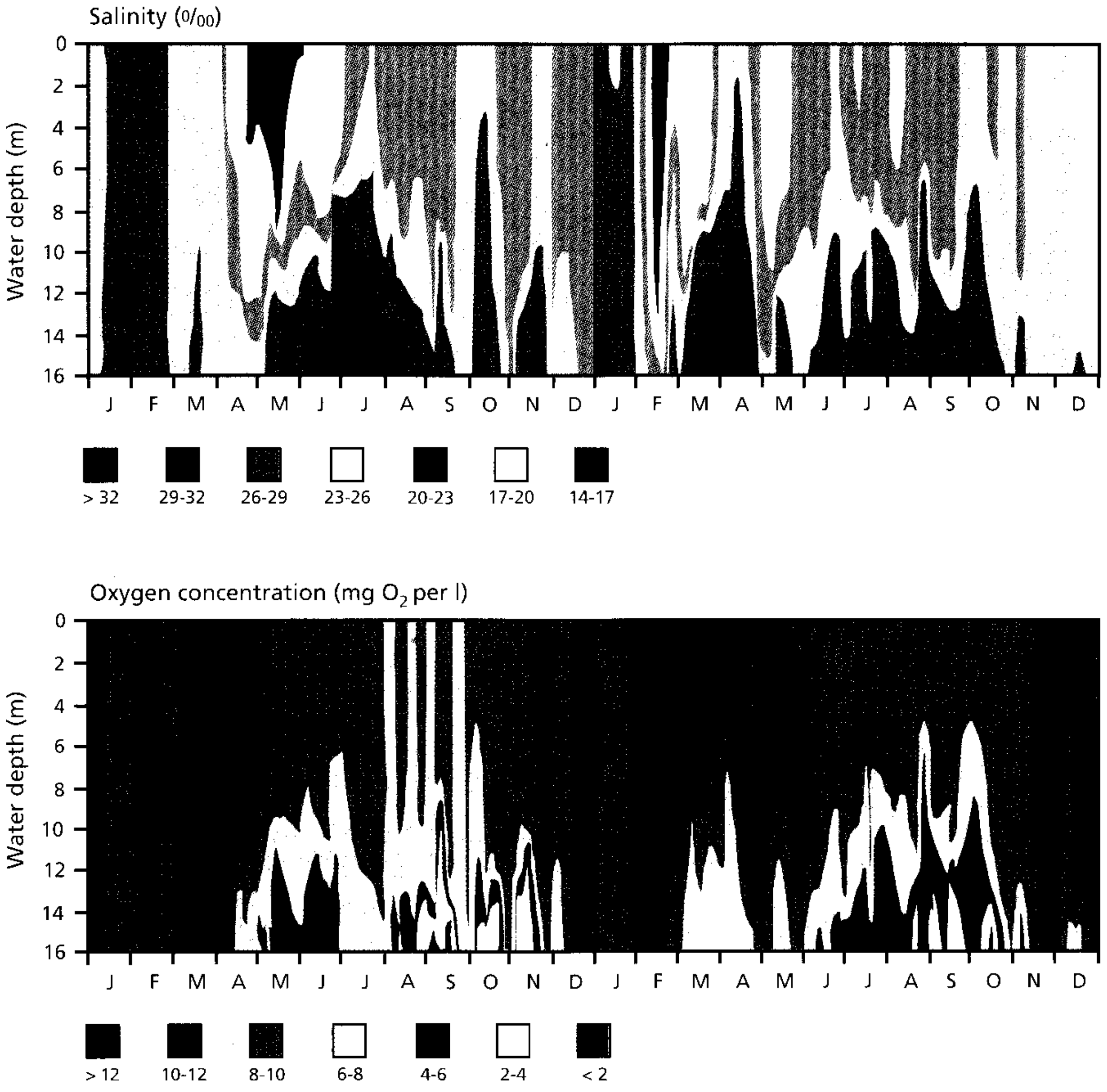


Figure 5.11

Weekly measurements of salinity and oxygen concentration in Århus Bight from January 1990 to January 1992 (from HAV90, Report 59, based on data from Århus County).

The minimum concentrations of oxygen actually measured in 1993 at the stations shown in Table 5.2 as part of the Nationwide Monitoring Programme were considerably lower than the calculated concentrations for the "1993" scenario, which underlines the fact that the assumptions made in the calculations (i.e. full implementation of the Action Plan on the Aquatic Environment) have not been fulfilled, and that the calculations are based on a typical normal year.

A real overview over oxygen conditions and the number of episodes of oxygen deficit can only be obtained by frequent measurement of the oxygen concentration in the bottom water. Thus it is important to be aware that transport of hypoxic bottom water from greater depths can lead to an acute, severe lowering of the oxygen content of the bottom water at coastal stations (HAV90, Report 4; Skyum et al., 1994). When the wind is westerly, the pycnocline in the Kattegat might rise in the western side of the Kattegat (see Section 4.4.1), whereby oxygen-poor water can be "imported" to the estuarine fjords on the eastern side of Jutland. Thus a fall in oxygen content of 6-7 mg O_2 per litre has been measured over the course of a single day in Vejle Fjord (HAV90, Report 4). This cannot be explained by enhanced local consumption, but only by the import of hypoxic water.

Similarly, weekly measurements in Århus Bight revealed one severe episode of oxygen deficit and several less severe episodes during the course of the summer. The episodes were caused by inflowing bottom water with high salinity and a low oxygen content (Figure 5.11). The data collected show that the episodes of oxygen deficit would probably not have been recorded if the measurements - as is often the case - had only been collected once a month.

One could be tempted to say that the number of episodes of oxygen deficit in the Danish marine waters depends on how frequently measurements are made. Such a conclusion is further strengthened by the fact that continuous measurements undertaken with remote sensing equipment at the bottom of Århus Bight during the above mentioned period revealed the occurrence of episodes of oxygen deficit of even shorter duration than those recorded by the weekly measurements (HAV90, Reports 23 and 38).

5.7.2 Sediment oxygen consumption and its effect on oxygen deficit

As the water column in coastal waters is usually stratified near the bottom, it is primarily oxygen consumption by the sediment that exhausts the bottom water oxygen pool. In Århus Bight, sediment oxygen consumption accounts for just under 90% of oxygen consumption in the bottom water. As a rule of thumb, one can say that oxygen consumption in the lower part of a stratified water column only exceeds the sediment oxygen consumption if the bottom water is five or more metres thick (HAV90, Report 57). Due to oxygen uptake by the sediment, the oxygen concentration in the few centimetres of water immediately above the sediment can be considerably lower than in the water ½-1 metre above the sediment, at which depth water samples are usually collected for routine monitoring such as under the Nationwide Monitoring Programme. This was clearly apparent from comparison of measurements of oxygen content made a few centimetres above the sediment in Århus Bight and those of the bottom water collected in the normal manner (HAV90, Reports 23 and 57). It is therefore important to also measure the oxygen concentration near the bottom if one is to obtain a real impression of the degree and extent of oxygen deficit. The available results thus indicate that the episodes of oxygen deficit hitherto recorded have actually been more widespread than believed.

The sediment's oxidation capacity

The sediment's oxidation capacity represents its capacity to retain reduced compounds (especially hydrogen sulphide) whose direct oxidation would otherwise require immediate consumption of oxygen. In this way, actual oxygen consumption is defrayed from the spring and summer to a later time during the year. The sediment's oxidation capacity or its buffering capacity towards hydrogen sulphide is closely coupled to the sediment pool of iron, which can oxidize and bind hydrogen sulphide.

Oxygen consumption by the sediment mainly results from the degradation of sedimented organic matter. However, only approximately half of the oxygen consumed by the sediment (HAV90, Report 57) is used for direct oxidation of organic matter (aerobic respiration, see Section 5.6.1), the remainder being used for the oxidation of the reduced compounds formed during anaerobic respiration (manganese reduction, iron reduction and sulphate reduction; see Section 5.6.1). Since sulphate reduction is the dominant form of anaerobic respiration in marine sediments (accounting for up to 95% of the anaerobic respiration in coastal waters; HAV90, Report 15), a considerable part of the oxygen consumed by the sediment is used to oxidize hydrogen sulphide. Actual oxygen consumption by the sediment can be reduced or delayed in relation to the actual amount of organic matter being degraded as the sediment is able to retain and accumulate large pools of

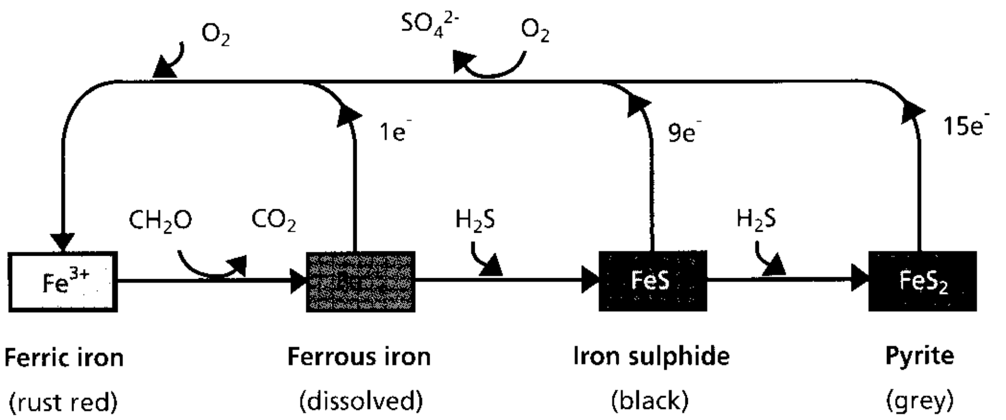


Figure 5.12

Schematic diagram of the oxidation and reduction of iron in sediment. Under anaerobic conditions, oxidized ferric iron is reduced with organic matter or sulphide. The reduced ferrous iron can bind hydrogen sulphide and form iron sulphide followed by pyrite. When oxygen becomes available, the reduced iron compounds are reoxidized to oxidized ferric iron and sulphate. The status of the iron in the sediment can be determined visually since ferric iron forms rust-red iron hydroxides, while iron sulphide is black and pyrite is grey (from Limfjord Committee, 1990).

reduced, oxygen-consuming substances, in particular hydrogen sulphide (H_2S), which precipitates out with iron as iron sulphides. This characteristic of the sediment is termed its oxidation capacity, or its hydrogen sulphide buffer capacity.

In the upper part of the sediment, iron is normally present in the oxidized ferric form. The extent of this zone can be identified as reddish-brown discolouration caused by ferric iron. Iron is oxidized in the uppermost few millimetres of the sediment where oxygen is present. This zone is termed the oxic zone. Under the oxic zone, where oxygen is absent, iron and manganese exist in the oxidized form. This part of the sediment is called the suboxic zone. It is in this zone that organic material can be oxidized with iron (see Section 5.6.1) leading to the formation of reduced ferrous iron (Figure 5.12). Sulphate reduction takes place in and especially under the suboxic zone, and the hydrogen sulphide produced can react directly with oxidized iron and dissolved ferrous iron leading to the formation of iron sulphide (FeS). The zone containing iron sulphide is also easy to identify as the iron sulphide colours the sediment black. With increasing depth in the sediment, the iron sulphide is consumed through further binding of hydrogen sulphide leading to the formation of pyrite (FeS_2), which colours the sediment grey (Figure 5.12).

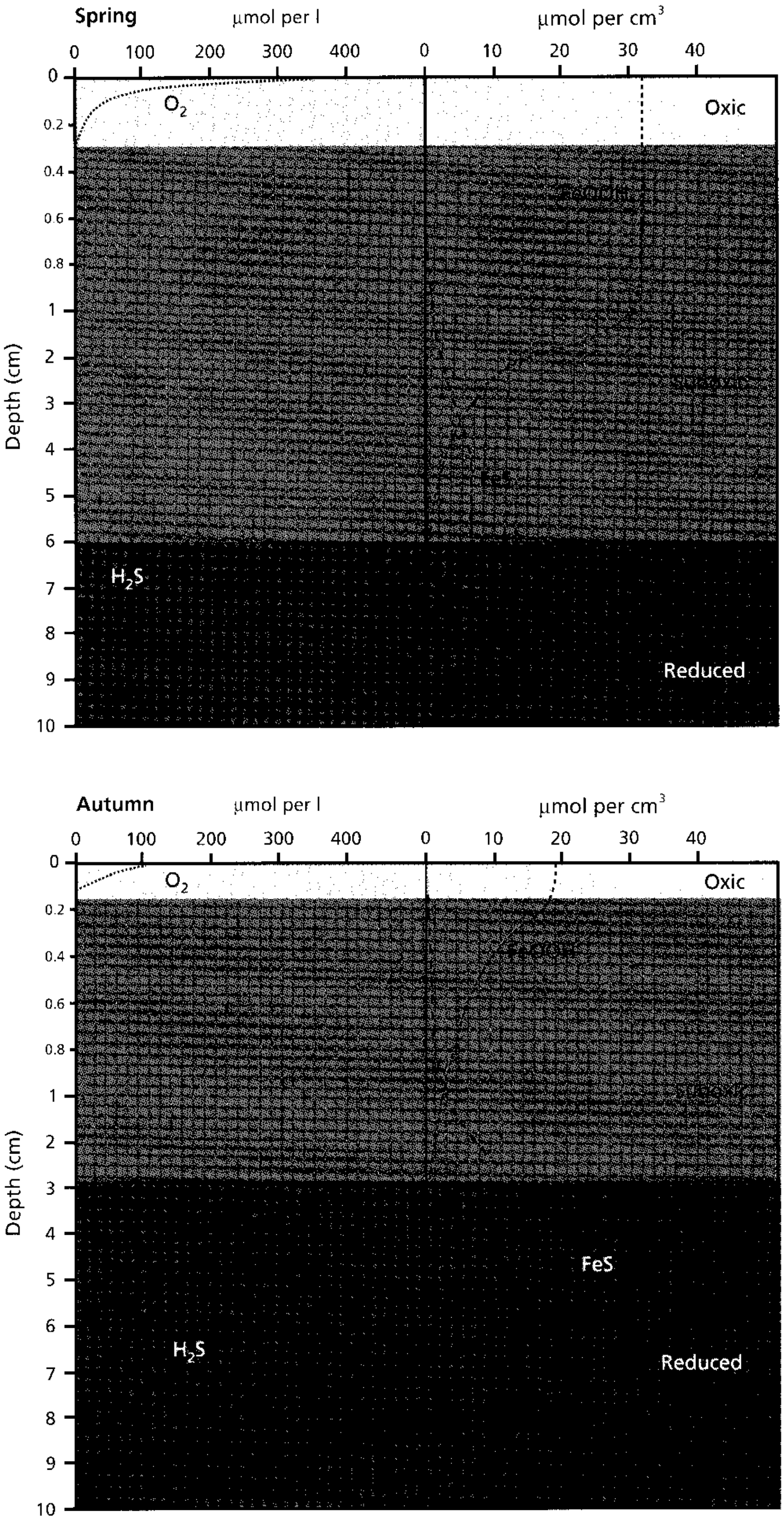
Hydrogen sulphide production from sulphate reduction is greatest in the summer, when the total mineralization of organic matter is greatest. However, due to the pool of the active iron in the sediment which binds hydrogen sulphide, the high sulphate reduction activity does not have an immediate direct effect on oxygen consumption in the summer. The sediment pool of active iron can be so great that the amount of hydrogen sulphide bound as iron sulphide can correspond to several months' oxygen consumption (HAV90, Report 15).

The sediment's oxidation capacity decreases and becomes used up during the course of the summer through binding of hydrogen sulphide to the iron, thereby allowing the reduced zone containing free hydrogen sulphide to penetrate higher up towards the sediment surface (Figure 5.13). When the sediment's oxidation capacity is nearly used up in the late summer, oxygen uptake by the sediment increases markedly. If mixing or renewal of the bottom water fails to take place for an extended period of time under these circumstances - for example due to stable pycnocline formation and still water - the oxygen concentration in the bottom water will fall, and actual oxygen deficit can occur.

In popular terms, one can refer to this as the sediment's "iron cap", which is closed as long as a layer of oxidized iron exists above the hydrogen sulphide front. When the pool of oxidized iron has been used up, the "iron cap" can open. A resultant escape of hydrogen sulphide from the sediment will cause extensive oxygen deficit since the hydrogen sulphide will be rapidly oxidized in the water column with considerable

Figur 5.13

Depth distribution of oxygen, hydrogen sulphide, and both oxidized and reduced iron compounds in the sediment of Århus Bight in the spring (upper panel) and autumn (lower panel). The sediment's oxidation capacity diminishes during the course of the summer and the hydrogen sulphide front moves closer to the sediment surface. Note that the depth scale changes after the first centimetre (redrawn from HAV90, Report 15).

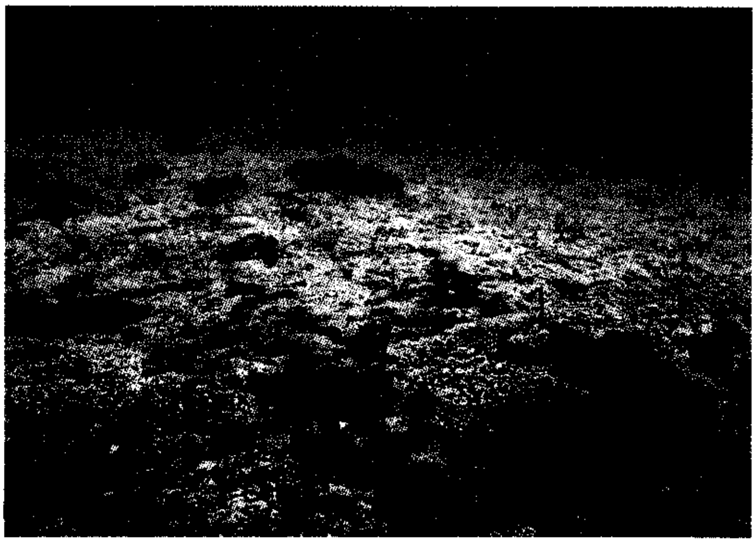


consumption of oxygen. Moreover, hydrogen sulphide is directly toxic for oxygen-consuming organisms, and escape of hydrogen sulphide has catastrophic consequences for benthic invertebrates and fish.

The so-called "shroud", where white sulphur bacteria form dense mats on the sediment surface, comprises a last defense against the escape of hydrogen sulphide. The bacteria obtain energy by oxidizing hydrogen sulphide (that diffuses up from the sediment) with oxygen taken up from the bottom water. The presence of a "shroud" on the sediment surface indicates a very critical balance where oxygen uptake from the water just counterbalances hydrogen sulphide production by the sediment. Even a modest reduction in oxygen input will shift this balance, thereby allowing hydrogen sulphide to escape into the water.

In such situations, intensive formation of methane can take place near the sediment surface, and methane can occur in such high concentrations that gas bubbles form in the sediment. When these methane bubbles are released from the sediment (for example during low-pressure weather conditions), a large part of the bottom material and large amounts of hydrogen sulphide can then be drawn up into the water column. When this happens, fish high up in the water column can be killed by the released hydrogen sulphide.

The sediment's oxidation capacity is thus a decisive determinant of how long the sediment can withstand low bottom water oxygen concentrations, and of when actual escape of hydrogen sulphide will take place. Under the HAV90 programme, simple analyses have been developed for determining the sediment's oxidation capacity. It transpired that the oxidation capacity varied considerably throughout the year and from sediment type to sediment type (HAV90, Reports 15 and 59). Thus during winter, the sediment in Århus Bight could withstand many days with an overlying anoxic water column before escape of hydrogen sulphide took place. During the summer period, however, anoxic conditions could only be withstood for a few days before hydrogen sulphide escaped from the sediment into the water column. The situation was worst in September and October, when hydrogen sulphide escaped within a day after exposure to an anoxic water column (Figure 5.14; HAV90, Report 59).

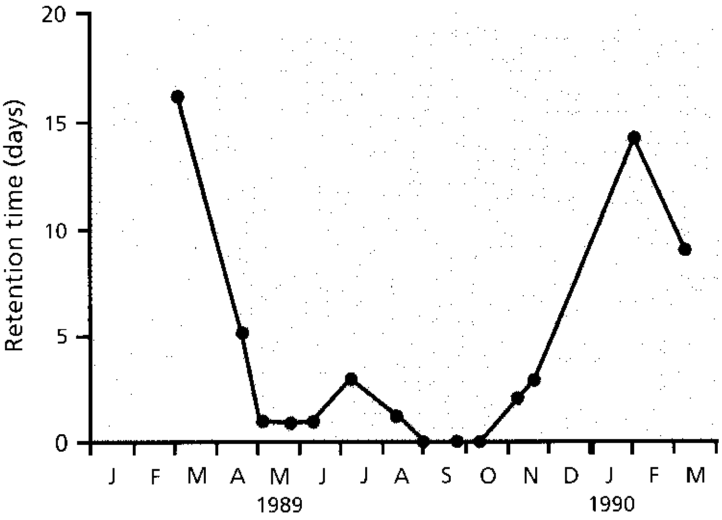


Peter Bondo Christensen/NERI

Re-establishment of the sediment's oxidation capacity depends among other things on oxygen availability, the reactivity of the reduced iron pools and the physical mixing of the sediment particles from the reduced zone. Even short-lasting resuspension of the uppermost sediment lasting under a minute can effectively reoxidize reduced iron compounds in the surface layer, and frequent resuspension can maintain an oxidized zone in the surface layer (HAV90, Report 36).

Effective ventilation of the sediment through faunal activity (bioturbation) will also increase the sediments' oxidation capacity as oxidized iron compounds are dug down into the sediment and reduced iron compounds are brought up into the oxic zone.

The primary build-up of the oxidation capacity presumably takes place in the winter (Figure 5.14), when the availability of oxygen is greatest and stormy weather can cause considerable resuspension of the sediment down to greater



Figur 5.14

The ability of sediment to retain hydrogen sulphide, as illustrated by an example from Århus Bight. The number of days before hydrogen sulphide escapes into the water column after the water column has become anoxic varies throughout the year as a result of changes in the sediment's oxidation capacity (from HAV90, Report 59).

sediment depths (HAV90, Reports 14 and 18). Resuspension is particularly important for sediment processes in coastal waters since the sediment is resuspended to a greater depth and at the same time is more reduced in these waters, among other reasons because of enhanced input of organic matter (HAV90, Reports 14 and 18).

When reduced sediment is resuspended, oxygen consumption in the bottom water can increase considerably within a few hours. The increase in oxygen consumption is proportionate to the depth to which the sediment is resuspended, and up to 80% of the oxygen consumed can be used to oxidize pyrite and other particulate ferrous compounds (HAV 90, Report 36). As resuspension takes place during periods of strong wind, when stratification of the water column is disrupted, the enhanced oxygen consumption will not lead to oxygen deficit under these conditions.

Under HAV90, methods have been developed for the relatively simple assessment of the sediment's oxidation capacity. The sediment pool of oxidized iron is greatest in the early spring, and the size of this pool is probably important for the extent and distribution of oxygen deficit and hydrogen sulphide problems in the late summer. If the spring pool of oxidized iron in a given area varies from year to year, various degrees of oxygen deficit may be possible in that area even if loading and weather conditions have been roughly the same throughout the various years. The sediment's oxidation capacity early in the year can therefore be used as an indication of the risk of the occurrence of oxygen deficit in the area in question in that same year. Moreover, a change in the sediment's oxidation capacity from one year to another might reflect changes in loading conditions. It will therefore be possible to employ the sediment's oxidation capacity as an indicator in the routine monitoring and documentation of the development in the environmental state of estuarine fjords and coastal waters.

6 HAV90 and monitoring of the state of the marine environment

The Nationwide Monitoring Programme under the Action Plan on the Aquatic Environment was initiated in 1989, the aim being to document and help assess the impact of the interventional measures implemented in accordance with the Action Plan (Danish EPA 1993). Under the programme, nutrient inputs from both point sources and diffuse sources are calculated regularly, and the environmental state of the groundwater, springbrooks, watercourses, lakes and marine waters is described.

While the HAV90 programme does not directly aim at assessing the Nationwide Monitoring Programme, HAV90 has yielded a number of research findings that can be used to discuss and assess a number of the monitoring activities, in particular the suitability of certain parameters for describing the development in the state of the marine environment.

6.1 Principles of monitoring programme design

An environmental impact can be defined as a change in state that arises as a result of changed environmental loading. The change in loading is the cause and the environmental impact is the effect.

Environmental impacts can also result from physical interventions such as dredging, mining, etc. Loading of the marine waters and their environmental state are followed by means of the Nationwide Monitoring Programme, while the processes that determine the state of the marine environment are studied through the HAV90 programme and other research activities.

6.1.1 Objective of the monitoring programme

Monitoring of the Danish marine environment is undertaken in order to be able to describe its state and identify and explain environmental impacts in the sea.

Knowledge of the causes of changes in environmental state enables appropriate selection of remedial measures to safeguard the future environmental state of the marine waters. This monitoring is also part of a formalized international cooperation, which in itself imposes demands on the scope and implementation of the programme.

An example of an environmental impact is an increase in the frequency of oxygen deficit as a result of eutrophication following enhanced nutrient loading. This impact can be monitored through regular measurement of the bottom water oxygen concentration. An example of a remedial measure is to reduce nitrogen loading of the marine environment.

Questions elucidating the objective of the monitoring programme

(from Fellows et al., 1995)

What is the state of the aquatic environment?

Where, how and why does the state of the aquatic environment change?

Are there problems with the aquatic environment and what causes them?

Are our environmental programmes effective?

Do we comply with our water quality objectives?

Klaus Bentzen/Biofoto

6.1.2 Fundamental requirements

If knowledge about the processes was complete, it would be possible to focus the monitoring solely on nutrient loading or solely on the impacts. In practice, however, neither of these procedures is adequate because knowledge of the processes is incomplete. For example, it is obviously not possible to forecast next summer's precipitation, solar radiation and water temperature. The monitoring must therefore encompass both loading and impacts and to a certain extent the specific course of the intervening processes.

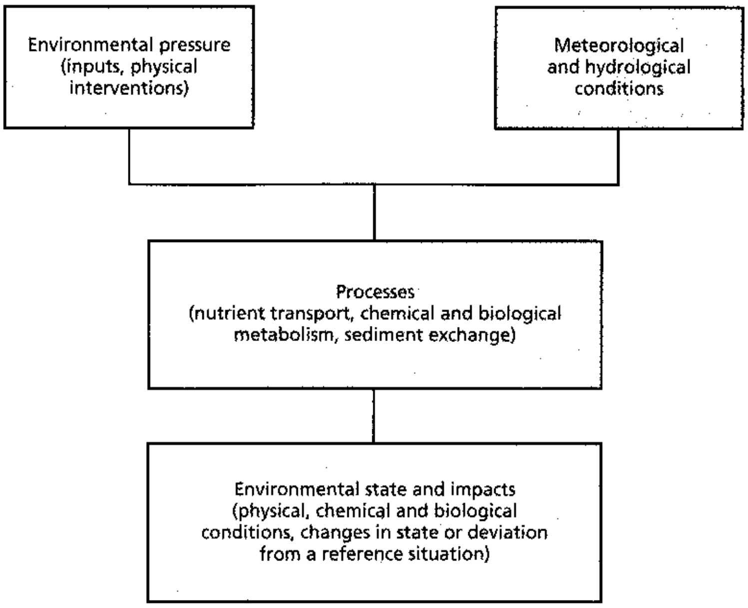


Figure 6.1

Elements of significance to monitoring and assessment of the environmental state of the sea.

Knowledge of the processes is a precondition for being able to predict states, as for example is needed when selecting remedial measures. However, the general physical, chemical and biological relationships themselves are best elucidated through specific studies and research rather than through continuous monitoring.

Many environmental impacts arise as a result of natural variation being considerable relative to the environmental impact. Among other reasons, this natural variation arises as a result of variation in loading, variation in the extent of the different water masses (limited by fronts and pycnoclines), seasonal variation in biology and chemistry, and both short-term (days) and long-term (months) meteorological variations.

The HAV90 programme has clearly confirmed that an understanding of the various environmental impacts necessitates a knowledge of medium-term climatic and hydrographic variation, i.e. variation in temperature, solar radiation, precipitation and evaporation, wind, ice cover, stratification, turbulence, and the overall exchange of water and salt between the Baltic Sea, the Kattegat and the North Sea.

For example, oxygen deficit is not only determined by nutrient availability or the organic matter pool, but also depends on factors such as precipitation, runoff, water temperature, wind-induced mixing of the water column, and bottom transport of water. Another example is that an eelgrass population is not just affected by nutrient availability, but also by natural erosion, sedimentation and disease. Ideally then, environmental monitoring should be able to differentiate between impacts attributable to loading and impacts attributable to other causes.

6.1.3 Scope of the monitoring programme

The monitoring needs to be organized in such a way that the following factors are recorded:

- Nutrient loading from point sources and diffuse sources
- Environmental state and changes (environmental impacts)
- Meteorological, hydrographic and biological conditions

The monitoring has to describe geographical variation, short-term variations and long-term variations in such a way that the impacts can be identified and defined with an acceptable (and known) degree of certainty, both with respect to geographical distribution and temporal pattern of change.

In addition to data collection, a monitoring programme also encompasses analysis of the collected data, as well as editing, distribution and reporting of the results. In order to ensure that there is no doubt about the function and role of the individual participants in the monitoring programme, the organization and sharing of responsibilities (from sample collection to data analysis to distribution and reporting) should be described in detail.

6.1.4 Adjustment of the current monitoring programme

The current monitoring programme should be optimized from the scientific and resource points of view in relation to its objective. This necessitates restricting the scope of the programme to selected substances and key indicators and deciding upon the extent of monitoring. Restriction of the programme should be undertaken as an overall decision as to what should be registered and where and how often registration should be undertaken.

In order to be able to prepare a nationwide description of the state of the marine environment, the following need to be improved:

- Definition of the operational goals for marine waters.
- Definition of the desired level of information in accordance with the monitoring programme objective, as well as an accompanying quality standard with regard to the ability to identify and describe various environmental impacts, and consequent amendment of the programme in accordance therewith.
- Adaptation of the monitoring to known causal relationships of particular importance to the Danish marine environment so as to render the monitoring more operational and less investigative (cf. Section 6.1.2). An example could be to improve coupling between the monitoring of impacts in the marine environment and the monitoring of meteorological and hydrological conditions.
- Definition of the extent to which it should be possible to use the monitoring for forecasting purposes, for example to forecast oxygen deficit or the occurrence of toxic algae.
- Safeguarding of rapid data flow, flexible data availability and a clear association between data collection and subsequent analysis and evaluation.

These improvements necessitate development of the monitoring in the direction of a more goal-oriented effort with respect to selection of the factors to be investigated and the methods, frequency and geographical coverage of sampling, so as to ensure that the data collection concentrates on providing a basis for solving a predefined problem. The results of the HAV90 programme can help lead to more direct focusing and effectivization of the monitoring programme.

Changes should obviously only be made to a general monitoring programme when there are specific reasons for doing so. Thus even changes justified on the basis of improved knowledge should be weighed against the need for continuity. Optimization of the monitoring programme should therefore be founded on the activities hitherto implemented.

6.1.5 Relevant impacts

The following general conditions and impacts are presently known to be of particular interest in connection with monitoring of the environmental state of Danish marine waters:

- Eutrophication, plankton biomass (especially phytoplankton), oxygen deficit and the impact on benthic invertebrates.
- The condition and distribution of the benthic vegetation, especially as reflected by the distribution and growth of eelgrass stands in relation to competing algal populations.
- The occurrence and impact of heavy metals and environmentally hazardous substances (primarily in ani-

mals, plants and sediment, but also in the water).

Also of interest is the impact of single events such as accidental spillage, nutrient discharges of limited duration, and physical interventions such as marine mining, the dumping of dredged materials and construction projects. Even though such actions are temporary, the impact can be long-lasting. This is the case, for example, when the benthic vegetation is damaged or removed. Impacts of such a specific nature are not specifically covered by routine monitoring, but can in practice overlap or interact with the impacts on which the routine monitoring programme focuses.

6.1.6 Time scale of the impacts

In the short term, nutrient input varies with the meteorological and hydrographic conditions. In the long term, it varies in line with the gradual changes in man-made inputs from agriculture and sewage works, etc.

The time scale for the various environmental impacts can vary from a few minutes or hours for the water phase, days or weeks for the biomass in the water, and up to months or years for biomass and sediment. While a change in state can occur rapidly at the sea floor, for example in the case of severe oxygen deficit event or of sea floor excavation, the impact can be long-lasting. Any monitoring must therefore take into account the time scale of the impacts being observed. This means, for example, that monitoring of the water phase can be largely based on permanently established self-recording equipment, while monitoring of the composition of the benthic vegetation and marine sediment can be undertaken with a longer interval between the individual measurements. For the same grounds, heavy metals and environmentally hazardous substances are usually best monitored in plants and animals or in sediment.

The marine environment monitoring programme should be able to demonstrate what effects a reduction in nutrient loading will have on the phytoplankton biomass or incidents of oxygen deficit, etc. Sample collection should therefore be planned in such a way as to be able to document a change (for example, 20% from one year to the following year) with a known (or estimated) probability (for example, 90%). However, this necessitates 1) that the impact can be represented operationally by a specific variable (for example, the bottom water oxygen concentration) and 2) that the temporal and spatial variation is known for the variable in question or at least that clear assumptions can be made about it.

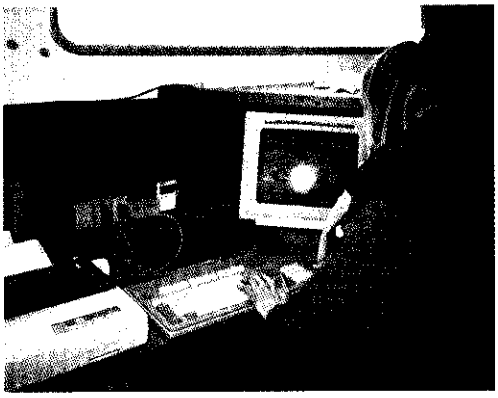
The statistical strength of the existing monitoring programme can be improved by using the specific knowledge about the temporal and spatial variation in the variables measured, and knowledge on the relationships between different variables. First and foremost, this necessitates that the collection of data provides a better foundation for the subsequent analyses. In addition, it is necessary to document a relationship between the objective and the monitoring activity, and establish specific preconditions for further optimization of the monitoring, especially determination of the sampling frequency.

6.1.7 Quality assurance

The environmental monitoring should be undertaken in a manner that 1) defines objectives and quality requirements, including precision and validity, 2) indicates methods and specific circumstances for data collection and

Power of a monitoring programme
(from Agger, 1994):

The power of the programme is a measure of its effectiveness in measuring a given impact, or in other words, the probability that the programme can identify a change in state that has actually occurred.



Helle Thomsen/Frederiksborg County

analysis and storage of the results, and 3) ensures coordination between the participating parties. This involves stipulating an operational strategy for the scope and extent of monitoring, as well as drawing up detailed documentation of both the technical and administrative procedures for the whole cycle of operations from sample collection and *in situ* measurements, to sample handling, analysis, control and storage of results.

6.1.8 Administration and use of the data

The purpose of data administration is to render the results of the environmental monitoring easily accessible to the various users. This requires centralized, systematic storage and maintenance of distribution channels for general purposes, including new and previously unknown uses. Moreover, for specific, known purposes, the collected data has to be regularly structured, compressed and presented in an appropriate, goal-oriented manner. There must be no room for doubt as to the role of the individual participants in the monitoring programme, and clear agreements have therefore to be drawn up as to when and how the data are to be submitted and processed (including when and how they are to be maintained).

The relationship between nutrient loading, environmental state and processes can be analysed using water quality models, which are suitable for summarizing both detailed mass balances and ecological states, and able to generalize and forecast the environmental state. Use-oriented knowledge of the quantitative relationship between loading and environmental state is necessary in order to be able to answer important questions such as "What would the environmental state have been like this year if the weather had been normal?", and "What will the environmental state be like if these loading reductions are implemented?"

6.2 Present monitoring of Danish open marine waters

The Nationwide Monitoring Programme for Danish marine waters set up under the Action Plan on the Aquatic Environment started in 1989. At the time the programme was established, it was decided to revise it after three years on the basis of the results and experience hitherto gained. The monitoring programme was thus revised in 1992. The revised monitoring programme for the period 1993-97 has been published in English (Danish EPA, 1993).

The monitoring programme for marine waters is planned such that monitoring of all estuarine fjords, bays and coastal waters is undertaken by the county authorities, while monitoring of the open marine waters is undertaken by the National Environmental Research Institute. In addition, data from the National Forest and Nature Agency, the Danish Fisheries Research Institute, the Danish Meteorological Institute, and environmental authorities in neighbouring countries is included in the evaluation of the results.

A characteristic of the Nationwide Monitoring Programme for marine waters is that monitoring of the coastal waters is largely based on the Counties' former monitoring programmes for non source-oriented monitoring. Similarly, the state monitoring of the open marine waters is characterized by the activities under the former Belt Sea Project (see Danish EPA, 1981) and the Danish monitoring obligations within the cooperation on protection of the marine environment in the Baltic Sea (see Baltic Marine Environment Protection Commission, 1988).

The Skagerrak and the North Sea are not covered by the monitoring programme to the same extent as the other marine waters, among other reasons, because international coordinated monitoring of these marine waters has not yet been established, and because the Action Plan on the Aquatic Environment is primarily directed towards the conditions in the inner Danish marine waters. It should be noted that the international programmes are not as restricted to the inputs, concentrations and impacts of nutrients in the aquatic environment as the Action Plan on the Aquatic Environment, but also monitor corresponding problems in relation to heavy metals and environmentally hazardous substances. In the case of the Wadden Sea, a joint monitoring programme is being drawn up with Germany and Holland.

The monitoring of the inner Danish marine waters is primarily based on measurements and observations in the free water masses and studies of the benthic animals and plants. The methods used for monitoring the marine environment are described in a number of publications (Danish EPA Marine Pollution Laboratory, 1988; as updated by Olrik, 1991; Nielsen et al., 1993; Ærtebjerg et al., 1993 and Krause-Jensen et al., 1995).

In addition to the monitoring undertaken as part of the Nationwide Monitoring Programme, the county authorities undertake monitoring cruises to chart the extent of oxygen deficit in relevant periods of the year, and the municipal authorities investigate bathing water quality in certain periods. Moreover, as part of their responsibilities under the Nature Protection Act and the Marine Environment Act, the county authorities undertake general supervision of the state of recipient waters, among other things in areas used for dumping of dredged materials or where there are point-source discharges. The results of these activities are not part of the monitoring programme and are not directly included in the nationwide status reports.

The determination of nutrient loading from the land (watercourses and direct discharges) is not part of the marine monitoring programme, but is a parallel activity under the Nationwide Monitoring Programme.

6.3 Hydrographic conditions and nutrient inputs from adjoining open marine waters

Knowledge of the hydrographic conditions is important for an understanding of production conditions in the sea. On one hand, the hydrographic conditions create a barrier to nutrient and organic matter exchange through stratification of the water masses and front formation. On the other hand, hydrography helps to diminish concentration differences. The large natural variation in hydrographic conditions has to be taken into account when interpreting the monitoring data.

Environmental conditions in the inner Danish marine waters are greatly affected by waves, water currents and large-scale transport of water and nutrients across the boundaries of the Skagerrak and the Baltic Sea (see Section 4.4). Quantification of the transport and bioavailability of transported nutrients is therefore important when determining the nutrient budget for the inner Danish marine waters.

6.3.1 Existing monitoring under the Action Plan on the Aquatic Environment

The salinity and temperature of the free water masses is measured at approx. 160 stations in the coastal waters and approx. 75 stations in the open marine


Jørgen Nørrevang Jensen/NERI

waters. The number of samples collected at each station varies between 1 and 14 per year.

In the latest revision of the monitoring programme, 19 intensive stations were established. These encompass stations located in the open Øresund and the Great Belt, stations located in a number of bays and estuarine fjords, where water exchange with the open marine waters is high, and stations located in closed estuarine fjords with a limited water exchange. The sampling frequency at these stations varies from 32 to 52 times per year. As a consequence of the higher sampling frequency, these stations contribute valuable information about the hydrographic conditions in the inner Danish marine waters.

At the stations in the coastal waters, the salinity and temperature are measured at maximum intervals of one metre (often 20 cm intervals) until the final position approx. 1 metre above the sea floor. At stations in the open marine waters, greater measurement intervals can be used.

Water transport through the Great Belt is calculated on the basis of the difference in sea level between Hornbæk in North Zealand and Gedser on Falster. The sea level data are made available by the Royal Danish Administration of Navigation and Hydrography, with any missing data being provided by the Danish Meteorological Institute. As the ratio of throughflow in the Little Belt, the Great Belt and the Øresund is usually considered to be 1:7:3, the total transport is assumed to be 11/7 of the transport through the Great Belt. Moreover, the net flow through the Belt Seas and the Øresund is of the same magnitude as the total net transport through the inner Danish marine waters.

6.3.2 Evaluation of existing activities

Hydrographic studies in the open marine waters are necessary partly in order to be able to establish mass balances for the inner Danish marine waters, and partly as boundary data for the hydrographic data for the estuarine fjords. Based on the hydrographic results obtained in the HAV90 programme, it can be concluded that many monitoring stations are not representative of the area that they are intended to cover, i.e. that the location of the stations is suboptimal. This is particularly so in the case of the stations in certain estuarine fjords and the stations located in the vicinity of fronts, where the hydrographic variation is greatest.

In connection with planning of the future monitoring programme it is recommended that preliminary hydrographic measurements be undertaken to determine suitable locations and the sampling frequency necessitated by the hydrographic variation. For this purpose, circulation models can also provide useful information. In the open marine waters, satellite images will be a valuable aid. In order to safeguard the value of the long time series of measure-

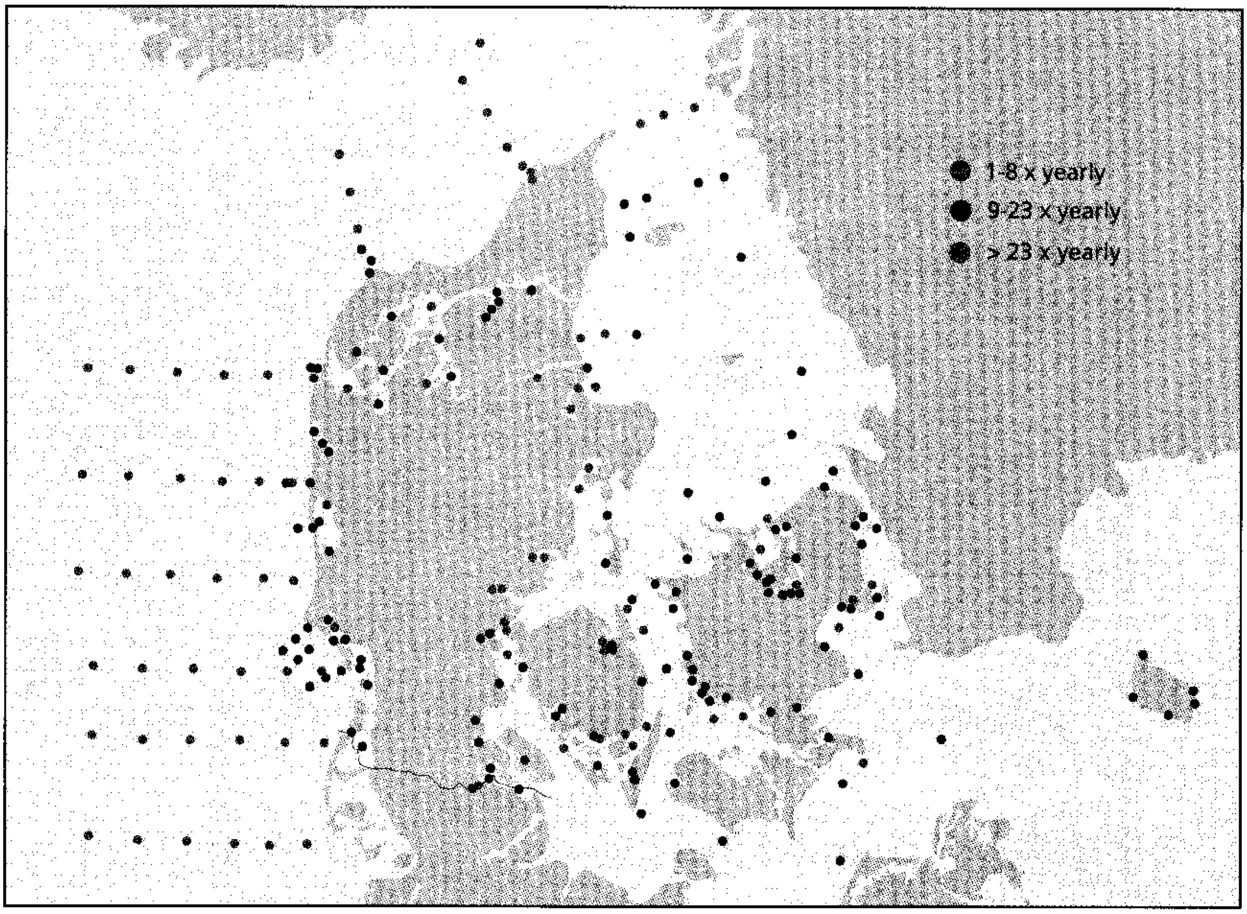


Figure 6.2

Overview of the stations where salinity, temperature and water nutrient concentration are regularly measured as part of the Nationwide Monitoring Programme under the Action Plan on the Aquatic Environment.

ments, monitoring at the relevant stations should be continued.

Variation is also great outside the fronts in the Danish marine waters. In order to be able to understand the effect of the variation on the environmental state, consideration should be given to reducing the number of general stations with a low sampling frequency and increasing the sampling frequency at a number of intensive stations. The stations should be located such that they are as representative of an area as possible, while at the same time ensuring that the temporal hydrographic variation is minimal. Moreover, the intensive stations should be located in such a manner as to provide the best possible support for the circulation models.

A central monitoring station in the southern Kattegat, possibly one equipped with self-recording equipment for the continuous measurement of current, salinity, temperature and oxygen content at several depths, would undoubtedly contribute to a better understanding of the various water chemistry parameters measured at the station. A fixed position with self-recording equipment will also enhance the information value of the data collected at other stations in the same area. Direct connection to self-recording mooring stations would allow the remainder of the monitoring to be undertaken more selectively and possibly only during "interesting" periods. The existing methods for determination of water transport through the Belt Seas and the Øresund is relatively crude and out of date. It would therefore be desirable to have a more detailed picture of the currents in both the surface water and the bottom water, as well as of the mixing between these water masses.

The exchange of nutrients between the inner Danish marine waters and the adjoining marine waters is considerable. The transport across the boundaries of these waters should therefore be determined with the same precision and frequency as inputs from the land and the atmosphere. However, the existing monitoring programme is not directed towards calculation of the import and export of nutrients across the boundaries of the adjoining marine waters, and estimates are presently only available for transport across the boundary of the Skagerrak for a period from the mid 1980s. Under HAV90, a close understanding has been obtained of the hydrographic conditions at the boundary of the Skagerrak and there has been good experience with a simple model of both nutrient transport and the oxygen situation in the inner Danish marine waters (HAV90, Reports 1, 29 and 49). These experiences should form the basis for a re-evaluation of monitoring in the Skagerrak area.

The modelling tools for determination of water transport across the boundaries are now available. However, in order to be able to regularly calculate nutrient transport, relatively frequent measurements of nutrients in the boundary zones are required. The frequency of water quality data should be increased so as to correspond to the variation in hydrographic conditions (e.g. a sampling frequency of 50-100 times per year). Among other ways, this could be achieved by collecting data from the Danish, Norwegian, Swedish and German monitoring programmes. Optimal utilization of these data, including their incorporation into existing transport models and calculation of transport across the boundaries, should be possible through a formalized cooperation between the countries. It should be noted that more detailed statistical analysis of the existing data is needed before the measurement frequency can be decided.

Recommendations for monitoring of hydrographic conditions and nutrient inputs from adjoining marine waters

The hydrographic parts of the monitoring programme should be restructured through the establishment of stations with self-recording equipment for recording of basic parameters such as salinity, temperature and oxygen concentration. The location of the stations should be determined according to the hydrographic conditions in order to obtain the greatest possible understanding of the influence of natural variation on the monitoring data. One should consider including actual hydrographic models for describing nutrient transport in the future monitoring of the marine environment. Import and export from and to the Skagerrak and the Baltic Sea should be calculated regularly as high-resolution time series. In this connection, it is recommended that formalized cooperation between Denmark, Norway, Sweden and Germany be strengthened. As the nutrient transports across the boundaries of the marine waters are considerable, it is obviously important to include these in the nutrient budget for the inner Danish marine waters.

6.4 Atmospheric inputs of nutrients

Atmospheric deposition has been measured for many years with a view to determining atmospheric deposition of nutrients on the land. However, it was not until the end of the 1970s and beginning of the 1980s that it was acknowledged that the input of nitrogen to the sea via the atmosphere is of great significance. Calculation of deposition over parts of the Danish marine waters has therefore been a permanent part of the Nationwide Monitoring Programme since its inception.

6.4.1 Existing monitoring under the Action Plan on the Aquatic Environment

The primary objective of the monitoring is to determine the magnitude of the atmospheric input of nutrients. A further goal is to describe the regional vari-

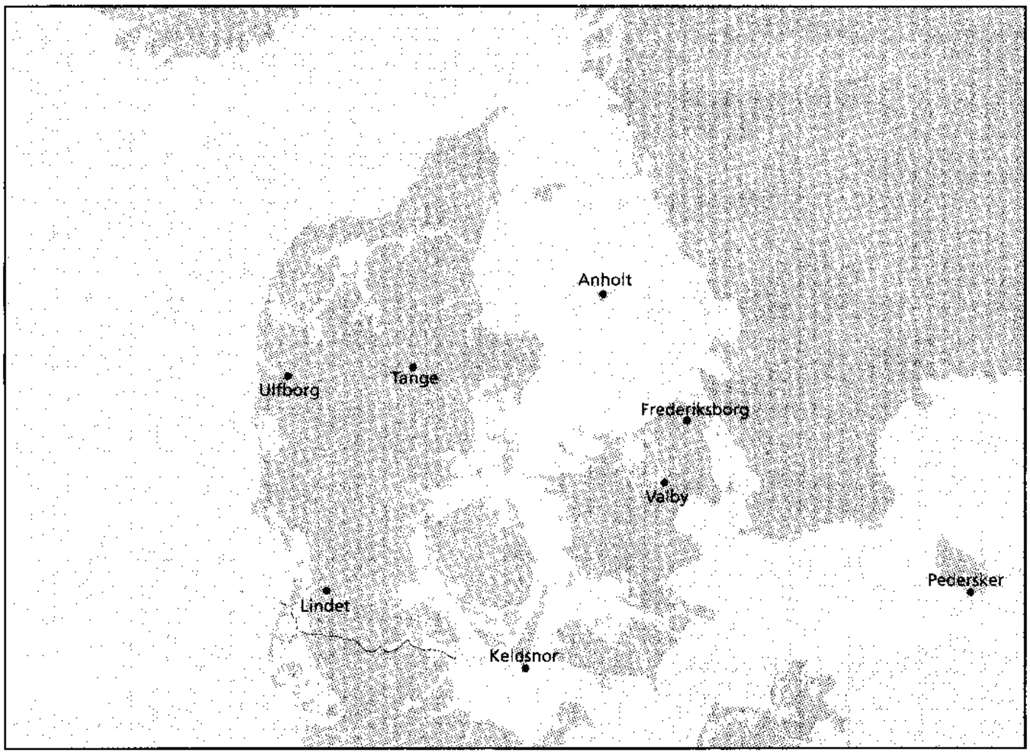


Figure 6.3

Overview of stations where atmospheric concentrations of nitrogen, etc. are monitored.

ation and development in nutrient input from the atmosphere. When the monitoring programme was established, it was agreed that the final programme should not be fixed until model development, calibration and validation had been undertaken under HAV90 (Danish EPA, 1989). This was completed at the end of 1995, and the monitoring programme has now been adjusted to meet a number of new requirements with respect to a greater geographical and temporal resolution.

The monitoring programme encompasses the collection of precipitation at 8 stations (Figure 6.3). At 7 of these stations, gas and particulate concentrations are also measured for determination of the dry deposition. The wet deposition is determined directly on the basis of analyses of ammonium and nitrate in the precipitation samples from the 8 monitoring stations.

The dry deposition is calculated from the nitrogen dioxide, ammonia and nitric acid content of the air, the ammonium and nitrate content of the microscopic particles floating in the air and the deposition rate of these substances and particles. The total annual deposition of inorganic nitrogen is calculated as the sum of both wet and dry deposition.

The deposition of phosphorus is not estimated within the framework of the existing monitoring programme.

Danish monitoring is largely undertaken in association with the European Monitoring and Evaluation Programme (EMEP) under the Convention on Long-Range Transboundary Air Pollution (UN-ECE LRTAP) as well as the international cooperation on protection of the Baltic Sea (HELCOM) and the North-eastern Atlantic Ocean (OSPARCOM).

6.4.2 Evaluation of existing activities

The station net in the monitoring programme originally encompassed 18 precipitation stations, of which 6 also measured air concentrations. This station net was fixed before the use of atmospheric transport and deposition models was introduced during HAV90.

The large number of stations served to provide an independent impression of the mean value and geographical variation in wet deposition, which is the most variable form of deposition.

In the light of experience gained under HAV90, the number of monitoring stations included in the monitoring programme has been reduced to 8. On the other hand, though, the resultant data are supplemented with calculations of wet and dry deposition calculated using the transport models developed under HAV90. Hence the monitoring programme is now based on both measurements and model calculations, with the two methods supporting each other.

At 7 stations the monitoring comprised measuring the air concentration of both particulates and gasses and collecting the precipitation, thereby enabling regular comparison between model calculations and the measurements. Monitoring at the station on Bornholm only encompasses collection of precipitation, however, and it is not possible to compare model calculations of atmospheric concentrations and dry deposition with actual measurements. Due to Bornholm's geographical location, consideration should be given to expanding the monitoring programme at this station to also include air concentrations.

Recommendations for monitoring and calculating atmospheric inputs

The atmospheric deposition of nitrogen comprises a considerable and variable part of nitrogen input to the Danish marine waters. It should therefore be calculated regularly on a seasonal basis. In future, the calculation should also be based on integration of measurements and model calculations so as to enable the models to be controlled and regularly updated. It is recommended that air concentrations should also be measured at the station on Bornholm and that studies should be initiated to determine organic nitrogen input to the sea from the atmosphere.

6.5 Nutrients

As already mentioned, the objective of the Action Plan on the Aquatic Environment is to reduce nitrogen and phosphorus loading of the Danish aquatic environment. Although delayed to a greater or lesser extent and varying in magnitude, changes in nutrient loading will be detectable in the estuarine fjords, coastal waters and open marine waters in the form of changes in the concentrations of inorganic nutrients in the winter and total nutrient concentrations in the growth season.

6.5.1 Existing monitoring under the Action Plan on the Aquatic Environment

Water samples are collected for:

- Total nitrogen (Tot-N)
- Inorganic nitrogen (NH_4, NO_2, NO_3)
- Total phosphorus (Tot-P)
- Orthophosphate (PO_4)
- Silicate (SiO_2)
- Chlorophyll (see Section 6.6)

The analyses are undertaken on individual or pooled samples from one or more depths in the photic zone above the pycnocline (if present). In addition, samples are collected ½-1 metre above the sea floor. If the water column is mixed, one can make do with a single sample. At the stations in the open parts of the Danish marine waters, samples are collected at standard depths; every 5 metres from the surface until a depth of 30 metres, thereafter every 10 metres until the sea floor.

Samples for determination of nutrients in coastal waters are collected at around 180 stations, including 19 intensive stations. In the latter case, the sampling frequency is 32 to 52 times per year. Similarly, water chemistry is measured at 25 stations in the open parts of the inner Danish marine waters with a frequency of 8-10 times per year, while 50 stations in the Skagerrak and the North Sea are visited once yearly (Figure 6.2).

6.5.2 Evaluation of existing activities

As nitrogen is the limiting nutrient in the majority of the Danish aquatic environment for most of the year, the concentrations of the individual compounds (ammonium, nitrite and nitrate) in the growth season are often so low that they cannot be determined using the recommended analysis methods. In addition, there are no standardized methods for the analysis of urea, which under certain conditions has proven to be an important nutrient for the phytoplankton (HAV90, Report 16). It would appear realistic to be able to considerably improve the sensitivity of the analysis methods used.

In the summer, inorganic nutrient turnover will often be very rapid. This means, for example, that the concentration of ammonium is very likely to change markedly in the interval between sample collection and analysis. For this reason, one should attempt to improve the sample collection and analysis procedures. For example, filtering of the samples immediately after collection will have a marked "conserving" effect on the inorganic nutrients.

The information value of summer measurements of nutrient concentrations should be critically evaluated. Nutrients are rapidly regenerated in the water column (Section 5.2.1) and a given concentration at a given time will therefore tell little about nutrient availability for primary production. Moreover, if the analysis is suboptimal, the concentrations cannot be used to assess growth limitation by nutrients such as nitrogen or phosphorus. Careful consideration should therefore be given to concentrating the work on measuring nutrient concentrations to the winter season. In addition, the winter nutrient concentrations could be related to winter runoff from the land.

It seems to be relevant to consider a marked reduction in the number of monitoring stations, among other reasons because of the concordant trends seen with phosphorus, where the concentration has fallen markedly in large parts of the coastal waters as a result of improved sewage treatment. Based on the experiences from the intensive measurements of runoff and nutrient concentrations in inflows and adjoining coastal waters, consideration should also be given to strengthening this practice in the future programme.

In the present programme, nutrient samples are collected in connection with measurement of the hydrographic parameters. However, in the interpretation and use of the results there is little co-analysis of the hydrographic data and the water chemistry data. Far greater attention should be paid to the close coupling between the hydrography (for example the influence of fresh water) and the nutrient content of the water at the time of sample collection when interpreting the water chemistry data.

Recommendations for monitoring of nutrient concentrations and loading

Experience from the existing monitoring programme shows that the stipulated sample collection and analysis methods for inorganic nutrients are suboptimal, and in many cases are insufficiently sensitive. The considerable resources devoted to the collection and analysis of nutrients should be put to better use by optimizing sample collection and analysis procedures and by concentrating the work on fewer strategically selected stations. Consideration should be given to restricting the work to the winter season and incorporating automatic sampling and analysis equipment. There is a need for better interpretation and use of the nutrient data where the data collected are to a greater extent coupled to the hydrographic conditions at the time of sample collection.

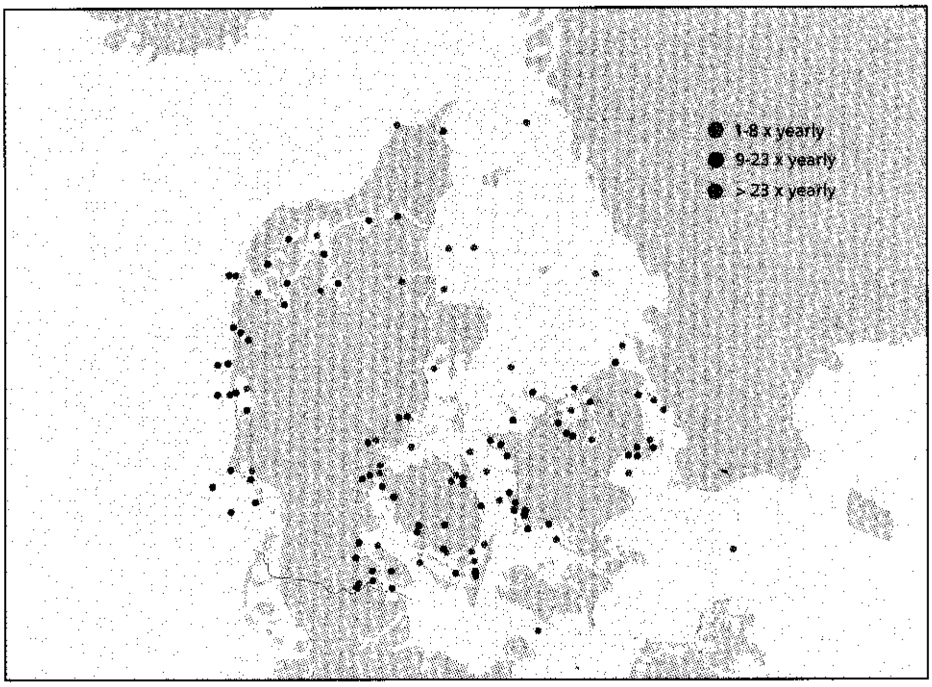


Figure 6.4

Overview of the stations at which phytoplankton species composition, biomass and production are monitored.

6.6 Phytoplankton and primary production

Phytoplankton comprise an important element in the current monitoring programme. This is because the phytoplankton in the open marine waters and in large parts of the coastal waters are the most important producers of organic matter and because their growth and biomass accumulation is considered to be limited by nutrient availability.

The phytoplankton consist of a number of different groups with more or less characteristic properties and environmental requirements.

Compared with macroalgae and rooted plants, the phytoplankton have a very short life cycle, typically from half a day to a few days.

Even though intense work has been undertaken on phytoplankton in a number of projects under the HAV90 programme, only few of the studies have contributed results of direct relevance for an evaluation of the Nationwide Monitoring Programme under the Action Plan on the Aquatic Environment.

6.6.1 Existing monitoring under the Action Plan on the Aquatic Environment

The phytoplankton monitoring is undertaken at about 50 coastal stations and 7 stations in the open parts of the inner Danish marine waters. It encompasses determination of light penetration (Secchi depth), species composition, number of individuals and biomass, as well as determination of chlorophyll *a*. In addition, potential phytoplankton production is determined at approx. 110 coastal stations as well as at the 7 stations in the inner Danish marine waters.

Species composition, number and biomass are determined 8 to 46 times per year, while measurements of primary production is undertaken 8 to 52 times per year. The samples are typically collected at the following depths: In the surface water (0.2 metre, corresponding to approx. 75% of the light intensity at the surface), ½ x the Secchi depth (approx. 25% of the light intensity at the surface), at the Secchi depth (approx. 10% of the light intensity at the surface), and at 2 x the Secchi depth (approx. 2% of the light intensity at the surface). If enhanced chlorophyll levels are detected in the vicinity of the pycnocline, an extra water sample is collected at that depth.

In addition, total phytoplankton biomass is estimated by filtering water samples and subsequently extracting and spectrophotometrically measuring the chlorophyll *a* content. The distribution and biomass of phytoplankton through the water column can also be determined using a fluorometer mounted on a so-called CTD probe.

As previously described, the potential primary production is a measure of the speed at which the phytoplankton can produce organic matter from inorganic nutrients using sunlight as the energy source. The purpose of determining the potential primary production is to follow possible effects of changes in loading on the production of organic matter in the free water masses.

6.6.2 Evaluation of existing activities

The phytoplankton comprise the functionally most important component of the Danish marine waters, being directly coupled to the vertical transport of nutrients and organic matter and oxygen deficit of the bottom water. As discussed in Section 5.3.1, the concentration of phytoplankton (measured as chlorophyll *a*) is closely correlated to the nutrient concentration and the transparency of the water (light availability) (HAV90, Report 30). As a supplement to determination of the phytoplankton biomass by means of chlorophyll analyses, the Nationwide Monitoring Programme includes analyses of phytoplankton species composition at a number of stations in order to obtain a measure of biomass in carbon units, and to follow the effect of reduced nutrient loading on species composition.

The reason for undertaking biomass determinations based on phytoplankton species composition is uncertainty as to whether chlorophyll *a* can be used as a measure of phytoplankton biomass in view of the fact that their chlorophyll content varies from species to species and with light and nutrient availability in the environment. Thus in the scientific literature, different carbon:chlorophyll ratios are often used depending on the season, typically 30-40 in the spring and 60-80 in the summer. Calculation of biomass on the basis of the species composition of the phytoplankton community necessitates extremely time-consuming identification and quantification of individual species, each of which is assumed to have a constant carbon concentration per unit volume. However, there is no documentation to indicate that this very time-consuming biomass calculation provides significantly more information than the far less resource-demanding chlorophyll analyses.

The basis for the detailed determination of phytoplankton species undertaken under the monitoring programme can be questioned. It thus seems unlikely that it would ever be possible to relate (small) shifts between species and families to changes in nutrient loading as our understanding of the environmental requirements and fate of the individual species is inadequate. It is also characteristic that the published reports and articles on the temporal development of algal communities alone focus on shifts between the main taxonomic groups such as the diatoms and dinoflagellates.

It therefore seems logical to undertake the analysis at group level, for example through the use of more or less group-specific chemical analyses such as pigment composition and concentration of biogenic silicate. This procedure would concomitantly eliminate the subjective element of species identification. The chemical analyses could be supplemented with detailed species determinations at a limited number of stations and points in time.

In contrast, detailed determination of species composition is absolutely necessary with regard to monitoring of the potentially toxic algae in connection with mussel fishery, etc. Such monitoring is not presently included in the Nationwide Monitoring Programme under the Action Plan on the Aquatic Environment.

Time series studies in the Dutch part of the Wadden Sea and the German Bight show that phytoplankton composition has changed markedly through the 1970s and 1980s, with a decline in diatoms and an increased occurrence of other groups, especially dinoflagellates (Brockmann et al., 1988; Cadée and Hegeman, 1986). The changes have mainly been attributed to changed input of the nutrients phosphorus, nitrogen and silicate.

With regards to Danish marine waters, statistical analyses of a far less comprehensive data set collected in the open part of the inner marine waters during the period 1982-93 have shown that inter-station differences in annual runoff, silicate concentration and in particular salinity can explain part of the variation between algae samples (Agger et al., 1994). On the other hand, though, it was not possible to demonstrate an unambiguous relationship between the composition of the phytoplankton community and a number of environmental variables such as the concentrations of nutrients, hydrography and wind energy.

As the various environmental factors cannot explain the changes, attention has focused on human (subjective) factors in the identification and quantification process that would be unavoidable in long time series. Even grouping the species at a general taxonomic level does not eliminate the presumed subjective factor (Agger et al., 1994). In view of the enormous resources devoted to phytoplankton monitoring, careful consideration should be given to what extent intensive determination of phytoplankton species should be included in a future monitoring programme.

Determination of phytoplankton primary production is undertaken at a large number of monitoring programme stations. Primary production is the only process rate that is routinely determined in the monitoring programme, and as such appears somewhat isolated. Phytoplankton productivity (Section 5.1) mainly depends on light availability, while biomass mainly correlates closely with nutrient availability. The spatial variation in the potential primary production seems to primarily result from differences in phytoplankton biomass rather than differences in phytoplankton productivity. It should thus be investigated whether it is possible to calculate phytoplankton annual production on the basis of light availability and biomass using a constant value for the light-saturated productivity. It is therefore proposed that the relationship between the maximum primary production and chlorophyll *a* should be calcu-

Recommendations for monitoring of phytoplankton

Determination of phytoplankton species composition, biomass and production are important elements of the existing monitoring programme. Experience hitherto gained has shown that subjective elements in the determination of species composition can be of considerable importance, and that the basis for using a detailed determination of species composition as a parameter in the monitoring is not well documented. In view of this, it is suggested that more objective methods of analysing the phytoplankton community be used in the future, possibly including determination at group level. In cases involving toxic algal blooms and the mass occurrence of individual species, detailed determination of species is still necessary. The data on primary production already collected should be subjected to a thorough analysis aimed at evaluating whether chlorophyll measurements could provide the desired information, and whether the measurements of primary production could be restricted to a limited number of stations, among others, the stations for which long time series are available. With these continued measurements, uniform use should be made of the ^{14}C technique.

lated for the data already collected. If it transpires that the variation in this relationship is small and does not correlate significantly with nutrient content and nutrient loading, there is no argument for retaining measurement of primary production, in which case determination of primary production should solely be made at the stations for which long time series of data are available.

6.7 Zooplankton

Zooplankton comprise a large number of groups of organisms that differ markedly with respect to both size and habits. The biomass of the individual groups reflects the dynamic balance between individual growth/reproduction rate, which is determined by food availability and temperature, and the loss rate, which is mainly determined by predation. When the monitoring programme started, there was some uncertainty as to the utility of zooplankton studies, and these were therefore accorded relatively low priority, both with respect to the number of stations and the sampling intensity.

6.7.1 Existing monitoring under the Action Plan on the Aquatic Environment

At selected stations, monitoring of the biological state of the water column is supplemented with registration of the species composition, number and biomass of protozooplankton (<0.2 mm) and mezozooplankton (0.2-2 mm). The monitoring of zooplankton is restricted to 16 stations in the coastal waters and 7 stations in the open marine waters. The sampling frequency for this monitoring is 6-32 and 7 times per year, respectively.

6.7.2 Evaluation of existing activities

Experience from the existing monitoring programme has done nothing to clarify the uncertainty concerning the usefulness of monitoring the zooplankton, and the results obtained do not seem to match up to the effort. Thus inclusion of zooplankton investigations in a revised monitoring programme cannot be recommended.

Recommendations for monitoring of zooplankton

It is recommended that zooplankton investigations should be omitted in connection with future monitoring of the environmental state of the Danish marine waters as the existing programme has not yet clarified the uncertainty concerning their usefulness.

6.8 Macroalgae and sea grasses

The benthic vegetation consists of very heterogeneous organisms ranging from slowly growing, perennial plants, to forms with short life cycles. Moreover, certain plants occur in large numbers, while others are only present as single individuals with little influence on the state of the marine waters or on nutrient and organic matter turnover. The results of research undertaken in coastal marine waters over the last few years, including the investigations undertaken in connection with HAV90, can to some extent be used to assess the value of vegetation investigations in monitoring work.

The distribution and composition of the macroalgal and rooted macrophyte (angiosperm) populations in the coastal waters has been systematically registered since 1989 as part of the Nationwide Monitoring Programme. The frequency with which the vegetation investigations should be undertaken and the degree of resolution to be used should - as is the case with all other monitoring parameters - be decided by weighing up resource use and the information value of the results.

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6.8.1 Existing monitoring under the Action Plan on the Aquatic Environment

Vegetation investigations are undertaken each year at 298 stations and transects distributed over the whole country. The methods for using the benthic vegetation in monitoring work are described in Krause-Jensen et al. (1995). According to the recommendations, the composition and distribution (coverage and depth limits) of the benthic vegetation should be determined and the bottom substrate described at one- to two-year intervals along fixed transects. In the case of massive occurrence of eutrophication-dependent macroalgae, the investigations can be undertaken several times per year to describe the seasonal variation. The large-scale distribution of the vegetation is determined by aerial photography.

The recommendations also mention a number of supplementary investigations that lie outside the regular monitoring programme. These include determination of biomass, shoot density and growth rates for eelgrass, the nutrient content of macroalgae and eelgrass, and bioassays to measure macroalgal growth, possibly also after addition of nutrients.

The recommendations do not include any assessment of the individual value of these parameters as monitoring tools.

The monitoring programme's vegetation investigations are very resource-demanding in that the necessary field work is very demanding and requires diver assistance. The proposed supplementary investigations are equally resource-demanding and involve considerable laboratory work.

6.8.2 Evaluation of existing activities

In many contexts the benthic vegetation has been championed as playing an important role in coastal waters as a structuring component and as a channel for nutrient turnover and transport (HAV90, Reports 22, 30, 41 and 43). This makes it extremely relevant to follow the temporal development in the composition and distribution of the vegetation. As mentioned in Section 5.4.2, empirical relationships have been established between the nutrient content of the coastal waters and the depth distribution of the vegetation. Registration of changes in distribution can therefore be used as an indication of changes in nutrient loading (HAV90, Report 30).

There is a need for a complete and detailed assessment of the vegetation's overall composition and distribution every 5-10 years, but it is hardly worthwhile undertaking such assessments every one or two years. Slowly growing plants such as eelgrass and perennial brown algae reflect the general trend in the environmental state of the coastal waters, and their depth distribution and areal coverage must be judged to have sufficient informational value to justify their investigation at the frequency given in the guidelines (Krause-Jensen et al., 1995). Interannual changes in the distribution of eelgrass should be analysed as a stochastic process driven by sediment transport in the case of shallow waters and by lack of light and oxygen deficit in the case of deep waters.

As discussed in Section 5.4.1, little is known about the regulation of the success and competitiveness of various other macroalgae. This even applies to the so-called eutrophication-dependent macroalgae (HAV90, Report 41), but their relative importance among the whole of the benthic vegetation and their influence on the ecology and recreational value of the marine waters justifies their continued monitoring.

In the case of the remaining vegetation, a detailed species description and frequent registration of coverage seems presently to be meaningless. There are no examples of such detailed descriptions having formed the basis for significant conclusions in the monitoring work. The absolute depth distribution for vegetation of this type would seem to provide sufficient information in itself. Areas with a very diverse vegetation should have a higher quality objective and in such areas, a high monitoring frequency can be necessary to demonstrate compliance with the quality objectives.

In very special cases it can be relevant to undertake the supplementary investigations mentioned above in order to describe areas subject to special problems, for example the definition of impact zones around point-source discharges. It should be noted, though, that actual quantitative measurements of nutrient content, biomass and growth in eelgrass and macroalgae is resource-demanding, and that the possibility of obtaining the same information through alternative and cheaper monitoring parameters should be very carefully considered.

6.9 Benthic invertebrates

The biomass and species composition of the benthic invertebrate communities has traditionally played a dominant role in monitoring marine environments, as has also been the case with the Nationwide Monitoring Programme under the Action Plan on the Aquatic Environ

Recommendations for monitoring of benthic vegetation

The trend in the overall composition and distribution of the benthic vegetation is a useful element in the monitoring programme, and the known relationship between loading and distribution of the vegetation comprises a good management tool for assessing and forecasting the environmental state. The benefit of more detailed determinations of the vegetation's species composition at a large number of stations is doubtful, however, and should therefore be subject to careful consideration.

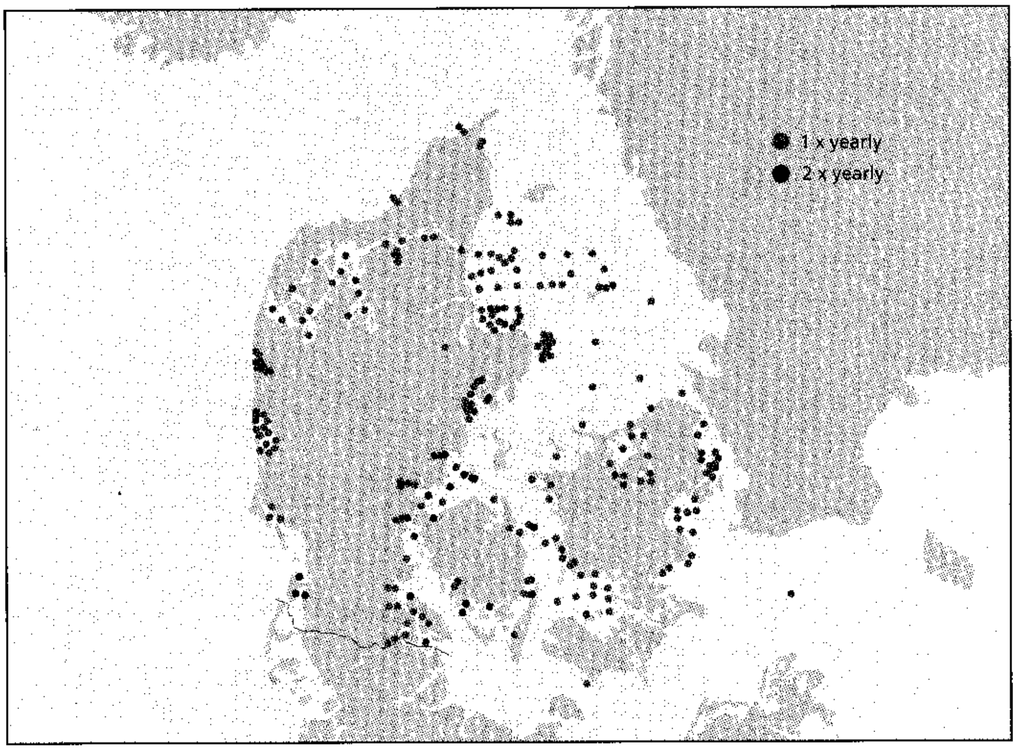


Figure 6.5

Overview of the stations where benthic invertebrate species composition and biomass are monitored.

ment. As with macroalgae and rooted macrophytes, the benthic invertebrates have a relatively long life cycle, and the biomass and composition of the benthic invertebrate communities is considered to reflect the sum of the influences that the area in question has been subjected to over the 1-2 year period preceding sample collection (e.g. food availability, oxygen conditions, etc.). Little work has been done on the benthic fauna under the HAV90 programme and an evaluation of benthic faunal monitoring must primarily be based on the results of the existing monitoring programme.

6.9.1 Existing monitoring under the Action Plan on the Aquatic Environment

The investigations comprise determination of species, number of individuals and biomass, and sometimes also the size distribution of the most common species of mussel.

The investigations are mainly undertaken in estuarine fjords and coastal waters directly affected by loading, in areas for which long time series are available, and in areas that are regularly subject to oxygen deficit. In the coastal waters, the benthic invertebrates are investigated at approx. 280 stations and along 6 transects. In the open marine waters, the monitoring encompasses investigations at 29 stations. Sampling is usually undertaken once a year, typically in March-May. In certain areas subject to direct loading, and where the effects of changes in loading are therefore expected to be rapidly detectable, sampling is undertaken 2-3 times per year.

6.9.2 Evaluation of existing activities

The invertebrate monitoring is subject to problems of both a biological and a statistical nature in relation to both planning and interpretation. Among other reasons, this is because the benthic invertebrates live unevenly distributed over the sea floor. The monitoring nevertheless documents species abundance and composition, and if longer time series are available, it is possible to evaluate the effect of changes in loading. Oxygen deficit of longer duration (>12 weeks) will markedly affect the benthic fauna and the effects can normally be recorded immediately. The benthic fauna in shallow waters can have a major influence on the phytoplankton content of the water and hence the water's transparency, while the benthic fauna in deeper waters, e.g. in the Kattegat, does not have any influence on the biological structure of the water column. The benthic fauna there feeds on that part of the production that sinks down through the pycnocline. Determinations of the benthic faunal biomass and species composition in shallow waters can be necessary in order to explain changes in the phytoplankton content of the water, while monitoring of the benthic fauna at deeper, stratified stations can ideally be related to organic matter sedimentation and the extent of oxygen deficit.

The results of the monitoring programme for the estuarine fjords and coastal waters have shown that the benthic fauna (biomass and composition) there is largely determined by time- and location-specific factors such as sediment structure, salinity, extent and duration of ice cover, local sewage effluent discharges, etc. In many areas, there have been marked changes in benthic faunal composition and biomass, sometimes even over a short period (5 years) that appear to be unrelated to variation in nutrient loading. However, visible impoverishment of the benthic fauna is always observed following incidents of oxygen deficit. Apart from these events, the benthic fauna in more shallow waters seems to be largely controlled by conditions and relationships that are as yet not fully understood.

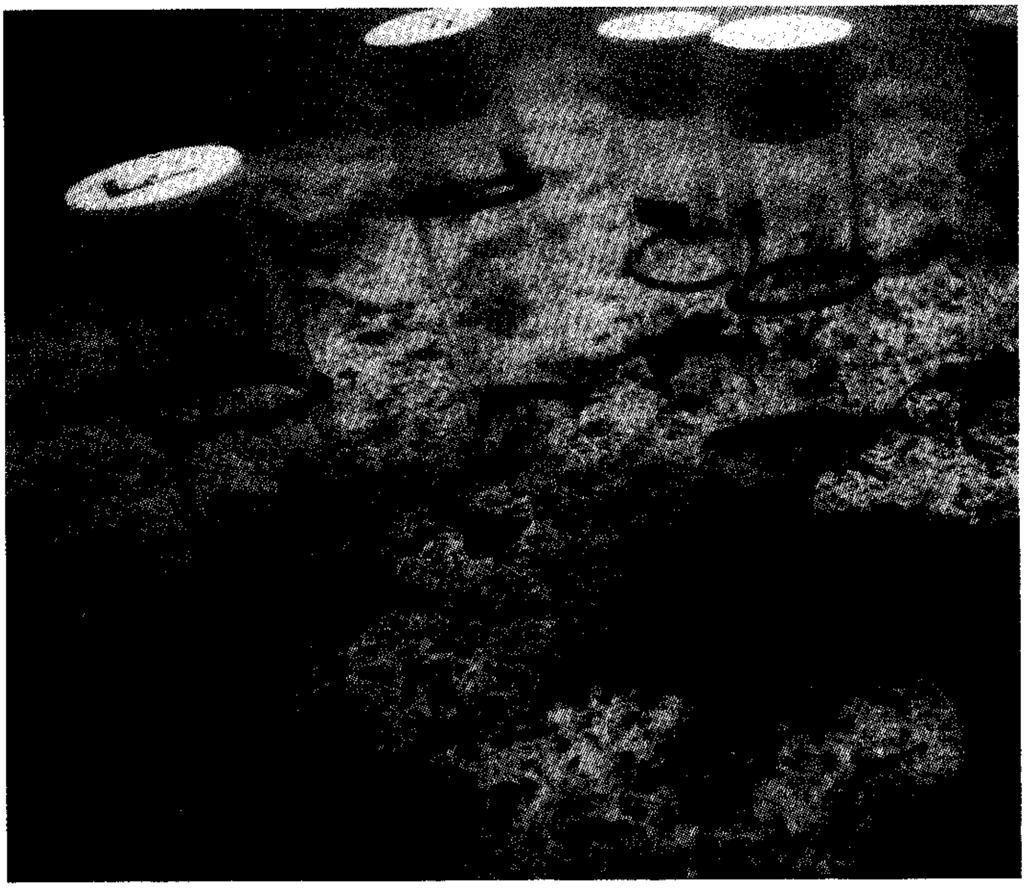
The existing programme has not solved problems in relation to the random variation and uncertainties associated with sample collection and analysis. Thus it is not yet possible to stipulate how many sampling stations and subsamples are necessary, or how these should be located to demonstrate an environmental impact.

In this connection, it does not seem logical that Danish monitoring in the open marine waters is based on sampling equipment differing from that used by the other countries participating in the cooperation on protection of the Baltic Sea environment (HELCOM). This makes direct comparison of the results difficult.

With respect to future monitoring of the marine waters, serious consideration should be given to concentrating the frequent sampling (1-2 times per year) at locations for which long time series are already available. This could eventually be supplemented with less frequent sampling (e.g. every 5th year) with a greater areal coverage in order to determine the long-term changes in benthic invertebrate composition. In the shallow waters (<10 m), it can be relevant to undertake extensive investigations of the benthic fauna, for example determination of the mussel populations' areal coverage in areas where water column parameters such as algal biomass are monitored.

Recommendations for monitoring of benthic fauna

Benthic faunal composition and biomass in fjords and coastal waters displays large (natural) variation that cannot be explained by changes in nutrient loading. It therefore seems scientifically unfounded to continue monitoring at the present level. Consideration should be given to concentrating monitoring of the benthic fauna in those sedimentation areas that are already included in the monitoring programme, and accord lower priority to the frequent and detailed monitoring of the benthic fauna in very shallow waters. Moreover, in areas where a description of the system is required, consideration should be given to developing methods to assess the filtrating epifauna and benthic fauna, e.g. mussels and tunicates, which can have a decisive influence on the abundance of phytoplankton in shallow estuarine fjords.


Peter Bondo Christensen/NERI

6.10 Sediments

The sea floor is a particularly important element in the ecosystems (see Section 5.6). Despite this, the sediments are rarely included in a description of the state of the ecosystems.

In the estuarine fjords and coastal waters, the sediment provides anchorage for plants and animals. The sediment plays a central role in mineralization of the sedimented organic material and hence in nutrient turnover.

The benthic oxygen production and the sediment's oxygen consumption in connection with the degradation of organic matter are decisive for the oxygen content of the bottom water.

Organic matter and nutrients can be permanently retained in deeper sediment layers, and nitrogen can be removed through denitrification in the sediment leading to the removal of nutrients from the ecosystems.

6.10.1 Existing monitoring under the Action Plan on the Aquatic Environment

In connection with monitoring of the benthic fauna, analysis is undertaken of the organic matter content and grain size distribution of the individual sediment samples. In selected areas, periodic analyses are also made of the sediment's weight loss on ignition and the sediment content of total nitrogen and total phosphorus.

6.10.2 Evaluation of existing activities

The information value of the existing sediment analyses is doubtful. There is apparently no direct relationship between organic matter mineralization and weight loss on ignition as non-degradable organic matter accounts for the majority of the sediment's weight loss on ignition. Similarly, the data on the sediment content of total nitrogen and total phosphorus provide no information as to how great a part of the nitrogen and phosphorus in the sediment actively enters into the nutrient cycles. With a view to assessing to what extent the data on total carbon, total nitrogen and total phosphorus in the sediments can yield information on changes in the sediment pools following changes in loading, a thorough analysis should be undertaken of the data hitherto collected. A decision could then be made as to whether to continue the analyses using an optimized analysis technique.

A number of projects under the HAV90 programme have shown that mineral cycling in the sediment influences nutrient dynamics in coastal waters (see Section 5.6), and that the sediment is of importance for nutrient transport (see Section 4.2) and oxygen conditions (see Section 5.7) in the coastal waters. In view of this, new and more informative sediment investigations could be incorporated into the monitoring of marine waters as a valuable supplement to the information on their environmental state that is currently obtained by measurements in the water column. Among other things, sediment monitoring can be advantageously included when one wants to quantify and describe environmental state and nutrient turnover in a specific area. In popular terms, one can say that the sediment is area-specific, and that it is the same sediment that one studies year after year at any given station. In contrast, the water column measured at any given station can derive from completely different water masses within the interval of a few days (see Section 4.4.1).

Monitoring of the sediments should be undertaken in such a manner as to provide the best possible information about the situation at and in the sea floor in order to give a qualitative evaluation of seasonal and long-term changes in the state of the sediment at a given location. Many of the results of the HAV90 projects are directly applicable when determining how sediment studies can be included as supplementary investigations under the monitoring programme. In this connection, particular consideration should be given to three different parameters: 1) Total benthic mineralization (benthic respiration), 2) Nutrient fluxes and 3) The sediment's oxidation capacity. As these parameters have not previously been described in connection with monitoring, they will be examined in some detail below.

The total benthic mineralization or total benthic respiration is a measure of the turnover of the sedimented material. By analysing this year after year, it is possible to follow the impact of loading on organic matter mineralization and hence on oxygen consumption in the bottom water. A time series for mineralization in the sediment would thus enable distinction to be made between the effect of loading, meteorological factors and hydrographic factors on oxygen consumption in a given area. Moreover, benthic mineralization can be used to assess how rapidly the bottom water can be depleted of oxygen upon stratification of the water column.

With a view to following the long-term changes in the state of the sediment and benthic mineralization as a consequence of changes in eutrophication, measurement of benthic mineralization at stations in deep water with a stable accumulation substrate is recommended. A relative measure of the benthic mineralization can be obtained by measuring one of the following processes: 1) Oxygen consumption by the sediment, 2) Carbon dioxide release by the sediment, 3) The sediment's sulphate reduction rate, or 4) Recording of the methane front. Making various assumptions, each of these process measurements can be used to estimate total mineralization in the sediment.

Oxygen consumption by the sediment is a relatively simple parameter to measure in the laboratory. The reliability of the measurements obtained is open to question, however, as oxygen consumption by the sediment varies with a number of physical and chemical parameters as discussed in Section 5.6.1. Oxygen consumption measured in the field can thus be significantly greater than oxygen consumption measured in the laboratory on the same sediment (HAV90, Report 57). In order to obtain more reliable and reproducible measurements of oxygen consumption, it is necessary to develop a relatively simple and easy-to-use instrument for the routine measurements of the sediment's oxygen consumption under *in situ* conditions.

The same applies if carbon dioxide production is to be used as a measure of organic matter turnover. Moreover, it is relatively difficult to undertake sufficiently accurate measurements of carbon dioxide concentrations, and the analytical error alone limits application of the method as a useful parameter for measurement of benthic mineralization. It should be mentioned that work is currently underway on the development of a method for determining anaerobic carbon dioxide production. This latter could be the best expression of the total benthic mineralization.

The sulphate reduction rate in the sediment is not particularly affected by current flow over the sediment and the number of bioturbating animals as sulphate reduction depends on the total anaerobic sediment volume. For example, while bioturbation of a sediment with a given density of bioturbating animals can enhance oxygen consumption by up to 60%, the sulphate reduction is only reduced by approx. 5% compared with an undisturbed sediment. Moreover, sulphate reduction measurements are very precise and reproducible, and the method can be rationalized considerably with a view to routine monitoring.

In order to follow changes in external loading of the sediment, benthic mineralization can thus be measured at a few selected stations. For this purpose, measurements of the sulphate reduction rate apparently seem to be the most suitable. The process measurements just need to be undertaken under the same experimental conditions each time. It is recommended to measure the process in February, when oxygen conditions are optimal, and in September-October, when oxygen conditions are traditionally poorest. The data obtained should serve as the basis for a database on changes in external loading of the marine sediment.

In addition, areas with high mineralization rates, i.e. areas where oxygen deficit is potentially initiated, can be monitored by following the depth in the sediment where methane bubbles form (see Section 5.6.1). Methane bubbles are acoustically impenetrable and can therefore be registered using seismic measuring equipment. The method has not yet been developed and tested, but the development of an easy method is recommended as such a method would be particularly valuable for monitoring of large areas of the sea floor.

As has been shown in several HAV90 projects, the sediment can be a particularly important source of nutrient input to the water column in estuarine fjords and coastal waters (see Section 5.6.2). Measurements of the nutrient flux between the sediment and the water column could therefore be included when assessing the significance of the sediment as a nutrient source - for example following a reduction in external loading. Nutrient fluxes should be determined on selected sediment types in a well-defined area with a measurement frequency determined by the turnover rate and the dynamics in the area. Moreover, fluxes could be advantageously coupled to mass balances for the area in question.

The sediment's oxidation capacity describes its ability to bind reduced compounds, especially hydrogen sulphide (see Section 5.7.2). It is primarily the sediments' active iron pool that is able to oxidize and retain hydrogen sulphide. Hence the hydrogen sulphide produced is not oxidized directly with oxygen. One can say that the sediment's oxidation capacity delays the actual oxygen consumption until the autumn, when the reduced iron compounds are reoxidized, thereby re-establishing the sediment's oxidation capacity.

The sediment's oxidation capacity can be described and followed visually, as the various iron compounds occur in characteristic colours in the sediment. Thus the sediment's oxidation capacity consists of the brown surface sediment containing oxidized iron, while the underlying black sediment contains the reduced iron sulphide compounds (see Section 5.7.2). A more precise measure of the sediment's oxidation capacity can be determined by adding hydrogen sulphide to the uppermost sediment layer, thereby measuring how much hydrogen sulphide the sediment can bind (HAV90, Report 15). The sediment's oxidation capacity is greatest in the early spring and declines through the summer in line with an increase in organic matter sedimentation and benthic mineralization. The oxidation capacity is lowest in the beginning of the autumn, immediately before the water temperature falls, and the autumn storms set in. At that point in time, the sediment's oxidation capacity reflects a long-standing balance between sedimentation of organic matter (organic matter loading) and oxygen supply to the sea floor. Long-term measurements of the oxidation capacity in the spring and autumn seasons will therefore be a good parameter to describe the trend in the environmental state of coastal waters.

The magnitude of the oxidation capacity in the early spring is probably one of the factors that determines whether or not serious oxygen deficit and hydrogen sulphide problems will occur in the following summer. A knowledge of the normal oxygen consumption and hydrogen sulphide production (the sulphate reduction rate) in a given sediment type would allow a measurement of the oxidation capacity in the early spring to be used to evaluate how great a part of the season's oxygen requirement can be covered by the oxidation capacity of the sediment in question. It will thus be possible to predict roughly how long the sediment can withstand low oxygen concentrations or anoxic conditions in the bottom water before this leads to the release of hydrogen sulphide and the risk of mass mortality in the water column.

Recommendations for monitoring of the condition of the marine sediment

It is recommended that new sediment investigations be included in the marine monitoring as a good supplement to the monitoring parameters traditionally measured in the water column. In the present monitoring programme, measurements of sediment weight loss on ignition, total nitrogen content and total phosphorus content are virtually the only sediment parameters included. The information value of these data should be analysed and use of the parameters re-evaluated. Measurements of benthic mineralization in the sediment could be introduced at a few selected stations in order to be able to follow changes in external loading of the sediment. The sediment's oxidation capacity, which is a relatively easily determined parameter, could be included to document the development in the state of the marine sediment (and hence the marine environment), as well as to provide a warning of possible oxygen deficit and hydrogen sulphide release. Measurements of nutrient fluxes could be included in areas where it is of importance to know the nutrient flux across the sediment surface (for example, when determining internal loading in estuarine fjords).

6.11 Oxygen conditions

The oxygen content of the bottom water is of decisive significance for the distribution and abundance of benthic animals and plants, for benthic mineralization in the sediment and for the sediment's ability to retain nutrients and toxic substances such as hydrogen sulphide (see Sections 5.4 to 5.7). Episodes of oxygen deficit in the coastal waters result in the death of several animals and plants. This has considerable impact on the biological structure and the whole food chain since re-establishment of the "normal state" can take many years.

The deterioration in oxygen conditions seen in the estuarine fjords, coastal waters and the inner Danish marine waters is a direct effect of the enhanced eutrophication, and the poor oxygen conditions were one of the reasons behind implementation of the Action Plan on the Aquatic Environment in 1987. For that reason too, it is extremely important to measure the bottom water oxygen concentration and follow the development in this parameter systematically throughout the year and from year to year. Moreover, in order to be able to determine the causes of oxygen deficit it is important to relate deterioration in oxygen conditions to a number of parameters that affect the oxygen content of the bottom water, e.g. winter runoff of nutrients (HAV90, Reports 1 and 29), organic matter production in the water column and the resulting sedimentation from the water column, turbulence and stability of the water column caused by wind and solar irradiation (HAV90, Report 51), the abundance of benthic grazers (HAV90, Reports 45 and 51), and the influx of hypoxic bottom water from adjoining areas (HAV90, Reports 4 and 39).

6.11.1 Existing monitoring under the Action Plan on the Aquatic Environment

The measurements of the oxygen concentration of the water are mainly undertaken at the same stations as used for determination of the water chemistry parameters (see Figure 6.2). The sampling frequency is typically 10 to 12 times per year. The latest revision of the programme included the establishment of 19 intensive stations, where the sampling frequency varies from 32 to 52 times per year. The intensive stations are located in the marine waters that receive the majority of the land-based loading from Danish sources, and where it will hopefully be possible to document a reduction in loading through measurable improvements in oxygen conditions over the space of a few years.

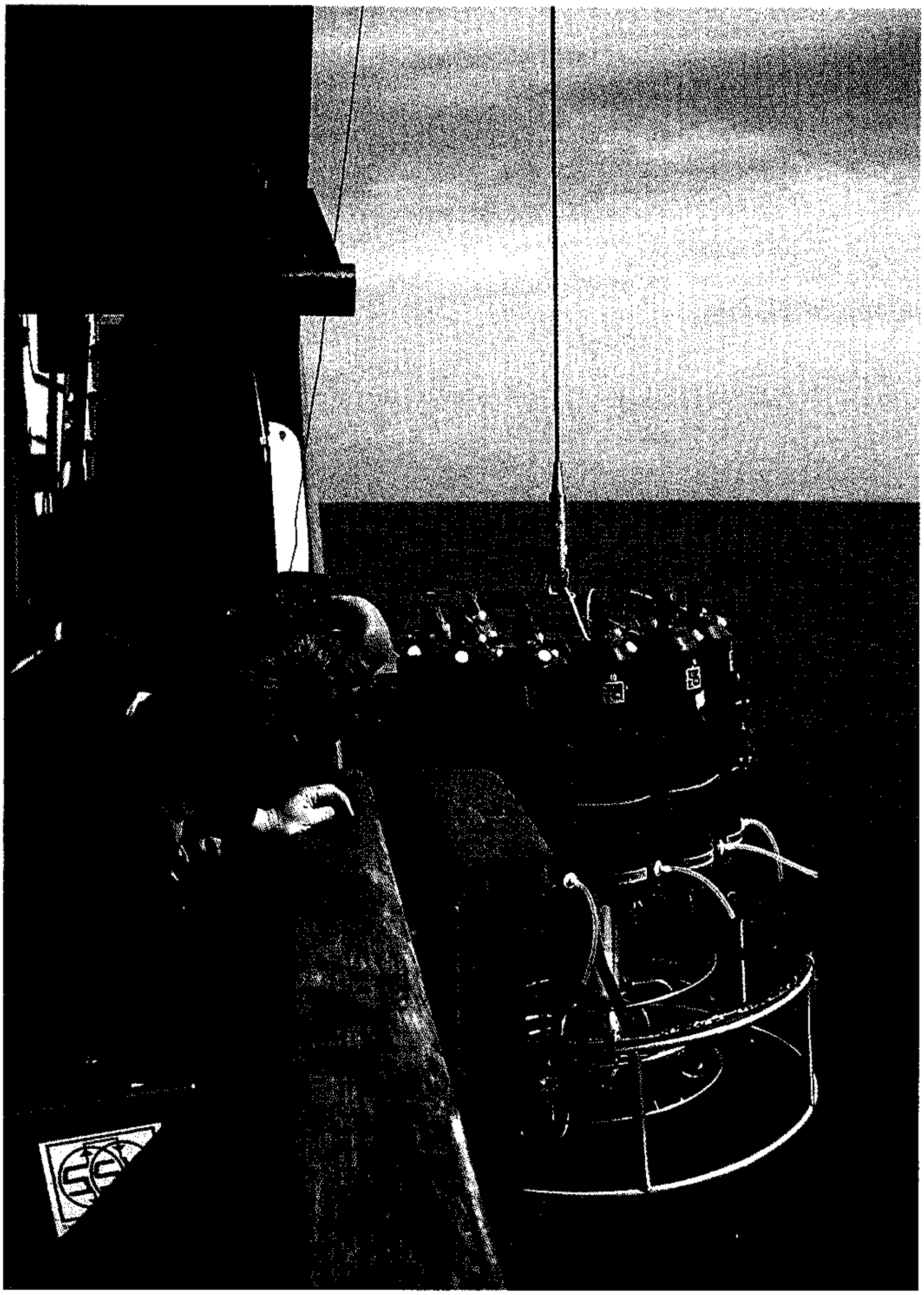
The oxygen content of the water is usually determined using a profiling CTD probe lowered through the water column. An oxygen electrode mounted on the probe provides continuous reading of the actual oxygen concentration.

In the case of the stations in the coastal waters, the oxygen data are usually measured at one-metre depth intervals until the final position, which is around 0.5 metre above the sea floor. At stations in the open marine waters, the oxygen content is measured in the surface water and at 5-metre depth intervals until 30 metres, and thereafter at 10-metre intervals until the final position 0.5 metre above the sea floor.

6.11.2 Evaluation of existing activities

The oxygen concentration of the water is an important parameter when documenting the effects of eutrophication. With long time series, it is possible to evaluate the effects of both loading conditions and the actual hydrographic and meteorological conditions. The oxygen concentrations are closely coupled to the hydrographic and meteorological conditions in the inner Danish marine waters, however, and in these areas it can therefore be difficult to demonstrate changes due solely to changes in loading. The development in oxygen conditions in the bottom water can nevertheless be determined in a statistically valid manner at a number of stations where the water masses are stratified, and where time series of oxygen concentrations are available.

The oxygen concentration of the bottom water is currently measured in connection with routine sampling of the water column. The oxygen concentration of the water can fall dramatically



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just above the sea floor as a result of oxygen consumption by the sediment (HAV90, Report 57). As underlined in Section 5.7, it is therefore of decisive importance to measure frequently and as close to the sediment as possible in order to obtain the true picture of the oxygen conditions and their development. In shallow estuarine fjords and coastal waters, the stratification of the water column can lie very close to the sea floor such that the oxygen concentration of the lowermost 10-30 cm can be extremely low, while the overlying water can be well oxygenated and well mixed. In such cases, a routine sample collected at a depth of 0.5-1 metre above the sediment will not reveal deteriorated oxygen conditions or incidents of oxygen deficit at the sea floor.

Based on the results of the HAV90 programme, there seems to be no doubt that the areas affected by oxygen deficit are far more widespread that one would expect from the data collected under the monitoring programme. For an optimal description of oxygen conditions in the bottom water it is imperative to measure the oxygen concentration a few centimetres above the sea floor. As the most commonly used measurement probes do not meet these requirements, there seems to be a great need to develop new instruments able to measure the oxygen concentration a few centimetres above the sediment surface or a new sampling tool able to collect undisturbed water samples from this depth.

The oxygen concentration of the bottom water can vary markedly from day to day in connection with bottom water transport. Such events can only be recorded by frequent measurements. As demonstrated in Section 5.7.1, there is a high risk that routine measurements (e.g. once per month) will fail to detect episodes of sudden oxygen deficit. Simultaneous measurements of oxygen content and salinity are therefore important in order to be able to trace horizontal or vertical transport of hypoxic bottom water and hence understand the development in oxygen conditions.

In order to monitor the oxygen content of the bottom water there therefore appears to be a need to further develop self-recording equipment able to continuously register the oxygen concentration and salinity of the water close to the sediment surface. The instruments should be placed in areas that are traditionally subject to oxygen deficit. The self-recording equipment will provide detailed information about oxygen conditions at the sea floor and the development thereof. Based on these measurements it would be possible to regularly update a detailed chart of oxygen conditions in the Danish marine waters.

In addition, there is a conspicuous need for a closer analysis of the effect of nutrient loading, hydrography, various biological components and meteorological factors on the emergence and distribution of oxygen deficit.

Recommendations for monitoring oxygen conditions and oxygen deficit

The deterioration in oxygen conditions seen in the Danish marine waters is a direct effect of the enhanced eutrophication. The oxygen concentration of the bottom water is therefore a central parameter in the monitoring of the environmental state of the marine waters. When measuring the oxygen concentration of the bottom water, it is important to measure as close to the sediment surface as possible in order to obtain the true picture of the occurrence and extent of possible oxygen deficit. The development and use of self-recording equipment able to continuously register and transmit data on salinity and oxygen concentration near the sediment surface is recommended. Measurements of the oxygen concentration of the bottom water should be spatially and temporally coordinated and should mainly be carried out in areas traditionally subject to oxygen deficit. The data obtained should be coupled to a number of physical and biological data in order to obtain a better understanding of how oxygen deficit arises in the individual areas so that necessary interventional measures can be initiated to ensure effective improvement in the oxygen content of the water.

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Undertitel: Conclusions and perspectives of the Marine Research Progamme HAV90

Forfattere: Christensen, Peter Bondo (redaktør); Møhlenberg, Flemming; Lund-Hansen, Lars C.; Borum, Jens; Christiansen, Christian; Larsen, Søren E; Hansen, Martin E.; Andersen, Jesper; Kirkegaard, Jørn

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Resumé:
Det danske vandmiljø har gennem flere årtier været belastet med næringsstoffer. Resultatet heraf er en generel forringelse af miljøtilstanden, der har medført ukontrolleret algevækst, dårlige lysforhold for bundplanter samt udbredt iltsvind og fiskedød. I erkendelse af disse problemer blev Vandmiljøplanen vedtaget i 1987 med det formål at nedbringe belastningen og forbedre miljøtilstanden af det danske vandmiljø. I forbindelse med Vandmiljøplanen blev Havforskningsprogram 90 igangsat. I bogen gøres der rede for, hvordan Havforskningsprogram 90 har bidraget med ny viden om tilførsel, transport, omsætning og effekter af næringsstoffer i de danske farvande. De fysiske og biologiske forhold i de danske fjorde, kystvande og i de åbne danske farvande beskrives. Endvidere vurderes det, hvordan den viden Havforskningsprogram 90 har bidraget med, kan anvendes i forbindelse med en optimering af overvågningen af havmiljøet.

Emneord: næringsstoffer; primærproduktion; hydrografi; iltforhold; stoftransport; omsætning; fjorde; kystvande; vandmiljøplanen; monitering; miljøtilstandsbeskrivelser; hav

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Danish Environmental Protection Agency

Abstract: Nutrients have been polluting the Danish marine environment for several decades. The result has been a general deterioration in environmental state leading to uncontrolled algal growth and poor light conditions for benthic plants, as well as widespread oxygen deficit and fish mortality. In acknowledgement of these problems, the Action Plan on the Aquatic Environment was adopted in 1987 with the objective of reducing nutrient loading of the Danish aquatic environment and improving its environmental state. The Marine Research Programme 1990 (HAV90) was established in connection with the Action Plan. This report examines the contribution of HAV90 to knowledge about the input, transport, turnover and impact of nutrients in Danish marine waters. The physical and biological conditions in the Danish estuarine fjords, coastal waters and open marine waters are described. In addition, the report evaluates how the new knowledge provided by HAV90 can be utilized to optimize monitoring of the marine environment.

Terms: Nutrients; primary production; hydrography; oxygen conditions; transport; turnover; mineralization; estuarine fjords; coastal waters; marine waters; Action Plan on the Aquatic Environment; monitoring; environmental state of the sea

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The Danish Marine Environment: Has Action Improved its State?

Nutrients have been polluting the Danish marine environment for several decades. The result has been a general deterioration in environmental state leading to uncontrolled algal growth and poor light conditions for benthic plants, as well as widespread oxygen deficit and fish mortality. In acknowledgement of these problems, the Action Plan on the Aquatic Environment was adopted in 1987 with the objective of reducing nutrient loading of the Danish aquatic environment and improving its environmental state. The Marine Research Programme 1990 (HAV90) was established in connection with the Action Plan. This report examines the contribution of HAV90 to knowledge about the input, transport, turnover and impact of nutrients in Danish marine waters. The physical and biological conditions in the Danish estuarine fjords, coastal waters and open marine waters are described. In addition, the report evaluates how the new knowledge provided by HAV90 can be utilized to optimize monitoring of the marine environment.

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