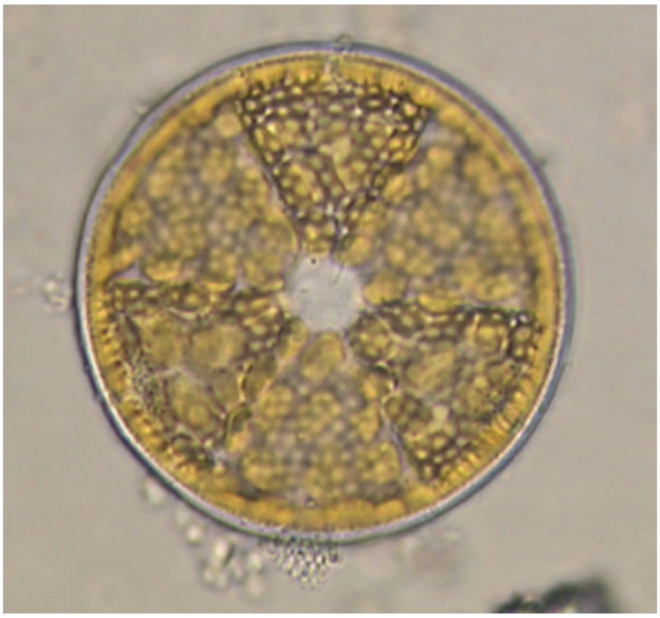
5. Eutrophication

Justus van Beusekom
Peter Bot
Jeanette Göbel
Michael Hanslik
Hermann-Josef Lenhart
Johannes Pätsch
Louis Peperzak
Thorkild Petenati
Karsten Reise



Diatom *Actinoptychus senarius* (Photo: J. v. Beusekom)

5.1 Introduction

Eutrophication is one of the factors that influence the quality of the Wadden Sea area. Since the earliest nutrient measurements in the Wadden Sea (Postma, 1954; Postma 1966; Hickel, 1989) a clear increase has been documented (*e.g.* de Jonge and Postma, 1974; Hickel, 1989; van Beusekom *et al.*, 2001). Among the negative effects associated with the increased nutrient loads are *Phaeocystis*-blooms (Lancelot *et al.*, 1987), a decline in seagrass (de Jonge and de Jong, 1992), increased blooms of green macroalgae (Reise and Siebert, 1994) and anoxic sediments ('black spots') (de Jong *et al.*, 1999).

A trilateral Target was adopted to aim for a Wadden Sea which can be regarded as a eutrophication non-problem area (Trilateral Wadden Sea Plan, 1997). The concept of the eutrophication problem and non-problem-areas has been developed in the framework of OSPAR (1997).

Target
A Wadden Sea which can be regarded as a eutrophication non-problem area

The following sections summarize the findings of the 1999 QSR (de Jong *et al.*, 1999), the results of a recent exercise to develop Wadden Sea specific eutrophication criteria and the results of the OSPAR Common Procedure in 2003. In the chapter 5.2 'Data analysis', recent trends in nutrient loads, nutrient concentrations and in phytoplankton and macroalgae biomass are described. A Target evaluation and recommendations are given. The present report updates and extends the data analysis of the 1999 QSR (de Jong *et al.*, 1999) and of the report on 'Wadden Sea Specific Eutrophication Criteria' (van Beusekom *et al.*, 2001).

5.1.1 Findings of the 1999 QSR

In the 1999 QSR trends in nutrient concentrations of the Wadden Sea were analyzed by Bakker *et al.* (1999) for the period 1985-1996. The authors noted that nutrient concentrations in the Wadden Sea during winter depend to a large extent on salinity. Therefore, actual concentrations cannot be directly compared unless they are standardized to a certain salinity. Details of the 'concentration – salinity' method are given in Bakker *et al.* (1999). The analysis in the 1993 and 1999 QSR (de Jong *et al.*, 1993; Bakker *et al.*, 1999) are based on winter concentrations normalized to standard salinities of 10 and 27.

The clearest decrease was observed for phosphate (PO_4, Dissolved Inorganic Phosphorus or DIP) which decreased by about 50% in most of the Wadden Sea. In the Dutch Wadden Sea winter phosphate concentrations of about 1 µM are observed, which gradually increase towards the estuaries of Weser and Elbe, where concentrations of 2-4 µM prevail. In the North Frisian and Danish Wadden Sea again concentrations of about 1 µM prevail.

No equivalent decrease was observed for nitrogen, although ammonium showed a clear downward trend in the Ems, Weser and Elbe estuaries, presumably due to the progressive imple-

The OSPAR Common Procedure

In 1997, the OSPAR Commission adopted the so-called 'Common Procedure' for the identification of the eutrophication status of the Maritime Area of the OSPAR Convention (OSPAR, 1997). The Common Procedure distinguishes three areas:

- 'Problem Areas' are those areas for which evidence of an undesirable disturbance to the marine ecosystem due to anthropogenic enrichment by nutrients exists
- 'Potential Problem Areas' are those areas for which there are reasonable grounds for concern that undesirable disturbance may occur
- 'Non-Problem Areas' are those for which such concerns do not exist.

The 'Common Procedure' consists of two steps, the 'Screening Procedure' and the 'Comprehensive Procedure' (COMP). The Screening Procedure identifies with a 'broad brush' approach those areas that are likely to be eutrophication Non-Problem Areas. It was not applied to the Wadden Sea because it was claimed to be at least a Potential-Problem Area. The Comprehensive Procedure identifies Problem Areas and Potential Problem Areas based on parameters from a 'holistic checklist' and if necessary based on region specific criteria. The latter were developed for the Wadden Sea by van Beusekom *et al.* (2001) and are grouped according to the Comprehensive Procedure below:

'Causative Factors' (Cat. I) are atmospheric and riverine nutrient input. The effect of the increased nutrient input is best seen in changes in the annual nutrient cycle.

'Supporting Factor' (Cat. II) for Wadden Sea eutrophication is the import of organic matter from the adjacent North Sea.

'Direct Effects' (Cat. III) of eutrophication could be observed in all biota of the Wadden Sea. However, no clear dose-response relation could be identified. Other factors like weather, temperature of more complex interaction also play important roles in the proliferation of eutrophication effects.

Indirect Effects such as changes in zoobenthos biomass and species composition were observed but no clear dose-response relation could be identified.

mentation and technical improvement of waste water treatment plants. Nitrate showed an upward trend in the western Dutch Wadden Sea and a downward trend in the Ems, Weser and Elbe estuaries. Winter nitrate concentrations in the Wadden Sea (27 psu) range between 20–110 µM but in most parts are about 50 µM. The 1999 QSR also stated that reductions in phosphate have not led to a reduction of biological phenomena which may be related to nutrient loading, notably average chlorophyll concentrations, the duration of *Phaeocystis* blooms in the Marsdiep and growth of macrozoobenthos. Although specific eutrophication criteria had not been developed by that time, the QSR 1999 concluded that the target had not yet been reached.

5.1.2 Wadden Sea specific eutrophication criteria

Recently, a literature study and data analysis was carried out aiming at developing Wadden Sea specific eutrophication criteria (van Beusekom *et al.*, 2001). The study was necessary to specify the trilateral Target 'to achieve a Wadden Sea which can be regarded as a eutrophication non-problem area'. The work was done in close cooperation with activities within the framework of the OSPAR Common Procedure through which relevant parts of the OSPAR Convention Area are designated as either non-problem, potential problem or problem areas with regard to eutrophication.

The literature review highlighted the importance of organic matter import from the North Sea for the Wadden Sea eutrophication. Statistical analysis of long term data from the Dutch Wadden Sea showed that high riverine input of TN (total nitrogen) enhances organic matter turnover as indicated by autumn values of N remineralisation products (NH_4, NO_2) in both the Rhine-influenced western part and in the North Sea-influenced eastern part of the Dutch Wadden Sea. It was proposed to use autumn values of N remineralisation products (NH_4+NO_2) as a measure of the eutrophication status.

In all Wadden Sea areas an increased eutrophication was observed from ~1960-1996. In both the southern Wadden Sea (Den Helder - Elbe) and in the northern Wadden Sea (Elbe - Esbjerg) primary production has increased. Whereas along the southern Wadden Sea variability of autumn values of N remineralisation products can be related to nitrogen input, no such relation is found in the northern Wadden Sea. Instead a possible relation between nitrate in the coastal zone and autumn values of N remineralisation products in the Sylt-Rømø Bight was found.

Two contrasting situations were postulated:

- the southern Wadden Sea with intense particle accumulation and a strong coupling of productivity and remineralisation with variations in nitrogen input via the Rhine and the Meuse and
- the northern Wadden Sea with less intense particle accumulation, where nutrient input from the west into the German Bight and not the Elbe river input determine primary production in the German Bight and consequently the organic matter import into the Wadden Sea.

Background concentrations of NH_4+NO_2 were proposed for the western Dutch Wadden Sea and amount to about 3 µM (situation in early 1930s). Accordingly, the present eutrophication status of the western Dutch Wadden Sea is on average 5 times higher than during the early 1930s. For the other Wadden Sea areas, background values were assigned based on present NH_4+NO_2 levels and assuming a similar increase in eutrophication status throughout the entire area. Based on the evaluation of eutrophication criteria, the Wadden Sea was assessed as a 'Eutrophication Problem Area'.

		The Netherlands	Germany	Denmark
Cat I:	Riverine Input (50% above background)	+	+	+
	Winter Concentrations	+	+	+
	Wadden Sea (>6-7 µM N)			
	Estuaries (>18-30 µM N)			
	N/P ratios	+	+	+
Cat II:	Chlorophyll levels (Max. >22-24 µg/l)	+	+	+
	Phytoplankton Indicator Species	+	+	-
	Macrophytes	+	+	+
Cat III:	Oxygen Problems	+	?	
	Changes/Kills of Macrobenthos	NK	?	-
	Changes in organic matter	+	?	-
Cat IV:	Algal toxins	+	+	+

Table 5.1: Summary of the Wadden Sea Eutrophication Assessment by OSPAR (OSPAR, 2003). All three Wadden Sea countries assessed the Wadden Sea as a Problem Area:'+' indicates that the assessment criterion was applied.

5.1.3 OSPAR eutrophication assessment

The whole OSPAR convention area was screened with the Common Procedure (see Box). The Wadden Sea was classified as a eutrophication problem area by Denmark, Germany and The Netherlands (OSPAR, 2003). As criteria, deviations from background levels were used. All three countries used nutrient enrichment, increased chlorophyll levels, problems with nuisance macroalgae and algal toxins as criteria. Differences and uncertainties in the assessment of the effects on macrobenthos and oxygen dynamics were apparent (Table 5.1).

5.2 Data analysis

5.2.1 Causative factors

5.2.1.1 River Input

Riverine input data is based on monitoring data that was interpolated to daily loads (Lenhart and Pätsch, 2001; updated until 2002). The major sources influencing the southern Wadden Sea are Haringvliet, Maassluis, Noordzeekanaal, IJsselmeer and Ems. The first sources are in a wider sense part of the Rhine - Meuse delta. Major sources for the central Wadden Sea (Jade - Eiderstedt) are the rivers Weser and Elbe. The latter rivers are also major nutrient sources for the northern Wadden Sea, where small rivers (Eider, Danish rivers) contribute about 6-7 %. The relative contributions of the above mentioned river sources are compiled in Table 5.2.

The high interannual variability of riverine nutrient input is largely due to two factors: differences in interannual freshwater discharge and a general decrease in nutrient concentrations. Figures 5.1–5.2 show that peaks in freshwater discharge coincide with peaks in nutrient loads. In general, the annual nutrient loads correlate significantly with the annual freshwater discharge. The correlation is much better for total nitrogen (TN) than total phosphorus (TP) (southern Wadden Sea: $r^2 = 0.62$ for TN and $r^2 = 0.37$ for TP; central Wadden Sea: $r^2 = 0.76$ for TN and $r^2 = 0.35$ for TP). Normalized nutrient loads (annual nutrient load divided by annual discharge) show a steady decreasing trend for TN and TP for the entire Wadden Sea (Figure 5.3). Since 1985 the specific TN load to the southern and central Wadden Sea decreased on average each year by 2.1-2.2%. The specific TP load decreased stronger than the specific TN load and amounted on average to 3.3% per year for the southern Wadden Sea and 2.5% per year for the central Wadden Sea.

Southern Wadden Sea			
Source	*Discharge*	*Total Nitrogen*	*Total Phosphorus*
Haringvliet	27.5%	27.2%	22.1%
Maassluis	47.4%	47.2%	57.2%
Noordzeekanaal	3.0%	2.9%	4.6%
IJsselmeer	19.3%	17.6%	13.8%
Ems	2.8%	4.6%	2.3%
Central and northern Wadden Sea			
Source	*Discharge*	*Total Nitrogen*	*Total Phosphorus*
Weser	31.1%	31.7%	30.1%
Elbe	62.0%	61.9%	64.3%
Eider	2.5%	2.2%	2.5%
County Ribe	3.4%	3.2%	2.1%
Jutland	0.9%	1.0%	0.9%

Table 5.2: Mean relative contribution of major fresh water sources to nutrient input into the southern (1977-2002) and central Wadden Sea (1980 to 2002). For the Eider and Danish rivers, data since 1990, resp. 1995 was used as reported to OSPAR (Data source: OSPAR, Umweltbundesamt).

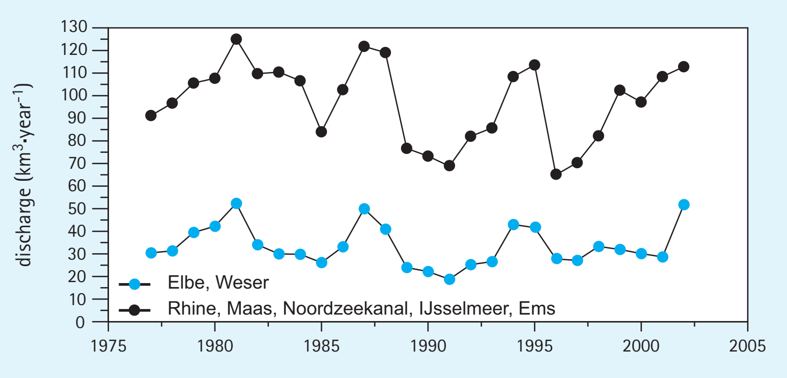


Figure 5.1: Major annual freshwater discharges influencing the southern Wadden Sea (Rhine, Meuse, Noordzeekanaal, IJsselmeer and Ems) and the central and northern Wadden Sea (Weser, Elbe). Data source: DONAR, Lenhart and Pätsch (2001).

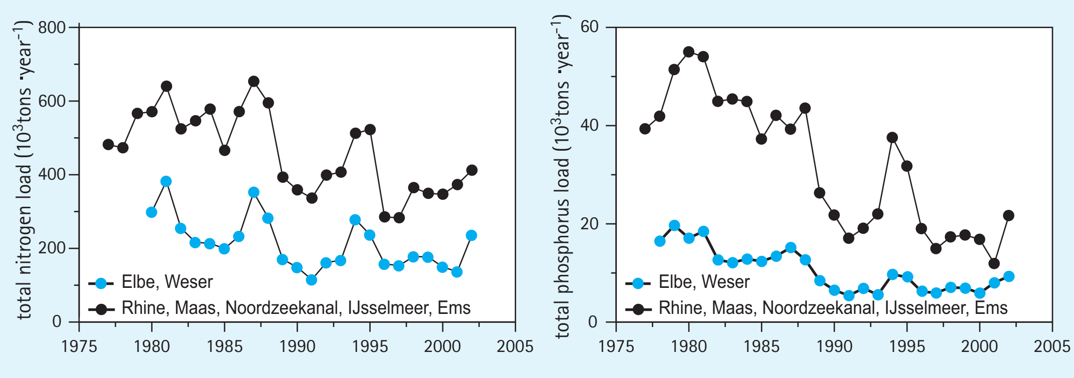


Figure 5.2: Major riverine TP and TN loads to the southern Wadden Sea (Rhine, Meuse, Noordzeekanaal, IJsselmeer and Ems) and to the central and northern Wadden Sea (Weser, Elbe). Data source: DONAR, Lenhart and Pätsch (2001).

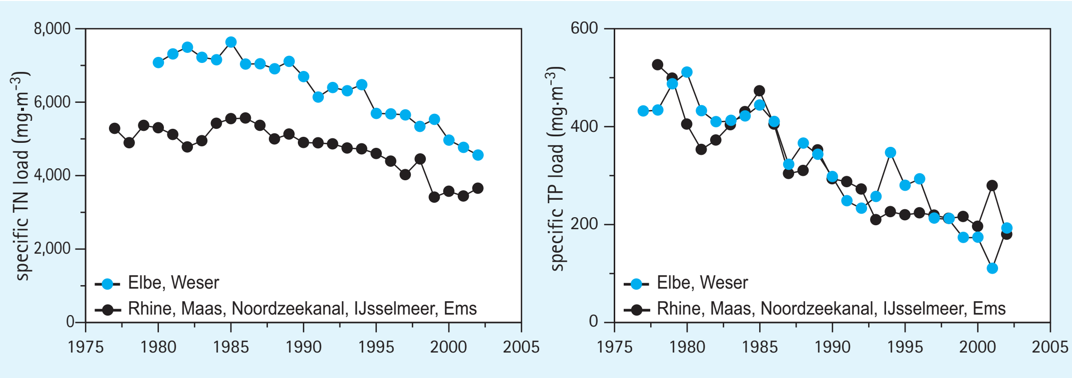


Figure 5.3: Specific nitrogen and phosphorus load (mean annual load / mean annual discharge) to the southern Wadden Sea (Rhine, Meuse, Noordzeekanaal, IJsselmeer and Ems) and to the central and northern Wadden Sea (Weser, Elbe). Data source: DONAR, Lenhart and Pätsch (2001).

5.2.1.2 Atmospheric Input

Van Beusekom *et al.* (2001) estimated a total (wet + dry) nitrogen deposition in the Wadden Sea of about 1.7 g N m^{-2} y^{-1}. Recent studies suggest a somewhat lower atmospheric deposition of about 1.2 g N m^{-2} y^{-1}: Model calculations predict a total atmospheric nitrogen deposition in the coastal North Sea of about 1 g N m^{-2} y^{-1} (de Leeuw *et al.*, 2001). Aertebjerg *et al.* (2002) indicate a total atmospheric deposition in the Danish Wadden of 1.2 –1.4 g N m^{-2} y^{-1}. OSPAR (2004) compiled time series around the North Sea. They mention an average wet deposition of 0.8 g N m^{-2} y^{-1} (total deposition: ~1.2 g N m^{-2} y^{-1}) with no trend. An estimated mean atmospheric N load of about 1.2 g N m^{-2} y^{-1} or 15.6 kT y^{-1} for the entire Wadden Sea shows that this atmospheric nitrogen input is comparable to the input of the Ems (*cf.* van Beusekom *et al.*, 2001).

5.2.1.3 Winter concentrations

Winter concentrations in the North Sea depend strongly on salinity (*e.g.* van Bennekom and Wetsteyn, 1990; Körner and Weichart, 1992). Monitoring data by the German Federal Maritime and Hydrographic Agency (BSH) reflects the gradual decrease in riverine nutrient input (van Beusekom *et al.*, 2004) and show a decrease of nitrate at a salinity of 30 from ~55 µM in 1978 to ~45 µM in 2000 – 2003 (actually, values for nitrate + nitrite were reported, but nitrite contributes only a small amount).

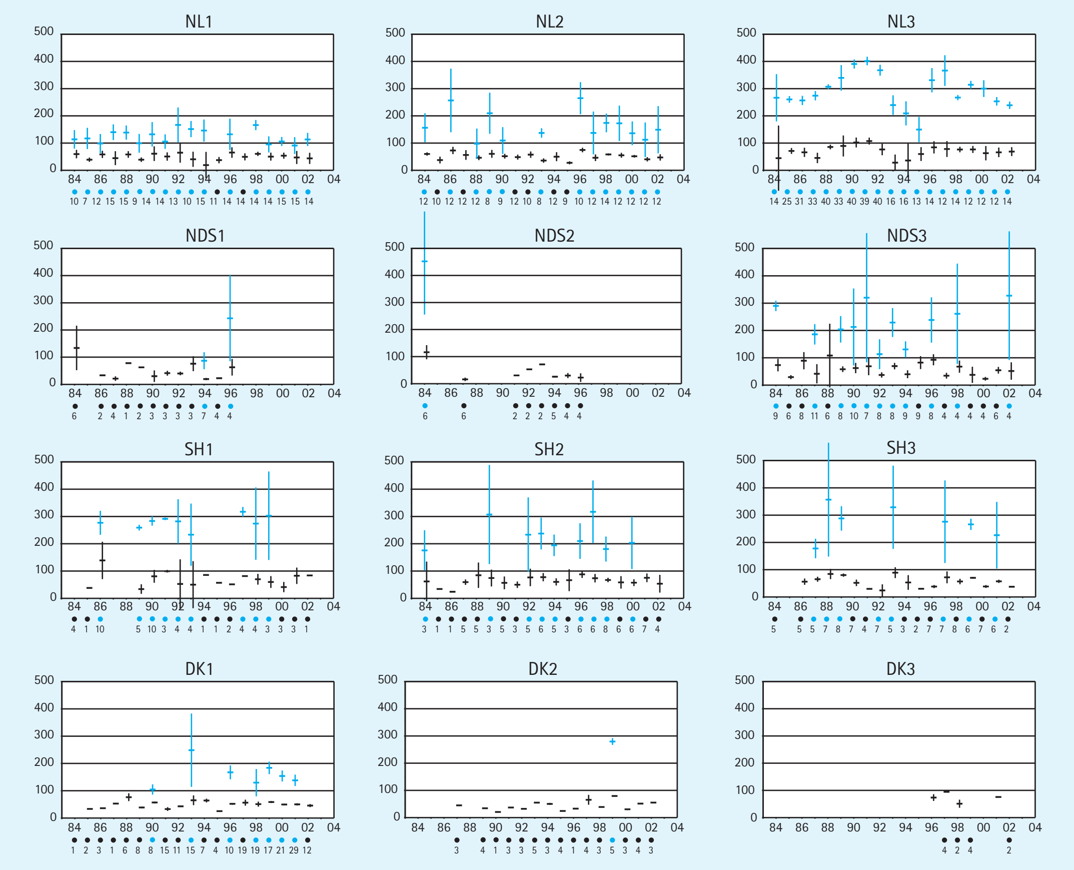


Figure 5.4: Trends in winter nitrate + nitrite concentrations (µmol/l) (December – February) in the 12 subareas of the Wadden Sea. The concentrations are normalized to a salinity of 10 (blue) and 27 (black). The horizontal lines represents the mean value, the vertical lines indicate the 95% confidence interval of the mean. Black dots: mean values based on salinity gradient. Blue dots: mean values (no significant salinity gradient). The numbers below the dots indicate the number of data used for the analysis. Data: TMAP Data Units.

Phosphate decreased in that period from ~2.5 µM to ~1.0 µM. Also in the Wadden Sea, winter nutrient concentrations correlate with salinity. In order to describe trends and to compare the different areas the winter concentrations were normalized to a salinity of 27. This estimate was only made if a significant correlation between nutrient concentrations and salinity was present. If not, the mean winter concentration was calculated. Details of this method are given in the 1999 QSR.

Figures 5.4 and 5.5 present updates of the QSR 1999 for nitrate (+ nitrite) and phosphate. Winter nitrate concentrations do not show a significant trend. Near estuaries the mean nitrate concentrations are somewhat higher (~65 µM) than in the other areas (~52 µM). Phosphate concentrations in winter did show a strong decrease from about 2 µM in 1985 to about 1.1 µM after 1995. Near estuaries the concentrations are higher and are at present ~ 2-3 µM.

5.2.2 Direct effects

5.2.2.1 Phytoplankton

Phytoplankton biomass and productivity

The analysis of chlorophyll data (an indicator of phytoplankton biomass) focuses on summer chlorophyll means (May-September) instead of annual means. The available data is summarized in Table 5.3. Long time series (15-27 years: Dutch Wadden Sea, Norderney, Sylt) that cover the entire seasonal cycle are shown in Figures 5.6 – 5.8.

Western Dutch Wadden Sea

Cadée and Hegeman (2002) summarize trends in phytoplankton biomass and productivity in the Marsdiep area (western Dutch Wadden Sea). They observed an increase in primary production from about 100-150 g C m^{-2} y^{-1} in 1965 to about 400 g C m^{-2} y^{-1} in 1994. Since then a decrease to values of about 200 g C m^{-2} y^{-1} has been observed. Mean annual chlorophyll levels decreased slightly.

The analysis of long-term phytoplankton composition in combination with nutrient budget data (Philippart *et al.*, 2000) suggested that the time series could be divided into three periods: a rich but phosphorus-controlled period (1974-1977), a more eutrophic, nitrogen-limited period (1978-1987) and a phosphate-limited period (1988-1993).

Mean summer chlorophyll-*a* levels (May-September) as observed by the Dutch Monitoring program amount to 18 µg Chl-*a*/l and are among

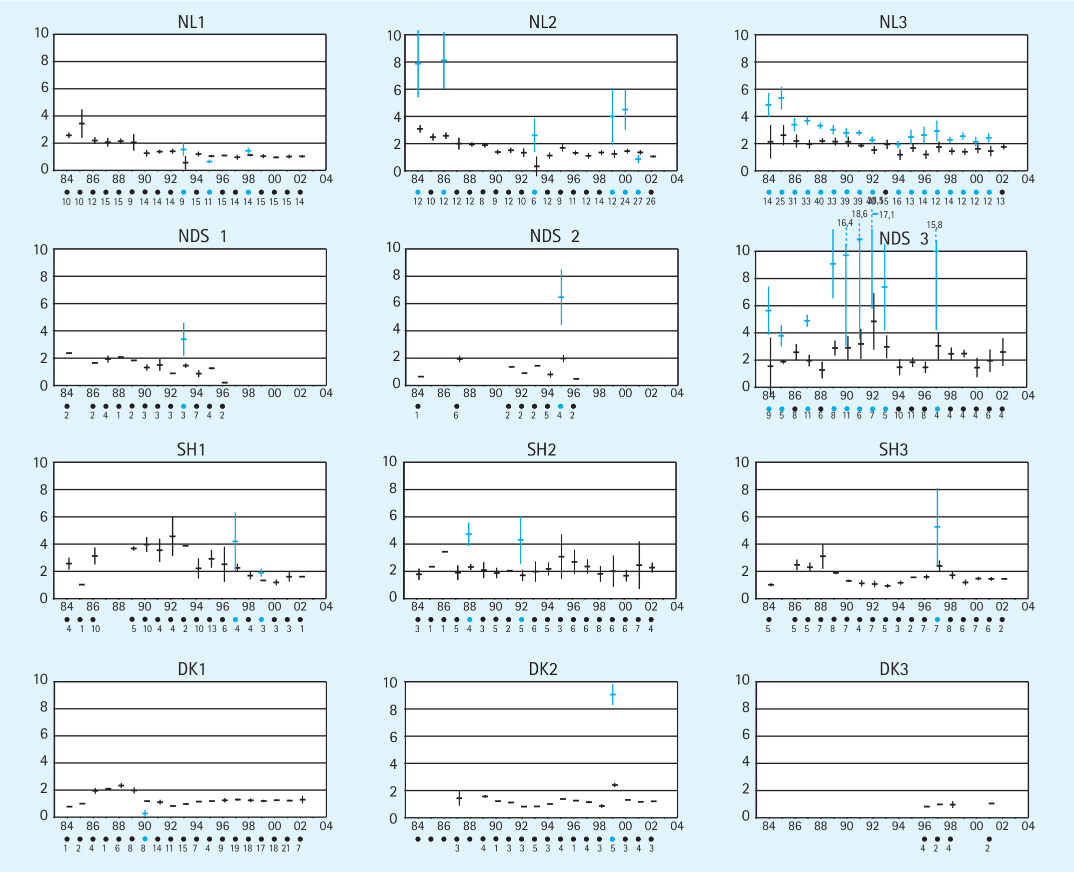


Figure 5.5: Trends in winter phosphate concentrations (µM) (December – February) in the 12 subareas of the Wadden Sea. The concentrations are normalized to a salinity of 10 (blue) and 27 (black). The horizontal lines represents the mean value, the vertical lines indicate the 95% confidence interval of the mean. Black dots: mean based on salinity gradient. Blue dots: mean values (no significant salinity gradient). The numbers below the dots indicate the number of data used for the analysis. Data: TMAP Data Units.

the highest in the Wadden Sea. They show a marked decrease from about 20 µg Chl-*a*/l in1976-1985 to about 11 µg Chl-*a*/l in 1996-2002.

Eastern Dutch Wadden Sea

Mean summer chlorophyll levels (May-September; Dutch Monitoring program) amount to 19.9 µg Chl-*a*/l and are the highest in the Wadden Sea. They show no decreasing trend.

Niedersachsen Wadden Sea

Mean summer chlorophyll concentrations at Norderney (~17 µg Chl-*a*/l) are lower than in the Dutch Wadden Sea. A decreasing trend from about 20 µg Chl-*a*/l around 1990 to ~15 µg Chl-*a*/l during the last five years has been observed.

Schleswig-Holstein Wadden Sea

Summer chlorophyll concentrations in the northern Wadden Sea are lower than in the southern Wadden Sea. A clear spatial gradient is present showing higher chlorophyll concentrations (~14 µg Chl-*a*/l) near the Elbe-Weser estuary decreasing to 6.3 µg Chl-*a*/l in the Sylt Rømø Bight. Only in the latter area, a decreasing trend is observed that correlates with TN loads from the Rhine/ Meuse and Elbe/Weser.

Danish Wadden Sea

Summer chlorophyll concentrations in the Danish Wadden Sea are about 8.6 µg Chl-*a*/l. No temporal trends or correlations with riverine input could be identified.

Spatial Trends

Summer levels in the southern Wadden Sea are about twice as high as in the central and northern Wadden Sea (Table 5.3). The highest levels are near the major nutrient sources (Dutch Wadden Sea: IJsselmeer. Southern Schleswig-Holstein Wadden Sea: Weser and Elbe) and decrease with increasing distance from the estuaries. The latter gradient is clearer in the northern Wadden Sea.

Relation with nutrient input

Relations with riverine nutrient input (Table 5.3) were identified for the western Dutch Wadden Sea, for Norderney (Niedersachsen Wadden Sea) and for the Sylt Rømø Bight (northern Wadden Sea). We chose the TN input via Rhine and Meuse as a common driver that possibly reflects Europe-wide climatic and agricultural trends (see below) In all cases a significant correlation (p<0.01) existed with the TN input during December (previous year) until August. The same time window was used in

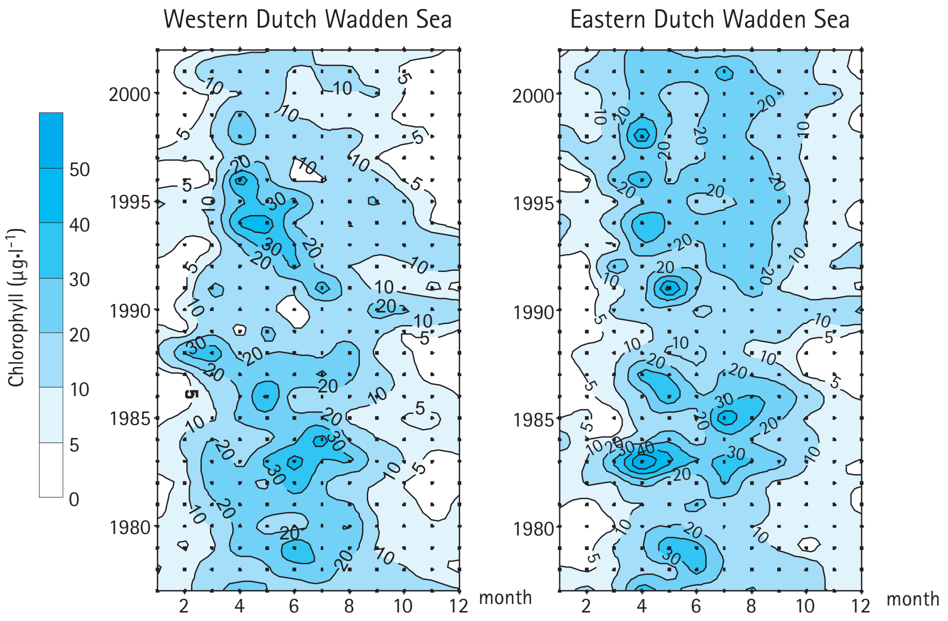


Figure 5.6: Seasonal cycle of chlorophyll in the western and eastern Dutch Wadden Sea, 1977-2002. Data: TMAP Data Units and DONAR.

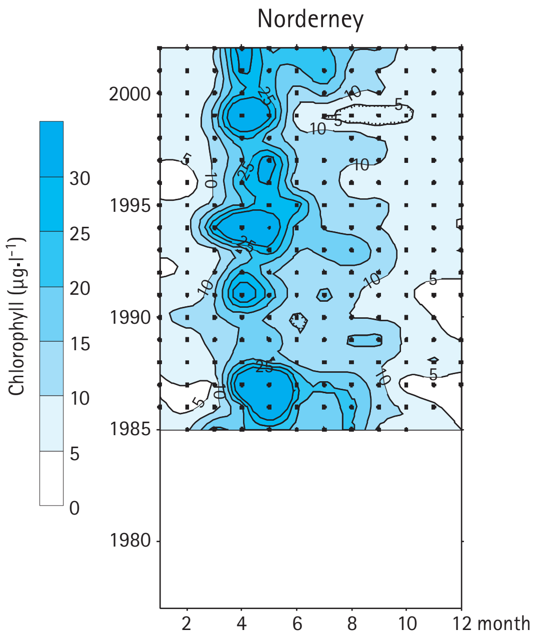


Figure 5.7 (left): Seasonal cycle of chlorophyll in the Niedersachsen Wadden Sea (Norderney), 1985-2002. Data: TMAP Data Units and NLÖ (M. Hanslik).

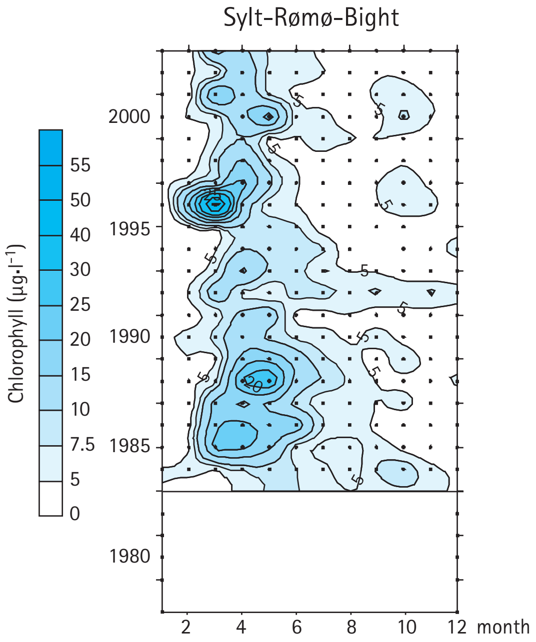


Figure 5.8 (right): Seasonal cycle of chlorophyll in the North Frisian Wadden Sea (Sylt-Rømø-Basin), 1983-2003. Data: TMAP Data Units and AWI (J. van Beusekom).

the eutrophication criteria study (van Beusekom *et al.*, 2001). In all cases, about 1/3 of the variability was explained by TN input. Interestingly, the relative influence of the riverine TN load on the chlorophyll levels (regression coefficient/ long-term mean chlorophyll) was similar for all sites (Table 5.3).

These results indicate that summer chlorophyll might be used as a eutrophication indicator. Using TN input via Rhine and Meuse does not necessarily imply that other sources are not important. The 'statistical significance' of the correlation with the Rhine/Meuse time-series is probably related to the size of this river system, reflecting both the general precipitation pattern over North Western Europe and Europe-wide changes in the use of fertilizers, implementation of water treatment plants, changes in land use and burning of fossil fuels. It should be noted that the temporal patterns in the Rhine-Meuse system are very similar to the patterns in the Weser-Elbe-system (Figure 5.1 – 5.3). In fact, TN and TP loads of both systems are significantly correlated (TN: $r^2=0.76$; $p<<0.00001$; N=23, TP: $R^2=0.81$; $p<<0.00001$; N=25).

Table 5.3:
Comparison of summer chlorophyll levels (µg/l; May-September) in different parts of the Wadden Sea and their correlation with TN input via Rhine and Meuse. In the case of a significant correlation a factor relating riverine input with chlorophyll levels is given. This factor is the slope of the regression multiplied by 10^6 divided by the mean chlorophyll level. The ‚statistical significance' of the correlation with the Rhine/Meuse time-series is probably related to the size of this river system, reflecting both the general precipitation pattern over Northwestern Europe and Europe-wide changes in the use of fertilizers, implementation of water treatment plants, changes in land use and burning of fossil fuels. Data source: TMAP Data Units, DONAR, LANU (J. Göbel), NLWKN (M. Hanslik), AWI (van Beusekom), Lenhart and Pätsch (2001).

Area	Period	Mean	Trend/Factor	Correlation and significance		
Western Dutch Wadden Sea	1976-2002	18.0	Yes/2.7	$r^2=0.43$	n=27	p=0.0002
Eastern Dutch Wadden Sea	1976-2002	19.9	No Trend			
Niedersachsen Wadden Sea (Norderney)	1988-2002	16.6	Yes/2.1	$r^2=0.308$	n=18	p=0.008
Southern Schleswig-Holstein	1990-2002	14.2	No Trend*	$r^2=0.002$	n=13	p=0.868
Northern Schleswig-Holstein	1990-2002	7.4	No Trend*	$r^2=0.12$	n=13	p=0.245
Sylt-Rømø-Bight	1984-2002	6.3	Yes/2.7	$r^2=0.345$	n=19	p=0.008
Danish Wadden Sea	1990-2002	8.6	No Trend*	$r^2=0.18$	n=12	p=0.15

*Also no trend with Elbe/Weser Input (Jan. - August).

Toxic and nuisance blooms

Dutch Wadden Sea

The duration of *Phaeocystis* blooms in the Marsdiep area decreased from a maximum of about 140 days during the early 1990s to about 60 days in 2000 (Phillipart *et al.*, 2000). Data from the Dutch monitoring program shows that since 1996, *Phaeocystis* sp. bloomed (>10^6 cells/l) between 68 and 33 days.

Since the 1999 QSR, some toxic blooms were observed: *Fibrocapsa japonica* bloomed once during 2001 (>10,000 cells /l), but no negative effects were reported. *Dinophysis acuminata* bloomed (>100 cells/l) 29 days during 2001 and 23 days during 2002. These blooms caused increased DSP (diarrhetic shellfish poisoning) levels in mussels.

Niedersachsen Wadden Sea

Some conspicuous blooms were observed. In September 1999 the dinoflagellate *Prorocentrum redfieldii* reached up to 320,000 cells/l between Spiekeroog and Wangerooge. Critical cell numbers of the dinoflagellate *Dinophysis* spp. were observed in late summer 1997, 2000, 2001 and 2002 and harvesting of mussels was temporarily stopped.

Schleswig-Holstein Wadden Sea

The most conspicuous blooming alga was *Chattonella*. This alga was responsible for fish kills in Danish and Norwegian waters in 1998. In that year the southern limits of the bloom were northwest of Sylt, where up to 0.17 Mio cells/l were observed. In May 2000, a *Chattonella* bloom reached up to 10^6 cells/l northwest of Sylt. No negative effects were observed in this part of the Wadden Sea. A major *Phaeocystis* bloom was observed in 2000. Toxic dinoflagellates (*Dinophysis* spp., *Alexandrium tamarense*) were regularly observed. In 1998, shellfish harvest was temporarily stopped south of Sylt. In 1999 up to 1000 cells/l were observed near Sylt - but without toxic effects.

Danish Wadden Sea

An overview of potentially toxic blooms was given by Aertebjerg *et al.* (2003). *Phaeocystis* blooms occurred each year along the Danish West coast (major bloom in 2000). The potentially toxic *Chattonella* bloomed along the Danish coast in 1998, 2000 and 2001. These blooms were accompanied by fish kills. *Karenia mikimotoi* (*Gyrodinium aureolum*) bloomed in 1997 accompanied with dead benthic invertebrates. *Prorocentrum micans* bloomed in 1997 and 1999. In 1999 DSP was found in shellfish. No toxic blooms were observed in 2002 and 2003 (Amterne Vadehavssamarbejde, 2003, 2004).

5.2.2.2 Macroalgae

Compared to rocky shores, macroalgae used to cover sediments only to a minor extent. However, from the late 1970s to 1980s green algae started to occur in thick mats covering vast areas of tidal sediments in the Wadden Sea (Reise, 1983; de Jonge *et al.*, 1993; Reise and Siebert 1994; Kolbe *et al.*, 1995) as well as in coastal areas elsewhere in the world (Fletcher, 1996). This development peaked in 1990-1993 with algal mats covering up to 20% of the intertidal area in the German Wadden Sea. Since then green algae remained abundant and thick mats occurred locally but never regained the massive proportions of the early 1990s. The summer of 2004 was the first with green algae returning back to their marginal occurrences prior to the 1980s. A monthly assessment of green algal mass at a site near Sylt, where no green algae occurred in the 1970s and earlier,

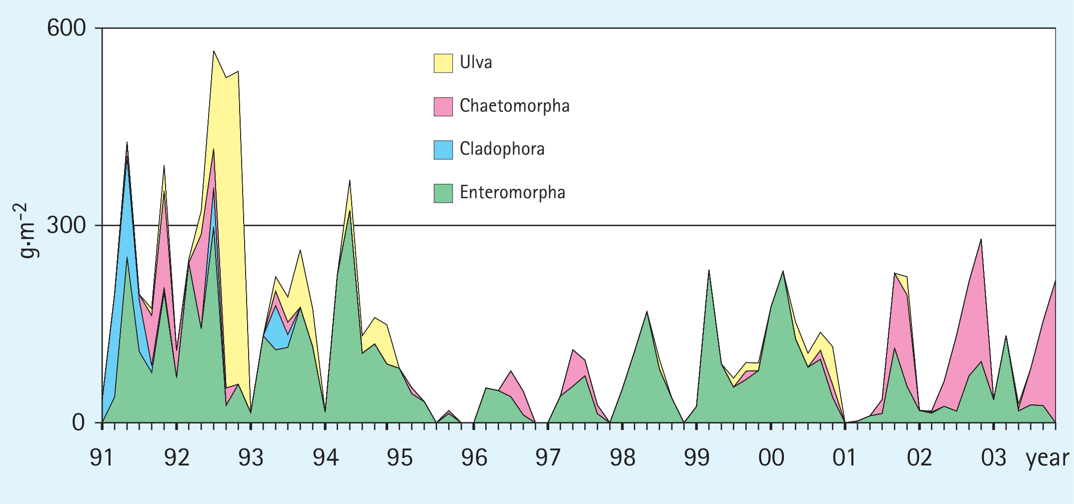


Figure 5.9: Phytomass (g organic dry weight per m^2) of green algal genera at a site in Königshafen near Sylt in the northern Wadden Sea, measured monthly from May to October on an area of 2500 m^2 between 1991 and 2003 (Reise, unpubl.).

reflects fairly well the general development throughout the 1990s and to the present (Figure 5.9). Interannual and seasonal fluctuations are large, filamentous *Enteromorpha* tend to dominate but occasionally other green algae achieve dominance. The sediment underneath algal mats turned anoxic, benthic animals escaped or died, and suffocated seagrass decayed.

Although massive green algal developments have been generally related to coastal eutrophication (Fletcher, 1996), there is no apparent spatial or temporal relation of this phenomenon to riverine nitrogen or phosphorus loads into the Wadden Sea. As several taxa of green algae are involved, a general cause or combination of causes is likely which may involve remineralisation rates and turbidity at the tidal flats, temperature and turbulence, nutrient competition with phytoplankton or grazing by invertebrates.

5.2.3 Indirect effects

5.2.3.1 Autumn NH_4+NO_2 as indicator of organic matter turn-over

In the report on 'Wadden Sea Specific Eutrophication Criteria' (van Beusekom *et al.*, 2001) it was suggested to use the intensity of the seasonal cycle of NH_4+NO_2 (more specifically, the autumn values) as an indicator of the organic matter turnover in the Wadden Sea. The seasonal cycles of the major component NH_4 are shown in Figures 5.10 - 5.12 for the Dutch Wadden Sea, the Niedersachsen Wadden Sea (Norderney) and the North Frisian Wadden Sea (Sylt). The analysis for the Dutch Wadden Sea was based on a multiple regression with mean autumn NH_4+NO_2 concentrations as the dependent variable and riverine TN input, autumn chlorophyll levels and temperature as independent variables.

We repeated the analysis for the Dutch Wadden Sea and for Norderney. The results confirm that the autumn values are good eutrophication indicators for the southern Wadden Sea. NH_4 and NO_2 concentrations in the Dutch Wadden show a gradual decrease in the Western part, but trends in the eastern part are less obvious. Nevertheless, in both parts of the Dutch Wadden Sea, the riverine total nitrogen input (December-August) was significantly correlated with the autumn NH_4+NO_2 levels (Table 5.4). Chlorophyll did not significantly influence the relation in the western Dutch Wadden Sea, but had a major impact in the eastern part. For the Niedersachsen Wadden Sea (Norderney) a significant partial correlation exists between the Rhine-Meuse TN input and autumn NH_4+NO_2 concentrations (years 1986-2001). The overall multiple correlation is not significant.

In contrast to the southern Wadden Sea, the autumn NH_4+NO_2 concentrations in the North Frisian Wadden Sea (Sylt) show an increasing trend suggesting an increased eutrophication status. NO_3 concentrations in autumn, however, show a decreasing trend (significantly correlated with the TN load via Rhine and Meuse). This suggests that autumn values of NH_4+NO_2 are not good indicators of organic matter turnover in the northern Wadden Sea. On the other hand, the lower NH_4+NO_2 values and lower summer chlorophyll levels in the northern Wadden Sea are in line with a generally lower eutrophication status of the northern Wadden Sea.

Figure 5.10: Annual and seasonal ammonium cycle in the Dutch Wadden Sea. Data: TMAP Data Units and DONAR.

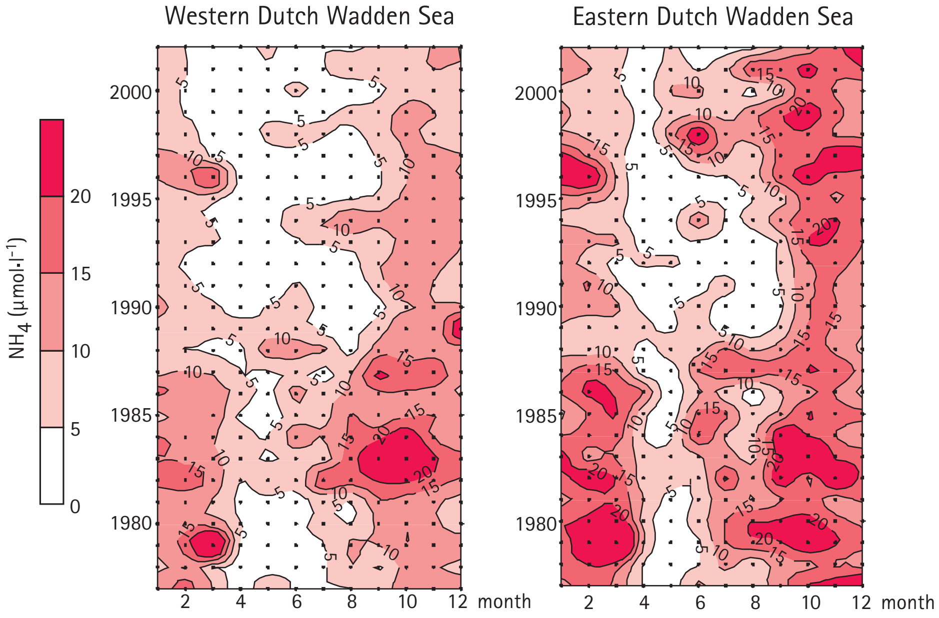


Figure 5.11 (left): Annual and seasonal ammonium cycle in the Niedersachsen Wadden Sea (Norderney). Data: TMAP Data Units and NLÖ (M. Hanslik).

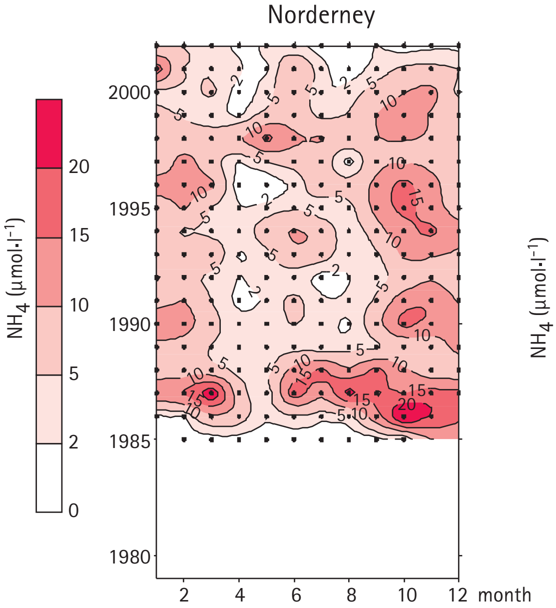
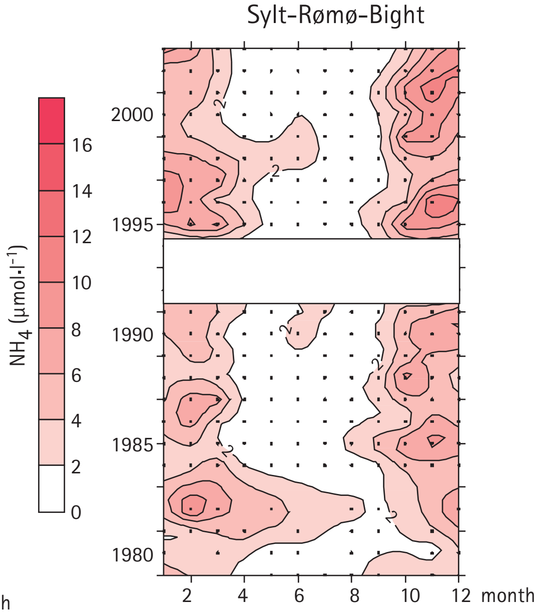


Figure 5.12 (right): Annual and seasonal ammonium cycle in the North Frisian Wadden Sea (Sylt Rømø Bight). Data: TMAP Data Units and AWI (J. van Beusekom).



5.2.4 Effects of decreased nutrient input

Within the framework of the Dutch EVA-II project evaluating the effects of shellfish fishery a model study was carried out on the effects of decreased riverine nutrient inputs in the western Dutch Wadden Sea (Brinkman and Smaal, 2003). The model showed a response in the form of decreased primary production, and therefore a decreased carrying capacity for filter feeding bivalves. Good field data for filter feeders, however, is not available to prove or refute the outcome of the model.

5.2.5 Target evaluation

Targets on the chemical quality of the Wadden Sea ecosystem aim at natural levels of nutrient concentrations and nutrient input. They are prerequisite for a naturally developing phytoplankton and phytobenthos.

Background concentrations of NH_4+NO_2 in autumn as a proxy of organic matter turnover in the Wadden Sea have been estimated at about 3 µM for the western Dutch Wadden Sea (van Beusekom *et al.*, 2001; van Beusekom, 2005). Background TN concentrations of about 45 µM (~0.6 mg/l) for rivers entering the North Sea have been estimated by Laane (1992) being about 7-8 times lower than present values of about 4-5 mg/l (Figure 5.3, left panel).

Riverine nutrient input shows a gradual decrease and the Wadden Sea ecosystem is responding: In several areas, summer chlorophyll levels and the intensity of organic matter turnover (using NH_4+NO_2 as a proxy) decrease and correlations with riverine nutrient input exist. The combination of dry years (low nutrient loads) and decreasing TN concentrations in the rivers Rhine and Meuse have lead to rather low TN loads during the 1990s. Still, NH_4+NO_2 levels are about 50% higher than those observed during the 1960's and about three times higher than under non-problem conditions (Table 5.5).

No background values for nutrients have been specifically deduced here for the other parts of the Wadden Sea or the North Sea coast because little reliable data exists from a time of low anthropogenic influences (OSPAR, 2000; Bakker *et al.*, 1999).

As a first approximation it can be assumed that all Wadden Sea areas have a similar relative deviation from pristine conditions as in the western Dutch Wadden Sea (Table 5.5; compare van Beusekom *et al.*, 2001). Comparing the background estimates with recent values shows that the entire Wadden Sea is a 'Eutrophication-Problem-Area' with present levels being three to five times higher than under pre-industrial conditions. This implies that the target has not been reached yet.

5.3 Conclusions

5.3.1 Main Results

The main results are grouped according to the categories used in the OSPAR 'Comprehensive Procedure'.

5.3.1.1 Category I: Nutrients

Riverine nutrient input showed a gradual decrease during the period 1997-2002. This is reflected by the phosphate concentrations in winter in the Wadden Sea that decreased since the mid 1980's to winter levels of about 1 µM. Salinity normalized nitrate + nitrite concentrations in the German Bight in winter reflect the decreasing TN load, but in the Wadden Sea proper no consistent trend is yet detectable.

5.3.1.2 Category II: Direct effects on primary producers

The decreasing nutrient input (TN loads by Rhine and Meuse) had a significant effect on the phytoplankton biomass (as chlorophyll) in summer in most of the southern Wadden Sea. In the northern Wadden Sea a less clear picture emerges. Only in the Sylt-Rømø-Bight, decreasing summer chlorophyll levels correlate with riverine TN input.

Western Dutch Wadden Sea (1977-2002)

Dependent:	Sum of NH_4 and NO_2 (Month 9-11)
Independent:	Rhine/Meuse TN load (Month 12-8)
Covariable:	Chlorophyll (Month 9-11), Temperature (Month 9-11)

Results

N=26	p=0.00078	R²=0.53	Outlier: none
Variable	Beta	B	P
TN load	0.66	0.00005	0.0003
Chl a	-0.11	-0.15	0.46
Temp	0.14	0.77	0.238

One outlier identified. Omission would increase R² from 0.53 to 0.56

Eastern Dutch Wadden Sea (1977-2002)

Dependent:	sum of NH_4 and NO_2 (Month 9-11)
Independent:	Rhine/Meuse TN load (Month 12-8)
Covariables:	Chlorophyll (Month 9-11), Temperature (Month 9-11)

Results

N=26	p=0.0081	R²=0.408	Outlier: none
Variable	Beta	B	P
TN load	0.36	0.00003	0.045
Chl a	-0.40	-0.62	0.029
Temp	0.20	1.16	0.25

No outliers identified.

Niedersachsen Wadden Sea (1986-2001)

Dependent:	sum of NH_4 and NO_2 (Month 9-11)
Independent:	Rhine/Meuse TN load (Month 12-8)
Covariables:	Chlorophyll (Month 9-11), Temperature (Month 9-11)

Results

N=16	p=0.15	R²=0.346	Outlier: none
Variable	Beta	B	P
TN load	0.60	0.00003	0.029
Chl a	-0.23	-0.47	0.36
Temp	-0.20	-0.96	0.44

No outliers identified.

Table 5.4: Results of the multiple regression between TN input via Rhine and Meuse and the N remineralisation in the Wadden Sea.

Toxic blooms are observed in all parts of the Wadden Sea, but no increasing trend or relations with nutrient input are evident. The most conspicuous blooms were observed in 1998 and 2000 along the Danish west coast, and were large, ichthyotoxic *Chattonella* blooms. The main nuisance blooms were due to *Phaeocystis*. Long-term data from the Marsdiep (western Dutch Wadden Sea) shows a decreasing trend in bloom duration. Present macroalgae abundance is below the maximum levels observed during the early 1990s.

5.3.1.3 Category III: Direct effects on organic matter

The decreasing nutrient input (TN loads by Rhine and Meuse) had a significant effect on the autumn NH_4+NO_2 values in the southern Wadden Sea. The autumn NH_4+NO_2 values are a good indicator of organic matter turnover in the southern Wadden Sea.

In the northern Wadden a less clear picture emerges. In the Sylt-Rømø-Bight an increasing trend of autumn NH_4+NO_2 values was observed suggesting an increased organic matter turnover but a decreasing trend in autumn NO_3 values was

Table 5.5:
Classification of the Wadden Sea into Non-Problem, Potential Problem and Problem Areas based on autumn concentrations of NH_4+NO_2 (µM) as proposed by van Beusekom *et al.* (2001) and modified with data from the recent study. The division into sub-regions is based on the availability of seasonal data. The present autumn values refer to values during the period 1997-2002. Non-problem conditions were based on background values for the western Dutch Wadden Sea. Values for the other areas are proportionally assigned on the basis present day values (1997-2002). Values for the Sylt Rømø Bight are based on the measured data and not calculated as in the table presented by van Beusekom *et al.* (2001). All threshold values were formally derived and an uncertainty range of ± 1µM should be added.

Area	Non-Problem conditions	Potential Problem conditions	Problem conditions	'Present' values (1997-2002)
Western Dutch Wadden Sea	<3.0 µM	3.0 µM <> 8.3 µM	> 8.3 µM	9.9 µM
Eastern Dutch Wadden Sea	<4.0 µM	4.0 µM <> 10.2 µM	> 10.2 µM	19.8 µM
Niedersachsen Wadden Sea	<3.2 µM	3.2 µM <> 8.2 µM	> 8.2 µM	10.1 µM
Sylt Rømø Bight	<1.9 µM	1.9 µM <> 4.2 µM	> 4.2 µM	6.1 µM
Danish Wadden Sea	<2.5 µM	2.5 µM <> 6.5 µM	> 6.5 µM	10.2 µM

observed that correlated with TN input. Data from the other parts of the northern Wadden Sea did not reveal any trends.

5.3.1.4 Regional differences

The data analysis highlights regional differences in Wadden Sea eutrophication. In general, the summer phytoplankton biomass and the autumn NH_4+NO_2 values in the southern Wadden Sea are about twice as high as in the northern Wadden Sea. This suggests a more intense eutrophication of the southern Wadden Sea. The reason for this fundamental difference is not yet known, but a possible relation with a more efficient particle accumulation in the southern Wadden Sea has been proposed (van Beusekom *et al.*, 2001). The geographical distribution of phytoplankton biomass reflects the importance of nutrient loads as higher values are observed near the main freshwater sources (Rhine-Meuse-IJsselmeer and Elbe-Weser).

5.3.1.5 Background values

Compared to background TN concentrations of about 45 µM (~0.6 mg/l) in rivers entering the North Sea (Laane, 1992) present day mean TN values of 4-5 mg/l are about 7-8 times higher. The present day organic matter turnover rates in the Wadden Sea (as indicated by NH_4+NO_2 values) are about 3-5 times higher than the rates expected with background riverine TN loads (Table 5.5). Van Raaphorst *et al.* (2000) estimated a background TN concentration in the Wadden Sea of 17 µM, being 6-7 times higher than present TDN (Total Dissolved Nitrogen) values. Brockmann *et al.* (2004) developed background values of TN and chlorophyll-*a* for the German Bight. They found about 3-5 times higher TN and chlorophyll levels in the Wadden Sea as compared to pristine conditions.

5.4 Recommendations

5.4.1 Management

The target of a Wadden Sea without eutrophication problems has not yet been reached. Therefore it is recommended continuing to implement current policies to reduce nutrient input, especially with regard to nitrogen compounds.

5.4.2 Monitoring and research

5.4.2.1 Comparison between the northern and southern Wadden Sea

The present study reveals some fundamental differences between the southern and northern Wadden Sea: In the southern Wadden Sea summer chlorophyll levels are found twice as high as in the northern part despite similar winter nutrient concentrations. NH_4+NO_2 also reach about two times higher levels in the southern parts compared to the northern parts. Also, suspended matter concentrations in the southern Wadden Sea are higher than in the northern Wadden Sea. A possible explanation is that the southern Wadden Sea accumulates suspended matter and organics more efficiently. Research directed towards understanding the differences between the northern and the southern Wadden Sea should be supported.

5.4.2.2 Exchange rates with the North Sea

In order to compare nutrient concentrations in the different parts of the Wadden Sea, especially if they are locally produced (such as NH_4 or NO_2) the residence time of water in different tidal basins should be known. Up to now, no estimates of residence times have been calculated for the entire Wadden Sea using the same methodology or model data.

5.4.2.3 Influence of filter feeders: in particular of new invaders

The present study suggests that summer chlorophyll levels may be used as an indicator of the eutrophication status because of the significant correlation with riverine nutrient input in some areas. In order to use this parameter as an assessment criterion, the role of suspension feeders in the summer chlorophyll dynamics should be investigated. Special emphasis should be directed toward invaders. *Crassostrea* and *Crepidula* are invaders, important filter feeders and recent trends towards warmer winter and summers suggest an enhanced spread (Diederich *et al.*, 2005; Thieltges *et al.*, 2004). Also, meroplankton data from the northern Wadden Sea shows an enhanced occurrence of larvae from *Ensis americanus* (M. Strasser, pers. comm.). It therefore remains an open question whether the recent decline in summer chlorophyll levels is due to a decreased riverine nutrient input or to increased filtration rates.

5.4.2.4 Importance of coverage of the entire seasonal cycle

The present study was based on nutrient and chlorophyll data that covers the entire annual cycle with a resolution of at least once a month and preferably more frequently during the growth season in order not to miss peaks in chlorophyll abundance. Not all monitoring programs have the necessary temporal resolution. Care should be taken that also in the future such data is available and that temporal and spatial resolution of monitoring programs is extended.

5.4.2.5 Residual nutrient potential in sediments

In order to estimate how fast the Wadden Sea can adapt to decreasing nutrient loads, the nutrient release from Wadden Sea sediments, especially from buried organic matter in deeper sediment layers, should be assessed.

5.4.2.6 Oxygen dynamics

The use of daily oxygen dynamics (production during the day, remineralisation during day and night) as an indicator of organic matter dynamics should be explored. Commercial sensor packages are available that guarantee a long stability of the sensors.

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