Nutrients and Eutrophication in Danish Marine Waters

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A Challenge for Science and Management

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A Challenge for Science and Management

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ISBN: 89-7772-728-2

See data sheet on page 126 for details.

Preface

The objective of this assessment report is to describe and document the effects and degree of nutrient enrichment and eutrophication status in all Danish marine waters by addressing the following questions:

- What is nutrient enrichment and eutrophication?
- What are the causes and actual effects?
- Temporal trends: what is natural variation and what is due to human activities?
- What has been done so far in Denmark to reduce eutrophication in Danish marine waters?
- How can the findings be used and transformed into an informed management strategy?

The assessment is written in order to fulfil the Danish obligations in relation to the OSPAR Common Procedure. However, the assessment covers not only the OSPAR areas: the North Sea, Skagerrak and Kattegat, but all Danish marine waters, including the transitional waters (the Sound and Belt Sea) between the Kattegat and the Baltic Sea, as well as the western parts of the Baltic Sea. This is because:

1) the outflow from the Baltic Sea has a large influence on the Kattegat – Belt Sea ecosystems, and
2) the eutrophic state and development of the Kattegat and Belt Sea runs in parallel and is interrelated.

The assessment focuses on factors and parameters that cause, control or respond to eutrophication. Special attention is put on ecological status and temporal trends. Seasonal variations and more system-orientated descriptions of the fluxes and turnover of nutrients have been mitigated. The assessment is not a comprehensive assessment of the health of the marine environment in Denmark or a textbook in marine ecology. The assessment is more or less an extended summary of more than 13 years of monitoring and subsequent production of different assessments reports on the state of the marine environment within the framework of the Danish National Monitoring and Assessment Programme (1988-2003).

Chapter 1

presents background information, definitions and descriptions of the cause-effect relationships as well as a brief reference to the Danish National Monitoring and Assessment Programme, which is the major source of data for this assessment.

Chapter 2

includes the technical and scientific assessment of the eutrophication status of the Danish marine waters and is structured according to the principles and guidelines adopted by OSPAR. Focus is on the state of the marine waters compared to the ecological quality objectives. The temporal trend is also addressed, both with respect to the observed data and indices corrected for variations in climate (run-off, temperature, insolation etc.).

Chapter 3

describes existing national strategies and measures implemented to abate nutrient enrichment and eutrophication.

Chapter 4

summarises the findings of sections 1, 2 and 3, assesses the overall eutrophication status of the Danish marine waters and discusses possible future actions.

The assessment includes a glossary and a list of acronyms in order to reach readers without a professional background in marine ecology or oceanography.

Suggestions for further reading as well as links to relevant web-sites on eutrophication and the health of the marine environment can be found at the end of the report.

A map of Danish marine waters mentioned in the assessment can be found at page 122.

Contents

All people in Denmark have less than 55 km to the sea.

Photo: CDanmark

Background, definition, causes and effects

1

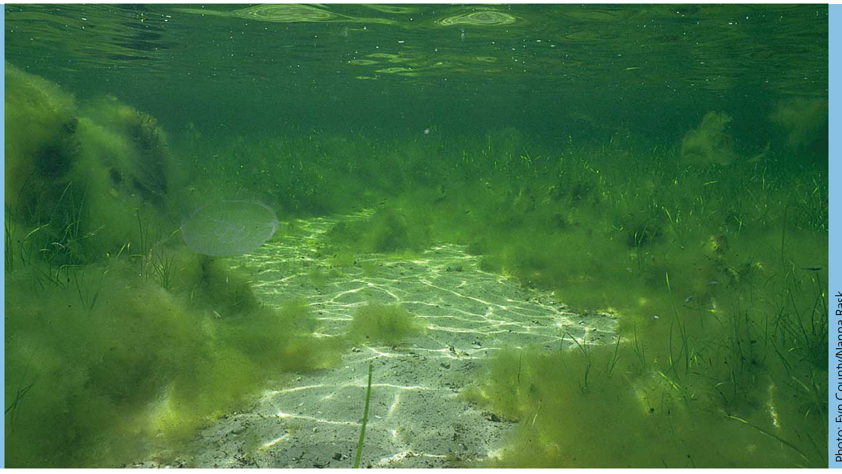
For more than 30 years, nutrient enrichment has been one of the major threats to the health of marine ecosystems and resources (Ryther & Dunstan 1971, Danish EPA 1984, Nixon 1995, Elmgren 2001). When nutrients are discharged or transported to the sea their inherent characteristics as plant nutrients affect and modify the structure and function of the ecosystem. The response to nutrient enrichment is called eutrophication.

Photo: NERI/Peter Bondo Christensen

Photo: NERI/Jan Damgaard

1.1

Definition



Eelgrass covered with filamentous green algae, a sign of nutrient enrichment.

There is no single and globally accepted definition of marine eutrophication. The word "eutrophication" has its roots in Greek where "eu" means "well" and "trope" means "nourishment".

Nixon (1995) defines marine eutrophication as "an increase in the supply of organic matter". The supply is not restricted to pelagic primary production, but also includes bacterial production, primary production of submerged aquatic vegetation, inputs of organic matter from land via rivers and point sources as well as the net advection from adjacent waters. The advantage of this definition is that it is short, simple and does not confuse causes and effects. The limitations of the definition are 2 fold. It does not take structural or qualitative changes due to nutrient enrichment into account, and it is difficult to make fully operational since the majority of existing marine monitoring programmes seldom include all the variables needed to estimate the total supply of organic matter to a given body of water.

Gray (1992) focuses on the direct effects of nutrient enrichment on productivity, the secondary effects where the produced organic material is not consumed by grazers, and the extreme and ultimate effects, which includes the growth of macroalgae, oxygen depletion and mortality of species. Richardson & Jørgensen (1996) focus both on the process, the associated effects of nutrient enrichment and natural versus cultural caused eutrophication. Prudently, Richardson & Jørgensen point out that when we speak of eutrophication it is cultural eutrophication or that, which is caused by anthropogenic activities, which is of interest.

The definition of eutrophication by OSPAR is: "Eutrophication means the enrichment of water by nutrients causing an accelerated growth of algae and higher form of plant life to produce an undesirable disturbance to the balance of organisms present in the water and to the quality of the water concerned, and therefore refers to the undesirable effects resulting from anthropogenic enrichment by nutrients" (OSPAR 1998). A number of EU Directives also defines eutrophication. In the Urban Wastewater Treatment Directive eutrophication means: "The enrichment of water by nutrients, especially compounds of nitrogen and/or phosphorus, causing an accelerated growth of algae and higher forms of plant life to produce an undesirable disturbance to the balance of organisms present in the water and to the quality of the water concerned" (EU 1991). The Nitrates Directives definition is almost identical, except that it is restricted to eutrophication from agriculture (EU 1991).

The differences between the various definitions leave the definition open for interpretation. However, this is not critical, as long as there is a common understanding of the effects and agreement upon the acceptable levels of deviations from a healthy marine environment. Eutrophication should be seen both as a process and as a continuum, since the background values may vary from area to area due to natural causes. For example, the productivity in the open Baltic Sea is relatively low compared to the southern and eastern parts of the North Sea. Therefore, when speaking of eutrophication, both the initial process and direct effects (sensu Nixon) and the derived primary and secondary effects should be taken into account, cf. box 1.

BOX 1 Definition of eutrophication

Eutrophication is the enhanced inputs of nutrients and organic matter leading to changes in primary production, biological structure and turnover and resulting in a higher trophic state. The causative factors are: elevated inputs of nutrients from land, atmosphere or adjacent seas, elevated winter DIN- and DIP concentrations, and increased winter N/P-ratios compared to the Redfield Ratio. In the case of marine waters, the primary or direct effects include: increased primary production, elevated levels of biomass and chlorophyll *a* concentrations, shift in species composition of phytoplankton, and shift from long lived macroalgae to short lived nuisance species. The secondary or indirect effects include increased or lowered oxygen concentrations, and changes in species composition and biomass of zoobenthos. Low oxygen concentrations in the bottom water (oxygen depletion, hypoxia) can further affect the fish, benthic invertebrates and plants. Total oxygen depletion (anoxia) 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 recolonise damaged areas, eutrophication can result in impoverished biological communities and impaired conditions.

1.2 Causes

Liquid manure spread on field in February.

Photo: Biofoto/Bent Lauge Madsen

The essential nutrients causing eutrophication are nitrogen in the form of nitrate or ammonium and phosphorus in the form of phosphate. In addition, inputs of bioavailable organic phosphorus and nitrogen can cause eutrophication, as bacteria can mineralise the organic phosphorus to phosphate and the organic nitrogen to ammonium, which is further oxidised to nitrite and nitrate.

Marine waters receive dissolved and particulate nutrients and organic matter from land via rivers and direct discharges, from the atmosphere and from adjacent seas (see Figure 1.1). In Denmark the most important direct sources are:

1) agriculture,
2) discharges from urban wastewater treatment plants, and
3) separate discharges from industries,

the first being the most important diffuse source. Discharges from point sources, losses from agriculture and atmospheric deposition are monitored as an integrated part of the National Aquatic Monitoring and Assessment Programme and reported annually (Conley et al. 2002).

The inputs from adjacent seas are also monitored within the national monitoring programme. There are three major avenues of advective transport of nutrients that must also be considered:

1) Inputs from the German Bight to the waters along the west coast of Jutland.
2) Inputs of inorganic nutrients from Skagerrak to the Kattegat bottom water.
3) Inputs of surface waters from the Baltic Sea to the Danish Straits and Kattegat.

All three sources have influence on the marine environment by supplying additional nutrients. The waters from the German Bight and the Baltic Sea have already received high inputs of nutrients. The input from the Baltic Sea differs from the two firsts because it actually dilutes bioavailable nitrogen concentrations in the Danish Straits and the Kattegat. The median winter surface concentrations of nitrate (1986–1993) in the water from the Baltic is 4.6 µM compared to the median concentrations in the waters in the Danish Straits and Kattegat, which are 7.3 (6.5–8.8) µM and 7.4 (6.0–9.7) µM, respectively.

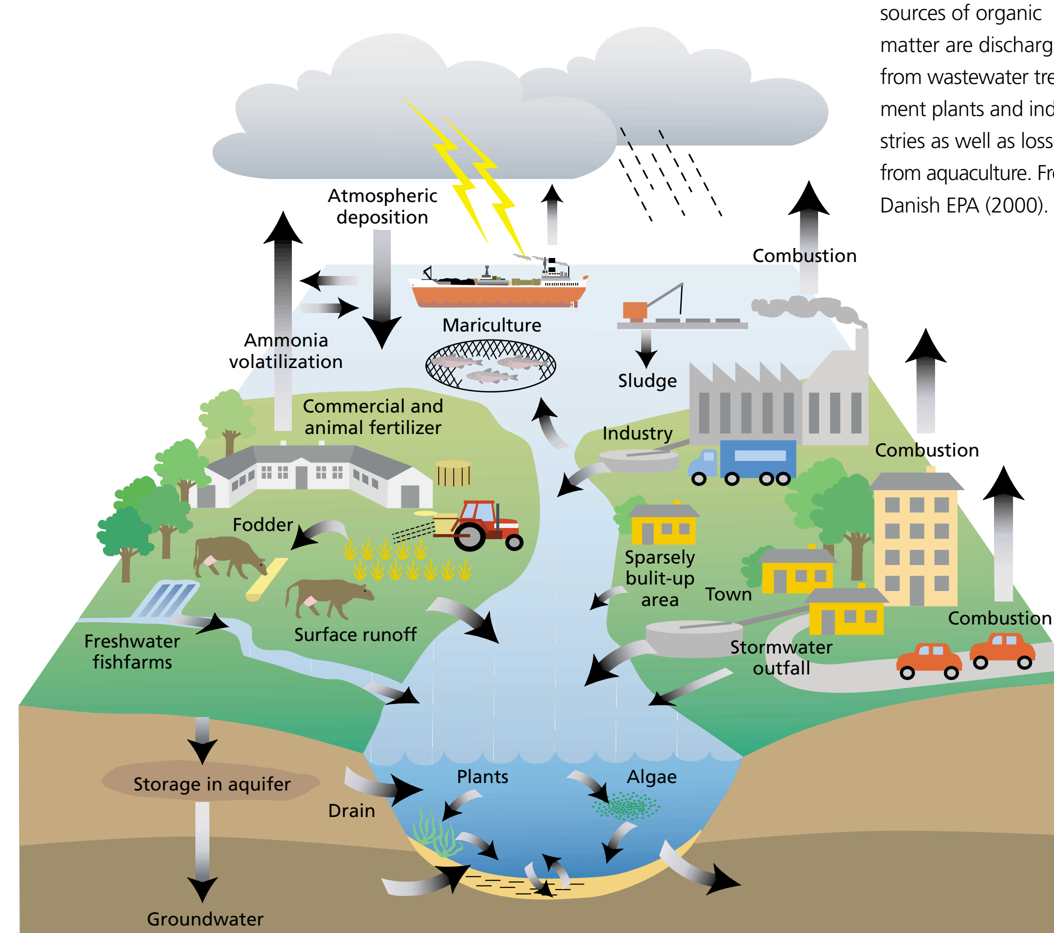


Figure 1.1
The nitrogen cycle in the aquatic environment. All relevant sources are shown. The major difference between the nitrogen and phosphorus cycles is that phosphorus is not emitted to the air and that there consequently is no anthropogenic deposition. The main anthropogenic sources of organic matter are discharges from wastewater treatment plants and industries as well as losses from aquaculture. From Danish EPA (2000).

1.3 Effects and consequences

Growth of the nuisance algae *Ulva* sp. is stimulated by high nutrient concentrations.

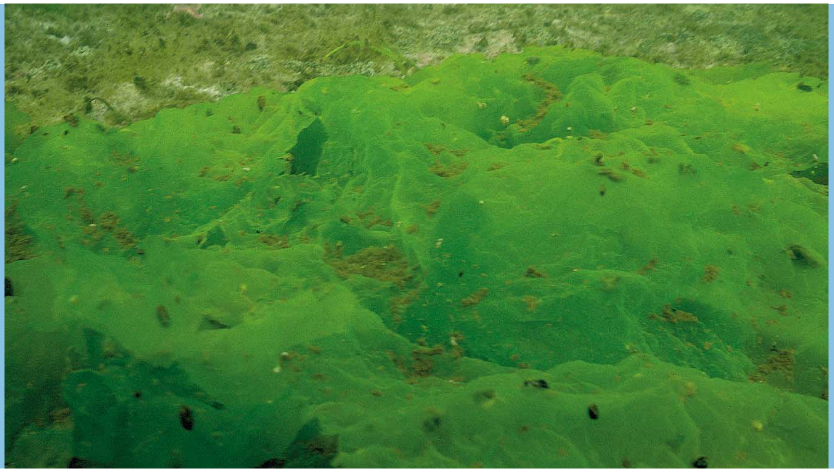


Photo: Fyn County/Nanna Rask

Overloading with nitrogen, phosphorus and organic matter can result in a series of undesirable effects. The major impacts of eutrophication include changes in the structure and functioning of marine ecosystems and reduction of biodiversity.

Nutrient concentrations

Eutrophication as nutrient enrichment means elevated and/or increased trends in inputs of nutrients from land, atmosphere or adjacent seas. And consequently elevated dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP) concentrations during winter.

Changes in N:P:Si ratio

The optimal DIN:DIP ratio (N/P-ratio) for phytoplankton growth is 16:1 (based on molar concentrations) and called the Redfield ratio. Significant lower deviations of the N/P-ratios indicate potential nitrogen limitation and higher N/P-ratios potential phosphorus limitation of phytoplankton primary production. Deviations from the Redfield ratio limit phytoplankton primary production, and affect phytoplankton biomass, species composition and consequently food web dynamics. Redfield ratios for diatoms for Si:N and Si:P ratios are 1:1 and 16:1, respectively (based on molar concentrations), and the abundance of silicate relative to nitrogen and phosphorus effect the growth of diatoms.

Phytoplankton primary production and biomass

Primary production is most often limited by the availability of light and nutrients. Nutrient enrichment will therefore increase phytoplankton primary production. Consequently there will be an increase in phytoplankton biomass. Elevated phytoplankton production and biomass will increase sedimentation of organic material. Changes in the pelagic ecosystem could enhance the sedimentation. See microbial loop below.

Microbial loop and the pelagic system

The microbial loop may be enhanced by changes in the species composition and functioning of the pelagic food web when growth of small flagellates rather than diatoms is stimulated. The shift in phytoplankton cell size leads to lower grazing by copepods and possibly an increased sedimentation. The smaller cells will on the other hand increase the relative importance of grazing by ciliates and heterotrophic dinoflagellates. A larger fraction of the primary production is consequently channelled through the protozooplankton before it is available to the copepods.

The general responses of pelagic ecosystems to nutrient enrichment can in principle be a gradual change towards:

1) Increased planktonic primary production compared to benthic primary production.
2) Microbial food webs dominate versus linear food chains.
3) Non-siliceous phytoplankton species dominate versus diatom species.
4) Gelatinous zooplankton (jellyfish) dominate versus crustacean zooplankton.

Light and sedimentation

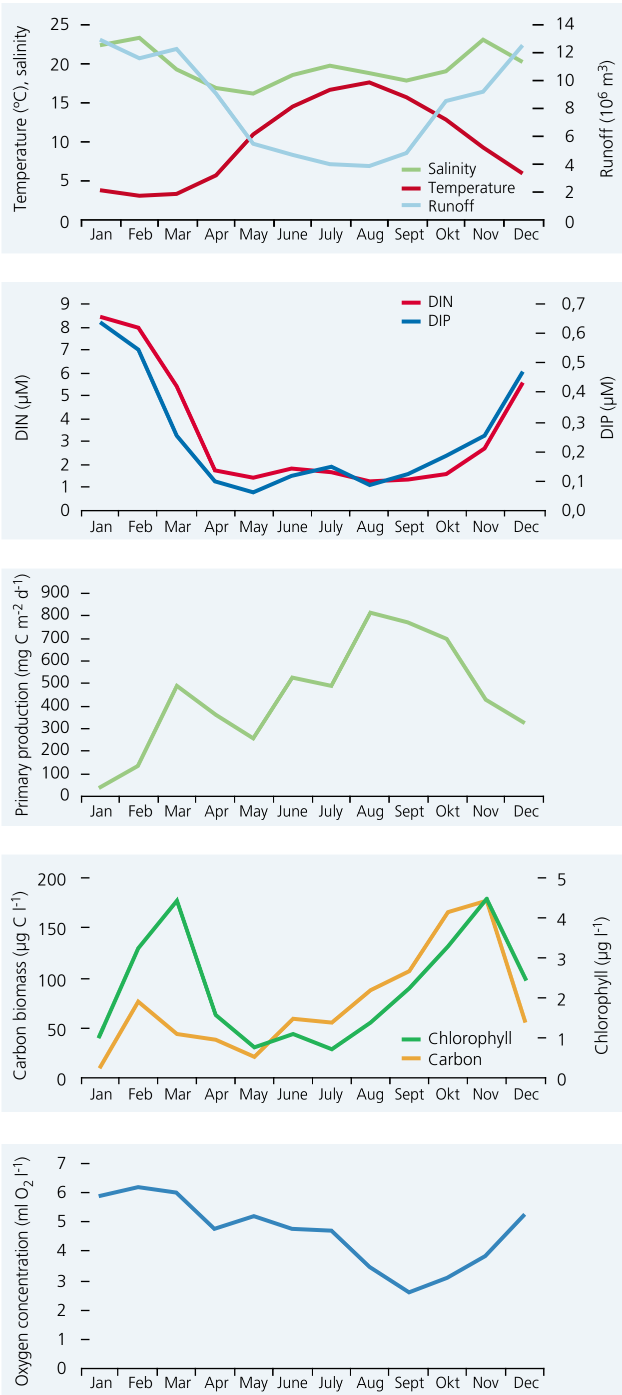
The Secchi depth, a measure of the turbidity and light penetration in the water column, is negatively affected by chlorophyll. Increased trends in inputs of nutrients increase phytoplankton biomass and reduce the Secchi depth. This decreases the colonisation depths of seagrasses and macroalgae.

Oxygen concentrations

Increased animal and bacterial activity at the bottom due to increased amounts of organic matter settling to the bottom increases the total oxygen demand. The increase can lead to oxygen depletion and release of H_2S from the sediment. This will induce changes in community structure or death of the benthic fauna. Bottom dwelling fish may either escape or die.

Phytoplankton respond rapidly to changes in nutrient concentrations and can be used as an indicator of eutrophication status.

Photo: Århus County/Helene Munk Sørensen



Seasonal signals

Many of the eutrophication effects as well as some of the driving forces have a pronounced seasonal variation. Fresh-water run-off, temperature and salinity have a strong seasonal signal. The same is the case for inorganic nutrient concentrations, phytoplankton primary production, chlorophyll *a* concentrations, phytoplankton biomass and oxygen concentration in bottom water. The seasonal variations are illustrated in Figure 1.2. This assessment report will, as mentioned in the preface, neither analyse the role of eutrophication on the seasonal succession in these parameters nor the changes in turn-over or fluxes of nutrients during spring, summer and autumn.

Figure 1.2
Seasonal variation at the station "Gniben" located in south-western Kattegat. Monthly averages during the period 1998-2001.

A – Runoff, salinity and temperature
B – N- and P-concentrations
C – Primary production
D – Chlorophyll *a* + Carbon-biomass
E – Oxygen concentration in bottom water

Sediments

In the Danish marine areas a significant portion of the primary production during the spring sediments to the sea bottom. An increase in primary production means that the sediment will experience elevated inputs of organic material. This leads to increased bacterial activity, hence an increase in oxygen demand.

Submerged aquatic vegetation

Eutrophication in general affects submerged vegetation in two different ways. Reduced light penetration and shadowing effect from phytoplankton can reduce the depth distribution, biomass, composition and species diversity of the plant community. Increased nutrient levels favour opportunistic macroalgae species. The stimulated growth of filamentous and annual nuisance species at the expense of perennials will result in a change in macroalgae community structure with reduced species diversity and reduced nurseries for fish. The dominance of filamentous macroalgae in shallow sheltered areas will increase the risk of local oxygen depletion.

Benthic fauna

The increased load of organic material to the bottom affects the macrozoobenthic community. The enrichment will enhance growth and increase species diversity and biomass. A change in community structure will follow favouring suspension and burrowing detritus feeders. Reduction in species diversity and biomass will follow at progressively higher levels of organic load, and opportunistic species will be favoured. Oxygen depletion will lead to a further reduction in species diversity, and mass mortality of most organisms, especially due to production of H_2S in sediments.

Social consequences

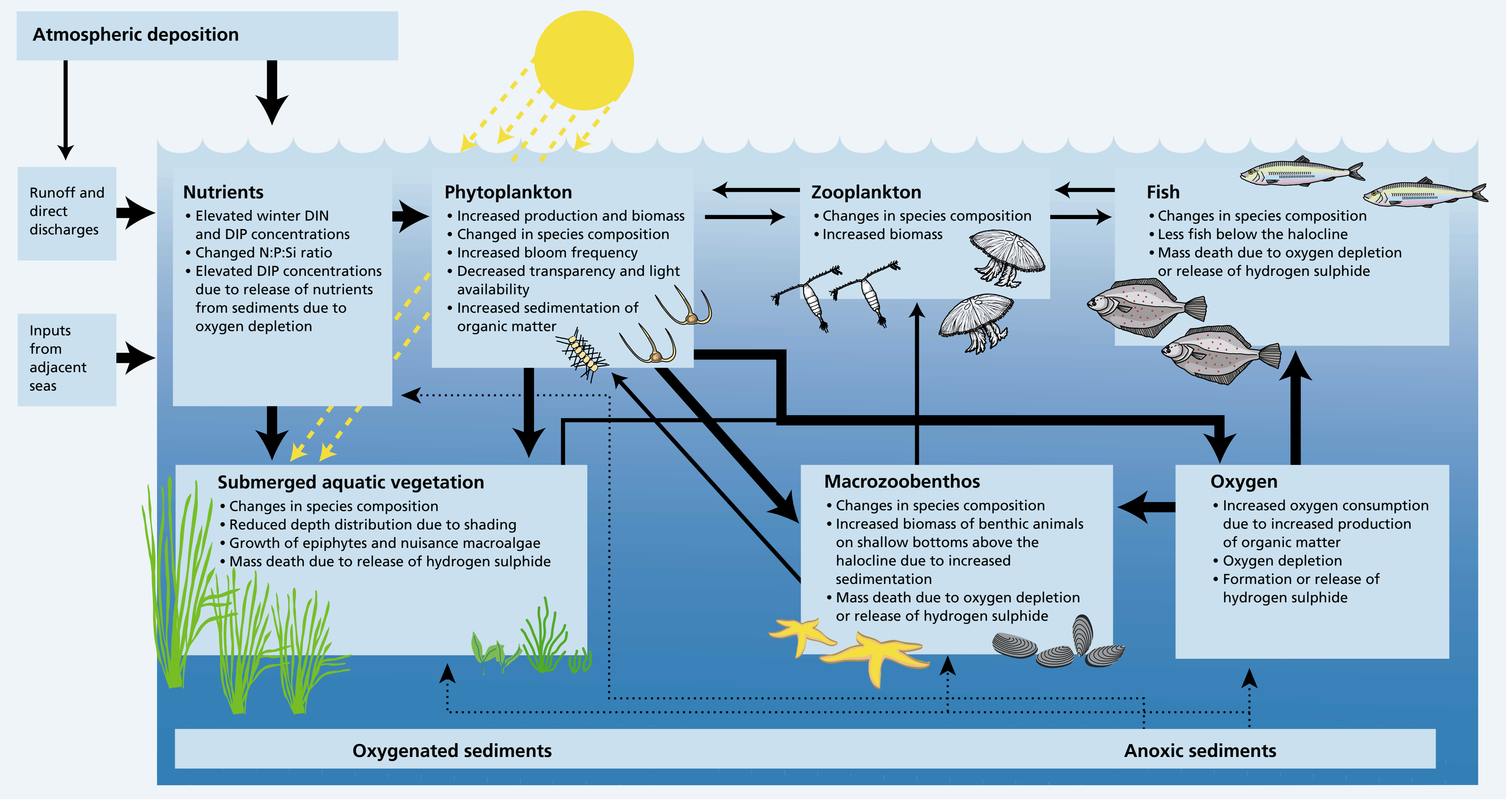
Reductions in dermersal fish and shellfish due to oxygen depletion and harmful algal blooms will reduce harvests. In the case of commercial fisheries these changes have large economic implications. The increased risk of toxic and harmful blooms will also affect mariculture, which can also be influenced by oxygen depletion. Another consequence of toxic algal blooms is the risk of shellfish poisoning of humans by algal toxins. The recreational value of beaches especially for swimming is reduced due to reduced water quality induced by discoloration and foam formation by algal blooms or decaying rotting macroalgae. This could particularly impact tourism at beaches.


Photo: NERI/Britta Munter

Conceptual understanding of eutrophication

Figure 1.3 illustrates in a simplified way the effects and consequences of nutrient enrichment and eutrophication in the marine environment.

Figure 1.3
Conceptual model of marine eutrophication with lines indicating interactions between the different ecological compartments. A balanced system in Danish marine waters is supposedly characterised by:
1) A short pelagic food chain (phytoplankton → zooplankton → fish)
2) Natural species compositions of planktonic and benthic organisms
3) A natural distribution of submerged aquatic vegetation
Nutrient enrichment results in changes in the structure and function of marine ecosystems as indicated with bold lines. Dashed lines indicate release of hydrogen sulphide (H_2S) and phosphorus, which is positively linked to oxygen depletion. Based on OSPAR 2001 and Rönnberg 2001.



The health of
the Danish marine
environment is
of great public
interest.

Photo: CDanmark

Technical-scientific assessment

2

This assessment is based on data from the Nationwide Aquatic Monitoring Programme (1988–1997) and the National Aquatic Monitoring and Assessment Programme (1998–2003) (See Danish EPA 2000 for details). The data used for this assessment covers the period 1989–2001 (in some cases only 1989–2000). In a limited number of analyses other data have been included for support.

The national monitoring programme is run in collaboration between the Danish Counties and NERI. The counties are responsible for the activities within the coastal waters. NERI carries out most of the monitoring of the open marine waters, co-ordinates the programme, runs the national marine database and produces annual reports on the state of the marine environment.

Marine eutrophication is an international problem and can only be solved by co-ordinated national and international efforts. The same principle applies for assessment of eutrophication status of marine waters receiving and transporting nutrients from different countries. Therefore, it is important that Denmark and the neighbouring countries (Germany, Norway, and Sweden) have almost harmonised ways of assessing the eutrophication status of common waters. Such common understanding of principles and criteria are discussed and agreed within OSPAR and HELCOM.

The OSPAR Strategy to Combat Eutrophication is together with the monitoring activities among the main drivers of the assessment process (OSPAR 1998). The strategy has the aim of identifying the eutrophication status of all parts of the convention area by the year 2002. The Common Procedure for the Identification of the Eutrophication Status of the Maritime Area is a main element of the strategy. The Common Procedure includes a checklist of qualitative assessment criteria to be used when assessing eutrophication status. In addition, a set of quantitative criteria has been developed in order to assist a harmonised assessment (OSPAR 2001). These assessment criteria fall into the following four categories:

I: Degree of nutrient enrichment.
II: Direct effects of nutrient enrichment.
III: Indirect effects of nutrient enrichment.
IV: Other possible effects of nutrient enrichment.

The harmonised assessment criteria and the assessment levels are summarised in Box 2.

Assessments of eutrophication status of the marine environment should be based on knowledge of how the situation would be without any anthropogenic influence. Two factors are important when assessment criteria are developed:

- What are the reference conditions for the given parameter?
- What are an acceptable deviation from reference conditions?

The principle of assessing the actual state of the environment in relation to the reference conditions is important. However, the critical factor is not the definition of background conditions but the decision on acceptable deviation from background values. The OSPAR assessment criteria acknowledge this and give the countries the opportunity to establish national, regional or even site-specific criteria.

Recent work in relation to the national implementation of the Water Framework Directive and the Habitat Directive has focused on reference conditions and classification of ecological quality for eelgrass and macroalgae and the parameters controlling the growth of submerged aquatic vegetation (chlorophyll, Secchi depth, runoff, nutrient concentrations, depth etc.). The on-going work with regard to classification of ecological quality shows:

- The acceptable deviation should be 15-20%, cf. Henriksen et al. 2001.
- A generally acceptable deviation of 25% will result in a limited number of false positive situations when compared to the existing Danish assessments principles, cf. Krause-Jensen et al. (subm.).
- The Swedish assessment criteria (Swedish EPA 2000) for macroalgae will be met almost every year, even in wet years with high anthropogenic inputs of nutrient, to the marine environment, cf. Henriksen et al. 2001.
- A 50% deviation from reference conditions for macrovegetation at reefs in Kattegat suggests that the reefs are not subject to eutrophication at all, cf. Henriksen et al. 2001.

The OSPAR eutrophication assessment criteria have therefore been adjusted at a national level. The Danish assessment criteria are:

- The acceptable deviation for winter DIN and DIP concentrations is 25%, cf. Henriksen et al. 2001.
- The acceptable deviation for maximum and mean chlorophyll *a* is 25%, cf. Henriksen et al. 2001. The growing season covers the period March – October.
- The acceptable deviation for macrophytes including macroalgae is 25%, cf. Krause-Jensen et al. (subm.) and Henriksen et al. 2001.
- The Danish oxygen depletion criteria are: severe acute oxygen depletion: 0-2 mg O_2 l^{-1}, oxygen depletion: 2-4 mg O_2 l^{-1}. These values have been national assessment criteria since the mid-1980s. The OSPAR criteria are: < 2 mg l^{-1} and 2-6 mg l^{-1}. These criteria are not applicable for Danish marine waters, where the oxygen concentrations due to natural reasons may be 5-6 mg l^{-1}. Such values are region specific and due to strong stratification in summer and autumn, which prevents the saline, cold bottom waters from being mixed with the brackish and oxygenated surface waters. The Danish assessment criteria match the natural effect criteria. Fish will try to avoid waters with oxygen concentrations below 4 mg l^{-1}. Fish and benthic invertebrates can only survive concentrations below 2 mg l^{-1} for a limited time.


Photo: NERI/Britta Munter

Box 2 summarises the OSPAR eutrophication quality objectives (EQO-eutro) and the Danish criteria used in this assessment.

Background data describing reference conditions when anthropogenic inputs of nutrients were at natural levels are scarce. Hence descriptions of ecological structure and function before the enrichment took place is subject to an element of uncertainty. Box 3 summarises the current understanding of the reference conditions in Danish marine waters.

The implementation of the EU Water Framework Directive and the development of Ecological Quality Objectives (EQOs) defining the ecological status of all European coastal waters will represent a major step forward. The descriptions of ecological status will be based on commonly agreed definitions of reference conditions. The basis for assessing the ecological status will change from expert judgements to operational and numeric quality classes.

An EU funded R&D project "Characterisation of the Baltic Sea Ecosystem: Dynamics and Function of Coastal Types" (CHARM) will be a major contribution to this in the Baltic Sea/ Kattegat Area. One of the products of the CHARM project, which runs for the years 2002-2004, is descriptions of reference conditions for nutrients, phytoplankton, submerged aquatic vegetation and macrozoobenthos.

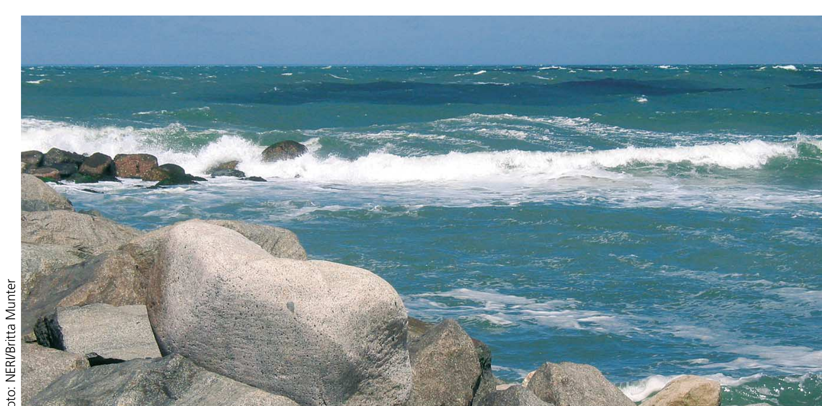


Photo: NERI/Britta Munter

BOX 2 The OSPAR eutrophication quality objectives (ECO-eutro) and the Danish criteria used in this assessment

OSPAR EAC	Danish ECO-eutro	See page
I: Degree of nutrient enrichment (causative factors)		
1 Riverine total N and total P inputs and direct discharges (RID) *Elevated inputs and/or increased trends (compared with previous years)*	**25 %**	**28–35**
2 Winter DIN- and/or DIP concentrations *Elevated level(s) (defined as concentration > 50 % above salinity related and/or region specific background concentration)*	**25 %**	**36–41**
3 Increased winter N/P ratio (Redfield N/P = 16) *Elevated cf. Redfield (>25)*	✔	**43–44**
II: Direct effects of nutrient enrichment (growing season)		
1 Maximum and mean Chlorophyll *a* concentration in March–October *Elevated level (defined as concentration > 50 % above spatial (offshore) / historical background concentrations)*	**25 %**	**46–51**
2 Region/area specific phytoplankton indicator species *Elevated levels (and increased duration)*	✔	**41–53**
3 Macrophytes including macroalgae (region specific) *Shift from long-lived to short-lived nuisance species (e.g. Ulva)*	✔	**68–76**
III: Indirect effects of nutrient enrichment (growing season)		
1 Degree of oxygen depletion *Decreased levels (<2 mg O_2 l^{-1}: acute toxicity; 2-6 mg O_2 l^{-1}: deficiency)*	**< 2 and 2–4 mg l^{-1}**	**58–76**
2 Changes/kills in zoobenthos and fish kills *Kills (in relation to oxygen depletion, H_2S and/or toxic algae)* *Long term changes in zoobenthos biomass and species composition*	✔	**76–79, 80–83**
3 Organic Carbon/Organic Matter (in sediments) *Elevated levels (in relation to III.1) (relevant in sedimentation areas)*	✔	**62–67**
IV: Other possible effects of nutrient enrichment (growing season)		
1 Algal toxins (DSP/PSP mussel infection events) *Incidence (related to Category II.2)*	✔	**52–53**

BOX 3 Background or reference conditions

Nutrients

Background winter concentrations for DIN in the Kattegat, the Skagerrak and the North Sea and in the Wadden Sea has within OSPAR provisionally been estimated to 4-5, 10, and 6.5 µmol l^{-1}, respectively. Winter DIP concentrations have been estimated to 0.4, 0.6 and 0.5 µmol l^{-1}, respectively.

Phytoplankton biomass and production

Chlorophyll *a* background concentration for offshore areas in the Skagerrak has within OSPAR been estimated to <1.25 µg l^{-1}, and for the North Sea coast to 2-10 µg l^{-1}. The phytoplankton primary production in the Kattegat and Belt Sea has increased from 80-100 mg C m^{-2} $year^{-1}$ in the 1950s – 1960s to 120-290 mg C m^{-2} $year^{-1}$ in the 1970s – 1980s (Ærtebjerg Nielsen et al. 1981; Richardson & Christoffersen 1991; Heilmann et al. 1994, Richardson & Heilmann 1995).

Oxygen

From scattered measurements of oxygen concentrations in Danish waters from the period 1902–1975 and more systematic measurements since then it seems that the major decrease took place from the 1960s to the late 1980s. In the Kiel Bight the bottom water oxygen concentration in July-August decreased from about 8 mg O_2 l^{-1} in the late 1950s to about 4 mg O_2 l^{-1} in the late 1980s (Babenerd 1991). Trend analysis of bottom water oxygen concentrations in late summer – autumn in the Kattegat and Belt Sea area generally shows a decrease of 1.5-2.2 mg O_2 l^{-1} during the period from mid 1970s to about 1990 (Ærtebjerg et al. 1998).

Eelgrass

In 1900, eelgrass was widely distributed in Danish coastal waters, and covered approximately 6726 km^2 or 1/7 of all Danish marine waters. In the 1930s, the world wide wasting disease substantially reduced eelgrass populations, especially in north-west Denmark. In 1941, eelgrass covered only 7% of the formerly vegetated areas, and occurred only in the southern, most brackish waters and in the low saline inner parts of Danish estuaries. Analyses of aerial photos from the period 1945–1990s, reveal an initial time lag of more than a decade before substantial re-colonisation of the shallow eelgrass populations began. The photos also show that large populations had recovered in the 1960s. Today eelgrass again occurs along most Danish coasts but has not reached the former area extension. Comparisons of eelgrass area distribution in two large regions, the Sound and Limfjorden, in 1900 and in the 1990s, suggest that the present distribution area of eelgrass in Danish coastal waters constitutes approximately 20-25% of that in 1900. Reduction in area distribution is partly attributed to loss of deep populations. In 1900 colonisation depths averaged 5-6 m in estuaries and 7-8 m in open waters, while in the 1990s the colonisation depths were about halved to 2-3 m in the estuaries and 4-5 m in open waters.

Macrozoobenthos

There have been changes of macrozoobenthos communities in the Kattegat area over the last 100 years. The reference material is mainly the large-scale mapping performed by C.G.J. Petersen at the end of the 19th and the beginning of the 20th century. Comparisons in the 1980s and 1990s indicate that biomass, and then probably secondary production, has increased with at least a factor of 2. Main contribution to the increase in deeper waters is from the suspension-feeding brittle star *Amphiura filiformis* and some polychaetes, whereas some amphipod crustaceans have decreased in importance. In shallower waters it is likely that biomass of bivalves have increased as has been documented from the eastern and southern Baltic Sea. Local reductions of benthic faunal biomass due to hypoxia seems to have occurred at times in recent decades both in the southern Kattegat, the Belt seas and some Danish estuaries.

2.1 Climate

Climate influences the ecological response to nutrient enrichment.

Photo: High-lights

The Danish marine waters are continuously affected by short term variations in freshwater runoff, air temperature, wind forcing and solar radiation, governing the nutrient load, water temperature, water exchange and stratification as well as irradiance available for primary production. Large inter annual variations are also present in these driving forces, especially concerning runoff. However, no general trend is detected in the time series over the last 25 years.

The climatic driving forces are used in later chapters in an attempt to correct the chemical and biological indicators for natural climatic induced variations.

Freshwater runoff from Denmark to the Kattegat and Belt Sea varied between a minimum of 4.84 km^3 in 1976 to a maximum of 12.52 km^3 in 1994. Runoff was generally low in the mid 1970s, high during the 1980s, 1994–95 and 1998–2000, and very low in 1976, 1989 and 1996–97 (Figure 2.1).

The annual mean air temperature at Sprogø in the middle of the Great Belt varied from 5.8°C in 1987 to 8.3°C in 1990 (Figure 2.2). The mean summer (May–Aug.) solar radiation measured close to Copenhagen varied from 175 to 244 W m^{-2} in 1987 and 1976, respectively (Figure 2.3).

The mean annual wind speed measured 70 m above sea level at Sprogø in the Great Belt varied from 6.3 m s^{-1} in 1985 to 7.1 m s^{-1} in 1994 (Figure 2.4).

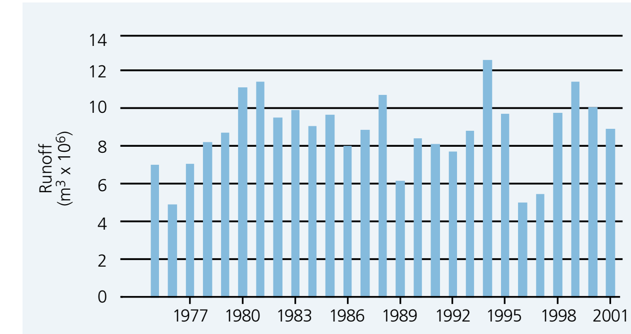


Figure 2.1
Annual runoff from Denmark to the Kattegat – Belt Sea area 1975-2001. (Data from NERI).

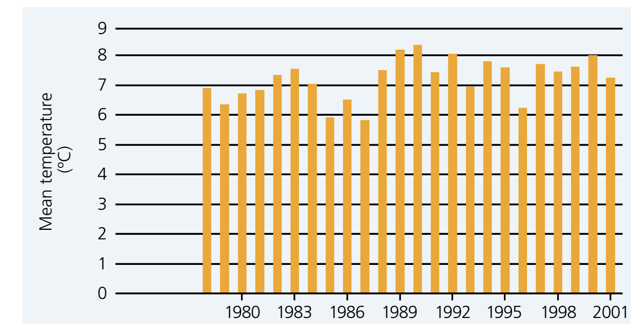


Figure 2.2
Annual mean air temperature measured at Sprogø/Risø 1978-2001. (Data from Sund og Bælt Holding and Wind Energy Department, Risø National Laboratory).

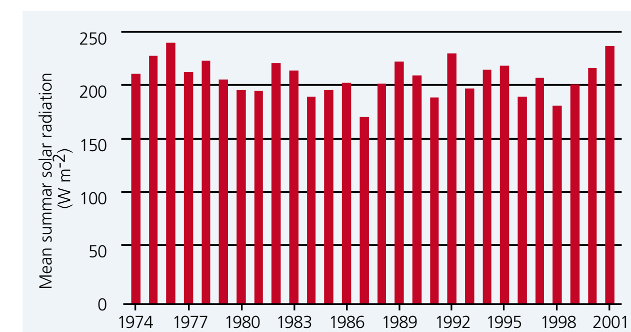


Figure 2.3
Mean summer (May-Aug.) solar radiation measured at Højbakkegård/Risø. (Data from Laboratory for Agrohydrology and Bioclimatology, Department of Agricultural Sciences, The Royal Veterinary and Agricultural University, and Wind Energy Department, Risø National Laboratory).

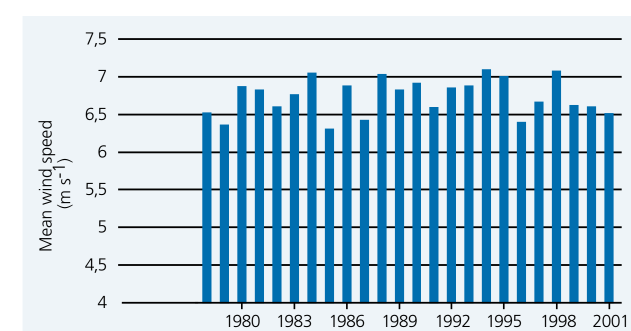
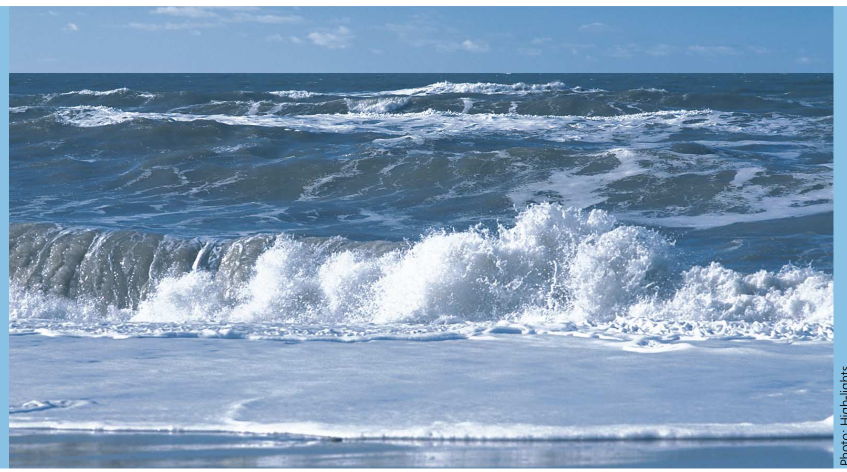


Figure 2.4
Mean annual wind speed at Sprogø/Risø 1978-2001. (Data from Sund og Bælt Holding and Wind Energy Department, Risø National Laboratory).

2.2 Hydrography

The Danish marine areas can be illustrated by the picture of Denmark and its islands situated in a river mouth with the Baltic Sea as the river.



The Danish marine area is very diverse and includes many semi-enclosed estuaries and fjords, open estuaries and bights, narrow straits, semi-enclosed seas as the Baltic and Kattegat and open shelf seas as the Skagerrak and North Sea (see page 122).

The annual freshwater net surplus of about 475 km^3 from the Baltic Sea passes through the Danish straits (Sound and Belt Sea) and Kattegat to the Skagerrak/North Sea. The salinity of the outflowing Baltic water is about 8 and forms a brackish surface layer in the transition area with the salinity increasing to 25-30 at the Skagerrak border due to mixing with saline bottom water. High saline Skagerrak water flows as bottom water into the Kattegat and Belt Sea. This creates a strong halocline in 13-15 m depth, which is re-enforced by a thermocline during summer. The salinity in the Kattegat – Belt Sea area has a general seasonal variation with the highest salinity in the surface and lowest in the bottom water during winter (Figure 2.5).

The German Bight annually receives about 37 km^3 freshwater from the rivers Elbe and Weser (mean 1980–86), and the southern North Sea Bight about 81 km^3 from the Rhine (Gerlac 1990). The Jutland Coastal Current annually transports about 1,500 km^3 water from the German Bight to the Skagerrak. The runoff to the Southern North Sea causes a salinity in the Jutland Coastal Current to be about 28–30 when it enters the Danish coastal waters in the German Bight. The salinity increases northward along the Danish coast as it is mixed with central North Sea water. The salinity distribution in the surface of the open Danish waters is shown in Figure 2.6.

The salinity in the estuaries and fjords depends on the amount of freshwater received, residence time and the salinity of the coastal water outside the estuary. Most of the Danish estuaries are shallow with only periodic stratification due to inflow of saline bottom water or establishment of a thermocline during calm and warm periods. Some fjords, such as Mariager Fjord, Flensborg Fjord and the deep open Åbenrå Fjord have permanent haloclines.

The seasonal amplitude of the surface temperature in open waters goes from 1-4°C in winter to 15–20°C in summer. The variation in the bottom water is from 4°C to 11°C. The annual mean surface temperature in Kattegat has increased significantly from 8.5 °C to 9.6°C in the period 1970–2000 (Figure 2.7).

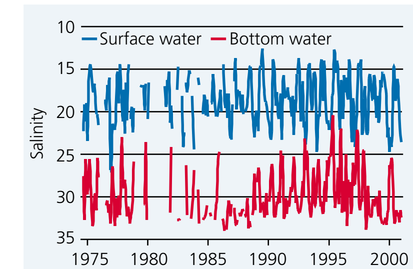


Figure 2.5
Median monthly salinity in the open Kattegat and Belt Sea surface water (0-10m) and bottom water (20-40m) 1975-2000. (After Henriksen et al. 2001).

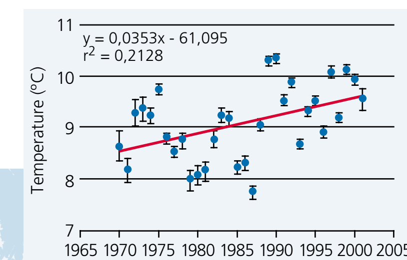


Figure 2.7
The development of annual mean surface (0-10 m) temperature in Kattegat 1970-2000.

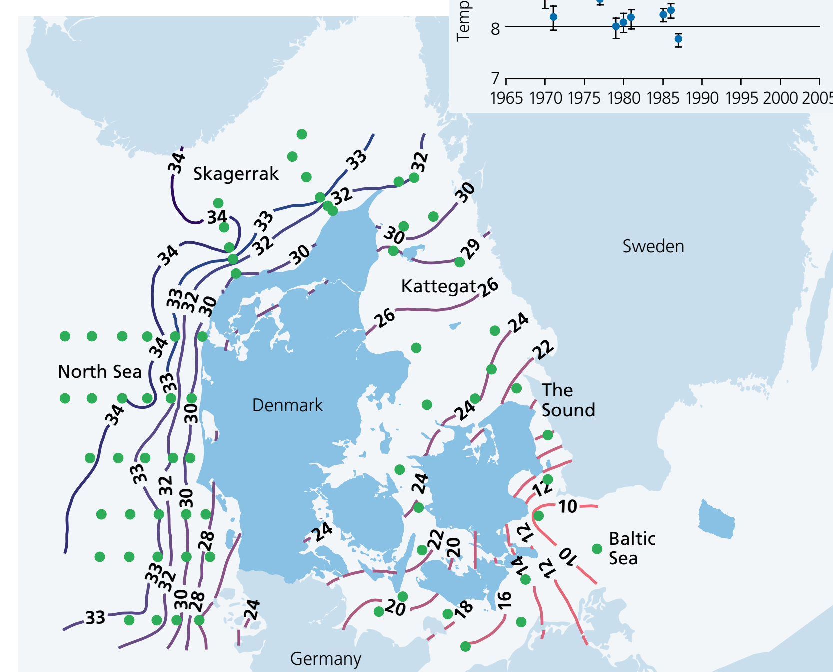


Figure 2.6
Interpolated distribution of surface salinity (mean 1-10 m) in February 2002.

2.3 Inputs from land-based sources, the atmosphere and adjacent seas

Freshwater runoff is the most important factor affecting nutrient concentrations in Danish coastal waters.

Photo: Biofoto/Svend Tougaard

The main increase in nutrient loads from land and atmosphere took place long before comprehensive load compilations were initiated in the late 1980s. Kronvang et al. (1993) recorded a 3.7% annual increase in the export of nitrogen (N) during the period 1967–1978 in 6 Danish rivers draining mainly agricultural catchment areas. They also estimated that the annual riverine N load to Danish coastal waters in the late 1960s was only about 60% of that in the 1980s. From long term time series of N and phosphorus (P) concentrations in a few North European rivers the EEA (2001) estimated that the N load has at least doubled from the 1950s to the 1980s in the North Sea – Baltic Sea region, and the P load increased fourfold from the 1940s to the 1970s. The EEA (2001) also estimated an increase in atmospheric N deposition of 80% and 100% from the late 1940s to the 1980s for the North Sea and Baltic Sea, respectively. In recent years the load to Danish waters has decreased, especially for P, but also for N from land and atmospheric sources.

Land-based sources

Detailed Danish nutrient load compilations were initiated in 1988. The development up to 2001 is shown in Figure 2.8. Nitrogen (N) comes primarily from leakage from agricultural soils, while point sources play a minor and decreasing role. Earlier, phosphorus (P) came mainly from point sources, e.g. domestic and industrial wastewater. However, improving sewage plants with P (and N) removal during the late 1980s – early 1990s has reduced the point source P load to surface waters (fresh and marine) by nearly 90%. This has reduced the overall P load and N load to marine waters by 60% and 14%, respectively, compared to 1990, and today the diffuse P load is higher than the point source P load (Bøgestrand 2001, Ærtebjerg et al. 2002).

The diffuse P and N loads follow the runoff creating large seasonal and inter-annual variations. For example, the N load might be twice as large in wet years (1994-1995) as in dry years (1996-1997) (Figure 2.8), which masks long term trends in loads. However, during the period 1990-2001 the diffuse N load corrected for inter-annual variations in runoff has decreased about 21% due to reduced use of N in agriculture (Bøgestrand 2001, Ærtebjerg et al. 2002).

The nutrient and BOD_5 loads to different Danish coastal areas in 2001 are shown in Table 2.1, and source apportionment for 2000 is shown in Table 2.2. The diffuse background load was about 10% of the total load for both N and P in 2000. Agriculture accounted for 88% of the N load and 45% of the P load to fresh- and marine waters. Direct point sources to marine waters accounted for 4% and 17% of the N and P load, respectively.

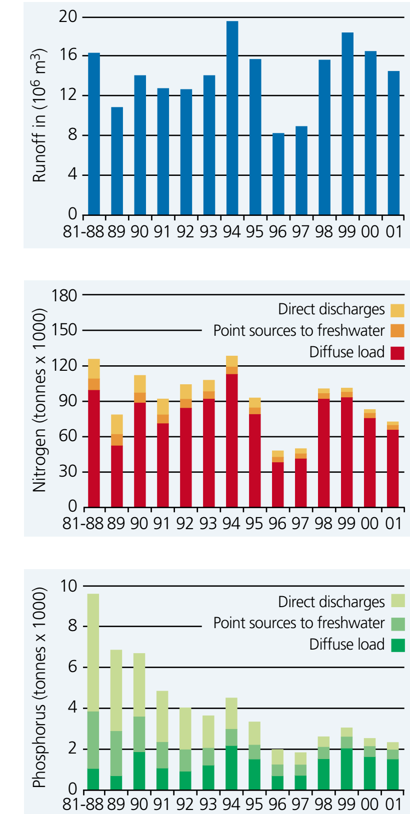


Figure 2.8
Annual freshwater runoff, and the total annual nitrogen and phosphorus load to Danish coastal waters in the period 1989-2001, divided between diffuse load, point sources to freshwater and direct point sources to marine waters. An estimate of the average annual load in the 1980s is shown for comparison. From Bøgestrand (2001).

Sea area	Drainage area	Runoff		Nitrogen	Phosphorus	BOD_5
	km^2	mm	10^6 m^3	tonnes	tonnes	tonnes
North Sea	10,860	449	4,852	17,500	530	6,500
Skagerrak	1,098	420	462	2,300	100	1,500
Kattegat	15,852	347	5,490	28,100	810	12,700
Belt Sea	12,346	241	3,061	20,400	670	10,500
The Sound	1,709	170	292	2,200	190	1,300
Baltic Sea	1,206	221	266	2,300	50	600
Total	**43,070**	**335**	**14,423**	**72,800**	**2,340**	**33,200**

Table 2.1
Runoff, total nitrogen, total phosphorus and BOD_5 load from Denmark to the main sea areas in 2001. Compiled from Ærtebjerg et al. 2002.

Table 2.2
Source apportionment of the Danish nitrogen (N), phosphorus (P) and BOD_5 load to coastal waters in 2000. Compiled from Bøgestrand (2001) and Danish EPA (2001).

Sources	Nitrogen	Phosphorus	BOD_5	Nitrogen	Phosphorus	BOD_5
	$t\ yr^{-1}$	$t\ yr^{-1}$	$t\ yr^{-1}$	%	%	%
Riverine inputs:						
A Diffuse load						
• Background	8,500	290	7,700	10.2	11.4	21.2
• Agriculture	73,700	1,150	9,200	88.4	45.1	25.3
• Settelments	1,000	220	3,850	1.2	0.3	10.6
B Point sources to freshwater						
• Sewage plants	2,475	250	1,800	3.0	9.8	5.0
• Industry	25	5	35	-	0.2	0.1
• Rainwater overflows	590	150	1,700	0.7	5.9	4.7
• Freshwater aquaculture	2,390	90	3,400	2.9	3.5	9.4
C Retension in freshwater	-8,880	-35	-85	-10.7	-1.4	-0.2
Total riverine load	79,800	2,120	27,600	95.7	83.1	75.9
Direct point sources:						
• Sewage plants	2,180	295	1,500	2.5	11.6	4.1
• Industry	870	55	4,900	1.0	2.2	13.5
• Rainwater overflows	170	45	500	0.2	1.8	1.4
• Mariculture	325	35	1,850	0.4	1.4	5.1
Total direct load	3,545	430	8,750	4.3	16.9	24.1
Total load:	**83,345**	**2,550**	**36,350**	**100**	**100**	**100**

Input from the atmosphere

The atmospheric deposition of inorganic nitrogen (NO_x and NH_x) is important on large sea surfaces, but insignificant in small estuaries, compared to other N sources. For the Kattegat and Belt Sea the atmospheric N deposition makes up about 30% of the total N load from surrounding land and atmosphere. The distribution of the deposition in 2001 on the Danish seas is shown in Figure 2.9. During the period 1989–2001 there is a decrease in the air concentration of N bound to particles and a tendency to a decrease in deposition of about 15% (Figure 2.10) (Ellerman et al. 2001; Ærtebjerg et al. 2002).

About 40% of the N deposition on all Danish marine waters in 2000 were in the reduced form (NH_x), which stems from ammonia evaporation from agricultural husbandry. The other 60% were in the form of oxidised nitrogen (NO_x) from the combustion of fossil fuels. About 11% of the total deposition on Danish marine waters came from Danish emissions, varying from 3% in the southern Belt Sea to 20% in the Skagerrak. Emissions from shipping made up 7% of the total deposition (Ellerman et al. 2001).

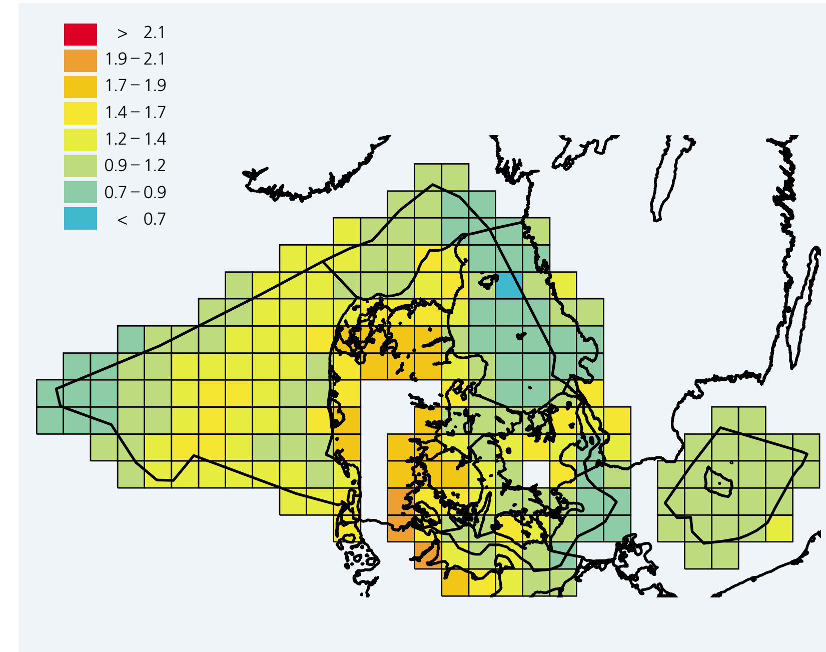


Figure 2.9
The atmospheric wet and dry deposition of inorganic nitrogen (NO_x+NH_x) in tonnes N km^{-2} at Danish sea areas in 2001. Grid size 30 km x 30 km. (From Ærtebjerg et al. 2002).

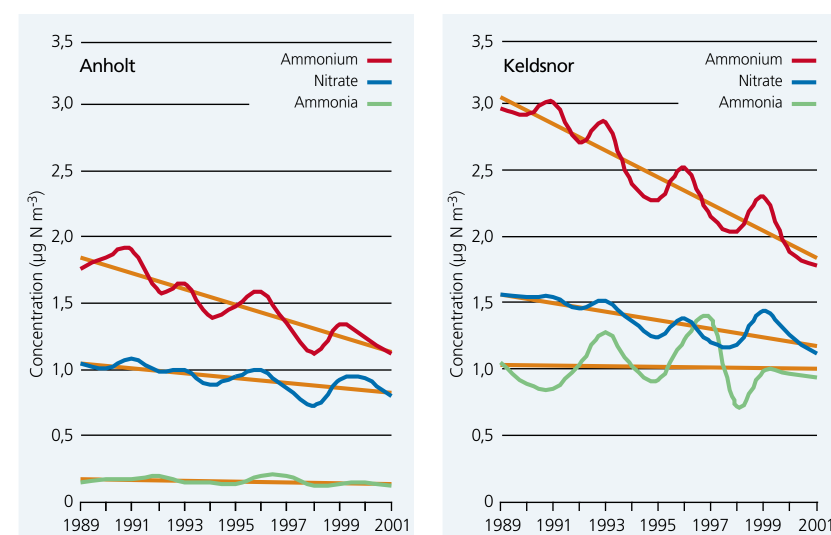


Figure 2.10
Annual means for the period 1989-2001 of concentrations of ammonia (green), particle bound ammonium (red) and sum-nitrate (blue) at Anholt in the middle of Kattegat and Keldsnor in the southern Belt Sea. (From Ellermann et al. 2002).

Nutrient input from adjacent seas and neighbouring countries

The exchange of water and nutrients between the Baltic Sea and Skagerrak through the Kattegat and the Belt Sea is intense. The annual freshwater net surplus of about 475 km^3 from the Baltic Sea passes through the Danish straits and Kattegat to the Skagerrak/ North Sea. The average annual net transports of N and P in the period 1974-1999 are shown in table 2.3 together with the loads from the atmosphere and surrounding countries in the period 1989–1996. The gross transports are much larger, especially at the Skagerrak border. Here an inflow of deep water rich in inorganic nutrients enters the Kattegat bottom water, and eventually is mixed to the surface water and re-exported to the Skagerrak, either in inorganic or organic form, dependent on the season. Due to shallow sills the inflow from the Baltic Sea to the Danish straits is Baltic surface water, which is low in bio-available nitrogen, due to the long residence time (about 25 years) of the Baltic Sea.

Evidently, there is a substantial net supply of both N and P to the Kattegat – Belt Sea area of on average about 125,000 tonnes N and 5,800 tonnes P per year. Some of the nitrogen is removed by denitrification. The rest is accumulated in the sediments together with P, some of it permanently, but much of it in labile pools. Especially large pools of phosphate are released from sediments to the overlying water column during summer and autumn, when the sediments become partly anoxic (Rasmussen et al., in press).

The Danish nutrient load to the North Sea, Skagerrak and Baltic Proper is small (Table 2.3.) compared to the advective transports and load from other countries. For example the Danish nitrogen load to the North Sea (including estuaries and the Wadden Sea) is 10–15% of the riverine load to the German Bight. Much of this is transported north along the Danish coast with the Jutland Coastal Current, which annually transports about 160,000 tonnes dissolved inorganic nitrogen (DIN) from the German Bight to Skagerrak. Episodically some of this water and associated nutrients might enter the Kattegat in some years, but it is generally exported to the North Atlantic with the Norwegian Coastal Current.

Load from the surrounding land dominates the nutrient budgets in the Danish estuaries. Dependent on the residence time, 12% to 95% of the N received, is exported from the estuaries to the open coastal areas. In the beginning of the 1990s, after reduction of the P-load, the estuaries exported more P than they actually received from land, the excess P coming from the sediment pools. In the latest years the P export from the estuaries generally equals the load from land (Henriksen et al. 2001).

Table 2.3
The average annual net supplies of N and P to Kattegat and the Belt Sea in 10^3 tonnes $year^{-1}$. Negative values mean transport out of the area. Based on Rasmussen et al. (in press).

	Denmark	Sweden	Germany	Atmosphere	Baltic Sea	Skagerrak	Sum
Nitrogen	60	26	12.5	44.5	150	-165	128
Phosphorus	3.38	0.54	0.35		11.44	-9.88	5.83

Nutrient budget for the Kattegat – Belt Sea area

An average annual nitrogen nutrient budget has been established for the Kattegat – Belt Sea area to evaluate the significance of the different contributions (Figure 2.11, Table 2.4). In the budget the land based nitrogen loads from Denmark, Sweden and Germany given in Table 2.3 are used. However, instead of the atmospheric deposition in the period 1989-96 the average deposition 1999–2001 was chosen, as these estimations are more reliable. The sources of emissions to the atmosphere were identified, and the contributions to the deposition from Denmark, Germany and Sweden added to their respective riverine and point source loads to determine the direct loads from the surrounding countries. The gross advective transports from the Baltic Sea and the Skagerrak in the period 1974–1999 were used instead of the net transports given in Table 2.3 (Ærtebjerg et al. 2002). Determined from the supply of total-N the Danish contribution to the Kattegat – Belt Sea area amounts to 12% (Table 2.4).

The bio-availability of the nitrogen in the different sources was calculated from measured concentrations of inorganic nitrogen and nitrogen built into phytoplankton, and compared to experimental results (Kaas et al. 1994). Including the bio-availability of the nitrogen sources in the budget increased the Danish contribution to 25% of the gross supply to the area (Figure 2.11, Table 2.4). However, some of the nitrogen supplied from the Skagerrak actually originates from the

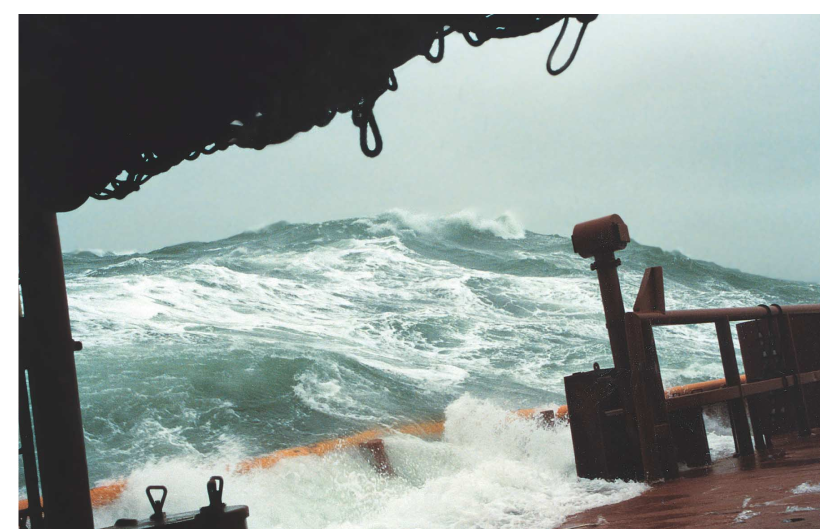


Photo: NERI/Gunni Ærtebjerg

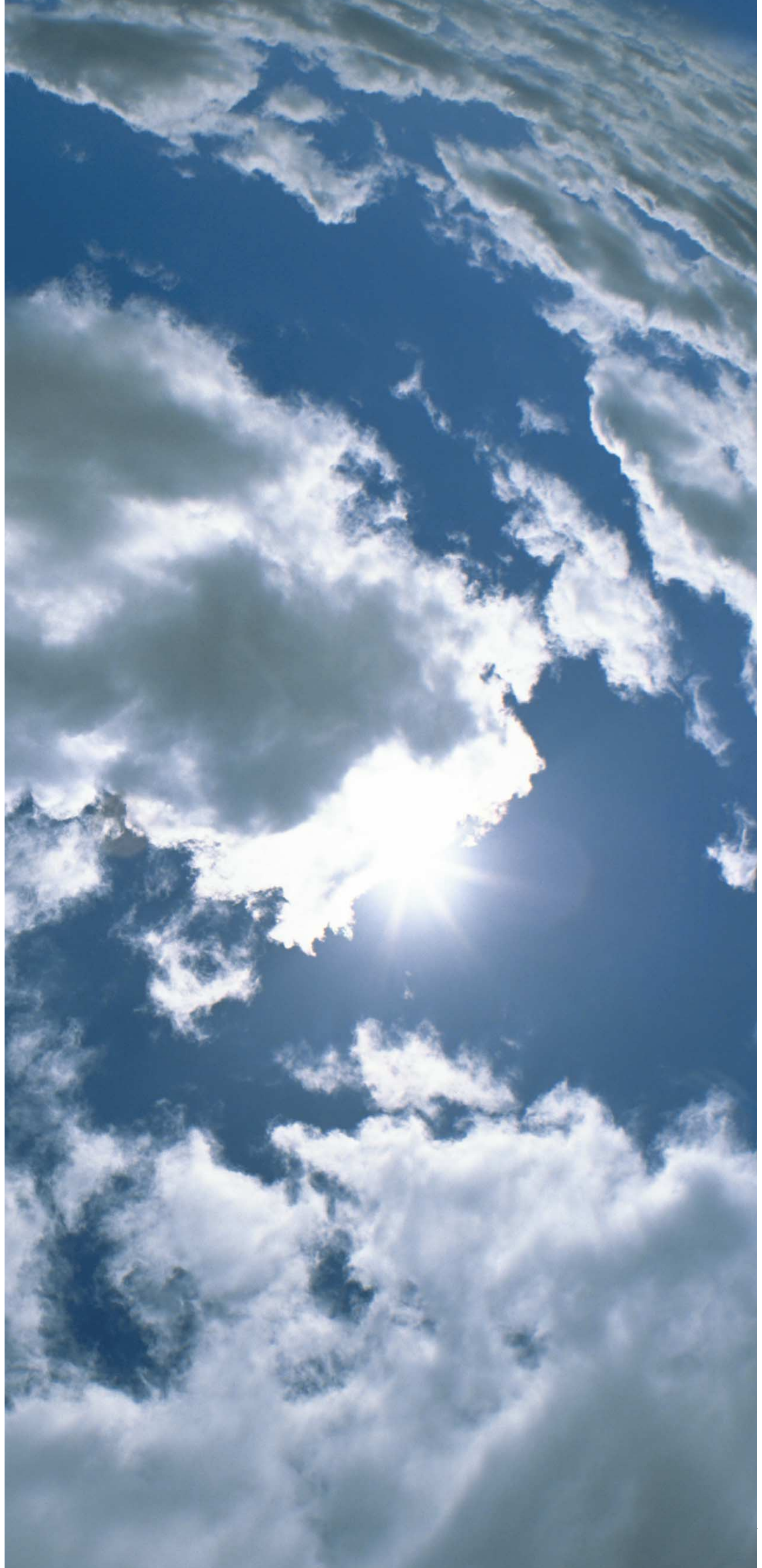


Photo: CDanmark

Kattegat and some is removed by denitrification or exported to the Baltic Sea. Taking this into account increases the Danish contribution of bioavailable nitrogen to 32%, the direct contributions from Sweden and Germany to 11% each, the contributions from the Baltic Sea and the Skagerrak to 14% and 19% respectively, and the contributions from other European countries via the atmosphere to 13% (Figure 2.11, Table 2.4) (Ærtebjerg et al. 2002).

	Total nitrogen	Bio-available nitrogen	Corrected for re-circulation	Percentage contributions
Denmark	70	64	64	32 %
Sweden	28	23	23	11 %
Germany	24	23	23	11 %
Other countries via the atmosphere	26	26	26	13 %
Skagerrak	223	89	32	19 %
Baltic Sea	217	28	28	14 %
Total	**588**	**253**	**203**	**100 %**
Danish contribution	**12 %**	**25 %**	**32 %**	

Table 2.4
Nitrogen sources to the Kattegat and Belt Sea in 1,000 tonnes per year. Period covered: see text.

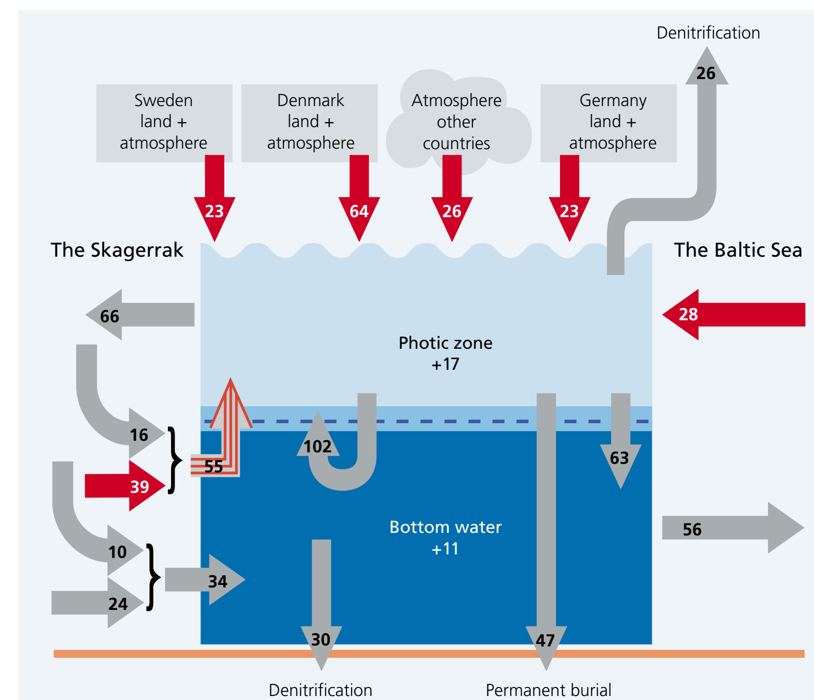


Figure 2.11
Transport of biological active nitrogen in the transition area between the Skagerrak and the Baltic. Loss to the bottom includes denitrification (30,000 tons) and permanent burial (47,000 tons). Period covered: see text.

2.4 Nutrient concentrations, nutrient ratios and nutrient limitation

A fraction of the water samples are analysed for inorganic nutrients, total nitrogen and phosphate and silicate.

Photos: NERI/Jens Christian Pedersen

According to the definition given in Chapter 1, eutrophication is caused by enrichment of the water by inorganic nutrients. In the Baltic water entering the Danish straits both winter nitrate and phosphate concentrations have about doubled from 1970 to the mid 1980s (Nausch et al. 1999). The same is the case for water entering from the German Bight to Danish North Sea waters with the Jutland Coastal Current (Hickel et al. 1995). In the Kattegat surface water the winter nitrate and phosphate concentrations have increased about 40% in the period 1971–1990 (Andersson 1996).

Nutrient concentrations

The lowest nutrient concentrations in Danish waters are observed in the Baltic Sea, and the highest in open waters are found in the German Bight of the North Sea. In the estuaries and coastal waters the concentrations vary from lower concentrations similar to what is found in open waters to high levels in estuaries with long residence times and high nutrient loads (Figure 2.12). The geographical variation of inorganic nitrogen nutrients (DIN = NO_3-N + NO_2-N + NH_4-N) is much larger (range factor 70) than for phosphate (DIP = PO_4-P) (factor 20).

The water in the Danish North Sea is essentially a mixture of two water masses: freshwater from the rivers to the southern North Sea and German Bight with high nutrient concentrations, and central North Sea water with high salinity (34–34.5) and low in

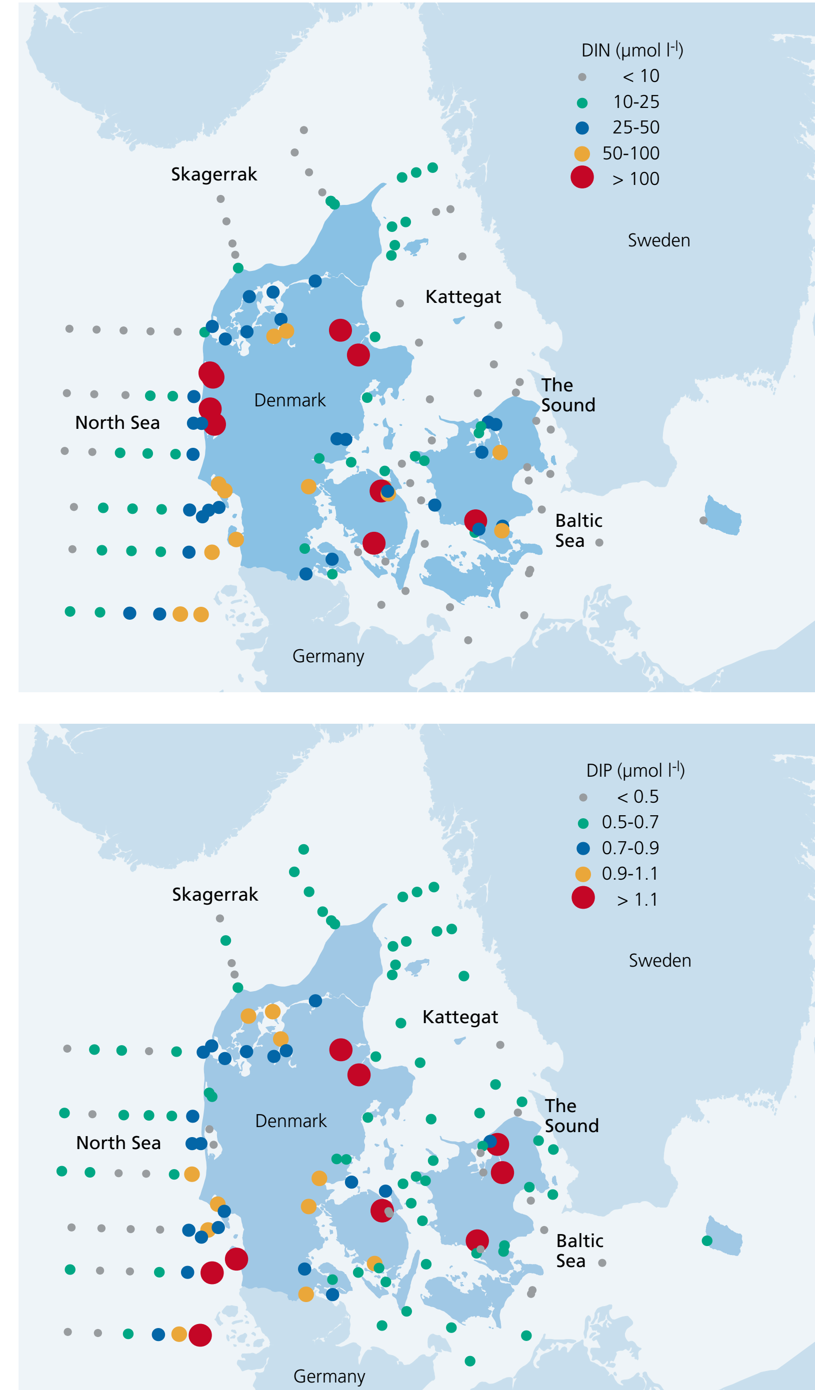


Figure 2.12
Mean winter concentrations of DIN and DIP, 1998–2001, in Danish marine waters.

nutrients. Therefore, the winter nutrient concentrations generally show an inverse linear correlation to the salinity (Figure 2.13). Likewise, the water in the Kattegat and Belt Sea essentially is a mixture of Baltic Sea surface water with low salinity (~8) and nutrient concentrations, and Skagerrak water with high salinity (34–35) and higher nutrient concentrations. However, the winter nutrient concentrations in the Kattegat and Belt Sea show a positive deviation from a linear relationship in the salinity interval 10–25, due to local supplies of nutrients in the Belt Sea and Kattegat. Freshwater runoff is too small compared to the Baltic outflow to influence the salinity significantly in the Belt Sea and Kattegat. In Skagerrak many different water masses and mixtures between them may be present: Jutland Coastal Current water from the German Bight (salinity 30–33), central North Sea water, North Atlantic water (salinity ~35), Kattegat surface water and locally influenced coastal waters (Figure 2.13). The water in the estuaries is generally a mixture between local freshwater runoff and coastal seawater from outside the estuary.

For assessing the development of nutrient concentrations in Danish

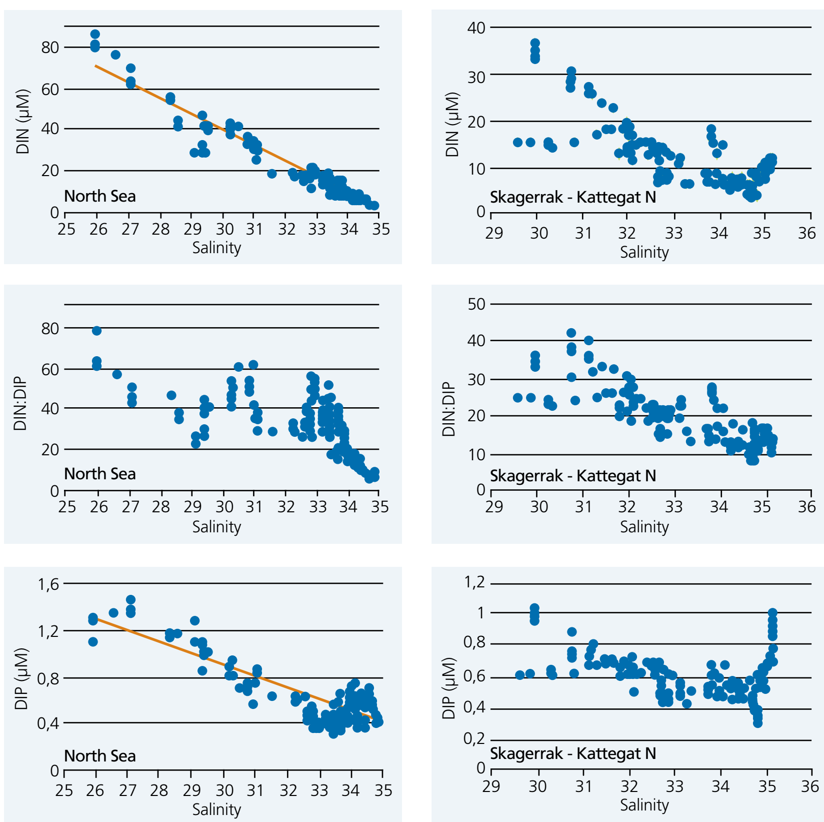
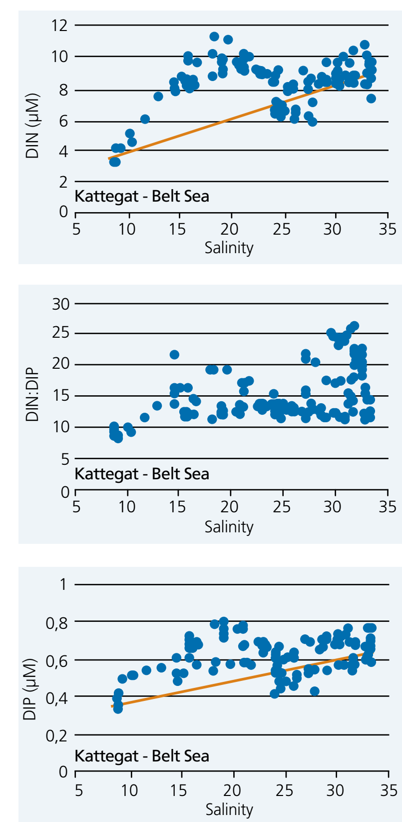


Figure 2.13
Relations of DIN, DIP and DIN:DIP ratio to salinity in February 2002 in the North Sea, Skagerrak and Kattegat-Belt Sea, respectively. The lines in the North Sea plots are linear regression lines, while the lines in the Kattegat-Belt Sea plots are theoretical mixing lines for mixtures of Baltic water and Skagerrak water.

BOX 4 Indices for annual mean levels of nutrients

Annual mean levels of nutrient concentrations were calculated by means of 3-factor analysis-of-variance (ANOVA) after log-transformation. The 3-factor ANOVA described variations between individual stations, years and months as categorical factors. The assumptions of the ANOVA were that seasonal and interannual variations in nutrient concentrations were similar at all stations, deviating only by a scaling factor.

The marginal distribution of yearly means were calculated and back-transformed into original scale to provide yearly indices for the mean annual nutrient concentration of all stations included in the analysis. The marginal yearly means correspond to yearly averages if monitoring data was balanced, that is equal number of observations for each month, each year at each station. The yearly nutrient mean levels were calculated by means of PROC GLM in SAS/STAT.

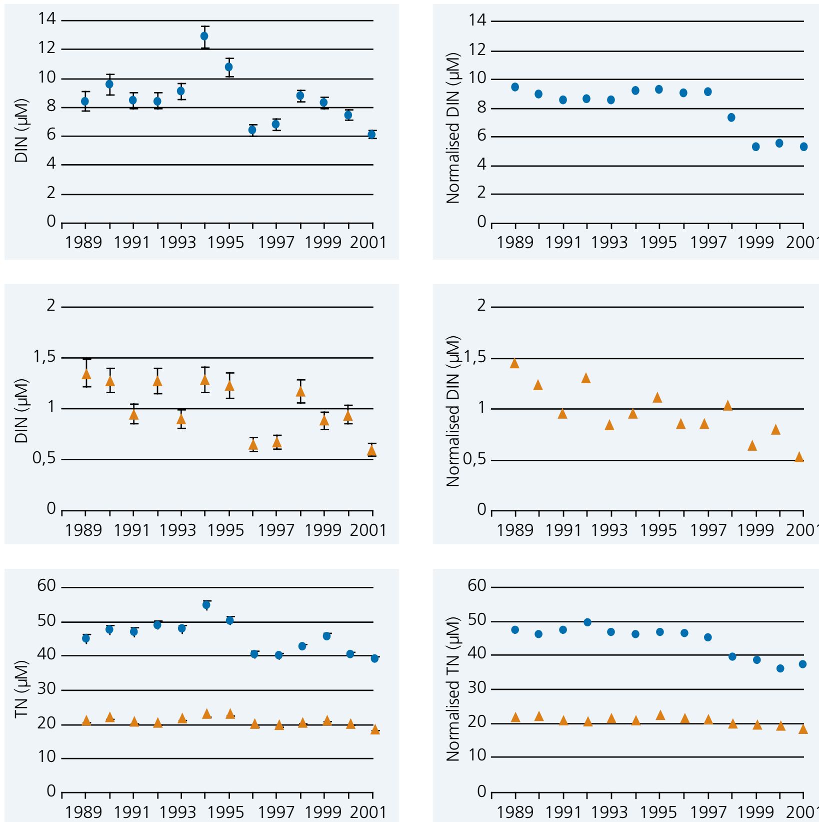


waters indices for mean annual concentrations of DIN, TN, DIP and TP in the upper mixed layer were developed for estuaries-coastal waters and the open Kattegat–Belt Sea, respectively (see box 4).

The indices for DIN and TN generally fluctuated around a constant level during the period 1989–2001, in both the estuaries–coastal waters and the open Kattegat-Belt Sea (except for a weak decreasing tendency for DIN in open waters). However, low concentrations were observed in the very dry years 1996 and 1997, when the land-based nitrogen load was about half of normal. The indices for DIP and TP decreased significantly in the estuaries–coastal waters, but was less pronounced in the open Kattegat–Belt Sea through the period 1989-2001 (Figure 2.14).

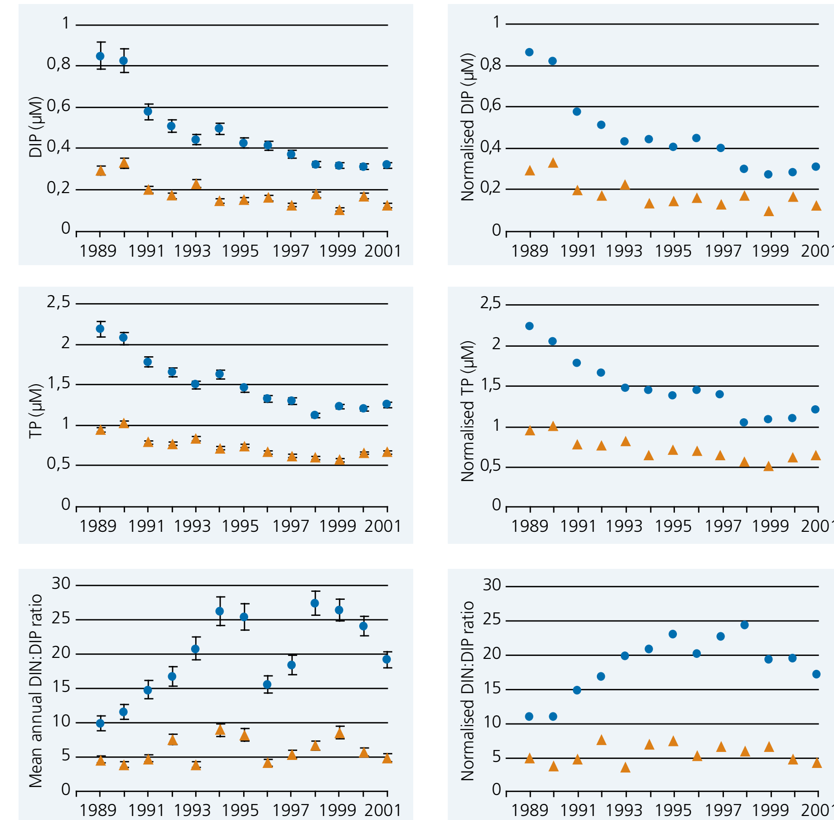
Freshwater runoff is the most important factor affecting nutrient concentrations in Danish waters. In estuaries and coastal waters the correlations between the indices for annual

Figure 2.14
Indices for annual mean concentrations of DIN, TN, DIP, TP and the DIN:DIP ratio (left column), as well as the same indices corrected for runoff variations (right column). 95% confidence limits are given for the uncorrected indices. Estuaries and coastal waters are shown with blue circles, and open Kattegat-Belt Sea with red triangles.



mean DIN and TN concentrations and runoff were highly significant for the period 1989–97 (Figure 2.15). The years 1998–2001 deviate from this, as the DIN and TN concentrations in Danish streams decreased during this period (Bøgestrand 2001). Likewise, significant correlations were found for DIP and TP in estuaries and coastal waters for the period 1992–1997. The years 1989–1991 were omitted as significant reductions in the phosphorus point source load took place in these years. In the open Kattegat–Belt Sea significant correlations were also found for DIN and TN, but not for DIP and TP. However, all the annual mean nutrient indices were corrected for runoff variations according to the correlations observed.

In the estuaries and coastal waters the DIN and TN indices normalised to mean runoff show a significant decrease in the later years 1998–2001, and the normalised DIP and TP indices have reached a constant low level in the same years. In the open Kattegat–Belt Sea the normalised indices for DIN, DIP and TP show a slow decrease over the whole period 1989–2001 (Figure 2.14).



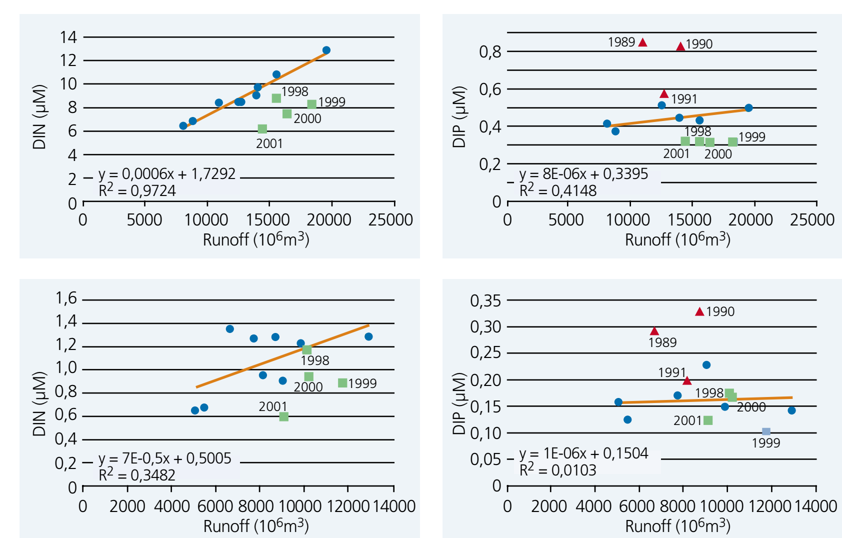


Figure 2.15
Annual mean indices for DIN and DIP in estuaries-coastal waters (upper row) and open Kattegat-Belt Sea (lower row) against runoff. The years 1998–2001 are marked with green squares, and the years 1989–1991 are marked with red triangles in the DIP diagrams.

Nutrient ratios

The optimal DIN:DIP ratio (N/P-ratio) for phytoplankton growth is 16:1 (based on molar concentrations) and is called the Redfield ratio. Significant deviations from 16 at low N/P-ratios might indicate potential nitrogen limitation and at high N/P-ratios potential phosphorus limitation of phytoplankton primary production. This might affect the biological state of the ecosystem, in particular the phytoplankton biomass, species composition and eventually food web dynamics.

In the open Belt Sea and Kattegat the N/P-ratio based on winter DIN and DIP concentrations is generally between 10 and 20 and thus does not deviate much from the Redfield ratio. In the North Sea the N/P-ratio is generally high ranging between 25 and 60, except in the saline central North Sea. In the Skagerrak N/P-ratios are also high at salinities lower than 33 (Figure 2.13 and 2.16). Generally the winter N/P-ratio in estuaries is high (>25) to very high (>100) (Figure 2.16).

N/P-ratios based on annual mean DIN and DIP indices in the estuaries-coastal waters show an increase from 1989 to 1998 parallel to the reduction in phosphorus load, and then a decrease to 2001 parallel to the decrease in nitrogen load per unit runoff. In the very dry years of 1996-97 with low nitrogen load the uncorrected N/P-ratio indices were much lower than in neighbouring years (Figure 2.14). In the open Kattegat-Belt Sea no general development is observed in the annual DIN:DIP indices during the period 1989–2001.

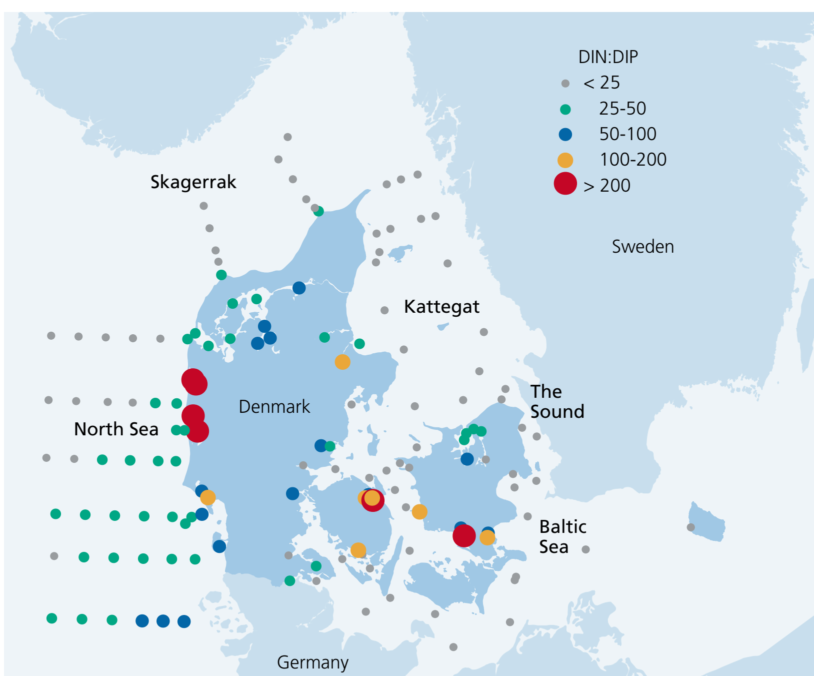


Figure 2.16
Mean winter DIN:DIP ratio 1998–2001 in Danish marine waters.

Nutrient limitations

A simple first order approach to assess potential nutrient limitation is to examine for time periods when nutrient concentrations are below the theoretical half-saturation constant (K_s) for uptake and to compare the stoichiometry to expected Redfield ratios. While crude, this has been found to be a robust approach to determine which nutrient is most limiting. The K_s values used are 2 µM for DIN, 0.2 µM for DIP and 2 µM for DSi (Fisher et al. 1992) and Redfield ratio is 16 for DIN:DIP.

In estuaries phytoplankton primary production is often potentially limited by low phosphate concentrations early in the productive season. In 2000 potential phosphate limitation in 6 estuaries extended from about 1 month in Horsens Fjord and Odense Fjord to 3 months in Skive Fjord and Limfjorden and up to 6 months in Ringkøbing Fjord. While no potential phosphate limitation was observed in Roskilde Fjord. Potential co-limitation by low concentrations of both DIN and phosphate was most pronounced in Horsens Fjord for a period of about 2 months. The estuaries, except Ringkøbing Fjord, were potentially nitrogen limited in late summer for one to two months (Figure 2.17A) (Henriksen et al. 2001). The number of days with poten-


Photo: NERI

Monitoring of the open marine waters in Denmark is made on board R/V Gunnar Thorson.

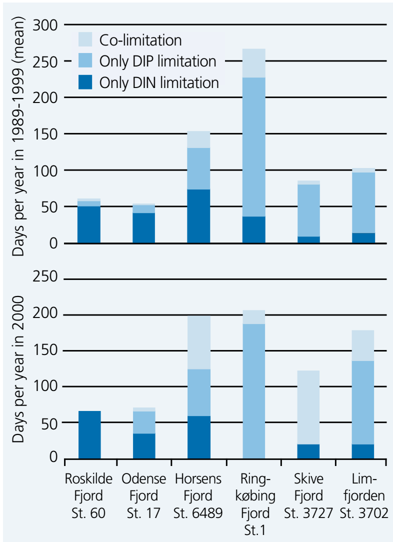


Figure 2.17 A
The number of days with potential nutrient limitation of the phytoplankton primary production given as mean for the period 1989–1999 (upper panel) and in 2000 (lower panel) in 6 Danish estuaries: Roskilde Fjord, Odense Fjord, Horsens Fjord, Ringkøbing Fjord, Skive Fjord and Limfjorden. (From Henriksen et al. 2001).

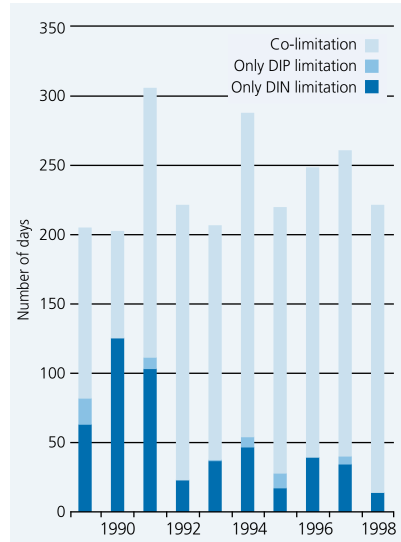


Figure 2.17 B
The number of days with potential nutrient limitation in the productive season in the years 1989–1998 at station 925 in the south-western Kattegat. (From HELCOM 2002).

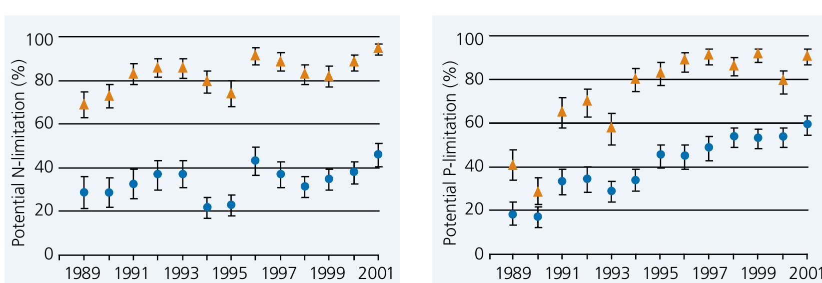


Figure 2.18
Indices for potential N limitation (left) and P limitation (right) of the phytoplankton primary production in the productive period March-September calculated as the probability of obtaining DIN or DIP concentrations below the theoretical half-saturation constants (K_s) for uptake. Indices for estuaries-coastal waters shown with blue circles, and for open Kattegat-Belt Sea with red triangels.

tial phosphate limitation has increased significantly in the estuaries since the early 1990s parallel to the decrease in phosphorus load from land (Figure 2.17).

Both nutrient concentrations and nutrient ratios suggest that DIN continues to be the nutrient potentially most limiting to phytoplankton biomass in the Kattegat and Belt Sea (Figure 2.17B). Phytoplankton were mostly potentially co-limited by DIN and DIP concentrations or limited by DIN concentrations (Ærtebjerg et al., 1998). Redfield ratios suggest that when phytoplankton were co-limited by DIN and DIP, that DIN is most often the most potentially limiting nutrient. Although phosphate was potentially limiting by itself only for limited periods each year, the periods that the open sea areas are co-limited by low concentrations of DIN and DIP has significantly increased with time (Figure 2.18). Dissolved silicate concentrations are occasionally low enough (< 2 µM) to limit diatom populations.

Conclusion

Improvement of the ecological state of the Danish marine waters calls for further reduction in the nitrogen load, as the primary production in the open Kattegat and Belt Sea is mainly nitrogen limited and the production in the estuaries is most often nitrogen limited during late summer and autumn. Further reduction in the phosphorus load to the open Kattegat and Belt Sea will probably have insignificant effect as phosphorus is seldom the most limiting nutrient, and because the phosphorus contributions from internal processes and neighbouring seas are large compared to the load from land (Rasmussen et al., in press). However, in the estuaries phosphorus limitation of the primary production in spring and early summer is pronounced and has increased after the substantial phosphorus load reductions in the early 1990s. Further reduction of the phosphorus load to the estuaries might further improve the environmental state.

2.5 Phytoplankton and harmful algal blooms

Diatoms dominate the phytoplankton biomass with important contributions from dinoflagellates and other organisms.

Photo: Biofoto/N.T. Nicoll

Phytoplankton are the base of pelagic food webs in aquatic systems. In addition, sedimentation of phytoplankton provides an essential nutritional input to the benthic fauna. With generation times ranging from <1 day to a few days phytoplankton respond rapidly to changes in nutrient concentrations. Therefore, phytoplankton have been included in the Danish monitoring programme since 1979 as an indicator of the eutrophication status. Phytoplankton are quantified as carbon biomass determined from microscopy or indirectly as the concentration of chlorophyll *a*, a pigment found in all autotrophic phytoplankton organisms.

No data exists on phytoplankton biomass or chlorophyll *a* concentrations under pristine conditions. Therefore present levels are generally compared with background concentrations in offshore areas. For Danish waters the offshore Skagerrak chlorophyll *a* concentration of 1.25 µg l^{-1} can be applied. However, this concentration represents the maximum concentrations for the growing season (spring-late summer) (OSPAR 2001). The OSPAR assessment criteria are not operational, and the Danish assessment has therefore been based on mean chlorophyll *a* concentrations in March-October.

Present levels

In 2001 the average phytoplankton biomass varied from 35 to 405 µg C l^{-1} at the 17 Danish stations sampled in 2001 and with a long-term sampling record of more than five years. In 12 out of 17 areas the average phytoplankton biomasses in 2001 were lower (8–61%) than the long-term averages (Table 2.5).

In 1999 and 2000 diatoms generally dominated the phytoplankton carbon biomass with important but somewhat smaller contributions from dinoflagellates (especially in 1999) and other organisms (Figure 2.19). This pattern of dominance has, however, changed over time, in particular in open sea areas. Here diatoms accounted for <20% up to 40% of the total biomass from 1979 until 1998 while dinoflagellate contribution to biomass increased from <23% during 1979 to 1985 to 28–65% after 1986. The increasing importance of dinoflagellates has been accompanied by reduced contributions from other groups, mainly nanoflagellates.

Table 2.5
Year 2001 average phytoplankton biomasses and biomasses relative to long–term averages for the given time periods at all Danish stations with quantitative phytoplankton sampling and a history of more than five years of sampling. Figures show percentage increase or decrease in biomass relative to long-term average.

Increase
Decrease

Geographical area	Period	2001 biomass µg C l^{-1}	2001 relative to long- term average
Sønderho, east	1990–2000	147	37
Ringkøbing Fjord	1989–2000	45	8
Nissum Bredning	1985–2000	117	25
Løgstør Bredning	1985–2000	133	4
Skive Fjord	1985–2000	255	10
Ålborg Bugt	1989–2000	67	43
Hevring Bugt	1989–2000	147	15
Århus Bugt	1989–2000	113	10
Mariager Fjord	1989–1996	230	25
Horsens Fjord	1989–2000	138	13
Vejle Fjord	1989–2000	176	14
Kolding Fjord	1989–2000	405	10
Little Belt, northern part	1989–2000	112	20
Gniben	1979–2000	41	61
Little Belt, southern part	1989–2000	121	14
Roskilde Fjord	1992–2000	44	40
The Sound, northern part	1979–2000	35	31

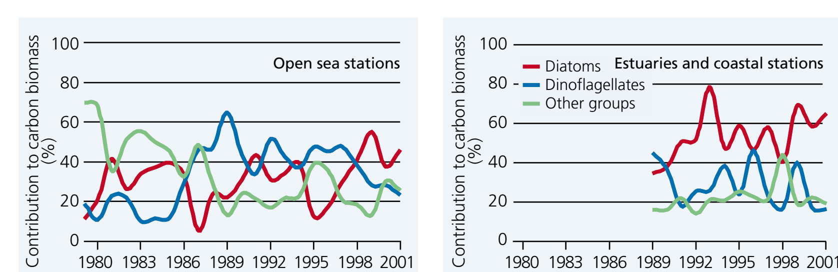


Figure 2.19
Contributions (%) of phytoplankton groups to annual average biomasses at sampling stations in open sea areas (left) and estuaries and coastal areas (right) of the Danish waters in the Baltic entrance area.

BOX 5 Indices for phytoplankton parametres

For each sampling station an average value is calculated for individual years and a global average of all annual averages. The annual indices are calculated as:

- Index (year, station) = average (year, station) x 100/global average (station)
- Subsequently a national index for a given year is calculated as the average of indices for all stations that year.
- Only stations with a minimum of 5 years sampling with a frequency of >5 samples year^{-1} were included.

In estuaries and coastal waters diatoms prominently dominated the phytoplankton (35–78%) since sampling was initiated in 1989 (Figure 2.19). The contributions from dinoflagellates have varied between 16% and 46% and the importance of other groups, mainly nanoflagellates, increased from 1989 to 1998.

Because diatoms dominate the spring bloom, of which a large fraction sediment to the bottom, they are important for the transfer of organic matter of pelagic origin to the benthic fauna. In addition, the input of organic matter to the water mass below the pycnocline will affect the subsequent development in bottom water oxygen conditions.

The biomass of diatoms has decreased significantly over the past 20 years in the open Kattegat and Belt Sea. During 1995–2000 the average biomass of diatoms in these areas was 50% of the biomass in the early 1980s. In estuaries and coastal areas no long-term trend in diatom biomass was found (Figure 2.20).

Primary production in the open sea areas has shown an overall decline with major year-to-year variations from 1977 to 1997 (Figure 2.21). The subsequent increase in primary production during 1998–2001 may be due to a reduction in the number of monitoring stations and changes in the sampling strategy in 1998. During 1993-2001 primary production was significantly correlated with runoff, wind and temperature. The primary production index adjusted to changes in climatic conditions shows a lower production during the 1990s than during the 1980s. Despite the apparent decrease in primary production from the 1980s to the 1990s, the annual prima-

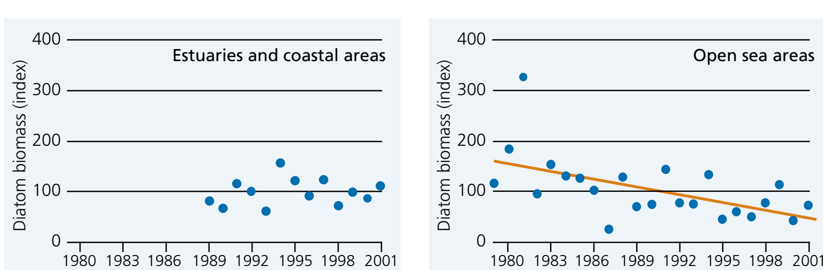


Figure 2.20
Annual averages of diatom biomass in Danish waters. Biomasses are given as indices (see box 5).

BOX 6 Adjustment of indices to climatic conditions

Indices of chlorophyll *a* concentrations, primary production and Secchi depth were correlated with indices of climatic conditions (e.g. runoff, wind, irradiance and temperature) by multiple linear regression. The model was optimised with respect to indices of climatic conditions (e.g. lag phase for runoff, irradiance during seasons where nutrients were expected not to limit primary production) and time period included in the regression.

Subsequently, indices adjusted for variations in climatic conditions were found as: Adjusted index = measured index – modelled value + 100.

The adjusted indices represent predicted indices under identical climatic conditions and thus serve to illustrate variations over time due to other factors than differences in climatic conditions.

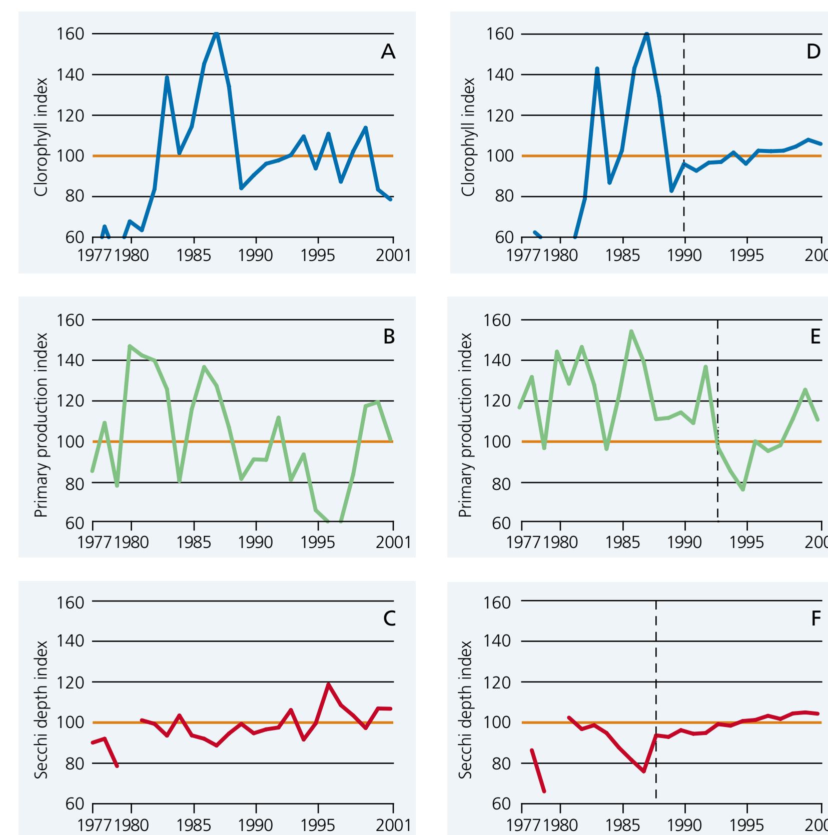


Figure 2.21
Indices for Secchi depth, chlorophyll concentrations and annual primary production in open sea areas. Indices are given for measured values (A, B and C) and adjusted for variations in climatic conditions (D, E and F). Adjustments for climatic variations are developed on data from time periods represented by hatched lines and up till 2001. Subsequently the adjustments were applied on data in all years.

ry production in the Kattegat area has increased 2- to 3-fold from the 1950s to 1984–1993, apparently as a result of eutrophication (Richardson & Heilmann 1995).

In estuaries and coastal areas primary production has decreased from 1980 to 1997 and subsequently increased during 1998-2001 (Figure 2.22). For the period 1993-2001 primary production was significantly correlated with runoff, irradiance and temperature. Index values adjusted for variations in climatic conditions showed a very consistent decline after 1993. This decline in primary production was presumably due to reduced phosphorus loading to the estuaries through the establishment of sewage treatment plants in the late 1980s and early 1990s and subsequent reduction in the nitrogen load both from point and diffuse sources.

Chlorophyll *a* concentrations have decreased in the open sea areas since the 1980s (Figure 2.21). However, mainly during the 1980s the year-to-year variations have been substantial and possibly related to the lack of standardised sampling strategies and methods for analyses prior to 1989. For the period 1990-2001 chlorophyll *a* concentrations

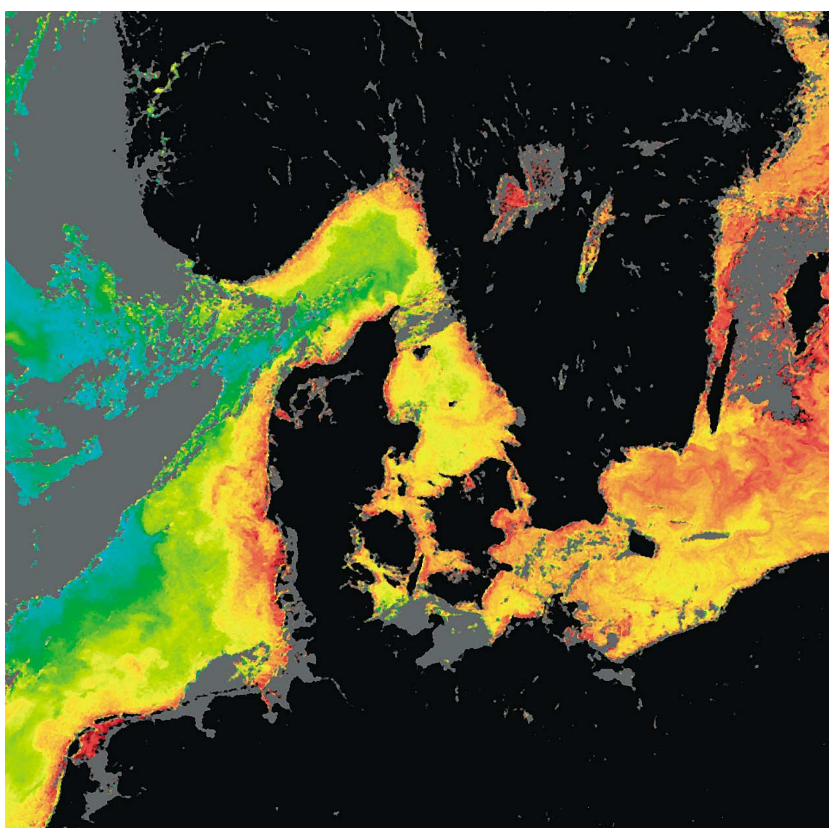


Image: SeaWiFS data from Orbimage processed by GRAS A/S, Denmark

Satellite image of chlorophyll in Danish marine waters, the North Sea and the Baltic Sea 16 July 2002. Red colours indicate high concentrations of chlorophyll.

correlated significantly with primarily irradiance during early spring and autumn. Chlorophyll *a* index values adjusted for variations in climatic conditions were very variable prior to 1990 and showed a general slight increase for the period 1990-2001. Since 1980 the concentrations of chlorophyll *a* in Danish open sea areas (Hansen et al. 2000) have been >50% above background concentrations (1.25 µg chl *a* l^{-1}) given by OSPAR (2001).

Chlorophyll *a* concentrations have decreased in estuaries and coastal waters since the mid 1980s (Figure 2.22). The concentrations of chlorophyll *a* correlated significantly with runoff during 1993–2001. When adjusted for variations in climatic conditions, chlorophyll *a* index values showed a very consistent decline from 1993 to 2001.

In open sea areas the Secchi depth, a measure of water transparency, has increased since the mid-1980s (Figure 2.21). The Secchi depth adjusted for variations in climatic conditions has increased despite a similar increase in chlorophyll concentration. In estuaries and coastal areas the decline in chlorophyll concentrations since the mid-1980s has been accompanied by increased Secchi depth (Figure 2.22).

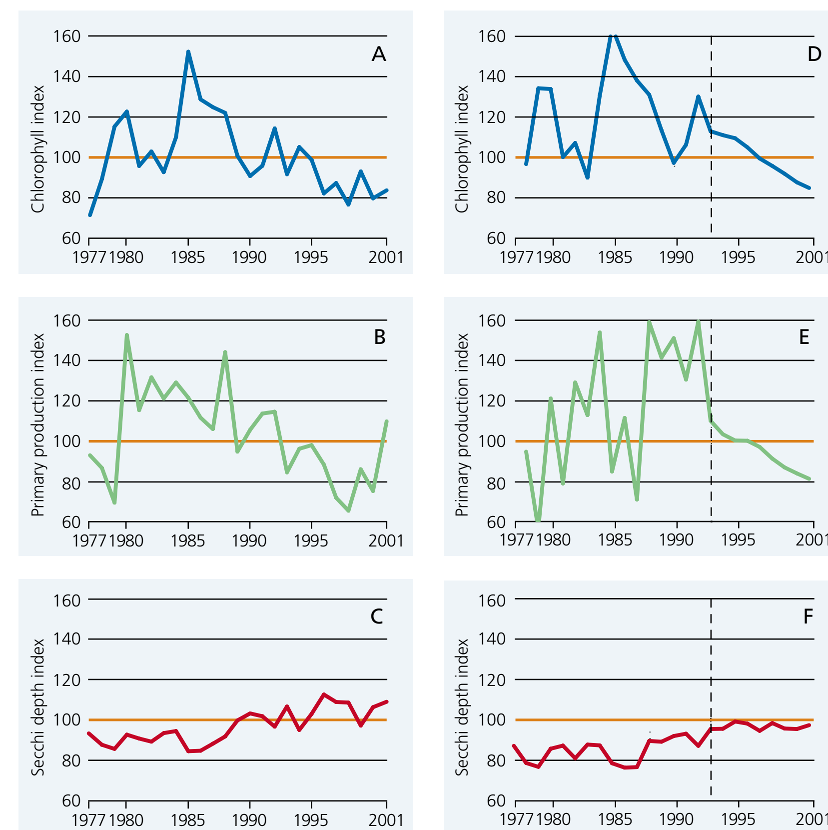


Figure 2.22
Indices for Secchi depth, chlorophyll concentrations and annual primary production in estuaries and coastal waters. Indices are given for measured values (A, B and C) and adjusted for variations in climatic conditions (D, E and F). Adjustements for climatic variations are developed on data from 1993–2001, but applied on data in all years.

Exceptional and harmful algal blooms

Several potentially toxic and harmful species of algae are common minor components of the phytoplankton communities in Danish waters. In some years, however, they form conspicuous blooms that may have severe effects on other organisms or on the tourist and fishing industries (Table 2.6). Blooms of some species, e.g. *Chrysochromulina polylepis*, have occurred only once, while blooms of other species are recurring, e.g. *Karenia mikimotoi* and *Chattonella* sp. The latter was found in high concentrations for the first time in 1998.

Potentially harmful species are registered and quantified in the national monitoring programme. In addition, the commercial bivalves fishermen and the mussel industry are undertaking monitoring of toxic phytoplankton and algal toxins in bivalve shellfish in all areas where shellfish are harvested. Areas may be closed for fishing of shellfish if toxic algae are found in concentrations above given limits (Bjergskov et al. 2001) or if algal toxins are detected in shellfish in concentrations above the limit for human consumption. Most registrations of shellfish containing algal toxins in concentrations above limits are from the 1980s and the early 1990s and from the eastern coast of Jutland (Figure 2.23) where the fished shellfish amounts to only one third of the catches in the Limfjorden in northern Jutland.

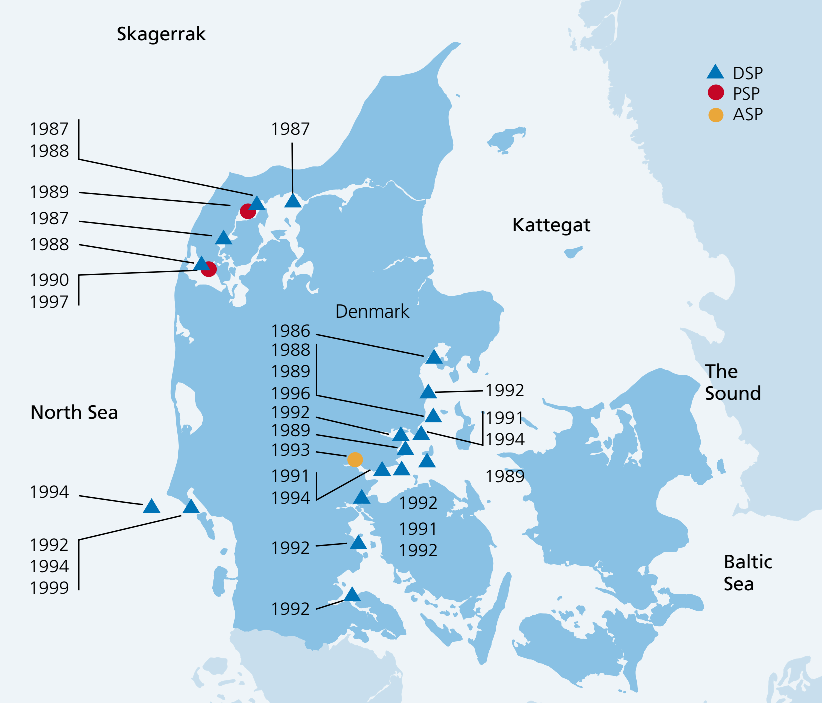


Figure 2.23
Registered accumulations in shellfish of algal toxins in concentrations above limits for human consumption. DSP, Diarrhetic Shellfish Poison; PSP, Paralytic Shellfish Poison and ASP, Amnesic Shellfish Poison. ASP detected in 1993 was analysed by a single laboratory and has not been confirmed by other laboratories. (From Bjergskov et al. 2001).

Species	Year	Month(s)	Geographical area	Maximum abundance or biomass	Effects Fish kills
Chattonella spp.	**1998**, 2000, **2001**	Jan-May	Århus Bugt, Danish west coast, Skagerrak, Kattegat	23 mill. l^{-1}	Fish kills
Chrysochromulina spp.	**1988**, 1992	May	Kattegat, Belt Sea	100 mill. l^{-1}	Fish kills, dead benthic invertebrates, macrophytes affected
Dictyocha speculum	**1983**, 1999	May-Jun	Little Belt, Alssund	25 mill. l^{-1}	Fish kills in maricultures associated with bloom
Gymnodinium chlorophorum	1999	Aug-Dec	Nissum Bredning W Kattegat	15 mill. l^{-1}	None reported
Karenia mikimotoi [1]	**1968**, 1981, **1997**	Aug-Oct	Skagerrak Danish west coast, Kattegat, Belt Sea	8.6 mill. l^{-1}	Dead benthic invertebrates
Nodularia spumigena [2]	**1975**, 1976, 1992, **1994**, **1995**, 1997, 1999, **2001**, 2002	Jul-Aug	Århus Bugt, W Kattegat, Belt Sea, W Baltic	869 µg C l^{-1}	Dogs dying after swimming in the water
Phaeocystis sp.	Yearly, **2000**	May-Jun	Danish west coast		Foam on beaches
Prorocentrum minimum	**1983**, 1984, 1987, **1989**, **1992**, **1993**, **1994**, **1995**, **1996**, 1997, **1999**	Jul-Oct	Most Danish estuaries and coastal areas	53 mill. l^{-1}	None reported
Pseudo-nitzschia spp.	1992, 1999, 2000	May-Nov	Kattegat, Belt Sea SW Kattegat Danish west coast	346 µg C l^{-1}	None reported

Table 2.6
Blooms of potentially toxic phytoplankton species or exceptional blooms in Danish waters. Years with major blooms are given, and the most significant ones marked in bold. Months indicate the most frequent time of year for blooms. Maximum abundance and effects refer to the most extreme episodes registered.

1 = *Gyrodinium aureolum*
2 = Maximum biomass given was total biomass of all cyanobacteria including *Aphanizomenon* sp. and *Anabaena* sp. registered in the national monitoring programme. Locally, much higher biomasses may have occured in accumulations along the shore.

2.6 ZOOPLANKTON

Copepods have an increased importance towards the sea while the relative importance of protozooplankton and meroplankton is highest in the estuaries.

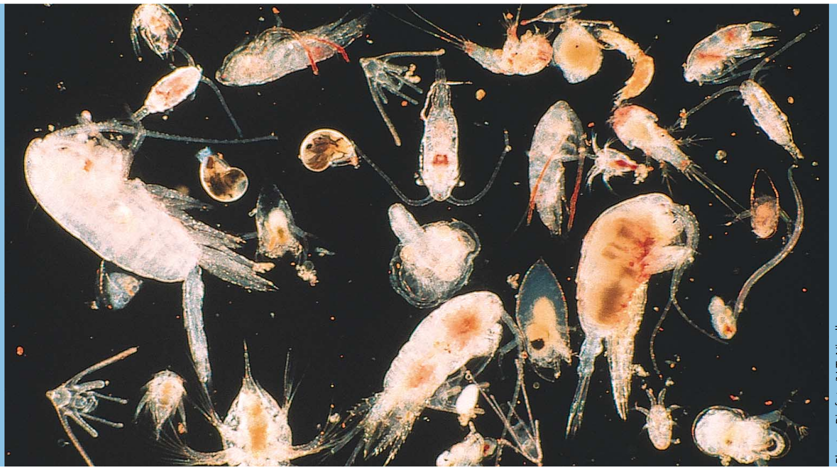


Photo: Biofoto/N.T. Nicoll

The zooplankton are an important link between the phytoplankton and higher trophic levels such as fish. Zooplankton constitute a diverse group of organisms with respect to size, life cycle and behaviour. The smallest size class, nanozooplankton (2-20 µm), are single celled organisms. The larger size class, the microzooplankton (20-200 µm) are dominated by ciliates and heterotrophic dinoflagellates, small metazooans as rotiferans and the earliest developmental stages of copepods. The largest size class, mesozooplankton (> 200 µm), consist of copepods, cladocerans and larvae of benthic invertebrates.The more conspicuous jellyfish often dominates the gelatinous plankton.

Due to the doubtful usefulness of zooplankton as an indicator of eutrophication, zooplankton have been given relatively low priority in the Danish monitoring programme with respect to the number of sampling stations and sampling frequency. From 1998 zooplankton was given even lower priority in open waters, but is still included in the monitoring of many coastal waters.

In general the diversity of the zooplankton community decreases with salinity from the North Sea to the Baltic Sea and from the open sea to the low salinity estuaries. However, diversity is high in the Kattegat and the Belt Sea due to the influence of both brackish and Atlantic species as a result of the inflow of water from the Baltic Proper and the Skagerrak-North Sea, respectively. The relative importance of protozooplankton, rotiferans, meroplankton and cladocerans is highest in the estuaries and decreases gradually towards the open sea. Conversely, the importance of copepods increases towards the sea.

During the period 1983-96 the winter biomass of mesozooplankton was generally low (2-5 mg C m^{-3}) in the open waters, increasing to a seasonal summer peak of about 30-40 mg C m^{-3}. Inter-regional differences were minor, also with respect to species composition. An analysis of copepod biomass data revealed a significant but only slight reduction in the mesozooplankton biomass from 1989 to 1997 at two out of three Kattegat stations (Ærtebjerg et al. 1998).

In the estuaries the composition and seasonal succession of the zooplankton community is much more variable than in the open sea. Both seasonal successions and time trends differ markedly among the estuaries monitored. In the Limfjord the mesozooplankton biomass has increased significantly since 1985, while the biomass of protozooplankton has decreased, though not significantly. In Ringkøbing Fjord the biomass of mesozooplankton has decreased significantly since 1989 while the protozooplankton biomass has increased, though not significantly. In Roskilde Fjord no time trend was observed in the biomass of either meso- or protozooplankton. The lack of general inter-fjord time trends is probably due to the effect of local conditions.

Eutrophication is believed to cause an increase in the relative importance of gelatinous zooplankton vs. crustacean zooplankton. Throughout the monitoring period several estuaries like Roskilde Fjord, Kertinge Nor and Limfjorden have suffered from occasional blooms of gelatinous zooplankton such as the jellyfish *Aurelia aurita* (Frederiksborg Amt & Roskilde Amt 2002, Fyns Amt 2002). The jellyfish graze on the mesozooplankton, which in turn leads to lowered grazing on the phytoplankton. In Kertinge Nor it has been shown that high abundance of jellyfish reduces the importance of zooplankton as grazers on phytoplankton to almost negligible levels (Petersen et al. 1999). Moreover, jellyfish are suspected to affect the recruitment of fish negatively, both by grazing on fish eggs and larvae and by affecting the

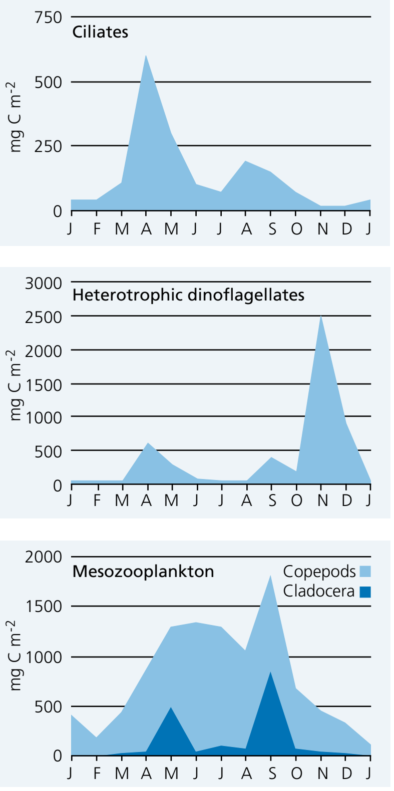


Figure 2.24
Seasonal variation in biomass (mg C m^{-2}) of ciliates, heterotrophic dinoflagellates and mesozooplankton in the southern part of Kattegat. (Modified from Nielsen & Hansen 1999).

feeding conditions for fish larvae and planktivorous fish by causing a decrease in the abundance of prey organisms such as copepods. Jellyfish themselves are in a sense a trophic dead end. Energy and organic matter that could otherwise be channelled into harvestable organisms is turned into non-utilisable jelly.

The cladoceran *Penilia avirostris*: an addition to the Danish fauna

Cladocerans have their main distribution in freshwater habitats and the number of species in Danish marine water is limited. Usually they constitute only a minor fraction of the mesozooplankton biomass, but due to parthenogenesis they can increase rapidly in numbers when growth conditions are favourable and occasionally they become quantitatively important grazers. The two dominating genera *Evadne* and *Podon* are believed to graze mainly on large phytoplankton cells and on protozooplankton (Egloff et al. 1997).

In the autumn 2001 a new cladoceran species *Penilia avirostris* was observed in plankton samples from Århus Bight and Kattegat (Ærtebjerg et al. 2002). This species has its main distribution in tropical and subtropical seas, where it at times dominates the mesozooplankton biomass. It feeds mostly on nanoplankton (2-20 µm) (Turner et al. 1988) and thus plays a different role in the pelagic food web than the other marine cladoceran species. Due to this *P. avirostris* may be an important link between bacterioplankton and higher consumers because of its predation on bacterivorous flagellates. *P. avirostris* was reported in the North Sea as early as 1948 and since 1999 it has been a steady component of the zooplankton community in the southern and eastern parts of the North Sea, typically in September/October. Since the first record in the North Sea it has spread progressively northward. For example it was found around Helgoland (Germany) in the early 1990s and was recorded in Koster Fjorden (Sweden) in 1997. In 2001 *P. avirostris* was observed in relatively low abundances of about 100 individuals m^{-3} in the Kattegat region, but in August-September 2002 it was among the dominating mesozoopankton species in the Sound with abundances up to 4000 individuals m^{-3} (Per Juel Hansen, pers comm). *P. avirostris* has the capacity to quickly build dense populations and significantly influence the food web structure and the fate of the primary production. Therefore it is important to follow closely the occurrence and development of this new, invasive species which is probably well establishhed in Danish waters.

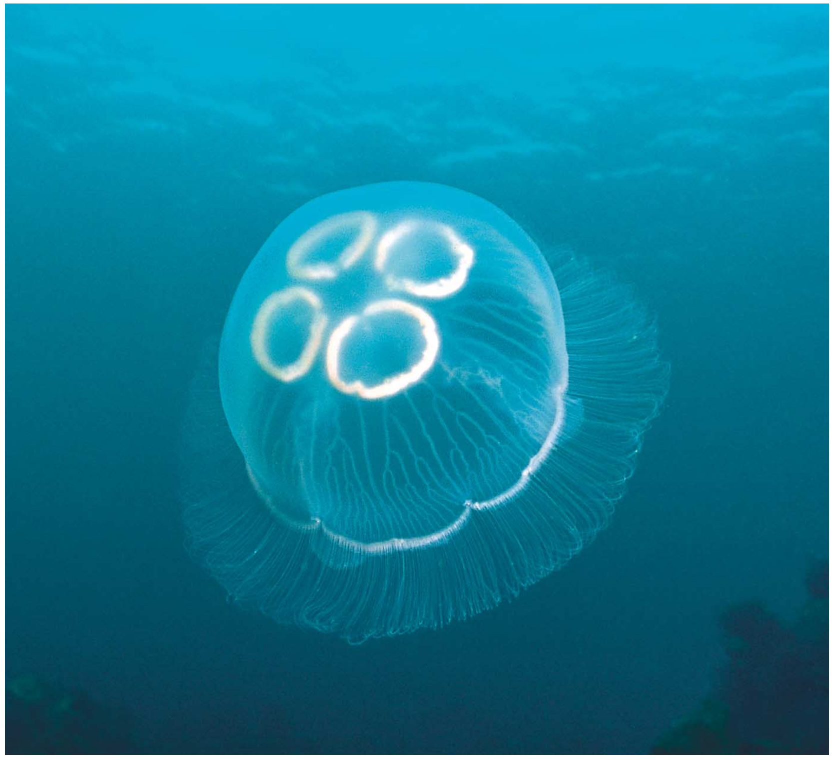


Photo: Ocean Photo, Norway/Erling Svensen

The size of zooplankton varies from single cell microzooplankton to large organisms as jelly fish.

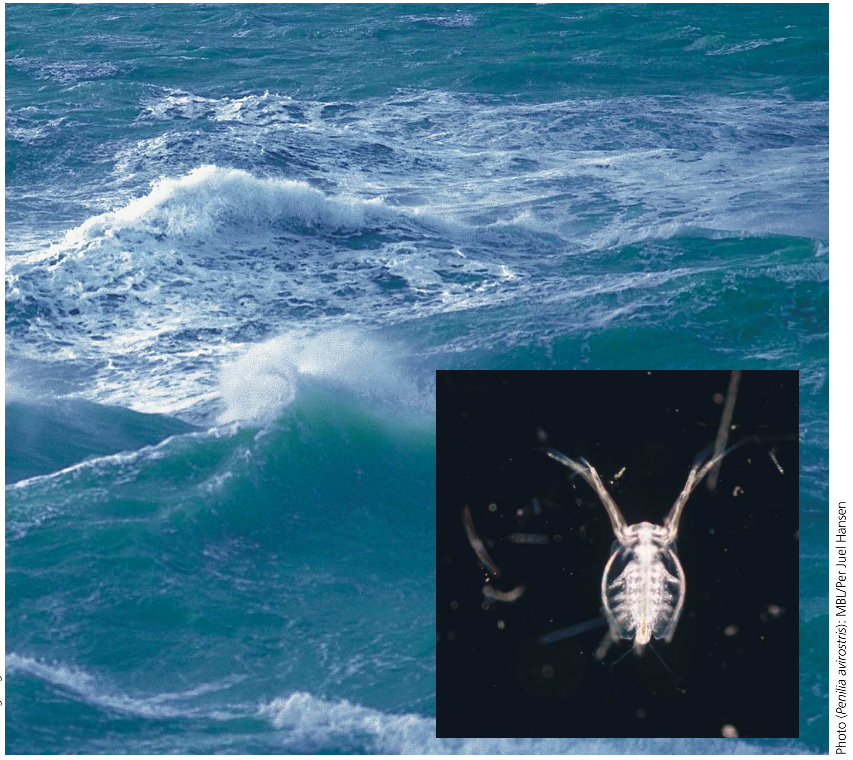


Photo:High-light

Photo (*Penilia avirostris*): MBL/Per Juel Hansen

Figure 2.25
The cladoceran *Penilia avirostris*, which is probably now established in Danish waters.

2.7 Oxygen depletion

The "cloud" is sulphur in the water due to hydrogen sulphide released from sediments during a period of oxygen depletion.

Photo: Fyn County/Nanna Rask

Nutrient enrichment/eutrophication may give rise to an increased rate of oxygen consumption, decreased oxygen concentrations and an increased frequency of oxygen depletion. In Denmark oxygen depletion is defined as oxygen concentrations below 4 mg l^{-1} (2.8 ml l^{-1}), and severe (acute) oxygen depletion as below 2 mg l^{-1} (1.4 ml l^{-1}). The observed oxygen concentrations in September 2001 and 2002 are shown in Figure 2.26.

Analyses of long term development in bottom water oxygen concentrations during late summer – autumn in the Kattegat-Belt Sea from the 1970s to late 1980s/1990s (Table 2.7) show significant decreases in all areas with a stratified water column, especially from the mid 1970s to the late 1980s. In the period 1989–2001 no general development in the summer-autumn bottom water minimum oxygen concentration was observed. However, a tendency for a rise in minimum oxygen concentration in spring (April-June) has been found (Hansen et al. 2000, Ærtebjerg et al. 2002).

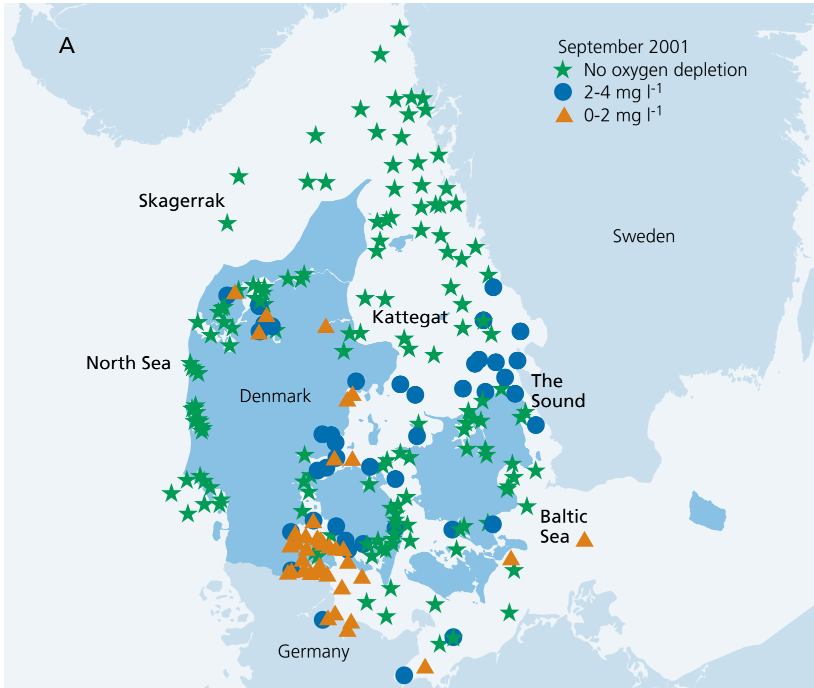
Oxygen depletion only occurs in stratified water columns where stratification prevents oxygen-rich surface waters to mix to the bottom. The oxygen concentration close to the sea bottom in stratified waters depends on two processes each varying in time and space: the consumption rate, which is mainly dependent on the supply of organic matter and the temperature, and the oxygen supply rate, which is mainly dependent on wind conditions. Therefore, it is difficult to assess, if a particular oxygen depletion incident is due to increased consumption rate or decreased supply rate of oxygen, and thus to relate the oxygen concentrations to nutrient loads.

Area	Period	Annual change	Reference
Kattegat	1971-82/90	-0.05-0.1 ml l^{-1}	Andersson & Rydberg 1988, 1993
Kattegat NE	1970-95	-0.2% saturation	HELCOM 1996
	1975-88	-1.16% saturation	Agger & Ærtebjerg 1996
Kattegat S	1975-88	-1.17-1.41% saturation	Agger & Ærtebjerg 1996
The Sound	1970-95	-0.5% saturation	HELCOM 1996
	1975-88	-1.10% saturation	Agger & Ærtebjerg 1996
Great Belt	1974-95	-0.7% saturation	HELCOM 1996
Little Belt S	1976-97	Decrease	Ærtebjerg et al. 1998
Fehmarn Belt	1975-97	Decrease	Ærtebjerg et al. 1998
	1979-93	-0.5% saturation	HELCOM 1996
	1975-88	-2.97% saturation	Agger & Ærtebjerg 1996
Kiel Bight	1957-86	-0.10-0.11 ml l^{-1}	Babenerd 1991
	1976-90	-0.15 ml l^{-1}	Weichart 1992

Table 2.7
Published statistical significant results of analyses of the development in bottom water oxygen concentrations late summer – autumn in the Kattegat-Belt Sea from the 1970s to late 1980s/1990s.

Therefore, oxygen level in the bottom layer (20–40 m) in the southern Kattegat and Belt Sea was modelled as a function of a temperature dependent gross oxygen consumption rate, water temperature and residence time. The later defined as the time since the bottom water advected below the pycnocline. The residuals between modelled and observed oxygen saturation was interpreted to arise from interannual variations in the availability of organic matter for respiration (Henriksen et al. 2001). In the period 1982–2000 the residuals (mean May–Sept.) correlated significantly to the runoff and N-load in the previous hydrological year (June–May). High runoff and load generally corresponded to lower oxygen levels than modelled, and low runoff and load as in 1996-1997 corresponded to higher oxygen levels than modelled (Figure 2.27). Hansen et al. (1995) made a scenario analysis of effects of reduced nitrogen input on oxygen conditions in the Kattegat and Belt Sea. They concluded, that the nationally and internationally agreed nitrogen load reductions would significantly improve the oxygen situation, but to reach the oxygen level in the 1950s it would probably be necessary also to lower the atmospheric nitrogen deposition.

Most of the Danish estuaries-coastal waters are shallow, and the wind can easily mix the water column to the bottom. Stratification only occurs periodically during calm and warm periods building up a thermocline, or by inflow of saline bottom water creating a temporary halocline. In a detailed study of a shallow Danish estuary (Skive Fjord/Lovns Bredning) it was possible to separate the effect of meteorological forcing (wind, solar radiation) and



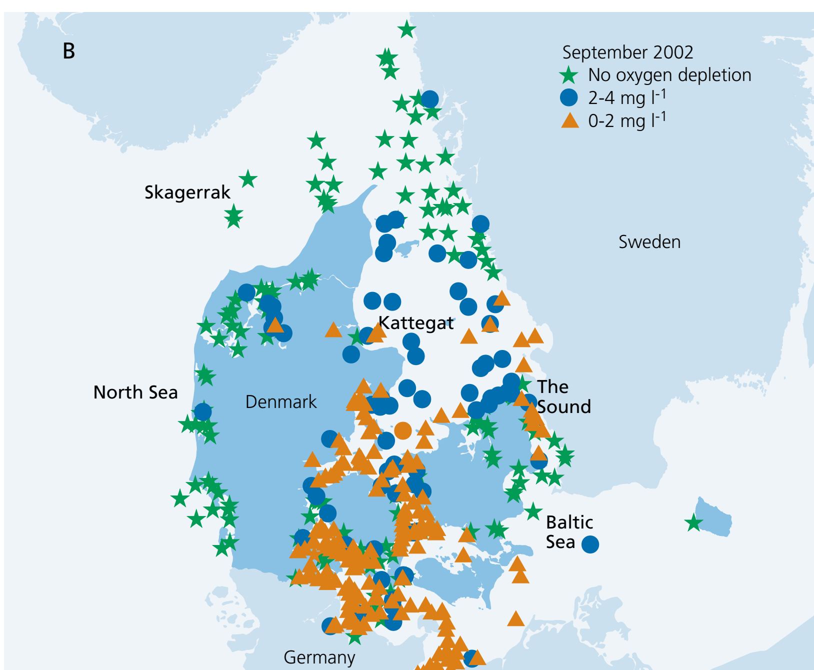


Figure 2.26
Oxygen depletion in Danish and neighbouring waters within September 2001 (A) and 2002 (B). Swedish and German monitoring data are included.

nutrient load on oxygen depletion in bottom water. During summer periods of stratification oxygen saturation could be attributed to the time elapsed after the onset of stratification and the accumulated nitrogen loading 10 months prior to measurement. Using 10 years meteorological data and an empirical model, it was calculated that a 25% reduction in nitrogen loading would reduce the number of days with severe oxygen depletion (<15% saturation) by more than 50% (Møhlenberg 1999).

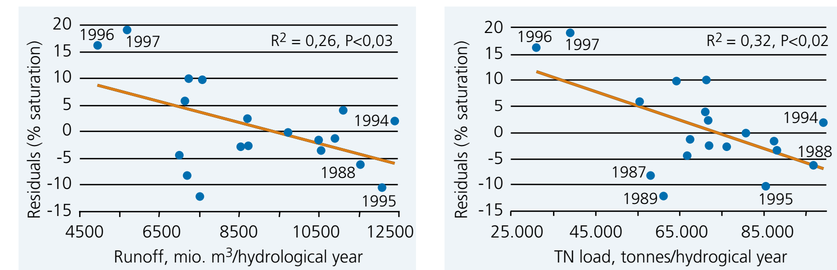


Figure 2.27
Residuals between modelled and observed oxygen saturation (mean May-September per year) as a function of (A) the runoff, and (B) the N-load during the previous hydrological year (June-May). The two hydrological years with lowest and the three hydrological years with highest runoff are indicated.

Sulphur formed by oxidation of hydrogen sulphide released from the sediment in Odense Fjord.

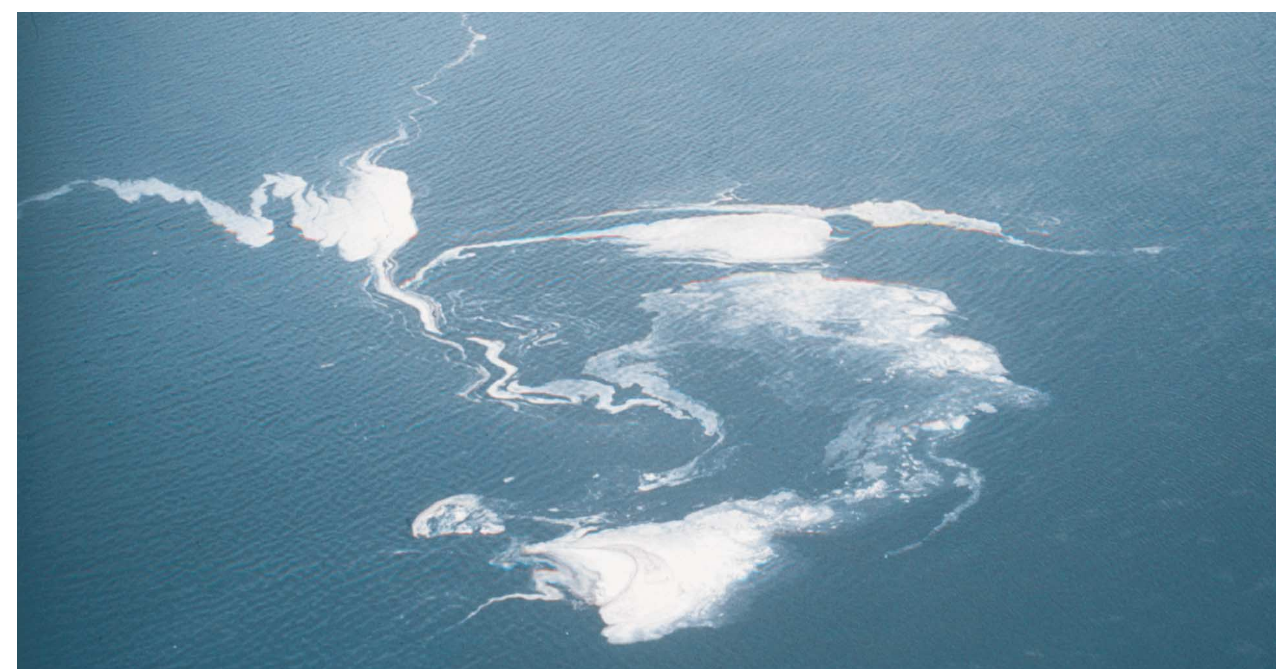
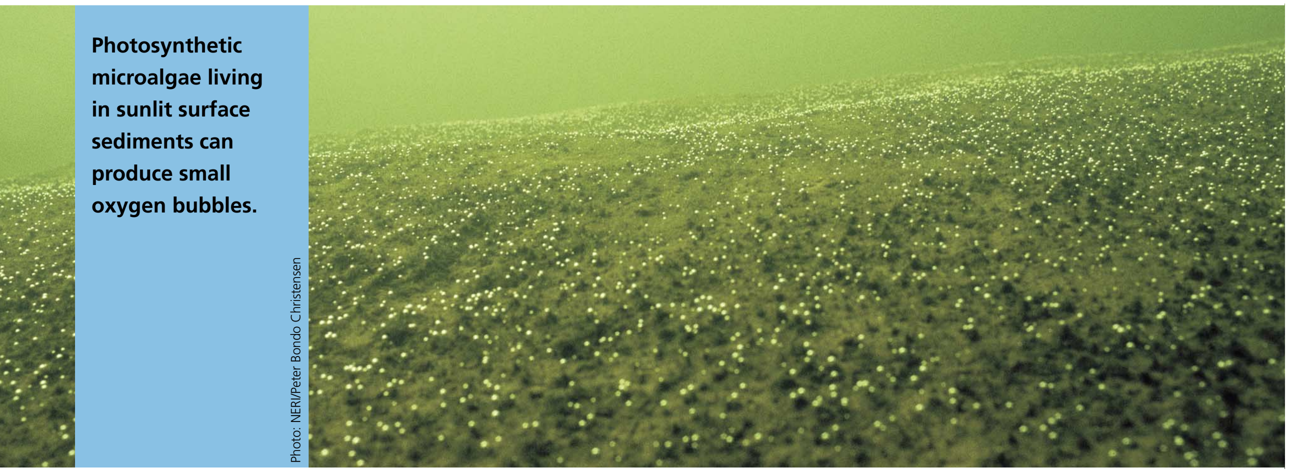


Photo: Fyn County/Søren Larsen

2.8 Degradation of organic matter in estuarine sediments



Photosynthetic microalgae living in sunlit surface sediments can produce small oxygen bubbles.

In marine sediments, organic matter is mainly degraded through bacterial processes, by which N and P bound in organic compounds as a result of primary production are released once again.

Up to half of the bacterial degradation taking place in the sediments proceeds through oxygen respiration (i.e. aerobically). The remaining degradation takes place anaerobically through respiration of nitrate, iron, manganese or sulphate (Jørgensen 1996).

Besides the release of CO_2, NH_4^+ and PO_4^{3-}, anaerobic degradation results in the formation of waste products (such as hydrogen sulphide from sulphate respiration) that are ultimately oxidised, thereby consuming the exact amount of oxygen that would have been used if the entire degradation process had been aerobic. Therefore, a measurement of the amount of oxygen consumed within the sediment in darkness will correspond quite closely to the total metabolism of organic matter going on within the sediment, since this measurement is the sum of aerobic and anaerobic degradation.

Oxygen

The sediment oxygen consumption describes a typical bell-shaped curve, the lowest values being found in the winter months and maximum values from May to September (Figure 2.28). This variation corresponds closely to the variation in water temperature. An analysis of the correlation between temperature and oxygen consumption shows that temperature explains 55% of oxygen consumption (R^2=0.5467, n=644, p<<0.0001). For the remaining part, the explanation probably lies in the amount of organic matter reaching the sea floor during spring and summer.

Nitrogen

The flux of nitrogen (and of phosphorus, for that matter) between the marine sediment and the bottom water is governed by differences in concentrations between pore water (within the sediment) and water column. Thus, sediments will always take up NH_4^+ or NO_3^- when water-column concentrations of the respective N compounds are greater than porewater concentrations, and accordingly release nitrogen to the bottom water when nitrogen porewater concentrations are higher.

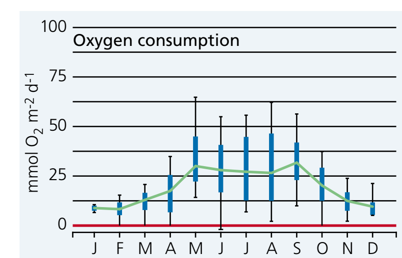


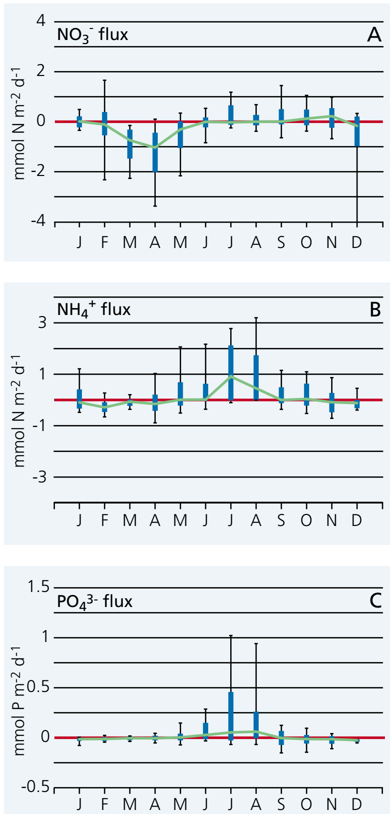
Fig 2.28

Box-Whiskers plot of the seasonal variations in sediment oxygen consumption/respiration expressed as the numerical magnitude of the O_2 flux measured in darkness. The dataset is a compilation of observations from 6 estuaries each represented with 3 stations sampled 16 times over a two-year period. Median (line), 25% and 75% quantiles (boxes) and 10% and 90% quantiles (bars) are shown.

Sheets of white sulphur bacteria on a mussel bed.

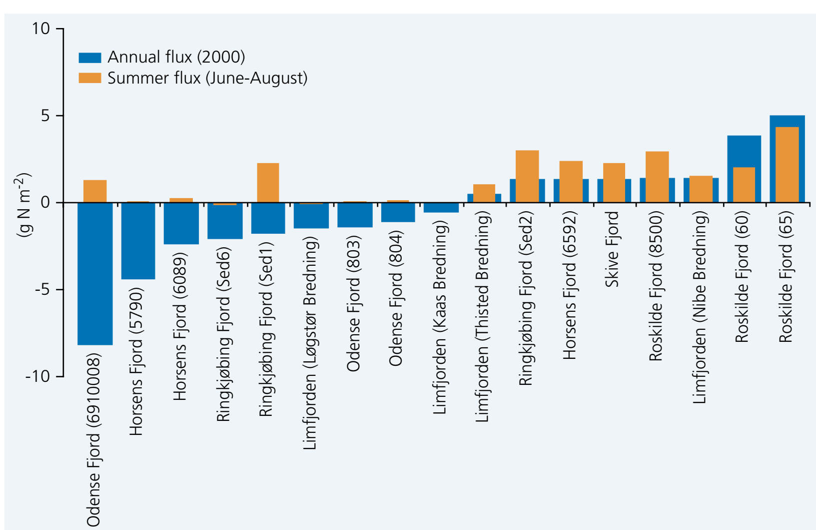
Photo: Fyn County/Nanna Rask

Figure 2.29
Box-Whiskers plot of the seasonal variations in the sediment NO_3^- flux (A), NH_4^+ flux (B) and PO_4^{3-} flux (C). Positive values indicate net release, and negative values indicate consumption. The dataset is a compilation of observations from 6 estuaries each represented with 3 stations sampled 16 times over a two-year period. Median (line), 25% and 75% quantiles (boxes) and 10% and 90% quantiles (bars) are shown.



From January to May, estuarine sediments take up dissolved inorganic nitrogen (DIN=NH_4^++NO_3^-), primarily in the form of NO_3^- (Figure 2.29). During this period, the water-column concentration of NO_3^- is high. Therefore, the sediments NO_3^- uptake may be a result of a lower pore-water concentration of NO_3^-, perhaps governed by denitrification activity and a high NO_3^- assimilation by active benthic microalgae. Not until the summer months (June, July and August) does the estuarine sediment release nitrogen in the form of NH_4^+ (Figure 2.30). Low water-column NO_3^- concentrations and a high sediment oxygen demand resulting in less favourable oxygen conditions cause both nitrification and denitrification to decline markedly or stop altogether. At the same time, NO_3^- assimilation ceases. Thus, in the summer months, NH_4^+ constitutes the major part of the DIN flux from sediment to water column.

Figure 2.30
Internal nitrogen supply in 2000 at 17 stations representing 6 types of estuaries, Roskilde Fjord, Odense Fjord, Horsens Fjord, Ringkøbing Fjord, Limfjorden and Skive Fjord, shown for the entire year (annual flux) and for the months of June, July and August (summer flux). Positive values indicate net release, and negative values indicate consumption.



The flux of nitrogen from the sediment to the water column continues into autumn; but gradually NO_3^- becomes dominating in the release of nitrogen (Figure 2.29 A and B). During autumn, the sediment oxygen demand decreases (Figure 2.28), and this causes the oxygen content of the sediment to increase. This means that nitrification gains more and more importance, and that more and more NH_4^+ is oxidised to NO_3^- (nitrified) within the sediment. As benthic microalgae only assimilate insignificant amounts of NO_3^- during autumn because of lowered activity (see Figure 2.29 A), NO_3^- accumulates within the sediment, even though some denitrification is taking place, and eventually diffuses from the sediment, since water-column NO_3^- concentrations, at least until November, are low.

Phosphorus

Through mineralisation, phosphorus is released as inorganic phosphate (PO_4^{3-}) (Eq. 1). Contrary to nitrogen compounds, a considerable amount of phosphate is bound more or less permanently within the sediment, while a smaller fraction is found dissolved in pore water.

Eq. 1:

$$106CO_2 + 16NH_4^+ + PO_4^{3-} + 106H_2O \underset{\text{Bacterial degradation}}{\overset{\text{Primary production}}{\rightleftharpoons}} (CH_2O)_{106}(NH_4^+)_{16}(PO_4^{3-}) + 53O_2$$

It is the pool of oxidised iron (Fe_{ox}) that binds part of the phosphate found in estuarine sediment (Jensen & Thamdrup 1993). Good oxygen conditions

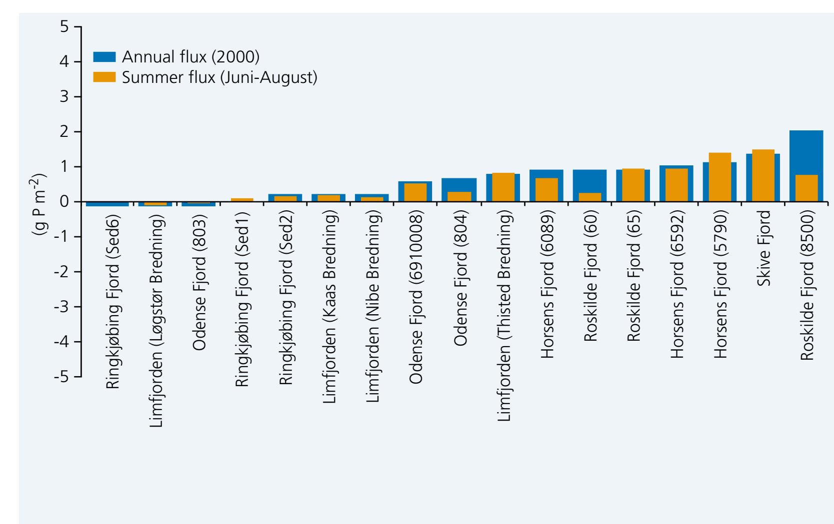


Figure 2.31
Internal phosphorus supply in 2000 at 17 stations representing 6 types of estuaries, Roskilde Fjord, Odense Fjord, Horsens Fjord, Ringkøbing Fjord, Limfjorden and Skive Fjord, shown for the entire year (annual flux) and for the months of June, July and August (summer flux). Positive values indicate net release, and negative values indicate consumption.

within the sediment increases the Fe_{ox} pool, which is able to retain either phosphate or hydrogen sulphide (through a reaction forming ferrous sulphide; FeS – see Eq. 2). On the other hand, poor oxygen conditions cause the pool of oxidised iron to grow gradually smaller. As the Fe_{ox} concentration decreases, phosphate is released from the sediment to the water column.

Eq. 2:

$$Fe_{ox} - PO_4^{3-} + H_2S \longrightarrow FeS + PO_4^{3-}$$

In the "typical" estuary the flux of PO_4^{3-} is insignificant in spring, autumn and winter (Figure 2.31). Significant PO_4^{3-} release from the sediment to the water column is seen only in June, July and August. This period coincides with NH_4^+ release to the water column, and, as described above, the release of PO_4^{3-} is caused by poor oxygen conditions within the sediment that stimulate hydrogen sulphide production, so to speak, leading to increased consumption of oxidised iron.

Internal nutrient load

Nation-wide observations of nutrient fluxes in Danish estuaries from Roskilde Fjord in the east to Ringkøbing Fjord in the west show that during the summer of 2000 (June-August) nitrogen was released from the sediment at 14 of 17 stations (Figure 2.29 C). At almost half of the stations an annual net release of nitrogen from the sediment to the water column was seen in 2000, and the flux of nitrogen during the summer months contributed most to the total net flux that year. Likewise, a net release of phosphorus took place during the summer months at all stations except three (Figure 2.31), and, on average, more than 75% of the total annual PO_4^{3-} release to the water column took place during this period.

It is in the summer months that water-column concentrations of nitrogen and phosphorus are low. Thus, growth of algae within the estuaries depends on a steady supply of nutrients to the water column from land (streams etc.), atmosphere, adjacent seas or through degradation of organic matter in the water column or the sediment. In June, July and August 2000, the total nutrient supply from land constituted 10% of the annual supply. Thus, a relatively low external nutrient supply during summer means that release of nitrogen and phosphorus through organic matter degradation in the sediment (the internal supply) may stimulate primary production in the estuaries at this time of year.

The internal and external supplies of nitrogen (NO_3^-+NH_4^+) and phosphorus (PO_4^{3-}) to four estuaries representing four different types of area, Roskilde Fjord, Odense Fjord, Horsens Fjord and Ringkøbing Fjord, in the period June-August 2000 are shown in Table 2.8, assessed as the total supply to the entire estuary. It is evident that fluxes from the sediment of both nitrogen and phosphorus contributed significantly to the nutrient supply reaching the estuaries in the summer of 2000. In this period, between 36 and 93% of the supply of phosphorus to the estuaries came from the sediment, and in the case of nitrogen, the internal supply was almost as large (10-78%).

Table 2.8
Internal vs. external supply of N and P to four types of estuary in the period June-August 2000

	Nitrogen				Phosphorus			
	Internal	External	Total	Internal	Internal	External	Total	Internal
	tonnes	tonnes	tonnes	%	tonnes	tonnes	tonnes	%
Roskilde	387,1	107,8	494,9	78%	81,7	8,3	90,0	91%
Odense	17,3	152,6	169,9	10%	7,2	6,5	13,7	53%
Horsens	39,7	108,0	147,7	27%	43,1	3,2	46,3	93%
Ringkøbing	263,8	884,8	1.148,7	23%	10,3	18,4	28,7	36%


Photo: NERI/Ole Schou Hansen

2.9 Submerged aquatic vegetation

Seagrasses and macroalgae enhance biodiversity by providing habitat and shelter for many species.


Photo: NERI/Peter Bondo Christensen

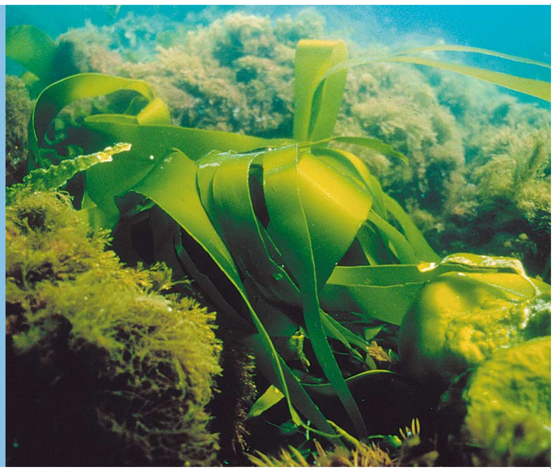


Photo: Biofoto/S.E. Sørensen

Eelgrass (*Zostera marina*) is the most widely distributed marine angiosperm in shallow Danish coastal waters. On hard substrates the vegetation is dominated by macroalgae. Growth of short-lived nuisance species of macroalgae is a problem in inner parts of some estuaries.

Eelgrass in coastal waters

Eelgrass and seagrasses in general often represent a large standing biomass and a high primary production that influence the overall functioning of coastal ecosystems. Seagrasses enhance biodiversity by providing habitat and shelter for many species; they are nursery and foraging areas for commercially important species of fish; they improve water quality by reducing particle loads and absorbing dissolved nutrients; they stabilise sediments and influence global carbon and nutrient cycling (see Hemminga & Duarte 2000). The many ecosystem services provided by eelgrasses have created a concern for the response of this species to eutrophication. This concern has been intensified over the last few decades where large-scale reductions in seagrass meadows have been reported in response to eutrophication from many areas (see Short & Wyllie-Echeverria 1996).

The following paragraphs summarise the development of Danish eelgrass meadows during the last century. The presentation is based on early reports on eelgrass distribution covering the period 1900-1940, aerial photos from the archives of KMS (The National Survey and Cadastre Agency) covering the period 1945–1990s and data from the national Danish monitoring programme on marine vegetation covering the period 1989–2001.

Long-term changes in eelgrass distribution

In Denmark, records of eelgrass distribution date back to around 1900, and provide a unique opportunity to describe long-term changes. In 1900, eelgrass was widely distributed in Danish coastal waters, and covered approximately 6726 km^2 or 1/7 of all Danish marine waters (Petersen 1901, 1914) (Figure 2.32). The standing crop made up almost 1 kg dw m^{-2} in the densest stands and the total annual eelgrass production was estimated at 8 million tonnes dry weight (Petersen 1914). In the 1930s, the world wide wasting disease substantially reduced eelgrass populations, especially in north-west Denmark where salinity is highest (Blegvad 1935). In 1941, eelgrass covered only 7% of the formerly vegetated areas and occurred only in the southern, most brackish waters and in the low saline inner parts of Danish estuaries (Lund 1941, Rasmussen 1977)(Figure 2.32). No national monitoring existed between 1941 and 1989 but analyses of aerial photos from the period 1945–1990s, reveal an initial time lag of more than a decade before substantial recolonisation of the shallow eelgrass populations began. The photos also show that large populations had recovered in the 1960s (Frederiksen et al. subm.).

Today eelgrass again occurs along most Danish coasts (Figure 2.32) but has not reached the former area extension (Olesen 1993, Boström et al. in press). Comparisons of eelgrass area distribution in two large regions, Øresund and Limfjorden, in 1900 and in the 1990s, suggest that the present distribution area of eelgrass in Danish coastal waters constitutes approximately 20–25% of that in 1900. The area distribution of eelgrass in Limfjorden was estimated at 345 km^2 in 1900 (Ostenfeld 1908) and only at 84 km^2 in 1994 (based on aerial photography data from the Limfjord counties). In Øresund, eelgrass covered about 705 km^2 in 1900 (Ostenfeld 1908) and only about 146 km^2 in 1996–2000 (Krause-Jensen et al. 2001). Differences in methodology may, however, influence these comparisons.

The large reduction in area distribution of Danish eelgrass meadows is partly attributed to loss of deep populations. In 1900, colonisation depths averaged 5–6 m in estuaries, and 7–8 m in open waters while in the 1990s, colonisation depths were reduced about 50% to 2-3 m in estuaries and 4–5 m in open waters (Figure 2.33) (Boström et al. in press). The deep populations are most likely lost as a consequence of eutrophication. Increased nitrogen concentrations stimulate phytoplankton growth and thereby reduce the transparency of the water column and restrict the colonisation depth (Nielsen et al. 2002).


Photo: NERI/Peter Bondo Christensen

Recent inter-annual fluctuations in eelgrass distribution

Since 1989, the Danish Aquatic Monitoring and Assessment Programme has included annual surveys of colonisation depth and cover of eelgrass along depth gradients in a wide range of estuaries and coastal waters.

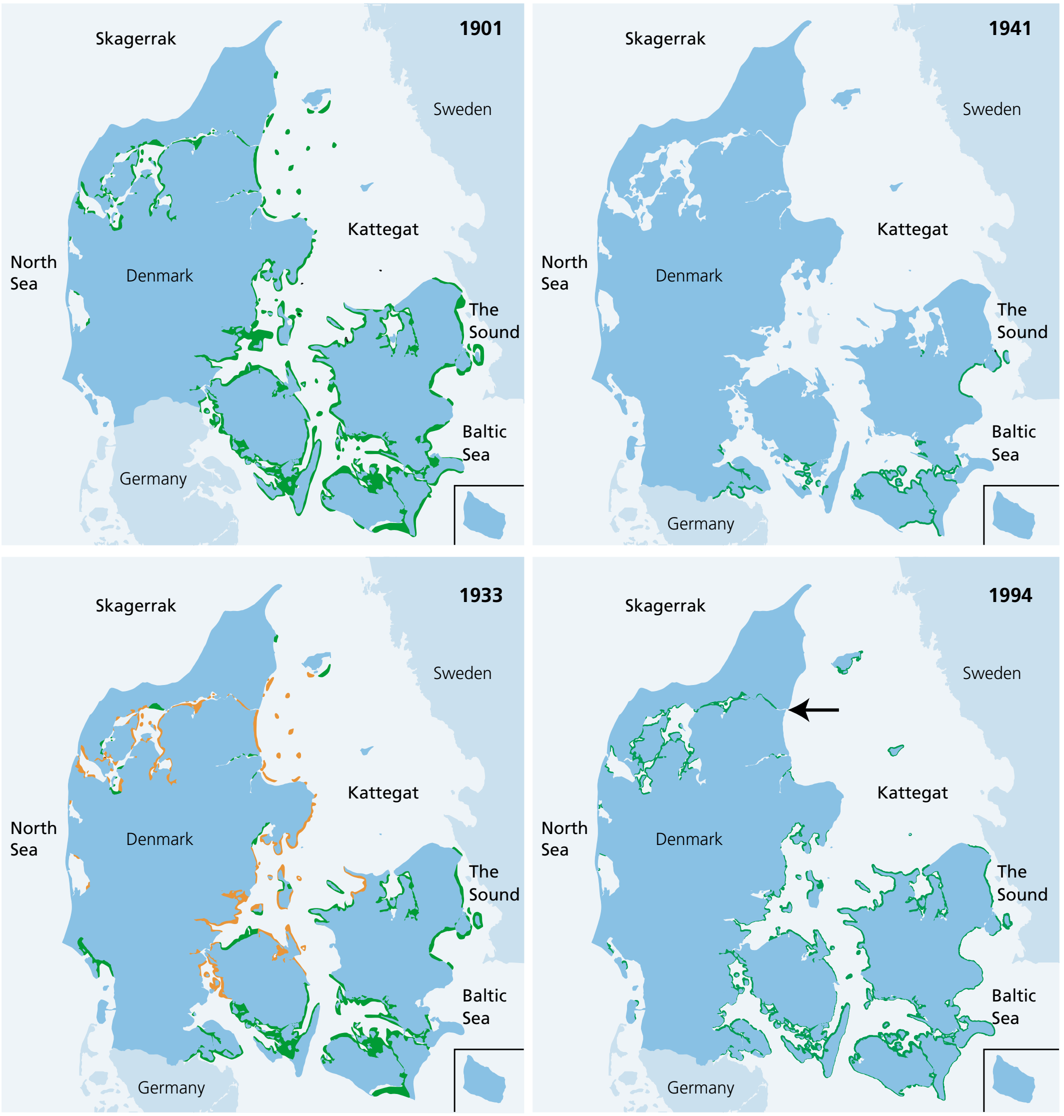


Figure 2.32
Map of eelgrass area distribution in Danish coastal waters in 1901 (redrawn after Petersen 1901), 1933 (redrawn after Blegvad 1935), 1941 (redrawn after Lund 1941) and 1994 (coarse map based on visual examination of aerial photos and data from the national Danish monitoring programme, produced by Jens Sund Laursen). Green areas indicate healthy eelgrass while orange areas (on the 1933 map) indicate where eelgrass was affected by the wasting disease but still present in 1933. The arrow shows the location of Limfjorden. (Boström et al. in press).

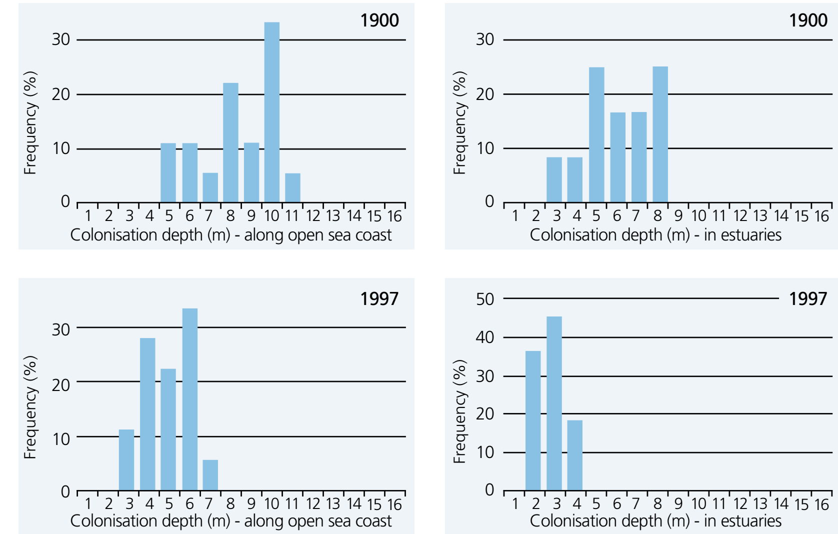


Figure 2.33
Maximum colonisation depth of Danish eelgrass patches along open coasts and in estuaries in 1900 and 1996/1997. Based on data from 18 sites along open coasts and 12 sites in estuaries investigated by Ostenfeld (1908) in 1900 and by the Danish Aquatic Monitoring and Assessment Programme in 1996/1997 (Boström et al. in press).

The colonisation depth of eelgrass reflects differences in water quality and physical setting along estuarine gradients. In the inner parts of estuaries, the annual mean colonisation depth ranged between 2.9 and 3.5 m, in outer parts between 3.3 and 4.3 m, and along open coasts between 4.7 and 5.8 m during the period 1989–2001 (Figure 2.34). Eelgrass colonisation depth shows no significant trend between 1989 and 2001 and does not reflect the sligh amelioration of water clarity observed through the same period (Ærtebjerg et al. 2002). Other regulating factors may blur the relationship between light and colonisation depth so that more marked changes in light climate are needed before colonisation depths increase. For example, eelgrass suddenly disappeared from several sites during the warm summers of 1992 and 1994 possibly due to combined exposure to anoxia, sulphide and extreme temperature (Goodman et al. 1995, Terrados et al. 1999).

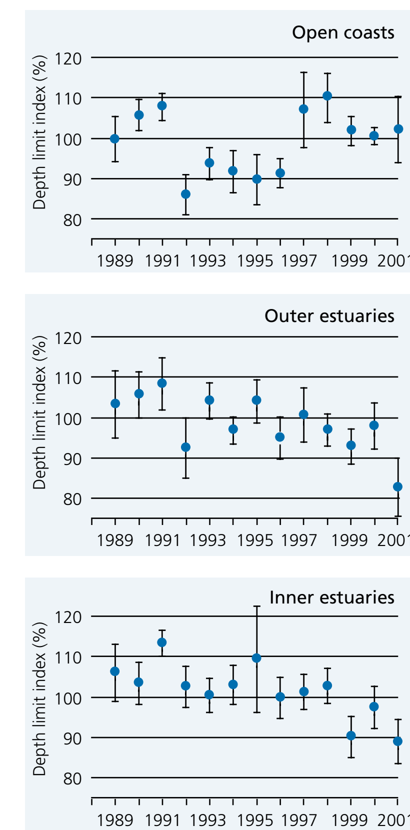
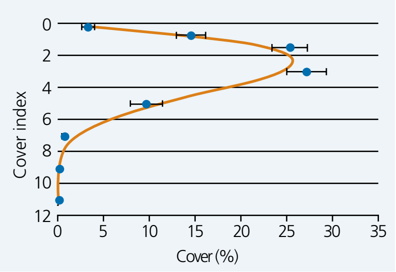


Figure 2.34
Index of maximal eelgrass colonisation depths (± s.e.) during the period 1989–2001 in inner estuaries (lower panel), outer estuaries (central panel) and along open coasts (upper panel). Index values represent colonisation depths of a given year relative to average colonisation depths of the period 1989–2001 (Ærtebjerg et al. 2002).

Figure 2.35
Eelgrass cover as a function of depth. Data represent average cover of 276 depth gradients monitored under the national Danish Aquatic Monitoring and Assessment Programme in 1994.



Eelgrass displays a bell-shaped distribution pattern along the depth gradient with maximum abundance at intermediate depth and lower abundance in shallow and deep water (Figure 2.35). Exposure, desiccation and ice-scour act to reduce eelgrass abundance in shallow water and render the populations extremely dynamic and unpredictable. In the deeper, more protected waters, reductions in eelgrass abundance towards the lower depth limit correlate with light attenuation (Sand-Jensen et al. 1997, Krause-Jensen et al. 2000) and are therefore more directly coupled to changes in eutrophication. The period 1989–2001 showed no significant trend in eelgrass cover at water depths above 2 m, but the cover of shallow populations was significantly reduced in inner estuaries and along open coasts (Henriksen et al. 2001). We have found no obvious explanation for this pattern.

In conclusion, eelgrass responds to several types of disturbances: changes in energy input (light), physical disturbances (e.g. wind, waves, extreme temperature, ice), chemical disturbances (e.g. anoxia, sulphide) and biological disturbances (e.g. the wasting disease). When eelgrass is used as a monitoring parameter to reflect changes in light climate due to eutrophication we should therefore be aware that other factors may affect the response. As the intensity of physical disturbances decline with depth, eelgrass colonisation depth and abundance from intermediate depths towards deeper waters are therefore likely to be better response parameters to eutrophication than the abundance of shallow populations.

Photo: NERI/Karsten Dahl

Short-lived nuisance macroalgae

Short-lived nuisance macroalgae are favoured by large supplies of nutrients (Pedersen 1995). Together with macroalgal species numbers and dominance patterns, the cover of nuisance species is therefore used as an indicator of the state of macroalgae in coastal areas in the Danish Aquatic Monitoring and Assessment Programme.

Information on these algae is relatively scarse and analyses of trends are therefore only possible for the inner part of estuaries at depth intervals of 0–1, 1-2 and 2–4 meter. During the monitoring period (1993–2001) average relative cover varied from 1–20% at 0–1 meter depth, 1–25 % at 1–2 meter depth and 0–20% at 2–4 meter depth. There were no significant changes during the period 1993 to 2001 (Kendalls-tau, $p > 0,05$) (see figure 2.36).

Macroalgae on reefs in open waters

As with seagrasses the macroalgae on the reefs in the open waters enhance biodiversity by providing habitat and shelter for many species. Furthermore they constitute a great part of the biodiversity in marine vegetation. The vegetation in the open waters consists of a multilayer of red and brown algal vegetation at water depths of 10–12 meters. At depths greater than 12–14 m total cover of upright algae decreases to a single layer with coverage less than 100% and cover decreases further with increased depth. In addition to upright forms, crust forming macroalgae cover stones and shells. The cover of crust forming algae is large, even at 24–25 meters depth.

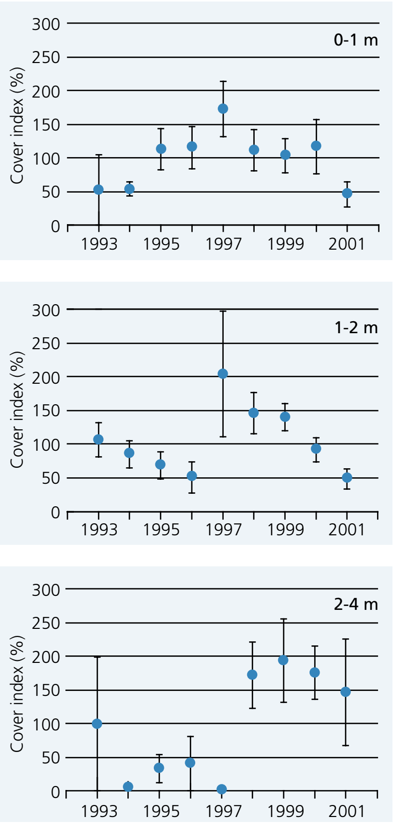


Figure 2.36
Cover index of loose lying nuisance macroalgal species in the inner parts of estuaries during the period 1993–2001. Data represent the depth intervals 0–1 m, 1–2 m and 2–4 m. The cover for each depth interval in a given year has been indexed relative to average cover of the depth interval during the period 1993–2001 (Ærtebjerg et al. 2002).

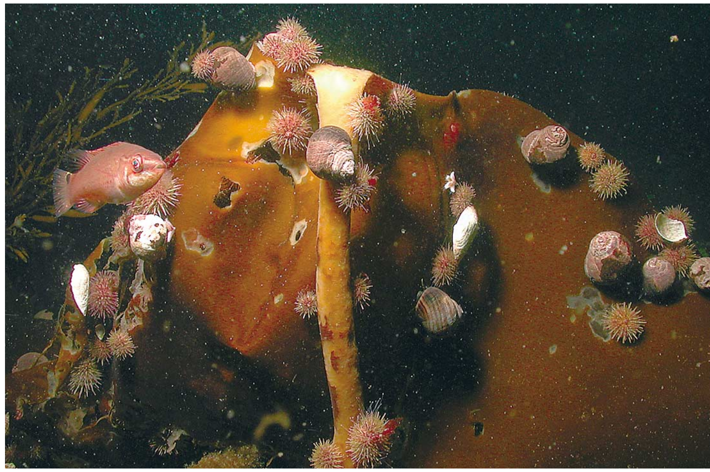


Photo: NERI/Karsten Dahl

Macroalgal vegetation is monitored at 9 stone-reefs and rocky bottom areas evenly distributed in the Kattegat, with one station located in the northern Belt Sea. The total relative cover of the upright forms is described along with specific cover of individual species including crust forming algae.

It has been shown that a good empirical correlation exists between the supply of the inorganic nutrients (nitrogen and phosphorus in freshwater inputs) and total cover of macroalgae at deep stations in the Kattegat during the period 1994 to 2000 (Henriksen et al. 2001). This means that high supplies of inorganic nutrients or freshwater leads to a reduced development of benthic vegetation. Exceptions are stations with an intense grazing pressure from the sea urchin *Strongylocentrotus droebachiensis*.

There is a corresponding significant correlation between the cover of benthic vegetation and the pelagic parameters, Secchi depth and chlorophyll concentration. This supports the hypothesis that the supply of nutrients influences light penetration to the bottom and thereby the environmental quality of the individual reef locations.

The total cover of the upright vegetation tended to increase in 2001 relative to the mean of the period 1994–2001 (Table 2.9). In general, algal coverage was low in years with relatively high runoff and high in years of low runoff. Accordingly there was no overall trend in the cover of macroalgae at the monitored reef stations (Figure 2.37).

Year	Month	Number of observations	Macroalgae coverage with reference to average coverage 1994-2001	P
1994	June	4	←→	–
	August	11	↓	–
1995	June	11	↑	–
	August	12	↓	–
1996	June	9	↓	–
	August	9	↑	*
1997	June	11	↑	***
	August	11	↑	***
1998	June	10	↓	*
	August	10	↓	**
1999	June	10	↓	*
	August	11	↓	***
2000	June	10	↓	–
	August	12	↓	–
2001	June	11	↑	–
	August	11	↑	–

Table 2.9
Macroalgal cover at a number of stonereefs in Kattegat relative to the average cover in the period 1994–2001.
↑ means that the majority of examined stations has a more developed vegetation cover.
↓ means that the majority of examined stations has a less developed vegetation cover.
←→ means that there is an equal number of stations with a less respectively more developed vegetation cover.
A signtest shows whether cover has increased or decreased relative to the mean for the period 1994-2001. * = P < 5%, ** = P < 1%, *** = P < 0,1%.

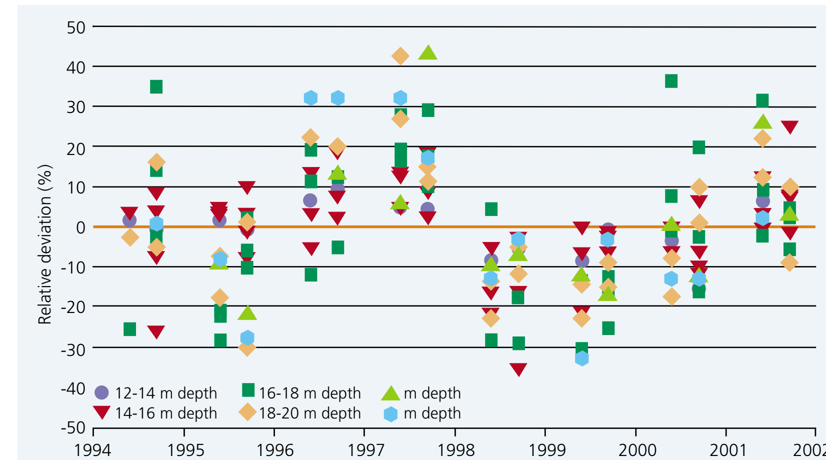


Figure 2.37
The relative deviation in macroalgal cover in relation to mean values for individual stations and time of investigation. Deviations are given in 2 meter depth intervals. Stations where algal abundance was limited by sea urchin grazing are left out.

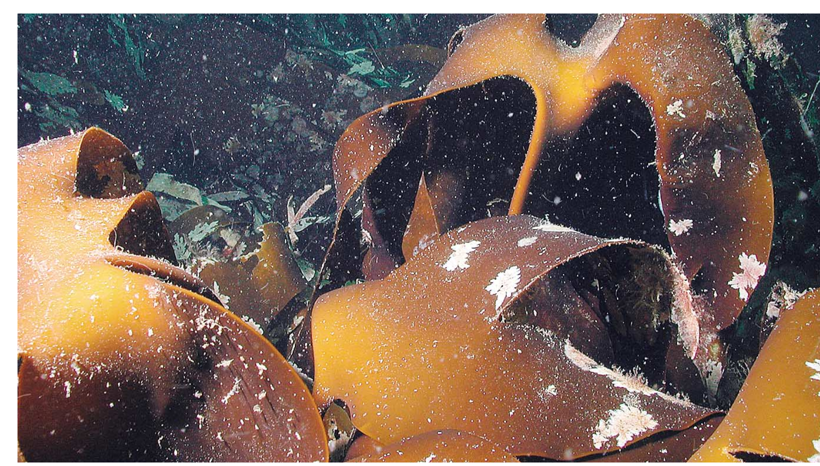


Photo: NERI/Karsten Dahl

2.10 Softbottom macrobenthos

Filter feeding bivalves are an important link between the pelagic and the benthic environment.

Photo: Biofoto/Michael Jensen

Benthic macrofauna in soft sediments plays an important role in the degradation of organic matter produced in the pelagic zone and several species serve as food for demersal fish. Since it is composed of many different species (in the Kattegat there are more than 500 species), benthic macrofauna furthermore constitute a great part of the biodiversity in the water surrounding Denmark. The macrofauna integrates environmental changes in the benthic environment and is a highly cost effective parameter to sample. Moreover, since this fauna often is limited by food, such as sedimenting phytoplankton biomass, macrozoobenthos is a useful parameter to describe changes in eutrophication.

Benthic macrofauna has been included in the Danish Monitoring Programme since 1979 and is measured with replicated quantitative sampling at fixed stations. Number of individuals and biomass (wet weight or dry weight) are measured for each species. Sampling occurs once a year typically in May/June. The number of fixed stations regularly visited at present include 24 stations in open sea areas mainly in the Kattegat and station grids in 22 estuaries and near coastal areas around Denmark.

Open sea areas

General trends in macrozoobenthos abundance in the Sound, the Kattegat and the Belt Sea follow a bimodal pattern over the last 20 years with peaks in the beginning of the 1980s and in the middle of the 1990s (Figure 2.38). While the first peak was dominated by both polychaetes and crustaceans, the peak in the 1990s was only dominated by polychaetes. Within the taxonomic groups different species dominated in different peaks and at different stations. Biomass did not show the same clear pattern as abundance. Biomass and total abundance showed the lowest values in the period 1998–2001 since the measurements started.

Over the two last decades changes in total abundance and biomass of macrobenthos are below the halocline in Danish open sea areas. Correlation analyses performed between the biological variables and two environmental variables related to climate, the North Atlantic Oscillation index (NAO-index) and runoff of freshwater from Denmark, showed significant positive correlation with a 1 or 2 years time lag, indicating influence of climate on benthic variations (Henriksen et al. 2001). In particular winter nutrient input, and the spring phytoplankton bloom, most likely influences the abundance of benthic macrofauna.

However, correcting for the linear effects of runoff, the general pattern in abundance is still there, suggesting the importance of other factors hitherto not identified. Some evidence indicates that reduced nitrogen nutrient concentrations and possibly reduced diatom abundance, when corrected for runoff, may have reinforced the decrease in benthos stocks in recent years.

Coastal areas

From 1998 the monitoring strategy for estuaries and coastal areas was changed from measurements on single stations to measurements on grids of stations in each area. Benthic fauna data sampled with consistent methods are now available from 25 different estuarine and bay areas from the period 1998 to 2001. Unlike the open Kattegat and the Belt Sea, where faunal changes in total abundance and biomass to a large degree are synchronised between stations, changes in coastal areas do not seem to be synchronised to the same degree. This is exemplified in Table 2.10 where total number of species in the 4 years are shown for each coastal area. The number of areas with increasing

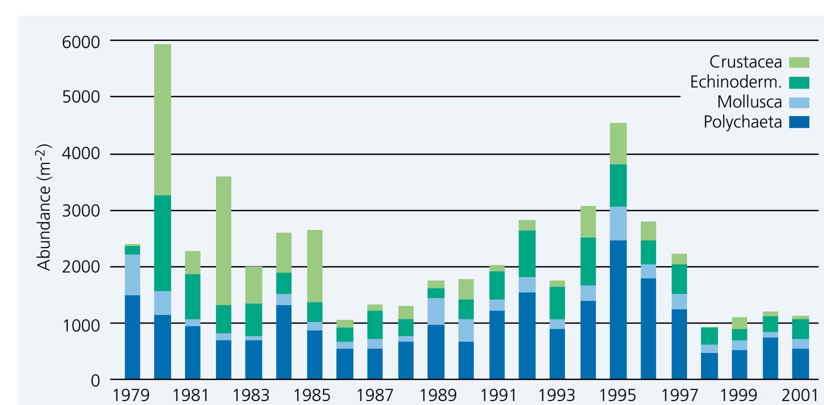


Figure 2.38
Temporal development of abundance at 3 stations of 17-55 m water depth, in the Kattegat-Sound-Belt Sea area partitioned on major taxonomic groups. Bristleworms (Polychaeta), Molluscs (Mollusca), Echinoderms (Echinodermata) and Crustaceans (Crustacea). Remaining taxa had a negligable part of the total abundance. Note the dramatic decrease in numbers of crustaceans over the 2 decades.

species numbers are about the same as the decreasing ones. Reasons for lack of synchrony between coastal areas is probably local factors like oxygen deficiency. For example, in Mariager Fjord fauna was more or less exterminated by oxygen deficiency in 1997 and thereafter a succession of species have taken place reflected by increasing number of species. In conclusion, there are no general synchronous changes in abundance, biomass or number of species in coastal areas over the last 4 years.

Kills of macrozoobenthos

The increase in oxygen consumption due to enhanced loads of organic matter to the bottom can lead to oxygen depletion and death of benthic fauna. Though these events are not part of the monitoring programme, many of the events are still recorded (see Table 2.11).

There are examples from Danish marine areas, like the southern Little Belt, where severe acute oxygen depletion and probably kills of macrobenthos have been an almost regular yearly event since the beginning of the last century. However, the area in the southern Little Belt where macrobenthos suffer from oxygen depletion is in recent years five times larger than 100 years ago (Marin ID 1988). Large scale oxygen depletion events with kills of macrobenthos belong to the present. A well known example is from 1986 when fishermen caught dead Norwegian lobsters (*Nephros norvegicus*) in the Kattegat. It is also likely that 2002 will be well-known for the extended oxygen depletion and resulting kills of macrobenthos.

Coastal area	m^2	1998	1999	2000	2001
Roskilde Bredning	0.51	29	29	23	30
Horsens Fjord	0.61	–	24	24	40
Vejle Fjord	10.07	–	52	36	55
Kolding Fjord	5.54	–	57	36	61
Ringkøbing Fjord	7.15	20	22	22	17
Nissum Fjord	6.44	30	29	33	28
Hevring Bugt	5.54	76	69	87	91
Øresund	6.44	68	51	54	52
Køge Bugt, central part	6.44	26	30	28	35
Odense Fjord	6.45	66	78	57	57
Ringgårdbassin	5.81	27	28	25	19
Roskilde Fjord, northern part	3.58	33	30	31	37
Isefjord	3.15	24	36	19	15
Kattegat	2.86	63	51	61	66
Lillebælt	5.54	35	50	51	27
Karrebæksminde Bugt	6.57	40	28	37	31
Skive Fjord	6.44	31	36	24	41
Nissum Bredning	6.44	33	31	49	34
Løgstør Bredning	6.44	42	34	32	35
Wadden Sea, northern part	26.66	43	43	41	47
Århus Bugt	6.03	62	46	54	57
Mariager Fjord	5.54	17	14	28	26
Flensborg Fjord	5.41	66	30	30	17
Wadden Sea, southern part	1.98	41	36	43	40
Nivå Bugt	3.58	–	62	65	57
Average species number		41.524	39.84	39.6	40.6

Table 2.10
Changes in macrofauna species numbers 1998-2001 in 25 coastal areas in Denmark. The first coloumn denotes total sampling area, red denotes a decrease compared to previous sampling, green denotes an increase and blue denotes no difference.

Year	Place	Cause
1981	North Sea, Hevring Bugt, Århus Bugt, Pæregård Strand, Dalby Bugt, Kalø Vig	Oxygen depletion
1983	Lillebælt, Kieler Bugt	Oxygen depletion
1985	Kattegat	Oxygen depletion
1986	Kattegat, Kieler Bugt	Oxygen depletion
1987	Sejrø Bugt, North coast of Sjælland, southern Lillebælt	Oxygen depletion
1988	Skagerrak, Kattegat	Harmful algal bloom
1988	Southern Kattegat, Limfjord, Århus Bugt,	Oxygen depletion
1989	Horsens Fjord	Oxygen depletion
1990	Århus Bugt, Northern Lillebælt	Oxygen depletion
1991	Haderslev Fjord	Oxygen depletion
1992	Haderslev Fjord	Oxygen depletion
1993	Vejle Fjord, Southern Lillebælt	Oxygen depletion
1994	Roskilde Fjord, Limfjord, Vejle Fjord, Nørrefjord, Flensborg Fjord, Sydfynske Øhav, Isefjord, Århus Bugt, Åbenrå Fjord, Genner Fjord, Flensborg Fjord, Lillebælt	Oxygen depletion
1995	Åbenrå Fjord, Roskilde Fjord	Oxygen depletion
1996	Limfjorden, Vejle Fjord, Lillebælt	Oxygen depletion
1997	Mariager Fjord, Limfjorden, Nakkebølle Fjord, South and east of Møn, Isefjord	Oxygen depletion
1998	Southern Lillebælt, Åbenrå Fjord Flensborg Fjord	Oxygen depletion
1999	Limfjord, Kalø Vig, Knebel Vig, Århus Bugt, Horsens Fjord, Vejle Fjord, Flensborg Fjord, sydlige Bælthav, Sydfynske Øhav	Oxygen depletion
2000	Langelandssund, Ebeltoft Vig, Århus Bugt, Odense Fjord, Limfjorden	Oxygen depletion
2001	Limfjorden, Århus Bugt	Oxygen depletion
2002	Limfjorden, Århus Bugt, Hevring Bugt, Mariager Fjord, Vejle Fjord, Ålborg Bugt, Kalø Vig, Åbenrå Fjord, Flensborg Fjord, coastal areas north and south of Fyn, Lillebælt	Oxygen depletion

Table 2.11
Recorded macrozoobenthos kills and their causes in Danish marine waters 1981–2002.

2.11 Fish kills in coastal waters

Fish kills are not the most common effect of eutrophication but illustrate severe effects of oxygen deficiency and harmful algal blooms.

Photo: Bent Lauge Madsen

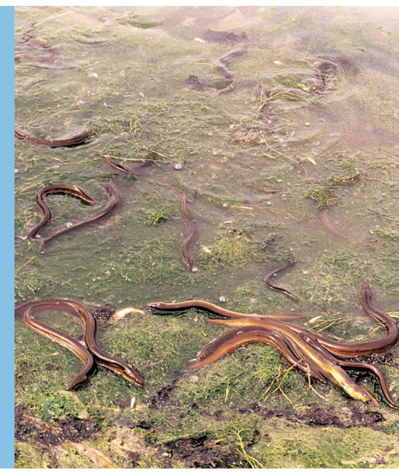


Photo: Århus County/Helene Munk Sørensen

Normally two types of events related to eutrophication can cause fish kills. It is either toxic algae or low oxygen concentrations. Low oxygen concentrations in the bottom waters result in the release of hydrogen sulphide (H_2S) from the sediments. The H_2S is lethal to most animals and the result of the sudden release is often extensive and leads to the immediate death of animals living at or near the sea floor as well as in the water column. This immediate effect, therefore, also includes fish. However, the most spectacular fish kills with dead or dying fish accumulating on the shores, as an example in 1981 and 2002, are due to upwelling of oxygen poor or H_2S containing bottom water to the surface along the coasts due to changing wind directions and forces, trapping the fish in these water masses with no chance to escape.

The Danish EPA published the first comprehensive national assessment of the effects of oxygen depletion and harmful algal blooms in 1984 (Danish EPA 1984) This report assessed fish kills in the Danish waters and concluded that fish kills were restricted, and were exceptional, but natural events, before the 1970s, and that the problem increased in the 1970- and early 1980s.

The four best known Danish examples of fish kills are from 1981, 1988, 1997 and 2002. In 1981 the kills were caused by severe oxygen depletion in most of the Danish waters (Danish EPA 1984). Fish kills in May and June 1988 were due to a large bloom of the flagellate *Chrysochromullina polylepis* (Lancelot et al. 1989). In 1997, almost all fish were killed in the inner part of Mariager Fjord due to oxygen depletion and release of H_2S in the entire water column. In October 2002 fish kills occurred several places along the Jutland east coast due to upwelling of oxygen poor and H_2S containing bottom water.

The ongoing national monitoring programme does not include fish monitoring. However, fish kills have been reported annually since 1989 as an integral part of the National Aquatic Monitoring and Assessment Program. Table 2.12 summarises the recorded

Year	Place	Cause
1981	Hevring Bugt, Århus Bugt, Pæregård Strand, Dalby Bugt, Båring Vig, Vejle Fjord, Limfjorden, including Thisted Bredning, Visby Bredning, Bjørnsholm Bugt, Risgårde Bredning, Skive Fjord and Lovns Bredning	Oxygen depletion
1981	Fjaltring Strand, Glyngøre Harbour	Harmful algal bloom
1982	North Sea, Køge Bugt, Holckenhavn, Kalø Vig, Isefjord	Oxygen depletion
1983	Lillebælt, Als Sund, Langelandssund	Harmful algal bloom
1987	Sejrø Bugt	Oxygen depletion
1988	North coast of Sjælland, Sejrø Bugt, Ringkøbing Fjord	Oxygen depletion
1988	North Sea, Skagerrak, Kattegat, and the northern part of Øresund	Harmful algal bloom
1989	Ringkøbing Fjord	Oxygen depletion
1990	Århus Bugt	Oxygen depletion
1990	Djurslands Østkyst	Oxygen depletion or harmful algal bloom
1991	Lillebælt	
1992	Lillebælt	Possible harmful algal bloom
1994	Årgab, Hovvig, Mariager Fjord, Vejle Fjord, Isefjord, Roskilde Fjord, Thisted Bredning, Skive Fjord, Lovns Bredning	Oxygen depletion
1995	Årgab, Hanstholm	Oxygen depletion
1997	Mariager Fjord, Vejle Fjord, Sydfynske Øhav, Korsør Nor, Isefjord	Oxygen depletion
1998	North Sea and Skagerrak	Harmful algal bloom
1999	Vejle Fjord	Oxygen depletion
2000	Kattegat, Smålandsfarvandet, Ebeltoft Vig, Sydfynske Øhav	Oxygen depletion
2001	Vejle Fjord	Oxygen depletion
2002	Ålborg Bugt, Hevring Bugt, Vejle Fjord, Kalø Vig, Øresund, Sydfynske Øhav	Oxygen depletion

Table 2.12
Recorded fish kills in Danish marine waters 1981–2002

Photo: NERI/Peter Bondo Christensen

fish kills in Danish marine waters. It might be argued that the situation has not improved since the mid 1980s, mainly because inputs of nutrients are still high, especially in wet years, and that the events of oxygen depletion that might trigger fish kills are tightly coupled to meteorological and hydrographic forcing.

Regional authorities have carried out studies on fish populations and fish kills in Limfjorden, Mariager Fjord, Ringkjøbing Fjord, Roskilde Fjord, the area around Rødsand, the Wadden Sea and Århus Bugt. Studies in Århus Bugt, which covers the period 1953–1998 and includes coherent data on fish, fisheries, zoobenthos and water quality, are summarised by Jensen (1999):

- The occurrence and composition of fish have changed significantly during the last 50 years, due to changes in fishing intensity and duration of oxygen depletion.
- Fishing intensity has had an impact on plaice (*Pleuronectes platessa*), which has decreased from the 1950s to the 1990s.
- Conversely, the dab (*Limanda limanda*) has become more frequent and is now the dominating flat fish in the bay.
- The mean length of dab has decreased since 1957 and is unambiguously linked to the duration of oxygen depletion. The growth is limited in years with longer periods of oxygen depletion compared to the situation in the 1950s. Less that 1% of dabs reach the minimum size limit of 25 cm.

Future possibilities to assess the health of coastal fish populations will improve from 2004, when monitoring of non-commercial fish in six representative coastal waters will be conducted on a regular basis within the monitoring and assessment programme.

Photo: NERI/Gunni Ærtebjerg

Photo: Biofoto/Kjeld Olesen

Christiansborg, home of the Danish Parliament.

Responses and adaptive management

3

Since the mid 1980s high priority has been given to the quality and protection of the aquatic environment in Denmark. The overall goal is to ensure that the waters are clean. The endeavours in this respect are described in Aquatic Environment 1999 (Danish EPA 2000) and summarised in Conley et al. (2002).

These papers state that Danish administrations shall work towards ensuring:

- That watercourses, lakes and marine waters are clean and of a satisfactory quality as regard to health and hygiene.
- That exploitation of water bodies and associated resources takes place in a sustainable manner.
- That the objectives of relevant international agreements will be fulfilled.

The central legal instrument to fulfil these political objectives is the Consolidated Environmental Protection Act, which aims to safeguard the environment, to support a sustainable social development, and to protect flora and fauna (Ministry of Environment and Energy 1998).

The general objectives for Danish marine waters are based on the Consolidated Environmental Protection Act, the 1992 Helsinki Convention on Protection of the Marine Environment in the Baltic Sea Region and the 1992 Convention for the Protection of the Marine Environment of the Northeast Atlantic. More specific objectives are:

- Anthropogenic pollution and human activities may only insignificantly or slightly affect fauna and flora.
- Nutrient levels have to be at or close to natural levels.
- Clarity of the water has to be normal or close to normal.
- Unnatural blooms of toxic planktonic algae must not occur.
- Pollution-dependent macroalgae must not occur.
- Oxygen deficiency may only occur in areas where this is natural.

Commercial exploitation, i.e. fishery, offshore industry, dumping of seabed material, recreational activities etc. has to be conducted in a manner that is sustainable and respects environmental and natural wealth.

3.1 Principles

The primary means of achieving the quality objectives for surface waters is a reduction in nutrient discharges, losses and emissions.

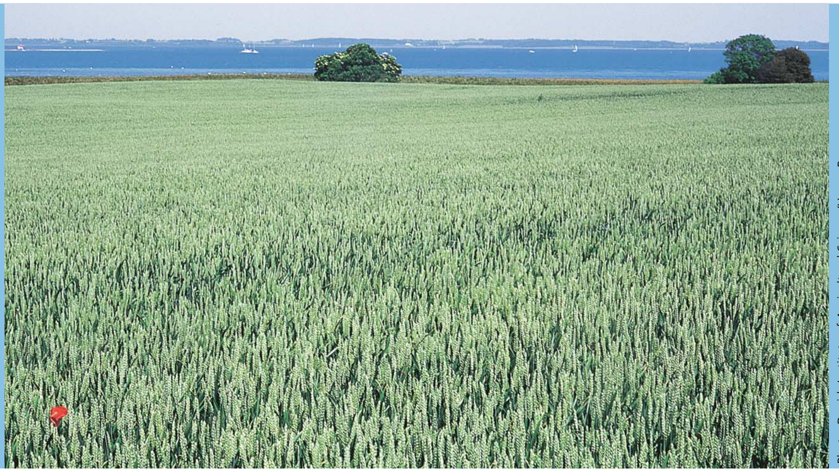


Photo: Danish Institute of Agricultural Science/Henny Rasmussen

One of the guiding principles in the Danish work on abatement of pollution in general and nutrient enrichment and eutrophication in particular is "strategic environmental planning".

The intentions of the principle is to deal with environmental problems in a coherent way and that policies are to be developed as a process with the following elements:

- Political agreements on goals.
- Implementation of agreed measures.
- Continuous monitoring and regular production of assessment reports, aiming at a higher level of understanding of the actual problem.
- Periodic evaluations and adjustments (if relevant) of goals and measures.

The principle which is illustrated in Figure 3.1 shall ensure that the goals can either be met with the agreed measures or – if goals are not met – that measures should be revised or even supplemented with additional measures. The overall goal is to ensure that environmental policies become more preventive, holistic and target orientated.

The Danish administration put emphasis on that the principles of strategic environmental planning are implemented at all levels and in all actions aiming at a healthier aquatic environment. Danish policies to improve the health of the marine environment have been and will be based on the available information on relations between society and environmental responses to changes, effects of measures and effectiveness of the measures etc.

The Danish policies and strategies to abate eutrophication of the aquatic environment are an illustrative example on how the concept of strategic environmental planning works. The strategies and measures as well as the chronology (1986-2002) are described in Chapter 3.2.

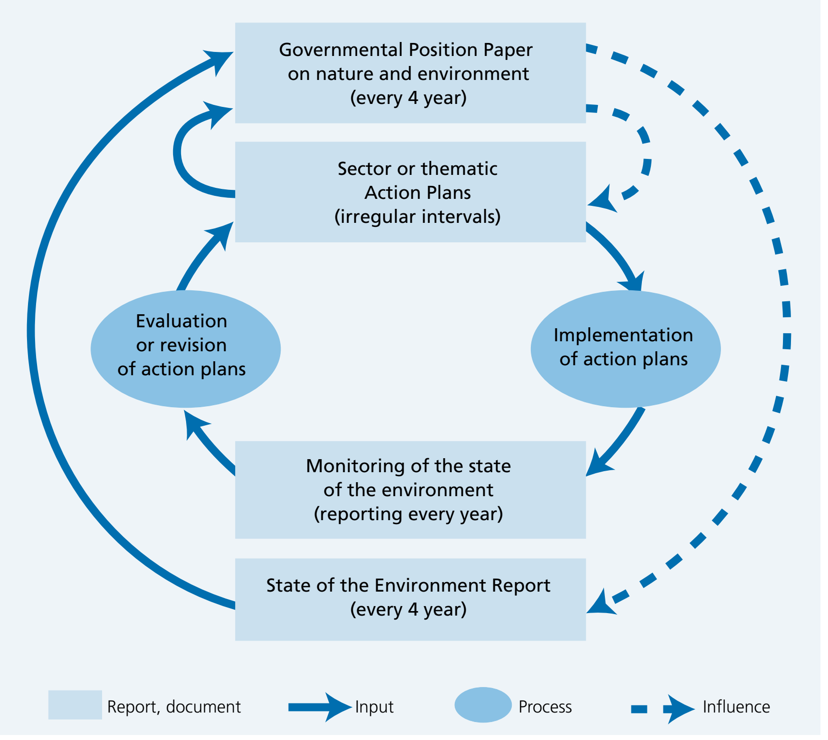


Figure 3.1 Illustration of the concept of strategic environmental planning.

3.2 Nutrient Reduction Strategies in Denmark

Photo: Scanpix

The Danish Parliament.

The primary means of achieving the quality objectives for surface waters is a reduction in nutrient discharges and emissions. In the January 1987 Action Plan on the Aquatic Environment and the April 1987 Report on the Action Plan on the Aquatic Environment the goal of reducing nitrogen and phosphorus loads to the aquatic environment was set to 50% and 80%, respectively. This corresponds to a reduction in annual discharges and losses from a level of around 283,000 tonnes N and 9,120 tonnes P at the time the plan was adopted to a level of ca. 141,600 tonnes N and ca. 1,820 tonnes P (see Table 3.1 for details). The Action Plan covers the 3 major sources: agriculture, municipal wastewater treatment plants and separate industrial discharges.

Tabel 3.1
Sector specific reduction targets for annual discharges and losses of nitrogen (tot-N) and phosphorus (tot-P) to the aquatic environment in Denmark (Danish EPA 2000).

	Nitrogen			Phosphorus		
	1987	÷ Reduction	= Target	1987	÷ Reduction	= Target
Agriculture	260.000	÷ 127.000	= 133.000	4.400[1)]	÷ 4.000	= 400
Municipal WWTPs	18.000	÷ 11.400	= 6.600	4.470	÷ 3.250	= 1.220
Separate industrial discharges	5.000	÷ 3.000	= 2.000	1.250	÷ 1.050	= 200
Total	283.000	÷ 141.400	= 141.600	9.120	÷ 8.050	= 1.820

1) Includes the farmyard load, i.e. does not include losses of phosphorus from agricultural fields.

It should also be noted that losses of phosphorus from cultivated land are not included, because of the uncertainties that are related to these estimates.

Specific reduction targets for the agricultural sector

Since the mid 1980s, a number of action plans and strategies have been adopted by the Danish Parliament to regulate development of the agricultural sector, one of the main sources of nutrients to the aquatic environment, and its impact on the aquatic environment. The action plans include:

- The 1985 NPo (Nitrogen, phosphorus and organic matter) Action Plan.
- The 1987 Action Plan against Pollution of the Danish Aquatic Environment with Nutrients (Action Plan on the Aquatic Environment).
- The 1991 Action Plan for Sustainable Agriculture.
- Parts of the Governments 10-Point Programme for Protection of the Groundwater and Drinking Water from 1994.
- The 1996 Follow-up on the Action Plan for Sustainable Agriculture.
- The 1998 Action Plan on the Aquatic Environment II.

Reduction targets for nitrogen and phosphorus stipulated in the Action Plan on the Aquatic Environment I are an approximate 50% reduction of nitrogen loads and the elimination of the phosphorus farmyard load to avoid unintended eutrophication of the aquatic environment. The reduction targets were to be attained by 1993 through the following measures carried out by the agricultural sector:

- Establishment of sufficient capacity to store 9 months of manure production so that manure can be stored until crop growth season begins.
- Establishment of crop rotation and fertilisation plans to ensure that nitrogen content of fertiliser is optimally exploited.
- Fields must have green cover during winter period.
- Manure has to be ploughed in or in some other way deployed into the soil within 12 hours of application.
- Limits on the amount of livestock manure applied to fields.

It soon became clear that it would not be possible to attain the reduction targets by 1993. The measures stipulated in the Action Plan on the Aquatic Environment I were therefore tightened in 1991 in the Action Plan for Sustainable Agriculture. The reduction target was maintained but the time frame was extended to the year 2000. The measures were:

- Fertilisation accounts so that fertiliser application can be documented.
- More stringent and fixed requirements on utilisation of the nitrogen content of livestock manure.
- All farms must establish sufficient capacity to store 9 months of manure production.
- A ban on the application of liquid manure between harvest time and February except on fields cultivated with winter rape or grass.

After the Action Plan for Sustainable Agriculture, there have been a number of follow-up plans for reducing the impact of the agricultural sector on the aquatic environment, including the Government's 1994 10-Point Programme for Protection of the Groundwater and Drinking Water in Denmark.

The need to further tighten the regulation of agricultural loads of nitrogen has become even more necessary because Denmark must comply with the EU Nitrates Directive by the year 2003. The directive restricts application of livestock manure to 170 kg N hectare^{-1} yr^{-1}. In the case of some types of farms this is less than levels currently permitted. Denmark has sought permission to derogate from the 170 kg N hectare^{-1} rule on cattle holdings so as to enable application of up to 230 kg N hectare^{-1} yr^{-1} on a small number of these holdings.

In February 1998, the Danish Parliament adopted several new instruments aimed at achieving the reduction targets stipulated in the Action Plan on the Aquatic Environment I. As a supplement to the Action Plan on the Aquatic Environment I, the Action Plan on the Aquatic Environment II will reduce nitrogen leaching by a further 37,000 tonnes N yr^{-1} so as to enable the reduction target of 100,000 tonnes N yr^{-1} to be achieved no later than the end of the year 2003 (table 3.2). The following measures have been implemented under the Action Plan on the Aquatic Environment II:

- Re-establishment of 16,000 hectares of wet meadow to help reduce nitrogen leaching to the aquatic environment due to their ability to convert nitrate to N_2.
- Afforestation in Denmark and planting 20,000 hectares forest before the year 2002.
- Agri-environmental measures including financial support to farmers willing to utilise sensitive agricultural areas in a more environmentally sound manner by using less fertiliser or by completely refraining from cultivating the land. There has hitherto been very little interest in this scheme.
- Improved fodder utilisation and changes in feeding practice.
- Implementation of stricter harmony criteria governing livestock density.
- Stricter requirements on utilisation of the N content of livestock manure.
- Converting 170,000 hectares to organic farming; catch crops on a further 6% of a farmers land.
- Reducing the nitrogen norm by 10%, e.g. farmers may now only apply nitrogen in amounts corresponding to 90% of the economically optimal level.

Photo: High-light

If the measures in the Action Plan on the Aquatic Environment II are implemented as changes in agricultural practice, 20 years of nitrate policy (1985-2003) is likely to result in a 100,000 tonnes N yr^{-1} reduction in leaching from agricultural land. Moreover, consumption of nitrogen in the form of commercial fertiliser will decrease from approximately 400,000 tonnes N yr^{-1} in 1985 to approximately 200,000 tonnes N yr^{-1} in 2003 (Iversen et al. 1998).

In connection with the Action Plan on the Aquatic Environment I it was estimated that nitrogen loads could be reduced by a total of 127,000 tonnes N yr^{-1} by 1993. The reduction targets were 100,000 tonnes N yr^{-1} for the nitrogen load from fields and 27,000 tonnes N yr^{-1} for the farmyard load. In the Action Plan for Sustainable Agri-

	1993	2000	2003
1. Action Plan on the Aquatic Environment I (1987):			
Optimal utilisation of livestock manure			
• NPo Action Plan	55,000		
• NPo Subsidy Act	5,000		
• Further initiatives	10,000		
Programme for improved utilisation of fertiliser			
• Systematic fertilisation plans	15,000		
• Improved application methods	5,000		
• Winter green fields – catch crops and ploughing down of straw	20,000		
• Winter green fields – further initiatives	8,000		
Structural measures	9,000		
Total	127,000	50,000	
2. Action Plan for Sustainable Agricultural Development (1991):			
• Improved utilisation of livestock manure		20,000-40,000	
• Reduction in commercial fertiliser consumption		8,000-15,000	
• Protection of groundwater in particularly vulnerable areas		1,000-2,000	
• Reduction in agricultural acreage		17,000-20,000	
• Structural development, other measures		15,000	
Total		77,000	89.900
3. Action Plan on the Aquatic Environment II (1998):			
• Wetlands			5,600
• Sensitive agricultural areas			1,900
• Afforestation			1,100
• Improved fodder utilisation			2,400
• Stricter livestock density requirements			300
• Stricter requirements on utilisation of N content of manure			10,600
• Organic farming			1,700
• Catch crops on a further 6% of the fields			3,000
• 10 % reduction in nitrogen standards for crops			10,500
Total			37,100
Grand total	127,000	127,000	127,000

Tabel 3.2
Summary of measures and estimated reductions (in tonnes N per year) in nitrogen discharges and losses from agriculture, cf. Action Plan on the Aquatic Environment I, Action Plan for Sustainable Agricultural Development, follow-ups hereto, and Action Plan on the Aquatic Environment II.

culture it was estimated that by the year 2000, the measures stipulated in the Action Plan on the Aquatic Environment I would only have reduced nitrogen loads by 50,000 tonnes N yr^{-1} and that further measures were therefore needed to achieve the total reduction of 127,000 tonnes N yr^{-1}.

The existing measures and targets under the Action Plan on the Aquatic Environment I and the Action Plan for Sustainable Agriculture were re-evaluated in 1998 in connection with the preparation of the Action Plan on the Aquatic Environment II. It was concluded that by the year 2003, the existing measures would reduce nitrogen loads by 89,900 tonnes N yr^{-1}. Together with the expected reduction under the Action Plan on the Aquatic Environment II, it was concluded that nitrogen loads would be reduced by 127,000 tonnes N yr^{-1} by 2003.

Not all measures in the Action Plan on the Aquatic Environment II will have taken full effect by 2003. The Action Plan on the Aquatic Environment II also encompasses so-called regional measures. These represent implementation of recommendations of the Drinking Water Committee concerning the protection of groundwater resources considered particularly vulnerable to nitrate pollution.


Photo: CDanmark

Specific reduction targets for municipal wastewater treatment plants

Discharges from municipal wastewater treatment plants are regulated by the Environmental Protection Act, the Urban Wastewater Directive and derivative statutory orders and official guidelines.

The EU Council Directive 91/271/EEC of 21 May 1991 concerning Urban Wastewater Treatment as amended by Commission Directive 98/15/EU of 27 February 1998 - commonly referred to as the Urban Wastewater Directive – is one of the most important legal documents in the EU legislation on the aquatic environment. The purpose of the directive is to protect the environment against negative effects associated with discharge of inadequately treated urban wastewater and biologically degradable industrial wastewater from enterprises within the food processing industry. According to the directive, wastewater discharges have to be subjected to a level of treatment appropriate to the environment at the place in question and the use to which the recipient water bodies in question are put. Denmark implemented the provisions of the directive in Danish legislation in 1994.

The Action Plan on the Aquatic Environment's reduction targets for municipal wastewater treatment plants were adjusted in 1990 on the basis of the results of the Nation-wide Monitoring Programme (Danish EPA, 1991). In the case of nitrogen, annual discharges in treated wastewater are to be reduced from ca. 18,000 tonnes N to ca. 6,600 tonnes N. Phosphorus discharges are to be reduced from ca. 4,470 tonnes P to ca. 1,220 tonnes P. The reduction in nitrogen discharges from municipal wastewater treatment plants corresponds to all new or upgraded plants exceeding 5,000 PE and all existing plants ex-ceeding 1,000 PE having to implement biological treatment with nitrogen removal down to an annual average of 8 mg N l^{-1}. In

1987 this was considered as low as it is practically possible to reach with biological nitrogen removal. As regards to phosphorus, municipal wastewater treatment plants exceeding 5,000 PE have to remove phosphorus down to an annual average of 1.5 mg P l^{-1}.

The reduction target for nitrogen of 6,600 tonnes N yr^{-1} was achieved in 1996, as was the reduction target for phosphorus of 1,200 tonnes P yr^{-1}.

Specific reduction targets for separate industrial discharges

The Environmental Protection Act, the EU Directive on Pollution Prevention and Control (IPPC Directive) and derivative statutory orders and official guidelines regulate separate industrial discharges.

The IPPC Directive aims at integrated prevention and control of pollution by major industries. The directive specifically regulates the energy industry (power stations and refineries, etc.), production and processing of metals, the mineral industry, the chemical industry, waste management plus a number of other activities such as paper manufacturers, textiles pretreatment and dyeing, slaughterhouses and dairies, as well as installations for intensive rearing of poultry and pigs exceeding a certain capacity. The IPPC Directive contains measures designed to prevent or, where that is not practicable, to reduce emissions to the atmosphere, water and land from the above mentioned activities.

Because of large differences between individual enterprises and their discharges of wastewater, the Action Plan on the Aquatic Environment I did not stipulate general discharge requirements for industry as for wastewater treatment plants. Industry was to reduce its discharges through application of BAT understood as the level of treatment that is technically attainable and economically viable for the industry in question.

Reduction targets for other sectors and sources

A number of other sectors and types of sources also contribute to nutrient loading to the aquatic environment. These include freshwater fish farms, mariculture, transport, combustion plants (heat and power production), sparsely built-up areas and stormwater outfalls. The Action Plans on the Aquatic Environment did not specify specific reduction targets for these sectors and types of source but instead describes a number of other measures.

Freshwater fish farms

The Ministry of Environment issued the Statutory Order on Freshwater Fish Farms on 5 April 1989 to reduce nutrient loading. It gives guidelines for the County authorities to stipulate the maximal permitted feed consumption at fish farms, minimum requirements as to treatment measures as well as minimum requirements as to utilisation and quality of feed.

Mariculture (seawater-based fish farming)

In 1987 a moratorium was placed on establishment of new farms and expansion of existing farms until 1990 when Statutory Order No. 640 on mariculture was issued. This stipulated general regulations on feed quality and con-


Photo: Biofoto/Morten Rasmussen

sumption as well as consumption of feed relative to production. In addition, upper limits were placed on nutrient discharges to the surrounding aquatic environment from each individual farm. In 1996 the Danish EPA requested the Counties not to issue any permits for new sea-based or land-based mariculture farms or for extensions of existing farms and were urged to assess whether environmental or operational benefits could be obtained by moving or merging existing farms. In June 2001 the 1996 request was lifted and the Danish EPA published a new strategy to reduce loads of nutrients and organic matter from mariculture. A revision of the existing Statutory Order is being negotiated and is expected to be implemented in 2003.

NO_x emissions

When the Action Plan on the Aquatic Environment was adopted in 1987, the Danish EPA was instructed to prepare a report containing a specific reduction programme for power station NO_x emissions. Regulation of NO_x emissions in Denmark has concentrated on improved combustion technology and flue gas abatement at power stations (e.g. Statutory Order No. 885 of 18 December 1991 on Limitation of Emissions of Sulphur Dioxide and Nitrogen Oxides from Power Stations), enhanced use of natural gas and renewable energy (e.g. the Government's 1990 Energy Action Plan) as well as implementation of the requirement for catalytic converters on cars (e.g. Ministry of Justice Statutory Order on Detailed Regulations for the Motor Vehicle Design and Equipment from 1990). Under the EEC Convention on Transboundary Air Pollution, Denmark has entered into an international agreement to reduce emissions of NO_x by 30% over the period 1986-98. However, the measures needed to meet this goal are inadequate in Europe as regards acidification and eutrophication. In June 1999, the EU Commission, therefore, issued proposals for two directives on acidification and ozone formation at ground level (Proposal for a Directive on National Emission Limits for Certain Polluting Substances and Proposal for a Directive on the Ozone Content of the Air). These two directives stipulate national limits for emissions of NH_3 and NO_x. In the case of Denmark, the proposed directives will limit ammonia (NH_3) emissions to 71,000 tonnes per year and nitrogen oxide (NO_x) emissions to 127,000 tonnes per year from 2010.

Sparsely build-up areas

The relative contribution of nutrients from sparsely built up areas has increased over the past 10 years because of point source reductions from wastewater treatment plants and industry. It is expected that future improvements in treatment of wastewater from sparsely built-up areas will occur resulting from initiatives in connection with the 1997 amendment of the Environmental Protection Act concerning wastewater treatment in rural areas. According to state instructions to the Counties concerning revision of the Regional Plans in 2001, the Countries have specified areas in which the treatment of wastewater from properties in rural areas is to be improved, they must stipulate quality objectives for individual recipient waters in its Regional Plan, identify watercourses and lakes that are vulnerable to pollution, and based on its knowledge of the environmental state and pollution load on the individual recipient waters, has to assign each individual recipient a maximal environmentally permissible level of pollution.


Photo: NERI/Helge Rørdam Olesen

Rainwater outfalls

Rainwater outfalls are one of the reasons that many watercourses and urban lakes as well as some coastal marine waters fail to meet the agreed quality objectives. Despite the increasing importance, there is a lack of knowedge of how to manage rainwater outflows. Ongoing work by the Wastewater Committee under the Danish Engineering Association and the Danish EPA is intended to result in proposals for guidelines that can be incorporated in official EPA guidelines.

Follow-up on the mid-term evaluation of Action Plan II

The effects for a number of measures in Action Plan II from 1998 are based on an assumed development in agricultural practises. Therefore, the plan was subject to a mid-term evaluation in 2000/2001. This evaluation concluded that the realised changes in agricultural practices could not match the expected changes. The losses of nitrogen from field were estimated to be 93,000 tonnes of N, indicating an annual under-fulfilment of 7,000 tonnes of N. The results of the political mid-term evaluation were presented in May 2001. The conclusions included:

- Changed rules for funding of reestablishment of wetland, in order to make this more attractive.
- Reduction of bread wheat subsidies in order to ensure that the area receiving subsidies matches the needs for bread wheat.
- Revision of nitrogen standards.

The amendments to Action Plan II include an over-fulfilment by 175 tonnes N yr^{-1} compared to the measures agreed in 1997.

An Action Plan III on the Aquatic Environment is on the programme of the Danish Government and is planned to be negotiated in 2003. The parties behind Action Plan I and II have agreed that Action Plan III shall focus on:

- The nitrogen balance of the Danish agricultural sector, in particular on the magnitude of losses from Danish agriculture in the mid 1980s.
- General measures to reduce discharges and losses from the agricultural sector.
- Losses of phosphorus from fields, which so far have been excluded from action plans.
- Possibilities to implement regional measures in order to protect specific regional waters.

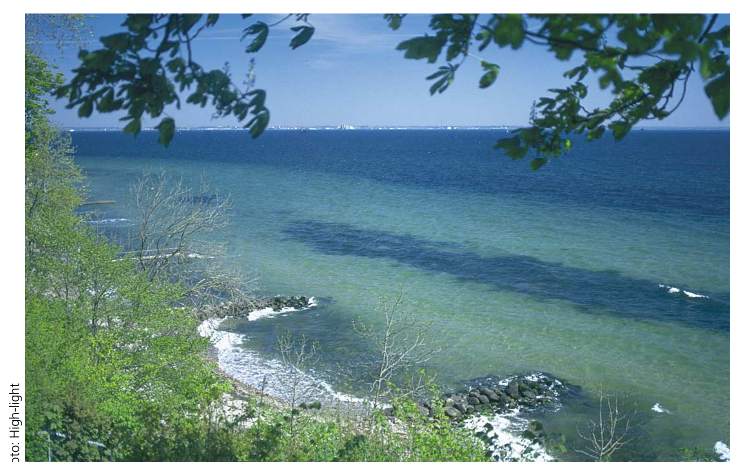


Photo: High-light

3.3 International co-operation to abate marine eutrophication

The sea is the link between states, but does not respect state borders.

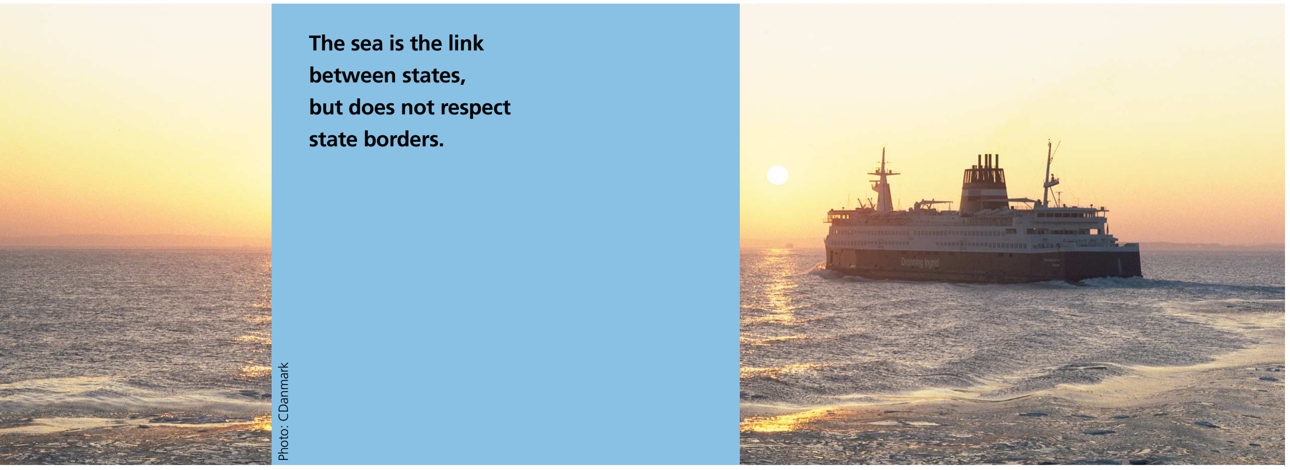


Photo: CDanmark

Eutrophication of the Danish parts of the Wadden Sea, along the west coast of Jutland and in open parts of Kattegat and the Baltic Sea is to a large extent caused by inputs from adjacent waters and to deposition from the atmosphere. The nutrients causing eutrophication originate from discharges, emissions and losses in other areas and are transported to Danish waters where they add to discharges and losses from Danish sources. International co-operation is essential to abate the problem in these areas. The efforts and results due to the Danish Action Plans on the Aquatic Environment, therefore, must be supplemented by parallel activities in neighbouring countries.

A number of international initiatives have been agreed and are likely to reduce the transport of nutrients to Danish waters.

At the North Sea Conference in London in November 1987, the countries of the North Sea adopted the goal of reducing nitrogen and phosphorus inputs by ca. 50% over the period 1985-95 in areas where these inputs are likely, directly or indirectly, to cause pollution. At ministerial conferences in The Hague (1990), Esbjerg (1995) and Bergen (2002), these reduction targets were reiterated and the need to take action against wastewater discharges and losses from agriculture was specified.

In June 1988, the Paris Commission adopted a 50% reduction target for nutrient inputs to marine waters susceptible to eutrophication and also adopted a programme to achieve the reductions. In 1989, the reduction target was specified in relation to specific sectors. In 1992, it was decided to integrate the Oslo and Paris Conventions, both of which aimed to prevent marine pollution from dumping and land-based sources of pollution. The objective of the successor – the OSPAR Convention – is to protect the marine environment of the Northeast Atlantic region. As a follow-up on the 1988 decision, the 1998 OSPAR Ministerial Meeting adopted a strategy to combat eutrophication. Included in the strategy is adoption of achieving a healthy marine environment where eutrophication does not occur by 2010.

At a ministerial meeting in February 1988, HELCOM adopted a declaration specifying a 50% reduction target for discharges of nutrients etc. over a 10-year period. In the Communiqué from the ministerial meeting in 1998, the ministers confirm that they have committed themselves to attaining the strategic goal from 1988 and to defining specific objectives that have to be achieved before the year 2005.

Comparing reduction targets of the Danish action plans with agreed reduction targets in OSPAR and the North Sea Conference, there are some differences. The Danish reduction targets make a total reduction of discharge and losses of nitrogen on the order of 50% and phosphorus on the order of 80% from three sectors, agriculture (only nitrogen), industry, and municipal wastewater plants. The OSPAR and North Sea Conference agreed reduction targets make a total reduction on the order of 50 % of the inputs of both phosphorus and nitrogen into areas where these inputs are likely, directly or indirectly to cause pollution.

Marine monitoring and assessment is another important area of international co-operation.

In connection with adoption of the Action Plan for the Aquatic Environment in 1987, a national monitoring programme was established to demonstrate the effectiveness of measures

The bridge in The Sound between Denmark and Sweden.

Photo: Biofoto/Lars Gejl

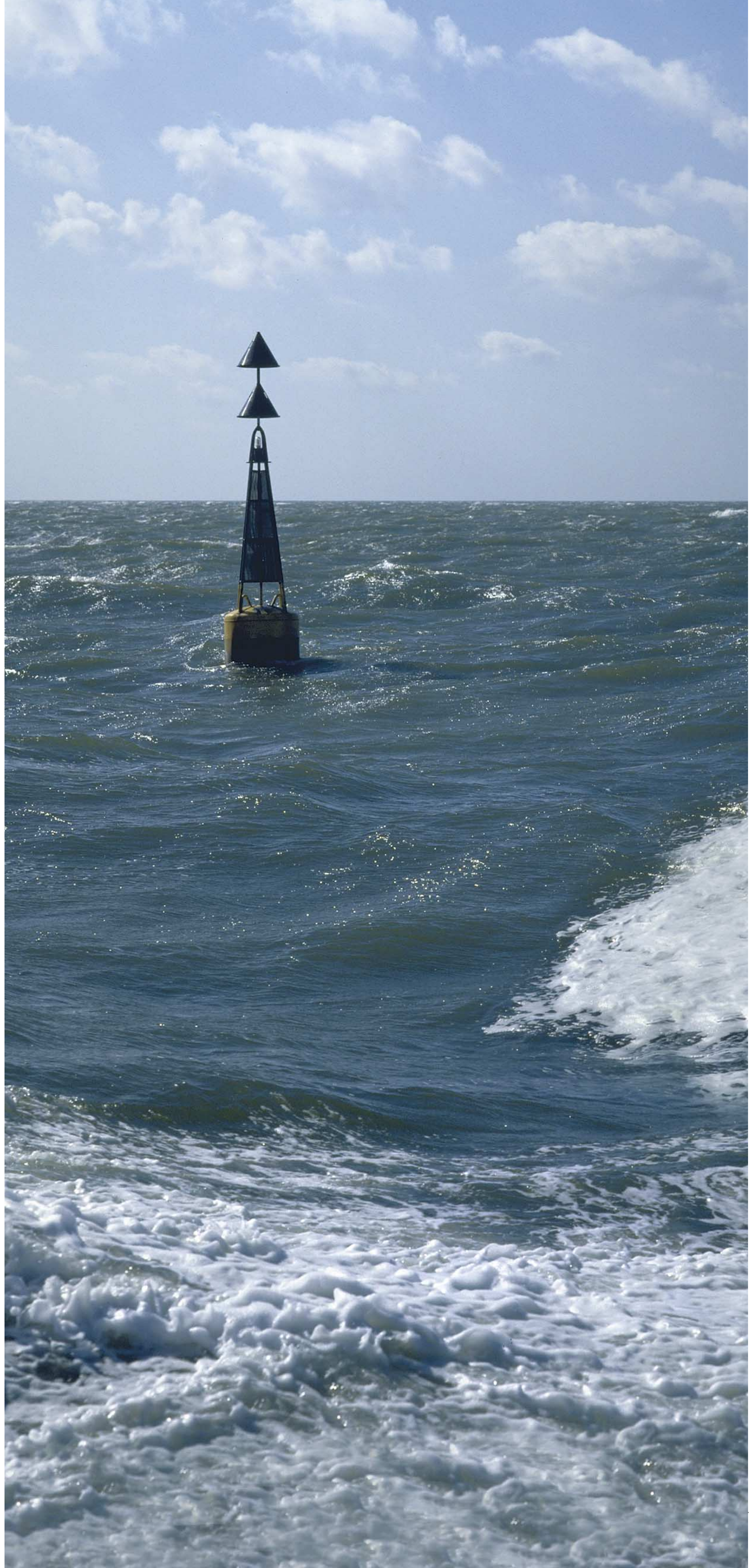


Photo: CDanmark

contained in the plan. The nation-wide programme was revised in 1992 and the latest revision in 1997–1998 resulted in implementation of the Danish Aquatic Monitoring and Assessment Programme 1998–2003 commonly referred to as NOVA–2003.

The monitoring and assessment-programme has been planned and designed on the basis of national and international obligations and the needs agreed by the Danish Parliament, OSPAR and HELCOM. The existing programme implements all national or international agreed monitoring and assessment activities, including parameters, numbers of stations, frequencies, quality assurance, data handling and reporting.

The Danish monitoring cruises are co-ordinated at different levels:

- Between counties.
- Between counties and NERI.
- Between NERI and Swedish, Norwegian and German institutions.

This added value of co-ordination reduces sailing time in many coastal and open waters. The stations sampled and methods are identical to the extent possible and the monitoring frequency of sampling a station are at a level which makes it possible to assess the eutrophication status of marine waters on a year-to-year and in some cases on a season-to-season basis.

The outcome of the Danish monitoring and assessment programme is evaluated and reported annually. County authorities are responsible for assessment of local areas and, wherever relevant, they include an assessment as to what extent the regional quality objectives for the aquatic environment have been met. Based on the regional reports and information from other national and international monitoring activities, NERI prepares a nation-wide assessment of discharges and environmental state. Oxygen depletion reports in August, September and October and crosscutting theme reports supplement the annual assessment. The annual assessment reports are also the basis for the Danish contribution to various international conventions and organisations.

Denmark and most countries bordering the North Sea and the Baltic Sea have so-far not been able to achieve the agreed reductions in the inputs of nutrients to the marine waters.

Biofoto/Jesper Plambech

Summary, conclusions and the future

4

The summary is based on the eutrophication status in the years 2000 and 2001, and the development since implementation of the Danish National Monitoring and Assessment Programme in 1989, the latter being an integral part of the Danish Action Plan on the Aquatic Environment from 1987.

Degree of nutrient enrichment

Nutrient load

Detailed nutrient load compilations to Danish waters were initiated in 1989, although the main increase in nutrient loads from land and atmosphere actually took place long before. As an example, the estimated annual riverine load of N to Danish coastal waters in the 1960s was about 60% of that in the 1980s and the P load increased four fold in the Baltic Sea, North Sea regions from the 1940s to the 1970s. A growing number of sewage treatment plants have reduced the Danish point source loads of P to surface waters (fresh and marine) since the late 1980s by nearly 90% and the total land based P load to marine waters has been reduced by 60% from 1990 to 2001. The improved sewage treatment has also reduced the overall N load by about 14%, while decrease in leaching from agricultural soils has reduced the N load with about 21%. All figures are corrected for variations in runoff.

Atmospheric deposition of inorganic nitrogen is important on large sea surfaces as Kattegat and the Belt Sea where atmospheric N deposition makes up about 30% of total N load from surrounding land and atmosphere. During the period 1989–2001 there was a decrease in the air concentration of N bound in particles and a tendency to a decreasing deposition of about 15%.

Nutrient concentrations

The assessment of trends in nutrient concentrations in Danish waters is based on indices for mean annual concentrations of DIN, TN, DIP and TP in the upper mixed layer developed for estuaries-coastal waters and the open Kattegat–Belt Sea.

The decreasing nutrient load to Danish waters is reflected in the nutrient concentrations. The nitrogen concentrations in 2001 were the lowest observed during the period 1989-2001 and at the same level as in the very dry years 1996 and 1997, even though the runoff was about normal. In the open waters of the Kattegat and Belt Sea the runoff corrected nitrogen concentrations shows a steady decrease since 1989. In the estuaries and coastal waters, a significant decrease was observed after 1997. In the estuaries and coastal waters, the phosphorus concentrations have stabilised at a low level after significant decreases in the beginning of the 1990s.

N/P ratio

The optimal N/P-ratio, the Redfield ratio, for phytoplankton growth is 16:1. In the open Belt Sea and Kattegat the winter DIN/DIP-ratio did not deviate much from the Redfield ratio and there was no general trend in annual mean N/P-ratio during the period 1989–2001.

In estuaries the winter DIN/DIP-ratio is high (>25) to very high (>100). Annual mean N/P-ratios in the estuaries-coastal waters showed an increase from 1989 to 1998 parallel to the reduction in phosphorus load, and then a decrease to 2001 parallel to the decrease in nitrogen load per runoff.

In the North Sea the N/P-ratio was generally high ranging between 25 and 60, except in the saline central North Sea water. Also in the Skagerrak N/P-ratios were high at salinities lower than 33.

Direct effects

Chlorophyl concentrations

Since 1980 absolute concentrations of chlorophyll *a* in Danish open sea areas have been >50% above background concentrations given by OSPAR. At first chlorophyll *a* concentrations seem to have decreased in open sea areas since 1980. However, year-to-year variations have been substantial. Chlorophyll *a* index values adjusted for variations in climatic conditions shows that chlorophyll *a* values were very constant in the period 1987-2001.

In estuaries and coastal waters chlorophyll *a* concentrations have decreased since the late 1980s. The chlorophyll *a* index values adjusted for variations in climatic conditions for 1993–2001 were at a consistent and decreasing lower level than that found in the mid 1980s.

Submerged aquatic vegetation

The colonisation depth of eelgrass reflects differences in water quality and physical setting along estuarine gradients. In the deeper, more protected waters, reductions in eelgrass abundance towards the lower depth limit correlate with light attenuation and are therefore more directly coupled to changes in eutrophication. During the period 1989-2000 eelgrass colonisation depth showed no significant trend and did not reflect the slight amelioration of water clarity observed through the same period. During the period 1989-2001 eelgrass cover deeper than 2 meters showed no significant trend, but the cover of shallow populations was significantly reduced in inner estuaries and along open coasts. There is no obvious explanation for this pattern. Though eelgrass colonisation depth and abundance from intermediate depths towards deeper waters are likely to be better response parameters to eutrophication than the abundance of shallow populations.

In 2001 many Danish estuaries still had an abundant cover of nuisance macroalgae. While there seemed to be a decrease in the relative cover of nuisance species at 0-1 and 1-2 meter depths since 1997, there was an increase in cover from 1998 to 2001 at 2-4 meters. In general, there where no significant changes during the period 1993 to 2001. The tendency of a reduction in relative cover was not true for some estuaries where relative cover had actually increased.


Photo: Fyn County/Nanna Rask

Results from 2001 showed that total cover of upright vegetation on reefs in open waters tended to increase according to the mean of the period 1994–2001. In general, algal coverage was low in years with relatively high runoff and high in years of low runoff during the period. Accordingly, there was no over all trend in the distribution on the monitored reef stations.

Indirect effects

Oxygen concentrations

Analyses of the development in bottom water oxygen concentrations during late summer/autumn in the Kattegat-Belt Sea from the 1970s to late 1980s/1990s showed significant decreases in all areas with a stratified water column. The decrease was especially pronounced from the mid 1970s to the late 1980s. There was no general development in the summer/autumn bottom water minimum oxygen concentration in the period 1989–2001. However, there was a tendency for an increase in minimum oxygen concentrations in spring (April–June). Nevertheless, at the end of August 2002 an unusually widespread and serious oxygen deficiency was observed in large areas of the inner Danish marine waters and common Danish-Swedish and Danish-German waters. In many areas of the southern Kattegat, the Sound and the Belt Sea oxygen levels in bottom waters were reduced to a level seldom or never seen before.

Macrozoobenthos

General trends in abundance of macrozoobenthos in the Sound, Kattegat and Belt Sea follow a bimodal pattern over the last 20 years with peaks in the beginning of the 1980s and in the middle of the 1990s. During the period 1998–2001 biomass and essentially total abundance of macrozoobenthos in the open waters showed the lowest values since the measurements started two decades ago. Some evidence indicates that reduced N-nutrient concentrations, and possibly reduced diatom abundance, when corrected for runoff, may have reinforced the decrease in zoobenthos stocks in recent years.

Correlation analyses between biological variables and the North Atlantic Oscillation index and runoff of freshwater from Denmark, showed significant positive correlations with 1 or 2 years time lag, thereby indicating that climate also influences variations in benthic macrofauna. In particular winter nutrient input, and likely the spring phytoplankton bloom, did influence benthic abundance.

The number of coastal areas with increasing species diversity were about the same as those with decreasing diversity during the period 1998–2001. Local factors like oxygen deficiency is a possible reason for these differences. During the same period there was no general change in abundance, biomass or number of species in coastal areas.


Photo: NERI/Peter Bondo Christensen

A Coastal areas	1998	1999	2000	2001	Assessment criteria in 2001					
					NC	MO	BF	SAV	NM	OD
1. North Sea and										
2. Skagerrak										
• North Sea, coastal parts	÷	÷	÷	÷	x	x				
• Ringkjøbing Fjord	÷	÷	÷	÷	x			x	x	
• Nissum Fjord	÷	÷	÷	÷	x	x		x		
• Vadehavet	÷	÷	÷	÷	x	x		x	x	
• Skagerrak, coastal parts	+/÷	+/÷	+/÷	+/÷	x					
3. Kattegat										
• Isefjord	÷	÷	÷	÷	x		x		x	x
• Limfjorden	÷	÷	÷	÷	x	x	x	x		x
• Mariager Fjord	÷	÷	÷	÷	x	x	x	x	x	x
• Randers Fjord	÷	÷	÷	÷	x		x	x		
• Roskilde Fjord	÷	÷	÷	÷	x	x	x	x		
• Kattegat, coastal southern parts	÷	÷	÷	÷	x	x			x	
• Kattegat, coastal western parts	÷	÷	÷	÷	x		x	x	x	
4. Northern Belt Sea										
• Horsens Fjord	÷	÷	÷	÷		x	x	x		x
• Odense Fjord	÷	÷	÷	÷	x	x		x	x	x
• Sejerø Bugt	÷	÷	÷	÷			x		x	x
• Århus Bugt/Kalø Vig	÷	÷	÷	÷	x	x	x	x		x
5. Little Belt										
• Augustenborg Fjord	÷	÷	÷	÷				x	x	
• Flensborg Fjord	÷	÷	÷	÷				x		x
• Kolding Fjord	÷	÷	÷	÷		x	x	x		
• Vejle Fjord	÷	÷	÷	÷		x	x	x		
• Åbenrå Fjord	÷	÷	÷	÷				x		x
6. Great Belt										
• Kertinge Nor	÷	÷	÷	÷	x		x		x	
• Kalundborg Fjord	÷	÷	÷	÷			x		x	x
• Korsør Nor	÷	÷	÷	÷			x		x	x
• Sydfynske Øhav	÷	÷	÷	÷	x		x		x	x
• Karrebæk Fjord	+/÷	+/÷	+/÷		x			x	x	x
• Karrebæksminde Bugt	+	+	+	+			x	x	x	x
• Dybsø Fjord	+	+	+	+	x			x	x	x
7. The Sound										
• Øresund, northern part	÷	÷	÷	÷				x	x	
• Køge Bugt	÷	÷	÷	÷			x	x	x	
8. Southern Belt Sea and										
9. Baltic Sea										
• Bornholm, coastal waters	÷	÷	÷	÷	x			x		
• Hjelm Bugt	÷	÷	÷	÷	x	x		x	x	x
• Præstø Fjord	÷	÷	÷	÷	x			x	x	x

B Open sea areas	1998	1999	2000	2001	Assessment criteria in 2001					
					NC	MO	BF	SAV	NM	OD
1. North Sea and										
2. Skagerrak										
• North Sea, open parts	+	+	+	+	x					
• Skagerrak, open parts	+	+	+	+	x					
3. Kattegat										
• Kattegat, northern open parts	+/÷	+/÷	+/÷	+/÷	x			x		
• Kattegat, central open parts	+/÷	+/÷	+/÷	+/÷	x			x		
4. Northern Belt Sea										
• Belt Sea, northern open parts	÷	÷	÷	÷	x					x
5. Little Belt										
• Little Belt, northern open parts	÷	÷	÷	÷		x	x	x		x
• Little Belt, southern open parts	÷	÷	÷	÷			x	x		x
6. Great Belt										
• Great Belt, open parts	÷	÷	÷	÷	x					x
7. The Sound										
• Øresund, northern part	÷	÷	÷	÷				x	x	x
• Køge Bugt	÷	÷	÷	÷			x	x	x	
8. Southern Belt Sea and										
9. Baltic Sea										
• Southern Belt Sea, open parts	÷	÷	÷	÷	x			x	x	x
• Arkona Bassin	÷	÷	÷	÷	x	x				x
• Baltic Sea, east of Bornholm	(÷)	(÷)	(÷)	(÷)	x	x				x

Table 4.1 A + B
Fulfilment of objectives and assessment criteria in selected coastal areas (A) and selected open sea areas (B) from 1998–2001. The assessment criteria are:
NC – Nutrient concentrations
MO – Mass occurrence of algae
BF – Benthic fauna
SAV – Submerged aquatic vegetation
NM – Annual nuisance macroalgae
OD – Oxygen depletion

EQOs impaired	÷
EQOs close to fulfilment	+/÷
EQOs fulfilled	+

Based on Ærtebjerg et al. 2002.


Photo: CDanmark

Effectiveness of strategies and measures

The national target of an 80% reduction of phosphorus from sewage plants and industry to fresh and marine waters was achieved already by 1996. The reductions of nitrogen discharges from sewage treatment plants have also been successful. The remaining and still unsolved problem is related to losses of nutrients from the agricultural sector in Denmark, even a 30% reduction in losses from the root zone has been achieved. However, this is not only the case in Denmark, as almost all countries bordering the North Sea and the Baltic Sea have so-far not been able to achieve the agreed reductions in the losses from agriculture.

It has been estimated that the Danish Action Plans on the Aquatic Environment in 2003 will result in a change in agricultural activities, which together with the reductions of discharges from industries and municipal waste water treatment plants, is likely to reduce discharges from these sources by nearly 50% (Grant et al. 2000). This corresponds to a reduction of nitrogen inputs to marine areas by at least 35%. The actual reductions in inputs to marine waters due to reductions in other sources and sectors (atmospheric emissions, scattered settlements, stormwater overflows, freshwater aquaculture, and mariculture) will be somewhat higher.

Photo: CDanmark

Despite the achieved reductions in the nutrient inputs to marine waters, the quality status of the majority of marine waters still does not fulfil the general quality objective with no or only a slight impact on flora and fauna. However, improvements can be seen in local areas.

The Danish government has in autumn 2002 taken initiatives to start discussions on new measures to be taken to combat eutrophication. The discussions are expected mainly to focus on discharges and losses of nitrogen and phosphorus from agriculture. Until recently, phosphorus from agriculture has not been considered an important source, as most of the phosphorus was considered to be retained in the root zone. However, improved knowledge on the phosphorus cycle indicates a greater loss of phosphorus from agriculture than taken into calculation in the previous action plans.

The strategies and measures to reach the goal of a healthy marine environment must focus on a reduction of discharges, emissions and losses for all relevant sources and on ecological quality objectives for the marine environment. With regard to reductions, the Danish Action Plans on the Aquatic Environment focus on the major sources in order to achieve cost/effective reductions. However, future action plans should include all relevant sources. With regard to ecological quality objectives, the Danish objectives from 1984 are normative. They have to be operational and expressed as numbers and values. This will be done as an integral part of the Danish implementation of the Water Framework Directive. This directive is a major player in the years to come. A successful implementation is a prerequisite for an informed management of marine eutrophication. The implementation process should not overlook the Habitat Directive and the work within HELCOM and OSPAR together with the future EU Marine

EQO-eutro

OSPAR COMP	Non-Problem Area		Problem Area		
Danish AEPS	Compliance		Non-Compliance (or Accommodated)		
EU WFD	High	Good	Moderate	Poor	Bad
EU Habitats Directive	Favourable Conservation Status		Unfavourable Conservation Status		
EU Urban Wastewater Directive	Less sensitive		Sensitive areas		
EU Nitrates Directive	Less vulnerable zones		Vulnerable zones		
EU Marine Strategy	Compliance with goals		Impaired ecosystem health		

EQO-eutro

Figure 4.1
Suggested identity between eutrophication related Ecological Quality Objectives (EQOs) according to OSPAR Comprehensive Procedure (COMP), the existing Danish Aquatic Environmental Planning System (AEPS), the Water Framework Directive (WFD), the Habitat Directive and the future EU Marine Strategy. (Modified from OSPAR ETG 01/7/1, Annex 6, 2001; Henriksen et al. 2001 and Pedersen et al. 2001).

Strategy. The quality objectives should be parallel as illustrated in Figure 4.1.

Conclusions

Eutrophication effects have been documented in all Danish marine waters every year since the beginning of the 1980s. At present it can be concluded that quality criteria has only been fulfilled in a restricted number of Danish estuaries, coastal and open water areas. The few coastal areas that meet the criteria are generally non-stratified shallow water areas with a relatively restricted load from land based sources. The causes for not fulfilling the criteria are primarily the effects of nutrient load and oxygen depletion.

With corrections for variations in precipitation, run off and other climatic related conditions it can be concluded that:

Nutrient loads

Since 1990 land based inputs of nitrogen and phosphorus to estuaries and coastal areas have been reduced by 35% and 60%, respectively. The reduction in nitrogen (21%) is mainly caused by reduced loses from agricultural soils while the reduction in phosphorus is due to extension of sewage treatment. Atmospheric nitrogen deposition to Danish marine waters seems to have declined about 15% since 1989.

Nutrient concentrations

Nitrogen concentrations in estuarine and coastal areas have decreased significantly after 1997 and since 1989 in the open waters. Concentrations of phosphorus have stabilised after a significant decrease in the beginning of the 1990s.

Direct effects

Water clarity increased and phytoplankton biomass and production decreased significantly in estuaries and coastal areas until the mid 1990s. The changes are less pronounced in open waters, although water clarity was higher and diatom biomass as well as phytoplankton production were lower in the 1990s than in the 1980s.

During the period 1989-2001 eelgrass cover at water depths above 2 meters increased in the outer part of the estuaries, but was significantly reduced at shallow depths in inner estuaries and along open coasts. The depth distribution has not increased, but in the inner estuaries actually decreased, possibly due to oxygen depletion.

The amount of nuisance macroalgae has been reduced (though this is not always noted in the cover) at shallow depths. Macroalgae cover at open water reefs shows no trends since 1994.

Indirect effects

The biomass of macrozoobenthos in open waters has decreased through the 1990s following a reduction in the biomass of diatoms and phytoplankton production. Macrozoobenthic communities in estuaries and coastal areas show large inter annual variations, which seem to be caused by recurrent oxygen depletion.

The future

The experience from the years 1996 and 1997, when precipitation and runoff were very low and the 50% reduction target for nitrogen reduction was actually met, clearly shows that the reduction target of 50% in the input to the marine area considerably improves the quality status of the marine environment. The 50% reduction in nitrogen inputs, therefore, needs to be met in order to reduce eutrophication problems in marine areas.

Trends in nutrient reductions are on the right track, both with respect to the reduction of discharges, emissions and losses of nutrients to marine waters and to the quality of the marine environment. But the road to fulfilment of eutrophication quality criteria is long and winding. The existing criteria and the acceptable deviations from reference conditions should be regarded as a starting point. The variability found for different parameters is naturally large. It might therefore be reasonable to develop global or type-specific assessment criteria and, taking these as a starting point, to develop site-specific assessment criteria.

Focusing on national reductions in inputs is reasonable. But inputs from adjacent seas should also be taken into account. It is likely that these inputs will decrease. However, future enlargement of the European Union is likely to result in a development of the agricultural sector in Poland and the Baltic States. This may result in an increase in losses form cultivated farmland and eventually an increase in inputs to the Baltic Sea, and thus an increase in the inputs to Danish waters from the Baltic Sea.

However, nutrient enrichment, eutrophication and oxygen depletion are naturally occurring phenomena. It is the extent in space and the duration and strength that is affected by human activities. These undesirable effects in our marine waters can not be avoided, but the anthropogenically induced strengthening of these phenomena should be reduced.

The implementation of the Water Framework Directive has to take the Habitat Directive and EU Marine Strategy into account, especially with regard to the objectives on ecological and conservation status. If not, the management of the ecosystems and resources in the Danish marine water will face different protection levels and

thus be complicated beyond reason.

It is likely that the implementation of the Water Framework Directive will lead to supplementary measures in catchment areas to specific coastal waters as vulnerable and sensitive estuaries and enclosed bays. The combination with legally binding quality objectives and integrated strategic management should make it possible to calculate backwards from the normative definition of good ecological status to concentrations, inputs, and other human activities affecting eutrophication status of marine waters. The key question in the future is whether diffuse sources can and will be adequately managed.

Photo: NERI/Gunni Ærtebjerg

Photo: High-light

GLOSSARY AND ABBREVIATIONS

Advection – the transfer of heat or matter by horizontal movement of water masses.
Aerobic – with the presense of oxygen. Is used to describe chemical processes or organisms that require oxygen. See also anaerobic.
Algae – a large assemblage of lower plants, formerly regarded as a single group, but now usually classified in eight separate divisions or phyla, including the blue-green algae (Cyanophyta), green algae (Chlorophyta), brown algae (Phaeophyta), red algae (Rhodophyta), diatoms and (Chrysophyta). Marine macroalgae are commonly known as seaweeds.
Ammonia (NH_3) – a colourless gas formed by decomposition of protein, nitrogenous bases and urea. It is easy soluble in water and its pungent smell is well known from ammonia water.
Ammonium (NH_4^+) – a nitrogen compound, an ion derived from ammonia.
Anaerobic – without the presense of oxygen. Is used to describe chemical processes or organisms that does not require oxygen. See also aerobic.
Anoxic – the state of oxygen depletion with absence of oxygen. Anoxic sediments and anoxic bottom waters are commonly produced where there is a depletion of oxygen, owing to very high organic productivity, and a lack of oxygen replenishment to the water or sediment, as in the case of stagnation or stratification of the body of water.
Aquatic – growing or living in or near water.
ASP – short for Amnesic Shellfish Poisoning. The poisoning is caused by intake of shellfish which has accumulated certain algal toxins.
Atmospheric deposition – deposition of nutrients, heavy metals and other pollutants from the atmosphere.
Autotroph – an organism which builds complex organic molecules from simple inorganic compounds. Also used to name organisms using photosynthesis in this process.
BAT – Best Available Techiques, means the most advanced activities, processes, and operating methods and the methods most effective in preventing or limiting pollution from a given sector.
Benthos – those organisms attached to, living on, in or near the sea bed, river bed or lake floor.
Bio-available – matter that is available for primary production or will become available within the residence time of the water in a given marine area.
Biomass – the weight of organisms in a

certain area either described with reference to volume or area.
Bluegreen algae – marine and freshwater unicellular, colonial or filamentous bacteria. Resembles algae in the way that they have chlorophyll pigments and can perform photosynthesis.
Brackish water - water with a salt concentration between 5-18ppt.
C – carbon, see carbon biomass.
Carbon biomass – biomass as the amount of carbon (C) in a given area or volume.
CHARM – an EU funded project which has been developed to provide a scientific foundation for fulfilling the requirements of the EC Water Framework Directive in Baltic coastal waters.
Chl *a* – see Chlorofyll *a*.
Chlorophyll *a* – *a* specific plant pigment essential for photosynthesis. It is quantitatively the most important pigment found in all photosynthetic phytoplankton cells.
Chlorophyll – any of several green pigments found in the chloroplasts of plants and in other photosynthetic organisms. They mainly absorb red and violet-blue light energy for the chemical processes of photosynthesis.
Cladoceran – water flea. A small crustacean with a carapace that forms a bivalved shield. The cladocerans are suspension feeders and collect food with fine bristles on the trunk appendages.
Ciliate – a diverse group of one celled animal like organims. They possess cilia for locomotion and in many species for suspension feeding.
Contaminants – are substances that are toxic to living organisms. Most of them are hard to degrade in a natural environment
Copepod – a small free-living or parasitic crustacean. One of the most abundant marine zooplankton organisms.
Cyanobacteria – see bluegreen algae.
Denitrification – reduction of nitrates to free nitrogen (N_2) by certain bacteria.
Deposition – see atmospheric deposition
Detritus – small pieces of dead and decomposing plant and animal material, i.e. organic material.
Diatom – a unicellular algae with silicified walls. Diatoms often make up the majority of the spring bloom phytoplankton biomass.
Diffuse sources – larger geographical area, excluding city areas, from which nutrients or contaminants are washed out to the sea (see also point sources).
DIN – dissolved inorganic nitrogen. The sum of nitrate, nitrite and ammonium i.e. nitrogen that can be absorbed by plants.
Dinoflagellate – any of numerous minute, chiefly marine protozoans of the order Dinoflagellata, characteristically having two flagella and a cellulose covering and forming one of the chief constituents of plankton. They include bioluminescent forms and forms that produce red tides.
DIP – dissolved inorganic phosphorus. The chemical form in which phosphorus can be absorbed by plants.
DSP – short for Diarrhetic Shellfish Poisoning. The poisoning is caused by intake of shellfish that has accumulated certain algal toxins.
Eelgrass (*Zostera marina*) – a submerged flowering plant that grows along the major part of the Danish coasts.
Emission – release of chemicals to the atmosphere.
EQO – Ecological Quality Objective.
Estuary – the transition area between a river and the sea, i.e. an estuary is a body of water that is formed when fresh water from rivers flow into and mixes with salt water from the ocean. In estuaries, the fresh river water is blocked from directly entering the open ocean either by the surrounding mainland, peninsulas, barrier islands, or fringing salt marshes.
EU – European Union.

Euphotic zone – the upper, illuminated zone of aquatic ecosystems. The zone of effective photosynthesis. In marine ecosystems it is much thinner than the deeper aphotic zone which is below the level of effective light penetration. It typically reaches 20–30 meters in coastal waters but extending to 100–200m in open ocean waters.
Eutrophication – eutrophication is enhanced inputs of nutrients and organic matter. Eutrophication can be a natural process, but is most often caused by humans. See also box 1.
Fauna – animal organisms.
Flagellates – microscopic unicellular organisms in aquatic systems. They move by the use of one or more flagella, a string-like extension from the cell. Amongst the flagellates are both heterotophs, autotrophs and mixotrophs.
Flora – plant organisms.
Food chain – refers to direct links between organisms that describes how food energy is transfered through the ecosystem from the smallest primary producers to top predators. An example from the marine ecosystem is planktonic algae → copepods → fish → seal.
Food web – a description of who eats who in an ecosystem. In its most simple form a food chain, but more commonly a net of organisms where several organisms are capable of eating the same food item.
Grazing – literally to feed on growing grasses and herbage the term refers to feeding habits of animals in the terrestrial environment. In the aquatic environment the analogue is organisms feeding on plant or plant like organisms. An example is copepods that graze on phytoplankton.
Halocline – a zone in which there are rapid, vertical changes in salinity. The halocline is usually well-developed in coastal regions where there is much freshwater input from rivers producing surface waters of low salinity, a zone where salinity increases rapidly with depth (the halocline) and a deeper zone of more saline, denser waters.
HELCOM – the Helsinki Commission.
Heterotroph – an organism that cannot synthesise its own food and is dependent on complex organic substances for nutrition. That is, it eats other organisms.
H_2S – hydrogensulfide.
Hypoxia – see oxygen depletion.
ICES – International Council for the Exploration of the Sea.
Inorganic – a chemichal substance that does not involve neither organic life nor the products of organic life, i.e. hydrocarbon groups.
K_s – half-saturation constant. Nutrient concentration at which the phytoplankton nutrient uptake rate is reduced to half the maximum uptake rate.
Macroalgae – macroalgae are plants that lack true roots, stems, leaves, and flowers. They mostly live attached to a hard substrate.
Macrozoobenthos – animals larger than 1 mm living attached to, on, in or near the sea bed, river bed or lake floor.
Marine – of, or pertaining to, the sea, the continuous body of water covering most of the earth's surface and surrounding its land masses. Marine waters may be fully saline, brackish or almost fresh.
Mesozooplankton – animal plankton of the size 0.2 – 2.0 mm.
Metabolism – the chemical change, constructive and destructive, occuring in living organisms.
Metazooan – multicellular, motile animal organisms with cells organized into tissues and controlled by a nervous system.
Microbial loop – a part of the pelagic planktonic food web consisting of bacteria,

flagellates and ciliates. Organisms in the microbial loop transfers energy from dissolved organic carbon back to the copepods.
Microzooplankton – animal plankton of the size 0.02 – 0.2 mm.
Mixotroph – an organism which is capable of performing photosynthesis as well a living partly as a heterotroph. Mixotrophy is commonly found among dinoflagellates. The mixotrophy appears to have different functions in different dinoflagellates; in some primarily phototrophic dinoflagellates feeding appears to be a mechanism for obtaining limiting inorganic nutrients, in some primarily heterotrophic dinoflagellates photosynthesis appears to be a mechanism for supplementing carbon metabolism.
Molar – designating a solution that contents one mole of solution per litre.
μ (prefix) – micro, 10^{-6}.
N – see nitrogen.
NAO – North Atlantic Oscillation is an index that is based on the difference in atmospheric pressure between the Azores and Iceland.
Nitrate (NO_3) – an important nitrogen containing nutrient. The chemical form in which plants uptake most of their nitrogen. It is the salt of nitric acid.
Nitrogen (N) – is a chemical element that constitutes about 80% of the atmosphere by volume. Nitrogen is an important part of proteins and is essential to living organisms.
Oxides of Nitrogen (NO_x) – chemical compounds, gases, formed by nitrogen and oxygen. NOx are formed by the combustion of oil, gasoline, coal and gas. NOx is soluble in water and reacts with water or substances in water to form nitrate.
Nutrient – chemical elements which are involved in the construction of living tissue that are needed by both plants and animals. The most important in terms of bulk are carbon, hydrogen and oxygen, with other essential ones including nitrogen, potassium, calcium, sulphur and phosphorus.
Oligotrophic – applied to waters or soils that are poor in nutrients and have low primary productivity. (See also eutrophic).
Organic – organic compounds contain the element carbon. Of, relating to, or derived from living organisms.
Organism – an individual form of life. An animal, plant or bacteria.
OSPAR – the Oslo and Paris Commission.
Oxygen – a non-metallic element constituting 21 percent of the atmosphere by volume. Oxygen is produced by autotrophic organisms and is vital to oxygen breathing organisms.
Oxygen depletion – a situation where the demand for oxygen has exceeded the supply of oxygen leading to low concentrations of oxygen. Low oxygen concentrations are normally found in the water close to the sea bottom. In Denmark, concentrations below 4 mg O_2 per liter are defined as oxygen depletion and concentrations below 2 mg O_2 per liter are defined as severe acute oxygen depletion.
P – see phosphorus.
Parthenogenesis – litterally it means virgin descent and refers to production og offspring where the female has not been fertilized by a male.
Pelagic – the open-water environment, or water column, as distinct from the bed or shore, inhabited by swimming marine organisms.
Phosphate (PO_4) – is an important phosphorus containing nutrient. It is the chemical form in which plants uptake phosphorus.
Phosphorus (P) – a non-metallic chemical element.
Photosynthesis – the process in green plants and certain other organisms by which carbohydrates are synthesised from carbon dioxide and water using light as an

energy source. Most forms of photosynthesis release oxygen as a by-product.
Phytoplankton – the plant plankton and primary producers (i.e. drifting, more or less microscopic, photosynthetic organisms) of aquatic ecosystems.
Plankton – free passively floating organisms (animals, plants, or microbes) in aquatic systems.
Point source – discharge from one point. The sources are sewage treatment plants, industrial plants, storm water runoff, fresh water aquaculture and mariculture.
Population – all the organisms that constitute a specific group or occur in a specified habitat.
Predator – an organism that lives by preying on other organisms.
Primary production – the production by autotrophs.
Protozooplankton – zooplankton consisting of only one cell.
Rotifer – or rotatoria commonly called wheel animals. A microscopic aquatic animal with at ciliated organ called a corona, which looks like a rotating wheel. Mostly a freshwater animal although some marine species exist.
Runoff – that part of rainfall that is not absorbed in soil but falls on or flows directly into streams and rivers.
Salinity – a measure of the total quantity of dissolved substances in water, in parts per thousand (ppt, per mille) by weight, when all organic matter has been completely oxidised, all carbonate has been converted to oxide, and bromide and iodide to chloride. The salinity of ocean water is in the range 33-38 ppt, with an average of 35 ppt.
Secchi depth – a measure of the clarity of the water.
Sediment – any material transported by water that will ultimately settle to the bottom after the water loses its transporting power. Fine waterborne matter deposited or accumulated in beds. Includes mobile or soft substrates such as cobbles, pebbles, sand and mud.
Stratification – in the sea it is a boundary between two water masses of different specific gravity. The stratification is typically formed by differences in temperature or salinity or both.
Tot-N – see TN.
Tot-P – see TP.
TN – total nitrogen, which includes dissolved inorganic nitrogen and organically bound nitrogen.
TP – total phosphorus, which includes dissoleved inorganic phosphorus and organically bound phosphorus.
Water column – the open-water environment, as distinct from the bed or shore, which may be inhabited by swimming marine or freshwater organisms. (See pelagic).
Wet deposition – deposition of matter by rain.
WFD – EU Water Framework Directive.
Zooplankton – small planktonic animals in fresh- or sea water with almost none or no swimming capacity. They are, therefore, transported randomly by water movements.

Where can I read more?

Relevant links

- OSPAR: http://www.ospar.org
- HELCOM: http://www.helcom.fi
- Department of Marine Ecology, NERI: http://www.dmu.dk/1_om_dmu/2_afdelinger/3_hav/default_en.asp
- Annual assessment reports on the status of the marine environment in Denmark: http://www.dmu.dk/1_Om_DMU/2_tvaer-funk/3_fdc_mar/publikationer.asp
- CHARM: http://charm.dmu.dk
- Marine monitoring in Denmark: http://m-fdc.dmu.dk

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Preface, Where can I read more?, and List of contributors, as well as the brief introductions to chapters 1, 2, and 4 have been drafted and edited by the editors.

The annex on the eutrophication status in the western Baltic Sea, the Danish Belt Sea, Kattegat, Skagerrak, North Sea and the Wadden Sea has been compiled by the Marine Division of the Danish Environmental Protection Agency.

Acknowledgements

The editors would like to thank:

- All the Danish Counties and their dedicated staff who are responsible for data collection in Danish coastal waters.
- Ole H. Manscher, Department of Marine Ecology, NERI for management of MADS, the National Marine Database System and retrieval of data, the latter accomplishment being a trade mark of a true professional.
- Associate professor Benni W. Hansen, Roskilde University Centre and senior scientist Daniel J. Conley, Université P. et M. Curie, Paris for helpful and constructive comments to a draft manuscript.
- Colin Stedmon, Department of Marine Ecology, NERI for linguistic corrections.
- Danish Environmental Protection Agency and National Monitoring Co-ordination Section (NERI) for financial support.

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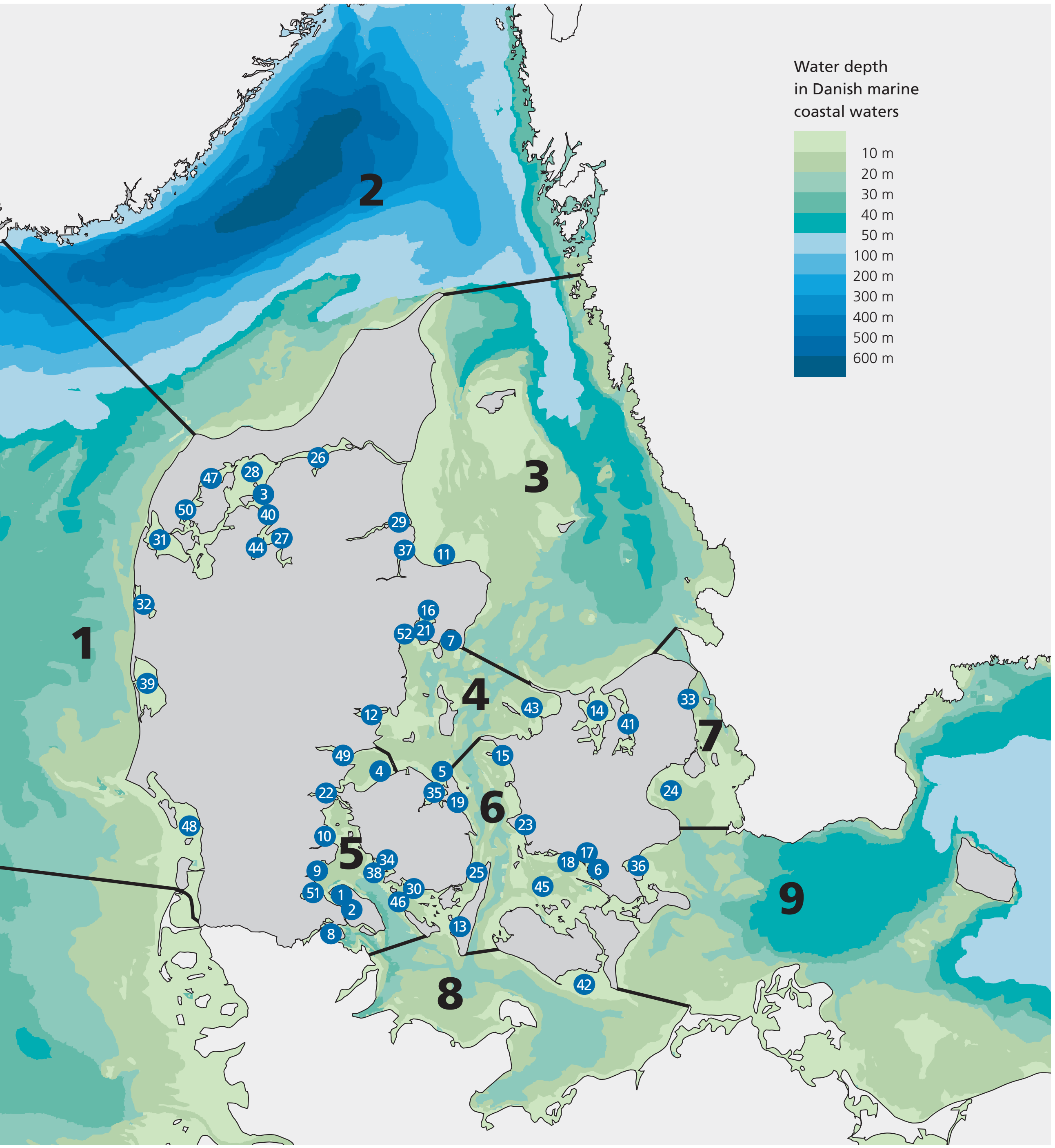

Annexes

Map of the Danish marine waters

The estuaries, coastal waters and open marine waters mentioned in the report are indicated on the map on the opposite page. Names referring to the numbers on the map are listed below. The translation of the Danish names to English are: "Bredning" – a broad; "Bugt" – a bay; "Bælt" – a belt; "Bælthav"– a belt sea; "Fjord" – an inlet, but often used as a general term for estuaries and should not be confused with the definition of a classical fjord with a sill; "Nor" – a cove; "Sund"– a strait or sound; "Vig" – a cove; "Øhav" – archipelago; "Farvand" – waters.

Danish marine sub areas

1 North Sea
2 Skagerrak
3 Kattegat
4 Northern Belt Sea
5 Little Belt
6 Great Belt
7 The Sound
8 Southern Belt Sea
9 Baltic Sea

Estuaries and coastal waters

1 Als Sund
2 Augustenborg Fjord
3 Bjørnsholm Bugt
4 Båring Vig
5 Dalby Bugt
6 Dybsø Fjord
7 Ebeltoft Vig
8 Flensborg Fjord
9 Genner Fjord
10 Haderslev Fjord
11 Hevring Bugt
12 Horsens Fjord
13 Hovvig
14 Isefjord
15 Kalundborg Fjord
16 Kalø Vig
17 Karrebæk Fjord
18 Karrebæksminde Bugt
19 Kertinge Nor
20 Kieler Bugt
21 Knebel Vig
22 Kolding Fjord
23 Korsør Nor
24 Køge Bugt
25 Langelandssund
26 Limfjorden
27 Lovns Bredning
28 Løgstør Bredning
29 Mariager Fjord
30 Nakkebølle Fjord
31 Nissum Bredning
32 Nissum Fjord
33 Nivå bugt
34 Nørrefjord
35 Odense Fjord
36 Præstø Fjord
37 Randers Fjord
38 Ringgård Bassin
39 Ringkøbing Fjord
40 Risgårde Bredning
41 Roskilde Fjord
42 Rødsand
43 Sejrø Bugt
44 Skive Fjord
45 Smålandsfarvandet
46 Sydfynske Øhav
47 Thisted Bredning
48 Vadehavet
49 Vejle Fjord
50 Visby Bredning
51 Åbenrå Fjord
52 Århus Bugt

Overall Classification

Key to the table at page 124 and 125

NI Riverine total N and total P inputs and direct discharges
DI Winter DIN and/or DIP concentrations
NP Increased winter N/P ratio
Ca Maximum and mean Chlorophyll *a* concentration
Ps Region/area specific phytoplankton indicator species
Mp Macrophytes including macroalgae
O_2 Degree of oxygen deficiency
Ck Changes/kills in zoobenthos and fish kills
Oc Organic carbon/organic matter
At Algal toxins (DSP/PSP mussel infection events)
\+ Increased trends, elevated levels, shifts or changes in the respective assessment parameters

Area	Category I Degree of nutrient enrichment	Category II Direct effects	Category III and IV Indirect effects/ other possible effects	Initial classification	Appraisal of all relevant information (concerning the harmonised assessment criteria their respective assessment levels and the supporting environmental factors)	Final classification	Assessment period
Baltic Sea	NI + DI + NP +	Ca + Ps + Mp +	O_2 + At ? Ck Oc	Problem area	Blooms of *Nodularia spumigena, Aphanizomenon*, oxygen depletion	Problem area	1989–2001
Southern Belt Sea	NI + DI + NP +	Ca + Ps + Mp +	O_2 + At ? Ck + Oc	Problem area	Elevated inputs and/or increased trends of nutrients. Elevated concentrations of DIN. Elevated chlorofyll *a* concentrations, Blooms of *Nodularia spumigena, Aphanizomenon, Karenia mikimotoi, Pseudo-nitzschia, Prorocentrum minimum* and *Chrysochromulina*, decreased depth limit of eelgrass, oxygen depletion	Problem area	1989–2001
Little Belt	NI + DI + NP +	Ca + Ps + Mp +	O_2 + At + Ck + Oc	Problem area	Elevated inputs and/or increased trends of nutrients. Elevated concentrations of DIN. Elevated chlorofyll *a* concentrations, Blooms of *Nodularia spumigena, Aphanizomenon, Dictyocha speculum, Karenia mikimotoi, Pseudo-nitzschia, Prorocentrum minimum* and *Chrysochromulina*, decreased depth limit of eelgrass, oxygen depletion and algae toxins found in mussels in some areas.	Problem area	1989–2001
Great Belt	NI + DI + NP +	Ca + Ps + Mp +	O_2 + At ? Ck Oc	Problem area	Elevated inputs and/or increased trends of nutrients. Elevated concentrations of DIN. Elevated chlorofyll *a* concentrations, Blooms of *Nodularia spumigena, Aphanizomenon, Karenia mikimotoi, Pseudo-nitzschia, Prorocentrum minimum* and *Chrysochromulina*, decreased depth limit of eelgrass, oxygen depletion	Problem area	1989–2001
The Sound	NI + DI + NP +	Ca + Ps + Mp +	O_2 + At ? Ck Oc	Problem area	Elevated inputs and/or increased trends of nutrients. Elevated concentrations of DIN. Elevated chlorofyll *a* concentrations, Blooms of *Nodularia spumigena, Aphanizomenon, Karenia mikimotoi, Pseudo-nitzschia, Prorocentrum minimum* and *Chrysochromulina*, decreased depth limit of eelgrass, oxygen depletion	Problem area	1989 - 2001
Northern Belt Sea	NI + DI + NP +	Ca + Ps + Mp +	O_2 + At + Ck + Oc	Problem area	Elevated inputs and/or increased trends of nutrients. Elevated concentrations of DIN. Elevated chlorofyll *a concentrations*, Blooms of *Nodularia spumigena, Karenia mikimotoi, Pseudo-nitzschia, Prorocentrum minimum* and *Chrysochromulina*, decreased depth limit of eelgrass, oxygen depletion and algae toxins found in mussels in some areas.	Problem area	1989–2001
Kattegat Coastal areas	NI + DI + NP +	Ca + Ps + Mp +	O_2 + At + Ck + Oc	Problem area	Elevated inputs and/or increased trends of nutrients. Elevated concentrations of DIN. Elevated chlorofyll *a* concentrations, Blooms of *Chatonella, Karenia mikimotoi, Pseudo-nitzschia, Gymnodinium chlorophorum, Prorocentrum minimum* and *Chrysochromulina*, decreased depth limit of eelgrass, oxygen depletion and algae toxins found in mussels in some areas (Limfjorden).	Problem area	1989–2001
Kattegat Open areas	NI + DI – NP –	Ca + Ps + Mp +/–	O_2 + At – Ck + Oc	Problem area	Elevated inputs and/or increased trends of nutrients. Elevated concentrations of DIN. Elevated chlorofyll *a* concentrations, Blooms of *Chatonella, Karenia mikimotoi, Gymnodinium chlorophorum* and *Chrysochromulina*. Oxygen depletion.	Problem area	1989–2001
Skagerrak Coastal area	NI + DI + NP +	Ca + Ps + Mp +	O_2 – At – Ck – Oc	Problem area	Concentration of N and P elevated due to transboundery input (Jutland Coastal Current from German Bigth). Elevated concentrations of DIN. Elevated chlorofyll *a* concentrations, Blooms of *Chatonella, Karenia mikimotoi* and *Gymnodinium chlorophorum*	Problem area	1989–2001
Skagerrak Open area	NI – DI – NP –	Ca + Ps + Mp	O_2 – At – Ck Oc	Problem area	Elevated chlorofyll *a* concentrations, Blooms of *Chatonella* and *Karenia mikimotoi*.	Problem area	1989–2001
North Sea Coastal area	NI + DI + NP +	Ca + Ps + Mp +	O_2 – At – Ck – Oc	Problem area	Concentration of N and P elevated due to transboundery input (Jutland Coasta Current from German Bigth). Blooms of *Phaocystis, Pseudo-nitzschia, Karenia mikimotoi* and *Chatonella*. The western limit of the area to be defined.	Problem area	1989–2001
Central North Sea	NI – DI – NP –	Ca ? Ps ? Mp ?	O_2 – At – Ck – Oc	Non problem area	No elevated nutrient concentrations. The limit between the open area and the coastal area needs to be specified. A possible potential problem area in between the coast and the open sea area should also be identified.	Non problem area	All available data
Wadden Sea	NI + DI + NP +	Ca + Ps – Mp +	O_2 – At + Ck – Oc	Problem area	Concentration of N and P elevated due to local and transboundery input (Jutland Coastal Current from German Bigth). Mass occurrence of algae, including annual nuissance macroalge. Algae toxins found in mussels in some areas.	Problem area	1989–2001

Data sheet

Title: Nutrients and Eutrophication in Danish Marine Waters
Subtitle: A Challenge for Science and Management

Editors (2003): Gunni Ærtebjerg, Jesper H. Andersen & Ole S. Hansen
Department: Department of Marine Ecology

Publisher: Ministry of the Environment, National Environmental Research Institute ©

Date of publication: March 2003
Editing complete: December 2002

Financial support: Danish Environmental Protection Agency and Environmental Monitoring Coordination Section (NERI)

Please cite as 2003: Ærtebjerg, G., Andersen, J.H. & Hansen, O.S. (Eds.): Nutrients and Eutrophication in Danish Marine Waters. A Challenge for Science and Management. National Environmental Research Institute. 126 pp.

Abstract: Eutrophication – or nutrient over-enrichment – of Danish marine waters can to a large extent be attributed to excess nutrients flowing from upstream watersheds into coastal waters. The nutrient enrichment can result in algae blooms, oxygen depletion, kills of fish and organisms living at the seabed as well as other undesired effects. The result is impairment of environmental and habitat quality objectives. This assessment report explains technical aspects of eutrophication and assesses the present situation. In addressing abatement strategies, the assessment discusses the importance of developing normalised indices and setting ecological quality objectives. The assessment also reviews the National Action Plans on the Aquatic Environment from 1987 and 1997 and other policy options for reducing the losses and discharges of nutrients.

Keywords: Eutrophication, nutrient enrichment, coastal waters, estuaries, nitrogen, phosphorus, oxygen depletion, phytoplankton, submerged aquatic vegetation, zoobenthos, Action Plan on the Aquatic Environment, environmental protection, management of aquatic resources

Layout and drawings: Britta Munter, Grafisk Værksted, NERI
Cover photos: Nanna Rask, Fyn County; Henny Rasmussen, DIAS & Bent Lauge Madsen

External referee: Benni W. Hansen, Roskilde University Centre, Denmark
Internal referee: Daniel J. Conley, Université P. et M. Curie, Paris, France

ISBN: 87–7772–728–2
ISSN (print): 0905–815X
ISSN (electronic): 1600–0048

Printed by: Schultz Grafisk, Certified under ISO 14001 and ISO 9002
Paper quality: Cyclus print
Number of pages: 126
Circulation: 800

Price: DKK 250,- (incl. 25% VAT, excl. freight)

Internet-version: The report is also available as a PDF-file from NERI's homepage
http://www.dmu.dk

For sale at:
Ministry of the Environment
Frontlinien
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