

## 4. Data Analysis of Long-term Series from the Wadden Sea

### 4.1 Introduction

In the previous Chapter the hypothesis was developed that a relation exists between the nitrogen input into the coastal zone and the nutrient cycles in the Wadden Sea. In this Chapter this hypothesis is tested with long-term data from the Wadden Sea. In Chapter 4.3 the influence of N input via Rhine and Meuse on the summer chlorophyll levels and on the seasonal nitrogen cycle in the Southern Wadden Sea will be dealt with. In Chapter 4.4 a comparison of the nitrogen cycle will be made with historic data from the western Dutch Wadden Sea. In Chapter 4.5 the influence of P input via Rhine and Meuse on the phosphorus cycle and on the N cycle will be investigated. Chapter 4.6 deals with the long-term data from the Northern Wadden Sea. In Chapter 4.7 the subareas from the Wadden Sea, for which sufficient data are available, are compared. Chapter 4.8 deals with *Phaeocystis* blooms. In 4.9 long-term changes in nutrient dynamics in the western Dutch Wadden Sea are discussed and a proposal for background autumn values of  $\text{NH}_4 + \text{NO}_2$  developed. Finally, in 4.10, the main conclusions from the data analysis are summarized.

### 4.2 Methods

The data analyses have been carried out with the multiple regression module of STATISTICA (1999). Outliers were rejected if the distance from the other data was more than 2 times the standard deviation. The number of rejected data was in most cases zero.

### 4.3 Southern Wadden Sea: Nitrogen 1977–1997

#### 4.3.1 Data Base

Table 4.1 presents the data sets used for the analysis. The reason for not including the data prior to 1977 is that large changes in the form of nitrogen discharged have taken place between the mid 60s and mid 70s. During the 60s ammonium and organic nitrogen were the dominant species. After implementation of waste water treatment, nitrate became the dominant species. This shift probably had a large impact on the filter func-

tion of the Rhine estuary by reducing its denitrification potential (c.f. Billén et al., 1985). The shift from ammonium to nitrate probably also influenced the phytoplankton composition of the coastal zone (see Chapter 3.6).

A further reason not to include data from the monitoring program during the early 1970s in the analysis is that there is reason to doubt the quality of the early monitoring data: A comparison with measurements carried out by the NIOZ during the same period shows large differences in salinity and nitrate and ammonium (results not shown).

Three areas were distinguished:

- Western Dutch Wadden Sea
- Eastern Dutch Wadden Sea
- Lower Saxonian Wadden Sea

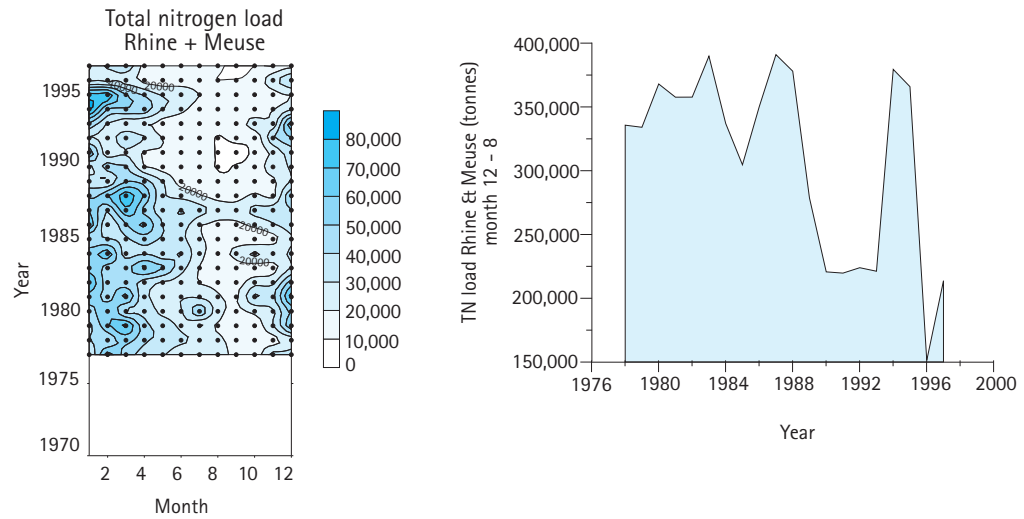
For these areas the following correlations have been investigated:

- For the summer period (April–September) the relation between *Total Nitrogen input* and *chlorophyll* ;
- For the autumn period (September–November) the relation between *Total Nitrogen (TN) input* and *Nrem (Nitrogen Remineralization products  $\text{NO}_2$  and  $\text{NH}_4$ )*. Autumn chlorophyll and temperature were used as co-variables.

Table 4.1:  
Data basis for the southern  
Wadden Sea.

Data type	Area	Period	Reference
Continuous monthly surveys	Dutch Wadden Sea	1977–present DONAR	Rijkswaterstaat,
River loads (near river mouth)	Haringvliet/Maassluis	1977–present Rijkswaterstaat, DONAR	Lenhart et al., 1996
NIOZ study annual cycle N	Dutch Wadden Sea	1960–1962	Postma, 1966
NIOZ study annual cycle N, P	Dutch Wadden Sea	1970–1972	NIOZ, 197
NIOZ annual cycle P	Dutch Wadden Sea	1949–1952	Postma, 1954
Older river data	Lobith (Dutch-German Border)	1951–1992	Rijkswaterstaat DONAR
<i>Phaeocystis</i> time series	Marsdiep	1971–1996	Cadée, unpublished Cadée and Hegeman, 1986
Norderney, weekly time series	Lower Saxonian Wadden Sea	1984–1998	Hanslik, pers. comm. Hanslik et al., 1998

**Figure 4.1:** The monthly discharge of Total Nitrogen (TN) of the rivers Rhine and Meuse via Maassluis and Haringvliet. In the right panel, the time serie of total load from December (previous year) to August is shown.

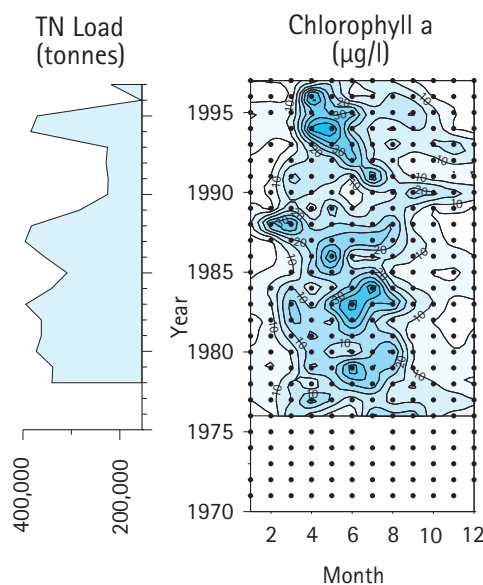


**4.3.2 Riverine Input**

Riverine input was calculated from the data base compiled by Lenhart et al. (1996) and updated with recent data from Rijkswaterstaat using the sum of the discharges at Maassluis and Haringvliet. This mainly represents the discharges via Rhine and Meuse. Especially during periods of high river flow discharge via the Haringvliet becomes important. The IJsselmeer discharge was not included for two reasons: Firstly, the IJsselmeer directly influences the western Dutch Wadden Sea but not the other areas. Secondly, a strong correlation exists between the discharges via the IJsselmeer and via the Rhine and Meuse, which makes it, in a statistical sense, extremely difficult to separate their effects.

In Figure 4.1 the Total Nitrogen load is presented as a month – year plot. Figure 4.1 shows that the first large winter discharge takes place in December. On the basis of the conceptual model it is expected that the total amount of nitrogen discharged into the coastal zone determines the production potential. For that reason the December discharge was included in the total sum of nitrogen that may influence the annual primary production in the coastal zone. To investigate the effect of the TN load on the remineralization in autumn (September–November), the monthly TN loads between December of the previous year and August were added and used to investigate the effect of TN load on the nutrient cycles and phytoplankton biomass. This time series, also presented in Figure 4.1, shows large inter-annual variations up to a factor of two. Conspicuous features are the high loads during the 80s, low loads during 1989–1993 and the high loads during 1994 and 1995.

**Figure 4.2:** A month–year plot of chlorophyll in the western Dutch Wadden Sea. Also shown at the left are the time series of TN load via Rhine and Meuse. The Y-axis of both graphs correspond.



**4.3.3 Western Dutch Wadden Sea**

Figure 4.2 compares the seasonal cycles of chlorophyll and TN load. The effect of TN load on the phytoplankton biomass is clearest during the nineties: During the low discharge period (1990–1993) low phytoplankton biomasses were found, increasing sharply during 1994 and 1995. The correlation between TN load and mean summer chlorophyll *a* levels (Fig. 4.3) was highly significant ( $r=0.65$ ;  $p<0.002$ ). This result corroborates the suggestion by Cadée (1992) that nitrogen discharges via the Rhine correlate with phytoplankton biomass in the Marsdiep area and the statistical analysis by de Jonge (1997) of a correlation between DIN input (Lobith data) and chlorophyll in the western Dutch Wadden Sea.

Figure 4.4 shows the year-month-plots of ammonium and nitrite in this area. For comparison the TN load is also shown. Because of the unproblematic analysis of nitrite and a good comparability with the NIOZ data (Helder, 1974) the nitrite data for the years 1971-1976 were included. Both ammonium and nitrite have a clear seasonal cycle with lowest concentrations in summer. Highest autumn concentrations are found during the mid-80s. Especially ammonium shows very low values during the period of low TN discharges in the early 90s. A multiple regression analysis between TN load and remineralized N (Nrem) with temperature and chlorophyll as co-variables showed a significant correlation (Table 4.2).

Table 4.2:  
Results of the multiple regression between TN input via Rhine and Meuse and the N remineralisation in the Wadden Sea.

Western Dutch Wadden Sea				
- Dependent:	Sum of $\text{NH}_4$ and $\text{NO}_2$ (Month 9-11)			
- Independent:	Rhine/Meuse TN load (Month 12-8)			
- Covariable:	Chlorophyll (Month 9-11) Temperature (Month 9-11)			
Results				
N=19	$p=0.0017$	$R^2=0.63$	Outlier: 1983	
Variable	Beta	B	p	
TN load	0.48	0.00003	0.012	
Chl a	-.42	-.41	0.022	
Temp	0.22	1.06	0.205	
Eastern Dutch Wadden Sea				
- Dependent:	Sum of $\text{NH}_4$ and $\text{NO}_2$ (Month 9-11)			
- Independent:	Rhine/Meuse TN load (Month 12-8)			
- Covariable:	Chlorophyll (Month 9-11) Temperature (Month 9-11)			
Results				
N=19	$p=0.0099$	$R^2=0.52$	Outlier: 1996	
Variable	Beta	B	p	
TN load	0.52	0.00005	0.014	
Chl a	-.37	-.55	0.07	
Temp	0.22	1.32	0.24	

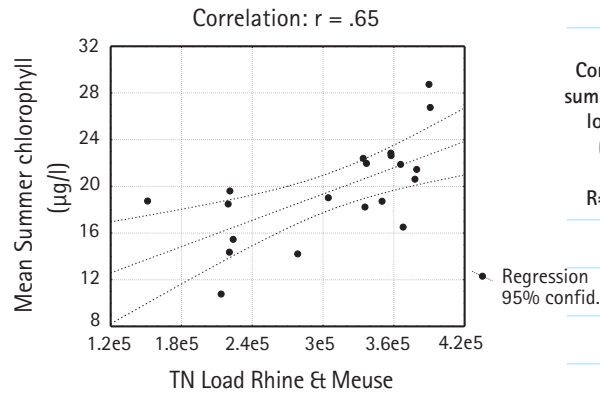


Figure 4.3:  
Correlation between mean summer chlorophyll and TN load of Rhine and Meuse (Tonnes) in the western Dutch Wadden Sea.  $R=0.65$ ;  $p<0.002$ ;  $N=20$ .

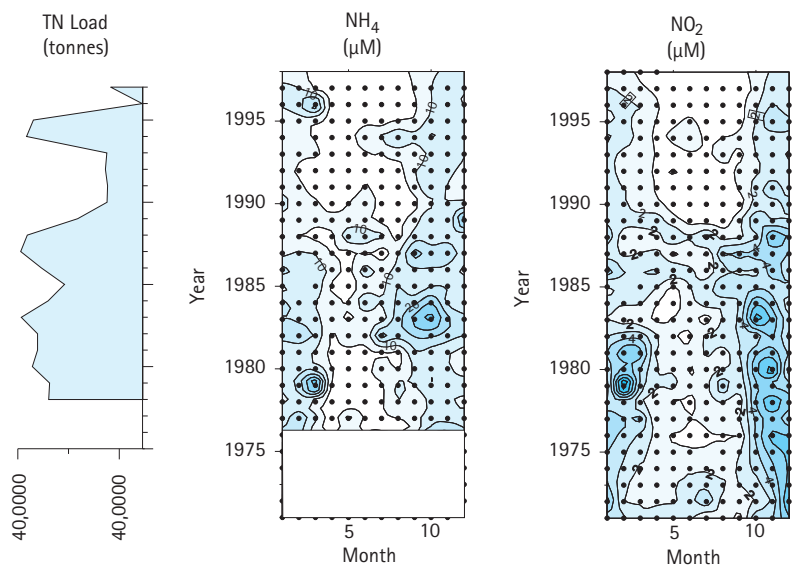


Figure 4.4:  
Month-year plots of ammonium and nitrite in the western Dutch Wadden Sea. For comparison the TN load (Rhine + Meuse) is shown on the left.

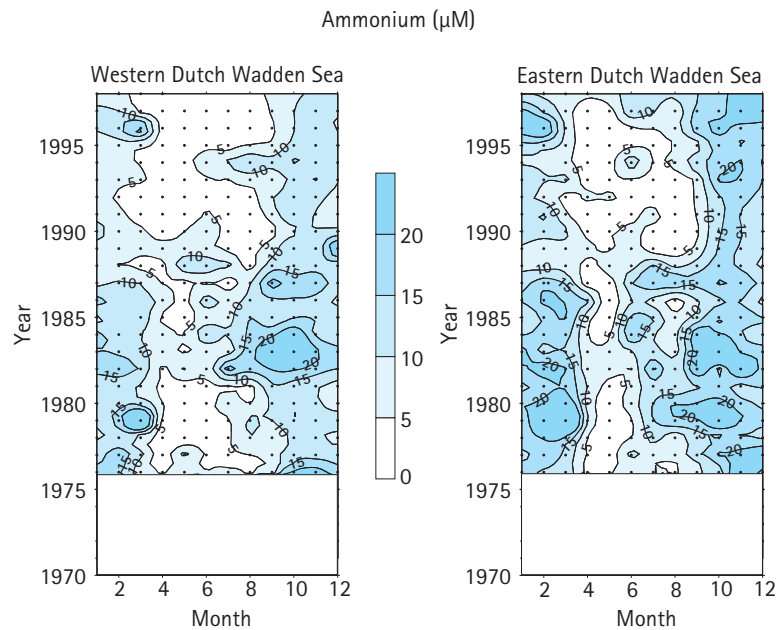


Figure 4.5:  
Comparison of the seasonal  
cycles of ammonium in the  
western and in the eastern  
Dutch Wadden Sea.

#### 4.3.4 Eastern Dutch Wadden Sea

The seasonal cycles of ammonium in the eastern Dutch Wadden Sea is similar to the seasonal cycle in the western part (Fig. 4.5). But in general, the concentrations in the eastern part are higher. This probably reflects the lower mean depth and higher surface to volume ratio of the eastern Dutch Wadden Sea. As a result, input from the sediment is less diluted. Also the inter-annual variation in both areas is similar to the highest concentrations during the early 80s and the lowest concentrations during the early 90s (compare Fig. 4.4).

The multiple regression analysis between TN load and Nrem with temperature and chlorophyll as co-variables showed a significant correlation for the eastern Dutch Wadden Sea (Table 4.2). No statistically significant correlation was found between TN Load and summer chlorophyll ( $r=0.00$ ;  $p=0.96$ ).

#### 4.3.5 Comparison of the Western and Eastern Dutch Wadden Sea

A comparison of the results from the multiple regression analysis shows the consistency of this approach: The magnitude of the influence of TN on Nrem is comparable in both areas. Also the negative influence of chlorophyll on the autumn Nrem levels is almost identical. The rationale behind the negative correlation is that in years with good growth conditions during autumn (probably good light conditions) part of the ammonium efflux is taken up by the phytoplankton. Temperature has a negative but not significant influence on Nrem

levels. It is interesting to note that the influence of temperature is almost identical in both areas.

#### 4.3.6 Comparison with Lower Saxony

Figure 4.6 compares the seasonal cycle and the inter-annual variability of ammonium in the eastern Dutch Wadden Sea and the Lower Saxonian Wadden Sea (Norderney). Ammonium concentrations in the Lower Saxonian Wadden Sea are somewhat lower than in the eastern Dutch Wadden Sea. The inter-annual pattern shows some similarities: The high values during 1987-1988, the low values during the early 90s and the higher values during 1994-1995. The mean autumn concentrations of Nrem show a significant correlation (Fig. 4.7;  $r=0.66$ ;  $p<0.03$ ;  $N=11$ ).

#### 4.3.7 Interpretation of the Statistical Analyses

The main conclusion from the above statistical analyses are:

- TN load determines the phytoplankton biomass in the western Dutch Wadden Sea
- TN load determines the remineralization intensity in the entire Dutch Wadden Sea
- The remineralization in the Lower Saxonian Wadden Sea shows similar inter-annual patterns as in the Dutch Wadden Sea.

The analyses support the conceptual model (Fig. 3.2). The model states that in years with high nitrogen loads more organic matter is produced in the North Sea and more organic matter is imported from the North Sea into the Wadden Sea. This

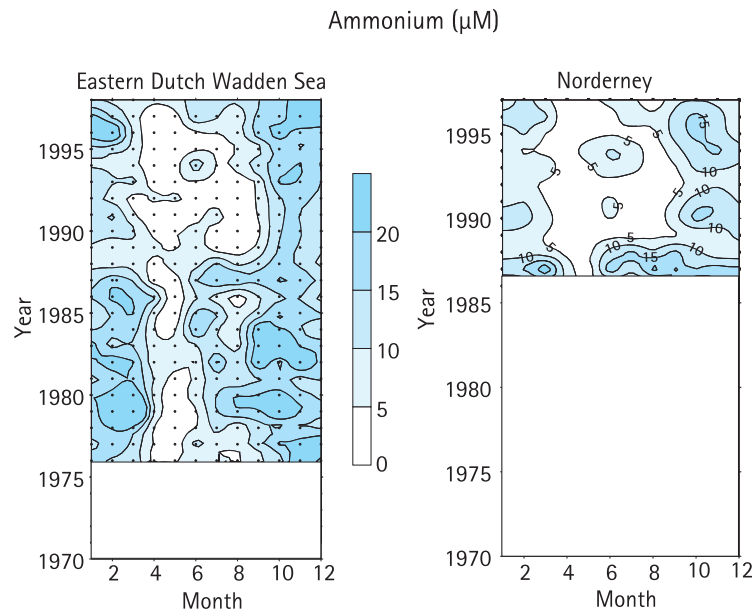


Figure 4.6: Comparison of the seasonal cycles of ammonium in the eastern Dutch Wadden Sea and in the Lower Saxonian Wadden Sea (Norderney).

model could be verified on the basis of literature data, carbon budgets and the statistical analysis presented above. Support for the first step is given by Hydes et al. (1999) who showed that in Dutch coastal waters a direct relation exists between the amount of nitrate prior to the onset of the spring phytoplankton bloom and the annual primary production. Carbon budgets underlined the importance of organic matter import for the productivity of the Wadden Sea (van Beusekom et al., 1999). The statistical analyses presented above show that during years with high TN loads

more organic matter is remineralized within the Wadden Sea. This supports the working hypothesis that during years with high TN loads more organic matter is imported than in years with low TN discharge. It is suggested that autumn ammonium + nitrite levels can be used as a measure of the eutrophication status of the Wadden Sea.

The main conclusions from the foregoing is that currently a direct relation exists between nutrient discharge via rivers and nutrient cycles in the Dutch and Lower Saxonian Wadden Sea.

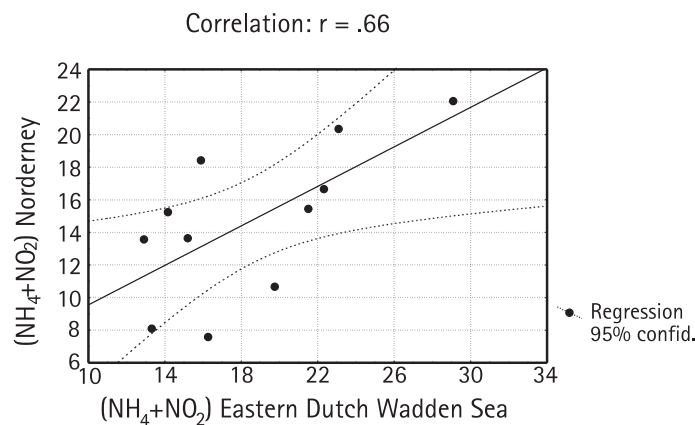


Figure 4.7: Correlation between mean autumn values of ammonium + nitrite in the eastern Dutch Wadden Sea and in the Lower Saxonian Wadden Sea. All values in are in  $\mu\text{M}$ .  $R=0.66$ ;  $p<0.03$ ;  $N=11$ .

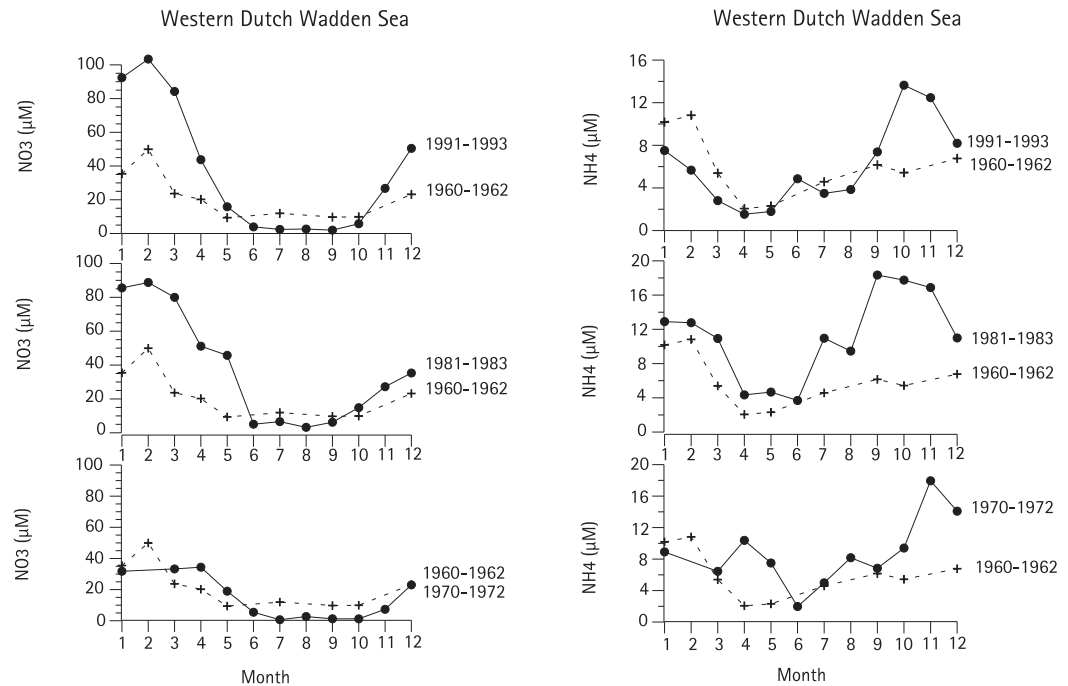


Figure 4.8:  
A comparison of historic nitrate and ammonium data from four decades in the western Dutch Wadden Sea. Data sources: (Postma 1966), (Helder 1974) and Rijkswaterstaat (DONAR).

#### 4.4 Comparison with "Historic" Dutch Data

In Figure 4.8 the seasonal cycles of nitrate and ammonium during four decades are compared. Observations from 1960-1961 are from Postma (1966), the observations from 1970-1972 from Helder (1974). The other data are from the Rijkswaterstaat data base. The years 1981-1983 represent wet years with high nitrate discharges, the years 1991-1993 dry years with low nitrate discharges.

Basically, during all periods a clear seasonal cycle was present (compare Fig. 3.4). The winter nitrate concentrations have increased during the 70s from about 40  $\mu\text{M}$  to almost 100  $\mu\text{M}$ . No clear differences exist between the wet and dry years. During summer, mostly very low concentrations were observed. The period of low concentrations was shortest during wet years (1981-1983). During the 60s summer concentrations were somewhat higher than during later summers.

The largest inter-decadal differences in the seasonal cycle of ammonium were observed during autumn. Only in the 60s no clear autumn maximum was observed, indicating low remineralization rates and a low organic matter import. During the other decades high autumn concentrations were observed. The period of high autumn concentrations was longest during the wet years of 1981-1983 and shortest during 1970-1972. In the 80s and 90s the autumn peak occurred in October. During 1970-1972 a sharp peak was observed in November. In this context one should take note of the fact that the forms in which nitrogen was imported into the coastal zone have changed from a dominance of organic nitrogen and ammonium to nitrate due to the implementation of waste water treatment plants (van Benekom and Wetsteijn, 1990). Therefore, the autumn peak during 1970-1972 may reflect both an increased remineralization and an increased nitrogen input. In any case, the clear increase in autumn ammonium indicates that also the organic matter import and the offshore primary production must have increased concomitantly. The latter is in line with increased primary production levels (van Beusekom and Diel-Christiansen, 1994).

#### 4.5 Dutch Long-term Data: Phosphorus 1977-1998

##### 4.5.1 Introduction

In this Chapter the influence of TP input via Rhine and Meuse on the phosphorus cycle in the Dutch Wadden Sea is investigated. Also the possible role of TP input on organic matter import and nitrogen remineralization is addressed. The rationale behind this is to test whether TN input or TP input is a better predictor for the organic matter import into the Wadden Sea and for the organic matter remineralization (ammonium and nitrite levels in autumn). The data used for the analysis of the phosphorus data are shown in Table 4.1.

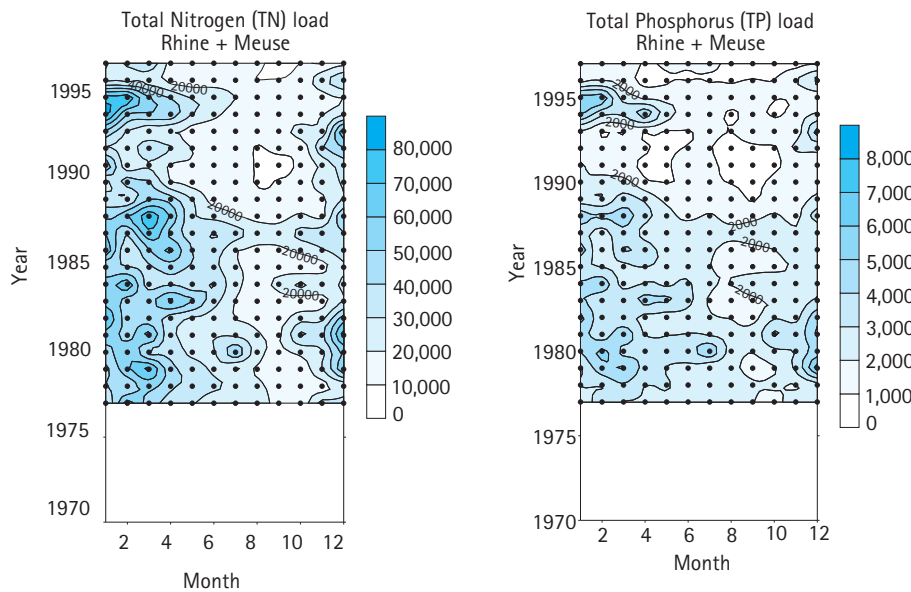


Figure 4.9: Comparison of the Total Nitrogen (TN) and Total Phosphorus (TP) load (tonnes/month) via Rhine and Meuse (Maassluis and Haringvliet).

#### 4.5.2 Riverine Input

Figure 4.9 compares the monthly TN loads and monthly Total Phosphorus loads (TP load) via Rhine and Meuse. Both discharge patterns are very similar. In contrast to the TN loads, the TP loads have clearly decreased (Fig. 4.10a). Still, large amounts can be transported into the North Sea during periods of high river discharge.

The estimates for TP load were calculated for two time intervals: month 12-8 and month 12-6. The first estimate (Fig. 4.10a) was used to enable a comparison between TN and TP load. The second estimate was used to compare the TP load with the phosphate summer maximum (month 7-8; see section 4.5.3). Figure 4.10b shows that a very good correlation exists between TN and TP input ( $n=20$ ;  $r=0.908$ ;  $p<0.0001$ ). This makes it extremely difficult to distinguish in a statistical sense between the effects of TN input and TP input on the organic matter remineralization in the Wadden Sea. Other arguments than pure statistics have to be used to discuss whether P or N determines the remineralization rates in the Wadden Sea.

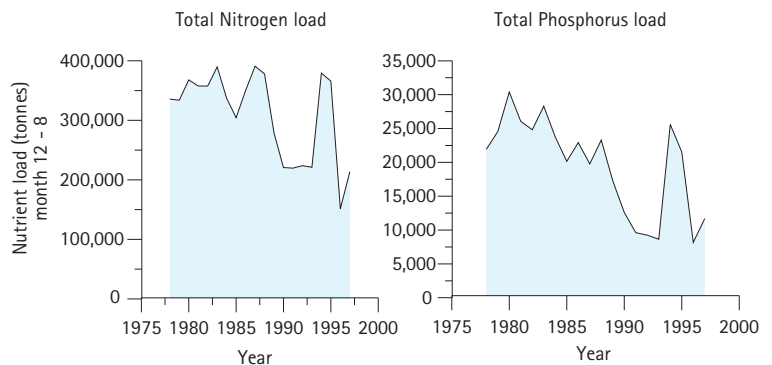


Figure 4.10a: Comparison of the TN load (month 12-8) shown at the left with the TP load (month 12-8) shown at the right.

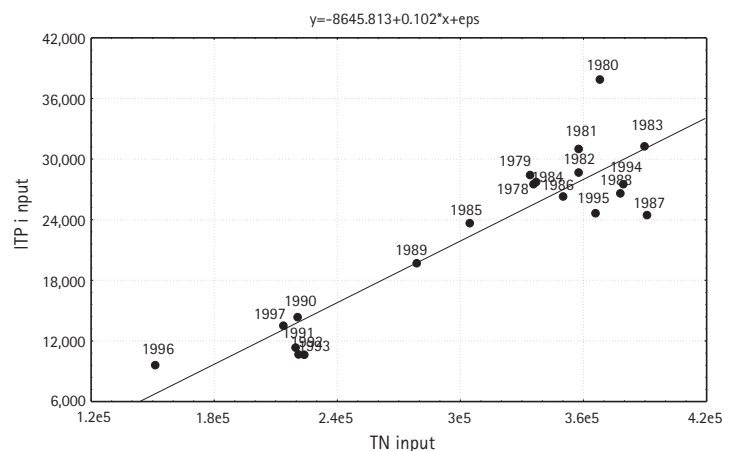


Figure 4.10b: Correlation between TP input and TN input via Rhine and Meuse (month 12-8).

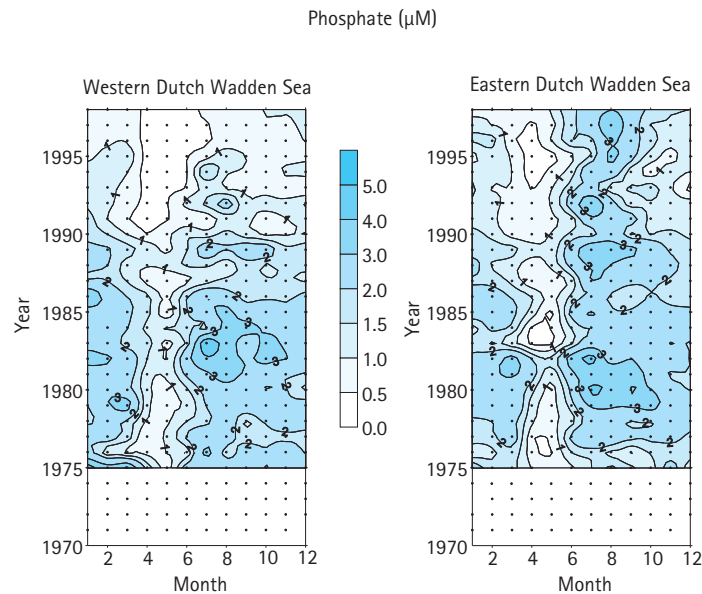


Figure 4.11a: Comparison of the seasonal cycles of Phosphate ( $\mu\text{M}$ ) in the eastern and in the western part of the Dutch Wadden Sea.

#### 4.5.3 TP Input and Phosphorus Cycle in the Western Dutch Wadden Sea

The phosphorus cycle in the western Dutch Wadden Sea shows a typical seasonal cycle with high winter concentrations, a minimum during May and a summer maximum during July and August (Fig. 4.11a). In agreement with the decreased TP load, the phosphorus concentrations in the western Dutch Wadden Sea reached a maximum during the mid 80s and decreased considerably since. The summer maximum exemplifies this trend with maxima of more than  $4 \mu\text{M}$  in 1983 decreasing to less than  $1 \mu\text{M}$  in 1996 and 1997. This decrease contrasts with the ammonium time series that did not show a concomitant decrease (Fig. 4.5).

Much of the seasonal and inter-annual variability of phosphate could be explained by riverine input with a simple linear regression or by a multiple regression using chlorophyll as a covariable. The TP input data of month 12 to month 6 were used for the analysis (Fig. 4.11b).

- **Winter:** The winter phosphate concentrations correlated significantly with TP input ( $r=0.83$ ;  $N = 18$ ;  $p < 0.00013$ ; one outlier: 1979) decreasing from  $2-3 \mu\text{M}$  during the 80s to less than  $1 \mu\text{M}$  during the 90s. The effect of chlorophyll was not significant.
- **Spring:** The phosphate minimum in spring could be explained by the winter phosphate concentrations and by the spring phytoplankton biomass ( $r=0.86$ ;  $N = 22$ ;  $p < 0.0000$ ).
- **Summer:** The summer maximum (month 7-8) could be explained by the TP load ( $r=0.71$ ;  $N = 20$ ;  $p < 0.0087$ ). The effect of temperature and phytoplankton biomass was not significant.

#### 4.5.4 TP Input and Phosphorus Cycle in the Eastern Dutch Wadden Sea

The seasonal cycle of phosphate in the eastern Dutch Wadden Sea showed the same features as in the western Dutch Wadden Sea, i.e. high winter concentrations, a spring minimum and high summer concentrations (Fig. 4.11a). In contrast to the western Dutch Wadden Sea, no clear decrease of the phosphate summer maximum was observed. As for the western part, much of the seasonal and inter-annual variability of phosphate could be explained by riverine input with a simple linear regression or with a multiple regression analysis using chlorophyll as a co-variable:

- **Winter:** The winter phosphate concentrations correlated significantly with TP input ( $r = 0.75$ ;  $N = 19$ ;  $p < 0.0012$ ) decreasing from  $2-3 \mu\text{M}$  during the 80s to about  $1 \mu\text{M}$  during the 90s. The effect of chlorophyll was not significant.
- **Spring:** The phosphate minimum in spring could be explained by the winter phosphate concentrations and by the phytoplankton biomass ( $r=0.79$ ;  $N = 20$ ;  $p < 0.001$ ).
- **Summer:** Variations in the summer maximum (month 7-8) were correlated with the phytoplankton biomass ( $r=0.77$ ;  $N=19$ ;  $p < 0.0006$ ). The effect of riverine input was not significant.

De Jonge et al. (1993a) suggested that especially the Fe hydroxides in the Wadden Sea might be a temporal phosphorus buffer. In the western Dutch Wadden Sea the TP load during the previous months (12-6) determined the phosphate release during July and August. For the western Dutch Wadden Sea the possibility that the phos-

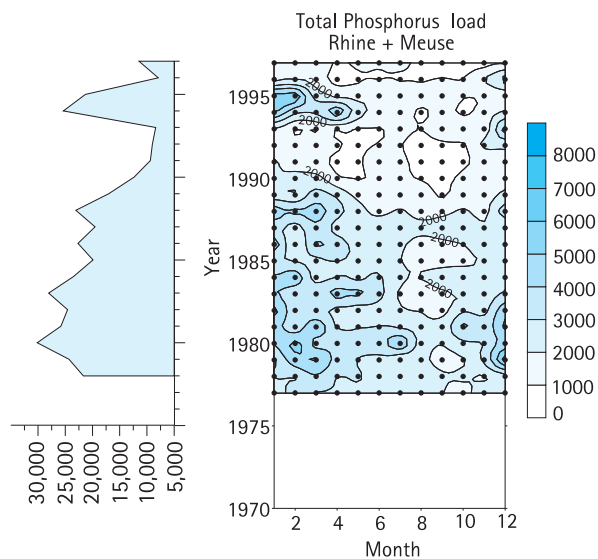


Figure 4.11b:  
Total Phosphorus load via  
Rhine and Meuse  
(Maassluis and Haringvliet).  
The left-hand graph shows  
the total load (Tonnes) from  
month 12 –6.

phate release also depends on the TP load during the previous years was investigated with a multiple regression. The analysis showed that the TP load during the two previous years slightly increased the correlation coefficient  $r$  from 0.71 to 0.8,1 but the effect of TP input during both previous years was not significant. This implies that the Wadden Sea reacts directly to TP input and that lag phenomena do not play a large role. De Jonge et al (loc.cit.) already pointed out that the production potential of bio-available phosphorus (mainly Fe hydroxide bound) was in the order of  $150 \text{ g C m}^{-2} \text{ y}^{-1}$ . This is enough to sustain the primary production in the Wadden Sea for roughly one year given an annual turnover rate of two. Apparently no large scale accumulation of bio-available phosphate occurs. Removal processes might play an important role in suppressing the amount of bioavailable phosphorus in the Wadden Sea (van Beusekom and de Jonge, 1997; van Beusekom et al., 1999).

#### 4.5.5 Conclusions from the Phosphorus Data

In winter, both parts of the Dutch Wadden Sea reacted in a similar fashion with decreasing phosphate concentrations on the decreased TP load. The long-term effect of the decreased TP load on the summer concentrations was completely different in both areas: In the western part the decrease of summer concentrations correlated with TP load, whereas a similar decrease was not observed in the eastern part. In contrast, phytoplankton did not influence the phosphate concentrations in the western part whereas it had a significant effect in the eastern part.

Most of the phosphorus input is in particulate form (e.g. van Beusekom and Brockmann 1998). Possibly, in the western Dutch Wadden Sea a large part of the P containing particles from the rivers is trapped and "processed" before being further transported to the eastern part. The summer phosphate signal in the western Dutch Wadden Sea thus rather reflects input of inorganic P containing particles and explains why the western part reacts so clearly on the decreased TP input. The remaining high summer phosphate concentration in the eastern part possibly reflects the remaining high primary production and organic matter (and organic P) import.

During the 90s, the summer phosphate concentrations in the western part were lower than in the eastern part. Possibly this reflects the greater mean depth in the western Dutch Wadden Sea and therefore a greater dilution of phosphorus input from the sediment into the water column. A similar explanation was proposed for the lower ammonium concentrations in the western Dutch Wadden Sea as compared to the eastern part.

#### 4.5.6 Influence of TP Input on the Nitrogen Cycle in the Dutch Wadden Sea

In addition to the above statistical analyses of the influence of TP input on the phosphorus cycle, the influence of TP input on the remineralization levels was investigated. As shown in Chapter 4.5.2 TP input and TN input are highly correlated. This explains why TP predicts the autumn remineralization as good as TN does (Table 4.3). Small differences exist: TN is a better predictor for the western Dutch Wadden Sea and TP a better pre-

**Table 4.3:**  
Results of the multiple regression between TP input via Rhine and Meuse and the N remineralisation in the Wadden Sea.

Western Dutch Wadden Sea				
- Dependent:	Sum of NH <sub>4</sub> and NO <sub>2</sub> (Month 9-11)			
- Independent:	Rhine/Meuse TP load (Month 12-8)			
- Covariable:	Chlorophyll (Month 9-11) Temperature (Month 9-11)			
Results				
N=19	p=0.0020	R <sup>2</sup> =0.62	Outlier: 1983	
Variable	Beta	B	p	
TP load	0.46	0.00024	0.015	
Chl a	-.41	-.40	0.026	
Temp	0.31	1.49	0.076	
Eastern Dutch Wadden Sea				
- Dependent:	Sum of NH <sub>4</sub> and NO <sub>2</sub> (Month 9-11)			
- Independent:	Rhine/Meuse TP load (Month 12-8)			
- Covariable:	Chlorophyll (Month 9-11) Temperature (Month 9-11)			
Results				
N=19	p=0.0029	R <sup>2</sup> =0.595	Outlier: 1996	
Variable	Beta	B	p	
TP load	0.58	0.00048	0.003	
Chl a	-.39	-.57	0.037	
Temp	0.22	1.31	0.206	

dictor for the eastern Dutch Wadden Sea. In accordance, TN input is a better predictor for summer chlorophyll levels in the western Dutch Wadden Sea ( $n=20$ ;  $r=0.65$ ;  $p<0.002$ ) than TP ( $n=20$ ;  $r=.506$ ;  $p<0.23$ ). Thus, in a statistical sense, no conclusions can be drawn whether P or N is the factor driving the organic matter import. This situation might change if the decreasing trend in phosphorus input continues and the primary production levels, chlorophyll *a* levels and the remineralization intensity stay at a high level. From the conceptual point of view, however, it makes sense to relate the autumn remineralization levels to TN input for two reasons: 1) Nitrogen limits the offshore primary production and 2) relating TN input to autumn concentrations of ammonium and nitrite (both nitrogen compounds) is more straightforward than using TP input.

A further problem with TP as the master nutrient is the fact that the TP input is dominated by the particulate P fraction: The comparison of summer phosphate levels in the western and eastern Dutch Wadden Sea suggests that the western Dutch Wadden Sea reacted stronger to the de-

creasing P input than the eastern Wadden Sea, presumably due to enhanced trapping and remineralization of particulate P compounds as compared to the eastern Wadden Sea. This contradicts the above statistical analysis that both parts of the Dutch Wadden Sea are equally influenced by the TP input. Further support that nitrogen and not phosphorus is the master nutrient is given by the results from the Sylt-Rømø Basin, where increased productivity and remineralization were observed (Asmus et al., 1998a, b), despite decreasing phosphate concentrations (Bakker et al., 1999).

## 4.6 Long-term Data from the Northern Wadden Sea

### 4.6.1 Available data sets

The data sets considered for the Northern Wadden Sea are listed in Table 4.4.

In the Sylt-Rømø Basin three different monitoring programs are carried out. A comparison of the data sets showed that in general comparability was low. Largest differences were found for ammonium, salinity and silicon. The phosphate data from the "Biologische Antstalt Helgoland" (BAH) were higher than from the other programs by a factor of two to three because unfiltered samples had been analyzed. The "Bund-Länder Messprogramm" (BLMP) data were not used in the analysis because the sample frequency was too low (4 times per year). The large difference between the data sets shows the importance of intercalibration exercises.

### 4.6.2 Eutrophication in the Sylt-Rømø Basin

Within the Northern Wadden Sea, the Sylt-Rømø Basin is probably the longest and best investigated area. These data will be used to discuss the eutrophication of the Northern Wadden Sea.

During the early 80s and the early 90s, R. and H. Asmus have studied the carbon flow of the intertidal Sylt-Rømø Basin. A comparison of the carbon budgets shows that both remineralization and primary production have increased by a factor of two (Asmus et al., 1998b; Fig. 4.12). The

**Table 4.4:**  
Long-term data sets for the Northern Wadden Sea.

Area	Period	Frequency	Reference
Riverine input, Ems, Weser, Elbe	1977-1992	weekly-monthly	Lenhart et al. 1996
Büsum Mole	1991-1993	weekly-bi-weekly	(Hesse and Tillmann 1995)
Danish Wadden Sea	1989-present	12-24 times annually	DMU
Sylt Rømø Basin	1989-present	12-24 times annually	DMU, Sønderjyllandsamt
BLMP	1984-present	4 times per year	
BAH	1972-1974	about weekly	(Martens and Elbrächter 1998)
BAH	1984 present	1-2 times per week	(Martens and Elbrächter 1998)

increased primary production is in line with an increased nitrate concentration in winter in the Sylt-Rømø Basin (Fig. 4.13). In contrast, the BLMP data and Danish monitoring data show decreasing phosphate concentrations (Bakker et al., 1999).

A correlation between Elbe TN load and autumn remineralization products in the Sylt-Rømø Basin did not show a significant correlation. However, a relation exists between the winter nitrate concentrations in the German Bight and the remineralization intensity in the Sylt-Rømø Basin (Fig. 4.14).

As for the Dutch Wadden Sea, nitrogen is the key element for the Northern Wadden Sea eutrophication. But in contrast to the Southern Wadden Sea, river discharge does not relate directly to the nutrients cycles in the Northern Wadden Sea. Instead, the winter concentrations of nitrate seem to dominate the production potential of the coastal zone along the Northern Wadden Sea, as well as, the import of organic matter into the Northern Wadden Sea. A nitrogen budget for the German Bight (Beddig et al., 1997) illustrates the importance of the annual amounts of nitrogen imported from the Dutch coastal zone ( $900.000 \text{ t y}^{-1}$ ) compared to the nitrogen load by the rivers Elbe, Weser and Ems ( $150.000 \text{ t y}^{-1}$ ). The different hydrography along the Southern Wadden Sea, where the river run-off is confined to a narrow band parallel to the coast, and the German Bight, where more diffuse current patterns exist, probably also adds to the difference in response of the Wadden Sea to river discharges. Possibly the stronger salinity gradient along the more sheltered Southern Wadden Sea allows a more efficient particle accumulation than in the more exposed Northern Wadden Sea.

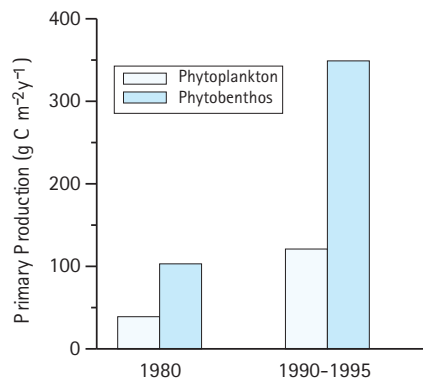


Figure 4.12: Increased primary production in the Sylt Rømø basin. (Data: Asmus et al. 1998).

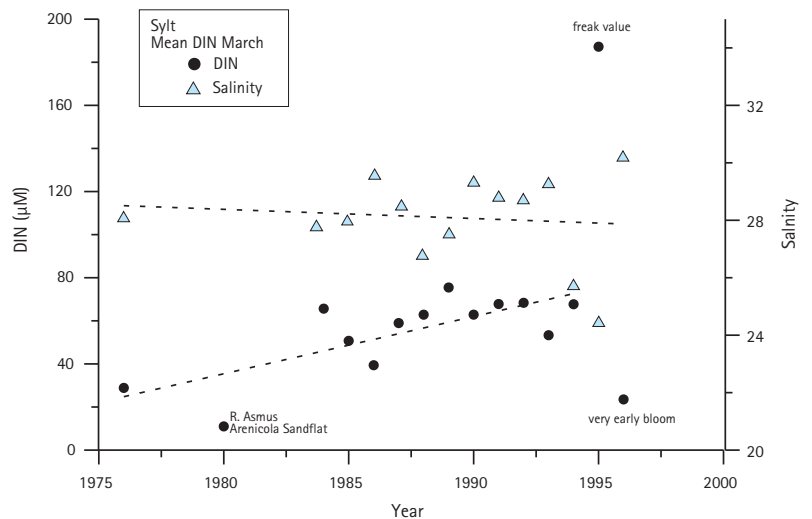


Figure 4.13: Increase of winter Dissolved Organic Nitrogen (DIN) concentrations (March) in the Sylt Rømø basin. Data: BAH/Wattenmeerstation Sylt.

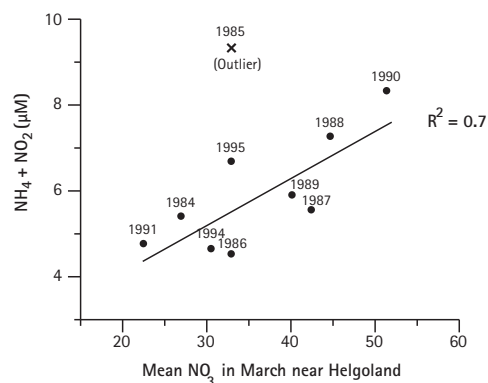


Figure 4.14: Possible relation between nitrate concentration in March in the German Bight (Helgoland Reede) and remineralized N products in autumn in the Sylt Rømø basin.

## 4.7 Comparison of Wadden Sea Subareas in the 1990s

### 4.7.1 Seasonal cycles of Nitrate, Ammonium, Phosphate and Chlorophyll

Since 1989 monitoring programs with a high temporal resolution have been carried out in the Wadden Sea. In order to compare the seasonal cycles from the different areas, the monthly means of all data from the 90s were calculated. In Figures 4.15–4.18 the seasonal cycles of nitrate, ammonium, chlorophyll and phosphate are shown.

In all areas a similar seasonal cycle of nitrate is found with high winter and autumn values and low summer values (Fig. 4.15). Differences exist in the winter maxima which range from about 100  $\mu\text{M}$  in the western Dutch and Danish Wadden Sea to 50  $\mu\text{M}$  in the Meldorf Bucht. Normally, the high winter values are associated with low salinities. Despite its vicinity to the Elbe river, the Meldorf Bucht shows the lowest values. This can be explained by the fact that only data from the very dry years 1991–1993 were available. The seasonal minimum is mostly reached in June and lasts until August or September. The very low summer values indicate that even in the Wadden Sea, nitrogen can reach very low levels below 1  $\mu\text{M}$ . The

autumn increase is very similar in all areas, reaching values of 40 to 60  $\mu\text{M}$  in December.

The ammonium data show some more interregional variability, although the concentrations and the seasonal cycle are comparable (Fig. 4.16). The seasonal cycle is characterized by high winter concentrations (8–12  $\mu\text{M}$ ), a spring minimum in April or May, a secondary maximum around June (not observed in the Danish Wadden Sea), minimum values in August and a strong increase afterwards. In all areas the autumn concentrations are similar or somewhat higher than in winter and range from 8–18  $\mu\text{M}$ . The highest autumn concentrations were found in the eastern Dutch Wadden Sea and the lowest in the Sylt-Rømø Basin.

The latter low values are possibly due to a systematic underestimation. A recent check of the method suggests an underestimation by a factor of about 1.7. Applying this factor makes the Sylt-Rømø Basin comparable to the other areas. An interesting difference between the Northern and Southern Wadden Sea is found in autumn: Whereas in the Southern Wadden Sea a clear ammonium maximum is found, this feature is not found in the Northern Wadden Sea. It remains an open question whether these differences are due to a less intense particle accumulation or due to a better flushing of the more exposed Northern Wad-

Figures 4.15 – 4.18: Comparison of the seasonal cycles of nitrate, ammonium, phosphate and chlorophyll in the different parts of the Wadden Sea. Data from the western Dutch Wadden Sea were used as reference (stippled line) for the other areas. (Data Sylt-Rømø Bight: nitrate: mean of DMU and BAH data; ammonium: BAH 1990–92, 1995–97; phosphate: DMU; chlorophyll: BAH)

Figure 4.15: Wadden Sea in the 1990 Seasonal cycle of nitrate ( $\mu\text{M}$ )

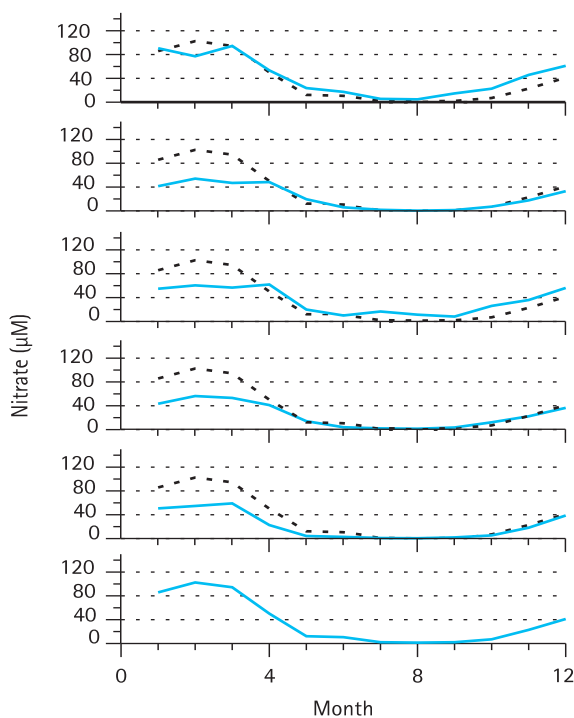
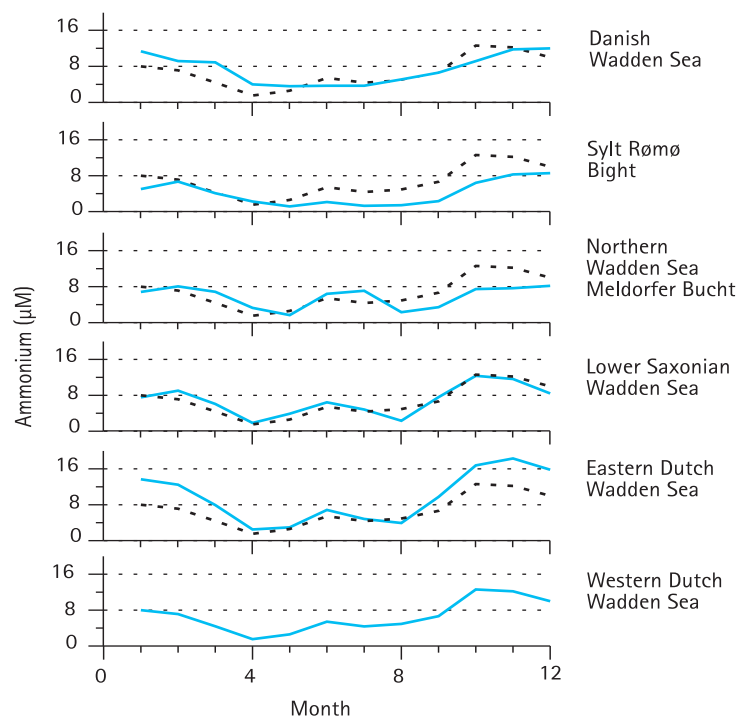


Figure 4.16: Wadden Sea in the 1990 Seasonal cycle of ammonium ( $\mu\text{M}$ )



den Sea. In any case, the differences in hydrography of the Northern and Southern Wadden Sea deserve further attention.

The phosphate seasonal cycle shows a similar shape in all areas and is characterized by high winter concentrations (1–1.5  $\mu\text{M}$ ), a spring minimum in April–May and a summer maximum in July–August (Fig. 4.17). The summer maximum is much higher than the winter maximum and ranges between about 2.5  $\mu\text{M}$  in the eastern Dutch Wadden Sea to about 1  $\mu\text{M}$  in the Sylt-Rømø Bight and in the Danish Wadden Sea. After the summer maximum, the concentrations level off at about 1.5  $\mu\text{M}$ .

The seasonal cycles of phytoplankton biomass (as chlorophyll) show the largest interregional differences (Fig. 4.18). In all areas a clear spring maximum is found with highest values in the Dutch Wadden Sea (about 35  $\mu\text{g/l}$ ) and lowest values in the Meldorfur Bucht (data only for 1991–1993). The spring maximum in the Southern Wadden Sea is reached in April and May. In the northern part of the Northern Wadden Sea the spring maximum is already reached in March. The further course of the seasonal cycle is rather region specific. In general, the phytoplankton biomass continuously decreases, but in some areas a small secondary summer maximum is found.

#### 4.7.2 Conclusions from the Interregional Comparison.

The similarity in the seasonal cycles of the different subregions of the Wadden Sea is striking. It suggests that basically the entire Wadden Sea functions in a similar fashion. Other indices of Wadden Sea "behaviour" also showed similarities: The production and remineralization capacity in both the Southern and the Northern Wadden Sea is similar (Asmus et al., 1998a; Asmus et al., 1998b), as well as, the order of magnitude of organic matter import (Table 3.2; van Beusekom et al., 1999). The latter estimates are always rough estimates inherent to the art of budget making. The seasonal cycles of nutrients reveal that differences indeed exist. In general, the highest intensities of phytoplankton activity (biomass) and remineralization (ammonium) are observed in the Dutch Wadden Sea. Another difference between the Southern and the Northern Wadden Sea is the timing of the spring bloom. This hints at better light conditions in the Northern Wadden Sea. Possibly, the different hydrography of the adjacent coastal zone off the Northern and Southern Wadden Sea plays a role here: Along the Southern Wadden Sea, strong westward currents and strong salinity gradients perpendicular to the coast exist. This results in an estuarine circulation pat-

Figure 4.17: Wadden Sea in the 1990  
Seasonal cycle of phosphate ( $\mu\text{M}$ )

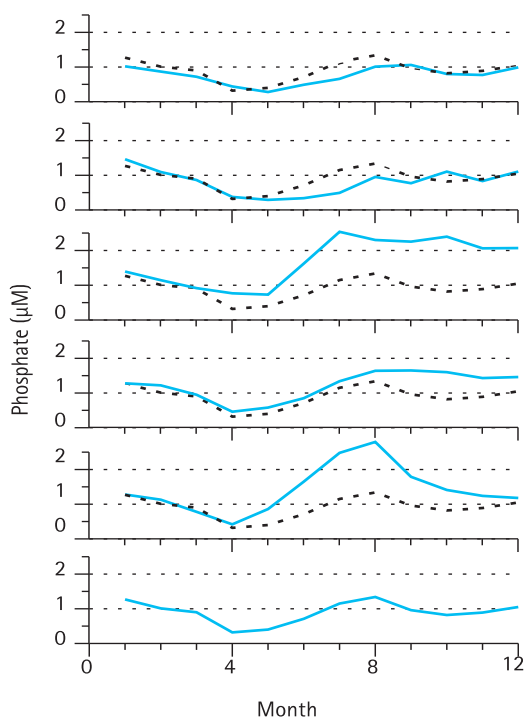
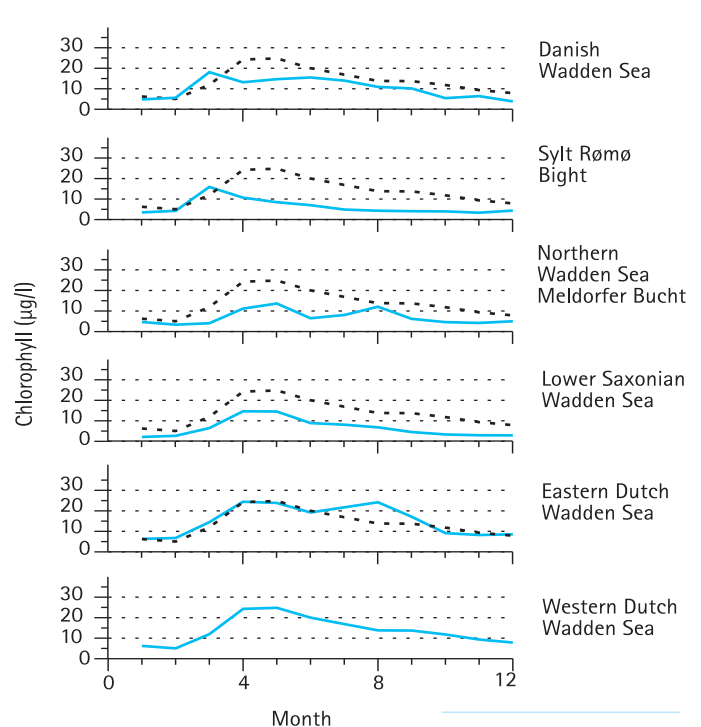
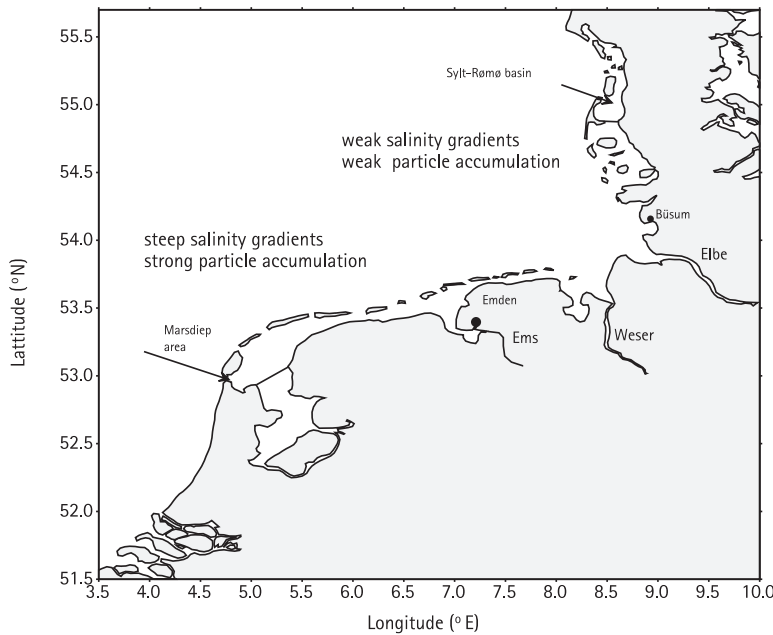


Figure 4.18: Wadden Sea in the 1990s  
Seasonal cycle of chlorophyll ( $\mu\text{g/l}$ )





**Figure 4.19:**  
A hypothesis on the different accumulation of particles along the Southern and Northern Wadden Sea.

tern, that effectively accumulates particulate matter towards the coast. In the German Bight the current patterns are more diffuse, possibly leading to a less efficient particle accumulation (Postma 1984; Hickel 1989; Fig. 4.19). The better light conditions might explain the earlier blooms in the Northern Wadden Sea. Carbon budgets do not support that less organic matter is imported into the Northern Wadden Sea, but it is questionable whether the budgets can resolve these differences.

It should be noted that both factors (organic matter import and particle import) have an opposed effect on the productivity: In the Wadden Sea, probably a co-limitation of light and nutrients occurs (van Beusekom et al., 1999; Tillmann et al., 2000). Less particle accumulation implies less nutrients but better light conditions for the primary producers to take advantage of the available nutrients.

## 4.8 Phaeocystis in the Marsdiep (Western Dutch Wadden Sea)

Data: G. Cadée

### 4.8.1 Introduction

One of the phenomena ascribed to coastal eutrophication is the occurrence of *Phaeocystis* blooms (Lancelot et al., 1987). The longest time series on *Phaeocystis* is available for the Marsdiep in the western Dutch Wadden Sea and was established by G. Cadée. Because of the importance of *Phaeocystis* blooms in the eutrophication debate, these data were investigated with the same data base of riverine input data as used for the nutrients in the Southern Wadden Sea.

Cadée and Hegeman (1986) observed during the early 70s short blooms of about 20 days. At present (after 1980) *Phaeocystis* blooms last between about 50 and 150 days per year (mean 105) implying an increase by a factor of three to seven compared to the early 70s (Cadée and Hegeman, 1991b). The increase becomes less dramatic if historic data are considered: Based on data by Cleve for the years 1897-1899, Cadée and Hegeman (1991a) estimated a bloom duration at the turn of the 19<sup>th</sup> century of about 55 days, implying on average a doubling during the past century (Fig. 4.20).

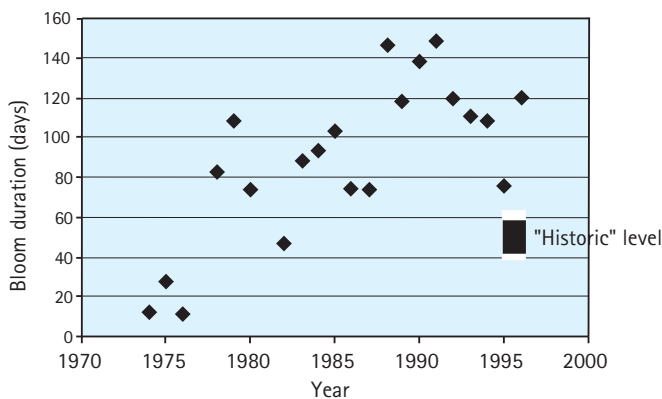
Evidence exists that the intensity of the *Phaeocystis* spring bloom is related to the amount of nitrate left after a silica limited spring diatom bloom (Lancelot and Billén, 1992). This directly links at least the intensity of *Phaeocystis* blooms with coastal eutrophication. But also the length of *Phaeocystis* blooms has been related to coastal eutrophication (Cadée and Hegeman, 1991b). Here, the relation between nitrogen discharge by Rhine and Meuse and the length of the *Phaeocystis* blooms is investigated. Evidence will be presented to suggest that two factors determine the bloom duration:

1. The relative importance of nitrate or ammonium as a nitrogen source;
2. Silicate loads.

### 4.8.2 Long-term Changes in the Nitrogen Load of the Rhine

In order to describe the long-term changes of Total Nitrogen loads via the Rhine into the North Sea data measured at Lobith (Dutch-German Border) were used because the Maassluis and Haringvliet data do not go back in time that far. For Lobith, total nitrogen data have been available

**Figure 4.20:**  
Bloom duration of *Phaeocystis globosa* in the Marsdiep, western Dutch Wadden Sea. Data: Cadée.



since 1966. No dissolved organic and particulate nitrogen data are available prior to 1966. Total Nitrogen loads from 1952 to 1965 were estimated from the ammonium loads, using the relation between ammonium and Kjeldahl Nitrogen (particulate and dissolved reduced nitrogen compounds). This extrapolation does not influence the statistical analyses, for which only data after 1974 were used.

Figure 4.21 presents the time series at Lobith. Total nitrogen loads continuously increased from 1952 onward and reached maximum values at the end of the 60s. Two periods during the early 70s and early 90s with relatively low loads are due to low river flows. Between 1974 and 1992 the relative contribution of ammonium-N to the Total N load decreased from 30% to almost 5% (Fig. 4.22). Figure 4.21 suggests that the maximum nitrogen loads into the North Sea were already reached during the early 70s. However, it has to be kept in mind that Figure 4.21 presents river data that do not reflect the factual input into the North Sea. For instance, Billén et al. (1985) pointed out that the implementation of waste water treatment would suppress the denitrification potential of the rivers and adjacent estuaries by decreasing the organic matter load and increasing the oxygen content. They warned for an increase in nitrogen loads by a factor of two. Measurements and modeling in the Westerschelde (Soetaert and Herman, 1995) support the suggestion by Billén et al. (1985). It is therefore plausible that due to the implementation of waste water treatment plants between the 60s and the late 70s the denitrification potential of the rivers and estuaries has decreased and the total nitrogen loads into the North Sea have increased, especially since the 70s. The doubling of nitrate in the outer Rhine estuary between 1960 and 1980 (van Bennekom and Wetsteijn, 1990), the doubling of winter nitrate in the Dutch Wadden Sea between 1972 and 1980 (Fig. 4.8) and the doubling of winter nitrate in the German Bight near Helgoland (Hickel et al., 1993) during the late 70s all are in line with a sudden shift towards nitrate as the main nitrogen form.

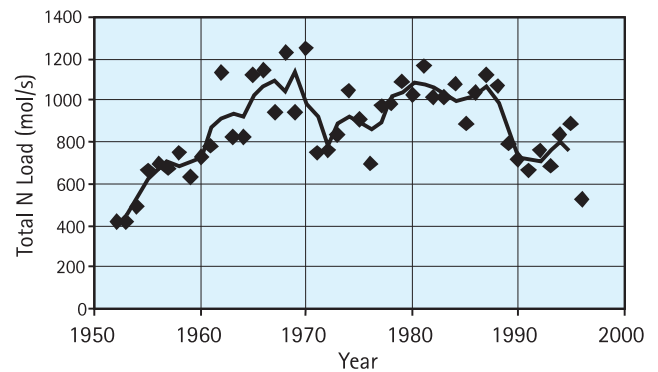


Figure 4.21:  
Mean annual Total Nitrogen load at Lobith (Dutch-German border). Total Nitrogen for the years 1952–1966 was estimated from a correlation between  $\text{NH}_4$  and Kjeldahl Nitrogen ( $r = 0.89$ ; see text). The solid line is the weighted mean:  $[(\text{load } y-1 + \text{load } y + \text{load } y+1)]/3$

Behrendt et al. (1999) proposed a different view on the increased riverine nitrate concentrations. They observed a good correlation between the surplus of agricultural nitrogen fertilization and nitrate concentrations in German rivers assuming a retention time of groundwater of about 10–30 years.

Probably both processes, increased fertilization and a reduced denitrification potential due to secondary treatment of waste water, have contributed to the increased nitrogen input into the coastal zone during the 70s.

Between 1985 and 1995 the nitrogen load of the river Rhine has decreased by about 25–30% (Berendt et al., 1999). According to these authors this reduction is probably due to the implementation of denitrification stages in wastewater treatment plants (–30%) and a reduction in the use of nitrogen fertilizers (–20%).

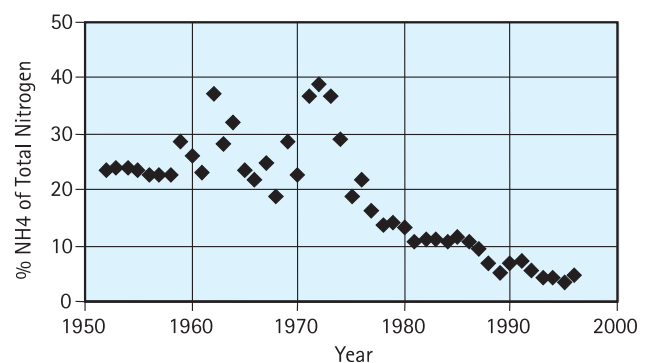
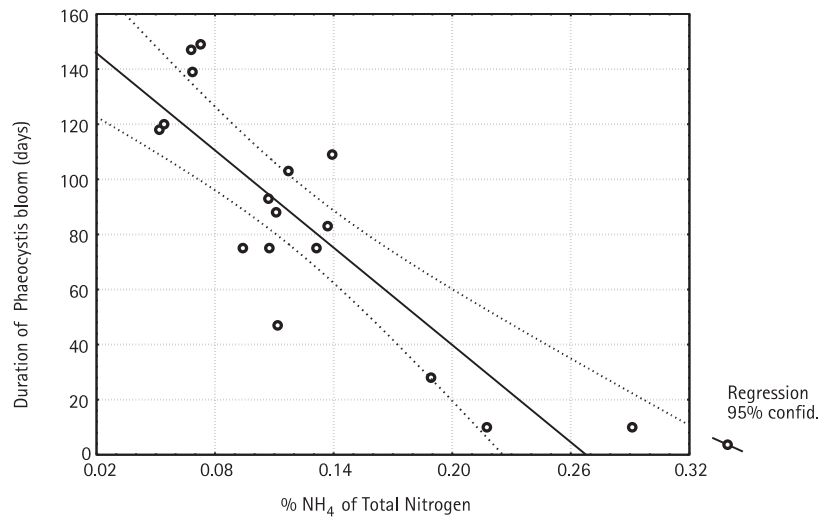


Figure 4.22:  
Proportion of ammonium of the Total Nitrogen load at Lobith (Dutch-German border). Total Nitrogen for the years 1952–1966 was estimated from a correlation between  $\text{NH}_4$  and Kjeldahl Nitrogen ( $r = 0.89$ ; see text).

Figure 4.23:  
Influence of the proportion  
of ammonium of the Total  
Nitrogen load (Lobith) on the  
duration of *Phaeocystis*  
blooms in the Marsdiep ( $r =$   
 $0.849$ ;  $N = 33$ ;  
 $p < 0.00002$ ).



#### 4.8.3 Rhine Nutrient Loads and Bloom Duration

A significant correlation exists between the relative contribution of ammonium to Total Nitrogen (Lobith) and the duration of *Phaeocystis* blooms in the Marsdiep area (Fig. 4.23). Experimental evidence is available to support that the shift from ammonium to nitrate as the major nitrogen source might have played a role in the increased bloom duration. Riegman et al. (1992) present experimental evidence that colonies are formed when nitrate is the main nitrogen source. If ammonium is the main source, *Phaeocystis* cells remain in a flagellate stage. Whereas the flagellate stage is easily controlled by grazers, the colonial form can develop large blooms because their large size (up to several mm) prevents grazing control. Thus not eutrophication as such but, ironically, the first steps to combat eutrophication may have led to the proliferation of *Phaeocystis*.

Since the 1980s nitrate remained the dominant form of nitrogen. Also the duration of *Phaeocystis* blooms remained high, be it with large inter-annual differences. A statistical analysis of the data since 1980 showed that, in general, the duration of the blooms was longest during relatively dry years with a low nitrogen river load (data not shown). At first sight this contrasts with the conclusions by Cadée and Hegeman (1986), Cadée and Hegeman (1991a) and Lancelot et al. (1987) of a relation between eutrophication and the proliferation of *Phaeocystis*.

An alternative interpretation of the above correlation is to relate the bloom duration to the amount of Si imported via Rhine and Meuse. The rationale for this approach is as follows: If enough Si is present, diatoms can outcompete other phy-

toplankton like flagellates (Officer and Ryther 1980; Egge and Asknes 1992). Riegman et al. (1992) suggested on the basis of continuous culture experiments with mixed phytoplankton populations, that some diatoms can successfully compete with *Phaeocystis* under N limited conditions.

Figure 4.24 presents a simple scatterplot of Si load versus bloom duration since 1978. During this period nitrate was the main nitrogen form in the river Rhine. A significant negative correlation was present between Si load and bloom duration ( $r=0.56$ ;  $N=18$ ;  $p<0.016$ ). Two outliers could be identified of which the most extreme case (1988) was omitted from further analysis. This increased  $r$  to 0.73 and the percentage of explained variability to 53%. The influence of nitrogen and Si on the bloom duration was further investigated with a multiple regression using two independent factors: Si load (Month 12–8) and the N/Si ratio. One data point (1988) was left out. Together, both factors explained almost 70% of the variability of the bloom duration, contributing equally to the correlation ( $r=0.830$ ;  $N=17$ ;  $p<0.010$ ), with Si load having a negative effect and N/Si ratio a positive effect on bloom duration.

The multiple regression suggests that *Phaeocystis* blooms can be influenced by eutrophication both directly and indirectly: Increased nitrogen loads will directly cause longer blooms. But freshwater eutrophication has also decreased the Si loads by the River Rhine (Elster, 1974) and in freshwater systems in general (Schelske and Storermer, 1971; van Bennekom and Salomons, 1981; Conley et al., 1993) thereby enhancing the effect of eutrophication on bloom duration.

The above regression function can be used to predict bloom duration under a given N load. The

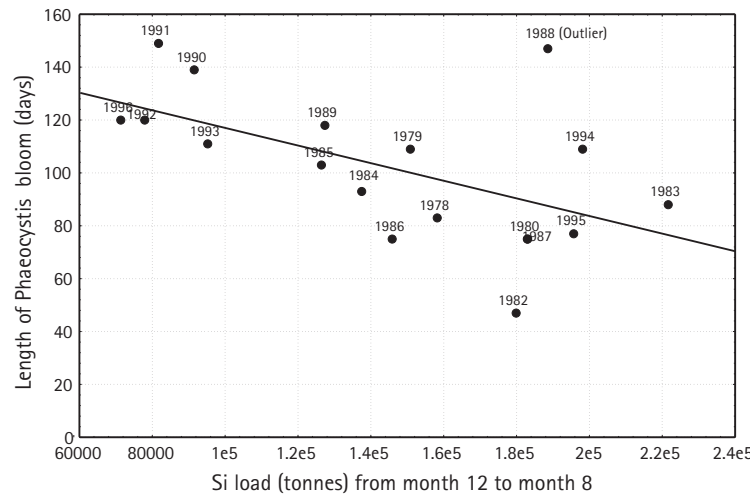


Figure 4.24:  
Influence of Si load (month  
12–8) via Rhine and Meuse  
on the duration of  
Phaeocystis blooms in the  
Marsdiep, western Dutch  
Wadden Sea.

Second International Conference on the Protection of the North Sea (London, 1987) agreed upon a 50% reduction of the 1985 input levels (by 1995). The regression function predicts a bloom duration of  $83 \pm 20$  days after a 50% reduction. At zero input levels a bloom duration of 70 days is predicted.

Compared to the historic bloom duration of about 50 days, our regression model predicts longer bloom duration even at very low N input. Possibly not only the river input but also the input via the Dover Channel influences the production potential of the Dutch coastal zone and - via import of organic matter from the coastal zone - also the production potential of the Wadden Sea (de Jonge, 1997). Indeed, nitrogen concentrations have approximately doubled since the early 60s. At present, the N/Si molar ratio in Channel water in winter (about 6) is higher than in the Rhine (about 4) suggesting that it stronger influences the flagellate/diatom ratio than the river Rhine does. Also

increased atmospheric nitrogen input increases the N/Si ratio in the North Sea.

In conclusion: The duration of *Phaeocystis* blooms is an indicator of the eutrophication status of the marine environment, especially in nitrate dominated systems. But it is difficult to be used as a measure to quantify "short term" changes in the eutrophication status. The sudden increase during the seventies is possibly due to a shift in the composition of the riverine nitrogen load from ammonium to nitrate as the major N fraction. Evidence exists that the present day mean level is higher than the background level due to nutrient enrichment of the coastal zone, but the present inter-annual variability is not explained by a positive correlation with river load. Instead, a negative correlation is found due to the effect of Si. On the other hand, high N/Si ratios favor long bloom duration. It is postulated that in years with high Si loads diatoms can better compete with *Phaeocystis* than in years with low Si loads.

## 4.9 Long-term Changes of Nutrient Dynamics in the Western Dutch Wadden Sea

### 4.9.1 Introduction

In the foregoing parts of this Chapter it was shown that a significant correlation exists between the riverine nutrient loads into the coastal zone of the North Sea and the intensity of autumn concentrations of nitrite and ammonium in the Dutch Wadden Sea. The rationale behind this correla-

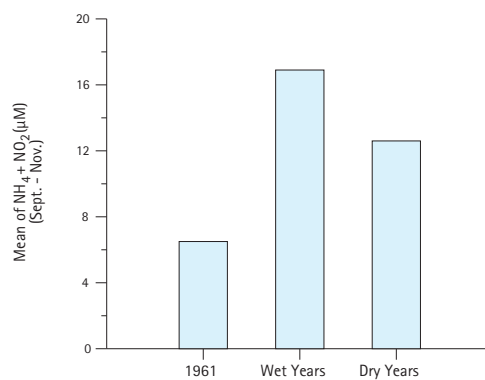


Figure 4.25: Long-term comparison of autumn values of ammonium and nitrite (µM) in the western Dutch Wadden Sea.

tion is that a certain amount of nutrients in the coastal zone will cause a certain amount of primary production, a proportional part of which will be imported into the Wadden Sea. The analyses support the observation that in wet years with high riverine nutrient loads more organic matter is remineralized in the Dutch Wadden Sea than in dry years. In this Section these data are put into a historic perspective by comparing them with the first observations of the annual nitrogen dynamics in the Dutch Wadden Sea by Postma (1966) in 1961. In Section 4.4 the seasonal cycle was compared with later years. Here, focus will be on the autumn values. On the basis of this comparison and nitrogen input data for 1932, background values will be presented for the western Dutch Wadden Sea.

### 4.9.2 Long-term Comparison of Autumn Ammonium and Nitrite Values

Figure 4.25 compares the autumn values of NH<sub>4</sub> + NO<sub>2</sub> in the western Dutch Wadden Sea for three periods:

- 1961,
- the five driest years during the 90s (1990, 1991, 1993, 1996-1997),
- the five wettest years (1980, 1987-1988, 1994-1995),

(Data: Postma, 1966; Rijkswaterstaat Monitoring Program 1975-1998).

In order to allow a comparison, the autumn levels of the data after 1975 were corrected for the ambient chlorophyll levels. These levels were somewhat higher during the dry years (Table 4.5). The values were corrected using the regression function presented in Table 4.2. No Chlorophyll data were available for 1961 and no correction was carried out.

During the five wettest years the autumn values were about three times higher and during the dry years about two times higher than in 1961. The comparison of the wet and dry years may be viewed upon as a natural experiment in which the coastal zone and the Wadden Sea was loaded with high and low amounts of nutrients. The comparison will be used to estimate the response of the Wadden Sea to future reductions of the riverine nitrogen loads.

In the following, the wet years will be taken as a reference. Compared to these years, the riverine nitrogen load (Rhine plus Meuse) during the dry years was about 45% lower. The effect on the autumn values (NH<sub>4</sub> + NO<sub>2</sub>) was less: about 25%. In other words, a 50% reduction of riverine nutrient loads will not translate into a 50% reduction but into a 30% reduction of the organic matter turnover in the western Dutch Wadden Sea. This is in line with the results of modeling exercises (ASMO, 1997; Lenhart, 1999) that predicted a reduction in the annual primary production in the open North Sea off the Dutch coast of about 30%. It is also in line with the conceptual model that predicts that the import of organic matter from the North Sea to the Wadden Sea is proportional to the offshore primary production. It is important to note that the effect of reduced nutrient input is similar in the IJsselmeer influenced western Dutch Wadden Sea and in the North Sea influenced eastern Dutch Wadden Sea (Table 4.6).

The low values during autumn 1961 indicate that the import of organic matter and the off-

Table 4.5: Comparison of autumn values in the western Dutch Wadden Sea during years with a high riverine TN load of Rhine and Meuse (1980, 1987, 1988, 1994, 1995) and years with a low TN load (1990, 1991, 1993, 1996, 1997). The TN load is given for months 12-8. The years with a high TN load are taken as a reference. Also shown is the sum of NH<sub>4</sub> + NO<sub>2</sub> corrected for the effect of Chlorophyll (See Table 4.2). The corrected values are normalized to the mean autumn Chlorophyll level (10.3 µg/l).

	Riverine Input		Eastern Dutch Wadden Sea			
	TN (tonnes)	%	Chl a (µg/l)	NH <sub>4</sub> + NO <sub>2</sub> (µM)	(NH <sub>4</sub> + NO <sub>2</sub> ) Corr. (µM)	%
High TN load:	367370	100	8.0	24.7	23.7	100
Low TN load:	218745	56	11.6	16.4	17.4	73

	Riverine Input		Western Dutch Wadden Sea			
	TN (tonnes)	%	Chl a (µg/l)	NH <sub>4</sub> + NO <sub>2</sub> (µM)	(NH <sub>4</sub> + NO <sub>2</sub> ) (µM)	Corr. %
High TN load:	36,7370	100	8.3	17.5	16.7	100
Low TN load:	20,5240	56	12.4	11.5	12.3	74

shore primary production were a factor of two to three lower than at present. In the following, sources and processes will be identified that have contributed to the increased organic matter turnover in the Dutch Wadden Sea.

The most obvious explanation for an increased organic matter turnover in the Wadden Sea is an increased riverine nitrogen load. This factor explains the differences between the dry and wet years shown in Fig. 4.25. But it does not explain the differences between the dry years during the 1990s and 1961, since available data for Lobith (Dutch German border) show similar annual loads (Fig. 4.21). Therefore, other factors must be responsible. Here focus will be on four processes:

- 1) Atmospheric nitrogen input.
- 2) Reduced estuarine denitrification.
- 3) Increased N flux via the Dover Channel.
- 4) Residual N fluxes from Wadden Sea sediments.

In the following discussion, the autumn values during the dry years are taken as a reference and the effect of changes in the above processes will be estimated. Table 4.7 summarizes the results.

Atmospheric input has markedly changed during the past decades. No reliable estimates of nitrogen input during 1961 are available. For simplicity's sake this will be put to zero. The present day atmospheric input is about 120 mmol y<sup>-1</sup> m<sup>-2</sup> (Chapter 3.3). The input has a two-fold effect on the organic matter loading of the Wadden Sea: it enhances local primary production directly through an extra input of nitrogen and indirectly by enhancing the offshore primary production, part of which is imported into the Wadden Sea. In the

open North Sea the annual atmospheric input can account for a new primary production of about 10 g C or an annual primary production of 50 g C (given an annual turnover of about 5, Chapter 3.6.1). This is about 15% of the annual primary production (e.g. Joint and Pomroy, 1993; van Beusekom and Diel-Christiansen, 1994). Most of the organic matter in the Wadden Sea is imported from the open North Sea. Therefore, atmospheric nitrogen input into the North Sea is responsible for about 15% of the organic matter import into the Wadden Sea. In addition, atmospheric input allows a new production of 10 g C within the Wadden Sea being about 10% of the annual import of organic matter. Taken together, atmospheric input is responsible for 25% of the present day organic matter turnover.

Although the riverine nitrogen load at Lobith was similar in 1961 and in the dry years during the 1990s, this does not imply that also the amount of nitrogen discharged into the North Sea was similar. Estuarine processes may significantly alter the amount of nitrogen that ultimately reaches the sea. In particular, denitrification can remove substantial amounts of nitrogen from estuaries. In well-flushed, oxygenated, nitrate-dominated estuaries the denitrification is low (e.g. Seizinger, 1988). To our knowledge, no estimates of the present day nitrogen removal in the Rhine estuary by denitrification are available. It can be estimated at about 15% since similar values prevail in the Elbe and in the Ems (compare Beddig et al., 1997 for the Elbe; van Beusekom and de Jonge, 1998 for the Ems). But during 1961 this could have been higher due two factors: a higher residence

Process	Effect on autumn values (NH <sub>4</sub> , NO <sub>2</sub> )		
	Starting Point	12.3 µM	(1990s)
Atmospheric nitrogen input			
Indirect Effect: North Sea	-15%	10.5 µM	
Direct Effect: Wadden Sea	-8%	9.5 µM	
Reduced estuarine reduction			
Nowadays: 15%			
1961: 30%	-10%	8.3 µM	
Increased N flux via Dover Channel	≤ -10% (?)		
Residual N flux from Wadden Sea sediments	≤ -10% (?)		
	End Point	6.5 µM	(1961)

Table 4.6:  
Comparison of autumn values in the eastern Dutch Wadden Sea during years with a high riverine TN load of Rhine and Meuse (1980, 1987, 1988, 1994, 1995) and years with a low TN load (1990, 1991, 1993, 1997). 1996 was not considered (outlier). The TN load is given for months 12–8. The years with a high TN load are taken as a reference. Also shown is the sum of NH<sub>4</sub> + NO<sub>2</sub> corrected for the effect of Chlorophyll (See Table 4.2). The corrected values are normalized to the mean autumn Chlorophyll level (10.0 µg/l).

Table 4.7:  
Break-down of the factors contributing to the increased eutrophication since 1961. Starting point is the mean autumn value of the five driest years with low riverine nitrogen loads since the start of the time series (1990, 1991, 1993, 1996, 1997) during which comparable riverine nitrogen loads were observed as in 1961.

time due to a larger and shallower estuary (less dredging, less wetland being diked, no Delta works) and a higher denitrification potential due to a higher organic matter content (Billén et al., 1985; see also Chapter 3.3.3). The high proportion of ammonium during 1961 (22% of Total Nitrogen, cf. Fig. 4.21) and the good correlation between ammonium and organic nitrogen (Fig. 4.21) indicate a higher organic matter content as compared to nowadays ( $\text{NH}_4 = 5\%$  of Total Nitrogen).

During 1961 the estuarine nitrogen loss through denitrification was probably higher than nowadays (15%) but less than 50% observed in the highly contaminated Schelde estuary (Billén et al., 1985). As a first approximation the denitrification during the early sixties is estimated at 30% being 15% higher than present. Model exercises are needed to confirm this estimate.

An increased nitrogen import via Dover Channel may have increased the primary production in the North Sea. Evidence exists that the fluxes through the Channel have increased (Laane et al., 1993) but the authors are reluctant to mention how much the import increased. Two factors have to be separated: the increased fluxes due to increased riverine input and an increased flux from the Atlantic Ocean. The effect of increased riverine input is probably already included in the regression analysis between autumn values and nitrogen input via Rhine + Meuse. Although only the input data from these rivers were used, they probably reflect changes in the nutrient load across most of Western Europe. Similar changes are due to inter-annual precipitation differences which probably are well reflected by large river systems such as Rhine and Meuse and to Europe-wide similarities in nitrogen emissions (parallel economic developments). The same probably holds for the long-term comparison (1961–1990s). Also it will be difficult to distinguish between a true increase in Atlantic Ocean derived nitrogen and nitrogen derived from increased atmospheric input. In any case, the effect will be less than 10% (Table 4.7).

The last factor that might have increased the autumn values are increased residual fluxes due to accumulation of organic matter. The immediate response of the  $\text{NH}_4/\text{NO}_2$  seasonal cycle to changes in organic matter import suggests that most of the imported organic matter is remineralized within one year. To investigate the effect of organic matter input from previous years on the autumn ammonium levels, input data lagged by one year were included in the statistical analysis shown in Table 4.2. No significant effects were found. This further suggests that the effect of re-

sidual nitrogen fluxes on the seasonal dynamics of nitrogen is low, but additional experiments are needed to estimate the nitrogen potential within Wadden Sea sediments. In accordance with Table 4.7 the effect is estimated to be less than 10%.

In conclusion, the most important factors that probably have increased the offshore primary production along the Dutch coast between 1961 and the dry years during the 1990s are an increased atmospheric input and a changed estuarine denitrification potential. But additional models and experiments are needed to support these suggestions.

#### 4.9.3 Background concentrations

One important criterion to evaluate the eutrophication status of the Wadden Sea is the deviation from a background value. In the foregoing it was suggested to use autumn values of ( $\text{NH}_4 + \text{NO}_2$ ) as a measure of eutrophication. As compared to the earliest data on the nitrogen cycle (1961), the present eutrophication is about two to three times higher. However, the 1961 values certainly do not represent background values since riverine nitrogen input was comparable to present day inputs observed during dry years. In the following paragraphs an attempt will be made to arrive at autumn background concentrations. The approach is based on the above discussion on the relative importance of the different nitrogen sources on the Wadden Sea eutrophication.

During 1961 the mean annual total nitrogen load of the river Rhine was about 700 mol/s (Fig. 4.21). This is about three to four times higher than the oldest available data for 1932 presented by van Bennekom et al. (1975). For 1932 these authors mentioned a mean annual load of inorganic nitrogen of about 150 mol/sec. As a first approximation the total organic nitrogen load will be set at 200 mol/s. For a first approximation of Wadden Sea background concentrations, the above value will be applied although true background concentrations in the pristine river Rhine would have been even lower. Two approaches will be followed by taking 1961 or the wet years with highest nitrogen loads (see Table 4.5) as a starting point.

Compared to the five years with highest nitrogen inputs, the annual load in 1932 was 82% lower. Nowadays, a 50% reduction of the riverine nitrogen input will result in 33% lower autumn values. Extrapolating this relation to 1932 predicts a reduction of the autumn values by 49% from 16.7 to 8.3  $\mu\text{M}$ . From this value the effect of the atmospheric input (2.8  $\mu\text{M}$ ; see Table 4.7) and of further sources (1.8  $\mu\text{M}$  see Table 4.7) have to be

subtracted. This results in a background value of  $3.7 \mu\text{M}$  ( $\text{NH}_4 + \text{NO}_2$ ).

Alternatively, 1961 can be taken as a starting point. The difference in the annual TN load is about 500 mol/s. Taking into account that due to the higher loading with organic matter during 1961 the nitrogen loss due to denitrification was about 15% higher, the difference becomes less: about 400 mol/sec. A difference of 400 mol/sec is similar to the effect of dry or wet years on the riverine nitrogen load (Fig 4.21). Its effect on the present day differences in autumn values of ammonium plus nitrite amounts to about  $4.4 \mu\text{M}$  (Table 4.5). Subtraction from the 1961 autumn values predicts autumn values in the 1930s of  $2.1 \mu\text{M}$ .

In conclusion, a first approximation of "background" autumn values of ( $\text{NH}_4 + \text{NO}_2$ ) is  $3 \mu\text{M}$  ( $\pm 1 \mu\text{M}$ ). This implies that already in 1961 the eutrophication status of the western Dutch Wadden Sea was a factor of two higher than in 1932. At present the eutrophication status is about five times higher.

#### 4.10 Main conclusions

1. A significant correlation exists between winter nitrate concentrations in the ICES boxes of the North Sea and annual primary production. In the Dutch and German coastal zone the initial primary biomass that can be formed from the available nitrogen is turned over about four- to fivefold to arrive at the annual production.
2. The relation between winter nitrate and annual primary production implies that increased nitrogen input results in increased primary production.
3. Carbon budgets show that the Wadden Sea imports organic matter (about  $100 \text{ g C m}^{-2} \text{ y}^{-1}$ ) from the adjacent coastal zone.
4. A simple calculation shows that the imported organic matter is the basis for the high primary production of the Wadden Sea.
5. A nitrogen induced increase of primary production in the coastal zone will cause an increased organic matter input into the Wadden Sea.
6. The variability of autumn values of N remineralization products ( $\text{NH}_4$ ,  $\text{NO}_2$ ) in both the IJsselmeer-influenced western part and in the North Sea-influenced eastern part of the Dutch Wadden Sea correlates in a similar fashion with the nitrogen input into the coastal zone, giving further support for a causal relation between N input, primary production in the coastal zone, and organic matter import into the Wadden Sea.
7. The autumn remineralization in the Lower Saxonian Wadden Sea (Norderney) shows no correlation with Rhine/Meuse TN input. The inter-annual autumn remineralization pattern correlates significantly with the pattern in the eastern Dutch Wadden Sea. This is in line with a common forcing factor which was identified as Rhine/Meuse TN input.
8. It is suggested that autumn values of N remineralization products ( $\text{NH}_4$ ,  $\text{NO}_2$ ) can be used as a measure of the eutrophication status.
9. For the western Dutch Wadden Sea background autumn values ( $\text{NH}_4 + \text{NO}_2$ ) of  $3 \mu\text{M}$  ( $\pm 1 \mu\text{M}$ ) are proposed. This implies that the eutrophication status has increased by a factor of five.
10. In all Wadden Sea areas increased eutrophication has been observed: In both the Southern Wadden Sea (western Dutch Wadden Sea) and in the Northern Wadden Sea (Sylt-Rømø Bight) primary production has increased.
11. Whereas along the Southern Wadden Sea the variability of autumn values of N remineralization products can be related to the variability in 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 remineralization products in the Sylt-Rømø Bight was found.
12. Quality assurance procedures and intercalibration of methods have proven to be very important for enabling intercomparison of data.
13. Two contrasting situations are postulated:
  - A) The Southern Wadden Sea with intense particle accumulation and a strong coupling of productivity and remineralization with variations in nitrogen input via Rhine and Meuse.
  - B) The Northern Wadden Sea with less intense particle accumulation, where not the Elbe river input, but nutrient input from the west into the German Bight determines primary production in the German Bight and consequently the organic matter import into the Wadden Sea.

