WADDEN SEA ECOSYSTEM No. 25

Quality Status Report 2009
Thematic Report No. 6

Eutrophication

J.E.E van Beusekom

P.V.M. Bot

J. Carstensen

J.H.M. Goebel

H. Lenhart

J. Pätsch

T. Petenati

T. Raabe

K. Reise

B. Wetsteijn

2009
Common Wadden Sea Secretariat
Trilateral Monitoring and Assessment Group

Colophon

Publisher
Common Wadden Sea Secretariat (CWSS), Wilhelmshaven, Germany;
Trilateral Monitoring and Assessment Group (TMAG).

Editors
Harald Marencic, Common Wadden Sea Secretariat (CWSS)
Virchowstr. 1, D - 26382 Wilhelmshaven, Germany

Jaap de Vlas, Rijkswaterstaat, Waterdienst
NL - Lelystad, The Netherlands

Language support
Seabury Salmon

Lay-out and technical editing
Common Wadden Sea Secretariat

Graphic support
Gerold Lüerßen

Published
2009

ISSN 0946-896X

This publication should be cited as:
J.E.E. van Beusekom, P.V.M. Bot, J. Carstensen, J.H.M. Goebel, H. Lenhart, J. Pätsch, T. Petenati, T. Raabe, K. Reise and B. Wetsteijn, 2009. Eutrophication. Thematic Report No. 6. In: Marencic, H. & Vlas, J. de (Eds.), 2009. Quality Status Report 2009. WaddenSea Ecosystem No. 25. Common Wadden Sea Secretariat, Trilateral Monitoring and Assessment Group, Wilhelmshaven, Germany.

1. Introduction

Eutrophication is one of the factors that influences 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 in nutrient concentrations 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.*, 1999a). Recently, decreasing riverine nutrient loads and decreasing phytoplankton standing stock have been observed in the Wadden Sea (Cadée and Hegeman, 2002; van Beusekom *et al.*, 2009).

A trilateral target was adopted to aim for "A Wadden Sea which can be regarded as a eutrophication non-problem area". The concept of the eutrophication problem and non-problem-areas was introduced in the framework of OSPAR (1997).

The following sections summarize the findings of the last QSR (Essink *et al.*, 2005), and the results of the OSPAR Common Procedure in 2008. In the chapter 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 QSR 2005 (Essink *et al.*, 2005).

1.1 Finding of the QSR 1999

In the 1999 Wadden Sea Quality Status Report, 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 are correlated with salinity. Therefore, actual concentrations cannot be directly compared unless they are standardized to a specific salinity. Details of the 'concentration – salinity' method are given in de Jong *et al.* (1999). The analysis in the 1999 and 1993 QSRs are based on winter concentrations normalized to standard salinities of 10 and 27. A decrease was observed for phosphate (PO_4, dissolved inorganic phosphorus or DIP), but no trend was observed for nitrogen nutrients. The QSR 1999 also stated that reductions in phosphate had 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.

1.2 Findings of the QSR 2004

In contrast to the 1999 QSR, the QSR 2004 (van Beusekom *et al.*, 2005) could demonstrate a decrease in riverine nutrient input. The effect on the eutrophication status was shown by two indicators: autumn NH_4+NO_2 concentrations (developed as a Wadden Sea Specific Eutrophication Criterion, [van Beusekom *et al.*, 2001] and applied in the 2004 QSR) and mean summer chlorophyll (developed for the QSR 2004).

Category I: Nutrients.

Riverine nutrient input showed a gradual decrease during the period 1997-2002. This was reflected by the phosphate concentrations in winter in the Wadden Sea that decreased since the mid 1980s 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 was detectable yet.

Category II: Direct effects on primary producers

Decreasing riverine TN loads had a significant effect on the phytoplankton biomass (as chlorophyll) in summer in most of the Southern Wadden Sea. In the Northern Wadden, a less clear picture emerges. Only in the List Tidal Basin, (decreasing) summer chlorophyll levels correlate with riverine TN input.

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, with large, ichthyotoxic *Chattonella* blooms. The main nuisance blooms were due to *Phaeocystis*. Long term data from the Marsdiep (Western Dutch Wadden Sea) show a decreasing trend in bloom duration. Present macroalgae abundance is below the maximum levels observed during the early 1990s.

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 were a good indicator of organic matter turnover in the Southern Wadden Sea, but not for the central and Northern Wadden Sea.

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 or more complex interactions 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.

Regional differences

The data analysis highlighted 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 were about two times higher than in the Northern Wadden Sea, suggesting a more intense eutrophication of the Southern Wadden Sea.

Background values

Compared to background TN concentrations in rivers entering the North Sea, mean TN values of 4-5 mg/l (~1990 – 2000) were about 7-8 times higher. The organic matter turnover rates in the Wadden Sea were estimated to be about 3-5 times compared to pristine conditions (van Beusekom, 2005).

1.2 OSPAR Eutrophication Assessment 2008 according to the Comprehensive Procedure

The OSPAR convention area was assessed with the Comprehensive Procedure for the period 2000 – 2005 (OSPAR 2008). The Wadden Sea was classified as a eutrophication problem area by Denmark, Germany and The Netherlands. As criteria, deviations from background levels were used. All three countries used nutrient enrichment, elevated chlorophyll levels, problems with nuisance algae and algal toxins/toxic algae as criteria. Differences and uncertainties in the assessment of the eutrophication effects on macroalgae, macrobenthos and oxygen dynamics are apparent (Table 1).

Table 1: Summary of the Wadden Sea Eutrophication Assessment by OSPAR (OSPAR 2008). All three Wadden Sea countries assessed the Wadden Sea as a Problem Area. Key to the table:
–: Neither increased trends nor elevated levels nor shifts nor changes in the respective assessment parameters
+: Increased trends, elevated levels, shifts or changes in the respective assessment parameters
?: Not enough data for an assessment or the data available is not fit for the purpose
Nr: Not relevant.

		The Netherlands	Germany	Denmark
Cat I:	Riverine Input	+	?	-
	Winter Concentrations	+	+	+
	N/P ratios	+	+	-
Cat II:	Chlorophyll levels (Max. and Mean)	+	+	+
	Area specific Phytoplankton Indicator Species	+	+	-
	Macrophytes	?	?	-
Cat III:	Oxygen Problems	-	Nr	-
	Changes/Kills of Macrobenthos	?	?	(+)
	Organic matter/Organic Carbon	-	+	-
Cat IV:	Algal toxins	-		-

2. Data analysis

Data analysis focussed on long (>15 years) time series covering the entire seasonal cycle with a temporal resolution of at least once a month. All available data were summarized to monthly means. We extended the approach adopted in the QSR 2004. In short, we analysed the riverine input and the responses of the different Wadden Sea regions to the riverine input levels. As proxies, we used the autumn levels of ammonium and nitrite (based on Wadden Specific Eutrophication Criteria, van Beusekom *et al.*, 2001) and summer chlorophyll levels (QSR 2004). As in the previous assessments, we focussed on nitrogen but acknowledge the conflicting views as to whether nitrogen or phosphorus ultimately limits the production levels in the Wadden Sea in some areas like the Western Dutch Wadden Sea (*e.g.*, Philippart *et al.*, 2007).

2.1 Causative factors

River Input

Riverine input data are based on monitoring data that were interpolated to daily loads (Lenhart and Pätsch, 2001; updated until 2006). The major sources influencing the Southern Wadden Sea are Haringvliet, Maassluis, Noordzeekanaal, IJsselmeer and Ems. The first four 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 QSR 2004.

The high inter-annual variability of riverine nutrient input is largely due to two factors: differences in inter-annual freshwater discharge and a general decrease in nutrient concentrations. Figures 1 and 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. Specific (normalized) nutrient loads (annual nutrient load divided by annual discharge) show a steadily decreasing trend for TN and TP for the major rivers entering the Wadden Sea (Figure 3). Since 1985, the specific TN load to the Southern and Central Wadden Sea decreased on average each year by 2.1%. The specific TP load decreased more strongly than the specific TN load, but during recent years the rate of decrease slows down. It now amounts to 2.9% per year for the Southern Wadden Sea and 2.1% per year for the Central Wadden Sea. Note that during the period 1985-2002 the rates were about 0.4% higher. Especially for the Elbe and Weser, a slow-down in the decrease in specific TP load is evident since about 1990.

Atmospheric Input

In the QSR 2004, a total (wet) nitrogen deposition in the Wadden Sea of about 0.8 g N m^{-2} y^{-1} was estimated (wet + dry deposition: 1.2 g N m^{-2} y^{-1}). Recent estimates in the framework of OSPAR (Bartnicki and Fagerli, 2006) support this estimate. Total annual wet deposition at the OSPAR monitoring station in the Southern Wadden Sea area ranged during 1990 and 2004 between ~700 and ~1200 mg N m^{-2} and in the northern

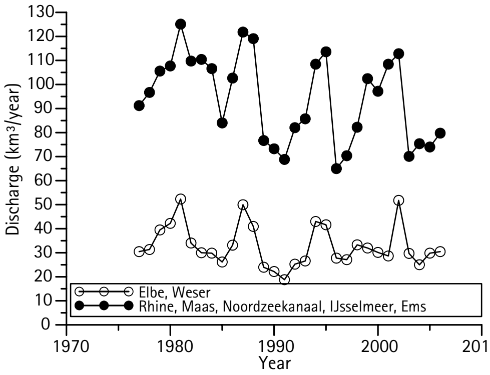


Figure 1: Major annual freshwater discharges influencing the Southern Wadden Sea (Rhine, Meuse, Noordzeekanaal, IJsselmeer and Ems) and the Central and Northern Wadden Sea (Weser, Elbe). Data source: DONAR, Lenhart & Pätsch (2001), updated to 2006.

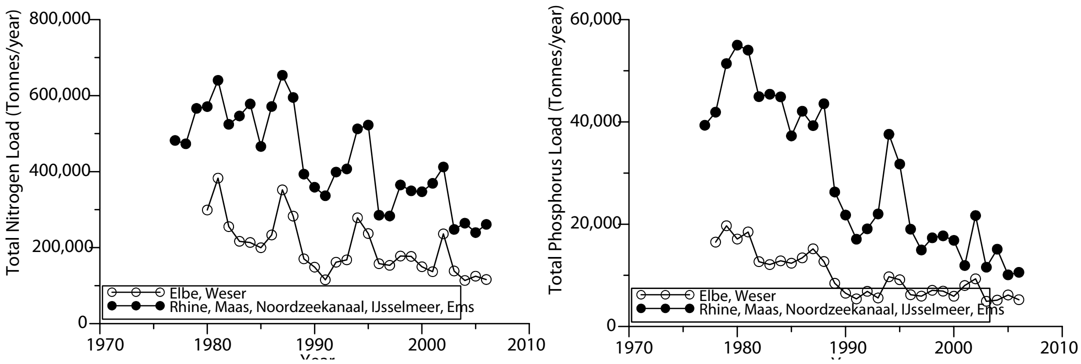
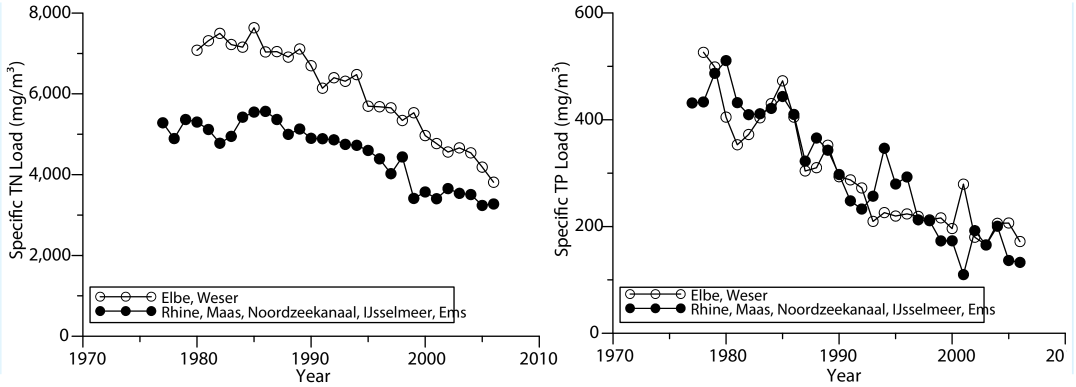


Figure 2: Major riverine TP and TN loads to the Southern Wadden Sea (Rhine, Meuse, Noordzeekanaal, IJsselmeer and Ems) and to the Central and Northern Wadden Sea (Weser, Elbe). Data source: DONAR, NLWKN, Lenhart and Pätsch (2001), updated to 2006.

Figure 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, NLWKN, Lenhart and Pätsch (2001), updated to 2006.



area between ~550 and ~1000 N m^{-2}. Between 1990 and 2004 no significant reduction in Area 8 (off-shore Wadden Sea and German Bight) occurred. Carstensen *et al.* (2008) analyzed the input data for the Danish Wadden Sea and observed a downward trend between 1990 and 2006.

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 BSH reflect the gradual decrease in riverine nutrient input (Weigelt-Krenz *et al.*, 2010) and show a decrease of DIN (dissolved inorganic nitrogen) at a salinity of 30 from ~60 µM in 1985 to ~45 µM in 2006. 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. In case of significant correlations, the concentration at a salinity of 10 was also estimated. Details of this method are given in the QSR 1999.

Figures 4 and 5 present updates of the QSR 2004 for nitrate and phosphate. The salinity normalized winter nitrate data (at salinity 27) now show a downward trend in some areas since the early 1990s. In the Dutch Wadden Sea, a slight decrease from around 50 µM (early 1990s) dropped to around 40 µM (since 2002). In the Ems river district (Ems estuary and Lower Saxony), winter nitrate decreased from 80 µM (early 1990s) to around 60 µM (since 2002). In Dithmarschen (Eider district), winter nitrate decreased from 70-80 µM (early 1990s) to around 50-60 µM (since 2002). In the North Frisian Wadden Sea and in the Danish Wadden Sea, no clear trends were observed. Salinity normalized concentrations were around 44-49 µM.

Two other studies indicate downward trends in the North Frisian and Danish Wadden Sea. Carstensen (2008) analyzed long-term monitoring data from the Danish Wadden Sea and also observed a decrease in TN levels in the Danish Wadden Sea. Van Beusekom *et al.* (2008) observed a downward long-term trend in winter nitrate concentrations in the List Tidal Basin of about 2% per year. The downward rate compares favourably with a similar riverine trend. The authors observed that, at a given salinity, the nitrate concentrations were always lower than in the adjacent German Bight and concluded that denitrification plays an important role in winter nitrate dynamics.

Salinity-normalized winter phosphate concentrations showed the strongest decrease between 1985 and 1995 (QSR 2004). Since then, no further changes are apparent for most areas and salinity normalized concentrations range between ~0.9 µM in the western Dutch Wadden Sea, and ~1.1 µM in the Danish Wadden Sea to around 1.8 µM near the Ems and Elbe estuaries. Only in the western Dutch Wadden Sea was a further decrease, of 1.4 µM during the early 1990s to about 0.9µM since 2002, observed.

2.2 Direct effects

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. We excluded data from March-April because at least in the North Frisian Wadden Sea the spring phytoplankton dynamics are related to winter temperatures (van Beusekom *et al.*, 2009).

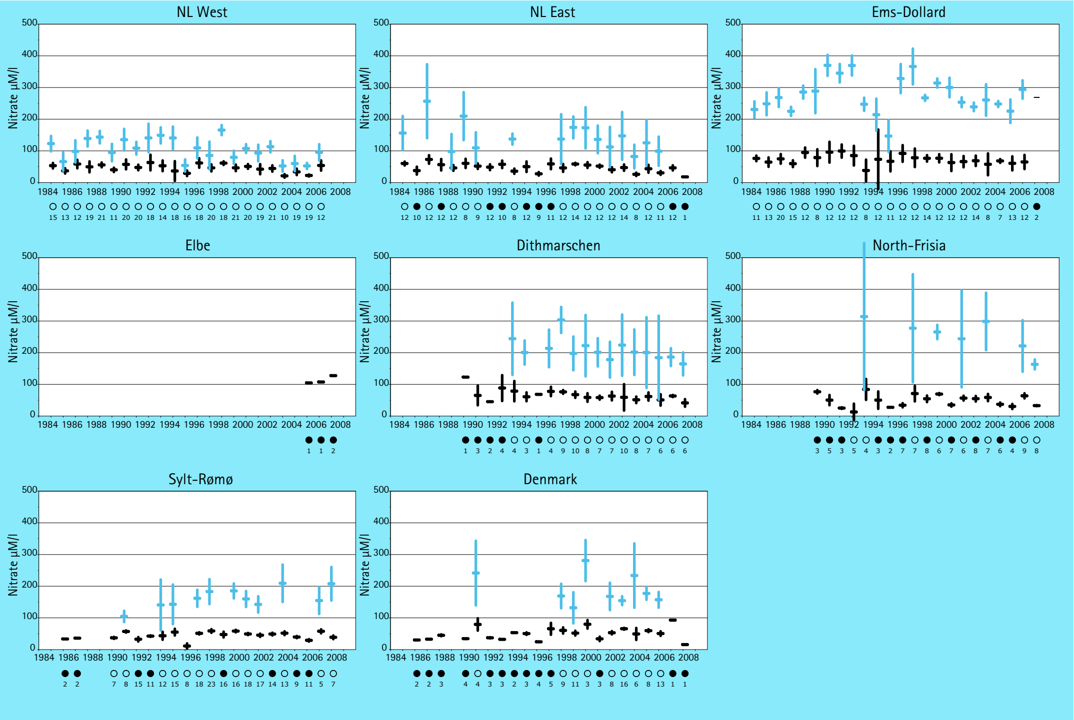


Figure 4: Trends in winter nitrate+nitrite concentrations (µM/l) (December-February) in the river basin districts of the Wadden Sea. The concentrations and standard deviations are normalized to a salinity of 30 (black symbols) and 27 (black symbols). Open dots below indicate a significant correlation with salinity. In this case, the concentration at salinity 27 was estimated. Solid dots indicate no significant correlation with salinity. Data source: TMAP Data Units.

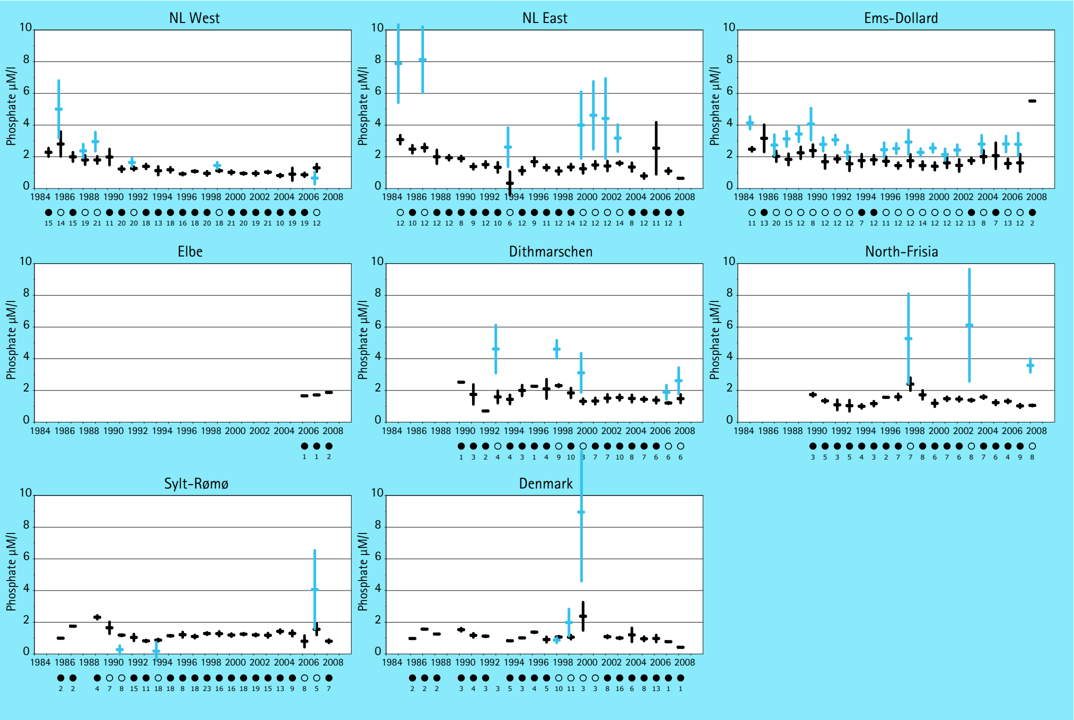


Figure 5: Trends in winter phosphate concentrations (µM/l) (December-February) in the river basin districts of the Wadden Sea. The concentrations and standard deviations are normalized to a salinity of 30 (black symbols) and 27 (black symbols). Open dots below indicate a significant correlation with salinity. In this case, the concentration at salinity 27 was estimated. Solid dots indicate no significant correlation with salinity. Data source: TMAP Data Units

Table 2:
Comparison of summer chlorophyll levels (µg/l; May-September) in different parts of the Wadden Sea (2000-2006) and their correlation with TN input (December-August) via Rhine and Meuse (Dutch Wadden Sea, Norderney) or via Weser and Elbe (Schleswig-Holstein, List Tidal Basin, Gradyb). For comparison, background values are included that were taken from the national reports prepared for the Second OSPAR Eutrophication Integrated Report on Eutrophication.
Data source: TMAP Data Units, DONAR (P. Bot), LANU (T. Petenati, J. Goebels), NLWKN (M. Hanslik), AWI (J. van Beusekom), Lenhart & Pätsch (2001, updated until 2006), DMU (J. Carstensen).

Area	Period	Trend	Correlation	Summer mean (2000-2006)	Background
Western Dutch Wadden Sea	1976-2006	Yes	r^2=0.59; n=30; p<0.0001	9.7 µg Chl/l	8 µg Chl/l
Eastern Dutch Wadden Sea	1976-2006	No	r^2=0.00; n=30; p=0.87	19.9 µg Chl/l	8 µg Chl/l
Lower Saxon Wadden Sea (Norderney)	1988-2006	Yes	r^2=0.450; n=22; p=0.0006	11.5 µg Chl/l	2-3 µg Chl/l
Southern Schleswig-Holstein	1998-2006	No*	r^2=0.00; n=9; p=0.98	12.8 µg Chl/l	2-3 µg Chl/l
Northern Schleswig-Holstein	1998-2006	No*	r^2=0.07; n=9; p=0.478	5.4 µg Chl/l	2-3 µg Chl/l
List Tidal Basin[1]	1984-2006	Yes**	r^2=0.31; n=23; p=0.0056	5.9 µg Chl/l	2-3 µg Chl/l
Gradyb[2]	1990-2006	Yes*	r^2=0.36; n=17; p=0.01	12.5 µg Chl/l	2 µg Chl/l

* Elbe/Weser Input (Jan.–Aug.).
** Also a significant trend with Rhine Meuse Input (Dec.-Aug.: r^2=0.345; n=23; p=0.003).
[1] Only German Data (AWI)
[2] Outlier: 2004.

The data analysis in the QSR 2005 was already based on this time window. The available data are summarized in Table 2. Long time series (18-30 years: Dutch Wadden Sea, Norderney, Sylt, Grådyb) that cover the entire seasonal cycle are shown in Figures 6 a-d. Recently, doubts arose whether the chlorophyll measurements by the different agencies and research institutes were comparable. We summarized the applied techniques in Table 3.

Western Dutch Wadden Sea

Cadée and Hegeman (2002) summarized trends in phytoplankton biomass and productivity at the NIOZ time series station in the Marsdiep area (Western Dutch Wadden Sea). They observed an increase in primary production from about 100-150 gC m^{-2} y^{-1} in 1965 to about 400 gC m^{-2} y^{-1} in 1994. Since then a decrease to values of about 200 gC m^{-2} y^{-1} was 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 nutrient-rich but phosphorus-controlled period (1974 - 1977), a more eutrophic, nitrogen-limited period (1978 - 1987) and a phosphate-limited period (1988-1993).

Philippart *et al.* (2007) re-analyzed primary production data by Cadée and Hegeman (2002) and reported lower primary production levels decreasing from a maximum of about 200 gC m^{-2} y^{-1} around 1990 to 150 gC m^{-2} y^{-1} since 2000. They observed a weak correlation between phytoplankton biomass and the limiting nutrients phosphate and silicon.

The present analysis (based on Dutch monitoring data) shows that mean summer chlorophyll levels (May-September) decreased from about 20 µg Chl-*a*/l in1976-1985 to about 11 µg Chl-*a*/l in 1996-2002 and 9.7 µg/l in the period 2000-2006.

Eastern Dutch Wadden Sea

Mean summer chlorophyll levels (May-September; Dutch Monitoring programme) amount to about 20 µg Chl-*a*/l and are the highest in the Wadden Sea. They show no decreasing trend. The mean for the period 2000-2006 is 19.9 µg Chl-*a*/l.

Table 3:
Methods used for determining Chlorophyll-*a*

Area	Period	Apparatus	Methods
Dutch Wadden Sea	1976-1988	Spectrophotometry	
Dutch Wadden Sea	1989-2006	HPLC	
Lower Saxon Wadden Sea (Norderney)	1988-2006	Spectrophotometry	Strickland and Parson
Southern Schleswig-Holstein	1998-2006	Spectrophotometry	Jeffrey & Humphrey (1975)
Northern Schleswig-Holstein	1998-2006	Spectrophotometry	Jeffrey & Humphrey (1975)
List Tidal Basin	1984-2006	Spectrophotometry	Jeffrey & Humphrey (1975)
Danish Wadden Sea	1990-2006	Spectrophotometry	

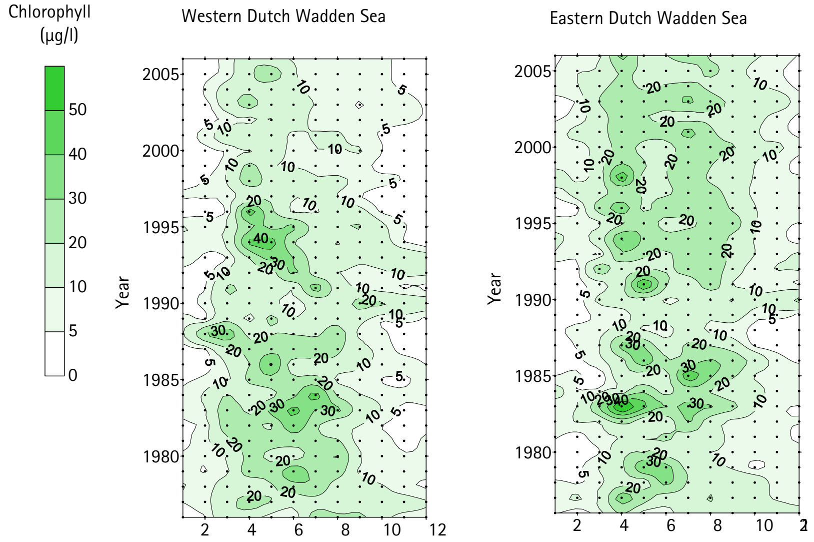
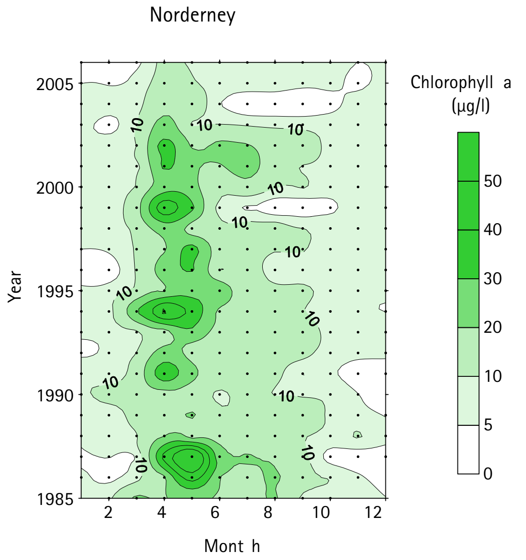


Figure 6a: Seasonal cycle of chlorophyll *a* in the Western and Eastern Dutch Wadden Sea, 1976-2006 Data source: TMAP Data Units and DONAR.



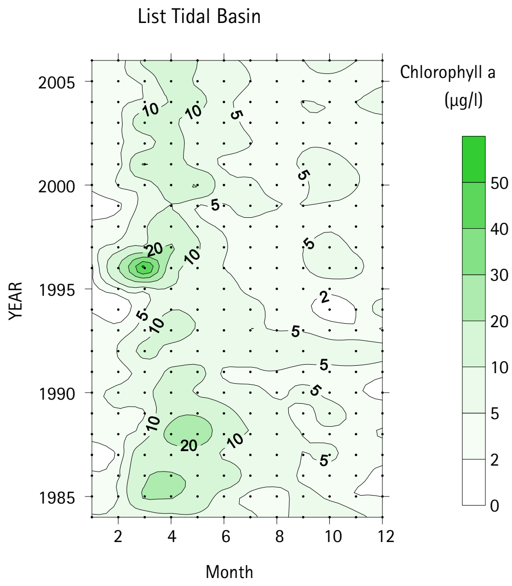


Figure 6b (left): Seasonal cycle of chlorophyll *a* in the Lower Saxonian Wadden Sea (Norderney), 1985-2006. Data source: TMAP Data Units and NLWKN (M. Hanslik).

Figure 6c (right): Seasonal cycle of chlorophyll *a* in the Northfrisian Wadden Sea (List Tidal Basin), 1984-2006. Data source: AWI (J. van Beusekom).

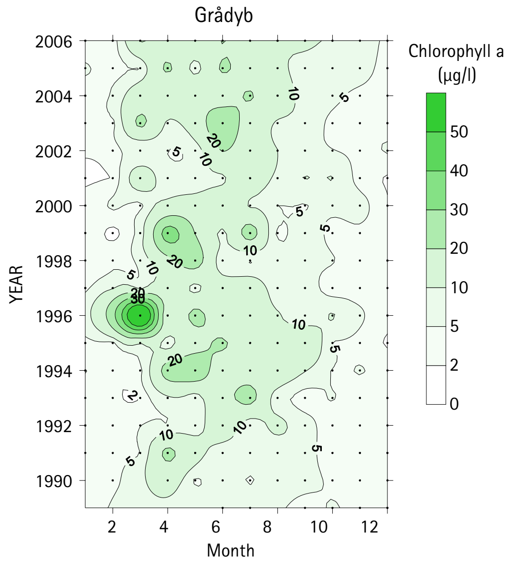


Figure 6d: Seasonal cycle of chlorophyll *a* in the Grådyb (Danish Wadden Sea), 1985-2006. Data source: DMU (J Carstensen)

Lower Saxon Wadden Sea

Mean summer chlorophyll concentrations at Norderney are similar to the Western Dutch Wadden Sea but lower than in the Eastern Dutch Wadden Sea. We observe a decreasing trend from about 20 µg Chl-*a*/l around 1990 to 11.5 µg during 2000-2006.

Schleswig-Holstein Wadden Sea

Primary production is not generally measured in the Schleswig-Holstein Wadden Sea. Loebl *et al.* (2007) reported an annual production of about 150 gC m^{-2} y^{-1} for the List Tidal Basin. Summer chlorophyll concentrations in the Northern Wadden Sea are generally lower than in the Southern Wadden Sea (J. Goebel, *pers. comm.*). Also, during the years 2000-2006, highest values prevailed south of the peninsula Eiderstedt in the vicinity of the estuaries of the rivers Weser and Elbe (12.8 µg Chl-*a*/l), decreasing to 5.4 µg Chl-*a*/l south of the island Amrum and 5.9 µg Chl-*a*/l in the List Tidal Basin (aka Sylt Rømø Bight). It should be noted that at a station in the Elbe Estuary (salinity ~25), a high mean value of about 20 µg Chl-*a*/l was found, but levels rapidly declined towards the German Bight.

Danish Wadden Sea

For the Lister Dyb (List Tidal Basin) and the Grådyb, continuous observations are present since the end of the 1980s. Chlorophyll estimates of two stations in the List Dyb area from the Danish monitoring programme of 6.0 and 8.2 µg/l (2000-2006) are in good agreement with the above mentioned German (AWI) data. Scattered summer chlorophyll data from the Juvre and Knude Dyb also indicated low summer chlorophyll levels, between 5 and 7 µg Chl-*a*/l. In the Grådyb – the northern edge of the Wadden Sea – higher mean summer values of about 12.5 µg Chl-*a*/l were observed.

Spatial Trends

Figure 7 summarizes the mean summer levels found during the period 2000-2006. In general, levels in the Southern Wadden Sea (about 10-20 µg Chl-*a*/l) are higher than in the Central and Northern Wadden Sea (5-13 µg Chl-*a*/l), but locally high values are also found in the Elbe estuary.

Relation with riverine Total Nitrogen input

To investigate the role of riverine nitrogen input on the summer chlorophyll levels, we distinguished

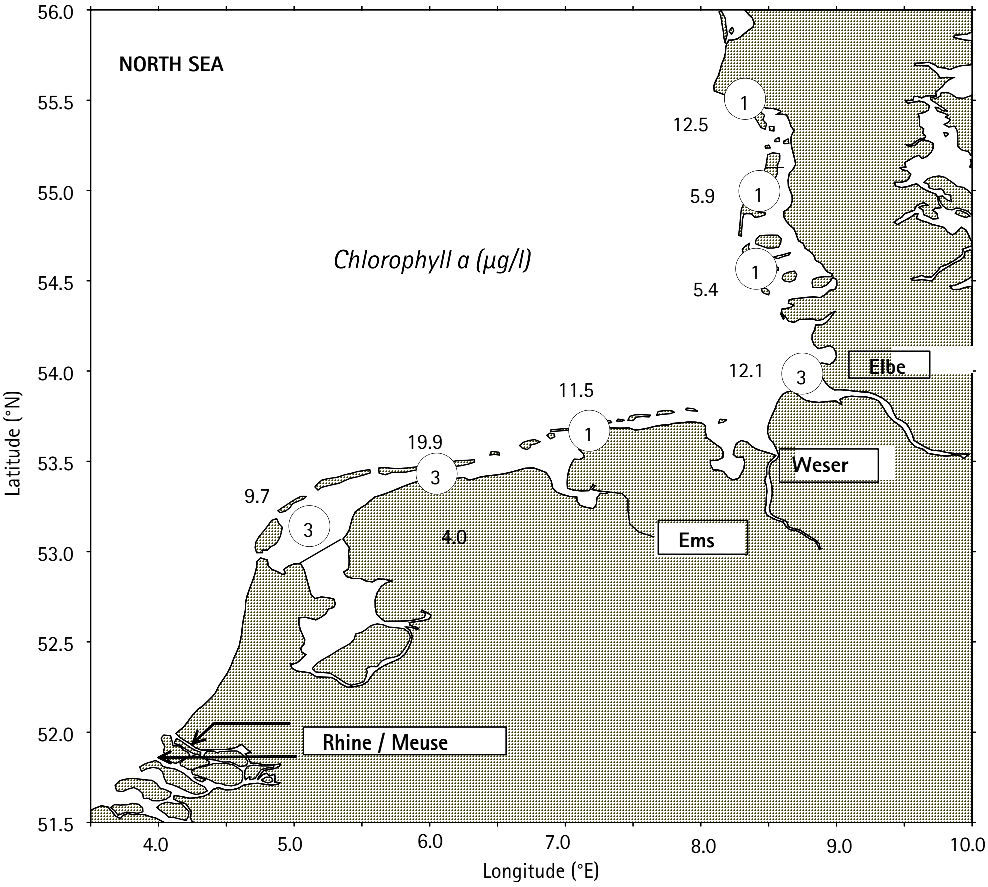


Figure 7: Spatial distribution of summer chlorophyll *a* (May-September) in the Wadden Sea during 2000-2006. Circles indicate the area considered and numbers inside indicate the number of stations used for the mean.

two areas. For the Southern Wadden Sea we used the Total Nitrogen load by the rivers Rhine and Meuse; for the Northern Wadden Sea we used the Total Nitrogen load by the rivers Weser and Elbe. We used the Total Nitrogen Input from December until August for the southern Wadden Sea and January-August for the Weser/Elbe. We did not use input data after August, as they cannot have a significant effect on the summer chlorophyll levels. These time windows were already used for the development of the Wadden Sea Eutrophication Criteria (van Beusekom *et al.*, 2001).

Significant correlations between chlorophyll summer means and riverine Total Nitrogen input via Rhine and Meuse were identified for the Western Dutch Wadden Sea and for Norderney (Lower Saxonian Wadden Sea). Significant correlations with riverine Total Nitrogen input via Weser and Elbe were identified in the Northern Wadden Sea for the List Tidal Basin (AWI-Sylt) and for the Grådyb (one outlier). In the Southern Wadden Sea, a larger part of the variability was explained by TN input (45-59%) than in the Northern Wadden Sea (31-36%). In all cases where a significant correlation with riverine TN input was found, summer chlorophyll levels significantly decreased with time. It is interesting to note that the inter-annual variability of summer chlorophyll levels in the list Tidal Basin could be explained by both the riverine TN input via Elbe and Weser and via the Rhine/Meuse. 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 1-3) and significantly correlate (QSR 2004). The above analysis confirms the results of the chlorophyll analysis in the QSR 2004. In addition, a significant correlation is now also observed for the Grådyb (Danish Wadden Sea). Based on the above results, we conclude that summer chlorophyll levels are a good indicator of the eutrophication status of the Wadden Sea.

Toxic and nuisance blooms

Dutch Wadden Sea

In general, no relation between toxic or nuisance species and nutrients was found (van Duren, 2006). Between 2000 and 2005, *Chrysochromulina* exceed reverence levels (10^6/l) six times, *Dinophysis* spec. exceeded reverence levels (10^2/l) six times and *Phaeocystis* exceeded reverence levels (10^7/l) seven times.

Lower Saxon Wadden Sea

Dinophysis is regularly found at numbers near the reference level (10^2/l), but in 2002 and 2005 this threshold was clearly exceeded. *Pseudonitzschia* sp. bloomed abundantly in 2005 with cell numbers exceeding $2*10^6$/l. *Phaeocystis* remains a major bloomer each year especially during 2004 and 2005. However, in general, the situation was regarded as non problematic.

Schleswig-Holstein Wadden Sea

Phaeocystis dominates the spring phytoplankton bloom each year after the demise of the diatom bloom, with cell numbers well above (10^6/l). In 2002 and 2003 *Dinophysis* exceeded the reference level (10^2/l) near the Danish border and near the Elbe estuary. *Alexandrium* reached elevated numbers only in 2001 and 2004.

Danish Wadden Sea

Blooms of *Phaeocystis* are observed almost every year in Grådyb (May-July) following the spring diatom bloom that is typically dominated by *Skeletonema costatum*. These blooms in Grådyb typically coincide with high *Phaeocystis* concentrations in the North Sea off the Danish Wadden Sea, suggesting that blooms in Grådyb could be imported. In List Dyb, blooms of *Phaeocystis* have not been recorded. In May 2004, a bloom of *Chatonella* (~100 µg C l^{-1}) was observed in Grådyb. Other toxic species are occasionally observed, but most commonly in small numbers.

Macroalgae

Compared to rocky shores, macroalgae used to cover sediments only to a minor extent. However, since 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 of the Schleswig-Holstein 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 one with green algae returning back to their marginal occurrences prior to the 1980s.

Based on aerial surveys, Reise (2008) estimated the areal coverage of green macroalgae in the entire Schleswig-Holstein Wadden Sea since

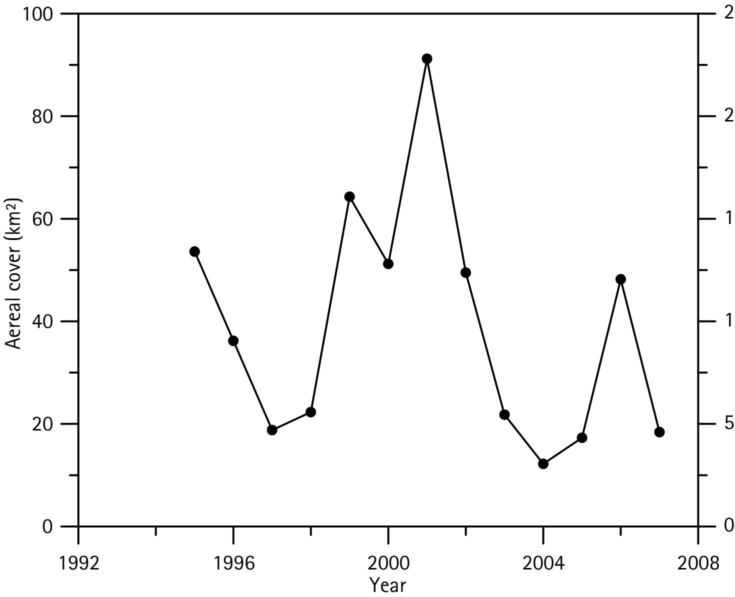


Figure 8a: Time series of area covered with green macroalgae (cover >20%) in the Northern Wadden Sea based on aerial surveys from 1995 until 2007. (Reise, *unpubl.*).

1995. The time series are presented in Figure 8a. Large interannual differences are apparent. The highest coverage was observed in 2001, the lowest in 2004. We investigated a possible relation between riverine TN input and coverage and used the same riverine TN input data used above for the analysis of summer chlorophyll levels in the Northern Wadden Sea (Figure 8b). Using all data, no significant correlation was found. One outlier (2001, year with highest coverage) could be identified. Omitting this year gave a significant correlation with TN input via Weser and Elbe. These results support that in the Wadden Sea, green macroalgae coverage is related to nutrient enrichment via rivers. However, the outlier 2001 and large variability not explained by riverine TN input indicate that other factors are involved in regulating the algae coverage.

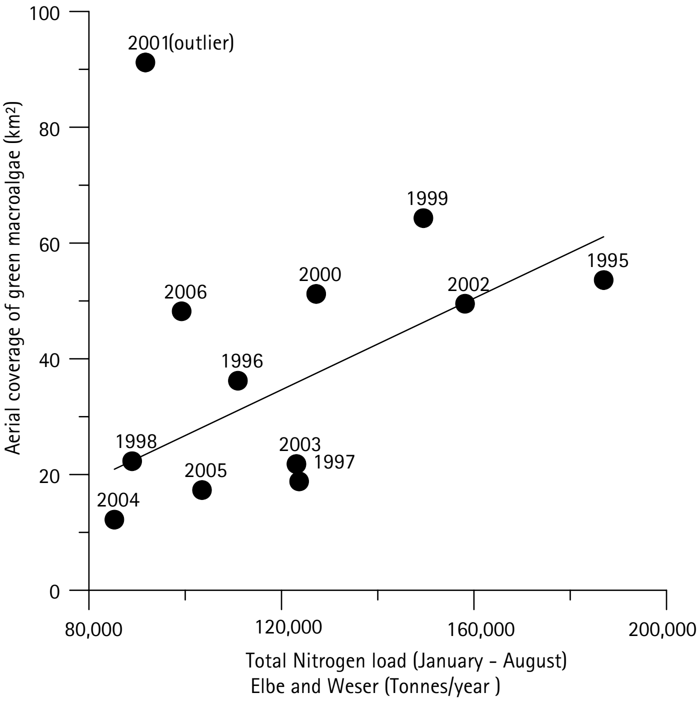


Figure 8b: Relation between area covered with green macroalgae and TN load via Weser and Elbe (total of Jan.-Aug.). One outlier (2001) was identified and excluded from the linear fit.

2.3 Indirect effects

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

In the report on Wadden Sea eutrophication criteria (van Beusekom *et al.*, 2001) it was suggested that the intensity of the seasonal cycle of NH_4+NO_2 (more specifically, the autumn values) should be used 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 9a-9d for the Dutch Wadden Sea, the Lower Saxon Wadden Sea (Norderney), the North Frisian Wadden Sea (List Tidal Basin) and the Grådyb (Danish Wadden Sea). In the Western Dutch Wadden Sea and in the Lower Saxon Wadden Sea (Norderney), a decreasing trend is present during summer and autumn. In the Grådyb, a decrease in summer values is evident.

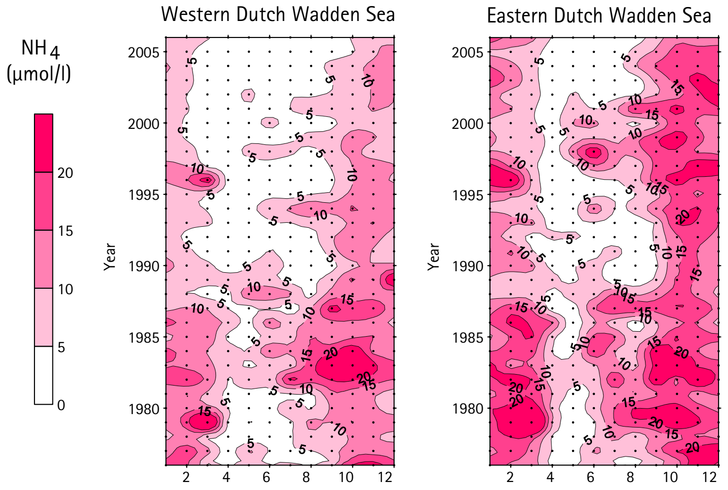


Figure 9a: Annual and seasonal ammonium cycle in the Dutch Wadden Sea. Data source: TMAP Data Units and DONAR.

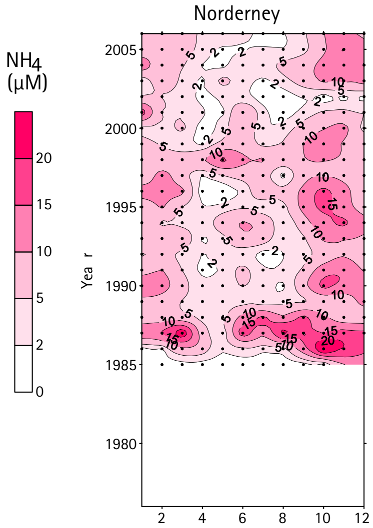


Figure 9b (left): Annual and seasonal ammonium cycle in the Lower Saxonian Wadden Sea/Norderney. Data source: TMAP Data Units and NLWKN (M. Hanslik).

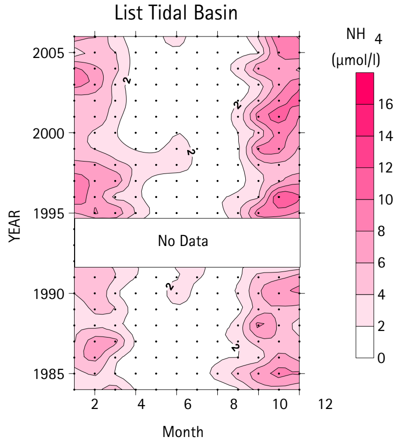


Figure 9c (right): Annual and seasonal ammonium cycle in the North Frisian Wadden Sea (List Tidal Basin). Data source: AWI (J. van Beusekom).

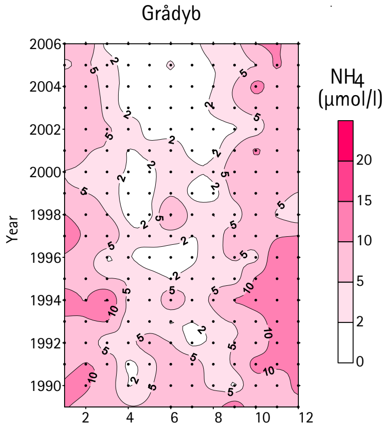


Figure 9d: Annual and seasonal ammonium cycle in the Grådyb (Danish Wadden Sea). Data source: TMAP Data Units and NERI (J. Carstensen).

Table 4:
Results of a multiple regression analysis between TN input via Rhine and Meuse and the autumn N remineralisation in the Wadden Sea.

Western Dutch Wadden Sea (1977-2006)

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

Results:

N=30	p=0.00003	R^2=0.59	Outlier: none
Variable	Beta	B	P
TN load	0.77	0.00005	0.000002
Chl a	-0.08	-0.12	0.53
Temp	0.04	0.76	0.78

One outlier could be identified. Omission would increase R^2 from 0.53 to 0.56

Eastern Dutch Wadden Sea (1977-2006)

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

Results:

N=30	p=0.0034	R^2=0.403	Outlier: none
Variable	Beta	B	P
TN load	0.44	0.00003	0.010
Chl a	-0.36	-0.54	0.033
Temp	0.05	-0.22	0.76

No outliers could be identified.

Lower Saxonian Wadden Sea (1987-2006)

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

Results:

N=20	P=0.042	R^2=0.393	Outlier: none
Variable	Beta	B	P
TN load	0.45	0.00002	0.044
Chl a	-0.51	-0.96	0.031
Temp	-0.24	-0.80	0.30

Period: 1987-2006

The analysis is 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. In the QSR 2004, we noted that significant correlations were only found for the Southern Wadden Sea. The present analysis confirms that the autumn values are good eutrophication indicators for the Southern Wadden Sea (Table 4). Chlorophyll did not significantly influence the relation in the Western Dutch Wadden Sea, but had a significant impact in the Eastern Dutch Wadden Sea and Norderney.

The mean autumn values of NH_4+NO_2 during 2000-2006 are presented in Figure 10. Highest concentrations are found in the southern Wadden. The spatial pattern strongly resembles the summer chlorophyll pattern and a significant correlation exists between both indices (Figure 11). Such a correlation is expected if both parameters are independent eutrophication proxies.

2.4 Effects of decreased nutrient input

The decreased riverine nutrient input since the mid-1980s has led to a lower eutrophication status in the Wadden Sea. We observe decreasing summer chlorophyll levels in the entire Wadden Sea and in the Southern Wadden Sea also a significant decrease in autumn NH_4+NO_2 levels (as a proxy for organic matter turnover). The increase in seagrass and a moderate green macroalgal cover may also be due to a decreasing eutrophication level.

Little information exists on a Wadden Sea-wide scale on the effects of the nutrient reductions on

Table 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 in sub-regions is based on the availability of seasonal data. The present autumn values refer to values during the period 2000-2006. Non-problem conditions were based on background values for the Western Dutch Wadden Sea. Values for the other areas proportionally assigned on the basis of present day values (Beusekom *et al.*, 2001). All threshold values were formally derived and an uncertainty range of ±1 µM should be added.

Area	Non-Problem conditions	Potential Problem conditions	Problem conditions	„Present" values (2000-2006)
Western Dutch Wadden Sea	<3.0 µM	3.0 µM <> 8.3 µM	> 8.3 µM	8.2µM
Eastern Dutch Wadden Sea	<4.0 µM	4.0 µM <> 10.2 µM	> 10.2 µM	16.8µM
Lower Sax. Wadden Sea	<3.2 µM	3.2 µM <> 8.2 µM	> 8.2 µM	9.9µM
List Tidal Basin	<1.9 µM	1.9 µM <> 4.2 µM	> 4.2 µM	5.9µM
Danish Wadden Sea	<2.5 µM	2.5 µM <> 6.5 µM	> 6.5 µM	8.3µM

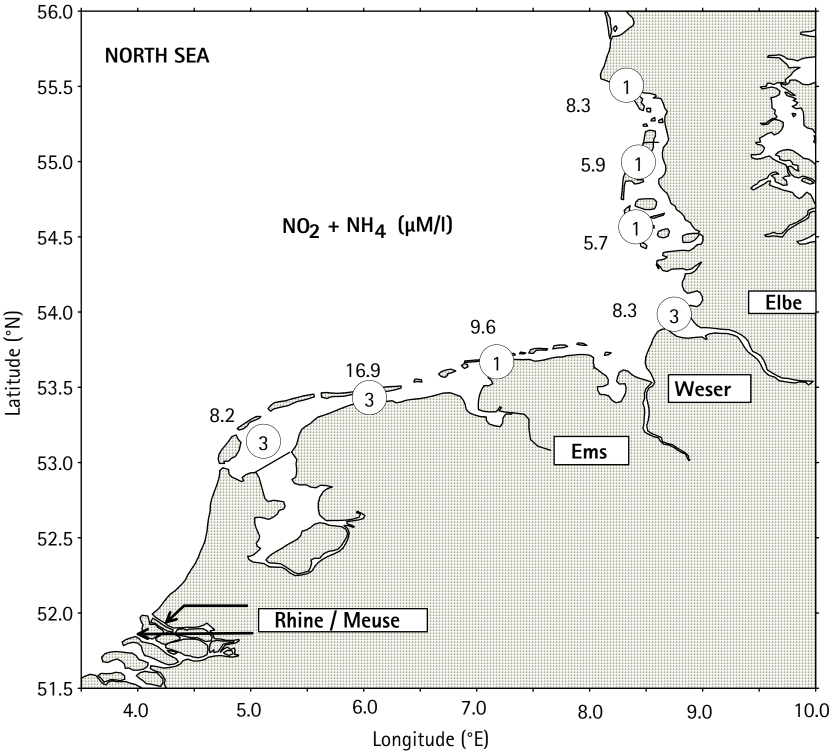


Figure 10: Spatial distribution of Autumn NH_4+NO_2 in the Wadden Sea during 2000-2006. Dots indicate the area considered. Circles indicate the area considered and numbers inside indicate the number of stations used for the mean. No NO_2 data were available for the Grådyb area and we added Wadden Sea average mean of 1.5 μM to an NH_4 value of 6.8 μM.

higher trophic levels. Based on time-series from the Western Dutch Wadden Sea, Philippart *et al.* (2007) also observed reduced primary production in the western Dutch Wadden Sea. The authors concluded that the decrease had repercussions for the entire ecosystem including macrobenthos and birds (Philippart *et al.*, 2007). The authors highlighted especially the limiting role of phosphorus and silicon.

2.5 Target evaluation

Nutrients

Targets on the chemical quality of the Wadden Sea ecosystem were adopted at the Leeuwarden Conference and aim at natural levels of nutrient concentrations and nutrient input. They are prerequisite for a naturally developing phytoplankton and phytobenthos. Background values of winter concentrations are used for the OSPAR assessments (*e.g.*, OSPAR 2008). For the Dutch Wadden Sea, background DIN levels of 6.5 μM were used (Baretta-Bekker *et al.*, 2008); for the German Wadden Sea, Brockmann *et al.* (2008) proposed DIN values of about 7-9 μM; and Andersen and Kaas (2008) used 11.5 μM for the Danish Wadden Sea. Compared to the present salinity-normalized DIN winter concentrations of about 40-60 μM, we conclude that background DIN concentrations have not been reached yet.

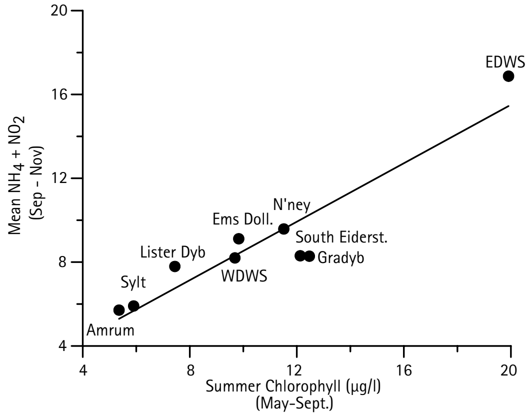


Figure 11: Correlation between mean summer chlorophyll *a* (μg/l) for 2000-2006 and mean autumn values of NH_4+NO_2 for 2000-2006 shown in Figures 7 and 10. Abbreviations: WDWS: Western Dutch Wadden Sea, EDWS: Eastern Dutch Wadden Sea, N'ney: Norderney.

For the Dutch Wadden Sea, background PO_4 levels of 0.5 μM were used by Baretta-Bekker *et al.* (2008); for the German Wadden Sea, Brockmann *et al.* (2007) proposed PO_4 values of about 0.4 μM; and Andersen and Kaas (2008) used 0.4 μM for the Danish Wadden Sea. Compared to the present salinity-normalized PO_4 winter concentrations of about 1.0-1.8 μM, we conclude that natural PO_4 concentrations have not been reached yet.

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 1.5-4 μM (van Beusekom *et al.*, 2001; van Beusekom, 2005) and present levels are clearly above this level (Table 5).

Riverine background concentrations for European rivers were estimated at about 20-71 µM N (~0.6 mg/l N) and 0.7 - 4.5 µM P by Laane (1992). Brockmann *et al.* (2007) reported lower TN values of about 20 µM (~0.3 mg/l N) and TP values of values of about 0.5 µM P. Despite the large uncertainty in the riverine background estimates, the present values of about 250 µM N and 5 µM P are clearly above the background estimates.

Chlorophyll

The data analysis confirms that enhanced riverine nutrient input led to higher phytoplankton stocks. The recent decrease in riverine nutrient loads has led to reduced phytoplankton standing stocks. The evaluation of present levels against background estimates is difficult because the three Wadden Sea countries use different estimates. Also, different time windows and different statistics are used. As a rule of thumb, the following conversions can be used. In general, annual mean chlorophyll levels are about 20% lower than summer chlorophyll levels (May-September; this study). 90 percentile values are about 2 times higher than mean values (*e.g.*, Baretta-Bekker *et al.*, 2008).

Background mean chlorophyll levels during the growth season (March-September) for the Dutch Wadden Sea are estimated at 8 µg Chl-*a*/l (Baretta-Bekker *et al.*, 2008). German estimates are almost two times lower and amount to 2-3 µg Chl-*a*/l. Danish background estimates of 1.9 µg Chl-*a*/l (May-September; Andersen and Kaas, 2008) and 4.0 µg Chl-*a*/l (May-September; Carstensen *et al.*, 2008) are in the same range as the German estimates. In all areas, present values are clearly higher than background values (Table 2).

3. Conclusions

3.1 Main Results

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

Category I: Nutrients.

Riverine nutrient input showed a gradual decrease during the period 1985-2006, with a rate of about 2% for TN and 2-3% for TP. This is reflected by the phosphate concentrations in winter in the Wadden Sea that decreased since the mid 1980s to winter levels of about 1.0-1.8 µM. Salinity normalized nitrate+nitrite concentrations in the German Bight in winter reflect the decreasing TN load, and in some Wadden Sea areas a decreasing trend is now apparent.

Background values

Compared to background estimates of winter nutrient concentrations, present values are clearly elevated.

Category II: Direct effects on primary producers

The decreasing nutrient input (TN loads by Rhine and Meuse or Weser and Elbe) had a significant effect on the phytoplankton biomass (as chlorophyll) in summer in the Southern Wadden Sea (Western Dutch Wadden Sea, Lower Saxonian Wadden Sea (Norderney). In the Northern Wadden Sea, decreasing TN loads by the rivers Weser and Elbe had a significant effect on the summer chlorophyll levels in the List Tidal Basin and in the Grådyb.

Toxic blooms are observed in all parts of the Wadden Sea, but no decreasing or increasing trend in relation to nutrient input is evident. The main nuisance blooms were due to *Phaeocystis*. Long term data from the Marsdiep (Western Dutch Wadden Sea) show a decreasing trend in bloom duration. Present macroalgae abundance in the Northern Wadden Sea correlates with riverine TN input and is below the maximum levels observed during the early 1990s.

Regional differences

In general, summer chlorophyll levels are higher in the Southern Wadden Sea than in the Northern Wadden Sea and are in line with the previous conclusion in QSR 2004 of a higher eutrophication status in the Southern Wadden Sea. However, within both Wadden Sea regions, large differences exist: hotspots are the Eastern Dutch Wadden Sea, the Elbe estuary and Gradyb. Lowest values are found in the Danish and North Frisian Wadden Sea (between Eiderstedt and Gradyb).

Background values

Compared to background estimates of summer chlorophyll levels, present values are clearly elevated.

Category III: Direct effects on organic matter

The autumn NH_4+NO_2 values are a good indicator of organic matter turnover in the Southern Wadden Sea. The decreasing nutrient input (TN loads by Rhine and Meuse) lead to decreasing autumn NH_4+NO_2 values in the Southern Wadden Sea. In the Northern Wadden Sea, a less clear picture emerges and no correlation with riverine TN input is observed.

Regional differences

The recent distribution patterns of autumn NH_4+NO_2 values show a similar pattern as summer chlorophyll and both proxies are strongly correlated ($r^2 = 0.87$; N = 7; p <0.00021; compare van Beusekom, 2006). This supports that the observed regional differences are real. Autumn values identify the same eutrophication hotspots and low eutrophication regions as summer chlorophyll.

Background values

Compared to background estimates of autumn NH_4+NO_2 values, present values are clearly elevated.

4. Assessment according to the WFD

The Water Framework Directive (EU) is an EU Directive adopted in 2000. It aims to (1) prevent further deterioration, protect and enhance the environmental status of aquatic systems and (2) promote the sustainable use of water, while progressively reducing or eliminating discharges, losses and emissions of pollutants and other pressures for the long-term protection and enhancement of the aquatic environment. Good ecological status, defined as a slight deviation from an undisturbed condition, should be reached by 2015. Depending on the water body being assessed, the Directive prescribes the use of certain biological quality indicators. For most of the Wadden Sea, they comprise phytoplankton, macrophytes and macrobenthos. Fish are additional quality indicators in transitional waters.

Based on a certain reference condition representing the high ecological status, metrics have to be developed that scale the status in five steps (high, good, moderate, poor, bad). The Directive is explicit in the prime use of biological indicators, but chemical indicators may support the assessment. Each country can develop its own metrics that are inter-calibrated in so-called GIGs (Geographical Intercalibration Groups). For the assessment of the phytoplankton eutrophication status in the Wadden Sea, two metrics are presently discussed: 1) the percentage of observations with *Phaeocystis* bloom conditions ($>10^7$ cells/l); and 2) deviations from a reference phytoplankton biomass. In the latter case the 90-percentile of chlorophyll-a during the period March-October is used as indicator. In the Wadden Sea area, no agreement has been reached yet on the reference conditions and boundaries between good and moderate for phytoplankton biomass.

5. Recommendations

5.1 Management

Current policies to reduce nutrient input have been successful with regard to phosphorus and nitrogen compounds. The decreasing nutrient loads into the coastal North Sea and directly into the Wadden Sea have led to a decreasing eutrophication status in the entire Wadden Sea. The target of a Wadden Sea without eutrophication problems has not been reached yet. Therefore it is recommended continuing policies to reduce nutrient input.

5.2 Monitoring and research

Regional differences within the Wadden Sea

The present study confirms the previous conclusion (QSR 2004) on regional differences within the international Wadden Sea. The reasons for these differences have to be revealed in order to be able to formulate region-specific standards for a good ecological status, as for instance demanded by the Water Framework Directive.

Interacting effects of regional change

During the past decade, the warming trend in the Wadden Sea area has become evident. Especially invading species seem to have taken advantage of this trend (Nehring *et al.*, 2009). Future research will have to tackle the question of how present trends (de-eutrophication, warming, proliferation of invading species, sea level rise) interact (Reise and van Beusekom, 2008). Monitoring and assessment strategies have to adapt at an early stage to account for changes ahead as previous assessment strategies may not be appropriate any more.

Importance of coverage of the entire seasonal cycle

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

New automated monitoring techniques

At present, techniques and strategies are developed in The Netherlands and Germany to implement automated monitoring stations. We suggest to stimulate international exchange of information and methods and in order to establish a coherent Wadden Sea-wide automated monitoring network. Care should be taken that the “classical time” series are continued.

Phosphorus versus Nitrogen limitation

In the present study, the temporal dynamics in eutrophication proxies were significantly correlated with riverine TN input. However, evidence suggests that at least part of the Wadden Sea (*e.g.*, Western Dutch Wadden Sea) is limited by phosphorus (*e.g.*, Philippart *et al.*, 2007) whereas at least for the Northern Wadden Sea nitrogen limitation is assumed (*e.g.*, Carstensen, 2008; van Beusekom *et al.*, 2009). Research is needed to understand the regional differences in nutrient limitation patterns and their implications for the coastal ecosystem.

Chlorophyll intercalibration

The different monitoring and research institutes in the Wadden sea area use different methods for assessing chlorophyll. This may hamper the areal comparison. Intercalibration exercises are needed to demonstrate the comparability of the methods used. Comparability of data is of utmost importance in the light of, *e.g.*, defining a good ecological status for the Water Framework Directive.

6. References

Andersen, J.H., Kaas, H., 2008. Danish assessment of eutrophication status in the North Sea, Skagerrak and Kattegat: OSPAR Common Procedure 2001-2005. DHI.

Bakker, J.F., Bartelds, W., Becker, P.H., Bester, K., Dijkhuizen, D., Frederiks, B., and Reineking, B., 1999. Marine Chemistry. Pp. 85-117. *In*: De Jong, F., Bakker, J.F., van Berkel, C.J.M., Dankers, N.M.J.A., Dahl, K., Gätje, C., Marencic, H. and Potel, P. (*Eds.*) 1999. Wadden Sea Quality Status Report. Wadden Sea Ecosystem No. 9. Common Wadden Sea Secretariat, Trilateral Monitoring and Assessment Group, Quality Status Report Group. Wilhelmshaven.

Baretta-Bekker, J.G., Bot, P.V.M., Prins, T.C. and Zevenboom, W., 2008. Report on the second application of the OSPAR Comprehensive Procedure to the Dutch marine Waters. Rijkswaterstaat, The Hague.

Bartnicki, J. and Fagerli, H., 2006. Atmospheric Nitrogen in the OSPAR Convention Area in the period 1990 - 2004. EMEP/MSC-W Technical Report 4/2006, Oslo.

Brockmann, U.H., Topcu, D. and Schütt, M., 2008. Assessment of the eutrophication status of the German Bight according to the OSPAR Comprehensive Procedure. University of Hamburg, Hamburg.

Cadée, G.C. and Hegeman, J., 2002. Phytoplankton in the Marsdiep at the end of the 20th century; 30 years monitoring biomass, primary production and *Phaeocystis* blooms. J. Sea Res. 48, 97-110.

Carstensen, J., 2008. Estimation of nutrient reductions to achieve phytoplankton ecological targets in the Wadden Sea, National Environmental Research Institute, University of Aarhus, 28 p. Research notes from NERI, no. 246.

Carstensen, J., Krause-Jensen, D., Dahl, K. and Henriksen, P. 2008. Macroalgae and phytoplankton as indicators of ecological status of Danish coastal waters. National Environmental Research Institute, University of Aarhus. 90 pp. NERI Technical Report No. 683.

Essink, K., Dettmann, C., Farke, H., Laursen, K., Lüerßen, G., Marencic, H. and Wiersinga, W. (*Eds.*), 2005. Wadden Sea Qualitiy Status Report 2004. Wadden Sea Ecosystem No. 19. Common Wadden Sea Secretariat, Wilhelmshaven, pp. 141-154.

Fletcher, R.L., 1996. The occurrence of "green tides" – a review. *In*: Schramm/Nienhuis (*Eds.*) Marine benthic vegetation. Ecological Studies, Springer-Verlag 123, 7-43.

Hickel, W., 1989. Inorganic micronutrients and the eutrophication in the Wadden Sea of Sylt (German Bight, North Sea). Proceedings of the 21st EMBS. Polish Academy of Science, Gdansk, pp. 309-318.

Jong, F. de, Kolbe K. and van Beusekom J., 1999a. Anoxic Sediment Surface. Pp. 121-123 in: De Jong, F., Bakker, J.F., van Berkel, C.J.M., Dankers, N.M.J.A., Dahl, K., Gätje, C., Marencic, H. and Potel, P. (*Eds.*). 1999 Wadden Sea Quality Status Report. Wadden Sea Ecosystem No. 9. Common Wadden Sea Secretariat, Trilateral Monitoring and Assessment Group, Quality Status Report Group. Wilhelmshaven

Jong, F. de, Bakker, J.F., van Berkel, C.J.M., Dankers, N.M.J.A., Dahl, K., Gätje, C., Marencic, H. and Potel, P., 1999b. 1999 Wadden Sea Quality Status Report. Wadden Sea Ecosystem No. 9. Common Wadden Sea Secretariat, Trilateral Monitoring and Assessment Group, Quality Status Report Group. Wilhelmshaven.

Jonge, V. N., de and Postma H., 1974. Phosphorus compounds in the Dutch Wadden Sea. *Netherlands Journal of Sea Research* 8: 139-153.

Jonge, V.N. de and Jong, D.J. de., 1992. Role of tide, ligth and fisheries in the decline of Zostera marina L. in the Dutch Wadden Sea. *Neth Inst. Sea Res. Publication Series* 20: 161-176.

Jonge, V.N. de, Essink, K. and Boddeke, R., 1993. The Dutch Wadden Sea : a changed ecosystem. Hydrobiologia 265: 45-71.

Kolbe, K., Kaminski, E., Michaelis, H., Obert, B. and Rahmel, J., 1995. Macroalgal mass development in the Wadden Sea: first experiences with a monitoring system. Helgoländer Meeresunters. 49, 519-528.

Körner, D. and Weichert G., 1992. Nutrients in the German Bight: Concentrations and trends. ICES Mar. Sci. Symp. 195: 159-176.

Laane, R.W.P.M., 1992. Background concentrations of natural compounds. Report DGW-92.033, Den Haag (NL), 84 p.

Lancelot, C., Billén, G., Sournia, A., Weisse, T., Colijn, F., Davies, M. J. W. and Wassman, P., 1987. *Phaeocystis* blooms and nutrient enrichment in the continental coastal zones of the North Sea. *Ambio* 16: 38-46.

Lenhart, H.-J. and Pätsch, J., 2001. Daily nutrient loads of the European continental rivers for the years 1977-1998. Berichte aus dem Zentrum für Meeres- und Klimaforschung; Reihe B: Ozeanographie, No 40, 146pp.

Nehring, S., K.Reise, M. Dankers and P.S. Kristensen, 2009. Alien species. Thematic Report No. 7. In: Marencic, H. & Vlas, J. de (Eds), 2009. Quality Status Report 2009. WaddenSea Ecosystem No. 25. Common Wadden Sea Secretariat, Trilateral Monitoring and Assessment Group, Wilhelmshaven, Germany.

OSPAR Commision, 2008. Second OSPAR Integrated Report on the Eutrophication Status of the OSPAR Maritime Area, Eutrophication Series. OSPAR.

Philippart, C. J. M., Cadée, G. C., van Raaphorst W. and Riegman, W., 2000. Long-term phytoplankton-nutrient interactions in a shallow coastal sea: algal community structure, nutrient budgets, and denitrification potential. *Limnology and Oceanography* 45: 131-144.

Philippart, C.J.M., Beukema, J.J., Cadée, G.C., Dekker, R., Goedhart, P.W., Iperen, J.M.v., Leopold, M.F. and Herman, P.M.J., 2007. Impact of nutrients on coastal communities. Ecosystems 10: 95-118.

Postma, H., 1954. Hydrography of the Dutch Wadden Sea. *Archives néerlandaises de Zoologie* 10: 405-511.

Postma, H., 1966. The cycle of nitrogen in the Wadden Sea and adjacent areas. *Netherlands Journal of Sea Research* 3: 186-221.

Reise, K. and Siebert I., 1994. Mass occurrence of green algae in the German Wadden Sea. *DHZ Suppl.* 1: 171-188.

Reise, K., 1983. Sewage, green algal mats anchored by lugworms and the effects on Turbellaria and small Polychaeta. Helgoländer Meeresunters. 36: 151-162.

Reise, K., 2008. Vorkommen von Grünalgen und Seegras im Nationalpark Schleswig-Holsteinisches Wattenmeer. Report Landesamt für Küsten- und Naturschutz, Tönning, Germany.

Reise, K. and van Beusekom, J., 2008. Interactive effects of global and regional change on a coastal ecosystem. Helgol Mar Res 62: 85-91.

van Bennekom, A. J. and Wetsteijn, F. J., 1990. The winter distribution of nutrients in the southern bight of the North Sea (1961-1978) and in the estuaries of the Scheldt and the Rhine/Meuse. Netherlands Journal of Sea Research 25: 75-87.

van Beusekom, J. E. E., Fock, H., Jong, F. de, Diel-Christiansen, S. and Christiansen, B., 2001. Wadden Sea Specific Eutrophication Criteria. Wadden Sea Ecosystem 14: 1-115.

van Beusekom, J.E.E., Bot, P.V.M., Goebel, J.H.M., Lenhart, H., Paetsch, J., Peperzak, L., Petenati, T. and Reise, K., 2005. Eutrophication. *In*: Essink, K., Dettmann, C., Farke, H., Laursen, K., Lüerßen, G., Marencic, H. and Wiersinga, W. (*Eds.*), Wadden Sea Quality Status Report 2004. Wadden Sea Ecosystem No. 19. Common Wadden Sea Secretariat, Wilhelmshaven, pp. 141-154.

van Beusekom, J.E.E., Loebl, M. and Martens, P., 2009. Distant riverine nutrient supply and local temperature drive the long-term phytoplankton development in a temperate coastal basin. J. Sea Res. 61: 26-33.

van Beusekom, J.E.E., Loebl, M. and Martens, P., 2009. Distant riverine nutrient supply and local temperature drive the long-term phytoplankton development in a temperate coastal basin. J. Sea Res. 61: 26-33.

van Duren, L., 2006. Overbemest of onderbelicht? Rapportnr RIKZ/2006.020, RIKZ Middelberg.