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).

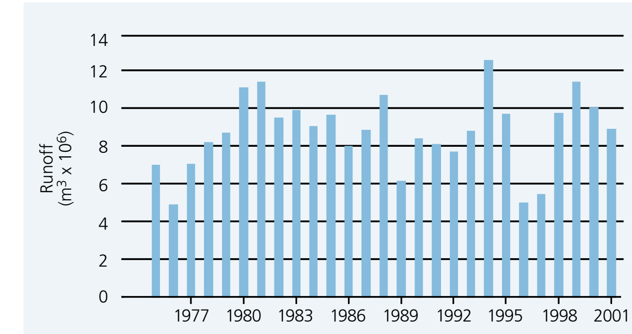


Figure 2.1
Annual runoff from Denmark to the Kattegat – Belt Sea area 1975-2001. (Data from NERI).

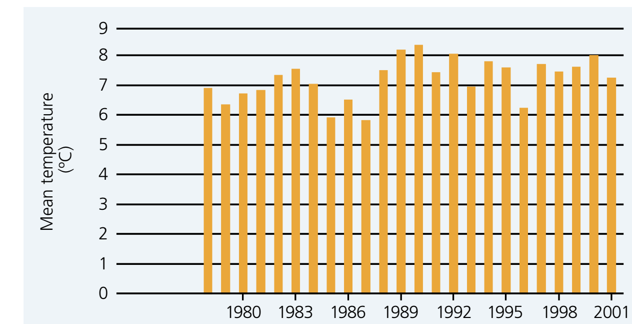


Figure 2.2
Annual mean air temperature measured at Sprogø/Risø 1978-2001. (Data from Sund og Bælt Holding and Wind Energy Department, Risø National Laboratory).

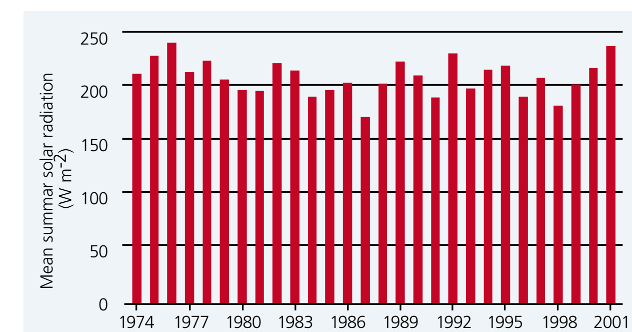


Figure 2.3
Mean summer (May-Aug.) solar radiation measured at Højbakkegård/Risø. (Data from Laboratory for Agrohydrology and Bioclimatology, Department of Agricultural Sciences, The Royal Veterinary and Agricultural University, and Wind Energy Department, Risø National Laboratory).

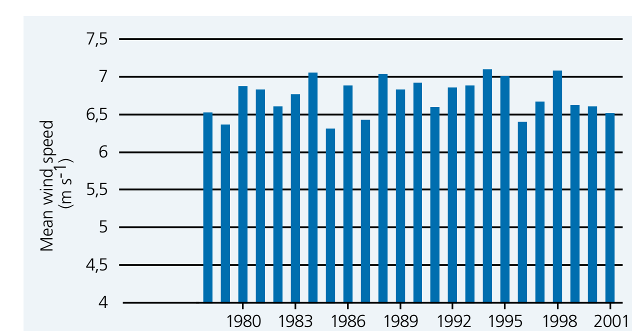


Figure 2.4
Mean annual wind speed at Sprogø/Risø 1978-2001. (Data from Sund og Bælt Holding and Wind Energy Department, Risø National Laboratory).

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.

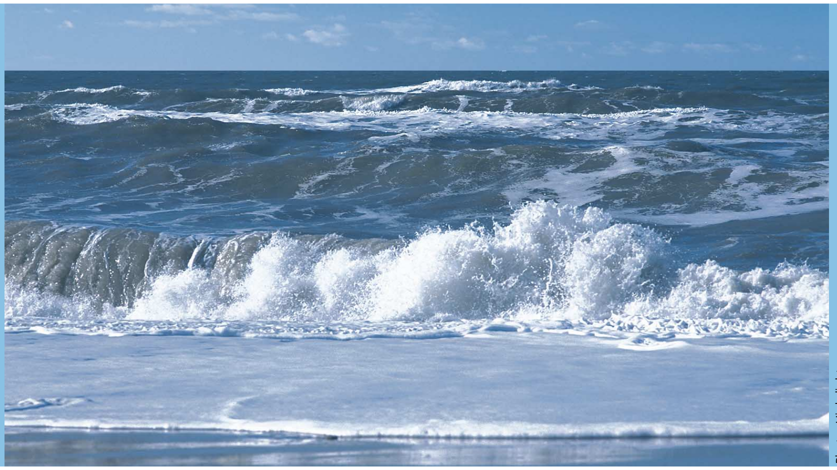


Photo: High-lights

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).

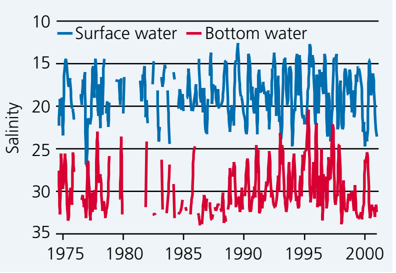


Figure 2.5
Median monthly salinity in the open Kattegat and Belt Sea surface water (0-10m) and bottom water (20-40m) 1975-2000. (After Henriksen et al. 2001).

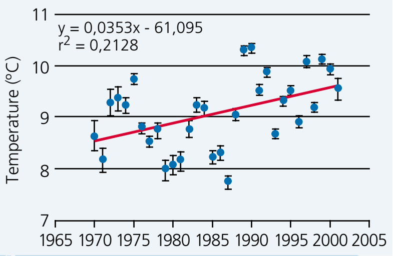


Figure 2.7
The development of annual mean surface (0-10 m) temperature in Kattegat 1970-2000.

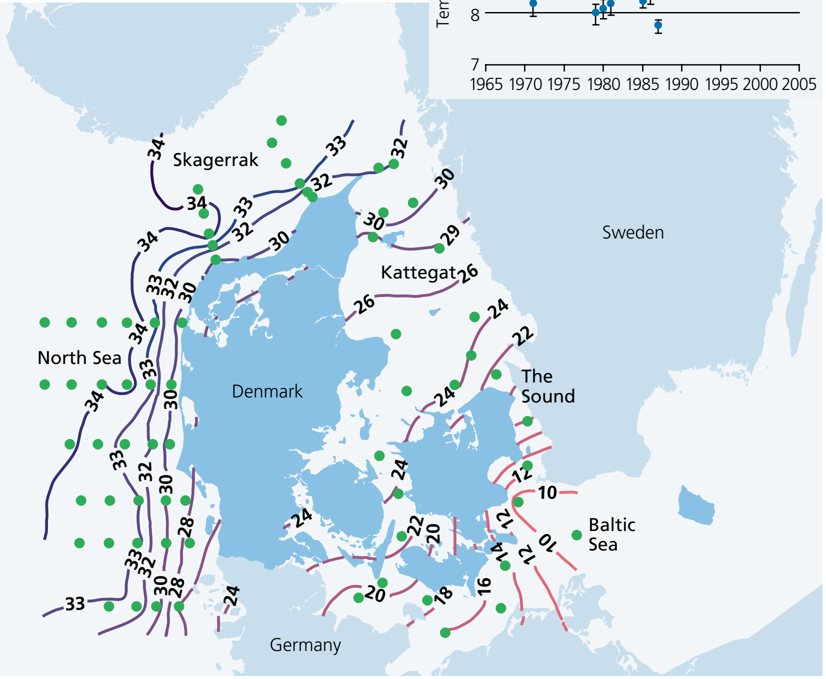


Figure 2.6
Interpolated distribution of surface salinity (mean 1-10 m) in February 2002.

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.

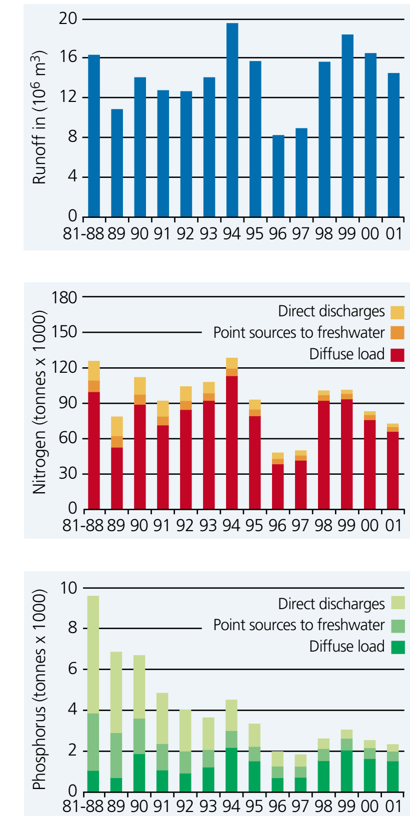


Figure 2.8
Annual freshwater runoff, and the total annual nitrogen and phosphorus load to Danish coastal waters in the period 1989-2001, divided between diffuse load, point sources to freshwater and direct point sources to marine waters. An estimate of the average annual load in the 1980s is shown for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

Sea area	Drainage area	Runoff		Nitrogen	Phosphorus	BOD_5
	km²	mm	10^6 m³	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).

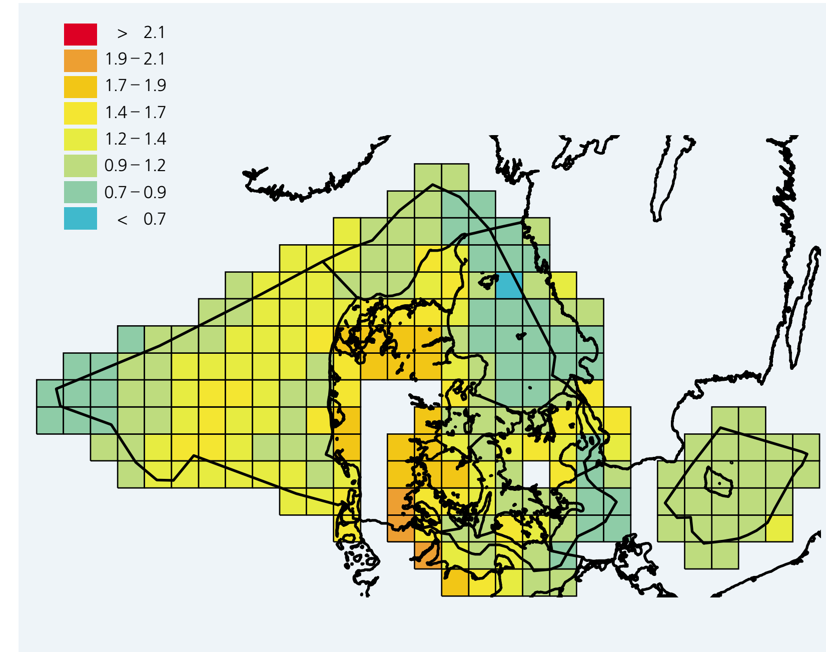


Figure 2.9
The atmospheric wet and dry deposition of inorganic nitrogen (NO_x+NH_x) in tonnes N km^{-2} at Danish sea areas in 2001. Grid size 30 km x 30 km. (From Ærtebjerg et al. 2002).

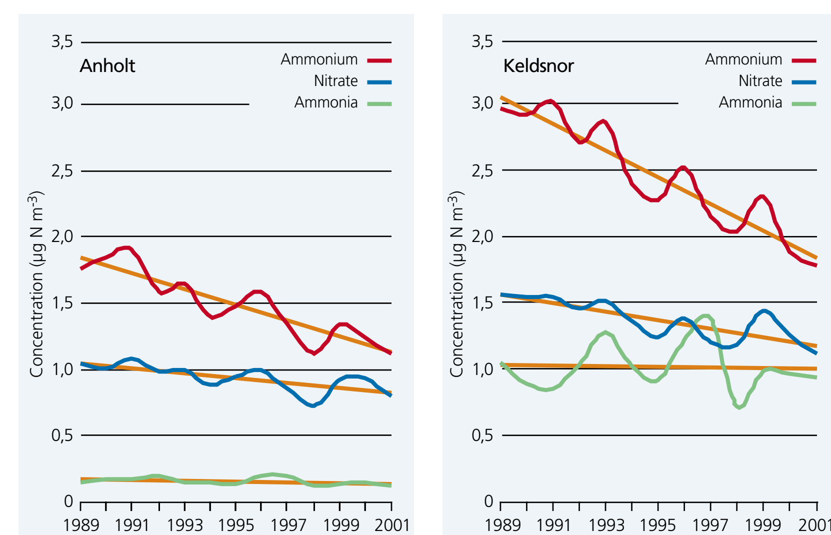


Figure 2.10
Annual means for the period 1989-2001 of concentrations of ammonia (green), particle bound ammonium (red) and sum-nitrate (blue) at Anholt in the middle of Kattegat and Keldsnor in the southern Belt Sea. (From Ellermann et al. 2002).

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.

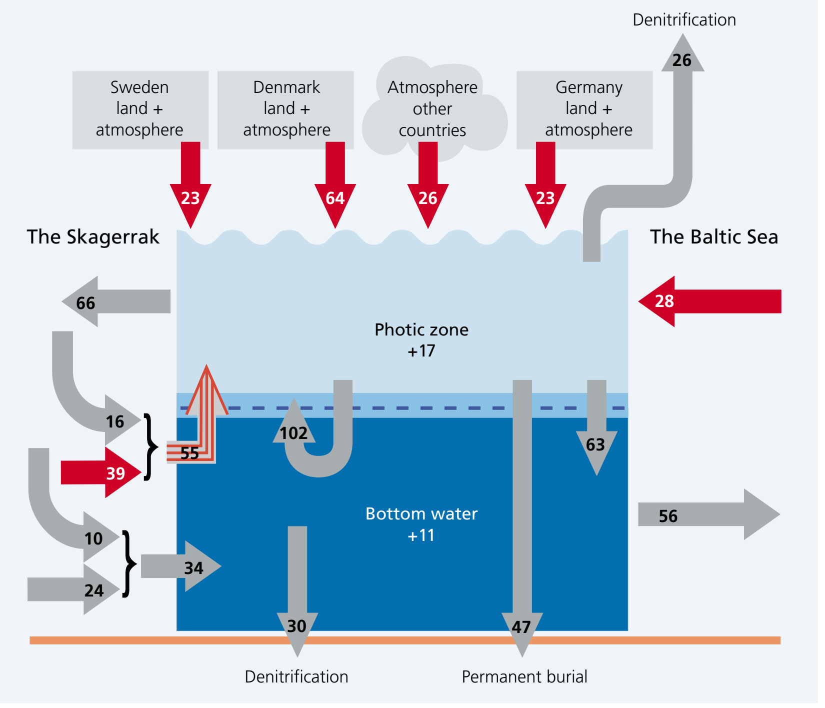


Figure 2.11
Transport of biological active nitrogen in the transition area between the Skagerrak and the Baltic. Loss to the bottom includes denitrification (30,000 tons) and permanent burial (47,000 tons). Period covered: see text.

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

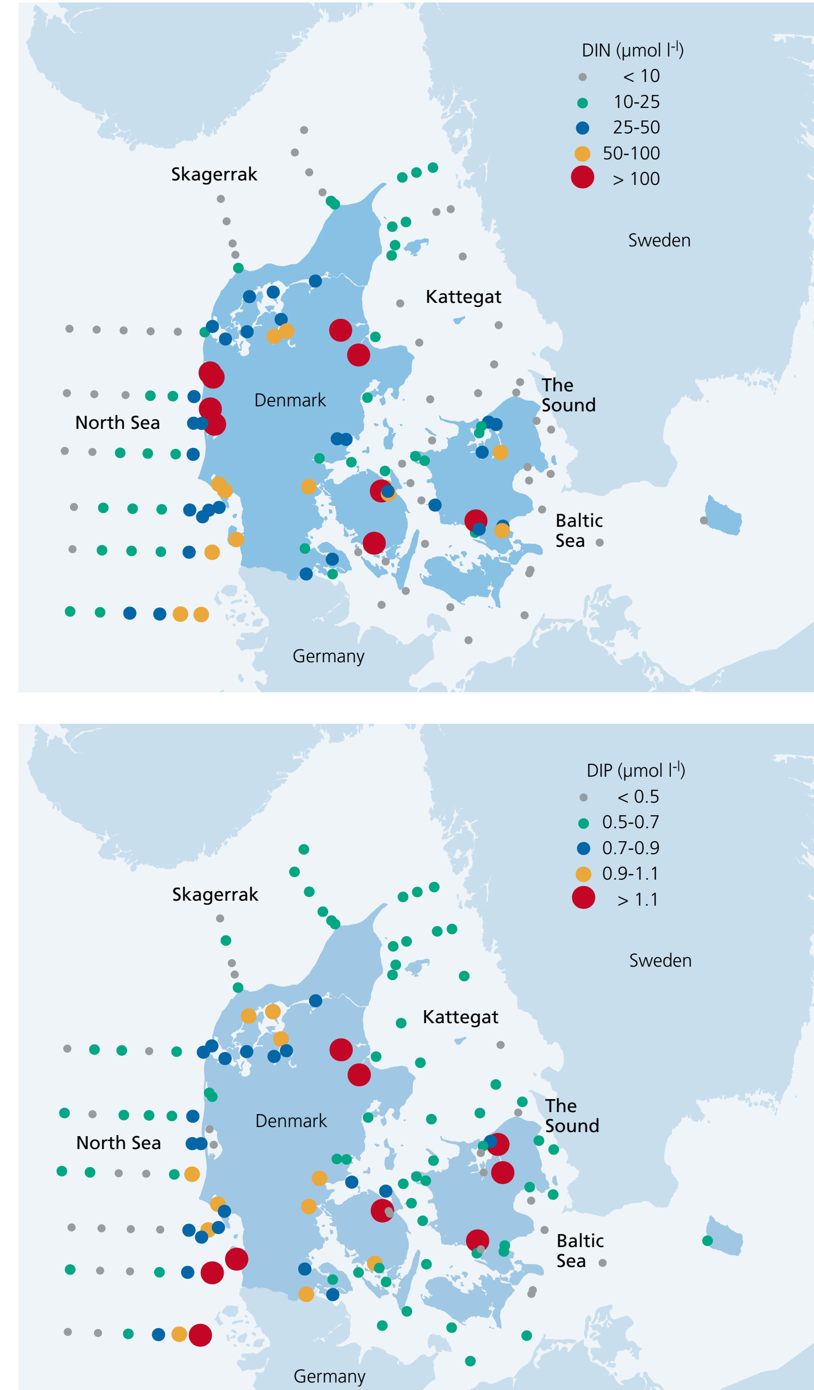


Figure 2.12
Mean winter concentrations of DIN and DIP, 1998–2001, in Danish marine waters.

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

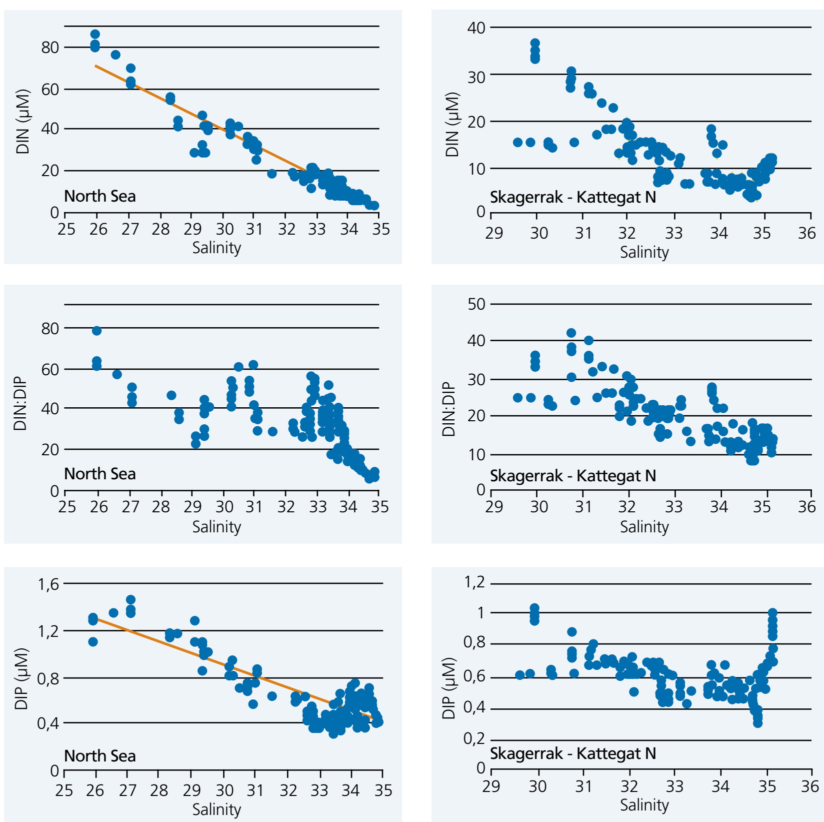
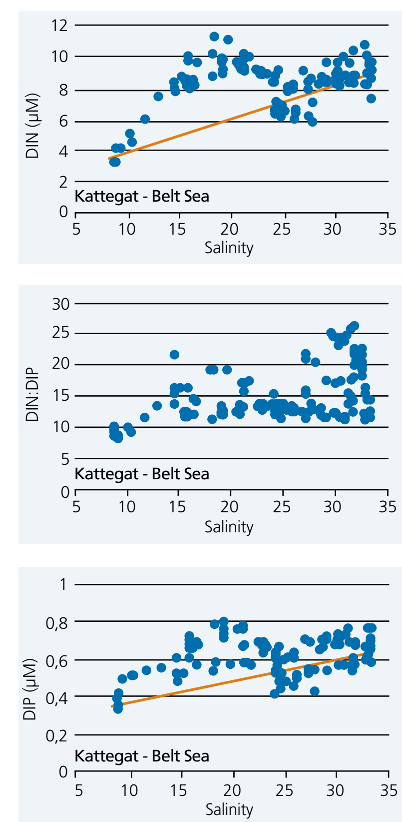


Figure 2.13
Relations of DIN, DIP and DIN:DIP ratio to salinity in February 2002 in the North Sea, Skagerrak and Kattegat-Belt Sea, respectively. The lines in the North Sea plots are linear regression lines, while the lines in the Kattegat-Belt Sea plots are theoretical mixing lines for mixtures of Baltic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

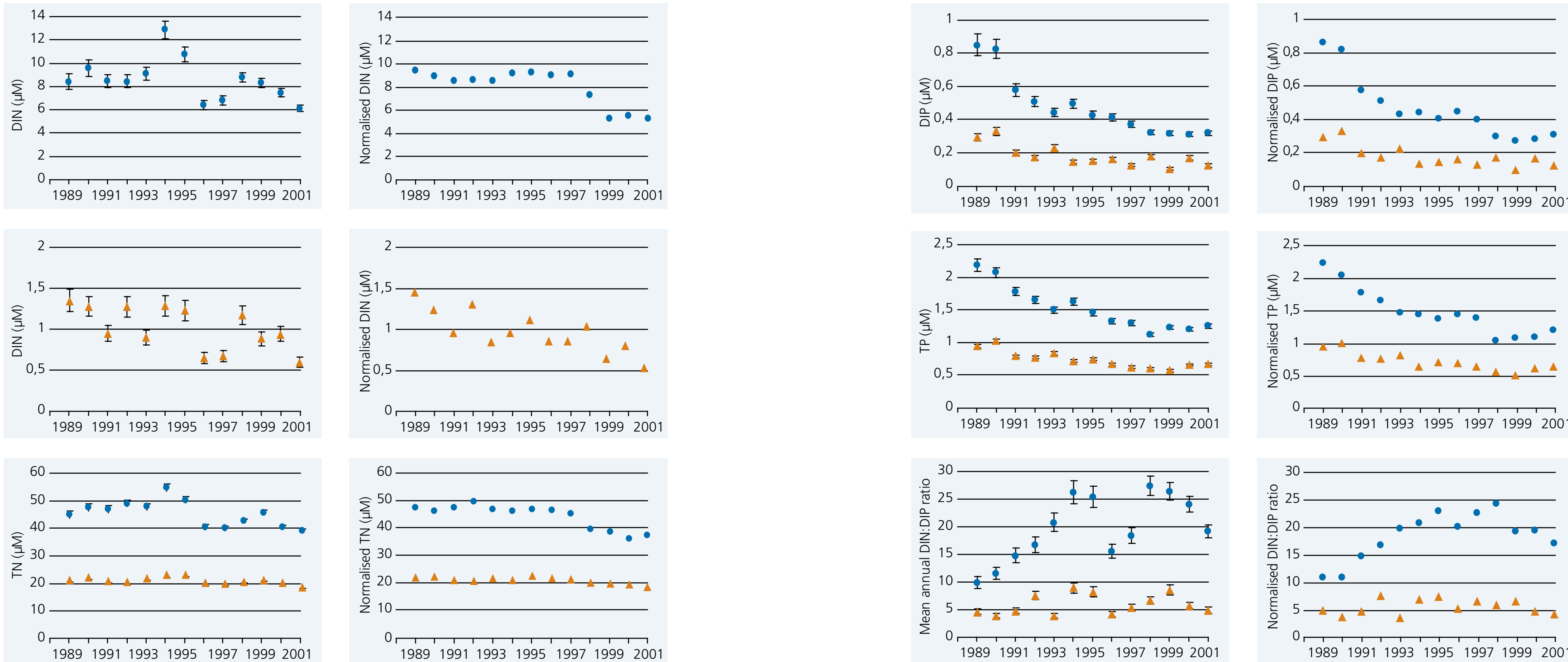


waters indices for mean annual concentrations of DIN, TN, DIP and TP in the upper mixed layer were developed for estuaries-coastal waters and the open Kattegat–Belt Sea, respectively (see box 4).

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).

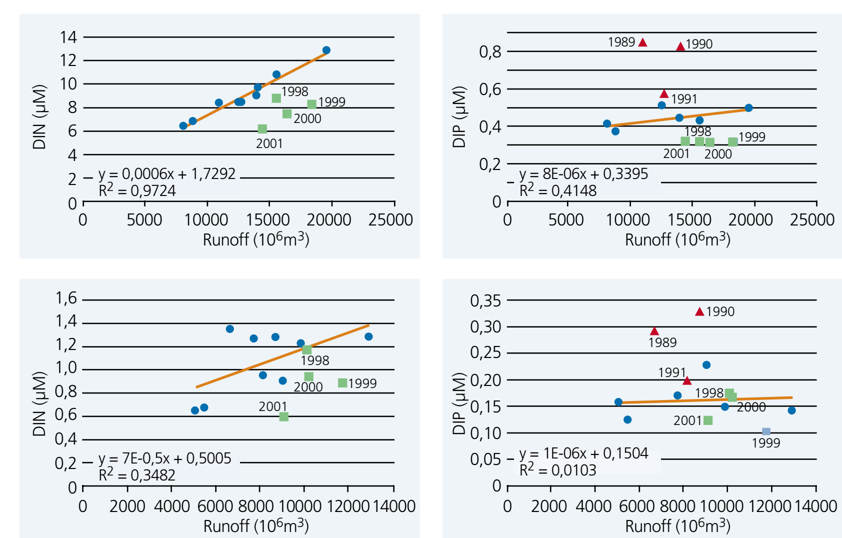


Figure 2.15
Annual mean indices for DIN and DIP in estuaries-coastal waters (upper row) and open Kattegat-Belt Sea (lower row) against runoff. The years 1998–2001 are marked with green squares, and the years 1989–1991 are marked with red triangles in the DIP diagrams.

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.

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-

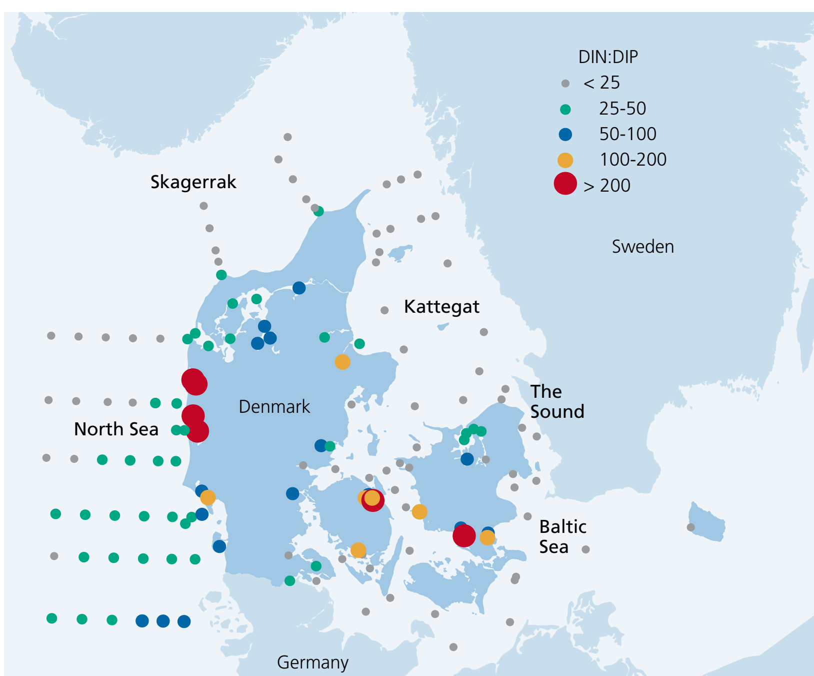


Figure 2.16
Mean winter DIN:DIP ratio 1998–2001 in Danish marine waters.

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

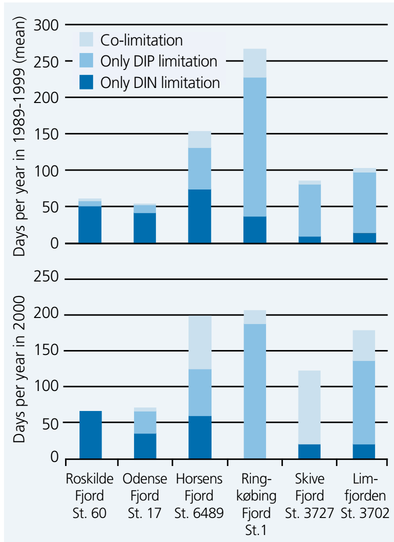


Figure 2.17 A

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).

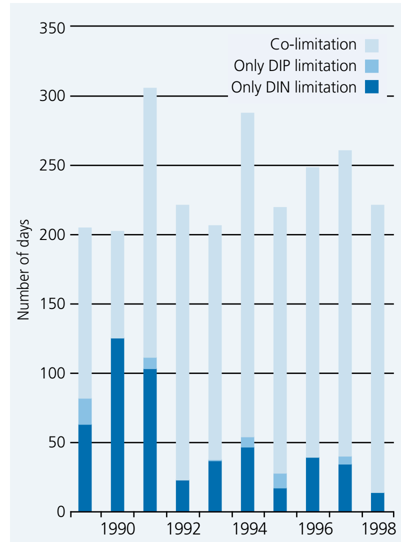


Figure 2.17 B

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).

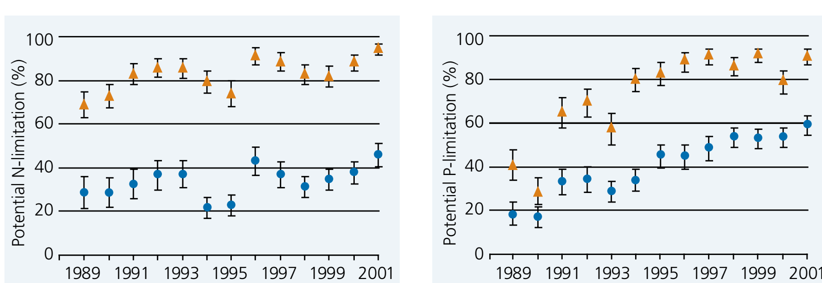


Figure 2.18

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.

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

Increase
Decrease

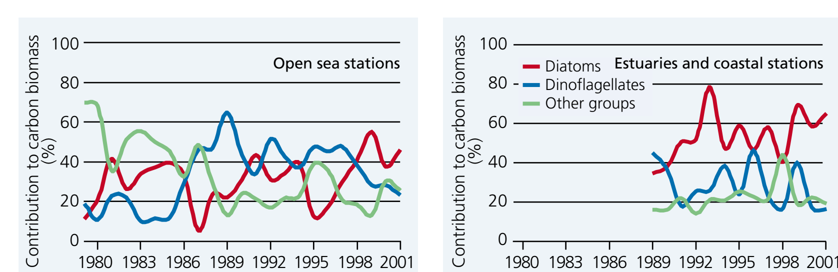


Figure 2.19
Contributions (%) of phytoplankton groups to annual average biomasses at sampling stations in open sea areas (left) and estuaries and coastal areas (right) of the Danish waters in the Baltic entrance area.