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Response to lowered nutrient discharges in the coastal waters around the island of Funen, Denmark

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Abstract

The Danish Action Plan for the Aquatic Environment of 1987 prescribes a 50% and 80% run-off reduction of nitrogen and phosphorus, respectively, to the aquatic environment. This is meant to reduce the seriously increasing eutrophication problems, such as widespread hypoxia and anoxia, in the coastal regions of Denmark. In spite of major investments in sewage treatment, these objectives have generally not been realised, primarily because of lack of substantial reductions in nitrogen run-off from diffuse agricultural sources. On the island of Funen, Denmark, precipitation in the last two years has been extremely low, leading to major decrease in nitrogen and phosphorus run-off to the surrounding coastal waters. For primarily meteorological reasons, the objectives of the Action Plan were thus fulfilled for the first time. Immediate response was registered in the coastal waters around Funen: very low nutrient concentrations during winter 1995/96, higher Secchi depths, lower phytoplankton production and biomass, increasing depth distribution of eelgrass (*Zostera marina*) and higher oxygen concentration in bottom-near water in spring and summer 1996 compared to previous years. This natural 'experiment' suggests that substantially lower nutrient loads to coastal marine systems can have an immediate, positive impact on oxygen conditions in bottom-near waters.

Introduction

In 1987, the Danish Government passed the Danish Action Plan for the Aquatic Environment, prescribing a 50% and 80% discharge reduction of total nitrogen and phosphorus, respectively, to the aquatic environment before 1993 (recently revised to the year 2000). The step was taken in order to reduce the severe eutrophication problems caused by the high nutrient loads, e.g. widespread hypoxia and anoxia registered annually since 1981 in the coastal waters of Denmark (Kronvang et al., 1993; Richardson & Jørgensen, 1996; Agger & Ærtebjerg, 1997). The outcome of the action plan is followed in a nationwide monitoring programme (Fyns Amt, 1991; Kronvang et al., 1993; Kaas et al., 1996).

Similar eutrophication problems have been encountered in, e.g. the Baltic Sea and the North Sea. Here, a general 50%-reduction of N and P loading has been agreed upon by many of the surrounding countries (HELCOM, 1993; Richardson, 1996b).

In the county of Funen, an 3486 km^2 island situated in the middle of Denmark with a population of c. 0.5 mill. people, investments in sewage treatment have resulted in considerable reductions of point-source discharges (from municipal and industrial waste water) of nitrogen and phosphorus since the enactment of the action plan. However, nutrient run-off from diffuse (also termed non-point) sources, constituting the major part of the total nitrogen load and mainly originating in agricultural practice, has only been marginally reduced. As the major part of the phosphorus run-off is derived from point sources, the overall result at Funen in 1995 was a decrease of N run-off by only 20% and a more substantial decrease of 65% in P run-off. Thus, up to 1995 the objectives of the Danish Action Plan have not yet been fulfilled; improvement of water quality has been observed in local areas only which formerly were heavily influenced by point-source discharges, e.g in various fjords and other shallow areas (Fyns Amt, 1996) as well as in Danish fjords in general (Miljøstyrelsen, 1995; Kaas et al., 1996). Decreasing nutrient levels in local coastal areas, as a result of substantial reductions in point-source discharges, have also been documented for other areas in this part of Europe, such as in the archipelagian waters of the northern Baltic Sea (Bonsdorff et al., 1997). This is in contrast to the overall increase in nutrient levels in more open coastal systems still heavily loaded by riverine input, fish farms, atmospheric deposition, etc (Brockmann et al., 1990; De Jonge et al., 1994; Bonsdorff et al., 1997).

The nutrient run-off from Funen was very low in 1995/96 due to the lowest precipitation recorded in this century, and the objectives of the Action Plan were actually more than fulfilled due to primarily meteorological reasons. The aim of this study was to follow the impact of this pronounced decrease in nutrient load on various chemical and biological variables in the adjacent coastal waters.

Study area

The coastal waters around Funen are situated at the transition between the Baltic Sea and Kattegat (Figure 1). The whole Baltic Sea-Kattegat-Skagerrak area is hydrographically very complex; in general, a surface layer of low-saline Baltic water (10–15 psu) flows northwards through the Danish Straits (Little Belt and Great Belt). A compensating stream of high-saline Skagerrak water (25–33 psu) near the bottom flows via Kattegat and the straits southwards to the Baltic Sea.

Generally, Kattegat and the straits are markedly stratified by a halocline from spring to autumn. The halocline in the coastal waters surrounding Funen is mostly situated at 10–15 m depth. This is exemplified in Figure 2, which shows isohalines of a typical summer stratification (August 26–30, 1996) together with water depths along the 14 coastal stations forming the monitoring route (Figure 1) visited regularly by the county of Funen. Figure 2 also illustrates the positions of the main sedimentation basins with stratified water column and stagnant bottom water in summer, i.e. in northern (NLB14) and southern Little Belt (LBT27 to SLB 43) and parts of the South Funen Archipelago (SLB44 and DSØ51). During winter, the water column is mostly well mixed due to the increased frequency of heavy winds and storms. In winters with extensive ice-cover, however, a weak stratification may occur. In the narrow straits in northern Little Belt (NLB 20) and the South Funen Archipelago (DSØ33), the water column is almost permanently mixed.

Residence time of the surface water has been calculated for the very dynamic area of northern Little Belt, and retention time for nutrients are estimated to be minimum 2 weeks in winter and 3 months in summer (Christiansen et al., 1994).

In the coastal waters around Funen, the winter (Dec.–Feb.) dissolved inorganic nutrient concentrations in the productive surface layer (20-year median) are in the ranges of 8–15 μM nitrogen and 0.8-1 μM phosphorus. Lowest concentrations are found during summer, where the nutrients periodically are below the detection limit, i.e.$<$1.1 μM for dissolved inorganic N ($<$0.36 μM for nitrate+nitrite and $<$0.71 μM for ammonium) and $<$0.16 μM for dissolved inorganic P.

Phytoplankton blooms, mainly consisting of diatoms and dinoflagellates, are encountered in spring and autumn and occasionally during summer. Cyanobacterial blooms are rare in the coastal waters around Funen, while other toxic or potentially toxic phytoplankton species have bloomed frequently since general monitoring was initiated in 1976. The annual phytoplankton primary production in the area generally ranges between 150 and 300 g C m^{-2} yr^{-1}.

Methods

In the coastal waters around Funen, 14 monitoring stations (Figure 1) are currently visited with a frequency of 26–52 $year^{-1}$. Water depth vary between 8 and 43 m. Salinity, temperature, oxygen, light penetration and fluorescence are monitored by CTD-registration (AROP) at depth intervals of 0.5-2 m in the water column. Secchi depths are recorded on each sampling occasion. Water is sampled at 1 m depth and 0.5 m above the bottom, representing above- and below-halocline water, respectively. These samples are analyzed for total (TN) and dissolved inorganic nitrogen (DIN: $NO_3{}^-$, $NO_2{}^-$, $NH_4{}^+$), total phosphorus (TP) and dissolved inorganic phosphorus (DIP: $PO_4{}^{3-}$), silica, oxygen and chlorophyll *a* (surface only). Samples down to a depth of 2% of incident light are also taken for determination of the (^{14}C-based) rate of primary production. All analyses are done according to Danish Standards (Miljøstyrelsen, 1988), corresponding to internationally approved standard methods. A similar monitoring programme in fjords

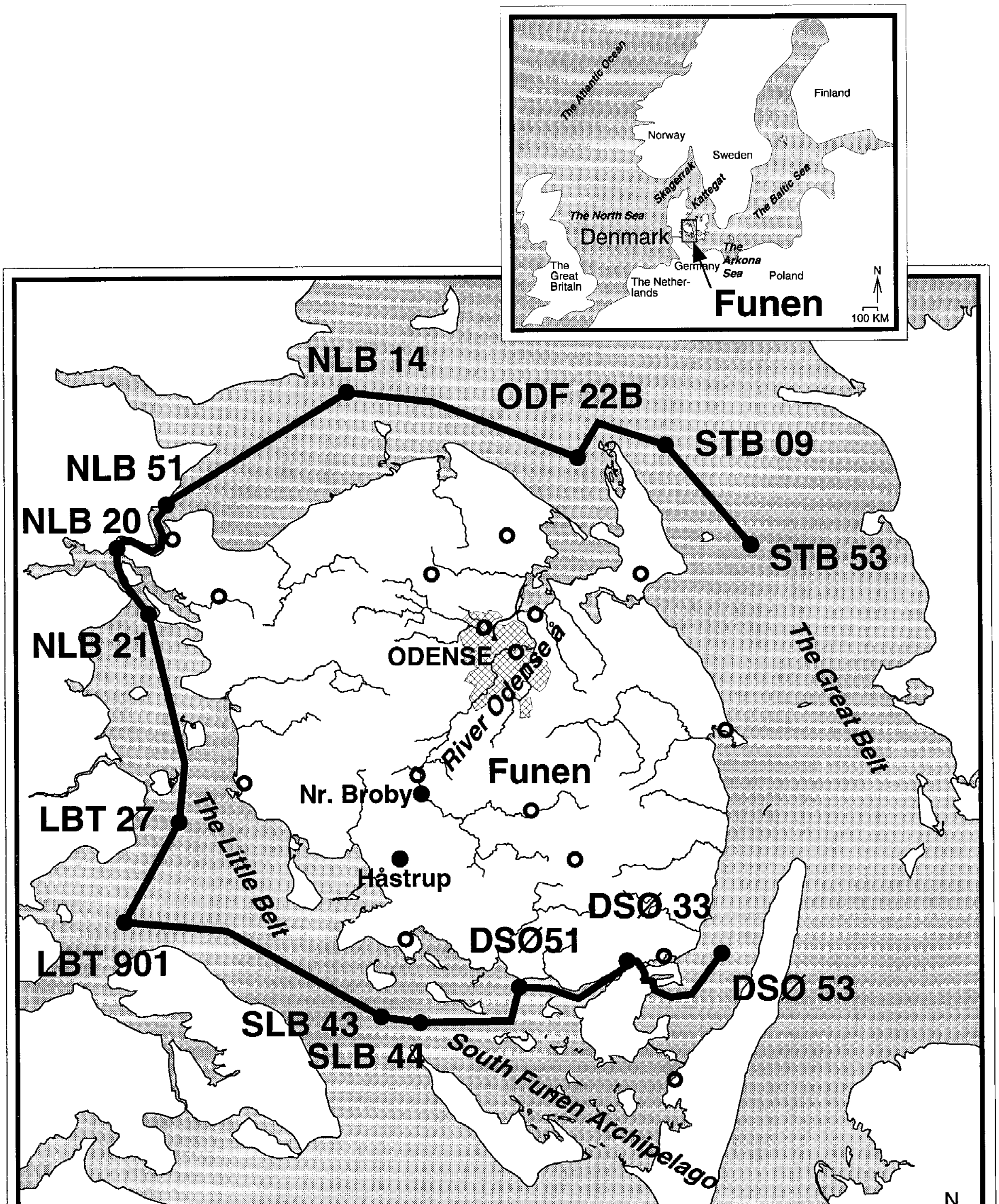

Figure 1. Map of Funen, Denmark and the surrounding coastal waters with 14 coastal stations, the hydrological station at Nr. Broby (River Odense Å), the 19 streams, the major sewage treatment plants (> 10 000 PE) and the meteorological station at Håstrup.

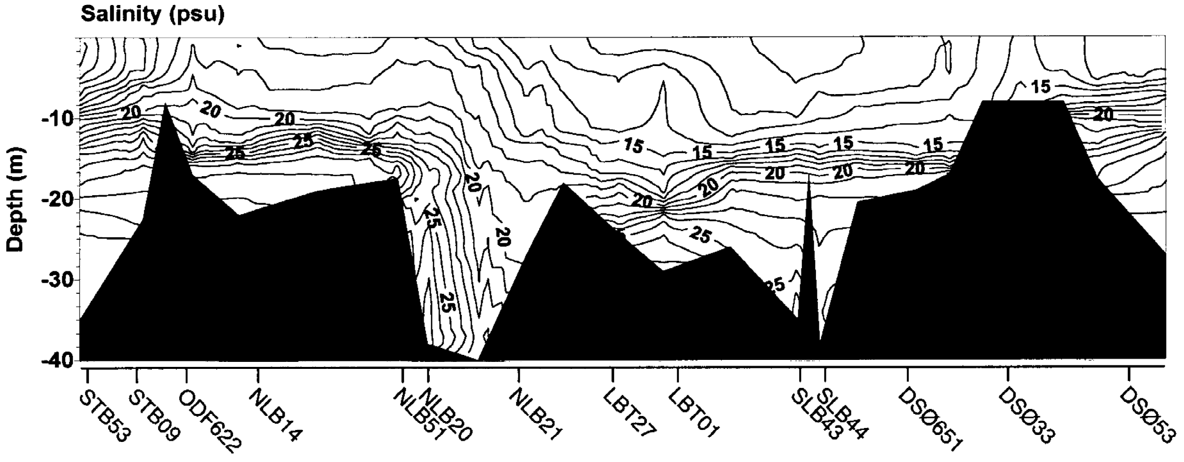

Figure 2. Depth profile along the monitoring route (stations spaced according to their relative distance). Isohalines show a typical, stratified summer situation (August 26–30, 1996).

and other shallow near-shore areas at Funen includes observations on macrophytes.

A calculation of total fresh water discharge from land to the coastal waters of Funen is based upon continuous measurements of water level in 19 streams representing 45% of the total catchment area of Funen (Figure 1). Nutrient run-off is calculated from daily to fortnightly measurements of TN and TP concentrations in these 19 streams and monthly flowproportional measurements of TN and TP in the outlets of 56 sewage treatment plants > 1000 PE (person equivalents). The nutrient run-off is divided into point sources and diffuse (i.e. non-point) sources. Point sources mainly comprise outlets from municipal and industrial sewage treatment plants (major plants > 10 000 PE shown in Figure 1), whereas diffuse sources comprise contributions from the open land (mainly agricultural areas).

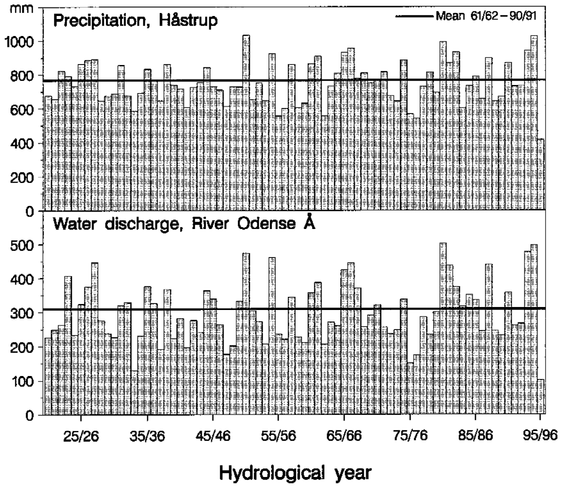

Figure 3. Precipitation (*upper*) at Håstrup (data from the Meteorological Institute of Denmark) and freshwater discharge (*lower*) at Nr. Broby, River Odense Å in the hydrological years 1920/21–1995/96.

Results and discussion

Freshwater and Nutrient run-off

At two sites on the island of Funen, hydrological data have been obtained since 1920; precipitation at Håstrup and water discharge in River Odense Å at Nr. Broby (Figure 1). The normal level of precipitation and freshwater discharge at these two sites in recent years (mean of the period 1961/62 to 1990/91), amount to 768 mm and 310 mm, respectively (Figure 3). In the hydrological year, May 1995–June 1996, severe drought in mid and southern Scandinavia (S. Rosenørn, pers. comm.) lead to both the lowest precipitation (410 mm) and freshwater discharge (101 mm) registered since 1920/21.

The extremely low freshwater discharge in the hydrological year 1995/96 (Figure 3) resulted in an estimated total freshwater run-off of 386*10^6 m^3 from the whole island of Funen in the calender year 1996 (Figure 4, *upper*). The freshwater run-off has annually varied between c. 350*10^6 and 1500*10^6 m^3 since 1976, when a general monitoring program was initiated. Freshwater run-off in 1996 was thus the second lowest since 1976.

Since 1976, also nitrogen and phosphorus run-off from the island of Funen have been estimated.

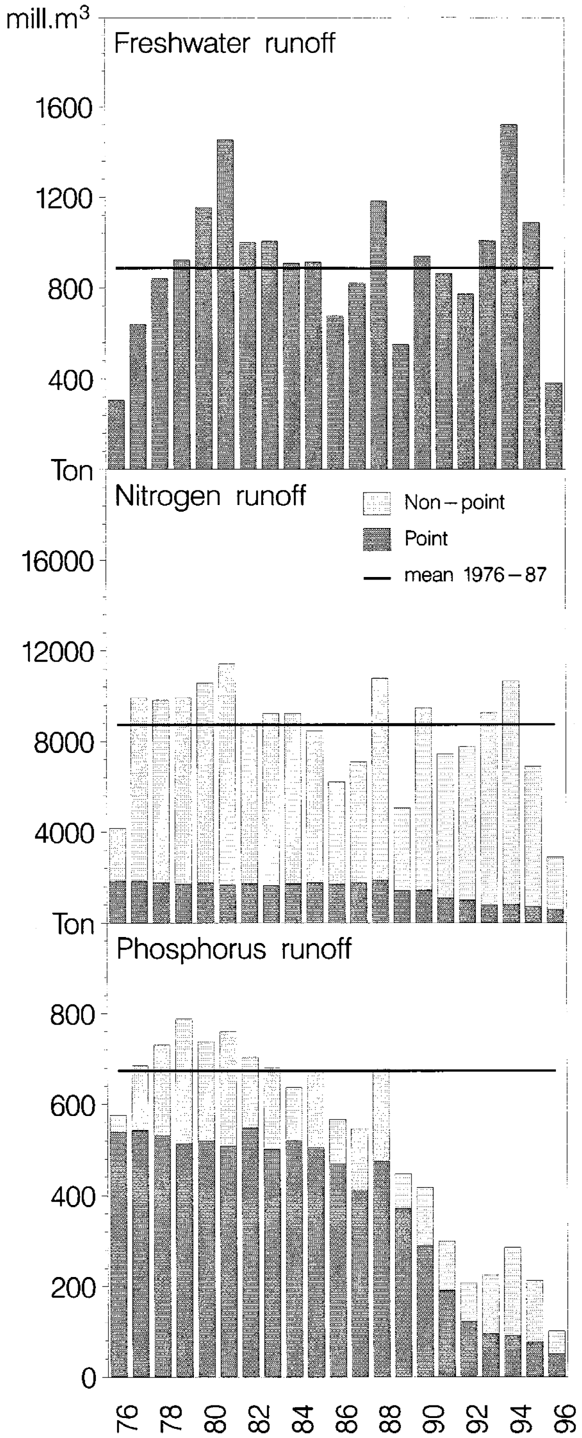

Figure 4. Total freshwater (*upper*) and total nitrogen (*mid*) and total phosphorus (*lower*) run-off from the island of Funen to the coastal waters calculated on a calendar year basis (1976–96). Horizontal lines indicate the mean for the period 1976–87 before implementation of the Danish Environmental Action Plan.

Table 1. Annual nitrogen and phosphorus loads (tonnes yr^{-1}) to the coastal waters of Funen (assumed area: 4000 km^2) in 1989–95 (mean) and 1996. Numbers in parentheses indicate % of the total load

	Mean 1989–95 tonnes yr^{-1}		1996 tonnes yr^{-1}	
	N	P	N	P
Atmosphere	5000 (38)	64 (18)	5000 (63)	64 (39)
Point sources	1030 (8)	177 (48)	570 (8)	52 (31)
Diffuse sources	7060 (54)	123 (34)	2320 (29)	50 (30)
Total	13 090 (100)	364 (100)	7890 (100)	166 (100)

Between 1976 and 1995, the range in annual run-off has been c. 4000–11500 tonnes of N and 200–800 tonnes of P, and the annual mean prior to enactment of the Environmental Plan was c. 9000 and 700 tonnes of N and P, respectively (Figure 4, *mid* and *lower*).

In years with normal precipitation, the total nutrient load of the coastal waters around Funen is dominated by riverine input and point source discharges, the latter including contributions from the only fish farm in the area. Atmospheric load is estimated to contribute about 5000 tonnes N and 64 tonnes P annually, assuming a 4000 km^2 area of the coastal waters around Funen (based on 1989–96 data; Fyns Amt, 1997a). Thus in years with low riverine input the aatmospheric load constitutes a major part of the total load, e.g. 63 and 39% for N and P, respectively, in 1996 (Table 1). Estimates of the atmospheric contribution to the total nitrogen load for the whole Kattegat and Belt Sea area during the 1980s (Agger & Ærtebjerg, 1997), and for the German Bight during 1989–92 (Beddig et al., 1997) are 25 and 30%, respectively.

The annual nitrogen run-off is tightly related to the annual freshwater run-off, showing no particular trend during the 1976–95 period, whereas the phosphorus run-off began to decrease sharply from around 1988 (Figure 4, *mid* and *lower*). The major part of the nitrogen run-off comes from diffuse sources and is agriculturally derived, and only a small part comes from point sources; the opposite was true for the phosphorus run-off until 1995 (Figure 4; Table 1). When corrected for year-to-year variation in precipitation, nitrogen run-off from diffuse sources has only been reduced by an estimated maximum of 15% (which is essentially the value that should be held up against the goals of the Action Plan) from 1987 to the present; the corresponding development for phosphorus has not been calculated. The considerable investments in sewage treatment since implementation of the Aquatic Environment Plan have for 1995 resulted in reductions of point-source discharges of 69 and 90% for nitrogen and phosphorus, respectively, compared to the 1976–87 mean. Phosphorus run-off from agriculturally derived diffuse sources is thus becoming increasingly important relative to the point-source run-off (Figure 4, *lower*), implying that the total phosphorus run-off becomes subject to the same hydrologically induced variations as the nitrogen run-off.

In 1995, the total nitrogen and phosphorus run-off from land had decreased by 20 and 65%, respectively, compared to the 1976–87 mean, due to these unequal reductions of point and diffuse sources and their relative contribution to the total run-off. In 1996, nutrient run-off was the lowest yet recorded, 2890 and 102 tonnes of N and P, respectively, as a consequence of the low freshwater run-off in combination with the advanced sewage treatment. That meant a decrease in terrestrial N and P load by 67 and 85%, respectively, compared to the mean for the period up to 1987, prior to the enactment of the Danish Action Plan. The objectives of the plan were thus fulfilled for the first time since the enactment, albeit primarily for metheorological reasons.

Preliminary data from 1996/97 (hydrological year up to March 1997) still show nitrogen and phosphorus run-off well below (66 and 82%, respectively) the level from 1979/80–1986/87 because of the continued drought (Fyns Amt, 1997b; Tornbjerg & Petersen, 1997).

Nutrient levels in the coastal waters

The increase in nutrient levels in many coastal marine systems due to anthropogenic impact is well-documented (e.g. Ryther & Dunstan, 1971; Kronvang et al., 1993; Bonsdorff et al., 1997), although the trend seems to have reversed in some areas in recent years, at least for phosphorus (e.g. De Jonge et al., 1994). In Denmark, the different trends since 1991/92 in nitrogen and phosphorus run-off are generally reflected in DIN and DIP winter concentrations in the Danish coastal waters. The lack of a trend for DIN, but markedly decreasing DIP concentrations in the Great Belt and Kattegat are thus in accordance with the slight, but not substantial, reduction in nitrogen run-off and the pronounced reduction in phosphorus run-off, respectively (Danmarks Statistik, 1997).

The pronounced influence of nutrient input from land on the concentrations in the inner Danish coastal waters is strongly supported by the fact that the increase in nitrogen concentrations in the Belt Sea and Kattegat surface layer from 1975–89 is significantly higher than the corresponding increase in both the Arcona Sea (representing inflowing Baltic water) and the Kattegat deep water (representing inflowing Skagerrak water) (Kronvang et al., 1993; Richardson, 1996b). Recent evidence is provided from the island of Funen by an intensive and ongoing study since 1988/89 of the relationship between local nitrogen run-off (River Odense Å; Figure 1) and nitrogen levels in the Great Belt (STB53; Figure 1) (Jürgensen et al., 1994). Modelling of each of the winters in this period shows that the increase in DIN in the Great Belt due to run-off ranged from 0 to as much as 5 μM in very dry and very wet years, respectively, corresponding to an 0–90% increase of DIN winter levels depending on the actual freshwater discharge for the various years (C. Jürgensen & N.H. Tornbjerg, submitted).

Table 2. Average (±SD) winter levels of nitrate (Jan–Feb) and ortho-phosphate (Jan–March) in the surface waters of the Arkona Sea (data from Nehring & Nausch 1996) and at STB 53, the Great Belt

	The Arkona Sea 1969–73	The Arkona Sea 1988–93	STB53 1988–1993
NO_3^- (μM)	2.7 ± 0.14	4.2 ± 0.79	8.2 ± 1.9
PO_4^{3-} (μM)	0.26 ± 0.07	0.61 ± 0.17	0.89 ± 0.03

Nutrient concentrations in the Baltic Sea are significantly lower than in the Belt Sea and Kattegat. Due to the long residence time of water (in the order of 20 years), nutrients are lost through sedimentation and denitrification and only about 10% of the nutrients loaded into the Baltic are generally exported to the Belt Sea (Wulff & Stigerbrandt, 1989). In the western Baltic (Arcona Sea; Figure 1), winter levels of DIN and DIP have almost doubled from 1969–73 to 1988–93, but they are still a factor of 1.5–2 lower than in the Great Belt (Nehring & Nausch, 1996; Table 2).

An unusual outflow of Baltic water into the Danish straits during winter 1995/96 was reflected in a surface salinity 3–5 psu lower than normal in the coastal waters around Funen (Figure 5, *left*). This is thus expected to result in somewhat lowered nutrient levels irrespective of the magnitude of local run-off. In the winter 1996/97, the salinity was at a normal level indicating no extraordinary input of Baltic water.

The winters 1995/96 and 1996/97 have actually shown very low nutrient levels in the coastal waters surrounding Funen (Figure 5) in accordance with the markedly reduced freshwater and nutrient run-off (Figures 3 and 4). Median levels of inorganic nutri-

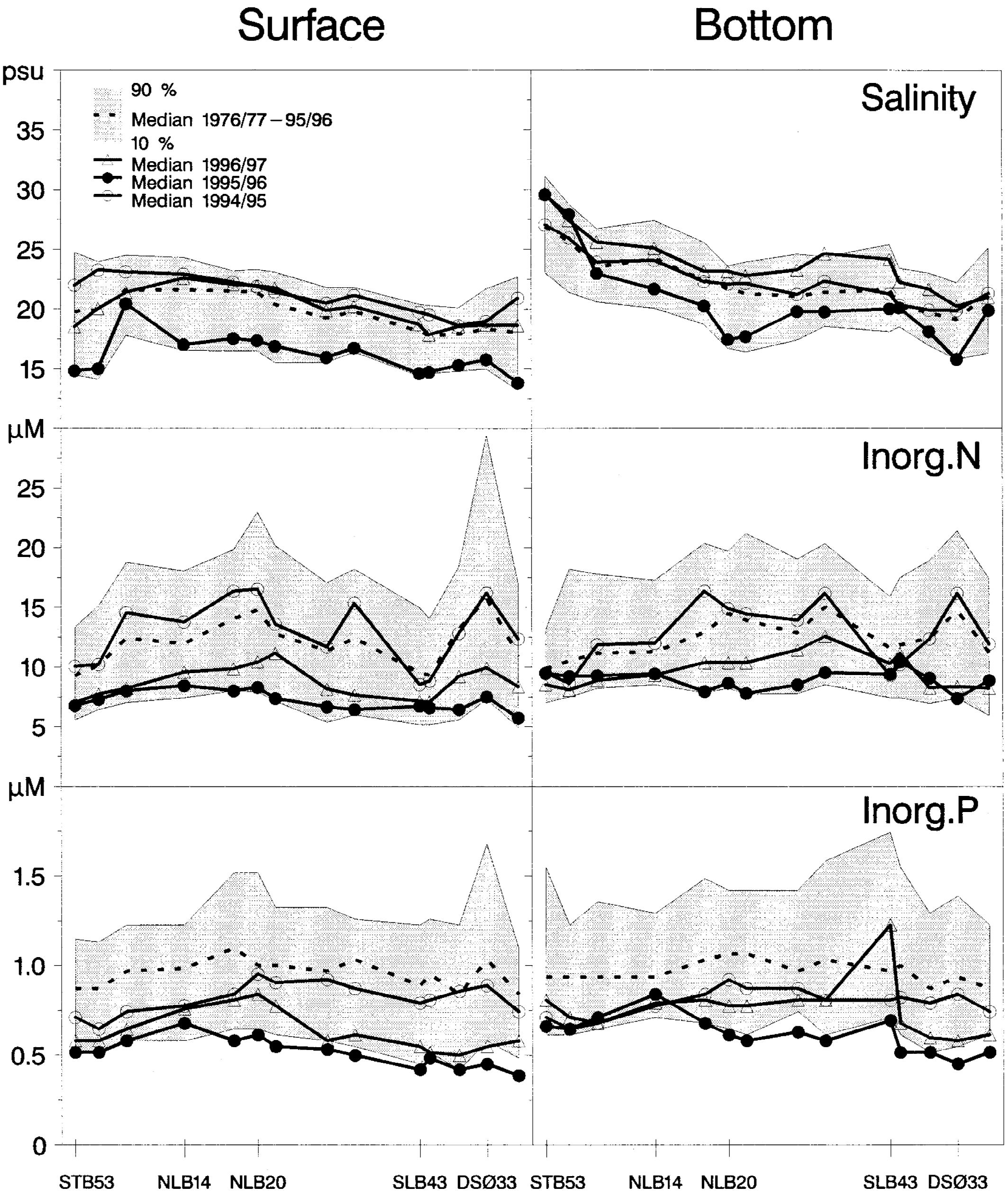

Figure 5. Winter (Dec.–Feb.) median levels of salinity, dissolved inorganic nitrogen (DIN) and phosphorus (DIP) in surface (*left*) and bottom waters (*right*) at the 14 monitoring stations around Funen in 1994/95, 1995/96 and 1996/97 (n=4–12 for each data point). For comparison, the long-term (1976/77–1995/96) median level (stippled line) with 10%- and 90%-percentiles (grey), is also shown.

ents in the surface waters were extremely low (5–8 and 0.4–0.7 μM for inorganic N and P, respectively, at the 14 stations) in the winter 1995/96 (Figure 5, *left*), when the influence of a very low run-off was enhanced by the extraordinary inflow of nutrient-poor Baltic water. This corresponds to more than 50% lower levels of DIN and DIP compared to the long-term (last 20 years) winter median and is in fact near or below the 10% percentile. The DIN and DIP levels still remained low, near the 10% percentile, in the winter 1996/97. For comparison, the relatively wet winter of 1994/95 (Figure 3) showed normal levels of DIN while

DIP concentrations were below the long-term median (Figure 5, *left*) in accordance with the previously mentioned trends in loading of N (not markedly reduced) and P (substantially reduced), respectively (Figure 4). The low levels registered in the dry winters of 1995/96 and 1996/97 are comparable to the levels registered in 1976–79 prior to the severe hypoxia and anoxia events in the 1980s (Fyns Amt, 1997a).

The low nutrient run-off and influence of Baltic water in the winter 1995/96 were also reflected in the bottom waters around Funen (Figure 5, *right*). Salinity was lower than normal and both DIN and DIP concentrations were near the 10% percentile. Nutrient contributions from the bottom waters to the surface in the upwelling and mixing zones in the narrow parts of Little Belt (NLB20, 21, 51) and the South Funen Archipelago (DSØ33) may thus have been less than usual.

Phytoplankton

Primary production rates have been steadily increasing in Danish coastal waters since the 1950s, concomitant with the increasing nutrient loads from land (Hansen et al., 1995). It has in fact more than doubled as shown for the open Kattegat (Richardson & Heilmann, 1995), and there are several other examples of smaller, similar or greater increases (e.g. De Jonge et al., 1994; Cadée, 1986). Thus, there seems to be direct or circumstantial evidence from a number of coastal marine systems for a general long-term link between enhanced nutrient availability and increasing primary production (De Jonge et al., 1994; Richardson, 1996a; Lohrenz et al., 1997). Such a link may also exist on a much shorter time scale, as shown during a 6-year period in the Gulf of Mexico (Lohrenz et al., 1997). The low levels of nutrients in winter 1995/96 together with the continued low nutrient run-off in spring 1996 at Funen would then be expected to lead to low phytoplankton growth and biomass in the following productive season.

Compared to the long-term (1976–95) median at the 14 coastal stations around Funen, unusually low chlorophyll *a* levels (about 1–4 μg l^{-1}lower) and primary production rates (about 200–400 mgC m^{-2} d^{-1} lower), both near the 10% percentile, as well as high Secchi depth levels (1–2 m higher) near the 90% percentile, were in fact registered during summer 1996 (Figure 6). Ærtebjerg (1996) obtained similar results that summer in the open areas of Kattegat and the Great Belt.

The actual mechanisms and magnitude by which winter and spring nutrient levels influence subsequent summer phytoplankton growth and biomass may be complex and include other factors than presented here, as discussed by Richardson (1996b) and Kiørboe (1996). The present data, however, suggest empirical evidence of an immediate response, at least under the circumstances prevailing in the summer 1996 and the preceding winter.

The results obtained during the summers 1994 and 1995 (Figure 6) call for a more detailed analysis, as both summers were preceded by relatively wet winters (Figures 3 and 4). While the summer of 1994 generally showed higher levels of chlorophyll *a* and primary production rates and lower Secchi depth levels than the long-term median, the summer 1995 results were not far from those obtained in 1996.

A trend towards longer periods with potential phosphate limitation has been shown for the 15-m deep Aarhus Bay, Denmark, following recent large (90%) reductions in point-source loading (Jørgensen, 1996). Kaas et al. (1996) suggest the same trend in many Danish fjords. The variation of DIN and DIP concentrations in surface waters of the Great Belt (STB 53) from 1992 to 1996, shown in Figure 7, points to a similar development with increasing periods of DIP concentrations below detection limit in spring and summer and increasing N:P ratios. It is generally agreed that nitrogen is the more important limiting nutrient for phytoplankton production in the coastal waters of Denmark (e.g. Richardson, 1996b) as well as in most other coastal systems (e.g., Smetacek et al., 1991; De Jonge et al., 1994). Phosphorus limitation may be of major importance, however, in some regions, such as the western part of the Dutch Wadden Sea (De Jonge, 1997). We thus speculate, that the low phytoplankton production and biomass in 1995 (Figure 6) to some extent was influenced by the unusual long period with potential phosphate limitation (Figure 7).

In 1996, summer phytoplankton blooms (>200 ugC/l) were less frequent than usual in the coastal waters of Funen (Fyns Amt, 1997a) as well as in the Danish waters in general (Jensen et al., 1997). For instance, the northern Little Belt area at NLB 14 is normally subject to summer diatom blooms but those were absent in 1996. The strong halocline in late summer with subsequent developing oxygen deficit (see below) and nutrient enrichment of the bottom waters in south Funen coastal areas, however, resulted in a phytoplankton bloom, registered as subsurface

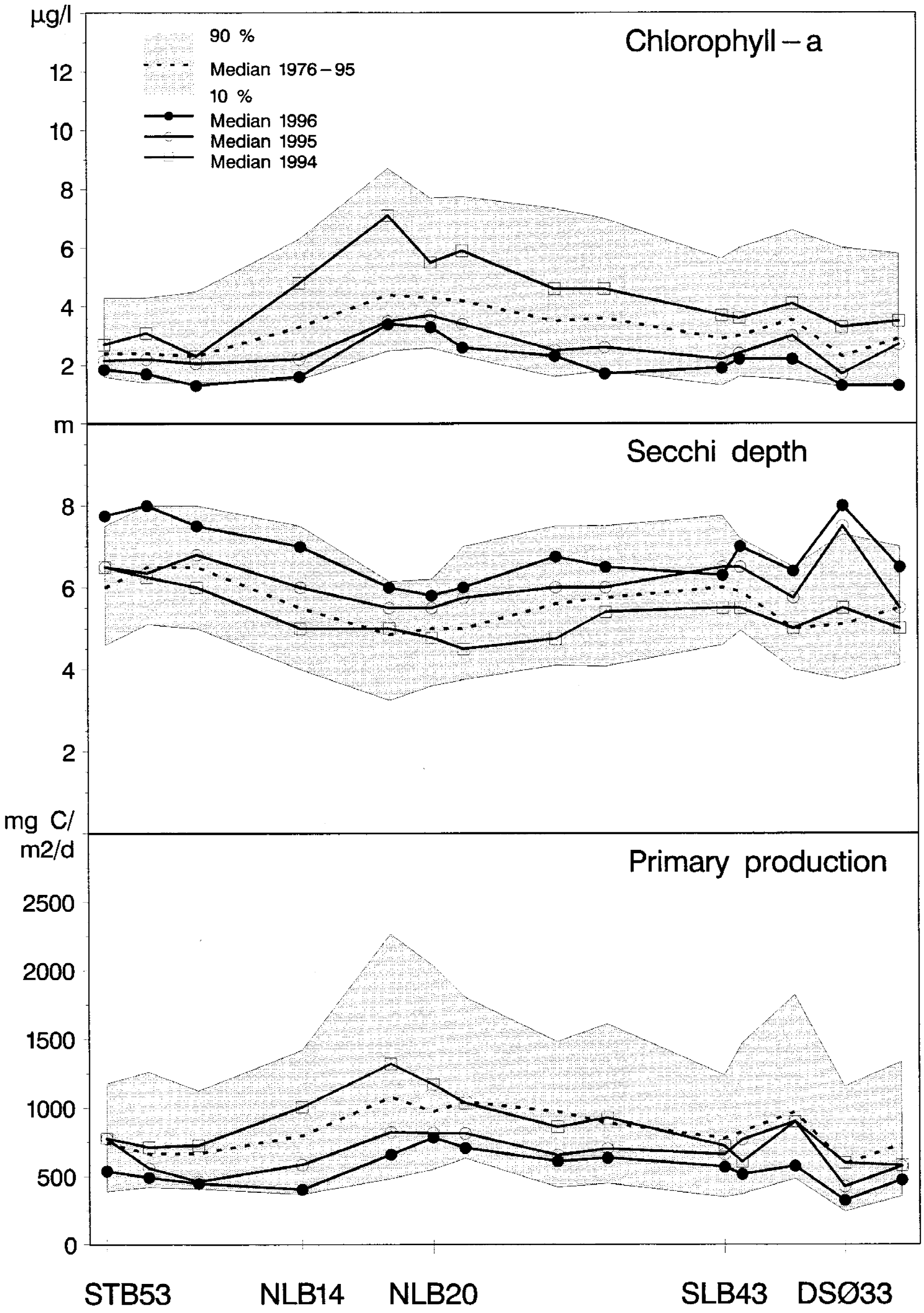

Figure 6. Summer (May–Sept.) median levels of chlorophyll *a* (1 m depth) Secchi depth and daily, depth-integrated primary production at the 14 monitoring stations around Funen in 1994, 1995 and 1996 (*n*=10–20 for each data point). For comparison, the long-term (1976–95) median level (stippled line) with 10%- and 90%-percentiles (grey), is also shown.

maxima mainly consisting of the mobile dinoflagellate *Prorocentrum minimum* ($> 6{*}10^6$ cells l^{-1}in late August).

Macrophytes

Nutrient enrichment of shallow coastal waters

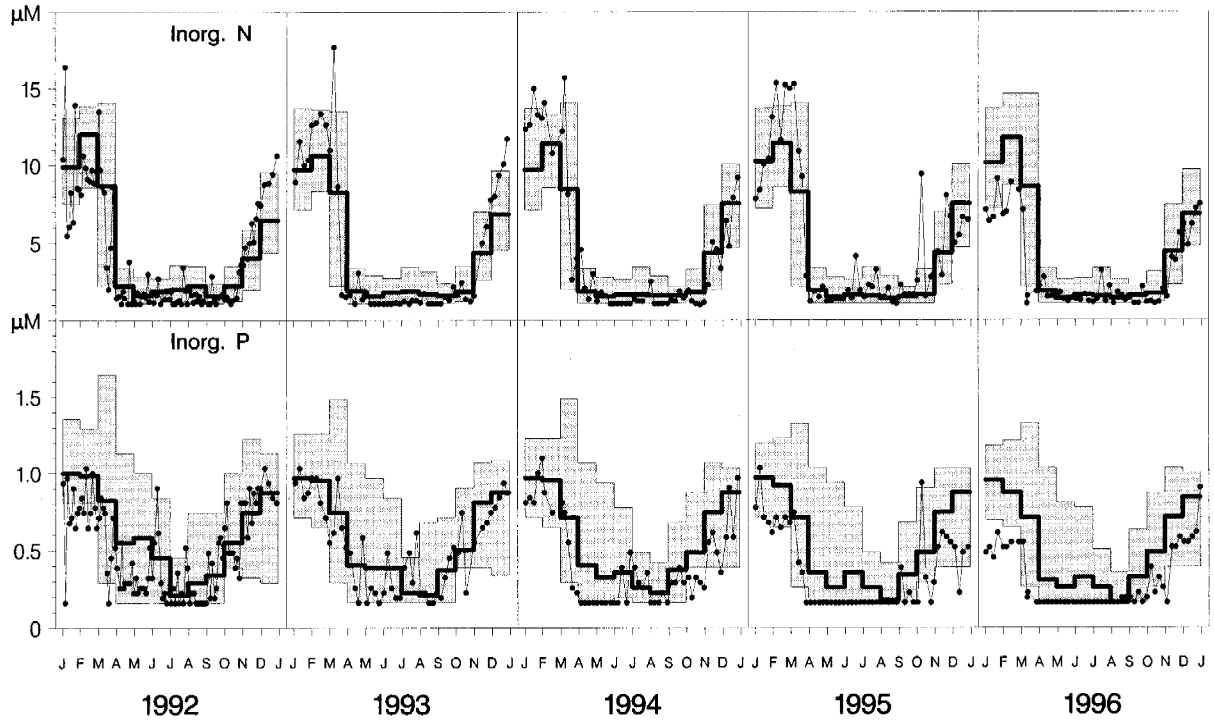

Figure 7. Seasonal variation of DIN (*upper*) and DIP concentrations (*lower*) in the surface waters of STB53, the Great Belt, during 1992–96. Points are single measurements (detection limits: 1.1 μM for N and 0.16 μM for P). The long-term monthly median (thick line) with 10%- and 90%-percentiles (grey), from 1988 to the respective year, are shown for comparison.

(<10 m) is generally known to change the balance among autotrophic components from dominance of perennial macroalgae and seagrasses toward dominance of ephemeral macroalgae and pelagic microalgae (Borum, 1996; Bonsdorff et al., 1997). Depth limits of eelgrass (*Zostera marina*) growth are closely related to transparency of the water column (Moore et al., 1996; Olesen, 1996). In shallow Danish coastal areas, where total nutrient concentration, phytoplankton biomass and light attenuation in the water column correlate, the lower depth limit of perennial macrophytes is a function of the total nutrient concentration (Borum, 1996) and hence, a function of summer concentrations of total nitrogen in coastal waters with primarily nitrogen limitation af phytoplankton production (Sand-Jensen et al., 1994). Reductions in depth limits and biomass of eelgrass beds following nutrient enrichment and increased turbidity have been registered in several coastal areas, e.g. the Dutch Wadden Sea (De Jonge et al., 1996). In many Danish estuarine areas and fjords, the depth limit of eelgrass has declined from around 5 m at the turn of the century (Ostenfeld, 1908) to around 2.5 m at present, i.e. a very substantial reduction in the areal coverage of eelgrass (Fyns Amt, 1991; Borum, 1996). Ephemeral macroalgae forming drifting algal mats, e.g. *Ulva lactuca, Ectocarpus siliculosus* and *Cladophora* spp., pose an increasing problem in many coastal regions, like the Baltic Sea (Bonsdorff et al., 1997) and the coastal waters around Funen (Fyns Amt, 1991), primarily due to their ability to benefit from high ambient nutrient concentrations (Pedersen & Borum, 1996).

In summer 1996, the low nutrient concentrations and the improved transparency of the water column in the coastal waters of Funen resulted in improved depth distribution of seed-germinated eelgrass, e.g. down to 7.5 m depth in the shallow parts af the South Funen Archipelago compared to a normal depth limit of about 6 m (1979–95). At several 2–4 m deep sites in the same area, where eelgrass had disappeared (1994-observations), primarily due to summer anoxia and accompanying sulfide release, a prominent recolonization of eelgrass took place (Fyns Amt, 1997a). Similar extensions of the depth limit of eelgrass were observed in many other Danish coastal waters (Jensen et al., 1997).

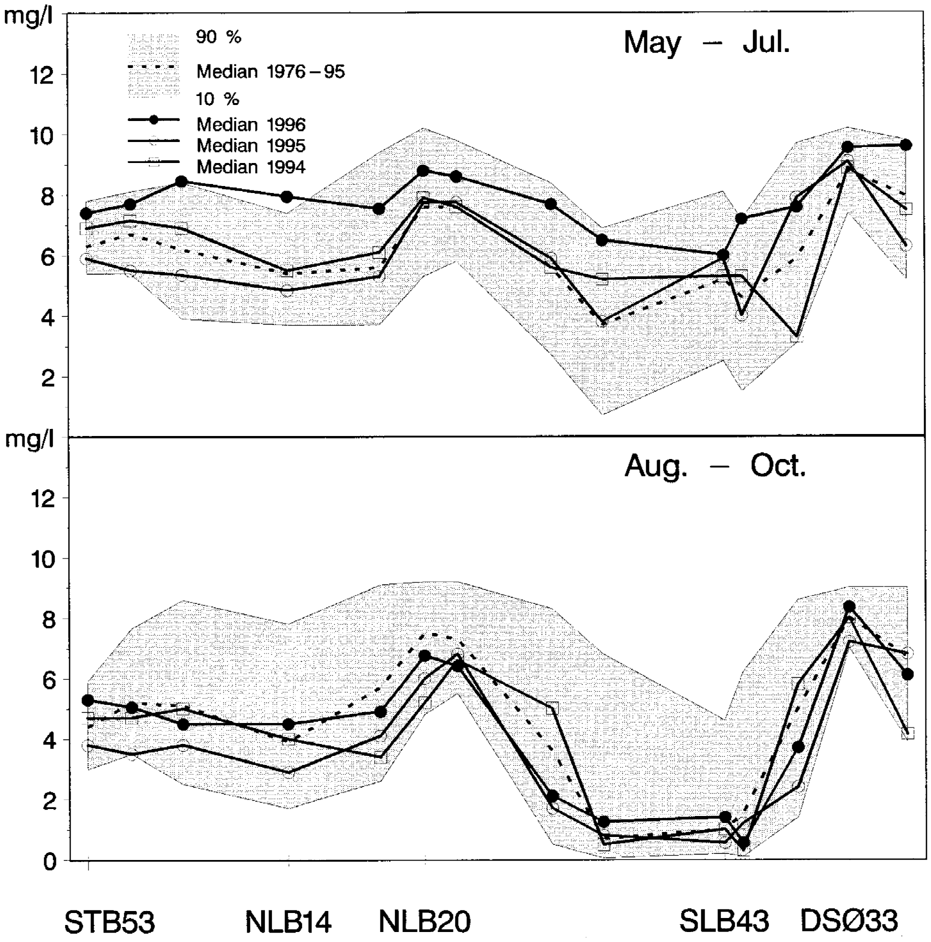

Figure 8. Median oxygen concentration in the bottom water of the 14 monitoring stations around Funen during early (May–July, *upper*) and late summer (Aug.–Oct., *lower*) in 1994, 1995 and 1996 (*n*=6–12 for each data point). For comparison, the long-term (1976–95) median level (stippled line) with 10%- and 90%-percentiles (grey) is also shown.

Oxygen content in bottom waters

Besides the sudden and large input of labile organic matter to the seafloor following sedimentation of a spring phytoplankton bloom, organic sedimentation continues throughout summer at a relatively constant level (Jensen et al., 1990; Richardson, 1996a). The coupling to oxygen conditions in the bottom water, however, may not be simple, as water column carbon flow is influenced by a multitude of interlinked factors (Kiørboe, 1996). Nonetheless, the correlation between the last 30 years of decreasing oxygen concentrations and increasing primary production rates in Kattegat bottom and surface waters, respectively, points to a likely causal link between the two trends (cf. Richardson, 1996b). This long-term evidence of the link between hypoxia and local primary production was recently supported in the short-term by experimental evidence from the Kattegat, (Richardson, 1996a). Therefore, it seems plausible that the all-round improvement of oxygen conditions in the bottom waters around Funen during summer 1996 (Figure 8, *upper*) is a direct result of the lower phytoplankton production and biomass in the surface waters (Figure 6), as the hydrographic regime was close to normal (Ærtebjerg, 1996). Thus, the bottom water oxygen content at all coastal stations around Funen was higher than normal in late spring and summer (May–July), i.e. about 1–3 mg O_2 l^{-1} higher than the long-term (1976–95) median and at or near the 90% percentile (Figure 8, *upper*).

The improved oxygen conditions in spring and summer did not continue into late summer, where hydrographic events might be especially critical for development of hypoxia and anoxia. In late summer, unusually warm and calm weather in combination with a strong outflow of low-saline Baltic water stabilized and lowered the halocline, thus reducing the volume of the bottom water layer, and oxygen deficit developed in various areas (Figure 8, *lower*). The oxygen depletion was most pronounced (<1 mg O_2 l^{-1}) in the main sedimentation basins of the southern Little Belt and the South Funen Archipelago. However, the duration and strength of the late-summer oxygen deficits were less severe compared to previous years in the coastal waters around Funen (Fyns Amt, 1997a) as well as in adjacent open areas of the Kattegat and the Great Belt (Ærtebjerg, 1996).

In a comparative study of four eutrophicated North Atlantic estuarine systems, De Jonge et al. (1994) concluded that whereas the onset of oxygen depletion is determined by hydrographical events (i.e. stratification of the water column), the increased nutrient loads and subsequent increased organic matter production are responsible for the extended duration and areal extension of the oxygen depletion. The present study suggests that actual reductions in nutrient loads to coastal systems can have an immediate, positive impact on oxygen conditions in the bottom waters.

An important point, however, is that the reduction in nitrogen run-off is not permanently achieved. High precipitation in the future may again lead to elevated levels of dissolved inorganic nutrients, especially nitrogen, and primary production in the coastal environment and hence, to the unfortunate events of pronounced oxygen deficit in the bottom waters around Funen.

It is concluded, however, that positive effects, such as presented here, can be achieved within a year in near-coastal, but relatively open, waters when both nitrogen as well as phosphorus input are substantially reduced. The benefits within a short time horizon of realizing the objectives of the Danish Action Plan as well as the internationally agreed Ministerial Declarations of reductions in the nutrient loading of the coastal waters are thus illustrated and emphasized by this natural ‘experiment.’

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