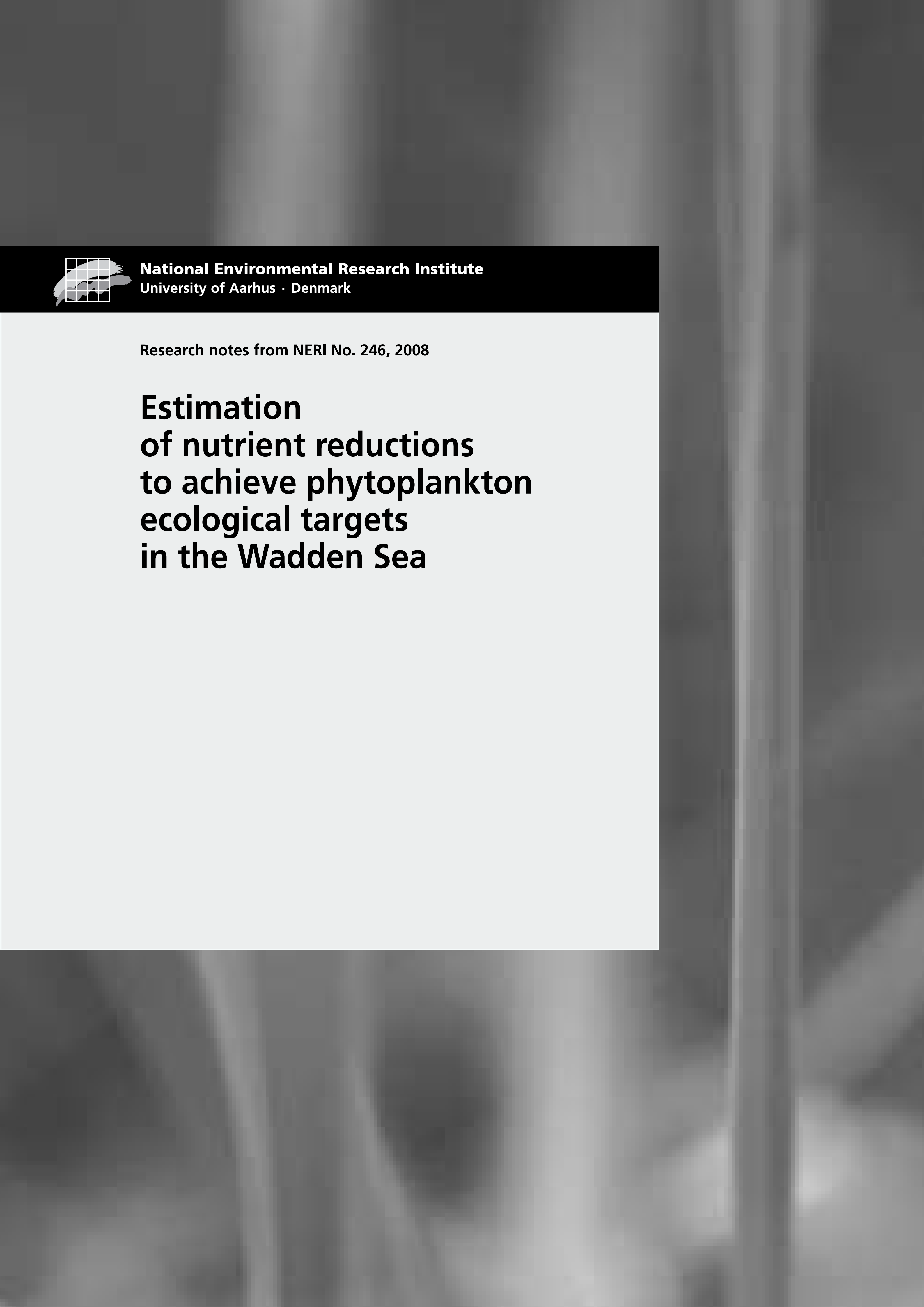

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Research notes from NERI No. 246, 2008

Estimation of nutrient reductions to achieve phytoplankton ecological targets in the Wadden Sea

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Estimation of nutrient reductions to achieve phytoplankton ecological targets in the Wadden Sea

Jacob Carstensen

Data sheet

Series title and no.: Research Notes from NERI no. 246

Title: Estimation of nutrient reductions to achieve phytoplankton ecological targets in the Wadden Sea

Authors: Jacob Carstensen
Department: Department of Marine Ecology

Publisher: National Environmental Research Institute ©
University of Aarhus - Denmark
URL: http://www.neri.dk

Year of publication: September 2008
Editing completed: August 2008

Referees: Peter Henriksen

Financial support: Environment Centre Ribe (Miljøcenter Ribe)

Please cite as: Carstensen, J. 2008: Estimation of nutrient reductions to achieve phytoplankton ecological targets in the Wadden Sea. National Environmental Research Institute, University of Aarhus, Denmark. 28 pp. - Research Notes from NERI no. 246.
http://www.dmu.dk/Pub/AR246.pdf

Abstract: Environmental targets for the WFD biological element phytoplankton have been set for the North Sea through the intercalibration process. The 90-percentile of the chlorophyll distribution has been selected as the indicator and in this report nitrogen inputs from local sources and the Elbe River have been linked to total nitrogen concentrations, which have subsequently been linked to the suggested indicator. Scenarios for nitrogen reductions from both types of sources have been calculated to assess if the proposed target values for good ecological status can be fulfilled. The results suggest that this is not possible, even if inputs from local sources are removed entirely. The proposed ecological target value that has been selected for a general value for the entire North Sea, does not apply to the Wadden Sea that has naturally elevated chlorophyll levels.

Keywords: Chlorophyll, ecological status, indicator precision, nitrogen inputs, Water Framework Directive

Layout: Anne van Acker

ISSN (electronic): 1399-9346

Number of pages: 28

Internet version: The report is available in electronic format (pdf) at NERI's website
http://www.dmu.dk/Pub/AR246.pdf

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Summary

The European Water Framework Directive aims at establishing good ecological status in all European waters by 2015. The objective of the intercalibration process is to harmonise ecological target setting between countries sharing similar water types. In the North East Atlantic Geographical Intercalibration Group, the 90-percentile of the chlorophyll *a* concentration (March-September) was chosen as the indicator for the biological element phytoplankton. A value of 7.5 µg l^{-1} has been selected as the boundary between good and moderate ecological status for the Danish Wadden Sea. The objective of this report is to assess if this target value is met with the present input of nitrogen and if not fulfilled, calculate the required reductions from local sources considering projected future reductions from the Elbe River. In 2001-2006 the 90-percentile of the chlorophyll *a* distribution was above 15 µg l^{-1} for the three different deeps comprising the Danish part of the Wadden Sea. Clearly, good ecological status is not achieved at present.

In this report, cause-effect relationships have been established between nitrogen inputs from local sources and the Elbe River to total nitrogen concentrations in the outer and inner Wadden Sea. The cause-effect relationships were supplemented by relationships between total nitrogen concentrations and chlorophyll *a* (means and 90-percentile). From these relationships scenarios for nutrient reductions from local sources (land and direct atmospheric deposition) were calculated and combined with scenarios for reduced nitrogen inputs from the Elbe River. Even for the largest considered reductions of nitrogen inputs, including a complete removal of local sources to the three sub-areas of the Wadden Sea, it is unlikely to achieve good ecological status. This suggests that the proposed target value for good ecological status from the intercalibration process cannot be applied to the Danish Wadden Sea.

Sammenfatning

Det europæiske vandrammedirektiv har som mål at etablere god økologisk tilstand i alt overfladevand i Europa senest i 2015. Formålet med interkalibreringsprocessen er at harmonisere de økologiske miljømål mellem medlemslande, som har vandområder med sammenfaldende typologi. I den nordatlantiske geografiske interkalibreringsgruppe (NEA GIG) er 90% percentilen for klorofyl *a* (marts-september) udvalgt som indikator for det biologiske element fytoplankton. Der er fastlagt en værdi for denne indikator på 7,5 µg l^{-1} som grænsen mellem god og moderat økologisk tilstand i den danske del af Vadehavet. Formålet med denne rapport er at vurdere, om dette miljømål kan opfyldes med de nuværende tilførsler af kvælstof eller om der skal foretages yderligere reduktioner, både fra lokale kilder til vadehavet og fra Elben. I perioden 2001-2006 er 90% percentilen over 15 µg l^{-1} for alle de 3 dyb i vadehavet, beregnet ud fra overvågningsdata med målte klorofyl *a* niveauer. Miljømålet for fytoplankton er derfor ikke opfyldt på nuværende tidspunkt.

Relationer mellem koncentrationer af total kvælstof som funktion af tilførsler fra både lokale kilder, direkte atmosfærisk deposition og Elben er etableret i denne rapport for både det ydre og indre Vadehav. Disse relationer er koblet til relationer mellem total kvælstof og klorofyl (90% percentilen). På basis af disse kombinerede relationer er effekten af reducerede kvælstoftilførsler, fra både lokale kilder og Elben, beregnet for den valgte indikator. Det fastlagte miljømål for god økologisk tilstand kan sandsynligvis ikke opfyldes for nogen af de 3 Vadehavsdyb, selv med de mest drastiske reduktioner i kvælstoftilførslen, hvilket indbefatter en total afskæring af tilførslen fra lokale kilder. Dette betyder, at det fra interkalibreringsprocessen foreslåede miljømål for god økologisk tilstand formentlig ikke er velegnet til den danske del af Vadehavet.

1 Introduction

This report is a contribution to the implementation of the European Water Framework Directive in the Wadden Sea. The work was initiated and financed by the Environment Centre Ribe (MC Ribe).

The WFD aims to achieve at least a good ecological status in all European rivers, lakes and coastal waters and demands that the ecological status is quantified based primarily on biological indicators, i.e. phytoplankton, benthic flora and fauna as well as fish. The WFD demands an evaluation of which water bodies are at risk of failing to meet good ecological status in 2015.

During the WFD intercalibration process, indicators of ecological quality elements and boundaries for good and moderate ecological status have been harmonised in geographical intercalibration groups (GIGs). The Wadden Sea was appointed as intercalibration site for the North East Atlantic GIG (NEA GIG). The outcome of the intercalibration in the NEA GIG was the selection of the 90-percentile from chlorophyll *a* concentrations (March-September) as indicator of phytoplankton biomass, and for the Danish part of the Wadden Sea the boundary between good and moderate ecological status was defined as 7.5 µg l^{-1} using this indicator.

The aim of this project is to determine:

- If present levels of chlorophyll *a* meet the requirements of good ecological status.

- If additional nitrogen reductions from local land-based sources are required to achieve good ecological status, taking into account that nitrogen inputs from the Elbe River are projected to decrease in the future.

The report is divided into three core chapters describing the cause-effect relationships from nutrient inputs to chlorophyll *a* levels. Based on this compound model expected values of the 90-percentile indicator were calculated for scenarios for nutrient inputs from local sources combined with three different scenarios of nutrient inputs from the Elbe River: 1) present state of 90,000 tons N yr^{-1}, 2) a reduction of 7.2% by 2015 corresponding to 83,520 tons N yr^{-1}, and 3) a target input of 70,000 tons N yr^{-1} to be achieved by 2027. For these scenarios it is assessed if the ecological target of 7.5 µg l^{-1} can be met within the ranges of these scenarios.

2 Nutrient inputs from land and atmosphere

In the present study, nutrient inputs to the Wadden Sea area included total nitrogen only, because nitrogen is considered the main limiting nutrient for primary production in the Wadden Sea.

2.1 Atmospheric deposition of nitrogen

Data on atmospheric deposition of nitrogen have been provided by MC Ribe as annual values to Grådyb (1996, 1998-2006), Knude Dyb (1998-2006), Juvre Dyb (1989-2006) and Lister Dyb (1989-2006). Atmospheric deposition to the Wadden Sea is largely dominated by long-distance transports and therefore annual deposition values are assumed to follow the same overall trend. There were not data for all years from Grådyb and Knude Dyb, and therefore annual values for missing years were estimated by 1) estimating the relative deposition of these two areas to the average deposition in Juvre Dyb and Lister Dyb (1998-2006), and 2) multiply this relative deposition to the average deposition in Juvre Dyb and Lister Dyb (1989-1997). With the exception of 1989 and partly 1990 there has been a decreasing trend in nitrogen deposition rates (*Figure 2.1*). For monthly apportionment annual values were equally divided over all months.

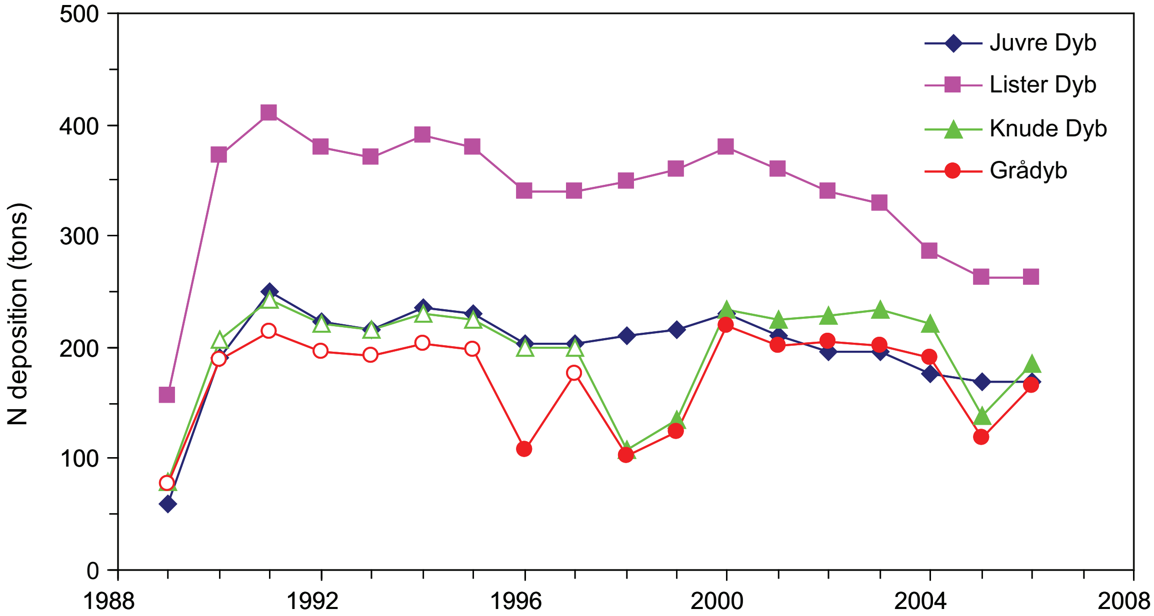

Figure 2.1 Atmospheric deposition to four sub-areas of the Danish part of the Wadden Sea. Depositions estimated as relative values following the approach above are marked with open symbols.

2.2 Local nitrogen inputs from land

Nitrogen inputs were provided by MC Ribe as monthly values to Grådyb (1987-2006), Knude Dyb (1987-2006), Juvre Dyb (1990-2006) and Lister Dyb (1990-2006). Nitrogen inputs to Juvre Dyb and Lister Dyb included the atmospheric deposition, which was consequently subtracted to produce comparable values of land-based inputs of total nitrogen. Annual nitrogen inputs were generally decreasing over the entire period with strong interannual variations following variations in freshwater discharge patterns (*Figure 2.2*).

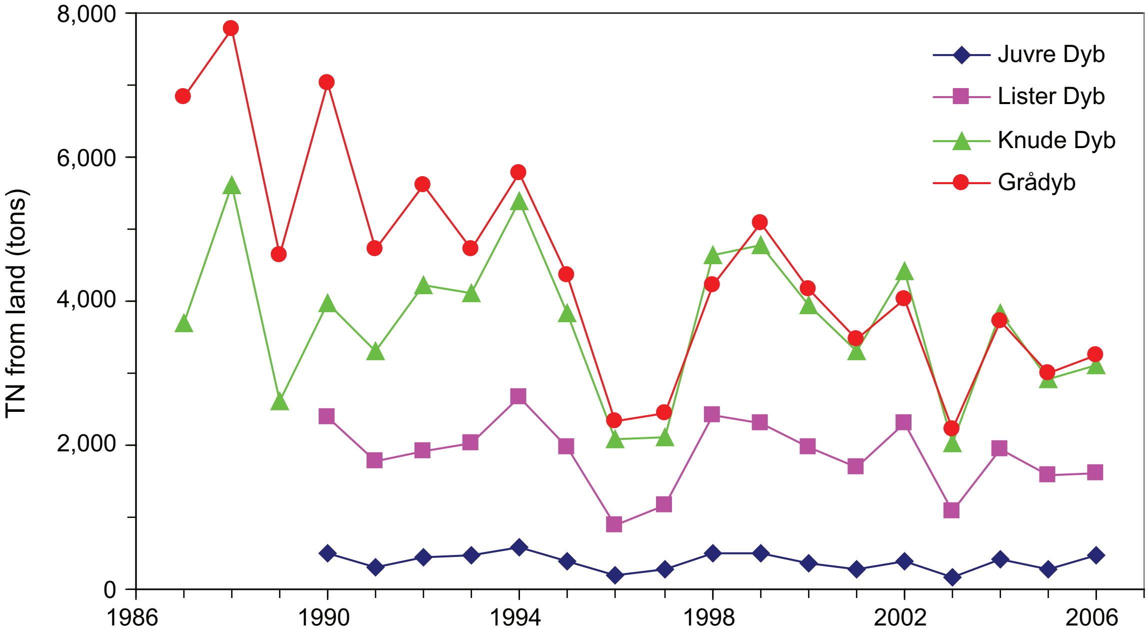

Figure 2.2 Annual inputs of total nitrogen from watersheds to the four sub-areas in the Danish part of the Wadden Sea.

2.3 Inputs from the Elbe River to the outer Wadden Sea

Annual nutrient inputs (1978-2006) and daily freshwater discharges (1874-2006) from the Elbe River, the largest contributor of many rivers to the south-eastern North Sea, were provided by ARGE ELBE. Freshwater inputs were from the gauge at Neu Darchau, which is upstream the tidal influence but does not include the entire watershed. The mean freshwater discharge at this gauge was 22.45 $km^3 yr^{-1}$ (1978-2006). Nutrient discharges were estimated at Hamburg-Seemannshöft, which is downstream of Hamburg and includes a considerable point source contribution. Estimated proportions of point sources to total emission sources from the working group HELCOM LAND of 34%, 37%, and 39% for the years 1985, 1995 and 1999, respectively, were used to estimate the total input from point sources in these years. In between these years, the point source contribution was linearly interpolated and assumed constant after 1999. The contribution from diffuse sources was high in the 1980s, but declined rapidly around 1990 (*Figure 2.3*) following the breakdown of Eastern European economies (*Hussian et al. 2004*).

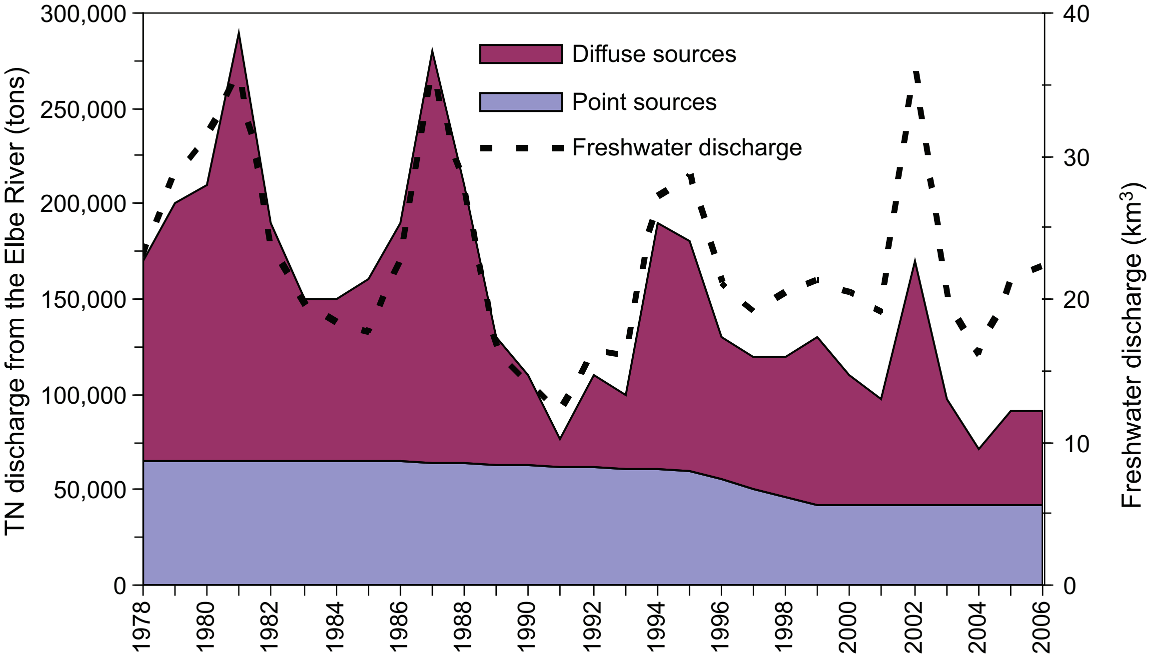

Figure 2.3 Annual discharges of freshwater and total nitrogen from the Elbe River, partitioned into diffuse and point sources. Freshwater discharges were measured at Neu Darchau (river km 536) and nutrient inputs were measured at Hamburg Seemannshöft (river km 629). Data provided by ARGE ELBE.

Annual TN discharge values were partitioned into monthly values assuming point sources equally distributed over months and diffuse sources distributed according to the freshwater discharge of the month. This procedure resulted in high TN discharge values from January to April and lower TN discharges in June through October (down to 50% of the winter-spring values). This procedure might produce biased data, since TN concentrations can vary with season.

3 Total nitrogen levels in the Wadden Sea in response to inputs from land and atmosphere

Hydrochemistry measurements from stations in the Wadden Sea and along the North Sea and Skagerrak coast (*Figure 3.1*) were extracted from the national database hosted at NERI (mads.dmu.dk). Data from 2007, not yet available in the national database, were provided as Excel files from MC Ribe.

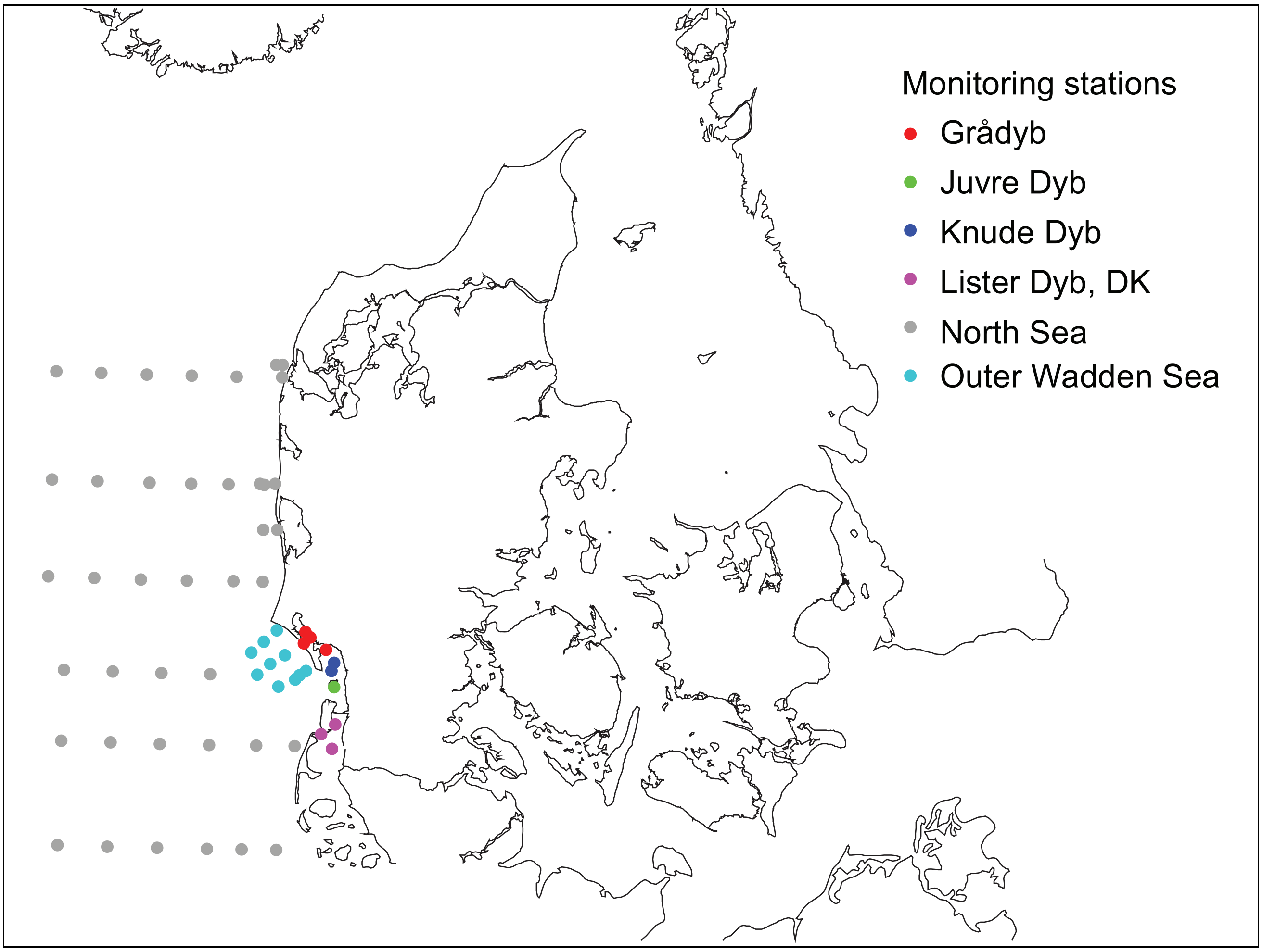

Figure 3.1 Stations divided into areas used in the present analysis.

In the Wadden Sea subareas monitoring stations were further sub-divided into inner and outer parts as listed in *Table 3.1*. For those areas represented by 2 stations, the mean of these stations will represent the area. These subdivisions are used for both TN and chlorophyll *a*.

Table 3.1 The 4 areas comprising the Danish part of the Wadden Sea subdivided into inner and outer parts with the monitoring stations used to characterise the different areas.

Wadden Sea area	Sub-division	Monitoring stations
Grådyb	Inner	1610002, 1610011
	Outer	1510022, 1610001
Knude Dyb	Inner	1620012
	Outer	1620014
Juvre Dyb	Inner	1630016
Lister Dyb	Inner DE	SJY2
	Inner DK	SJY3
	Outer	SJY1

3.1 Conceptual model for TN

Total nitrogen in marine waters, as opposed to inorganic nitrogen, is a relatively stable measurement variable that is governed by mixing processes of different water masses, sources (atmospheric deposition and nitrogen fixing), and sinks (denitrification and burial). In the Wadden Sea mixing is the most important mechanism for determining TN concentrations, and the magnitude of sources and sinks are assumed constant relative to the large interannual variations in nitrogen inputs from freshwater sources. The concept behind the relationships established in this section is shown in *Figure 3.2*.

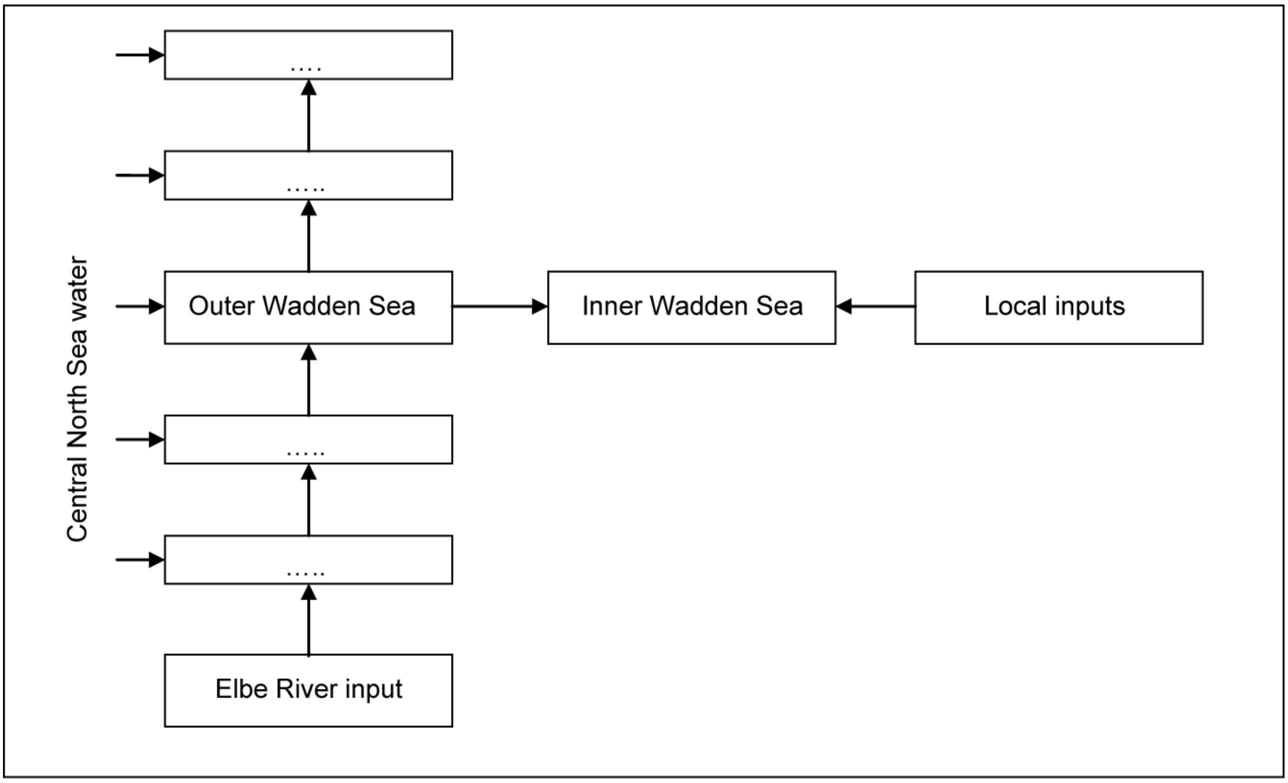

Figure 3.2 Conceptual model depicting the main sources affecting TN concentrations in the Wadden Sea. The outer Wadden Sea is influenced by discharges from the Elbe River mixed with central North Sea water, whereas TN concentrations in the inner Wadden Sea is determined from mixing of outer Wadden Sea water with local inputs.

TN concentration in the outer Wadden Sea was determined from mixing discharges from the Elbe River with central North Sea water, characterised by a constant TN level and a salinity of 35. Small local inputs, including the inner Wadden Sea, are assumed negligible for TN levels in the outer Wadden Sea compared to the large input from the Elbe River. Similarly, TN concentrations in the inner Wadden Sea were determined from mixing local nutrient inputs with concentrations in the outer Wadden Sea. Salinity is used as conservative tracer for the different water masses.

3.2 TN relationships for outer Wadden Sea

Distinctive gradients (both north-south and east-west) in salinity and nutrient concentrations characterise the outer Wadden Sea and the North Sea in general, and any analysis of data from this area must take variations in salinity into account. Salinity levels typically range from 28 to 35 over the entire study area and between 30 and 33 for the outer Wadden Sea. TN concentrations typically range from 10 to 100 µmol l^{-1} for the North Sea area and from 15 to 100 µmol l^{-1} in the outer Wadden Sea (*Figure 3.1*). In simple terms, the TN concentration in the outer Wadden Sea is determined from mixing of central North Sea water (salinity ~35) and inputs from the Elbe River. The TN concentration in the central North Sea is assumed constant (µ), whereas the TN gradient with respect to salinity varies between years and between months.

$$TN_{ij}=\mu+month_i\times(salinity_{ij}-35)+year_j\times(salinity_{ij}-35) \qquad (3.1)$$

This approach is the same as in *Carstensen et al. (2008)* applied to years from 1990 to 2006 using the first 6 months of the year only. Month-specific gradients with respect to salinity were similar to those in *Carstensen et al. (2008)* whereas year-specific gradients extrapolated to zero salinity were compared to flow-weighted concentrations, i.e. total nitrogen discharge divided by freshwater discharge from the Elbe River (*Figure 3.3*). This analysis shows that there was good correspondence between yearly gradients and TN concentrations discharged from the Elbe River. Only 1996 seems to deviate from the overall pattern, and 1996 was exceptional in the sense that extremely low concentrations were measured along the west coast (see also *Carstensen et al. 2008*).

Both the month-specific salinity gradients ($p < 0.0001$) and the year-specific salinity gradients ($p < 0.0001$) were highly significant, with the strongest seasonal gradients for January-March and slowly decreasing yearly gradients from 1990 to 2006, as indicated by decreasing intercepts for zero salinity (*Figure 3.3*). The constant TN concentration at salinity 35 was estimated to be 13.46 (±0.67) µmol l^{-1}. The model for TN explained $R^2 = 78.3\%$ of the total variation.

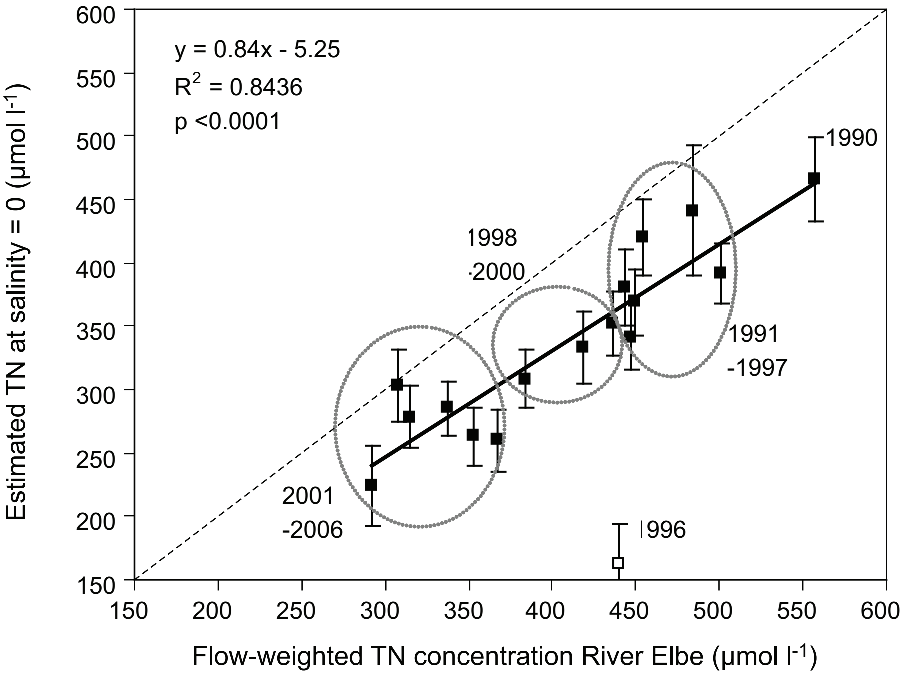

Figure 3.3 Annual flow-weighted TN concentrations in the Elbe River compared to estimated TN concentrations based on the salinity-TN regression model. Data from 1996 were not included in the regression.

The model gives confidence in establishing a relationship linking nitrogen discharge directly to TN concentrations in the outer Wadden Sea. This model is achieved by formulating the slope in (*3.1*) directly as a function of flow-weighted concentrations ($TN_{Elbe}=TN/Q$).

$$TN_{ij}=\mu+month_i\times(salinity_{ij}-35)+(TN_{Elbe}-13.46)/35\times(salinity_{ij}-35) \qquad (3.2)$$

Annual flow-weighted concentrations were used, since they resulted in a better model than flow-weighted concentrations for the first 6 months obtained by the monthly apportionment described in Section 2. The reason for this is most likely that the suggested monthly apportionment is too simple giving higher TN concentrations in summer and autumn than winter and spring. The month-specific salinity gradient and the TN_{Elbe}-specific gradients were highly significant (both $p <0.0001$), and the model explained R^2 = 73.4% of the total variation, however with 15 degrees of freedom (parameters) less than in (*3.1*).

Yearly TN mean levels (January-June) using (*3.1*) and 3 scenarios for reduced TN discharge from the Elbe River using (*3.2*) were predicted for an average salinity of 31.86 for the outer Wadden Sea (*Figure 3.4*). It is observed that TN concentrations when adjusted for variations in salinity have decreased continuously from 1990 to 2006, noting that 1996 was an exceptional year for the monitoring data. The 3 scenarios show that reduced nitrogen input from the Elbe River will result in TN levels (January-June) around 30 µmol l^{-1} (S1: 33.24 (±0.68) µmol l^{-1}, S2: 31.90 (±0.76) µmol l^{-1}, S3: 29.11 (±0.96) µmol l^{-1}).

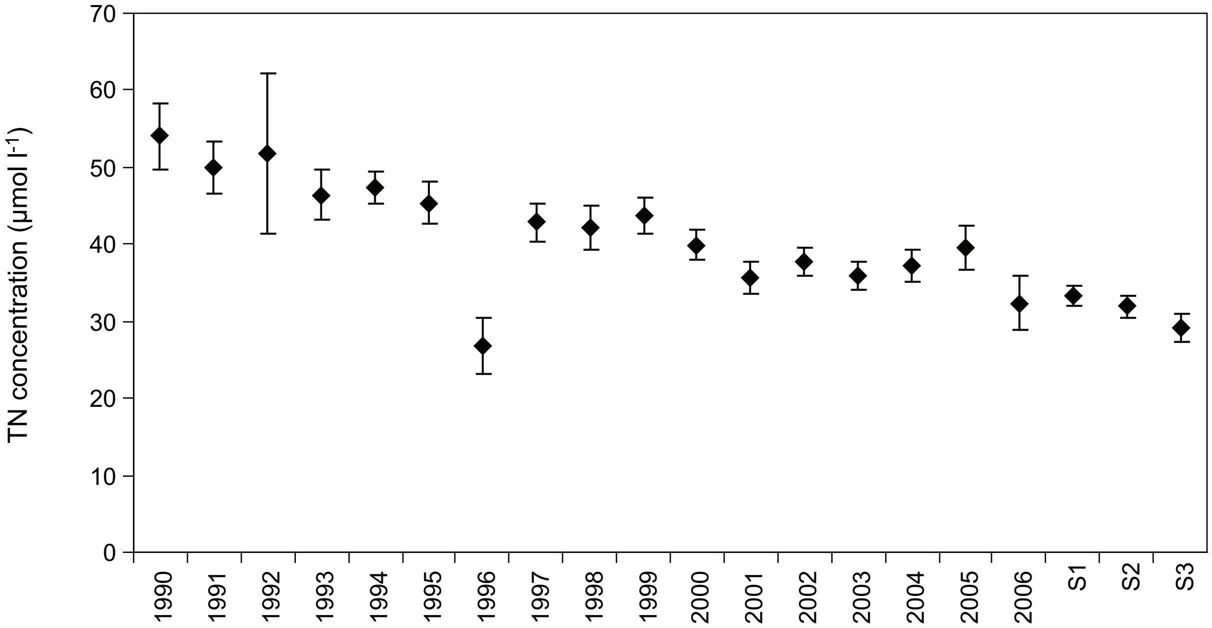

Figure 3.4 Yearly mean levels (January-June) for TN in the outer Wadden Sea for an average salinity of 31.86 compared to 3 scenarios for TN discharges from the Elbe River (S1 = 90,000 tons, S2 = 83,520 tons, S3 = 70,000 tons for an average flow year of 22.45 km^3).

3.3 TN relationships for the inner Wadden Sea

Winter and spring mean levels for TN (January-June) were calculated using a model taking seasonal, interannual, station-specific and salinity-specific variations into account after log-transforming TN using the following regression model:

Log(TN) = area station(area) month month×sali year year(area) (*3.3*)

Marginal means for year(area), i.e. area-specific yearly TN means, were calculated from the model and backtransformed to geometric means using the exponential function.

The longest time series were obtained for Grådyb and Lister Dyb, both areas showing declines in TN concentrations, also in the most recent years when TN levels were adjusted for variations in TN concentrations obtained from the outer Wadden Sea (*Figure 3.4*). TN levels in the inner Wadden Sea were typically 10-40 µmol l^{-1} higher than in the outer Wadden Sea.

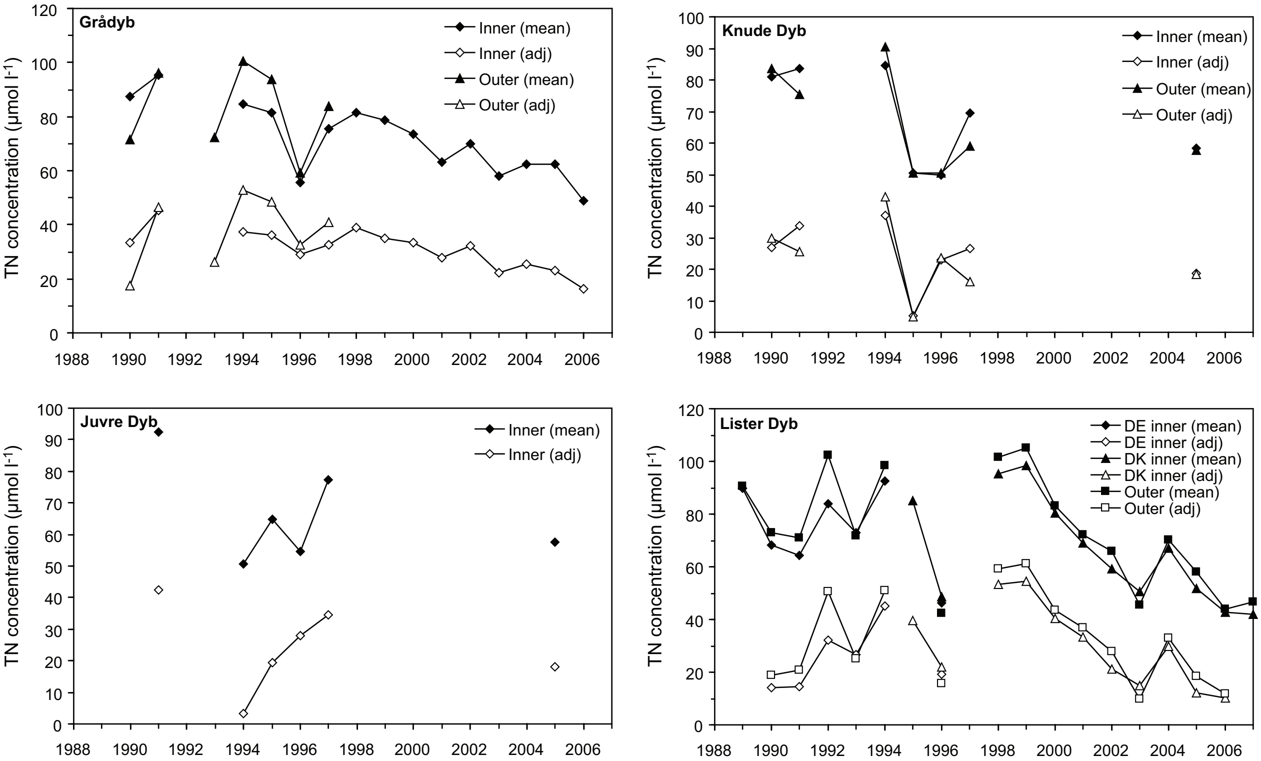

Figure 3.5 Annual mean TN levels in the different subareas of the Danish part of the Wadden Sea. Adjusted mean levels were calculated as area-specific means minus the mean TN level from the outer Wadden Sea (see *Figure 3.4*).

It was assumed that elevated TN concentrations were linked proportionally (no intercept) to local total inputs of nitrogen (i.e. both atmospheric inputs (*Figure 2.1*) and land-based inputs (*Figure 2.2*)), since it was necessary to constrain these regressions due to limited number of annual values. It was not possible to separate the effect on TN concentrations from the two sources of nitrogen, land and atmosphere. The underlying assumption of proportionality is that the internal inputs of nitrogen from the sediments follow the same trends as the external inputs, although it should be acknowledged that there can be a delayed response.

This assumption seemed justified from the annual values for at least 3 of the 4 subareas in the inner Wadden Sea (*Figure 3.6*). The only exception is Juvre Dyb, which is influenced by relatively small local inputs of nitrogen and a limited number of annual values. Moreover, Juvre Dyb had a regression coefficient deviating substantially from the other sub-areas, which would imply a strong response to changes in nitrogen inputs. It is therefore questionable if the elevated concentrations in Juvre Dyb can be entirely attributed to local inputs from land and atmosphere. This suggests that the approach of linking TN levels to local nitrogen inputs and boundary conditions may be inappropriate for Juvre Dyb. For the 3 other sub-areas similar regressions were obtained, however, with slightly higher slopes for Lister Dyb. These higher slopes in Lister Dyb are most likely due to higher hydraulic retention times in Lister Dyb (~90 d) compared to both Grådyb and Knude Dyb (both ~13-17 d). Differences in the slopes between inner and outer parts of the sub-areas were small. For all 4 sub-areas total nitrogen input explained R^2 = 28.3% of the total variation, whereas excluding Juvre Dyb from the regression increased R^2 to 37.3%.

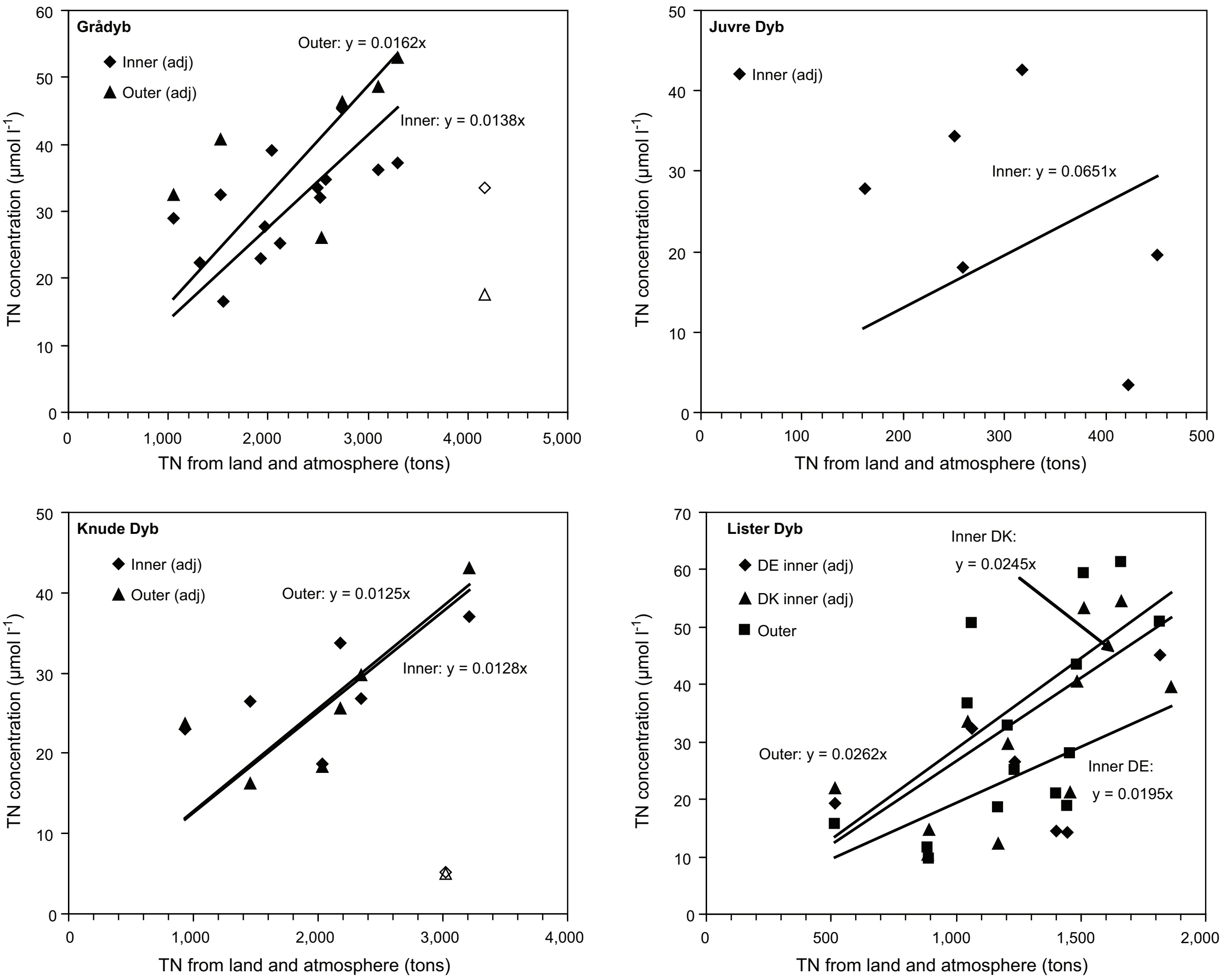

Figure 3.6 Elevated TN mean levels (January-June), i.e. TN levels in the inner Wadden Sea minus TN levels in the outer Wadden Sea, versus total input of TN from land and atmosphere. Deviating years in Grådyb (1990) and Knude Dyb (1995), marked with open symbols, were not included in the regressions.

4 Chlorophyll *a* response to changing nutrient levels in the Wadden Sea

Measurements of chlorophyll *a* in the Wadden Sea were extracted from the national database MADS (1988-2006) and supplemented with data from MC Ribe for 2007. The stations used in the analysis and division into sub-areas follow the same procedure as for TN in Section 3 (*Figure 3.1* and *Table 3.1*, respectively).

4.1 Indicators for phytoplankton biomass

Different indicators of phytoplankton biomass have been proposed in the different geographical intercalibration groups (GIG). In the Baltic GIG the mean chlorophyll *a* (May-September) has been decided, whereas the NEA GIG has decided to use the 90-percentile of chlorophyll *a* in the period from March to September. In the Baltic GIG good relationships have been established between mean levels of TN and chlorophyll *a*, whereas such relationships have not been established in NEA GIG and neither has the precision of different indicators been assessed before deciding on the appropriate indicator. In *Carstensen et al. (2008)* it was documented that mean values are the most precise indicator derived from monitoring data, and that the 90-percentile is substantially more uncertain (typically 3-5 times) for moderate sample sizes.

One potential problem of including March and April into the biomass indicator is that monitoring in these months may capture the spring bloom leading to large uncertainty in the indicators. This can be exemplified by calculating the residual variation of using (*3.3*) on log-transformed chlorophyll *a* concentrations using 1) March-September and 2) May-September. For March-September residual variation is 0.6968 (R^2 = 29.2%) and for May-September residual variation is 0.5916 (R^2 = 38.8%). Thus, a better model for chlorophyll *a* is obtained when March and April are not included. However, using seasonal means as indicators of phytoplankton biomass, the increased residual variation, when including March and April, can be compensated by the increased number of observations in these two months. This will require that observations from these two month comprise an additional 39% to the number of observations from May-September. Considering that the two periods cover 7 and 5 months, respectively, a regular sampling program will result in 40% extra observations in March and April. Thus, mean chlorophyll *a* indicators based on the two periods will have the same precision, provided that March and April contribute additional 40% observations to those from May to September. It is, however, anticipated that using the 90-percentile as indicator will be considerably more sensitive to whether the spring bloom has been captured in the monitoring data.

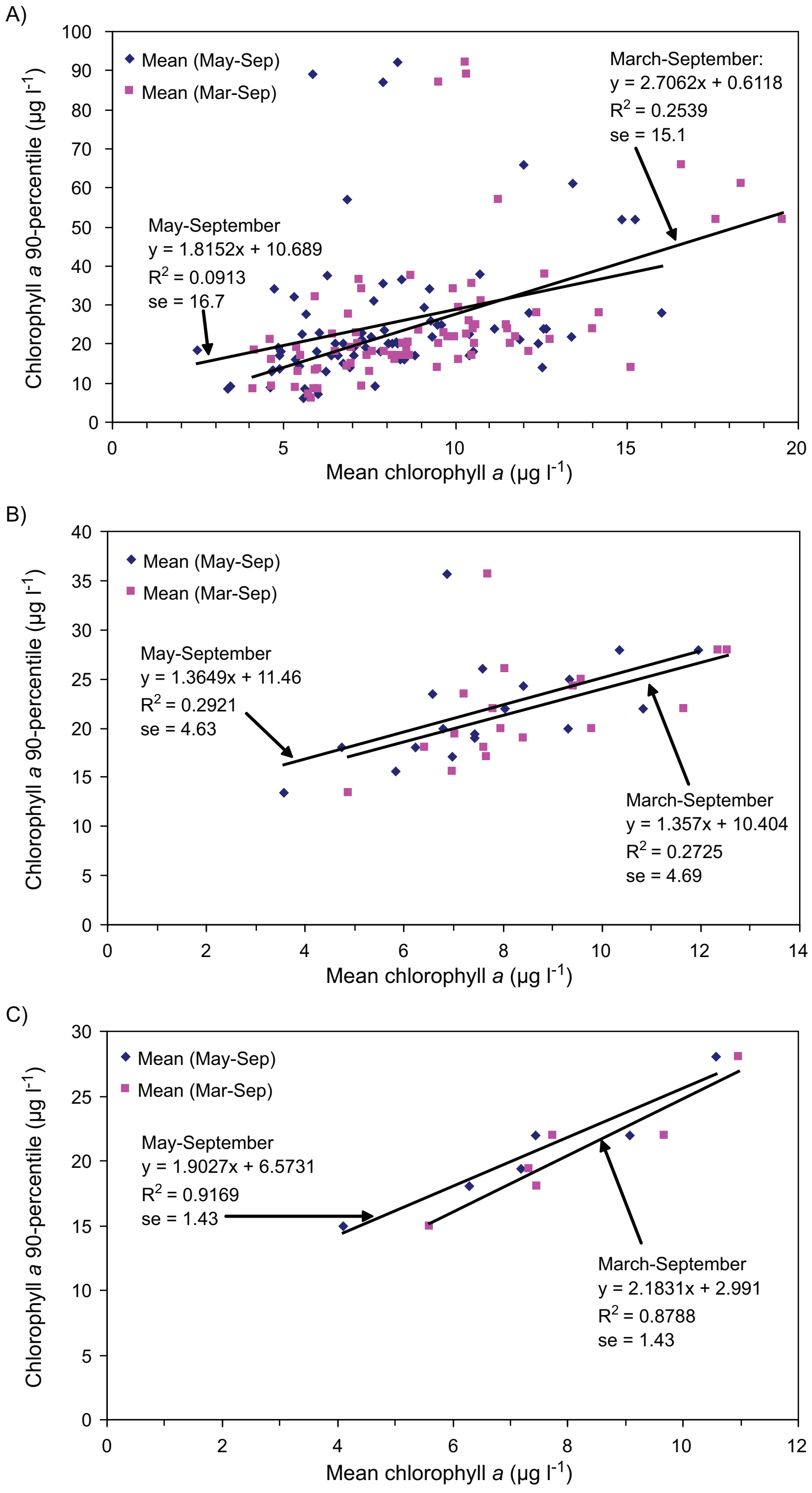

Figure 4.1 Relationships between mean chlorophyll *a* (March-September and May-September) and the 90-percentile of the chlorophyll *a* distribution for A) annual values, B) 3-year values, and C) 6-year values. The 3-year periods were 1989-1991, 1992-1994, etc, whereas the 6-year periods were 1989-1994, 1995-2000 and 2001-2006. Different sub-areas covering the same period are shown as individual observation points. Note the difference in scaling for the plots.

The indicator based on the 90-percentile of the chlorophyll *a* distribution is highly uncertain when calculated on an annual basis, typically around 10 observations for March-September in the later years. In such cases the 90-percentile is based on the two largest observations in a right-skewed distribution, and in some years the 90-percentile will be biased by the spring bloom or other atypical observations. Therefore, relationships between the 90-percentile and mean chlorophyll *a* observations were established for annual values, 3-year values and 6-year values (*Figure 4.1*). The sensitivity of the 90-percentile to extreme observations is apparent for annual values resulting in large scatter around the regression lines. This scatter is substantially reduced using 3-year values, although the period 1989-1991 did result in one clear outlier for Lister Dyb (90-percentile of 35.6 µg l^{-1} in *Figure 4.1B*). For the 6-year values this scatter, caused by extreme observations, seems to have disappeared and reliable relationships between mean values and 90-percentiles were established, as predicted from theory.

The regression lines obtained are indeed different with slopes ranging from 1.35 to 2.7, and similarly the estimated standard error of the residuals decreased from around 15-16 (annual values) to 4.6 (3-year values) to 1.43 (6-year values). This residual variation was reduced substantially more than the increased number of observations could account for (anticipated reduction for 3-year values: $\sqrt{3} \approx 1.73$; for 6-year values: $\sqrt{6} \approx 2.45$). This illustrates the problem of using the 90-percentile as indicator of phytoplankton biomass when based on a low number of monitoring observations. For ecological status assessment this indicator should be based on 6-year values to obtain the most precise indicator.

It is noteworthy that none of the 90-percentiles based on 3-year or 6-year periods were below the threshold of 7.5 µg l^{-1} for good ecological status, and only few annual values were below the threshold. In fact, if the regression lines for the 6-year values were extrapolated, the threshold of 7.5 µg l^{-1} would be reached for a mean chlorophyll *a* of 0.5 µg l^{-1} (May-September) or 2.1 µg l^{-1} (March-September).

4.2 Relationship between total nitrogen and chlorophyll *a* in the Wadden Sea

Relationships between TN concentrations and chlorophyll *a* on the log-log scale, similar to those reported in *Carstensen et al. (2008)*, were established. Better relationships were obtained using May-September for chlorophyll *a* than March-September. First, specific relationships were estimated for each sub-area to investigate if there were spatial differences in the relationships (*Figure 4.2*).

The inner sub-areas generally had higher chlorophyll *a* levels, but none of the inner sub-areas showed significant relationships to TN levels (*Figure 4.2*), suggesting that other factors than nitrogen could limit the phytoplankton biomass in these inner parts of the Wadden Sea. A plausible explanation to the relatively lower chlorophyll *a* levels in the outer parts, despite similar TN levels, is that the bio-available TN fraction is large in the inner parts and production controlled by light, but the bio-available fraction of TN decreases along the estuarine gradient causing a shift towards nitrogen limitation. Consequently, only the outer parts of the Wadden Sea areas were used for estimating the effect of TN levels on chlorophyll *a*.

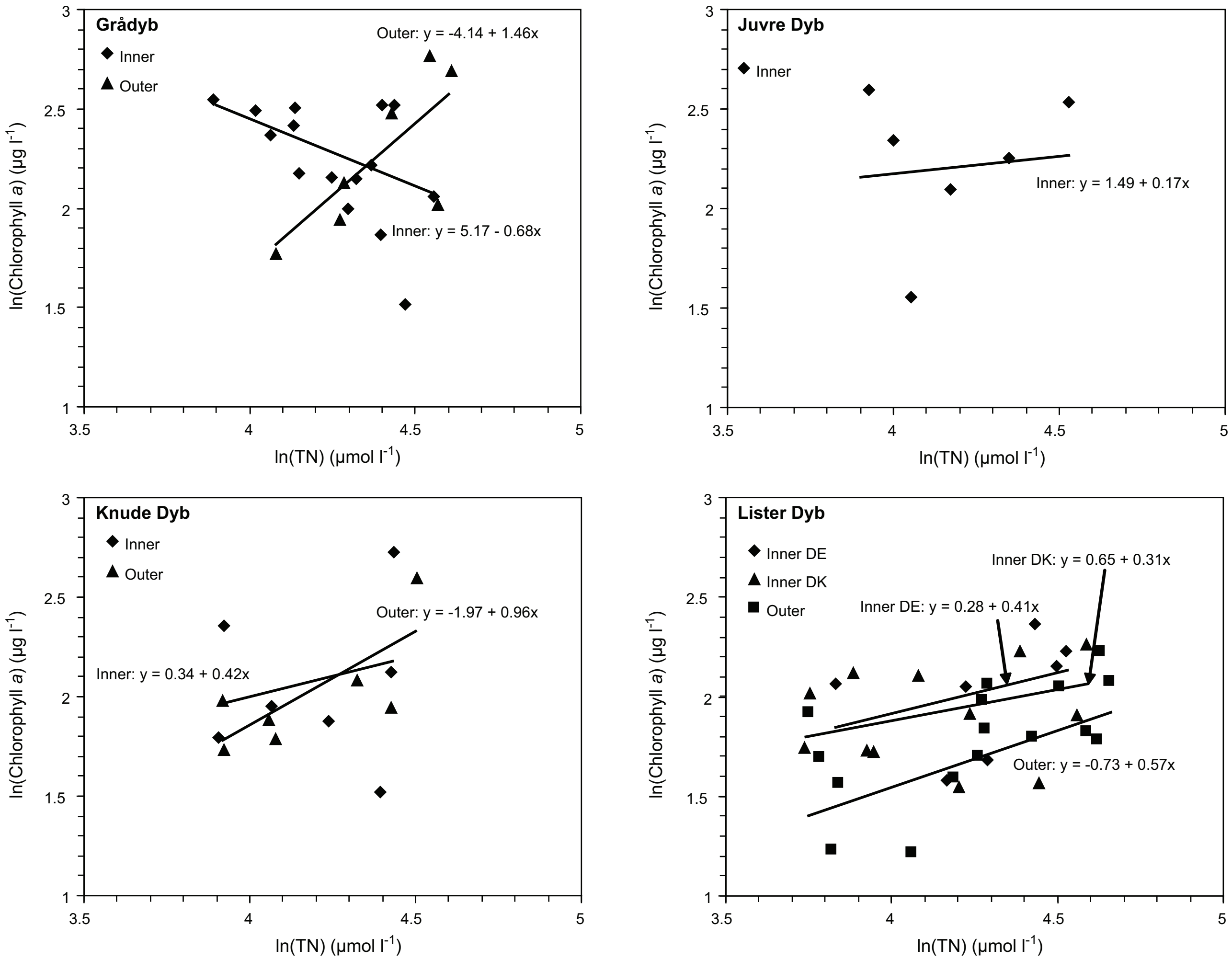

Figure 4.2 Relationships between chlorophyll *a* and TN, both ln-transformed, for each sub-area. Significant relationship was obtained for outer Lister Dyb (p = 0.0281), borderline significant relationships were obtained for outer Grådyb (p = 0.0526) and outer Knude Dyb (p = 0.0518), whereas other relationships were not significant.

Secondly, in order to obtain more robust estimates of the chlorophyll *a* to TN relationships a combined model for the 3 outer parts were formulated as:

$$\ln(chla) = site + b \cdot \ln(TN) \qquad (4.1)$$

which for the non-transformed variables corresponds to a power functional relationship as

$$\mathrm{Chla} = \mathrm{k(site)} \times \mathrm{TN}^{b} \qquad (4.2)$$

The common slope (b) was estimated as 0.67 (±0.18) and the site-specific intercepts varied from -1.16 to -0.69 on the log-scale (*Figure 4.3*), corresponding to site-specific factor in (*4.2*) ranging from 0.31 to 0.50. The lowest factor was found for Lister Dyb (0.31), which has the highest retention time, and Grådyb and Knude Dyb had similar factors (~0.45-0.50). The higher retention time in Lister Dyb allows for larger assimilation of bio-available nitrogen in the inner parts, which explain a relatively smaller fraction of TN converted into phytoplankton biomass in the outer part. The relationship (*4.1*) explained R^2 = 55% of the total variation.

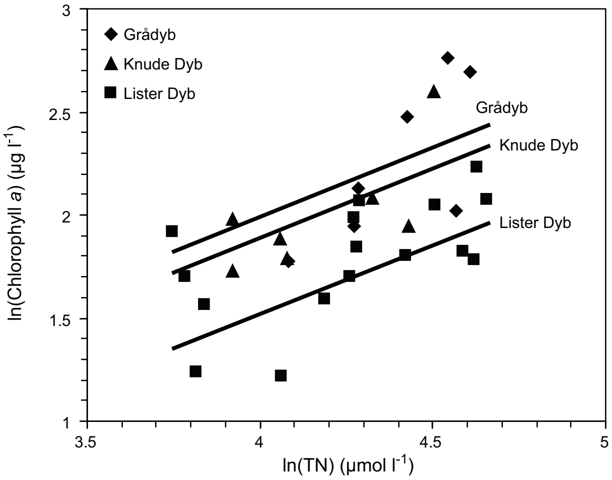

Figure 4.3 Summer chlorophyll *a* (May-September) versus winter-spring TN (January-June) with the estimated relationship having 3 site-specific intercepts (*4.1*). Both variables are ln-transformed.

5 Ecological targets for chlorophyll *a* in the Wadden Sea

In this section scenarios for nutrient reductions in the Grådyb, Knude Dyb and Lister Dyb watersheds will be addressed through 1) calculating TN winter-spring levels in the 3 sub-areas for different reduction scenarios, 2) converting these into expected changes in mean summer chlorophyll *a* concentrations and 3) translating these into 90-percentile values for assessing if the target value (7.5 µg l^{-1}) for phytoplankton biomass can be achieved with the reduction scenarios. These calculations are based on the relationships established in Sections 3 and 4. The fulfilment of the good ecological status will be addressed for outer parts of Grådyb, Knude Dyb and Lister Dyb only, since these areas were the only having significant relationships. However, it should be stressed that the inner parts of these sub-areas did have chlorophyll *a* levels comparable to the outer parts (*Figure 4.2*), and lowering nutrient inputs could lead to increased nitrogen limitation in these sub-areas.

The calculations include 3 reduction scenarios for the Elbe River (S1: 90,000 tons N yr^{-1}, S2: 83,520 tons yr^{-1}, and S3: 70,000 tons N yr^{-1}) combined with scenarios of nutrient input (January-June) to Grådyb and Knude Dyb ranging from 2000 to 0 tons N yr^{-1} and to Lister Dyb ranging from 1000 to 0 tons N yr^{-1}. These ranges for nutrient input include levels of the most recent years down to zero influence from local inputs.

5.1 Scenarios for TN concentrations

Scenarios for S1-S3 on TN levels in the outer Wadden Sea were calculated in Section 3 and these values were used as inputs to the proportional TN loading-concentration relationships for the sub-areas of the Wadden Sea (*Figure 3.6*). The scenarios suggest that TN concentrations can be lowered from present day level around 50-60 µmol l^{-1} down to the same levels as for the outer Wadden Sea obtained for S1-S3 (*Table 5.1*). The uncertainty of these predictions is similarly reduced because the proportional relationships fixing the elevated TN concentration to intercept at zero (*Figure 3.6*) has a decreasing uncertainty reaching zero at the intercept.

It should be acknowledged that these scenarios are based on the assumption that elevated TN concentrations (TN level in Wadden Sea sub-area minus TN level in outer Wadden Sea) depend entirely on local inputs from land and atmosphere. This is a steady-state assumption neglecting that once local nitrogen inputs are reduced it will take time before a new balance between local inputs and regenerated inputs from the sediments has been established. The implicit assumption is also that if local inputs are reduced to zero then TN concentrations in the Wadden Sea will converge towards levels in the outer Wadden Sea by shear exchange of water. The predicted TN concentrations (January-June) will be used as input for prediction of the mean summer chlorophyll *a* concentration.

Table 5.1 Predicted TN mean level (µmol l^{-1}) and standard error of prediction for 3 reduction scenarios in the Elbe River combined with reductions in local total nitrogen inputs (land and atmosphere). Local TN input and predicted TN levels are January-June levels.

Sub-area	Local TN input	S1 (90,000 tons N yr^{-1})		S2 (83,520 tons N yr^{-1})		S3 (70,000 tons N yr^{-1})	
		TN pred.	Std. error	TN pred.	Std. error	TN pred.	Std. error
Grådyb outer	2000	65.7	3.99	64.4	4.01	61.6	4.05
Grådyb outer	1800	62.5	3.61	61.1	3.62	58.3	3.67
Grådyb outer	1600	59.2	3.22	57.9	3.24	55.1	3.29
Grådyb outer	1400	56.0	2.84	54.6	2.86	51.8	2.92
Grådyb outer	1200	52.7	2.46	51.4	2.48	48.6	2.55
Grådyb outer	1000	49.5	2.08	48.1	2.11	45.3	2.19
Grådyb outer	800	46.2	1.72	44.9	1.75	42.1	1.84
Grådyb outer	600	43.0	1.36	41.6	1.40	38.9	1.52
Grådyb outer	400	39.7	1.04	38.4	1.09	35.6	1.24
Grådyb outer	200	36.5	0.79	35.1	0.86	32.4	1.04
Grådyb outer	0	33.2	0.68	31.9	0.76	29.1	0.96
Knude Dyb outer	2000	58.3	4.66	57.0	4.67	54.2	4.71
Knude Dyb outer	1800	55.8	4.20	54.5	4.22	51.7	4.26
Knude Dyb outer	1600	53.3	3.75	52.0	3.76	49.2	3.81
Knude Dyb outer	1400	50.8	3.30	49.4	3.31	46.7	3.37
Knude Dyb outer	1200	48.3	2.85	46.9	2.87	44.2	2.93
Knude Dyb outer	1000	45.8	2.40	44.4	2.43	41.6	2.50
Knude Dyb outer	800	43.3	1.97	41.9	1.99	39.1	2.08
Knude Dyb outer	600	40.8	1.54	39.4	1.58	36.6	1.68
Knude Dyb outer	400	38.3	1.15	36.9	1.20	34.1	1.33
Knude Dyb outer	200	35.7	0.82	34.4	0.89	31.6	1.07
Knude Dyb outer	0	33.2	0.68	31.9	0.76	29.1	0.96
Lister Dyb outer	1000	59.4	2.51	58.1	2.53	55.3	2.60
Lister Dyb outer	900	56.8	2.28	55.5	2.30	52.7	2.38
Lister Dyb outer	800	54.2	2.05	52.8	2.08	50.1	2.16
Lister Dyb outer	700	51.6	1.82	50.2	1.85	47.4	1.95
Lister Dyb outer	600	48.9	1.60	47.6	1.64	44.8	1.74
Lister Dyb outer	500	46.3	1.39	45.0	1.43	42.2	1.54
Lister Dyb outer	400	43.7	1.18	42.4	1.23	39.6	1.36
Lister Dyb outer	300	41.1	1.00	39.8	1.05	37.0	1.20
Lister Dyb outer	200	38.5	0.84	37.1	0.90	34.3	1.08
Lister Dyb outer	100	35.9	0.73	34.5	0.80	31.7	0.99
Lister Dyb outer	0	33.2	0.68	31.9	0.76	29.1	0.96

5.2 Scenarios for mean summer chlorophyll *a*

The established relationship between the ln-transformed TN levels (January-June) and summer chlorophyll *a* levels (May-September) (*Figure 4.3*) were used as the next step for calculating the effect of the proposed scenarios of nutrient reductions from the Elbe River and local inputs into the 3 considered sub-areas. To assess the uncertainty on estimated mean chlorophyll *a* levels deriving from the uncertainty of the input into the regression (ln(TN)), 100 randomly simulated TN levels derived from the distribution in *Table 5.1* were used as input. The uncertainty of the output (ln(chla)) was calculated as a combination of uncertainty in the chlorophyll *a* – TN model and uncertainty in the estimated TN levels from the scenarios (*Table 5.1*). The scenarios suggest that summer mean chlorophyll *a* can be reduced from around 8 µg l^{-1} to ca. 5 µg l^{-1} in Grådyb, from around 7 µg l^{-1} to 4.5 µg l^{-1} in Knude Dyb, and from around 5 µg l^{-1} to 3 µg l^{-1} with a projected nitrogen input of 70,000 tons yr^{-1} from the

Elbe River and no local nitrogen inputs (*Table 5.2*). The uncertainties of these predictions ranged from ±0.36 to ±1.13 µg l^{-1} (*Table 5.2*). Thus, given that local inputs were substantially reduced there would still be a considerable phytoplankton biomass resulting from exchanges with the outer Wadden Sea.

Table 5.2 Predicted mean summer chlorophyll *a* (µg l^{-1}) and standard error of prediction for 3 reduction scenarios in the Elbe River combined with reductions in local total nitrogen inputs (land and atmosphere). Local TN input are January-June and chlorophyll *a* levels are May-September.

Sub-area	Local TN input	S1 (90,000 tons N yr^{-1})		S2 (83,520 tons N yr^{-1})		S3 (70,000 tons N yr^{-1})	
		Chla pred.	Std. error	Chla pred.	Std. error	Chla pred.	Std. error
Grådyb outer	2000	8.32	1.13	8.21	1.13	7.99	1.12
Grådyb outer	1800	8.09	1.10	7.99	1.10	7.63	1.10
Grådyb outer	1600	7.79	1.08	7.62	1.08	7.44	1.08
Grådyb outer	1400	7.48	1.07	7.39	1.08	7.14	1.08
Grådyb outer	1200	7.21	1.07	7.11	1.07	6.86	1.08
Grådyb outer	1000	6.92	1.07	6.80	1.07	6.56	1.08
Grådyb outer	800	6.64	1.06	6.48	1.07	6.23	1.08
Grådyb outer	600	6.31	1.07	6.15	1.08	5.93	1.09
Grådyb outer	400	5.99	1.08	5.87	1.08	5.58	1.09
Grådyb outer	200	5.66	1.09	5.56	1.09	5.25	1.10
Grådyb outer	0	5.35	1.10	5.22	1.10	4.93	1.11
Knude Dyb outer	2000	6.97	0.91	6.86	0.92	6.67	0.90
Knude Dyb outer	1800	6.73	0.90	6.67	0.88	6.43	0.88
Knude Dyb outer	1600	6.57	0.88	6.43	0.88	6.19	0.87
Knude Dyb outer	1400	6.33	0.86	6.23	0.85	5.97	0.85
Knude Dyb outer	1200	6.18	0.84	6.06	0.85	5.77	0.85
Knude Dyb outer	1000	5.95	0.83	5.81	0.83	5.58	0.84
Knude Dyb outer	800	5.72	0.82	5.61	0.82	5.37	0.83
Knude Dyb outer	600	5.50	0.82	5.35	0.83	5.13	0.83
Knude Dyb outer	400	5.30	0.82	5.17	0.83	4.90	0.84
Knude Dyb outer	200	5.05	0.82	4.94	0.83	4.66	0.84
Knude Dyb outer	0	4.83	0.83	4.69	0.84	4.44	0.85
Lister Dyb outer	1000	4.83	0.36	4.78	0.37	4.62	0.38
Lister Dyb outer	900	4.71	0.37	4.64	0.37	4.45	0.39
Lister Dyb outer	800	4.57	0.37	4.48	0.38	4.31	0.40
Lister Dyb outer	700	4.40	0.39	4.34	0.39	4.17	0.41
Lister Dyb outer	600	4.25	0.39	4.19	0.40	4.00	0.42
Lister Dyb outer	500	4.10	0.41	4.03	0.42	3.86	0.44
Lister Dyb outer	400	3.95	0.43	3.88	0.43	3.71	0.46
Lister Dyb outer	300	3.80	0.44	3.72	0.45	3.54	0.48
Lister Dyb outer	200	3.63	0.46	3.56	0.47	3.39	0.49
Lister Dyb outer	100	3.47	0.48	3.40	0.49	3.21	0.51
Lister Dyb outer	0	3.30	0.50	3.22	0.51	3.03	0.53

5.3 Scenarios for chlorophyll *a* 90-percentile

The established relationship between summer mean chlorophyll *a* concentration (May-September) and the 90-percentile of the chlorophyll *a* distribution (*Figure 4.1*) was used as the final step to calculate the effect of the nutrient reduction scenarios on the indicator proposed by the NEA GIG, i.e. the 90-percentile. The uncertainty on the 90-percentile estimates included uncertainty from the regression (*Figure 4.1*) as well as uncertainty in the mean chlorophyll *a* levels used as input to the regression (*Table 5.2*). This was achieved by estimating the prediction error of 100 simulated mean chlorophyll levels and combining this with the prediction error from the regression. Thus, the uncertainty of the estimated 90-percentiles included uncertainty from all 3 relationships used, propagating the uncertainty of one scenario calculation through the subsequent regression.

Table 5.3 Predicted 90-percentile of the chlorophyll *a* distribution (µg l^{-1}) and standard error of prediction for 3 reduction scenarios in the Elbe River combined with reductions in local total nitrogen inputs (land and atmosphere). Local TN input are January-June and chlorophyll *a* levels are March-September.

Sub-area	Local TN input	S1 (90,000 tons N yr^{-1})		S2 (83,520 tons N yr^{-1})		S3 (70,000 tons N yr^{-1})	
		Chla pred.	Std. error	Chla pred.	Std. error	Chla pred.	Std. error
Grådyb outer	2000	22.08	2.23	22.12	2.23	22.18	2.30
Grådyb outer	1800	21.63	2.22	21.58	2.24	21.65	2.21
Grådyb outer	1600	21.02	2.16	21.05	2.17	21.03	2.15
Grådyb outer	1400	20.52	2.20	20.55	2.17	20.54	2.18
Grådyb outer	1200	20.05	2.14	19.99	2.19	19.93	2.17
Grådyb outer	1000	19.41	2.17	19.41	2.10	19.46	2.19
Grådyb outer	800	18.88	2.20	18.85	2.18	18.86	2.21
Grådyb outer	600	18.18	2.17	18.24	2.18	18.20	2.17
Grådyb outer	400	17.69	2.23	17.62	2.21	17.58	2.24
Grådyb outer	200	16.96	2.29	17.04	2.29	17.02	2.26
Grådyb outer	0	16.43	2.35	16.44	2.32	16.37	2.35
Knude Dyb outer	2000	19.52	1.85	19.59	1.88	19.58	1.86
Knude Dyb outer	1800	19.11	1.82	19.17	1.84	19.11	1.85
Knude Dyb outer	1600	18.73	1.85	18.77	1.84	18.78	1.85
Knude Dyb outer	1400	18.35	1.78	18.39	1.77	18.31	1.84
Knude Dyb outer	1200	18.03	1.81	17.99	1.79	17.95	1.82
Knude Dyb outer	1000	17.57	1.83	17.57	1.82	17.60	1.79
Knude Dyb outer	800	17.17	1.82	17.18	1.76	17.13	1.78
Knude Dyb outer	600	16.69	1.80	16.69	1.86	16.74	1.82
Knude Dyb outer	400	16.33	1.84	16.28	1.84	16.36	1.84
Knude Dyb outer	200	15.86	1.90	15.89	1.89	15.88	1.88
Knude Dyb outer	0	15.41	1.93	15.44	1.96	15.39	1.88
Lister Dyb outer	1000	15.59	1.22	15.59	1.22	15.60	1.21
Lister Dyb outer	900	15.34	1.25	15.33	1.25	15.29	1.25
Lister Dyb outer	800	15.04	1.28	15.05	1.30	15.07	1.29
Lister Dyb outer	700	14.75	1.34	14.75	1.32	14.77	1.31
Lister Dyb outer	600	14.45	1.38	14.47	1.37	14.45	1.37
Lister Dyb outer	500	14.16	1.42	14.14	1.43	14.21	1.42
Lister Dyb outer	400	13.90	1.47	13.87	1.48	13.90	1.46
Lister Dyb outer	300	13.56	1.51	13.62	1.51	13.59	1.51
Lister Dyb outer	200	13.28	1.57	13.29	1.57	13.32	1.57
Lister Dyb outer	100	12.98	1.64	12.98	1.63	12.96	1.64
Lister Dyb outer	0	12.62	1.67	12.68	1.67	12.62	1.69

The model predictions suggest that the 90-percentile of the chlorophyll *a* distribution can be reduced from around 22 µg l^{-1} to 16 µg l^{-1} in Grådyb, from around 19.5 µg l^{-1} to 15.5 µg l^{-1} in Knude Dyb, and from around 15.5 µg l^{-1} to 12.5 µg l^{-1} in Lister Dyb with a projected nitrogen input of 70,000 tons yr^{-1} from the Elbe River and no local nitrogen inputs (*Table 5.3*). The uncertainties of these predictions ranged from ±1.21 to ±2.35 µg l^{-1} (*Table 5.3*). Thus, given that local inputs were substantially reduced there would still be high chlorophyll concentrations in the 3 sub-areas.

6 Conclusions

In this study we have first established cause-effect relationships from 1) annual nitrogen inputs from the Elbe River to TN concentrations (January-June) in the outer Wadden Sea, 2) TN concentrations in the outer Wadden Sea (January-June) and local total nitrogen inputs (January-June) to TN concentrations (January-June) in 3 sub-areas of the Wadden Sea, 3) TN concentrations (January-June) to mean summer chlorophyll *a* concentrations (May-September) in 3 sub-areas of the Wadden Sea, 4) mean summer chlorophyll *a* concentrations (May-September) to the 90-percentile of the chlorophyll *a* distribution (March-September) based on 6-year periods. For the three different sub-areas of the Wadden Sea 11 scenarios for reducing local nitrogen inputs combined with 3 scenarios for nitrogen inputs from the Elbe River were proposed, and these scenarios were calculated through the chain comprised by the 4 relationships described above, including the uncertainties from each regression analysis.

The boundary for good ecological status has been defined by the NEA GIG as the 90-percentile of the chlorophyll *a* distribution (March-September) not exceeding 7.5 µg l^{-1}. This indicator is extremely variable on an annual basis when the number of monitoring observations is typically around 10, and it is suggested to calculate the indicator on a 6-year period to reduce the random variability. For the 6-year period from 2001 to 2006 the 90-percentile of the chlorophyll *a* distribution (March-September) was 28, 17 and 15 µg l^{-1} for outer Grådyb, outer Knude Dyb and outer Lister Dyb, respectively. Obviously, these areas do not fulfil the phytoplankton biomass criterion for good ecological status.

Considering the proposed scenarios for reduced nitrogen inputs from both local sources and the Elbe River, the 90-percentile may potentially be lowered to levels around 19, 17 and 14 µg l^{-1} for outer Grådyb, outer Knude Dyb and outer Lister Dyb, respectively. These values derived from the scenario calculations represent expectation values for the 90-percentile indication. This does not mean that calculated indicators cannot get lower than these values. Calculated 90-percentiles can vary substantially by shear randomness for small sample sizes, and as the number of monitoring observations increases the calculated indicator will, however slowly, approach the values given in *Tables 5.1-5.3*. This study does not attempt to calculate probabilities of fulfilling the good ecological target for different number of monitoring samples, but it is unlikely that any of the 3 sub-areas will fulfil the phytoplankton biomass criterion for good ecological status, even if local nitrogen inputs from both land and atmosphere could be reduced to zero. To exemplify the problem of meeting the good ecological target in the Danish part of the Wadden Sea, the 90-percentiles of the chlorophyll *a* distribution in the outer Wadden Sea were 18 µg l^{-1} (1989-1994), 22 µg l^{-1} (1995-2000), and 16 µg l^{-1} (2001-2006). Thus, it is also unlikely that the outer Wadden Sea, which has lower nutrient levels than the Wadden Sea, will fulfil the good ecological status criterion.

7 References

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Further information: www.neri.dk

National Environmental Research Institute
Frederiksborgvej 399
PO Box 358
DK-4000 Roskilde
Denmark
Tel: +45 4630 1200
Fax: +45 4630 1114

Management
Personnel and Economy Secretariat
Monitoring, Advice and Research Secretariat
Department of Policy Analysis
Department of Atmospheric Environment
Department of Marine Ecology
Department of Environmental Chemistry and Microbiology
Department of Arctic Environment

National Environmental Research Institute
Vejlsøvej 25
PO Box 314
DK-8600 Silkeborg
Denmark
Tel: +45 8920 1400
Fax: +45 8920 1414

Monitoring, Advice and Research Secretariat
Department of Marine Ecology
Department of Terrestrial Ecology
Department of Freshwater Ecology

National Environmental Research Institute
Grenåvej 14, Kalø
DK-8410 Rønde
Denmark
Tel: +45 8920 1700
Fax: +45 8920 1514

Department of Wildlife Ecology and Biodiversity

246 Estimation of nutrient reductions to achieve phytoplankton ecological targets in the Wadden Sea

Environmental targets for the WFD biological element phytoplankton have been set for the North Sea through the intercalibration process. The 90-percentile of the chlorophyll distribution has been selected as the indicator and in this report nitrogen inputs from local sources and the Elbe River have been linked to total nitrogen concentrations, which have subsequently been linked to the suggested indicator. Scenarios for nitrogen reductions from both types of sources have been calculated to assess if the proposed target values for good ecological status can be fulfilled. The results suggest that this is not possible, even if inputs from local sources are removed entirely. The proposed ecological target value that has been selected for a general value for the entire North Sea, does not apply to the Wadden Sea that has naturally elevated chlorophyll levels.

National Environmental Researh Institute
University of Aarhus · Denmark

ISSN 1399-9346