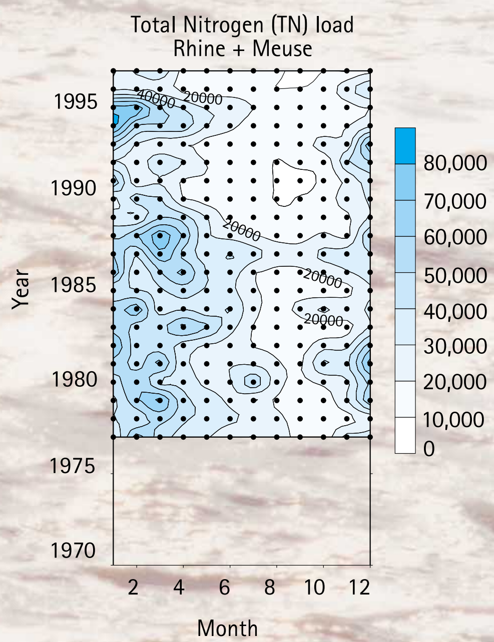
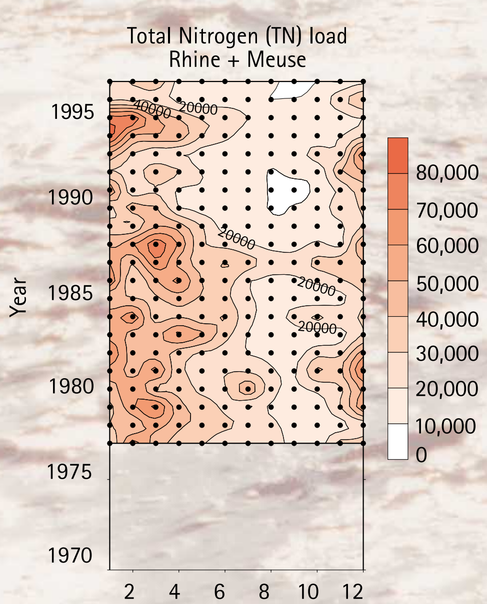
Wadden Sea Specific Eutrophication Criteria





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Wadden Sea Specific Eutrophication Criteria

Colophon

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WADDEN SEA ECOSYSTEM No. 14

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2001
Common Wadden Sea Secretariat

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Summary

In this report the results of a literature study and data analysis aiming at developing Wadden Sea specific eutrophication criteria are presented. The study was necessary to specify the trilateral Ecological Target "*to achieve a Wadden Sea which can be regarded as a eutrophication Non-Problem Area*", which has been adopted at the 7th Trilateral Governmental Wadden Sea Conference (Leeuwarden, NL, 1994). The work was done in close cooperation with activities in the framework of the OSPAR Common Procedure through which the whole OSPAR Convention Area will be designated as either Non-Problem, Potential-Problem or Problem Area with regard to eutrophication.

Based on available literature a Conceptual Model was developed that links riverine nutrient input with the nutrient cycles in the Wadden Sea. The fundamental steps are that

(1) nitrogen presently limits the primary production of the coastal zone and

(2) the Wadden Sea imports organic matter from the North Sea coastal zone.

On the basis of statistical analyses of long-term data from the Dutch Wadden Sea it could be made plausible that nitrogen currently determines the Wadden Sea eutrophication. It was furthermore shown that the variability of autumn values of N remineralization products (NH_4, NO_2) in both the Rhine-influenced western part and in the North Sea-influenced eastern part of the Dutch Wadden Sea correlated in a similar fashion with the nitrogen input into the coastal zone via the rivers Rhine and Meuse. The autumn remineralization in the Lower Saxonian Wadden Sea (Norderney) showed no correlation with the Total Nitrogen input of these rivers. However, the inter-annual autumn remineralization pattern correlated significantly with the pattern in the eastern Dutch Wadden Sea. On the basis of these results it is proposed to use autumn values of N remineralization products ($NH_4 + NO_2$) as an indicator of the eutrophication status of the Wadden Sea.

In this study the Wadden Sea has been divided into two subareas, the Southern and the Northern Wadden Sea. The Southern Wadden Sea has been defined as the area between the western Dutch Wadden Sea and the Elbe estuary. The Northern Wadden Sea has been defined as the area between the Elbe estuary and the Skallingen peninsula. In both the Southern and the Northern Wadden Sea eutrophication and primary production have increased. 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 has been found for 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.

Two contrasting situations are postulated:

(1) 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 and

(2) the Northern Wadden Sea with less intense particle accumulation, where mainly nutrient input from the west into the German Bight and, to a lesser extent, from Elbe river input determine primary production in the German Bight and, consequently, the organic matter import into the Wadden Sea.

Based on a literature survey the parameters from the "Holistic Checklist" of the Common Procedure were evaluated for their applicability as eutrophication indicators for the Wadden Sea. The *Causative Factors* are atmospheric and riverine nutrient input. The effect of the increased nutrient input is best seen in changes in the annual nutrient cycle. A Wadden Sea specific *Supporting Factor* is the import of organic matter from the adjacent coastal zone. *Direct Effects* of eutrophication can be observed in all biota of the Wadden Sea. However, no clear dose-response relation could be identified. Other factors such as

weather, temperature or more complex interactions also play important roles in the proliferation of eutrophication effects. This also holds true for the *Indirect Effects* such as changes in zoobenthos biomass and species composition.

Based on the evaluation of eutrophication criteria, a combination of two models is proposed to assess the eutrophication status of the Wadden Sea. Because of data availability, the first model was only developed for the western Dutch Wadden Sea and is based on the causative factor nutrient input.

The assessment of the eutrophication status of the Wadden Sea according to Model I is based on the relation between riverine and atmospheric nutrient input and autumn values of ammonium plus nitrite. These values reflect the amount of organic matter that was turned over during the previous summer. The transition from Non-Problem Conditions to Potential-Problem Conditions has been defined as autumn values exceeding the background concentrations. Background concentrations of ammonium plus nitrite were derived for the western Dutch Wadden Sea and amount to 3±1 µM (situation in early 1930s). According to this Model the present eutrophication status of the western Dutch Wadden Sea is 5 times higher than during the early 1930s.

Model II is based on the relation between the occurrence of eutrophication phenomena and a certain nutrient input level. The transition from Non-Problem Conditions to Potential-Problem Conditions was set at 50% of the eutrophication level after 1980. The transition is based on the observation that after about 1970 the organic matter turnover in the Wadden Sea doubled and that after 1970 also most problems associated with Wadden Sea eutrophication occurred. According to Model I the transition from Non-Problem Conditions to Potential-Problem Conditions corresponds for the western Dutch Wadden Sea to autumn NH_4 + NO_2 values of 8.3 µM implying this area to be a Problem Area.

The background concentrations and the threshold concentrations for Problem Conditions developed for the western Dutch Wadden Sea were transposed to the other areas of the Wadden Sea, proportional to the present day autumn values in the subareas. In all subareas the present day autumn values are higher than the threshold concentrations, suggesting that the entire Wadden Sea is a Problem Area. For the Wadden Sea to reach the status of a Potential-Problem Area a 50% reduction of riverine nutrient loads is not sufficient. Atmospheric nitrogen input has to be reduced as well. To reach the status of a Non-Problem Area the riverine nutrient loads and atmospheric nitrogen deposition have to be reduced to natural background levels.

1. Introduction

1.1 The Wadden Sea Eutrophication Target

In 1994, at the 7th Trilateral Governmental Wadden Sea Conference (Leeuwarden, NL), a catalogue of common Targets for the protection of the Wadden Sea Cooperation Area was agreed upon. With regard to eutrophication the Target "to achieve a Wadden Sea which can be regarded as a eutrophication Non-Problem Area" was defined. The rationale for this specific formulation can be found in developments in the framework of the Oslo and Paris Convention (OSPAR). Here work was going on aiming at defining the OSPAR Convention Area in terms of Problem, Potential-Problem and Non-Problem Areas with regard to eutrophication.

In order to be able to evaluate the Wadden Sea eutrophication target the development of Wadden Sea specific criteria was necessary.

To this end a trilateral project was carried out with support from the Dutch Ministry of Transport and Public Works, the German Federal Ministry of the Environment, Nature Conservation and Nuclear Safety and the Danish Ministry for Environment and Energy. The results of the project, which was carried out in the period December 1997 till December 1999, are presented in this report.

1.2 The 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). In the Common Procedure eutrophication Problem Areas have been defined as areas for which there is evidence of an undesirable disturbance to the marine ecosystem due to anthropogenic enrichment by nutrients. Potential-Problem Areas are those areas for which there are reasonable grounds for concern that undesirable disturbance may occur and Non-Problem Areas are those for which such concerns do not exist. For the application of the Common Procedure assessment criteria are needed. In the Common Procedure room is given for the development of region-specific criteria because of regional differences with respect to demographic and hydrodynamic conditions. The full text of the Common Procedure is in Annex 1.

The Common Procedure consists of two steps, the Screening Procedure and the Comprehensive Procedure. The purpose of the Screening Procedure is to compile information on demographic, physical, and nutrient related information, data series etc. as a first state-of-the-art analysis. By this, areas are identified which are likely to be eutrophication Non-Problem Areas. Furthermore, the information status of the coastal areas is identified. Depending on the information status, the Comprehensive Procedure can be applied in case of sufficient information. This concerns all areas which, after having been evaluated in the Screening Procedure, could not be classified as Non-Problem Areas.

The Screening Procedure was not applied to the Wadden Sea, nor to any other Dutch, German or Danish sea areas because none of these waters was claimed to be a Non-Problem Area. Sufficient data are available for applying the Comprehensive Procedure.

1.3 Outline of the Report

This report is structured in accordance with the Common Procedure.

Although the Screening Procedure was not applied, it was considered useful to provide basic information about the physical and chemical environment of the Wadden Sea before embarking upon the Comprehensive Procedure. Therefore, in Chapter 2, a brief description is given of typical geomorphological, hydrological and climatological aspects of the Wadden Sea.

In Chapter 3 a detailed description is presented of nutrient related information.

Chapters 4, 5, 6 and 7 cover the elements from the Comprehensive Procedure.

In Chapter 4, a conceptual model for the relation between nutrient input into the coastal zone and the remineralization/primary production cycle in the Wadden Sea is presented. The concept is based on literature from the past decades, and on recent studies in the German Wadden Sea. The concept reflects the specific hydrodynamic features of the Wadden Sea system relevant for the selection and evaluation of parameters indicative of eutrophication and eutrophication effects. Furthermore, the results of a comprehensive analysis of long-term data series of the most relevant parameters are presented. It concerns riverine nutrient inputs, nutrient levels and duration of *Phaeocystis* blooms.

In Chapter 5 the results of the data analysis and of literature research are applied to the Checklist from the Comprehensive Procedure. An important input to this Chapter was also delivered by a trilateral Expert Workshop, which was held at the Alfred Wegener Institute on Sylt in October 1999. During the Workshop the relevance, the applicability and feasibility for the Wadden Sea of the parameters from the Checklist of the Common Procedure were comprehensively discussed. At the Workshop also a proposal for a methodology for the integrated assessment of the eutrophication indicators was developed. The full report of the Workshop is in Annex 2.

In Chapter 6 two different models are discussed for an integrated assessment of the parameters which were identified as most suitable for use as indicators of undesirable effects of nutrient enrichment.

Finally, in Chapter 7, these models are applied to the Wadden Sea in order to determine the eutrophication status of the different regions of the area.

2. Area Description

2.1 Introduction

In this Chapter a number of specific physical features of the Wadden Sea and the adjacent coastal zone, which are of relevance for eutrophication, are briefly described. It concerns the physical geography, hydrography and geomorphology of the Wadden Sea. In addition, several proposals for a subdivision of the area on the basis of the physical characteristics are discussed. Finally, possible impacts of changes in weather and climate are addressed.

2.2 Physical Geography

The Wadden Sea is a shallow coastal area with extensive tidal flats. The Wadden Sea environment is very dynamic, the forces of wind and water lead to the formation and erosion of the typical landscape elements of the area: tidal flats, salt marshes, sandbanks and islands. The Wadden Sea region includes the whole coastal area from Den Helder in The Netherlands to the Skallingen peninsula in Denmark, about 500 km of coastline. It is a strip of tidal flats, sandbanks and islands on average some 10 km wide, although in some areas it can reach a width of more than 30 km (Figure 2.1). The Wadden Sea Area - including the islands and the coastal zone up till 3 nautical miles offshore - has a size of some 13000 km^2 .

Twenty three islands with sand dunes and 14 high sands without dunes form a barrier to the open North Sea. In the past the natural processes of accretion and erosion caused the islands to slowly change their position. However, in the inner German Bight, where the tidal range exceeds 2.9 m, such barrier islands are missing. In the last century the majority of the islands have been kept in place by fortifications, dikes, groynes and, more recently, beach nourishment.

The coastal zone along the Wadden Sea is shallow, with depths less than 30 m. Only in the German Bight a more complicated topography is dominated by the Elbe Rinne - an old river bed formed during the last ice age - which runs in an approximate southeast-northwest direction. The depth of the German Bight ranges from 10 m along the Wadden Sea to 43 m in the Elbe Rinne.

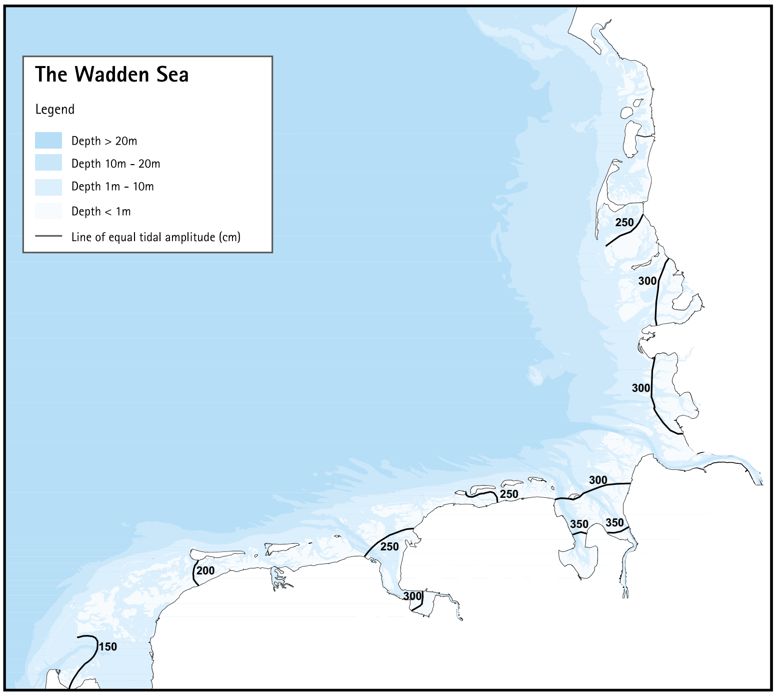


Figure 2.1: Map of the Wadden Sea showing eu- and sublittoral areas and lines of equal tidal amplitude.

2.3 Hydrography

Several rivers debouch into the Wadden Sea. The total yearly average fresh water volume which enters the Wadden Sea is some 60 km^3. The most important rivers are the Elbe (long-term average discharge: 856 m^3 s^{-1}), the Weser (long-term average discharge: 358 m^3 s^{-1}), the Ems (long-term average discharge: 88 m^3 s^{-1}) and the IJssel (via

Figure 2.2: Catchment area of the Wadden Sea.

the IJsselmeer: long-term average discharge: 555 m^3 s^{-1}) (all data: OSPAR, 1998a). The catchment area of the Wadden Sea adds up to some 230,000 km^2. It extends to the Southeast as far as the Chechian-Austrian border (Fig. 2.2). In addition to the rivers that directly discharge into the Wadden Sea, the rivers Rhine and Meuse contribute large amounts of solids and nutrients to the Wadden Sea via the continental coastal current of the North Sea.

The daily tides are the major determining factor in the Wadden Sea hydrology. With each flood on average 15 km^3 of sea water enter the Wadden Sea, thereby doubling the volume from 15 km^3 (estimated average low-tide volume) to some 30 km^3 (estimated average high tide volume). Some 70% (3000 km^2) of the Wadden Sea tidal flats have an emersion time of less than 50%, whereas only 200 km^2 of the tidal flats have an emersion-time of more than 67% (Philippart et al., 1992).

Tides are generated by the gravity fields of the sun and moon. The tidal amplitude is about 1.5 m at the northern and western edges of the region and about 3 to 4 m in the inner German Bight. Changes in the tidal amplitude are due to the phases of the moon and wind forcing. In Figure 2.1 lines of equal tidal amplitude (in cm) are shown together with the distribution of subtidal and intertidal areas.

The general circulation pattern of the water masses in the coastal zone adjacent to the Wadden Sea is first eastward towards the German Bight and then northward towards the Skagerrak. Along the southern Wadden Sea a strong salinity gradient is present. The zone of maximum salinity which indicates the core of the Atlantic water that entered via the Dover Channel, lies about 30-60 km offshore. The coastal water along the Wadden Sea is permanently mixed due to the strong tidal currents. The German Bight is characterized by a complicated hydrography (Krause et al., 1986). Basically, a mixture of Atlantic water and continental runoff (mainly Rhine) enters the German Bight from the west and leaves to the north. The central part of the German Bight is stratified in summer. The vertical density gradient is due to both thermal and salinity differences.

The circulation patterns in the North Sea strongly depend on the wind pattern (e.g. Backhaus and Maier-Reimer, 1983). For example, NW-winds prevent or delay the Rhine/Meuse-plume to spread into the German Bight. In turn, under such conditions, the contribution from the German rivers remains trapped in this area (Nauta et al., 1992). The water circulation in the Wadden Sea is also strongly influenced by the wind field (Dick et al., 1999).

2.4 Transport of Solids

The sediments of the Wadden Sea originate almost completely from the coastal zone of the North Sea. The import of sand and silt by flood currents into the Wadden Sea results in a net sedimentation of sand and silt inside the Wadden Sea. The tidal volume constitutes 40 to 50% of the total water volume of the Wadden Sea at high tide, illustrating the importance of tidal currents as transport mechanism.

According to its size, suspended matter remains in the water column until the current velocity or wave action decreases sufficiently to allow settling (see Chapter 3.3.3 for details). In this respect a gradient exists of coarse sand near the high-energy major gullies, to fine silts near the small, low-energy gullies and sheltered tidal flats. The sediment imported into the Wadden Sea consists of up to 90% sand, whereas silt, which is the sediment fraction with a grain size smaller than 63 micrometers, is the dominant type in very sheltered areas. The relation between accumulated fine-grained material and the volume of exchanged water is found to be in the same order of magnitude in different parts of the Wadden Sea and is probably a characterizing parameter of the sedimentation in tidal areas (Bartholdy and Madsen, 1985).

Another important factor which increases the deposition of suspended matter is the activity of pelagic and benthic organisms. These aggregate silt particles as faeces and pseudo-faeces, or secrete sticky substances that enhance particle flocculation. By their physical presence species can create sheltered places where suspended matter is easily settled. Examples are eelgrass communities and mussel banks. In the mixing zone a turbidity maximum develops caused by accumulation of marine particles transported towards the mixing zone by a landward undercurrent (estuarine circulation) and, to a lesser degree, by flocculation of dissolved substances. Coagulation of suspended matter occurs in transition zones between fresh and salt water. This results in an increased sedimentation in estuarine environments.

The concentration of suspended matter throughout the Wadden Sea shows large fluctuations, both in space and time, depending on, amongst others, water currents and wave action. The closing of tidal basins exerts a major influence on the tidal regime and the erosion sedimentation cycle. One example is the closing of the former Zuiderzee in The Netherlands. Effects of such changes may last for several decades (Thijsse, 1950; Rietveld 1963).

2.5 Subdivision

The Wadden Sea can be separated into geographical regions with different characteristics. The western part of the Dutch Wadden Sea, up to the Terschelling tidal divide, is sheltered by barrier islands and contains a relatively small area of intertidal flats (some 50% of the area). The eastern part of the Dutch Wadden Sea and most of the Niedersachsen and Danish Wadden Sea are also sheltered by barrier islands. Here almost 80% of the area is intertidal. The area between the Weser estuary and the island of Amrum is relatively open to the North Sea. Due to embankments only five large sheltered bays have remained: the Ho Bugt in Denmark, the Meldorfer Bucht in Schleswig-Holstein, the Jadebusen and the Leybucht in Niedersachsen and the Dollard on the Dutch-German border.

Reise (1995; 1996) divided the Wadden Sea region into three subregions based on the tidal amplitude: A southern and a northern area sheltered by barrier islands with a tidal range of 1.5 to 3 m and a central part of the Wadden Sea with a tidal range of 3 to 4 m. This central part consists of the estuaries of the rivers Weser and Elbe and the Dithmarscher Wadden Sea area up to the Eiderstedt peninsula, and has no barrier islands.

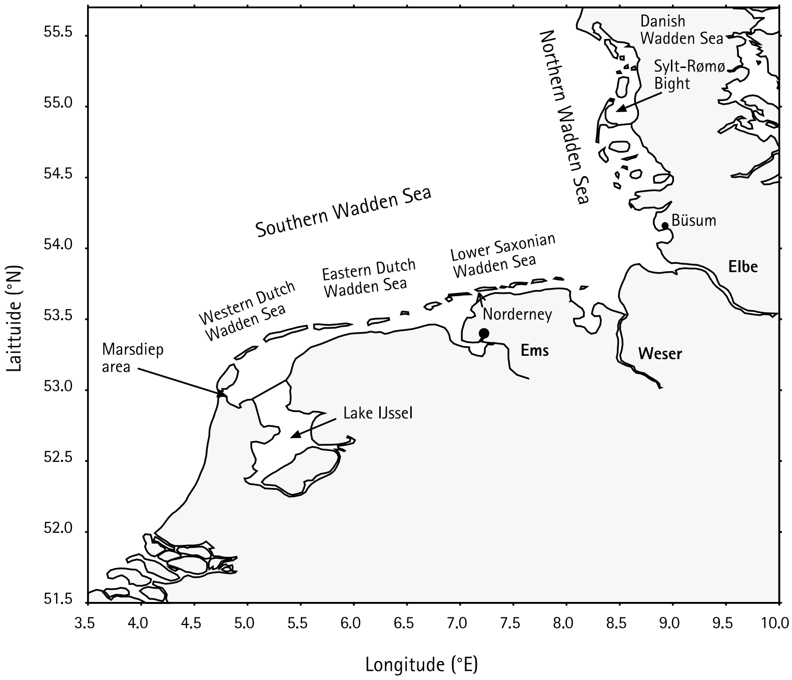


Figure 2.3: Map of the Wadden Sea with the main subareas used in the data analysis.

Bakker et al. (1999) classified the Wadden Sea into 12 areas, mainly on the basis of their salinity characteristics (marine or estuarine):

1. Western Dutch Wadden Sea (marine);
2. Eastern Dutch Wadden Sea (marine);
3. Ems Dollard estuary (estuarine);
4. Niedersachsen Wadden Sea (marine);
5. Jade Basin (marine);
6. Weser estuary (estuarine);
7. Elbe estuary (estuarine);
8. Eider estuary (estuarine);
9. Halligen area (marine);
10. Sylt Rømø Basin (marine);
11. Ribe and Konge Å estuary (marine);
12. Grådyb area (marine).

A subdivision always bases on the available data. Since not for all of the above areas long-term data are available, a somewhat courser subdivision will be used. For a large scale comparison the term *Southern Wadden Sea* for the area between the western Dutch Wadden Sea and the Elbe Estuary and *Northern Wadden Sea* for the Wadden Sea between the Elbe Estuary and Skallingen will be used (Fig. 2.3).

2.6 Climate and Weather

2.6.1 Weather

Within the Wadden Sea area there is little difference in climatic conditions. Only in the northern regions the average winter temperature is lower. This results in a higher mortality of cockle stocks, which are susceptible to low temperatures, and significantly more days with ice cover. Moving ice can cause great damage to intertidal mussel beds and ice damage is more severe in the Danish part of the Wadden Sea than in other parts.

2.6.2 Climate Change

In its report "Climate Change 1995, the science of climate change" (IPCC, 1995) the Intergovernmental Panel on Climate Change made the following very cautious statement: "The balance of evidence suggests that there is a discernible human influence on climate". In any case, there is now clear evidence that human activities have affected concentrations, distributions and life cycles of the so-called greenhouse gases. For instance, carbon dioxide concentrations have increased by almost 30% from about 280 ppmv (parts per million of volume) in the late 18th century to 358 ppmv in 1994 (IPCC, 1995) as a result of human activities. For the future an anthropogenic temperature rise in the order of 1 to 3.5°C by 2100 is predicted (Kattenberg et al., 1995).

As a result of this global warming, changes in sea level rise and storminess might occur.

Recent modeling results show that global warming may also lead to modifications in the oceanic circulation pattern in the North Atlantic (e.g. Rahmstorf, 1999). This might also influence the influx of Atlantic Water into the North Sea and the circulation patterns along the Wadden Sea.

2.6.3 The North Atlantic Oscillation

Based on continuously improving data sources a large-scale, long-term oscillation of the climate in the North Atlantic domain with a periodicity of eight years was detected (Lamb and Peppler, 1987; Hurrell, 1995). This so-called North Atlantic Oscillation Index (NAOI) is defined as the difference between the normalized pressure anomalies in winter (December-March) at Punta Delgada (Azores) and Akureyri (Iceland), or Lisbon (Portugal) and Stykkisholmur (Iceland), respectively. The long-term mean reference period is 1961-1990, and 1864-1994, respectively. A high index (>+1) is associated with strong westerly winds, and a low index (<-1) represents weak westerly winds. A "normal" index covers the mid-range from -1 to +1 and stands for a zonal circulation of average strength. Ecologically, however, not only the direct implications of the wind direction, but mainly the associated effects play a role. An example for years with a high NAO Index up to +3 are the winters of 1989-1994 (Becker and Pauly, 1996). On the other hand, the very cold winter of 1979/80 had an NAO Index of –2.

Due to the relatively small water volume in the shallow Wadden Sea, water temperatures are influenced in particular by air temperature and insolation. Therefore, winter temperatures are lower and summer temperatures are significantly higher compared to the adjacent North Sea water (Postma, 1983). However, comparisons of the long-term variability of water and air temperatures offshore and at the Dutch coast, led to the conclusion that the underlying patterns are also partly determined by the global climate pattern (de Vooys, 1990). The implication of this is that the presently debated trend of globally rising air temperatures (Houghton et al., 1996; Watson et al., 1996) will superimpose its effects on the "normal" oscillation inherent in our climate. Sterr (1995) defined the following scenario to address the possible consequences of anthropogenic climate change for the southern North Sea coast:

1. An estimated increase of average air temperatures by 1.5-3°C in the next hundred years, possibly increasing more in winter than in summer.
2. Coinciding, a substantial rise in average sea level and tidal range.
3. More frequent and more extreme strong wind events, in particular westerly winds, with a coinciding increase in wave height and wave impact.
4. Modification of the salinity in the German Bight due to changes in precipitation.

Of course, changes in precipitation will change the river discharge and thereby the nutrient loads into the coastal zone. This aspect is dealt with in detail in the data analysis presented in Chapter 4.

3. Nutrients in the Wadden Sea and Adjacent Coastal Zone

In this Chapter some relevant background information on the biogeochemistry of nutrients is presented. First, nutrient input via the major river Rhine and nutrient concentrations in the coastal zone will be dealt with. For the Wadden Sea the seasonal cycle of nutrients and their local sinks and sources will be addressed. Finally, the studies on the relation between eutrophication of the Wadden Sea and nutrient loading of the Wadden Sea will be discussed. On the basis of the available information a conceptual model will be proposed that serves as a rationale behind the data analysis presented in Chapter 4.

3.1 Eutrophication of Rivers as Exemplified by the Rhine

The major river system influencing the coastal zone adjacent to the Wadden Sea is the Rhine/Meuse system. The changes in nutrient loads have been well documented. In Figure 3.1 the eutrophication history of PO_4 and of Dissolved Inorganic Nitrogen (DIN) of the river Rhine near Lobith (German-Dutch border) is presented. It shows the increasing phosphate loads reaching a maximum in the mid eighties and decreasing since. DIN on the other hand already reached high loads in the late sixties and remained high since. Whereas these data basically reflect the eutrophication history of the river Rhine, they probably do not reflect the actual history of nitrogen and phosphorus input into the coastal zone. These inputs can be significantly altered by estuarine processes. For instance, Billén et al. (1985) concluded that reducing the organic matter loading of rivers by secondary treatment would reduce the denitrification capacity of the river and the estuaries and increase the nitrogen load into the coastal zone by a factor of two to three. Changes in the residence time, e.g. due to deepening of estuaries or the embankment of wetlands, will also decrease the denitrification capacity (Seitzinger, 1988; Billén and Garnier, 1997) and increase the amount of nitrogen that ultimately reaches the coastal zone.

3.2 The Coastal Zone

The water mass along the continental North Sea coast is an admixture of continental runoff and Atlantic Water. Increased nutrient concentrations are documented for both the Dover Channel and the Dutch and German coastal zone. Only winter data will be discussed because during this season the phytoplankton activity is at a minimum and trends in nutrients are clearest (van Bennekom and Wetsteijn, 1990).

Laane et al. (1993) reviewed the evolution of nutrients in the Channel Water and concluded that from about 1965 to about 1985 nutrient concentrations had increased (PO_4: from 0.4 µM to 0.4–1.0 µM; NO_3: from about 1-5 µM to 5-20 µM). The authors hesitated to mention a factor by which the nutrient concentration in the Channel had increased. Between 1930 and 1965 no big changes took place.

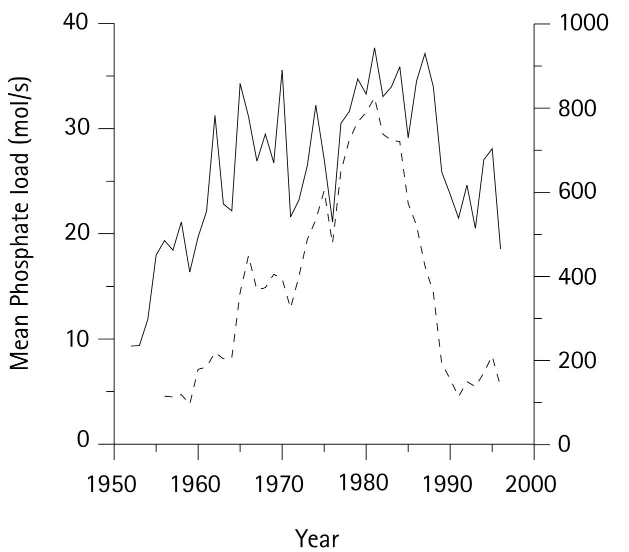


Figure 3.1: Mean annual load of PO_4 (dashed line) and Dissolved Inorganic Nitrogen (solid line) at Lobith.

Van Bennekom and Wetsteijn (1990, winter data until 1979) and Klein and van Buuren (1992, additional data until 1990) reviewed the distribution of nutrients in the Southern Bight during winter. In Dutch coastal waters dissolved phosphate, nitrate and silicate directly depend on salinity. During winter 1935/36 the phosphate concentrations in the coastal water were below 1 µM (Kalle 1937). They have increased especially since about 1960. This increase and the maximum winter concentrations around 1980 (1-3 µM) are consistent with the phosphate time series of the river Rhine presented earlier. Since 1981 the phosphate concentrations in the Dutch coastal water have decreased. Nitrate concentrations increased by a factor of 1.5 from 1960 to 1978 but in contrast to phosphate no decrease but a further (small) increase was observed since. At present (salinity dependent) concentrations of about 60 µM NO_3 and of about 1 µM PO_4 are found along the Dutch Wadden Sea (Database: DONAR, RIKZ).

Changes in the nutrient status of the German Bight are illustrated by the Helgoland time series (Hickel et al., 1993). Phosphate concentrations (winter) have increased from about 0.7 µM in the 60s to a maximum value of about 1.1 µM in the early 80s and have since then decreased to present values of about 0.7 µM. Nitrate concentrations increased from 10–20 µM in the 60s to 20–40 µM in the 90s and have remained high.

Compared to the Wadden Sea, the seasonal cycle of nutrients in the coastal zone is rather straightforward. After the spring bloom nutrients are depleted to low levels and in summer elevated concentrations are only found near estuaries and, for phosphate, also near the Wadden Sea (Brockmann et al., 1990).

3.3 The Wadden Sea

In this section various aspects of the nutrient biogeochemistry, relevant for interpreting the Wadden Sea nutrient dynamics as revealed by the time series, will be addressed.

3.3.1 Seasonal Cycles of Nutrients

Nitrogen

Nitrogen input into the coastal zone is at present dominated by dissolved inorganic fractions (NO_3, NH_4 and NO_2) accounting for about 80% of total N input. Nitrate is at present the dominant form of nitrogen accounting for about 75% of total N input, whereas ammonium is unimportant (about 5%). During the 70s, before the large scale implementation of waste water treatment plants, ammonium could account for up to 40% of total N input (van Bennekom and Wetsteijn, 1990; see also Chapter 4).

The dissolved inorganic N fractions dominating in sea water are ammonium and nitrate. Ammonium is the only inorganic N nutrient that can be directly metabolized by phytoplankton and is the preferred nitrogen source of eelgrass. By contrast, utilization of nitrate depends on a two-stage enzymatic reduction: (1) nitrate to nitrite and (2) nitrite to ammonium.

Postma (1966) and Helder (1974) were the first to describe the seasonal cycle of nitrogen in the Wadden Sea. For nitrate, nitrite and ammonium they found a clear annual cycle with low values in spring and summer and high values in autumn. Ammonium is the major nitrogen species released after the remineralization of organic matter. High ammonium effluxes from the sediment are observed during summer (e.g. Rutgers van der Loeff et al., 1981; Asmus et al., 1998c) but the low prevailing concentrations during summer suggest that primary producers consume all of the released ammonium. During the autumn a typical sequence of maxima in nitrogen remineralization products was observed: An ammonium maximum in October, a nitrite maximum in November and a nitrate maximum in winter. The sequence reflects a shift from reduced inorganic nitrogen to oxidized nitrogen.

Apart from its role as a nutrient for primary producers, nitrate also plays a role in microbial processes as a source of oxygen. During this process – denitrification - significant amounts of nitrate can be transformed to nitrogen gas and be removed from the system. Denitrification will be dealt with in more detail in section 3.3.3 on sinks and sources.

Phosphorus

In contrast to the nitrogen input into the coastal zone, which is clearly dominated by the dissolved fraction, particulate phosphorus input contributes significantly to total phosphorus input. The long-term average for the rivers Rhine and Meuse is about 35-40% but during recent years the particulate phosphorus fraction has dominated (1990-1997: 43-48%). A similar situation is found in the rivers Ems and Elbe (van Beusekom and de Jonge, 1998; van Beusekom and Brockmann, 1998). Recently, the importance of inorganic particulate phosphorus and especially of phosphate adsorbtion on iron hydroxides has been recognized (e.g. Froelich, 1988). In riverine suspended matter the contribution of iron-bound phosphorus can be as high as 50% of total particulate phosphorus (van Beusekom and Brockmann, 1998). In Wadden Sea suspended matter, particulate organic phosphorus and iron-bound phosphate are of equal importance (van Beusekom and de Jonge, 1997; van Beusekom and Brockmann, 1998).

The first observations on the phosphorus cycle in the Wadden Sea were made by Postma (1954) during the years 1949-1952. Winter concentrations were about 0.8 µM. Minimum concentrations of about 0.1 µM were reached in May and gradually increased thereafter. Based on phosphorus budgets, Postma (1954) underlined the importance of particulate matter import from the North Sea. He developed the idea that particulate organic phosphorus was imported, remineralized within the Wadden Sea and exported to the North Sea as Dissolved Inorganic Phosphorus (DIP). In 1970-72 the seasonal cycle had changed (de Jonge and Postma, 1974). Winter concentrations were about 1.7 µM decreasing to about 0.5 µM in May and increased to a summer maximum of about 2.5 µM in July. This change was contributed to increased phophorus input into the coastal zone. Using a similar approach as Postma (1954), the authors estimated that organic particulate phosphorus import had increased by a factor of 3, presumably due to an increased primary production in the adjacent North Sea. The summer phosphate maximum has been interpreted as an indicator of increased eutrophication of the Wadden Sea (e.g. Hickel, 1989).

The seasonal phosphorus dynamics in Wadden Sea sediments have not been studied yet. But the phosphorus cycle is probably similar to the cycle described by Jensen et al. (1995) in sediments from the Aarhus Bay: During winter Fe/P ratios in iron hydroxides from the oxic sediment layer of about 10 prevail. These ratios represent an equilibrium under marine conditions (Sundby et al., 1992; de Jonge et al., 1993a; Slomp et al., 1996; van Beusekom and Brockmann, 1998). During and after the spring bloom large amounts of organic matter are transferred to the sediment, where they are remineralized. Part of the released P is adsorbed onto iron hydroxides, decreasing the Fe/P ratios in the oxic zone. Due to remineralization, the depth of the oxic zone decreases, iron hydroxides are reduced and dissolved Fe^{2+} and PO_4 are released. If all dissolved Fe and PO_4 would diffuse upward into the oxic zone and reprecipitate there, this would have no effect on the Fe/P ratios in iron hydroxides of the oxic zone. However, part of the reduced Fe is lost as FeS. This results in a decreased ratio between Fe^{2+} and PO_4 and, after precipitation in the oxic zone, to decreased Fe/P ratios in iron hydroxides. In Aarhus Bay the Fe/P ratio in iron hydroxides continuously decreased from 10 in winter to about 2 during summer. The PO_4 efflux was positively related with the Fe/P ratio in iron hydroxides. The Fe/P ratio of 2 was interpreted by Jensen et al. (1995) as the ratio at which the buffer capacity of the sediment was exhausted. The above scenario can explain why phosphorus release is observed during a limited period of time only.

Recent observations during the TRANSWATT Project (Transport, Transfer and Transformation of Bio-elements in the Wadden Sea) indicate the release of dissolved phosphate from sediments also in the inner parts of the North Frisian Wadden Sea (Dick et al., 1999). For the summer period the latter authors calculated an export rate to the North Sea of 0.7 tonnes PO_4 per tide for an area of 100 km^2 , equalling a release of about 0.4-0.5 mmol PO_4 m^{-2} day^{-1} from the sediment. This value is in the range of release rates measured in other temporal coastal zones during summer: Rutgers van der Loeff et al. (1981) observed a maximum release of about 1 mmol P m^{-2} day^{-1} in June in the inner part of the Ems estuary (Dollard). During the other seasons these authors found no significant phosphate efflux from the sediment. Sometimes an influx into the sediment was observed. Jensen et al. (1995) studied phosphorus cycling in Aarhus Bay on a seasonal basis and observed a maximum phosphate efflux of 0.5 mmol PO_4 m^{-2} day^{-1} which occurred during a short period in June. During the other seasons the PO_4 efflux was mostly below 0.2 mmol PO_4 m^{-2} day^{-1}. In winter even an influx into the sediment was observed. The annual average DIP efflux amounted to 0.1 mmol m^{-2} day^{-1}. Asmus and Asmus (1998b) stressed the importance of benthic communities for the exchange of matter between sediment and water.

Silicon

Little work has been carried out on the biogeochemistry of silicon in the Wadden Sea, despite its role as an essential nutrient for diatoms. The most comprehensive study was carried out by van Bennekom and co-workers (van Bennekom et al., 1974) for the western Dutch Wadden Sea. A distinct seasonal cycle is present with limiting silicate concentrations from April to September, due to uptake by diatoms. Low Si concentrations limited the diatom spring bloom but sufficient nutrients were left to enable the further development of a flagellate (*Phaeocystis)* bloom (van Bennekom et al., 1975). The major source of silicate during summer was release, especially from muddy sediments. On an annual basis the Wadden Sea acted as a sink of riverine dissolved silicate, advected via the coastal zone and IJsselmeer into the western Wadden Sea: About half of the silicate was removed by diatom growth and less than a third of this was remineralized.

3.3.2 Nutrient Ratios

The rationale for analyzing nutrient ratios is derived from the so-called Redfield-Ratio. This ratio is based on a global perspective which shows that carbon and the nutrients N and P are incorporated by phytoplankton (and released) in a remarkably constant ratio of C:N:P=106:16:1 (e.g. Broecker and Peng, 1982). This is a global average and large deviations exists among different species (e.g. Sakshaug and Olsen, 1986). Also the ambient nutrient levels influence the N:P ratio in phytoplankton. Smayda (1990) noted that numerous investigators have focused on ratios to evaluate which nutrient was more limiting to the community production. Thus, extreme high N:P ratios indicate a possible P limitation. Smayda (1990) suggested the possibility that changed nutrient ratios might play a role in shifts in species composition and in recent observations of increased phytoplankton blooms. In his discussion Smayda focused on a shift from diatoms to non-silicifying algae due to increased N:Si and P:Si ratios. During recent years the possible role of extreme N:P ratios in inducing toxic algal blooms has been addressed. For instance, Maestrini and Granélli (1991) suggested that the high N:P ratios observed in the Skagerrak before the toxic bloom of *Chrysochromulina polylepis* was instrumental in triggering the toxicity. This item is further discussed by Colijn (1992), Zevenboom (1997) and Hodgkiss and Ho (1997). Apart from changed N:P:Si ratios also changes in the form of nitrogen might be of importance: Riegman et al. (1992) presented evidence that if nitrate was the major nitrogen source, colony formation of *Phaeocystis* was triggered, whereas *Phaeocystis* occured as single cells if ammonium was the main nitrogen source. Lancelot (1995) suggested that the decreasing ammonium input by the river Rhine might have triggered colony formation in *Phaeocystis* and induced the large blooms observed during the 80s (e.g. Cadée and Hegeman, 1986).

3.3.3 Sources and Sinks

In this section the sources and sinks of the nutrients nitrogen and phosphorus in the Wadden Sea will be shortly reviewed. As sources the accumulation of particles from the North Sea, local discharge and atmospheric input are addressed. Major nutrient sinks are denitrification, a process that removes nitrogen from the system, and apatite formation, a process that immobilizes phosphate through the formation of phosphate-carbonate minerals.

Particle Accumulation

The Wadden Sea is a deposition area for suspended matter (Eisma and Irion, 1988). The mechanism behind the particle accumulation is as follows: in the coastal zone the near-bottom residual current transports particulate matter, including locally produced organic matter, towards the coast. Postma (1984) defined a "line of no return": Particles coastward of this line can be trapped in the Wadden Sea. Within the Wadden Sea particulate matter is accumulated by the tides due to the differences in the ebb and flood currents (van Straaten and Kuenen, 1957; Postma, 1967). The accumulation of fines in the Wadden Sea has a clear seasonal cycle: During summer large amounts can accumulate (centimeters/year) that are eroded during winter. The remaining sedimentation rates are in the order of mm per year (de Haas and Eisma, 1993).

Postma (1954) already pointed out the importance of particle import from the North Sea for nutrient and carbon budgets of the Wadden Sea. De Jonge and Postma (1974) discussed that, due to an increased primary production resulting from increased phosphorus loads by the river Rhine, the import of organic phosphorus and the release of remineralized phosphate had increased about twofold. The relation between increased primary production in the coastal zone and increased particulate nutrient import from the coastal zone into the Wadden Sea is one of the central starting points for the present study.

Local Discharges

Results for the German Wadden Sea (Hesse et al., 1997; Hesse et al., 1995), the Dutch Wadden Sea (de Jonge, 1997; Nienhuis, 1992) and the Wadden Sea of Lower Saxony (Kohl et al., 1994) enable the evaluation of the importance of small point sources along the coast in relation to major imports (Table 3.1). As a rule, the relative import ratio of 100 (major rivers): 3 (minor rivers): 1 (hinterland drainage, release from point sources) can be applied.

Table 3.1: Estimated N loads of different source category in rank order. „Hinterland drainage" includes waste water treatment effluent directly introduced into the Wadden Sea and similar anthropogenic sources. For references see text.

Category	Region	Load N per year (kt)
Hinterland drainage	Lower Saxony	1.3
Hinterland drainage	Schleswig-Holstein	2.0
Hinterland drainage	IJsselmeer	2.2
Minor river	Eider	4.0
Minor river	Ems	11.0
Major river	Weser	70-85
Major river	Elbe	180-200
Major river	Rhine	350-390

Atmospheric inputs

OSPAR (1998b) estimated the total wet + dry deposition in the greater North Sea at 0.91 g N m^{-2} y^{-1}. This estimate was based on coastal measurements (period: 1987-1995; range: 0.6 – 1.9 g N m^{-2} y^{-1}) and extrapolated by model calculations. Two-third was wet deposition. On average, the atmospheric deposition was about 50% of riverine and direct N input. The large inter-annual differences in riverine input (1990-1996) should be noted (range: 948 kton in 1996 to 1468 kton in 1994). Atmospheric deposition also shows large inter-annual differences. For instance, the wet deposition at Westerland (Sylt) ranged in consecutive years between 0.47 g N m^{-2} y^{-1} (1995) and 1.1 g N m^{-2} y^{-1} (1994).

According to OSPAR (1996) the atmospheric deposition (wet + dry) along the Dutch and German coast (including the German Bight) is about 1.7 g N m^{-2} y^{-1}. Beddig et al. (1997) estimated the total deposition in the German Bight between 1 g N m^{-2} y^{-1} (model calculations) and 3 gN m^{-2} y^{-1} (measurements at a research platform NW of Helgoland).

Based upon data from four stations in the Wadden Sea (1988-1991) an average wet deposition of 1.14 g N m^2 y^{-1} was calculated by de Jong et al., 1993. Assuming that total deposition is 50% higher (see above) the total average atmospheric deposition rate is about 1.7 g N m^{-2} y^{-1} or about 15 kT N y^{-1} for the entire Wadden Sea.

The above data show the large differences in the estimates of atmospheric deposition. As a first approximation an annual atmospheric total N deposition of 1.7 g N m^{-2} y^{-1} (120 mmol m^2 y^{-1}) will be assumed.

Estimated N loads of different source categories in rank order show that an atmospheric input of 1.7 g N m^{-2} y^{-1} is comparable to the input of the Ems and equals the input of polders and hinterland drainage (Table 3.1). For the Ems estuary van Beusekom and de Jonge (1998) estimated that atmospheric deposition equalled about 25% of nitrogen import via particle accumulation from the North Sea.

Denitrification

Denitrification is a major nitrogen sink in the Wadden Sea (van Beusekom and de Jonge, 1998; Philippart et al., 2000; van Beusekom et al., 1999). Unfortunately, only few direct measurements exist. In the western Dutch Wadden Sea Kieskamp et al. (1991) reported a denitrification rate of 110 mmol m^{-2} y^{-1} as measured with the Acetylen Blocking Method. Based on a nitrogen budget for the Ems estuary van Beusekom and de Jonge (1998) estimated a denitrification of 900 mmol m^{-2} y^{-1}. Assuming that Kieskamp et al. (1991) underestimated the "true" denitrification with a factor of 5 (see van Beusekom et al., 1999, for a full discussion), both estimates give comparable results (about 600 - 900 mmol m^{-2} y^{-1}). In the Sylt Rømø Basin much lower denitrification rates of about 50 mmol m^{-2} y^{-1} were observed with the Ion Pairing Method (Jensen et al., 1996; Bruns et al., 1998). These low values are probably due to nitrate limitation. Low summer nitrate concentrations are typical for the North Frisian Wadden Sea (Hesse et al., 1995). Recent nitrogen budgets for the Wadden Sea suggest that estimates range from 19 to 35% of total nitrogen input (van Beusekom and de Jonge, 1998; Philippart et al., 2000). Much of the uncertainty regarding denitrification rates is related to the applied methods (e.g. Lohse et al., 1996; Cornwell et al., 1999).

Apatite: A Major Phosphorus Sink

In the previous section it was shown that the seasonal cycle of phosphorus is modified by the interaction with iron hydroxides, which can buffer phosphorus for some months. The high phosphorus concentrations that occur in the sediment at the oxic-anoxic interface open the possibility of authigenic (locally produced) Ca-P mineral precipitation (e.g. apatites, cf. van Cappellen and Berner, 1988; Ruttenberg and Berner, 1993; Slomp et al., 1996). Once formed, these minerals are very stable and are a long-term phosphorus sink (Ruttenberg and Berner, 1993).

De Jonge et al. (1993a) showed that Ca-P minerals are the major form of phosphorus in Wadden Sea sediments. Van Beusekom and de Jonge (1997, 1998) and van Beusekom et al. (1999) presented evidence that local precipitation of authigenic Ca-P minerals in the Wadden Sea plays a key role in the phosphorus cycle of the Wadden Sea. Based on a phosphorus budget for part of the Wadden Sea – the Ems estuary – they showed that about 25% of the phosphorus imported into the estuary was transformed to apatites. Once formed, these minerals apparently do not easily redissolve. Therefore, their formation is important in removing phosphorus from the coastal biogeochemical cycle on longer, geological time scales (Ruttenberg and Berner, 1993). For the eutrophication of the Wadden Sea this finding is of importance because the Wadden Sea does not endlessly accumulate bioavailable phosphorus but continuously removes phosphate from the system. In a way, the formation of apatites is the equivalent to denitrification in immobilizing part of the nutrient burden of the Wadden Sea.

For freshwater systems evidence exists that apatites can be a source of phosphorus (Smith et al., 1978). The authigenic phosphorus minerals formed in the Wadden Sea sediments certainly have a certain potential to release phosphorus. Experiments with Wadden Sea sediments, however, showed that they are of limited importance as a phosphorus source (de Jonge et al., 1993a). Biogeochemical budgets show that the formation and not the dissolution of apatites is the dominant process (van Beusekom and de Jonge, 1998).

3.4 Recent Trends in Nutrient Concentrations (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 depend to a large extent on salinity. Therefore, actual concentrations cannot be directly compared unless they are standardized to a certain salinity. Details of the "concentration salinity" method are given in de Jong et al. (1993). The analysis in the 1999 and 1993 QSRs are based on winter concentrations normalized to standard salinities of 10 and 27 psu.

The clearest decrease was observed for phosphate which decreased by about 50% in most of the Wadden Sea. Phosphate input via the IJsselmeer even decreased by 90%. In the western Wadden Sea and Danish Wadden Sea winter phosphate concentrations of about 1 µM are observed which gradually increase towards the estuaries of Weser and Elbe where concentrations of 2-4 µM prevail.

No equivalent decrease was observed for nitrogen, although ammonium showed a clear downward trend in the Ems, Weser and Elbe estuary, presumably due to the progressive implementation and technical improvement of waste water treatment plants. Nitrate showed an upward trend in the western Dutch Wadden Sea and a downward trend in the Ems, Weser and Elbe estuaries. Winter nitrate concentrations in the Wadden Sea (27 psu) range between 20–110 µM but are about 50 µM in most parts.

Compared to historic data (see Chapter 4) especially the present nitrate levels are clearly higher than about 4 decades ago.

3.5 Changes in Primary Productivity of the Wadden Sea

De Jonge and Postma (1974) were the first to infer an increased remineralization rate in the Wadden Sea due to an increased primary production in the coastal zone and an increased import of particulate organic phosphorus into the Wadden Sea. The increased primary production in the coastal zone was presumably due to an increased phosphorus input by the river Rhine. The earliest estimate of the Wadden Sea primary production of 20-40 g C m^{-2} y^{-1} was made by Postma (1954) and based on chlorophyll data. Between 1965 and 1975 values of about 125 g C m^{-2} y^{-1} prevailed, which sharply increased to 300–500 g C m^{-2} y^{-1} during the 1980s and remained on a high level since (Cadée and Hegeman, 1993; de Jonge, 1997). The benthic primary production doubled from about 100 g C m^{-2} y^{-1} in 1968 to 200 gC m^{-2} y^{-1} in 1982 (Cadée, 1984). In the outer Ems estuary pelagic primary production doubled from about 240 g C m^{-2} y^{-1} in 1972-1973 to about 400–500 g C m^{-2} y^{-1} in 1976-1980 (Cadée and Hegeman, 1974; Colijn and Ludden, 1983). In the Sylt Rømø Bay, Asmus et al. (1998b) observed a doubling of benthic and pelagic primary production from 1980 to 1992-1994.

Several explanations have been put forward to relate the increased phytoplankton standing stock and increased annual primary production with nutrient loading of the Wadden Sea. De Jonge (1990) successfully related changes in mean annual chlorophyll in the Marsdiep area and annual primary production (pre-1987) with the dissolved inorganic phosphate load from the IJsselmeer into the Marsdiep area. Based on more recent primary production data Cadée and Hegeman (1993) showed that despite decreasing phosphate loads the primary production in the Wadden Sea remained high. They observed a good correlation between annual primary production and annual Rhine discharge and suggested that the nitrogen load of the river Rhine kept the phytoplankton production in the Dutch coastal zone at a high level despite decreasing P discharges. De Jonge (1997) argued that an increased nutrient load of the Southern Bight via the Dover Channel (Laane et al., 1993) had compensated the decreased phosphate input into the western Wadden Sea via the IJsselmeer. It should be noted that the statistical analysis by de Jonge (1997) showed that DIN loads from the IJsselmeer were the best predictor for mean chlorophyll levels in the Marsdiep area (r=0.60).

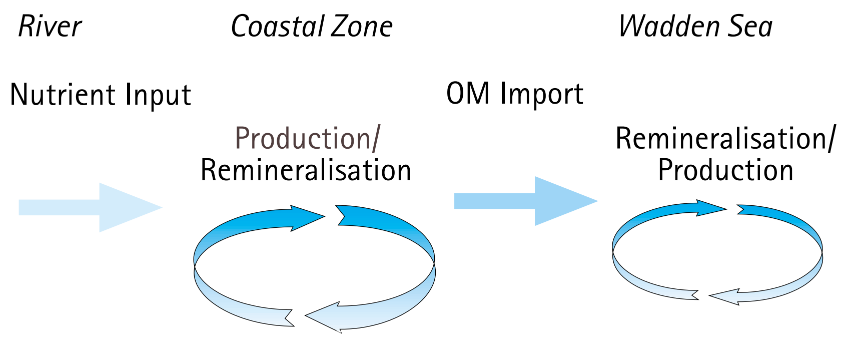


Figure 3.2: Conceptual model linking nutrient input via rivers with the nutrient seasonal cycle within the Wadden Sea.

De Jonge and Essink (1991) demonstrated a positive correlation between primary production in the Ems estuary and freshwater discharges in the period 1972-1980.

3.6 The Conceptual Model

The previous sections highlighted three essential features of the Wadden Sea: Firstly, the Wadden Sea imports organic matter (Postma, 1954), secondly, the annual nutrient cycles in the Wadden Sea have changed due to an increased import of organic matter from the North Sea (de Jonge and Postma, 1974) and thirdly, the primary production levels within the Wadden Sea have increased (Cadée and Hegeman, 1993; de Jonge, 1997).

Direct discharges into the Wadden Sea and an increased organic matter import may enhance the local productivity of the Wadden Sea, and indeed both pathways have been considered to explain changes in Wadden Sea primary production (see section 3.5). Focus will be put on organic matter import from the coastal zone into the Wadden Sea because this allows the comparison of freshwater influenced areas like the western Dutch Wadden Sea with marine influenced areas like the eastern Dutch Wadden Sea.

The conceptual model behind the data analysis is as follows (Fig. 3.2): Nutrients are imported into the coastal zone. Here, nutrients enable a certain amount of primary production. Part of the primary produced organic matter in the coastal zone is imported into the Wadden Sea. Within the Wadden Sea primary production is supported by nutrient release from remineralized organic matter. Focus will be on nitrogen for three reasons: Firstly, it is the limiting factor for North Sea primary production. Secondly, the decreasing trend in phosphate input and phosphate concentrations in the Wadden Sea contradict the sustained high or even increased primary production levels. Thirdly, the phosphorus cycle in the Wadden Sea is strongly influenced by interactions with iron-hydroxides which hampers a straightforward interpretation of the annual P cycle, whereas the N cycle and, in particular the ammonium cycle, is more directly related to the cycle of organic matter. In the following sections evidence will be compiled in support of the conceptual model.

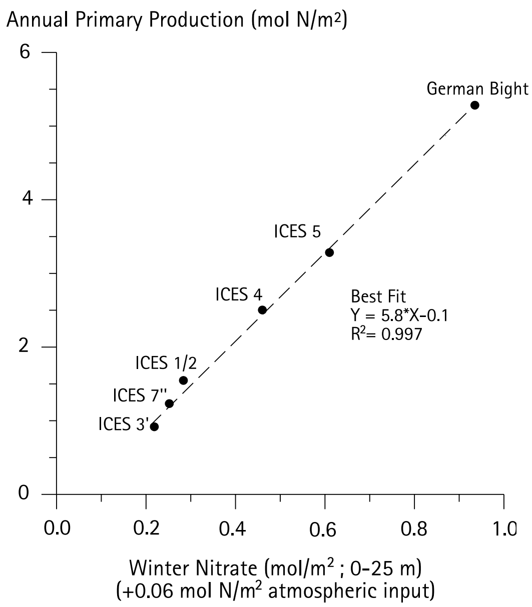


Figure 3.3: Relation between nitrate stock in winter and annual primary production. Data: Joint and Pomry (1993), van Beusekom and Diel-Christiansen (1994), German Bight: van Beusekom et al. (1999) and Rick et al. (1998).

3.6.1 Nitrogen Limitation of the North Sea

Consensus exists that the Wadden Sea has experienced increased eutrophication (e.g. de Jonge and Postma, 1974). It has been a matter of debate whether phosphorus or nitrogen is the limiting nutrient (de Jonge, 1990; Cadée and Hegeman, 1993). Evidence exists that nitrogen determines the primary production in the North Sea: A comparison of winter nitrate stocks and annual primary production shows a significant correlation suggesting that nitrogen determines the annual primary production (Fig. 3.3). The "new" primary production has to be turned over about 5 times to explain the annual primary production. Hydes et al. (1999) compared, in a similar way as described above, the annual primary production in the southern North Sea with the amount of nitrate available in March before the onset of the spring phytoplankton bloom, and the nitrogen load by rivers and atmosphere during the growth period. They concluded a turnover of five times for ICES Box 7' (central North Sea), ICES Box 4 (Dutch coastal zone) and ICES Box 5 (German Bight). In ICES Box 3b (English east coast) a lower factor of 2 was calculated. The latter low value was explained by the adverse light conditions suppressing primary production in this area.

3.6.2 Phytoplankton Biomass and Primary Production in the Coastal Zone

Evidence exists that along the Dutch coast nutrient loads by the river Rhine determine the phytoplankton biomass (Schaub and Gieskes 1991). Cadée (1992) observed a positive correlation between phytoplankton biomass in the Marsdiep and Rhine flow. He suggested nitrogen as the causative factor. De Jonge (1997) observed significant positive correlations between annual DIN load via IJsselmeer and chlorophyll in the Marsdiep (r=0.60) and DIN input via Rhine and chlorophyll in the Marsdiep (r=0.46). On the basis of data from 1950–1986 de Jonge (1990) found that phosphorus loads via the IJsselmeer were the best predictor of phytoplankton biomass and production levels in the western Dutch Wadden Sea. Due to the decreased P load and remaining high primary production levels, the correlations between phosphorus input and annual production levels after 1996 were not significant anymore. However, still significant correlations between phosphorus loads and annual phytoplankton biomass were found (highest: r=0.48; TP input via IJsselmeer) although not as good as for the period 1950-1986.

3.6.3 Import of Organic Matter

From a global perspective, coastal zones are heterotrophic (Smith and Hollibaugh 1993): More organic matter is accumulated and degraded than is locally produced. Heip et al. (1995) reviewed carbon budgets from temperate coastal zones and arrived at the same conclusion. They suggested that import of organic matter may enhance local primary production if enough light is available.

The importance of organic matter for the Wadden Sea has already been pointed out by Postma (1954). Based on a hydrographic model in combination with actually observed gradients, Dick et al. (1999) estimated for the northern Wadden Sea an organic matter import of about 100 g C m^{-2} y^{-1}. Based on phosphate gradients Hesse et al. (1992) estimated an annual organic matter input into the northern Wadden Sea of about 85 g C m^{-2} y^{-1}. Van Beusekom et al. (1999) reviewed annual carbon budgets from different parts of the Wadden Sea. They showed that organic matter import is a general feature of the Wadden Sea and concluded that about 100 g C m^{-2} y^{-1} are imported (Table 3.2). This estimate is somewhat lower than 200–300 g C m^{-2} y^{-1} postulated by Postma (1984) and de Jonge and Postma (1974). In conclusion, an annual import of organic matter of about 100 g C m^{-2} y^{-1} seems a fair estimate for the Wadden Sea.

A simple calculation illustrates the importance of organic matter import for the productivity of the Wadden Sea: Van Beusekom et al. (loc. cit.) concluded that organic matter is turned over about two to three times in the Wadden Sea. This turnover rate does not reflect the degradability of the organic matter, but rather reflects the efficiency with which the primary producers can make use of the released nutrients. The Sylt-Rømø Basin carbon budget (Table 3.2) supports a similar turnover rate: A three-fold turnover of the imported organic matter (about 100 g C m^{-2} y^{-1}) can account

Table 3.2: Carbon budgets from the Wadden Sea (van Beusekom et al., 1999).

Area	Production (g C m^{-2} y^{-1})	Remineralisation (g C m^{-2} y^{-1})	Net. Import (g C m^{-2} y^{-1})
W. Dutch Wadden Sea	298	450	152
Ems Estuary	210	290	80
Büsum	200	280	80
Sylt-Rømø Bight	309	419	123

for the annual primary production of 309 g C m^{-2} y^{-1}. Primary production based on available nitrogen in the water column is less important: The winter DIN concentrations amount up to 80 µM. Fresh water input is negligible (Asmus and Asmus, 1998a). Given a mean depth of 2.5 m this enables a new production of 15 g C m^{-2} y^{-1}. Applying an annual turnover of about three, this biomass can only explain 20% of the annual primary production of 309 g C m^{-2} y^{-1}. Of course, nitrogen release from organic matter that accumulated during the previous years may fuel local primary production. In the above calculation, however, steady state will be assumed: On an annual basis, nitrogen release from the sediment is compensated for by an equal nitrogen flux into the sediment.

3.6.4 Nitrogen loads and Wadden Sea nutrient cycles: A Hypothesis

On the basis of the above literature analysis it is concluded that evidence exists to support the conceptual model. The fundamental steps are that:

- Nitrogen presently limits the primary production of the coastal zone.
- The Wadden Sea imports organic matter from the North Sea coastal zone.

The above statistical analyses (3.6.2) do not unambiguously show that either P or N limits the primary production in the Wadden Sea. But, because there is evidence to suggest that N limits the primary production in the coastal zone and because the import of organic matter from the North Sea is important in sustaining the high productivity in the Wadden Sea, nitrogen is suggested to be presently the major nutrient influencing the Wadden Sea eutrophication.

In the data analysis presented in the next Chapter the main focus will be on the influence of nitrogen input into the coastal zone and - via a proportional primary production and import of part of this organic matter - on the nitrogen cycle of the Wadden Sea. In Figure 3.4 the mean seasonal cycle of phytoplankton biomass (chlorophyll) and the main remineralization products nitrite and ammonium are shown. Despite the import and remineralization of organic matter, the concentrations of nitrite and ammonium are low during summer. This suggests that the phytoplankton is capable of removing more nitrogen from the water column than is released by remineralization processes. However, in autumn, when the light conditions deteriorate, the phytoplankton biomass decreases and an autumn peak of nitrite and ammonium can develop. In the data analysis the hypothesis is tested that, during years with a high nitrogen input, more organic matter is remineralized within the Wadden Sea due to a higher offshore productivity. Thus, it is expected that during years with a high nitrogen input, a higher autumn peak of nitrite and ammonium can develop than during years with a low nitrogen input.

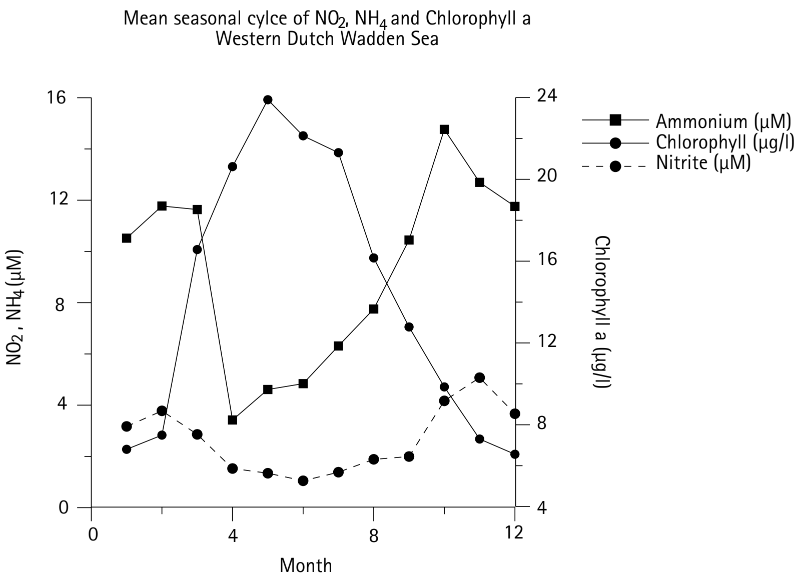


Figure 3.4: Mean seasonal cycle of ammonium, nitrite and chlorophyll a in the western Dutch Wadden Sea.

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 $NH_4 + NO_2$ 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 function 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 NO_2 and 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
Phaeocystis 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

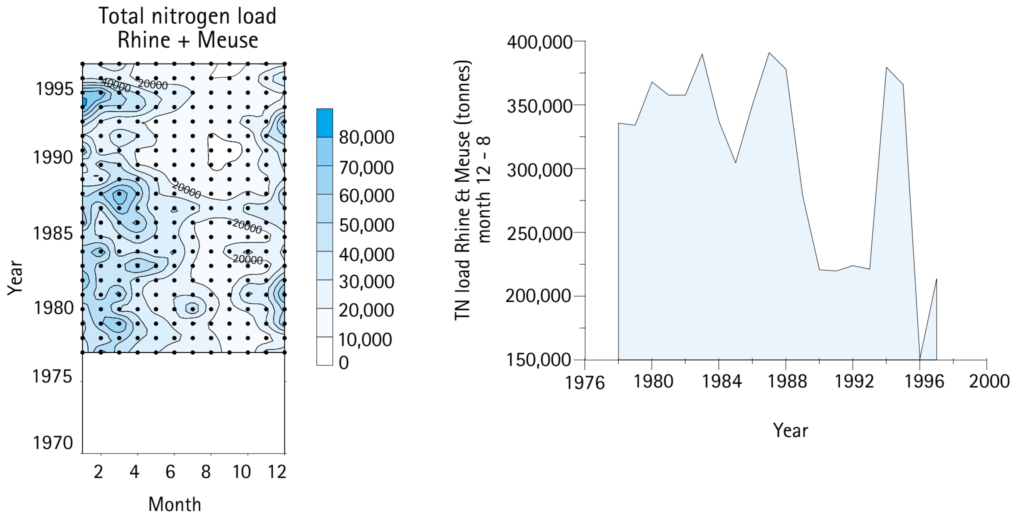


Figure 4.1: The monthly discharge of Total Nitrogen (TN) of the rivers Rhine and Meuse via Maassluis and Haringvliet. In the right panel, the time serie of total load from December (previous year) to August is shown.

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.

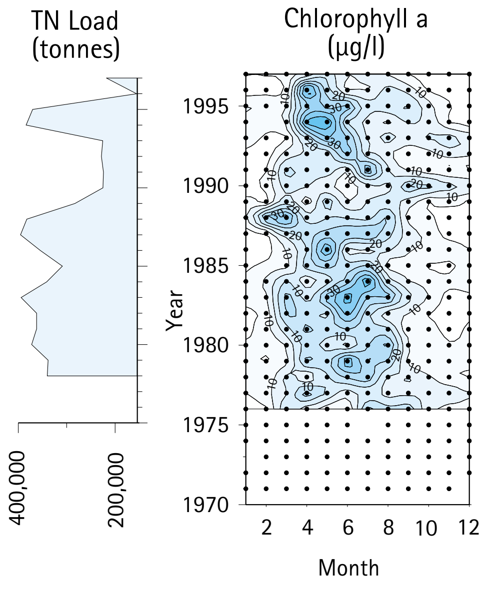


Figure 4.2: A month-year plot of chlorophyll in the western Dutch Wadden Sea. Also shown at the left are the time series of TN load via Rhine and Meuse. The Y-axis of both graphs correspond.

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.

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 covariables showed a significant correlation (Table 4.2).

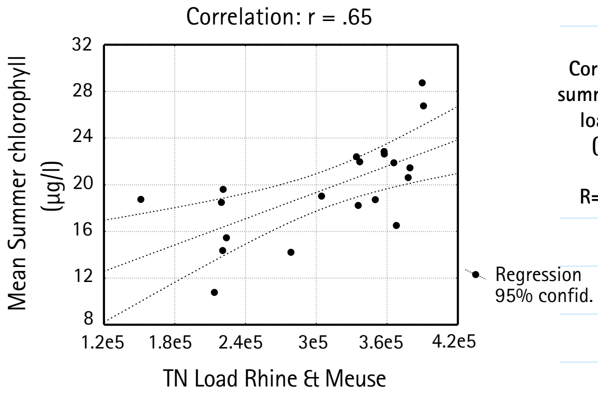


Figure 4.3: Correlation between mean summer chlorophyll and TN load of Rhine and Meuse (Tonnes) in the western Dutch Wadden Sea. R=0.65; p<0.002; N=20.

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 NH_4 and NO_2 (Month 9-11)			
- Independent:	Rhine/Meuse TN load (Month 12-8)			
- Covariable:	Chlorophyll (Month 9-11)			
	Temperature (Month 9-11)			
Results				
N=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 NH_4 and NO_2 (Month 9-11)			
- Independent:	Rhine/Meuse TN load (Month 12-8)			
- Covariable:	Chlorophyll (Month 9-11)			
	Temperature (Month 9-11)			
Results				
N=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	

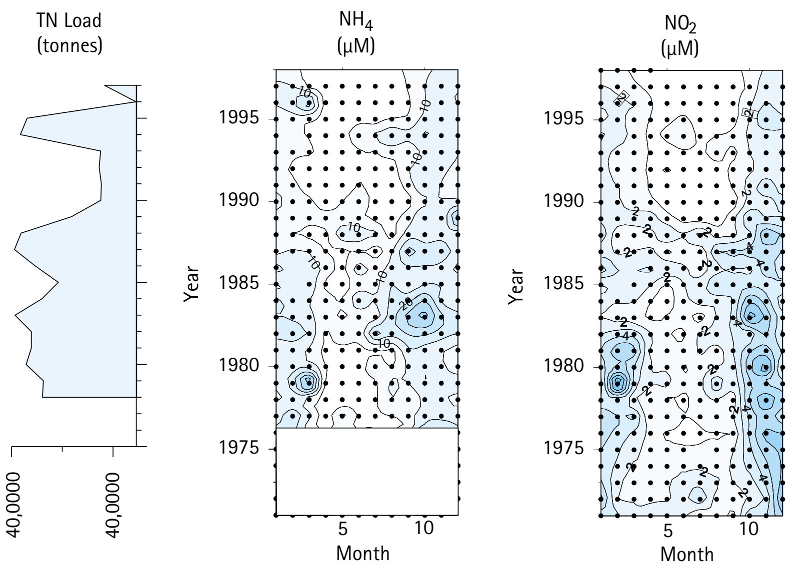


Figure 4.4: Month-year plots of ammonium and nitrite in the western Dutch Wadden Sea. For comparison the TN load (Rhine + Meuse) is shown on the left.

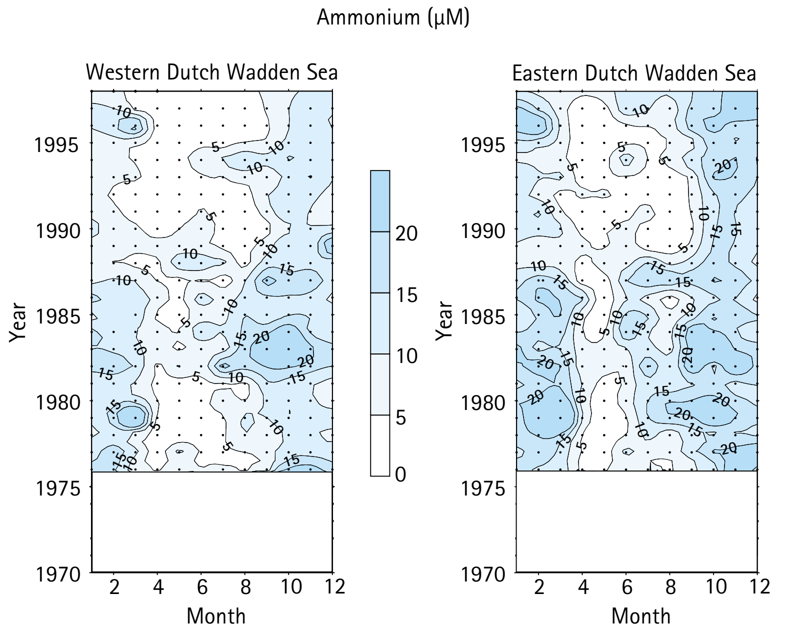


Figure 4.5: Comparison ot the seasonal cycles of ammonium in the western and in the eastern Dutch Wadden Sea.

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

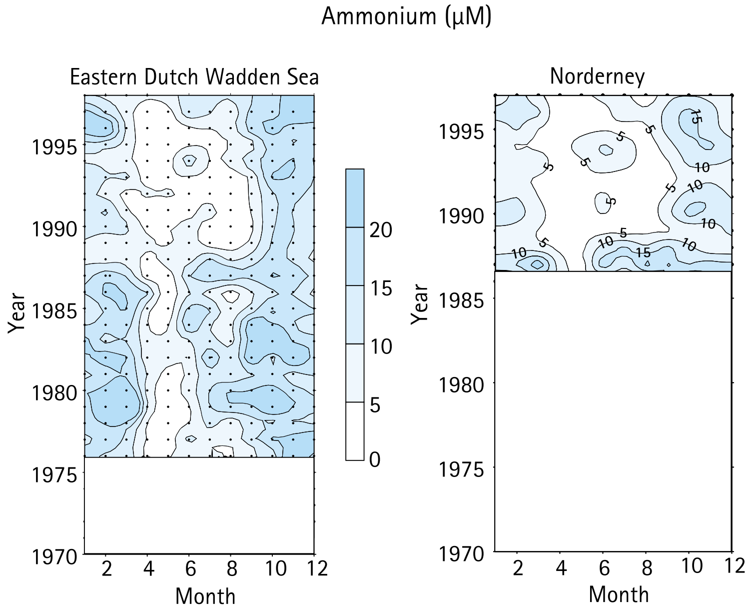


Figure 4.6: Comparison ot the seasonal cycles of ammonium in the eastern Dutch Wadden Sea and in the Lower Saxonian Wadden Sea (Norderney).

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.

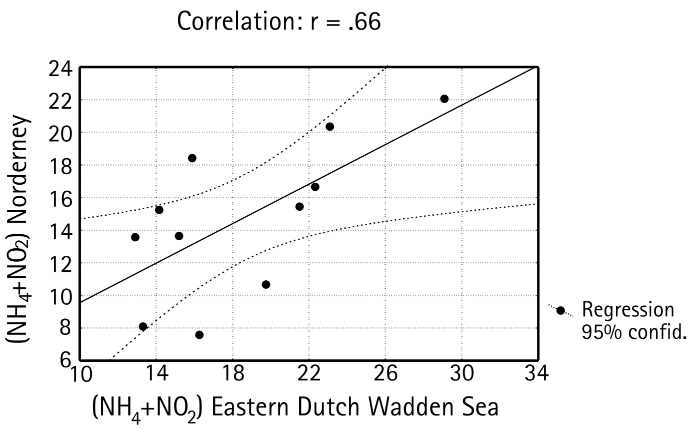


Figure 4.7: Correlation between mean autumn values of ammonium + nitrite in the eastern Dutch Wadden Sea and in the Lower Saxonian Wadden Sea. All values in are in µM. R=0.66; p<0.03; N=11.

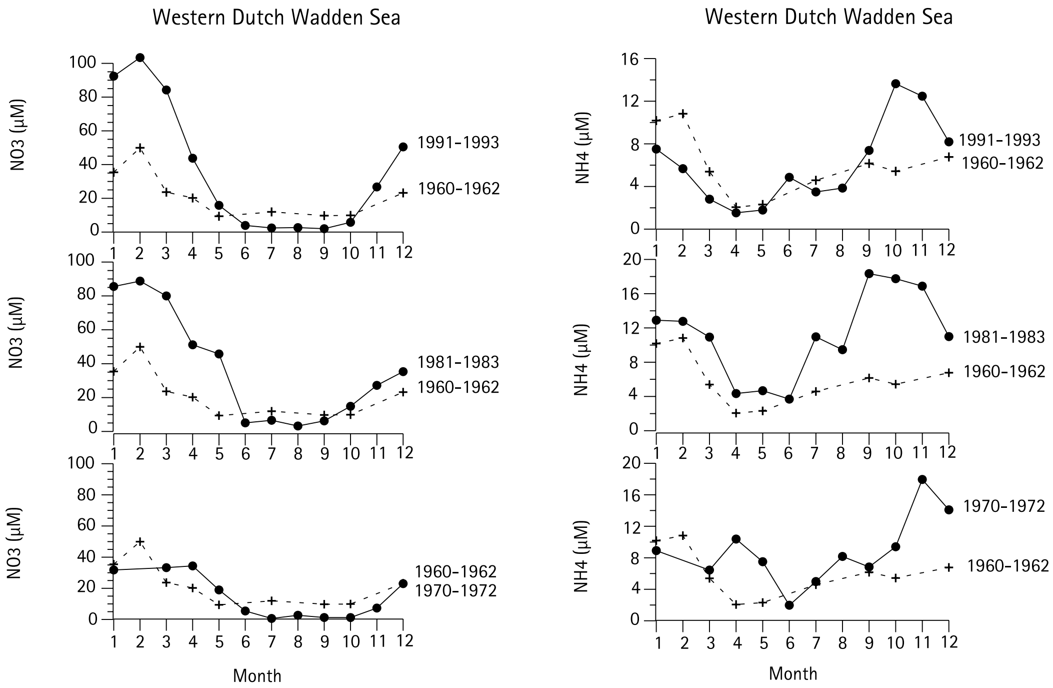


Figure 4.8:
A comparison of historic nitrate and ammonium data from four decades in the western Dutch Wadden Sea. Data sources: (Postma 1966), (Helder 1974) and Rijkswaterstaat (DONAR).

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 µM to almost 100 µM. 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 Bennekom 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.

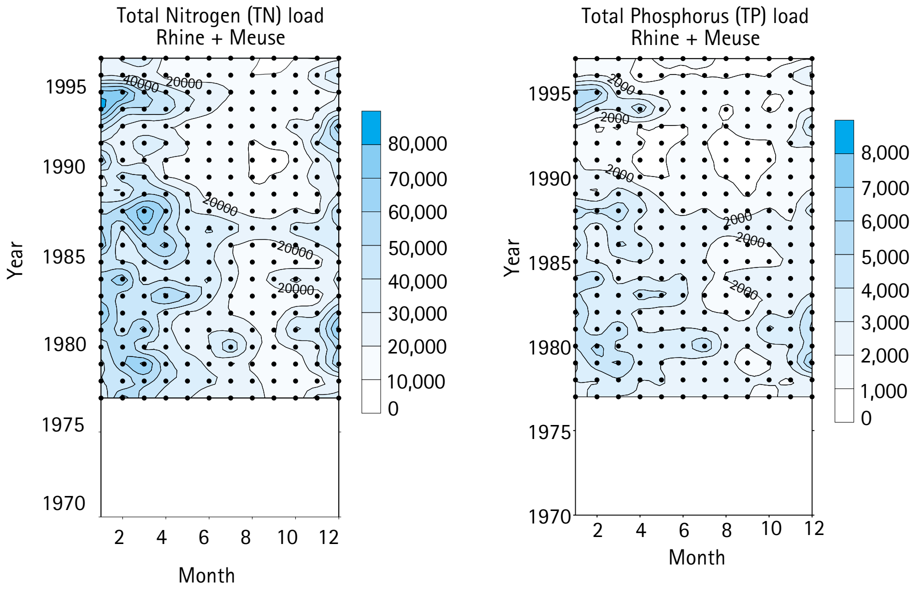


Figure 4.9: Comparison of the Total Nitrogen (TN) and Total Phosphorus (TP) load (tonnes/month) via Rhine and Meuse (Maassluis and Haringvliet).

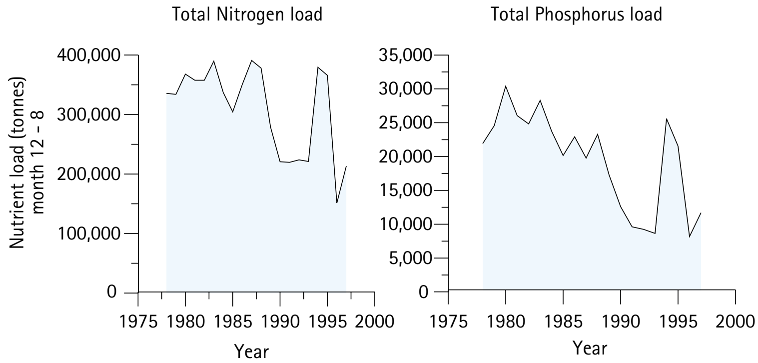


Figure 4.10a: Comparison of the TN load (month 12-8) shown at the left with the TP load (month 12-8) shown at the right.

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.

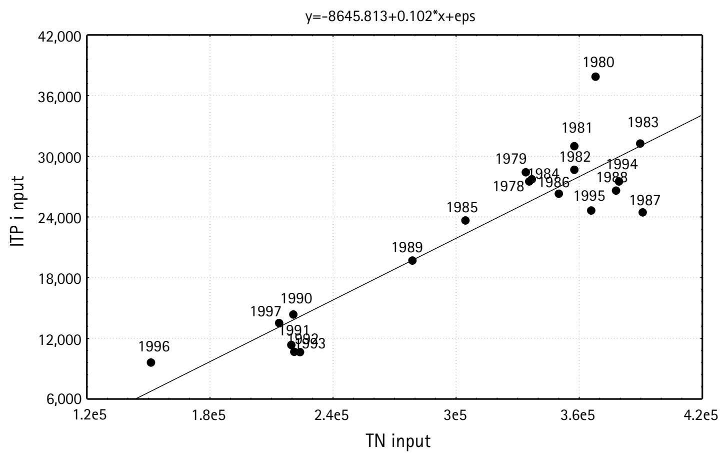


Figure 4.10b: Correlation between TP input and TN input via Rhine and Meuse (month 12-8).

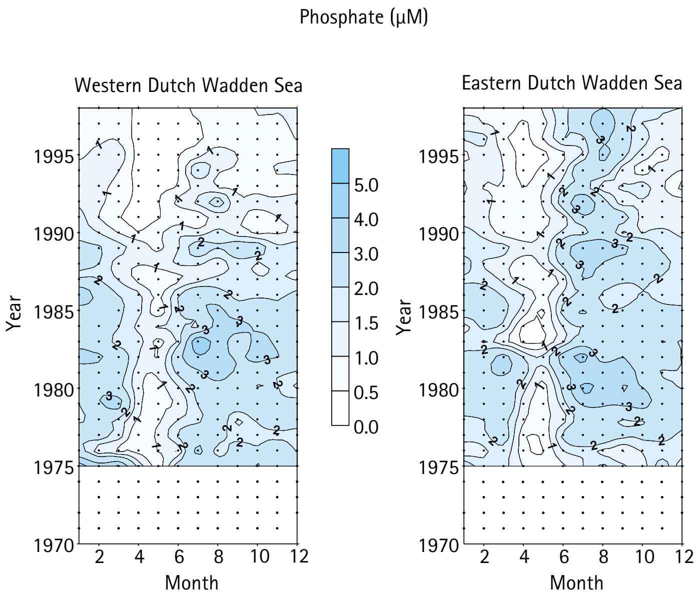


Figure 4.11a: Comparison of the seasonal cycles of Phosphate (µM) in the eastern and in the western part of the Dutch Wadden Sea.

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 µM in 1983 decreasing to less than 1 µM 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 µM during the 80s to less than 1 µM 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 µM during the 80s to about 1 µM 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-

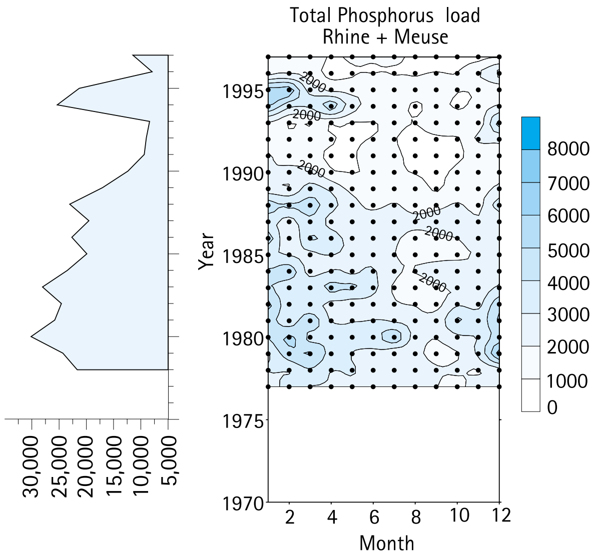


Figure 4.11b: Total Phosphorus load via Rhine and Meuse (Maassluis and Haringvliet). The left-hand graph shows the total load (Tonnes) from month 12 –6.

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 g C m^{-2} 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 bioavailable 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_4 and NO_2 (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^2=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_4 and NO_2 (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^2=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 decreasing 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 Messprogram" (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 t y^{-1}) compared to the nitrogen load by the rivers Elbe, Weser and Ems (150.000 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.

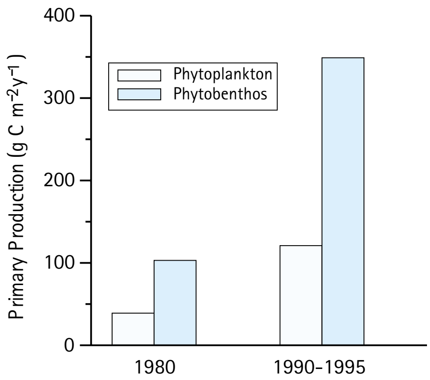


Figure 4.12: Increased primary production in the Sylt Rømø basin. (Data: Asmus et al. 1998).

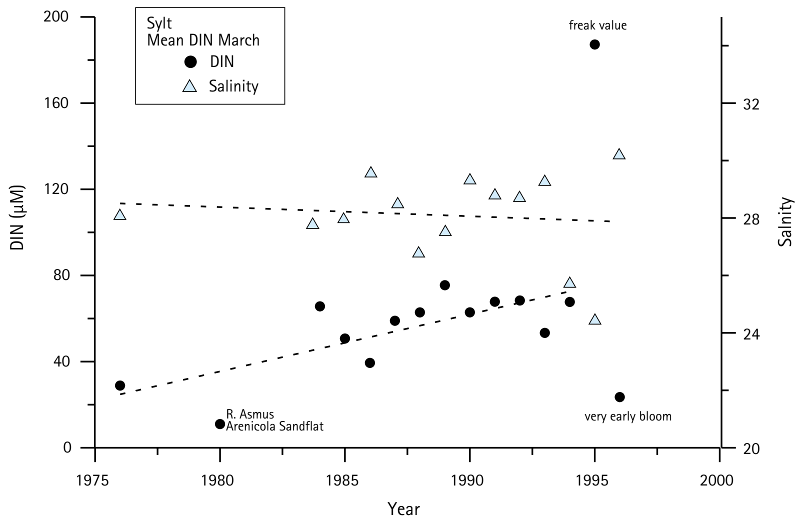


Figure 4.13: Increase of winter Dissolved Organic Nitrogen (DIN) concentrations (March) in the Sylt Rømø basin. Data: BAH/ Wattenmeerstation Sylt.

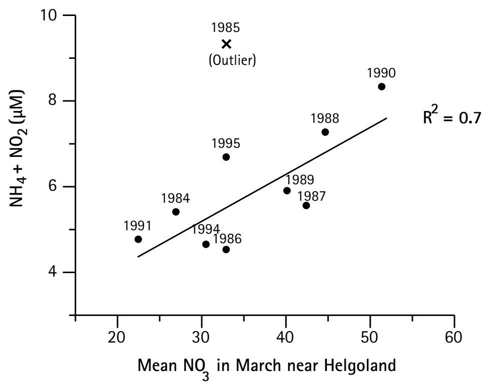


Figure 4.14: Possible relation between nitrate concentration in March in the German Bight (Helgoland Reede) and remineralized N products in autumn in the Sylt Rømø basin.

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)

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 µM in the western Dutch and Danish Wadden Sea to 50 µM in the Meldorfer Bucht. Normally, the high winter values are associated with low salinities. Despite its vicinity to the Elbe river, the Meldorfer 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 µM. The autumn increase is very similar in all areas, reaching values of 40 to 60 µM 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 µM), 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 µM. 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-

Figure 4.15: Wadden Sea in the 1990
Seasonal cycle of nitrate (µM)

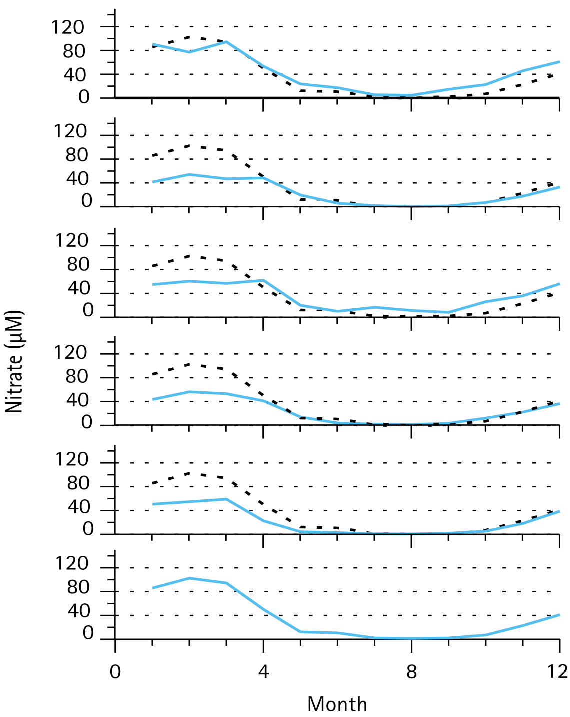
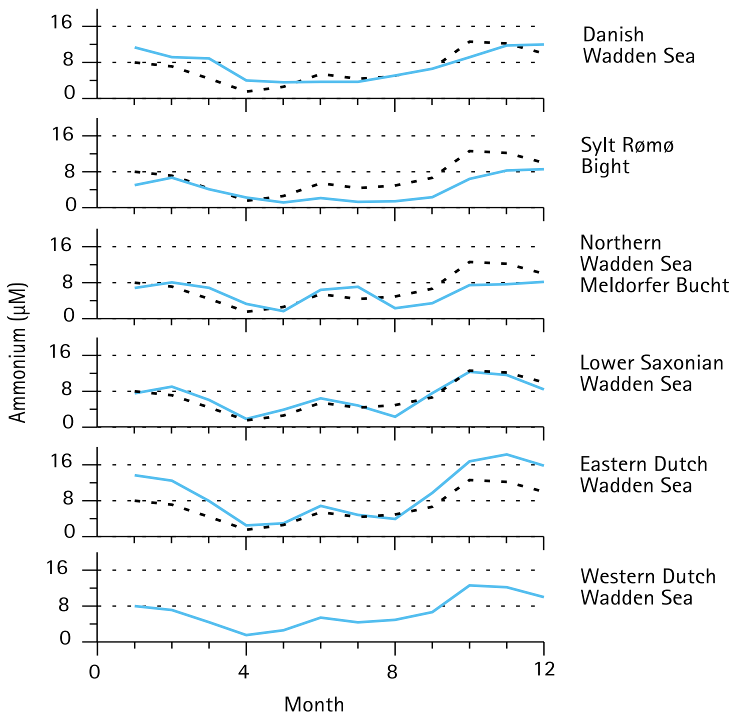


Figure 4.16: Wadden Sea in the 1990
Seasonal cycle of ammonium (µM)



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 µM), 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 µM in the eastern Dutch Wadden Sea to about 1 µM in the Sylt-Rømø Bight and in the Danish Wadden Sea. After the summer maximum, the concentrations level off at about 1.5 µM.

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 µg/l) and lowest values in the Meldorfer 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 phospate (µM)

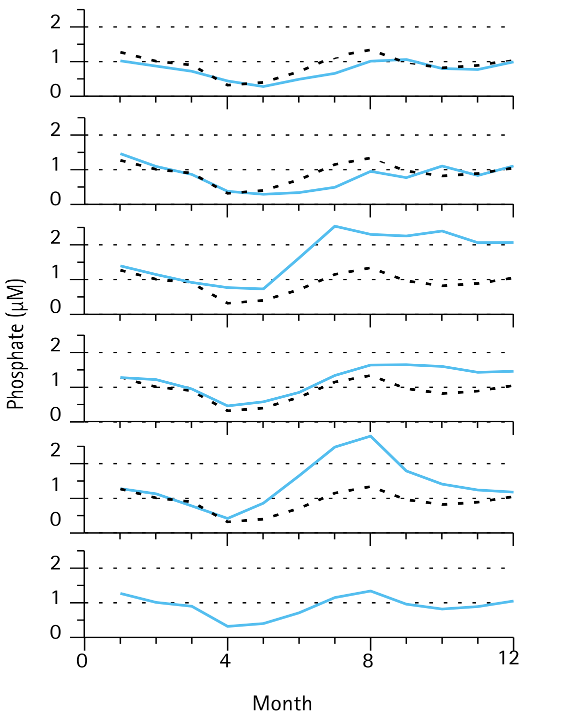
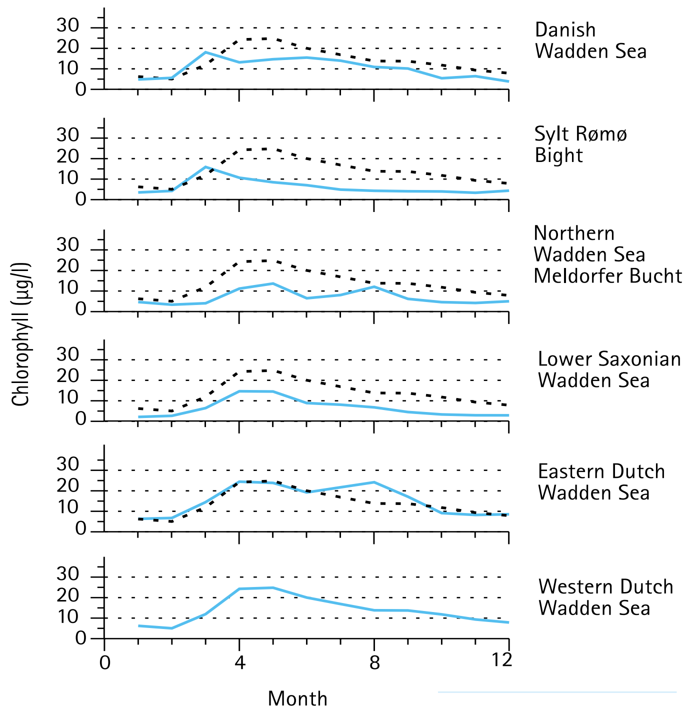


Figure 4.18: Wadden Sea in the 1990s
Seasonal cycle of chlorophyll (µg/l)



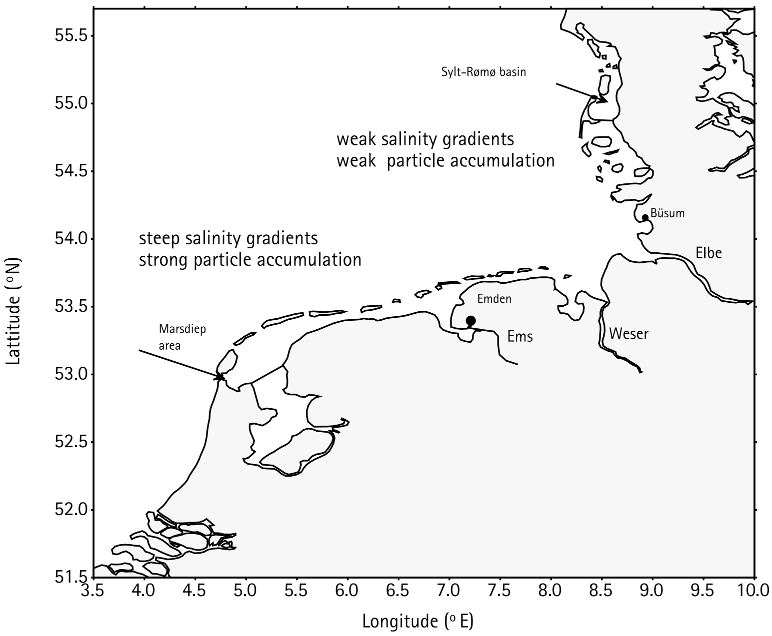
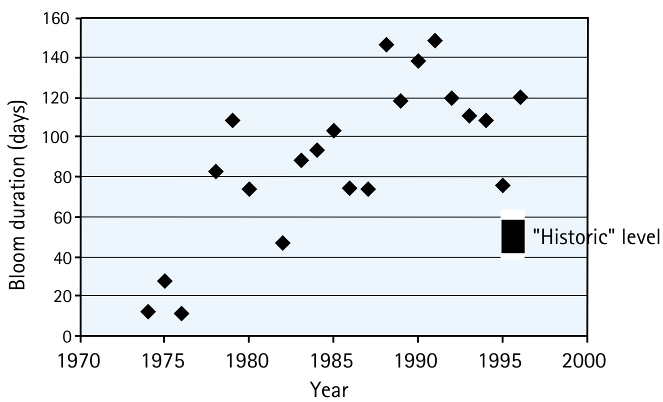


Figure 4.19: A hypothesis on the different accumulation of particles along the Southern and Northern Wadden Sea.

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.

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



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 19th 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 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.

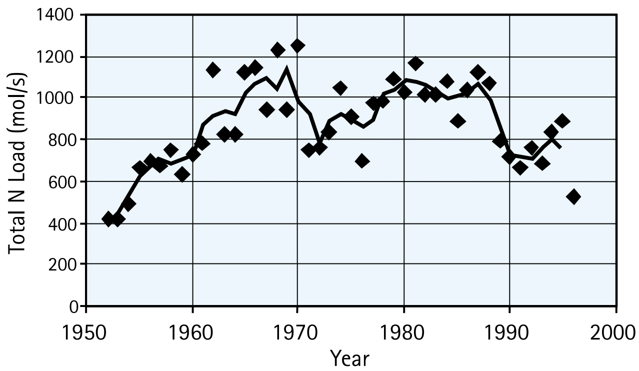


Figure 4.21: Mean annual Total Nitrogen load at Lobith (Dutch-German border). Total Nitrogen for the years 1952-1966 was estimated from a correlation between NH4 and Kjeldahl Nitrogen (r = 0.89; see text). The solid line is the weighted mean: [(load y-1 + load y + load y+1)/3]

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%).

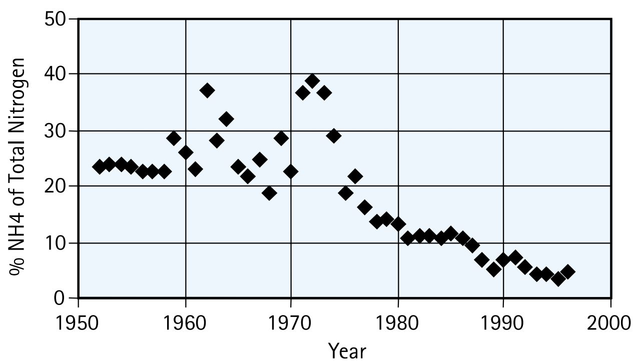


Figure 4.22: Proportion of ammonium of the Total Nitrogen load at Lobith (Dutch-German border). Total Nitrogen for the years 1952-1966 was estimated from a correlation between NH4 and Kjeldahl Nitrogen (r = 0.89; see text).

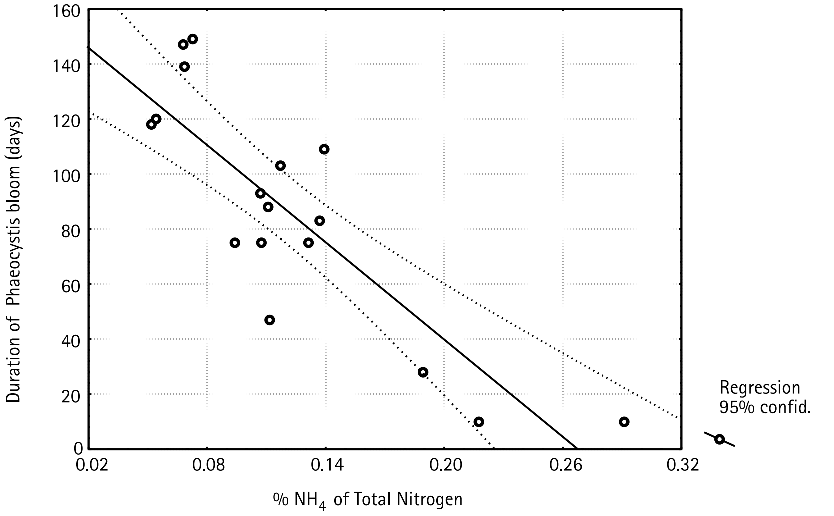


Figure 4.23: Influence of the proportion of ammonium of the Total Nitrogen load (Lobith) on the duration of Phaeocystis blooms in the Marsdiep ($r = 0.849$; $N = 33$; $p<0.00002$).

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 phytoplankton 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 Stoermer, 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

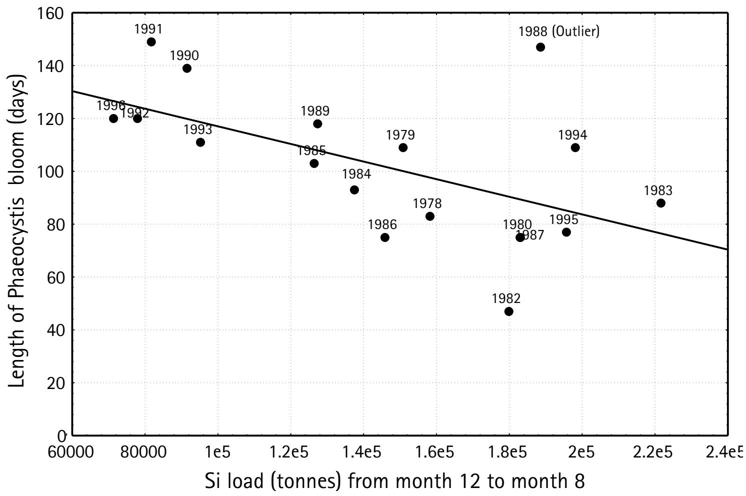


Figure 4.24: Influence of Si load (month 12-8) via Rhine and Meuse on the duration of Phaeocystis blooms in the Marsdiep, western Dutch Wadden Sea.

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 ± 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 correlation 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.

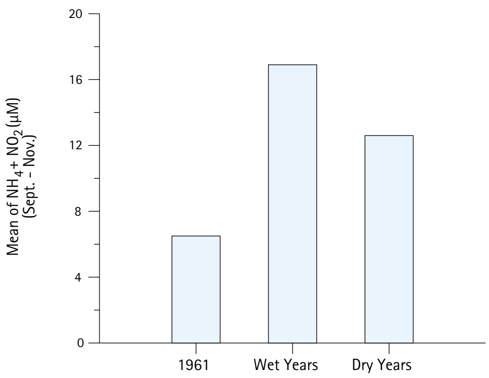


Figure 4.25: Long-term comparison of autumn values of ammonium and nitrite (µM) in the western Dutch Wadden Sea.

4.9.2 Long-term Comparison of Autumn Ammonium and Nitrite Values

Figure 4.25 compares the autumn values of NH_4 + NO_2 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_4 + NO_2) 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_4 + NO_2 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_4 + NO_2 (µM)	(NH_4 + NO_2) 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)	$NH_4 + NO_2$ (µM)	$(NH_4 + NO_2)$ Corr. (µM)	%
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

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 $NH_4 + NO_2$ 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).

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^{-1} m^{-2} (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, oxigenated, 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_4, NO_2)		
	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 4.7: Break-down of the factors contributing to the increased eutrophication since 1961. Starting point is the mean autumn value of the 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 (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 NH_4/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 residual 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 (NH_4 + 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 µM. From this value the effect of the atmospheric input (2.8 µM; see Table 4.7) and of further sources (1.8 µM see Table 4.7) have to be subtracted. This results in a background value of 3.7 µM ($NH_4 + NO_2$).

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 µM (Table 4.5). Substraction from the 1961 autumn values predicts autumn values in the 1930s of 2.1 µM.

In conclusion, a first approximation of "background" autumn values of ($NH_4 + NO_2$) is 3 µM (±1 µM). 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 g C m^{-2} 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 (NH_4, 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 (NH_4, NO_2) can be used as a measure of the eutrophication status.
9. For the western Dutch Wadden Sea background autumn values ($NH_4 + NO_2$) of 3 µM (±1 µM) 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.

5. Customizing the Checklist from the Common Procedure

5.1 Introduction

The Comprehensive Procedure was developed within the framework of the Oslo and Paris Convention for the Protection of the Northeast Atlantic (OSPAR). Its aim is, through a holistic assessment, to categorize the OSPAR maritime area into eutrophication Non-Problem, Potential-Problem and Problem Areas (see also Chapter 1). The principle parameters to be used in this assessment have been listed in the so-called "Checklist for an holistic assessment" ("the Checklist"). This Checklist is in Annex 1 of this report.

The aim of this Chapter is to evaluate the parameters from the Checklist for their applicability to the Wadden Sea. For this evaluation two main criteria have been used, namely:

- relevance for eutrophication processes in the Wadden Sea;
- availability of data.

The material for the evaluation derives from three sources:

- The data analysis from Chapter 4, including the conceptual framework;
- The outcome of the trilateral expert Workshop, carried out in the framework of this project, the full report of which is in Annex 2;
- An analysis of relevant literature (mainly Chapters 3 and 5).

The results of the evaluation have been summarized in the overview table 5.2.

5.2 The Causative Factors

The first category of parameters listed in the Checklist contains the so-called causative factors. It concerns qualitative parameters indicative of the degree of nitrogen, phosphorus and silicate enrichment, taking account of sources, trends, ratios, fluxes and cycles of nutrients.

In Chapters 3 and 4, relevant information on nutrients in the Wadden Sea has been summarized. Based on the available knowledge, a conceptual model for nutrient cycling in the Wadden Sea was proposed. According to this model the primary production in the North Sea coastal zone and the import of part of this primary produced organic matter into the Wadden Sea are essential factors for the eutrophication of the Wadden Sea. On the basis of the data analysis in Chapter 4 and the outcome of the expert Workshop, both nitrogen and phosphorus can be regarded as indicative of eutrophication in the Wadden Sea. Silicate is an important nutrient which limits diatom growth and plays a major role in shifts from diatoms to flagellates.

The data analysis shows that at present the remineralization intensity (autumn NH_4 +NO_2 values) in the Southern Wadden Sea is directly linked to nutrient input via Rhine and Meuse. Because of the tight correlation between TN and TP input, the question whether P or N is the limiting nutrient could not be answered in a statistical sense. From the conceptual point of view it was discussed that at present nitrogen is the limiting factor. Cadée and Hegeman (1993) stressed the remaining high primary production levels despite decreasing phosphate levels in the Marsdiep area (Southern Wadden Sea). The decreasing phosphate concentrations, the constantly high winter nitrogen concentrations and the increasing production and remineralization levels in the Sylt-Rømø Bight support, that also in the northern Wadden Sea nitrogen is presently the main element responsible for eutrophication.

The available data suggest a two- to threefold increase in Wadden Sea productivity and remineralization during the last decades. These trends were observed both in the Southern and the Northern Wadden Sea and are in line with an increased nutrient input via rivers, atmosphere and the Dover Channel. The relative contribution of these sources to the Wadden Sea eutrophication is still unclear. Furthermore, it is unclear whether during the period of increased eutrophication one or more shifts from a nitrogen limited to phosphorus limited productivity in the coastal zone occurred. Regarding future eutrophication it is unclear when and how the coastal productivity and, in response to that, the Wadden Sea productivity and remineralization will respond to the decreasing phosphorus input (will P become limiting?).

Both the Workshop and the data analysis concluded that the yearly cycle of nutrients is an important indicative parameter of the eutrophication status of the Wadden Sea.

5.3 The Supporting Environmental Factors

The second category of parameters deals with supporting environmental factors.

These can be defined as parameters which may have a substantial influence on eutrophication processes. In the Checklist the following factors are given:

5.3.1 Light

The role of turbidity in limiting Wadden Sea phytoplankton production has been stressed by Colijn (1983), Cadée (1986) and Tillmann et al. (2000). Colijn (1983) observed decreasing phytoplankton production towards the interior of the Wadden Sea (Ems estuary). Cadée (1986) found a linear relationship between turbidity, expressed as amount of suspended matter, and the start of the spring bloom: The clearer the water, the earlier the spring bloom started. The delay of the start of the plankton bloom due to increased turbidity was one month. Light availability as a limiting factor was investigated by Tillmann et al. (2000) and Hesse et al. (1997). For the Wadden Sea area, average ratios of ambient light conditions to potential photosynthetic light saturation of 0.1 to 0.6 could be found, indicating that photosynthesis hardly ever operated under light saturated conditions. From average daily light condition data over a two-year period, it could be inferred that only during 4 weeks light conditions were sufficient to supply a full photosynthetic production rate, at which nutrients could be potentially limiting (2 weeks each for potential N- and P-limitation). Based on the assumption of 5 hours of photosynthesis per day, there would be 21 weeks per year with sufficient light conditions for full production rates and potential nutrient limitation (potential limitation for N during 4 weeks, for P during 9 weeks and for Si during 8 weeks). Hence, under the optimistic assumption of a daily 5 hour period of photosynthetic activity, 80% of the year would be light limited. The important influence of light limitation is also visible in the differences between inner, i.e. turbid, and outer, i.e. less turbid, parts of the estuaries, and the differences between sheltered and tidally mixed areas mentioned above. Light limitation is also considered an important factor for phytoplankton dynamics in the Dutch coastal waters (Gieskes and Kraay, 1975).

Light availability is also an important prerequisite for eelgrass development in the Wadden Sea (Philippart, 1995). De Jonge and de Jong (1992) suggested that impoverished light conditions in the Wadden Sea prevented the reestablishment of eelgrass in the Dutch Wadden Sea after a "wasting disease" in the early 30s had decimated the eelgrass stands.

Despite the light limitation, an increased primary production was observed, suggesting a colimitation of light and nutrients (e.g. Cloern, 1999). Van Beusekom et al. (1999) discussed that, on an annual basis, the imported organic matter in the Wadden Sea (main nutrient source) is turned over about three times. This factor of three is lower than a turnover rate of about five found in the coastal zone, presumably due to the better light conditions in the coastal zone. Thus, due to the sub-optimal light conditions in the Wadden Sea, primary producers cannot take full advantage of available nutrients.

It can be concluded that light availability and irradiance are important supporting factors for interpreting eutrophication.

5.3.2 Hydrodynamics

The specific hydrodynamic features of the Wadden Sea which have been described in Chapters 2, 3 and 4, are the direct basis for the conceptual model applied throughout this study. The two main factors are:

(1) The accumulation of fine-grained material from the coastal zone towards the Wadden Sea and within the Wadden Sea;

(2) The influence of wind forcing on the water circulation within the Wadden Sea.

In Chapter 4 the contrasting settings of the Northern and Southern Wadden Sea were mentioned: Along the Southern Wadden Sea a more intense particle accumulation due to strong salinity gradients and a more sheltered deposition environment, was postulated, as compared to the Northern Wadden Sea, which is more exposed to wind and wave action and has less strong salinity gradients towards the adjacent coastal zone.

An example of the relevance of hydrodynamic conditions for the proper evaluation of eutrophication phenomena is the case of areas with anoxic sediment surface ("black areas") in the East Frisian Wadden Sea in 1996 (see also 5.5). One of the main factors indirectly responsible for the occurrence of large anoxic areas was the fact that a predominantly northward surface current and a complementary southward deep current had transported large amounts of organic material, in this case from a *Coscinodiscus concinnus* bloom into the Wadden Sea (de Jong et al., 1999a).

It is concluded that hydrodynamics must be regarded as an important factor for the analysis of eutrophication effects. However, detailed hydrodynamical time series (variation in retention time etc.) in relation to existing oceanographic time series are lacking for the Wadden Sea.

5.3.3 Climate and Weather

In Chapter 2 basic information about the climatic conditions in the Wadden Sea was given. In this section a more detailed discussion about the relevance of temperature and wind forcing for biological processes in the Wadden Sea is presented.

Temperature

Temperature is one of the key factors structuring marine communities. The temperature tolerance range may limit the geographical distribution of a species. Lusitanian immigrants, as observed in the plankton after the 1989 saltwater intrusion (Lindley et al., 1990; CPR Survey Team, 1992; Greve, 1994) may conquer a niche in the food web, depending particularly on the winter temperatures. An increased abundance of southerly fish species in the southern North Sea and Wadden Sea in recent years correlates with overall higher temperatures (Lozán et al., 1994; Heessen, 1996). In the benthos, some, up-to-now, nonresident species established in recent years (Reise, 1994), without causing noticeable disturbances of the resident species (Michaelis and Reise, 1994).

The Wadden Sea is a highly dynamic system which is subject to large temperature fluctuations at various temporal and spatial scales. Therefore, only eurytherm organisms (organisms which can live under different temperature regimes) thrive in the Wadden Sea and are supposed to be only little affected by changing temperatures, particularly during the growing season in summer. However, for organisms living at the limit of their distribution, small changes in temperature range may have severe effects on their growth, reproduction and mortality.

Effects of Winter Temperatures

Overwintering is a particularly critical period during the life cycle of many planktic and benthic, as well as, bird species. During this time, relatively small differences in mean temperature and in temperature extremes can have a strong influence on survival as well as on biomass and recruitment success in the following spring (Beukema, 1982). In particular, the sessile macrobenthos of the regularly exposed tidal flats is subject to the various winter conditions such as the extreme subzero temperatures, wind chill and ice shear, or, on the other hand, warm temperatures, high predator densities and sediment displacement due to storm surges.

During winter, several species (e.g. the polychaetes *Lanice conchilega, Harmothoe lunulata, Nephtys hombergii*, the bivalves Abr*a tenuis, Mysella bidentata, Antinoella sarsi, Angulus tenuis, Cerastoderma edule*, and the decapods *Crangon crangon* and *Carcinus maenas*; Beukema, 1990) suffer high mortality. They become either absent or scarce in the Wadden Sea, or they retreat from the intertidal areas to the subtidal zone (Beukema, 1990; Reise, 1993). Their stocks are usually re-established after 1-2 years. Other species, in particular those of the intertidal zone, such as the snails *Littorina* spp., the barnacle *Balanus* spp., the bivalves *Macoma baltica* and *Mytilus edulis* are very resistant, even to freezing (e.g. Theede, 1981).

Contrary to the reduced species diversity after extremely severe winters, series of mild winters may lead to a higher diversity and stable total biomass in the benthos due to reduced mortality and the advection of immigrants (Beukema, 1992). The reproduction of a number of macrozoobenthic species, i.e. the release of meroplanktic larvae, is triggered by a water temperature of 5°C (Bayne, 1965). After warm winters, a long spawning period from February onwards can be observed. After cold winters, the temperature increase in spring is more rapid and leads to a distinct spawning peak as late as May (Martens, 1992; Pulfrich, 1997). Whereas after cold winters, the recruitment of macrobenthic species was often found to be exceptionally high (Beukema, 1982; Dörjes et al., 1986; Beukema, 1992), a series of mild winters resulted in repeated recruitment failure of several bivalve species (Beukema, 1992). A detailed discussion of temperature effects is given in Diel-Christiansen and Christiansen (1999).

Effects of Fluctuating Summer Temperatures

The effects of annual temperature fluctuations on the Wadden Sea ecosystem are less pronounced in the warm seasons than in winter. Of course, physiological rates and the population development of plankton and benthos depend on temperature to a certain extent. However, the ecological consequences of temperature fluctuations are rarely distinguishable from other sources of variability in a highly complex ecosystem such as the Wadden Sea.

Some indications exist for the influence of higher temperatures on specific compartments of the Wadden Sea ecosystem. For example, higher than average summer temperatures may cause low survival in the eelgrass *Zostera marina* (Reise, 1994) and references therein). The collapse of *Phaeocystis globosa* blooms may be related to high temperatures in summer (Elbrächter, 1994). The distribution of *Spartina anglica* on salt marshes may be favored by increased temperatures (Reise, 1994).

Wind

Wind, as well as, tides introduce kinetic energy into the system and determine the degree of mixing. Turbulence can affect primary production by increasing turbidity, hinder suspension feeders from feeding and increase contact rates between predator and prey. Wind also has a large influence on the dynamics of microphytobenthos, due to sediment resuspension (de Jonge, 1992; de Jonge and van Beusekom, 1995).

Since 1990 wind forcing in the Wadden Sea and the German Bight has increased considerably (Data presented by Fock in ICES, 1999). This view was supported by an analysis by Hoftstede and Schmidt (1999). They showed that mainly the NW-component of the wind, i.e. the surge enhancing component for the German Bight, had been enhanced since 1960.

Under certain wind conditions (e.g. easterlies), upwelling may induce the formation of blooms. Hickel (1997) stressed the importance of such blooms in the North Sea for the import of organic material into the Wadden Sea.

Assessment

It is concluded that weather conditions are essential for the analysis of eutrophication effects. It is in this respect important to differentiate between long-term and short-term changes in weather conditions. Long-term changes, for example due to changes in the North Atlantic circulation, must be taken into consideration when assessing long-term changes in stocks of, for example phytoplankton, zooplankton and macrozoobenthos. Short-term changes are particularly relevant for the Wadden Sea because of its relatively low buffering capacity for temperature changes.

5.3.4 Grazing

Zooplankton

Zooplankton forms an important link in the trophic structure of coastal ecosystems by making part of the primary production available to higher trophic levels. As a result of grazing, the zooplankton may also be able to control phytoplankton at low levels ("top-down control") under certain conditions (Verity and Smetacek, 1996).

The increase of the phytoplankton spring bloom duration and intensity during the previous decades, as observed in the Marsdiep area (Cadée and Hegeman, 1991a), has been accompanied by a four- to eight- fold increase in the adult density of the dominant copepod *Temora longicornis* (Fransz et al., 1992). It appears that the stimulating effect of the dominant phytoplankton species in spring (*Phaeocystis*) on the growth of *T. longicornis* is mediated by protozoans, mainly herbivore ciliates and heterotrophic dinoflagellates which feed on *Phaeocystis* and are then predated by copepods (Hansen et al., 1993). The latter authors conclude, therefore, that copepod predation may even enhance the *Phaeocystis* bloom in spring.

The spring bloom of *Phaeocystis* is usually followed by a succession of other flagellates and diatom species (e.g. Cadée, 1986; Brussaard et al., 1995). During the summer period, grazing by zooplankton matches primary production in both the coastal zone (Daan, 1989) and in offshore North Sea areas (Fransz and Gieskes, 1984; Roff et al., 1988). Knowledge about the importance of zooplankton grazing in the Wadden Sea is, however, still insufficient. Because the importance of herbivores seems to increase during the summer period, an elevated production of copepod biomass and reproduction rate may be expected in response to increased nutrient inputs but no data are available to support this hypothesis. Mesocosm experiments with model tidal flat systems, simulating the Wadden Sea ecosystem, reveal that nutrient loading resulted in a linear increase in biomass of the (dominant) copepod *Eurytemora affinis*, whereas phytoplankton levels were similar between treatments (Scholten et al., 1995).

Effects of Toxicants

Together with the input of nutrients, concentrations of toxic compounds have increased in the past decades. It has been shown from enclosure experiments that many substances reduce copepod production, thereby reducing the grazing pressure upon the phytoplankton. The toxic effect of, e.g. tributyltin (TBT) reduced copepod growth and caused a shift in zooplankton species composition (Jak et al., 1998) thereby diminishing the proportion of phytoplankton being grazed. This effect may have important consequences for eutrophication phenomena and the amount of production being passed on to higher trophic levels, e.g. fish. An important group of toxicants that may affect zooplankton are insecticides, which reach seasonal peak values during the growing season. There is still not enough known about the actual consequences of pesticides in general on the functioning of plankton communities.

Benthic Grazers

For the microphytobenthos Reise (1992) assumes that one third of the production on tidal flats is utilized by macrozoobenthos. Small-scale patchiness in microphytobenthos distribution is subject to the gardening phenomenon, i.e. the reinforcement of plant production due to small scale animal excretions in burrows etc..

A similar relationship between benthic bivalves and phytoplankton was observed by Prins et al. (1998) and Smaal et al. (1994). Due to excretion, phytoplankton development was enhanced. However, Smaal and co-workers recognized that this effect was observable only in one out of four mesocosm tanks, when mussel excretions replenished the nutrient pool during a spring experiment. Generally, in their experiments mussels played a minor role in the nutrient balance. Prins and co-workers concluded that bivalves could become a limiting factor for phytoplankton if mussel clearance time and phytoplankton turn-over time were equal and both were shorter than the water residence time.

Due to tidal mixing in the Wadden Sea, the actual water residence time is rather short, so that bivalve grazing is not likely to considerably control phytoplankton. However, locally filter feeders may be important: Cadée and Hegeman (1974) suggested that low chlorophyll levels near mussel beds were due to filter feeding. For embanked estuaries a (e.g. Oosterschelde, van der Tol and Scholten, 1998) a clear relationship between benthic biomass and nutrient transfer by means of phytoplankton exists.

Assessment

It is concluded that grazing of phytoplankton and phytobenthos is important for the evaluation of eutrophication effects. However, seasonal events are or have been studied on local and limited temporal scales only. Available data are not sufficient to observe past temporal trends, and current monitoring programs will not allow this in future (Jak et al., 1998). This was also underlined by the participants in the Workshop. The effects of zooplankton grazing (and also of parasites) on e.g. phytoplankton were not regarded fully applicable for indicating eutrophication effects because of the limited data base and because the causal and quantitative mechanisms are not yet fully understood. These parameters were therefore classified as potentially applicable.

Benthic grazers and suspension feeders (e.g. mussel beds) were regarded fully applicable supporting factors for the analysis of eutrophication effects.

5.4 The Direct Effects of Nutrient Enrichment

The third category of parameters in the Checklist addresses direct effects of nutrient enrichment. Direct effects mainly relate to changes in primary production and shifts in species composition due to changes in nutrient loading and nutrient ratios.

In this section the effects of nutrient enrichment on phytoplankton, macrophytes and microphytobenthos are discussed.

5.4.1 Phytoplankton

Biomass and Primary Production

Continuous long-term biomass records as of 1969 exist for the Marsdiep inlet in the Dutch Wadden Sea. The Dutch monitoring program in the Wadden Sea has assessed chlorophyll since 1976. For the East Frisian Wadden Sea (Norderney) a time series since 1984 exists, mainly focusing on *Phaeocystis* (Hanslik et al., 1998). In the Sylt-Rømø Basin chlorophyll has been measured since 1984 and primary production since 1993 (Asmus et al., 1998b). For the Danish Wadden Sea time series for primary production and biomass exist, both as of1989 (Madsen et al., 1999).

Annual average chlorophyll values in the Marsdiep increased from 3 to 6 μg/l from 1972 to 1976 and from 6 to 15 μg/l in the period 1977 to 1991 (Cadée, 1992). These values are comparable to the range observed for the East Frisian Wadden Sea (Norderney) with 6 to 11.3 μg/l (1988-1997). In the Sylt-Rømø Basin annual chlorophyll ranged between 5 and 11 μg/l (1984-1996) and in the Danish Wadden Sea between 4 and 11 μg/l (1991-1997).

Monthly chlorophyll values for four locations in the Wadden Sea (Marsdiep, Norderney Schleswig-Holstein south and Schleswig-Holstein north) are presented in the 1999 Wadden Sea QSR (de Jong et al., 1999b). On the basis of these series (Marsdiep 1984-1996; Norderney 1985-1996; Schleswig-Holstein 1990-1996) it wase concluded that there are spatial differences, the highest values occurring in the Marsdiep and Norderney and the lowest in the northern part of the Schleswig-Holstein Wadden Sea. No temporal trends could be discerned at any of the four locations despite considerable reductions in phosphate loading in most parts of the Wadden Sea. In Chapter 4 the mean seasonal cycles of chlorophyll during the 90s were compared for different parts of the Wadden Sea. There, it was also concluded that the highest phytoplankton biomass values were observed in the eastern Dutch Wadden Sea and lowest values in the northern part of the Northern Wadden Sea. Apparently, the largest biomass is found near the large rivers (Rhine, Elbe).

Primary production has been measured less intensively than biomass. A time series has been published for the Marsdiep area (Cadée and Hegeman, 1993). A comprehensive summary of published measurements is presented in Table 5.1, showing clear regional and temporal differences. In general, the inner parts of the estuaries and the Wadden Sea have lower production values than the seaward areas. It is furthermore evident that primary production has increased during the past decades. In the Marsdiep, phytoplankton primary production increased from 40 g C m^{-2} y^{-1} in 1950 (estimated on the basis of chlorophyll data; Postma, 1954) to 150 to 200 g C m^{-2} y^{-1} in the period 1960 to 1976 and to values of >250 g C m^{-2} y^{-1} in the period after 1977. For the Sylt-Rømø area an increase from 52 g C m^{-2} y^{-1} in 1980 to 160 g C m^{-2} y^{-1} in 1994/95 was found (Asmus et al., 1998a, b).

Available data indicate that in the Marsdiep area primary production exceeds the levels observed in other parts of the Wadden Sea. In the period before 1977 the Marsdiep values ranged between 150 and 200 g C m^{-2} y^{-1}. Comparable values for the western Dutch Wadden Sea were approximately 100 g C m^{-2} y^{-1} (Cadée and Hegeman, 1974). In the period 1977 to 1992 values for the Marsdiep area ranged between 250 g C m^{-2} y^{-1} (1 value) and >330 g C m^{-2} y^{-1} (5 values). Comparable values for the rest of the Wadden Sea were in the range of 150 g C m^{-2} y^{-1} (Büsum, Dithmarscher Wadden Sea), 160 g C m^{-2} y^{-1} (Sylt-Rømø) and app. 175 to 200 g C m^{-2} y^{-1} (Danish Wadden Sea station Hjerting based on estimated 480 mg C m^{-2} per day, after data from Madsen et al., 1999). Thus, in both time periods considered (<1997 vs. >1977) the primary production rate in the Marsdiep was approximately two times as high as in the other parts of the Wadden Sea. The rates of primary production in the Wadden Sea are lower than in the adjacent coastal zone where values up to 400-500 g C m^{-2} y^{-1} are found (van Beusekom and Christiansen, 1994; Tillmann et al., 2000).

The increased production rates of the Marsdiep area can be related to the nutrient supply of the Marsdiep inlet by both the river Rhine and the IJsselmeer. Until 1987 a good correlation was found with phosphorus input via the IJsselmeer (de Jonge, 1990), but later observations did not fit into this relation (de Jonge, 1997). Noting that the primary production remained high despite decreasing phosphorus levels, Cadée and Hegeman (1993) suggested nitrogen input via the River Rhine to be responsible for the high production levels (see further Chapter 3.5).

The data analysis presented in Chapter 4 shows that nitrogen input via the Rhine and Meuse is the best predictor of phytoplankton biomass in the Dutch Wadden Sea. For the other areas neither a relation between nutrient input and primary production nor between phytoplankton biomass and nutrients was found.

Table 5.1: Annual primary production estimates for phytoplankton and microphytobenthos in different regions of the Wadden Sea.

Area	Annual production (g C m^{-2} y^{-1})	Source
Phytoplankton		
Ems Dollard (1976-80)		
Inner	70	(Colijn 1983)
Middle	91	
Outer	283	
Marsdiep area		
1950	40	(Cadée and Hegeman, 1993; de Jonge, 1990)
1960 – early 70s	150-200	
1981-1992	250-520	
1972-73		
Western Dutch Wadden Sea	100	(Cadée and Hegeman, 1974)
Eastern Dutch Wadden Sea	120	
Ems estuary	55	
Dollard	13	
Northern IJsselmeer	400	
Sylt-Rømø Bight		
1980	52	(estimates after Asmus *et al.*, 1998b)
1984/85	90	
1994-1995	160	
Büsum Wadden Sea	152	(Tillmann *et al.* 2000)
1995-1996		
Microphytobenthos		
Sylt-Rømø: intertidal		
1980	115-152	(Asmus *et al.*, 1998b)
1993 - 94	329-362	
Western Dutch Wadden Sea		
1960	app. 100	(Cadée, 1984)
1981	app. 200	

Blooms

Essential in the assessment of the suitability of plankton bloom development as an indicator of eutrophication is, whether a link can be established between changes in bloom parameters (intensity, frequency, duration) and changes in nutrient parameters (loads, concentrations, ratios).

For the Wadden Sea there are two time series of sufficient duration allowing for such an analysis. It concerns the *Phaeocystis* time series in the Marsdiep and at Norderney.

For the Marsdiep series data are available as of 1974. The duration of *Phaeocystis* blooms in the Marsdiep, expressed as number of days with more than 1000 cells/ml, increased from around 30 days in the early 1970s to 120 to 150 days around 1990, indicating a continuing increase not observed in diatom plankton (Cadée, 1992).

Riegman et al. (1992) reported on experiments with growth rates of different phytoplankton species at various N:P ratios. They concluded that non-colonial *Phaeocystis* is the best competitor at low N:P ratios and that colony-forming blooms can be expected in N-controlled environments with nitrate as the main nitrogen source. These authors emphasized that novel nuisance algal blooms are more probably the results of major shifts in N:P ratio than of a general N+P enrichment. They expected a decrease of *Phaeocystis* blooms in the Marsdiep when P becomes the limiting factor again. Latest data on the development of the length of *Phaeocystis* blooms in the Marsdiep do not (yet) support this hypothesis: The N:P ratio increased considerably since the beginning of the 1990s which was not the case for the length of the *Phaeocystis* blooms (de Jong et al, 1999b).

In the data analysis presented in Chapter 4 the focus was not put on local nutrient ratios in the western Dutch Wadden Sea but on the nutrient ratios in the rivers Rhine and Meuse. The duration of the *Phaeocystis* blooms correlated strongly with the proportion of ammonium in Total Nitrogen: With decreasing ammonium and increasing importance of nitrate the duration of *Phaeocystis* blooms increased. This corroborates the laboratory experiments by Riegman et al. (1992) who showed that nitrate as the main nitrogen stimulated colony formation. The reduced grazing on *Phaeocystis* due to colony formation apparently enabled the long bloom duration. A second factor was the Si input: During years with a high Si input shorter blooms were observed presumably due to a higher Si availability and a better competitive advantage of diatoms as compared to *Phaeocystis*.

Species Composition

Cadée (1986) analyzed species composition for Marsdiep phytoplankton. For the years considered, there was no clear trend of changes in the most dominant species in relation to nutrients. Cadée (1986) found a decrease and subsequent increase in bloom duration (days with more than 1000 cells per ml) in the Marsdiep in the years 1969 to 1985 for diatoms and a steep linear increase in flagellates, comparable to the shift in species composition towards dominance of flagellates found at the station Helgoland Roads (Hickel et al., 1995; Hickel et al., 1997). The length of season for diatoms in the Marsdiep roughly doubled from about 80 to about 160 days, while the length of season for flagellates increased from 0 in 1969 to 320 days in 1985.

Philippart et al. (2000) analyzed the species composition of the Marsdiep time series in relation to the local nutrient dynamics with a principal component analysis. They distinguished three periods: 1974-1978 (P limited, low trophic state), 1979-1987 (N limited and high trophic state) and 1988-1994 (P limited and high trophic state). During each period a specific species composition was observed.

Heinis et al. (1995) indicated, for the period 1990-1993, that diatoms and flagellates were the dominating species in the Dutch Wadden Sea. Diatom blooms occurred both in spring and in summer or late summer. *Phaeocystis* blooms were highest in the Marsdiep in April and May.

Potentially toxic species such as *Dinophysis* spp., *Alexandrium tamarense* and *Gyrodinium aureolum* were observed in low densities in summer.

Vrieling et al. (1996) found the toxic diatom *Pseudonitzschia multiseriata* in summer and autumn.

Hanslik et al. (1994) reported on the most conspicuous algal species in the Niedersachsen Wadden Sea in the period 1982-1991. These were the flagellate *Phaeocystis globosa* and the dinoflagellate *Noctiluca scintillans* of which blooms occurred in April-May and March-July, respectively. Also, blooms of diatoms (*Rhizosolenia*, *Leptocylindrus*, *Chaetoceros*, *Odontella*, *Skeletonema*, *Asterionellopsis* and *Nitzschia*) were observed, although not as regularly as *Phaeocystis* and *Noctiluca* .

Potentially toxic *Dinophysis* spp. were present in the period 1988-1993 between April and November (Hanslik and Rahmel, 1995). According to these authors, these algae are transported into the Wadden Sea from the open North Sea. The highest numbers were recorded in the eastern part of the Niedersachsen Wadden Sea.

In the Schleswig-Holstein Wadden Sea diatoms were the dominating phytoplankton in the period 1990 to 1996, for example *Rhizosolenia delicatula* in 1991 and *Coscinodiscus concinnus* in 1996. The dinoflagellate *Ceratium furca* was dominant in autumn 1993. *Phaeocystis* blooms occurred almost every year in early summer (Göbel, pers. comm.).

In summer 1990, conspicuous amounts of an, until then, unknown green dinoflagellate, recently described by Elbrächter and Schnepf (1996) as *Gymnodinium chlorophorum* (sp. nov.), were observed in the German Wadden Sea. These cells were transported from an exceptional bloom center in the adjacent coastal water (west of the island Helgoland) into the Wadden Sea (Nehring et al., 1995). In 1996, phytoplankton development in the North Frisian area started very early with a massive bloom of *Odontella aurita* in March, amounting to cell concentrations of about 1 million/l (Tillmann, unpublished).

In the period 1990-1996, potentially toxic forms of *Alexandrium* spp. never exceeded 400 cells/l in the northern German Wadden Sea. In summer 1990 (end of August), the toxic *Dinophysis acuminata* occurred in densities of up to 3000 cells/l in the estuarine southern part of the Schleswig-Holstein Wadden Sea (Nehring et al., 1995).

The phytoplankton community of the Schleswig-Holstein Wadden Sea has, in recent years, been modified by the intrusion of forms hitherto unknown to the region, such as the warm-water diatom *Thalassiosira hendeyi* and the toxic Raphidophycea *Fibrocapsa japonica* (Tillmann et al., 1996).

In 1995 *Fibrocapsa japonica* was found for the first time in the region, amounting to densities of 30,000 cells/l. In the summer of 1997 this species was also found in Dutch coastal waters in densities up to 2000 cells/l (Rademaker et al., 1998). Cadée (1986) analyzed species composition for Marsdiep phytoplankton. For the years considered no clear trend of change in relation to nutrients was visible on species level concerning the most dominant species.

Phytoplankton: Assessment

Primary production and phytoplankton biomass are important indicators of direct eutrophication effects. At least for the western Dutch Wadden Sea a relation between nutrient status and species composition, as well as, a relation between phytoplankton biomass and nitrogen input could be established. It is, however, stressed that several co-factors, most notably light, temperature and grazing, are essential in the assessment whether changes in nutrient loading are indeed the main causative factor for changes in primary production and biomass.

As stated in the Workshop (Annex 2) primary production should be preferred over chlorophyll measurements since simple chlorophyll measurements cannot distinguish between Wadden Sea borne and advected phytoplankton, whereas production measurements refer to the actual in situ production.

The participants in the Workshop considered *Phaeocystis* bloom parameters suitable direct indicators of eutrophication, an important reason being the relatively long data series available. It was stressed, however, that a consistent bloom definition is necessary. It was in this respect stated that it is important to distinguish between single cell blooms and colonial blooms.

The analyses of *Phaeocystis* bloom data, presented in Chapter 4 and in the Workshop report (Annex 2), indicate the problems encountered in using this parameter as a direct indicator of the eutrophication status.

Species composition, seasonal cycles and bloom-forming taxa other than *Phaeocystis* require more research before they can be applied as eutrophication criteria.

5.4.2 Macrophytes

Macroalgae

In the course of the past century, abundance and distribution patterns of different groups of macroalgae in the Wadden Sea have changed considerably.

The biomass of subtidal red and brown algae has decreased. Perennial macroalgae like *Fucus* species depend on stable hard substrate. Due to the present poor state of the littoral mussel beds in The Netherlands, the *Fucus* vegetation has declined in this part of the Wadden Sea (Schories et al., 1997).

The occurrence of littoral green algae, on the other hand, has increased strongly (Reise et al., 1989). First records for the North Frisian Wadden Sea were made in the 1920s (Reise, 1983). These records showed that *Enteromorpha* in the intertidal area was restricted to habitats at the high tide line. The first observations of green macroalgae becoming more widely distributed than before are from the late 1950s when an increase in density was observed in the Dutch Wadden Sea. In the 1970s such developments were also observed in the German and Danish parts of the Wadden Sea (Reise and Siebert, 1994; Reise, 1997). The dominating species belonged to the genus *Ulva* in the Dutch (Reise, 1997), to *Enteromorpha* and *Ulva* in the Lower Saxonian Wadden Sea (Kolbe et al., 1995) and to *Enteromorpha* in the northern parts (Reise, 1997). Presently the algal flora in the Sylt-Rømø area consists of 3 species of Ulva and

12 species of *Enteromorpha* (Lotze in Reise et al., 1997). Mass developments of *Enteromorpha*, *Ulva*, *Chaetomorpha* and *Cladophora* were observed on tidal flats during the summer months of the late 1980s and early 1990s. Green algae do not occur in the inner parts of estuaries, in spite of high amounts of nutrients. Growth conditions are assumed to be unfavorable because of high turbidity and muddy sediment (Reise and Siebert, 1994).

Extensive algal mats were found in 1988 and 1989 in the Dutch part (de Jonge and Pelletier after Reise, 1994) and after 1989 in the German part of the Wadden Sea (Michaelis et al., 1992; Reise and Siebert, 1994). For the Danish and northern German Wadden Sea a peak was observed in 1990-91, after which a gradual decline occurred. An increase was again observed in summer of 1999. A peak in the East Frisian Wadden Sea was observed in 1992 (Siebert and Reise, 1997).

Reise (1997) stated that, since mass developments of green macroalgae had not been observed before 1979, they must be regarded as a new phenomenon related to land-based nutrient inputs.

In the intertidal area, locally a coverage of up to 50 to 80% was observed (Siebert and Reise, 1997). In 1992 on average 12.5% coverage was reached in the North Frisian Wadden Sea, compared to 0.9% in 1983. In Lower Saxony 10% to 15% coverage was reached in the years 1990 to 1994, but only 2.5% in 1995 (Michaelis, 1997).

Mass developments of macrophytes did not occur in the central Wadden Sea (Weser/Jade to Eiderstedt), probably due to inadequate germination substrate and high turbidity (Reise and Siebert, 1994).

Investigations into the life cycles of *Enteromorpha* species revealed the importance of excess nutrient supply during bloom development. In experiments, growth was not accomplished without additional nutrient supplies (Lotze in Reise et al., 1997). Besides nutrients, temperature is limiting growth during spring. Also wind conditions determine duration of mass occurrences in the Wadden Sea. Stormy weather sweeps the algal mats through tidal gullies to subtidal areas or to salt marsh stands (Siebert and Reise, 1997). Further critical factors are suitable substrates for spore germination (sand or particles >250 µm preferred, i.e. *Hydrobia* shells, see Schories, 1995) and light availability.

Although frequently consumption of spores and thalli by lugworms (*Arenicola marina*) and snails (*Littorina littorea*) has been observed, grazing seems not to limit expansion of green algal mats (Schories, 1995). Arenicola enhances formation of green algal mats through anchoring of floating mats in its burrows (Reise, 1983).

Eelgrass

Two species of eelgrass must be discerned : *Zostera marina* and *Z. noltii*. The larger *Z. marina* suffered from an endophytic disease (*Labyrinthula zosterae*, Reise, 1997) and declined irreversibly on subtidal stands since the 1930s. Intertidally both species are still present.

For the Dutch Wadden Sea the area covered by eelgrass beds declined from 65 to 150 km^2 in the pre-1930s to present values of less than 1 km^2 (de Jonge and Ruiter, 1996). By comparing historical records of intertidal and subtidal distribution of eelgrass, de Jonge and Ruiter (1996) found a shift from subtidal towards increased intertidal distributions already before 1930, and assigned this shift to increased turbidity linked to the closure of the Zuiderzee. Again, light was assumed to be the major factor (de Jonge and de Jong, 1992). A decline of intertidal stands of the smaller *Z. noltii* was observed from the 1970s to the 1980s (Philippart, 1995).

A progressive decline of both species in the Lower Saxon Wadden Sea has been observed since the 1970s (Kastler and Michaelis, 1997).

The development in the Northern Wadden Sea is contrasting the decline in the Southern Wadden Sea. In the Sylt-Rømø area, *Z. noltii* dominated in discrete patches in the 1970s. Following the severe winter of 1978/79 this species became more widespread but scattered and *Z. marina* gradually achieved dominance throughout the 1980s. The total coverage of eelgrass was higher than in the decade before. This reversed gradually since 1988 and in the 1990s *Z. noltii* dominated again.

At present, *Zostera* coverage in the Wadden Sea area can be estimated at 4.8% of the intertidal flats (Reise, 1994). The lowest coverage (i.e. failing re-establishment sensu de Jonge and Ruiter, 1996) occurs in the Dutch Wadden Sea, probably due to intensive mechanical disturbance of the seafloor by different types of fisheries (e.g. effects of lugworm fishing and dredging see Beukema, 1995; van der Veer et al., 1985), the closing of the Zuiderzee in 1932 and pollution (de Jonge and Ruiter, 1996). The highest intertidal coverage with 14.6% was observed in 1991 for the North Frisian Wadden Sea, representing more than 60% of all eelgrass stands.

The evidently increasing south-north gradient has been related to a hypothesised decrease in turbidity (Reise, 1997) in the same way as the decline of intertidal local populations has been related to local increases in turbidity (Philippart, 1995). In Section 5.4.1 it was stated that in the Marsdiep area primary production is twice as high as in the rest of the Wadden Sea. Furthermore, both the Lower Saxon and the Dutch Wadden Sea showed comparable levels of chlorophyll. This would exactly mirror the distribution of eelgrass in the Wadden Sea with a distinction between southern and northern populations. The effects of epiphyte shading have been investigated by Philippart (1995). Shading can account for up to 80% reduction of light. In turn, shading can be counterbalanced by grazing of the epiphytic algae by the mudsnail *Hydrobia ulvae*, which can consume 25 to 100% of the epiphyte standing stock.

The development of the *Zostera* population in Lake Grevelingen, an oligo- to mesotrophic Dutch coastal lagoon enclosed in 1953, is of particular interest, since it shows that the decline in *Zostera* is a complicated process that cannot be reduced to one or two key factors. In Lake Grevelingen *Zostera marina* stands declined since 1978 but are still present. Herman et al. (1996) related this decline to a parallel decrease in silicon concentrations in the water column, since these two parameters showed the best correlation of all combinations tested. However, this relationship is highly speculative (Herman et al., 1996). Subsequent investigations could not support the silicon hypothesis (Kamermans et al., 1999).

Nienhuis et al. (1996) discussed the decline of *Z. marina* in Lake Grevelingen in a wider context: (1) Harsh winters causing direct harm by destroying shallow tidal stands and indirectly by causing anoxia in shallow subtidal habitats: (2) A reduction of ammonium, the preferred N-source, (3) Reduced germination at salinities above 30 PSU. Light limitation was no reason for the observed decline since light availability increased due to decreased turbulance. But, as they stated, it remains a rather incomplete picture of the fate of this *Zostera* population. For other populations a decline due to eutrophication was reported (references in Herman et al., 1996; Nienhuis et al., 1996).

Van Katwijk et al. (1997) presented experimental evidence that ammonium already has a toxic effect on eelgras at concentrations of about 25 µM. They suggested that the toxic effect is most pronounced during autumn (low irradiance, relatively high temperatures, increasing ammonium concentrations). Although the concentrations are mostly below 25 µM in the water column (see Chapter 4, Figs 4.5, 4.16), the near-bed ammonium concentration might be substantially higher.

Macrophytes: Assessment

Macroalgal biomass is a potential eutrophication indicator. According to the Workshop macroalgal coverage may be used as an indirect indicator of biomass. Because no comprehensive data source exists, it should be used as a descriptive indicator. Macroalgal development and distribution cannot be explained by eutrophication alone and other factors must be taken into consideration such as hydrodynamic forces, climate, grazing, light availability, turbidity, sediment type and sediment mobility.

Eelgrass population dynamics are apparently too complex and their distribution is too local to allow for the application of eelgrass parameters as easy-to-handle indicators of eutrophication. Eelgrass recovery is probably hampered by eutrophication. At the Workshop eelgrass coverage was considered a potential indicator, possibly related to the toxicity of ammonium.

The parameters „shifts in species composition" and „reduced depth distribution" were not considered suitable indicators by the Workshop participants, mainly because of the insufficient data basis.

5.4.3 Microphytobenthos

Asmus (1999) summarized the present knowledge on microphytobenthos dynamics in the Wadden Sea: In the Wadden Sea. One long-time series of microphytobenthos primary production, ranging from 1968 until 1981, exists for the Marsdiep tidal area (Cadée, 1984). This series clearly shows an increasing trend of microphytobenthos primary production, which has nearly doubled during this period. Recent data on microbenthic primary production show high values in all parts of the Wadden Sea. Extensive studies in the Ems-Dollard estuary revealed a range between 60 and 250 g C m^{-2} y^{-1} depending on the elevation of the tidal flat (Colijn and de Jonge, 1984). In the Sylt-Rømø Bay benthic primary production doubled to tripled between 1980 and 1993/94/95 (Asmus et al., 1998b). However, this was only a two-point comparison and not a continuous time series as in the Marsdiep tidal basin. Here, the microbenthic production increased proportionally to the discharge of phosphate from Lake IJssel (de Jonge and Essink, 1991). This significant correlation emphasizes that the high level of microbenthic primary production is probably the result of eutrophication. Although benthic diatoms benefit from high nutrient concentration in the pore water of the sediment, there is experimental evidence of nutrient limitation in microphytobenthos (Sundbäck and

Granéli, 1988) and of an increase of primary production of microphytobenthos due to fertilization (Nilsson et al., 1991). Under eutrophic conditions the increased biomass of benthic diatoms is composed of a reduced number of species (Peletier, 1996; Agatz et al., 1999). In general, primary production of microphytobenthos contributes from 29 to 55% to the total annual primary production of phytoplankton, eelgrass, macroalgae and microphytobenthos in different parts of the Wadden Sea, including the estuaries (Nienhuis, 1993).

Microphytobenthos: Assessment

Because of the lack of data the parameters microphytobenthos biomass and primary production must be considered only potentially applicable in the assessment of the eutrophication status.

5.5 The Indirect Effects

Indirect effects of nutrient enrichment are second and higher order effects caused by changes in the directly affected parameters described in 5.4.

In the Checklist of the Comprehensive Procedure five categories of indirect effects of nutrient enrichment are listed, namely organic carbon, oxygen, zoobenthos/fish, benthic community structure and ecosystem structure.

5.5.1 Organic Carbon, Organic Matter

Because enhanced primary production is one effect of eutrophication, an increased organic carbon content can be regarded as a subsequent effect, since all organic matter is ultimately derived from primary production. Whereas dissolved nutrients are subject to manifold recycling and remineralization during the year and are only indirect indicators of eutrophication processes, the dynamics of organic matter may give more precise information about the amount of matter turned over in the Wadden Sea. Some indications of an increased organic matter turnover exist:

- Gerlach (1990) reported a change of bacterial distribution in the German Bight between the 1960s and the 1980s (after work of Gunkel and Klings), corresponding with an increase of BOD (biological oxygen demand) from 1.3 mg O_2/l (1965) to 2.8 mg O_2/l (1985).
- De Jonge and Postma (1974) inferred a two- to threefold increase in organic matter import into the western Dutch Wadden Sea.
- Asmus et al. (1998b) observed a two- to threefold increase in oxygen consumption rates in the water.

Results from TRANSWATT (Hesse et al., 1997; Brockmann et al., 1999) indicate the importance of dissolved and particulate organic matter in nutrient budgets. Hesse et al. (1997) also indicated that particulate and dissolved carbohydrates play an important role in the pelagic carbon budget. In the analysis of causative factors (Chapter 4) the TN load of the Rhine has been considered which not only consists of DIN and DON but also includes the particulate organic N fraction (PON). The participants in the Workshop (Annex 2) considered the parameter organic matter of high importance, but stressed that there are no time series available to use organic matter as an indicator of eutrophication effects in the Wadden Sea. There are some data on water column measurements for the Marsdiep (Cadée, 1982) and for the Sylt-Rømø area (Schneider et al., 1998). A major drawback of using organic matter as an indicator of eutrophication is that most of the organic carbon associated with particulate matter is dead, refractory matter (Manuels and Postma, 1974). No continuous measurements on organic matter in sediments exist, neither for foam and slime.

5.5.2 Oxygen

Typical oxygen signs of eutrophication in the water column are daytime supersaturation and nighttime depletion due to respiration. Experimental persistent oxygen depletion occurred in mesocosms which contained a benthos compartment, but not in nutrient enriched mesocosms without benthos cores (Doering et al., 1989), indicating high oxygen requirements of the densely populated benthic subsystem. Oxygen depletion in the sea may occur under stratified conditions when the water column turnover time is lower than oxygen turnover time (Gerlach, 1984; Kruse and Rasmussen, 1995). For the Wadden Sea, oxygen depletion due to stratification is not relevant, because stratification does not occur in this well-mixed area. According to the Workshop, oxygen concentrations in the water column are therefore no suitable indicator of eutrophication. In general, the data basis is rather poor. Oxygen is a standard parameter in the Dutch Wadden Sea monitoring program. The data from 1972-1997 show a slightly decreasing trend (van den Bergs et al., 1999). Continuous measurements in the period 1996-1998 showed no extremely low oxygen values, concentrations being mostly above 7 mg/l but with large daily fluctuations (van den Bergs et al., 1999). According to the Workshop (Annex 2) the daily oxygen cycle changes under eutrophied conditions into a situation with supersaturation at daytime and under-saturation during the night.

The potential use of the daily oxygen cycle was underlined by the Workshop. The oxygen consumption rate was not considered suitable as a eutrophication indicator mainly because of the lack of data. The few available data do, however, indicate an increased consumption rate (Asmus et al., 1998a, b).

The sediment oxygen values were regarded more relevant for the Wadden Sea. Already in the 1970s Michaelis (1987) observed a decrease of the thickness of the oxidized layer in sandy sediments of the Jadebusen, compared to the 1930s. However, Michaelis (1997) showed that after 1970 no clear trend could be observed.

Since the mid 1980s spots with black anoxic sediment surface layers ("Black Spots") have been reported, especially on sandy sediments in the Niedersachsen Wadden Sea (Kolbe, 1995; Farke, 1997). Höpner and Michaelis (1994) have reviewed the investigations into the phenomenology and causes of Black Spots. A general increase in the supply of organic material to the sediment and a subsequent reduction of the thickness of the oxic layer could not be substantiated. It could be shown, however, that generally, the burial of organic material (mainly macroalgae) is responsible for the occurrence of Black Spots. The phenomenon itself is not new, but the extent to which it occurs had not been reported before and is most probably related to the increased abundance of algae, mainly macroalgae, but possibly also planktonic algae.

In the spring of 1996 large anoxic sediment areas were observed in the East Frisian part of the Niedersachsen Wadden Sea. By the end of May 24 km^2 of the littoral had become anoxic and on 12 June the anoxic area had reached a coverage of 36 km^2 (Michaelis, 1997). The anoxic conditions in the sediment surface were accompanied by a massive mortality of the benthic fauna.

According to Bakker (1997) and Ærtebjerg (1997) the situation in the Dutch and Danish Wadden Sea was not different from previous years. In the eastern Dutch Wadden Sea an area with small Black Spots had been investigated. Sulfide profiles suggested a source within the sediment (algae, cockles) to be held responsible for the anoxia. In the Danish Wadden Sea the Black Spots found had most probably been caused by bird trampling.

De Jong et al. (1999a) concluded on the basis of a retrospective analysis of the circumstances accompanying the event, together with a comparison with historical records, that the occurrence of the black areas in the spring of 1996 had most probably been the result of an exceptional coincidence of meteorological and biological developments. The main determining elements were a cold winter favoring the early blooming of *Coscinodiscus concinnus* in the Wadden Sea and the adjacent North Sea, the additional import of organic material, including vegetable oil, from the offshore bloom into the Wadden Sea caused by a net landward bottom current (enhanced by the predominant easterly winds), upwelling and a sudden temperature increase of 15°C in the middle of May, enhancing biochemical degradation of the organic material. Some questions remained, however. The first is whether the East Frisian Wadden Sea has a more than average sensitivity to high organic loading. The second is whether there has been an increase in primary production in the North Sea off Norderney as a result of eutrophication and thus a higher potential for the import of organic material into the Wadden Sea. Some support for an increased primary production is given in Chapter 3. Finally, local nutrient emissions may have played a role in the event.

At the Workshop (Annex 2) monitoring of coverage of Black Spots by means of aerial photography was considered highly important.

5.5.3 Zoobenthos and Fish

In the Checklist the parameter mortality of zoobenthos and fish due to low oxygen concentrations is listed. In the Wadden Sea occasionally fish mortality occurs (e.g. Essink; 1989). Also benthos mortality is occasionally observed as a result of anoxic sediments. This is comprehensively covered in 5.5.2. Obviously, increased zoobenthos and fish mortality due to suboxic conditions can be seen as a eutrophication effect. But because of its irregular occurrence, zoobenthos and fish mortality was not regarded by the Workshop as a useful eutrophication criterion. The exception is benthos mortality as a result of anoxic sediments (Black Spots).

5.5.4 Benthic Community Structure

Introduction

Theoretical Assumptions

The hypothesis of a significant change in macrobenthic community structure as an indirect consequence of nutrient enrichment of the coastal waters is based on the following assumptions:

1. Macrobenthic species composition, abundance and biomass, as the expressions of species and population growth rates and predatory losses, are bottom-up controlled. This means, growth is food limited and the macrobenthic stock is basically the expression of temperature- and

food-limited growth, and not the product of physical impacts (e.g. substrate limitation, sediment displacements, wave action, exposure time, bottom trawling) and biological controls (predation by birds, fish, crustaceans; parasite-induced mortality, migrations to suitable environment).

2. The staple food of macrobenthos is autotrophic phytoplankton, microphytobenthos and non-living organic material. The primary production is increasing upon increasing TON concentrations in the water column.
3. Macrobenthic species can utilize the increased primary production. This means that food quality and time of enhanced food availability meet the macrozoobenthos' demands.

According to Pearson and Rosenberg (1978) pollution and organic enrichment are followed by taxonomic alterations in the community structure. Whereas slight stress can be coped with by individual adaptation, a long-lasting and increasing intensity of unidirectional stress results in the replacement of species, genera, families and ultimately orders. Short-term variations in the environment demand flexibility of the individual behavioral and of the population´s genetic capacities and thus favor the more r-strategists in the r-K continuum concept (see a.o. Branch, 1984; Stearns, 1984; Warwick, 1986). Pearson and Rosenberg (1978) proposed a conceptual framework in which benthic communities change through three successive states (temporally or spatially), depending on the amount of organic matter reaching the sediments:

1. Initially, the species present react with an increase in growth rate, resulting in higher biomass and abundance.
2. If the organic loading increases, the „normal" resident species are replaced by opportunistic species (mainly polychaetes) which increase the benthic biomass.
3. A further increase leads to the disappearance of benthic animal species and ultimately to azoic sediments.

In this sense eutrophication, or better, the indirect effect of nutrient enrichment on the benthic communities, is seen as a stress factor acting upon the environment. The implications of this have been elaborated by Heip (1995):

In detail, the mechanism of a low or moderate eutrophication on the macrozoobenthos includes the following steps:

Nutrient enrichment from anthropogenic sources (N/P ratio increasingly biased towards N, silicate constant) leads to an

↓

increase in primary production (phytoplankton, flagellates more than diatoms; microphytobenthos) due to longer periods without nutrient limitation and/or higher absolute production (Cadée, 1992). This allows for an

↓

increased energy intake (feeding) by macrozoobenthos (suspension and deposit feeders). Consequently,

↓

growth rates of macrozoobenthos increase and

↓

higher reproductive output leads to higher spatfall/more successful recruitment

↓

higher species abundance - maximum just after spatfall

↓

higher biomass - the new generation will be reduced in numbers but gain weight/biomass and species composition changes towards species which can cope well with the increased nutrient supply/primary production and related changes.

Drawbacks to Theoretical Assumptions

Food limitation. Indications for food limitation of macrofaunal production are a high contribution of macrofauna to total benthic biomass, leaving only little organic material for the meiofauna to thrive on (Witte and Zijlstra, 1984), and the increase in macrofaunal biomass in the western Dutch Wadden Sea after a significant increase in primary production (Beukema and Cadée, 1986) with a 2 years time lag (Beukema and Cadée, 1997). However, these indications are not consistent all over the Wadden Sea.

The work of Beukema and Cadée (1997) and Madsen and Jensen (1987) points to the high relevance of type of location for the species´ potential for growth and reproduction: Only species communities not exposed to severe stress due to long exposure times, wave impact, or other stress factors do have the potential to react to enhanced feeding conditions. If those optimal locations are not evenly distributed all over the Wadden Sea, then one can expect the macrofaunal reaction to eutrophication to be substantially different in the different areas.

Competition. Regarding the utilization of enhanced food supply, all important species have to be considered when changes in biomass are evaluated.

Mussels have often been neglected in macrozoobenthos investigations, although mussels/mussel cultures can make up 65% of the subtidal (Dekker, 1989) and ca. 23% of the intertidal macrobenthic biomass (Beukema, 1976). They are thus direct competitors to other suspension feeding macrofauna. It is assumed that 30% of the annual primary production of the western Dutch Wadden Sea is consumed by mussels (Dankers and Koelemaij, 1989). The mean annual mussel landings more than tripled from the 1960s to the 1980s (Meixner, 1992; de Jonge et al., 1996).

Predation. If the macrofaunal production increases, so do the stocks of predators and thus the energy channeled through macrobenthos to top predators. Measurements of standing stocks do not necessarily reflect an increased production. Observed changes in standing stock with time could be due to a lag time for adaptation of the predator populations. Assuming a comparable physical forcing in all Wadden Sea areas, leading to comparable growth and recruitment conditions, a varying degree of predation on the macrofauna should have a significant impact on the standing stocks.

The stocks of breeding and moulting bivalve-eating birds like eider ducks (Swennen, 1976) increased during the last decades (Nehls et al., 1988; de Jonge et al., 1993b). It is assumed that the birds exploited a newly developed niche, i.e. the extended mussel cultures: In the western Dutch Wadden Sea eiders now harvest as much as approximately half the landings of the mussel fishery (Swennen et al., 1989). De Jonge et al. (1993b) reported an increase in the oystercatcher breeding population in the western Dutch Wadden Sea parallel to the increase in macrobenthos biomass.

From the 1950s to the 1980s/1990s an overall increase in the stocks of shrimps (*Crangon crangon*) has been assumed (de Jonge et al., 1993b; Lozán, 1994). Changes in the community structure of potential predators, possibly due to increased turbidity/reduced visibility, with a shift from visual predators, such as juvenile dab, to non-visual predators such as juvenile plaice (de Jonge et al., 1993b), may have altered the predation pressure on macrozoobenthos.

Food quality. As shown by Beukema and Cadée (1997), at least some macrobenthic species do not grow equally well on all types of food, but thrive better on phytoplankton which contains a large fraction of diatoms. This means, at least for suspension feeding bivalves, that not only the overall quantity of available food determines the rate of benthic production and ultimately the macrofauna standing stock, but that the food quality is just as important. As a consequence, the algae species promoted by increased N and P loads may be of limited food value for some macrobenthic species.

Nutrients. Si is the primary factor limiting diatom production (Gieskes and van Bennekom, 1973; van Bennekom et al., 1975). The Si concentrations in the coastal waters are dependant on the freshwater discharge by the large rivers (van Bennekom and Wetsteijn, 1990). The Dutch and German time series indicate that diatoms have not been able to take advantage of the increased nutrient levels and that their stocks have not increased during the last decades (Cadée, 1992; Hickel et al., 1993). Eutrophication in the Wadden Sea started in the early 1960s with increasing P loading which lasted until the end of the 1970s, after which inputs gradually declined. The increase of N loading started already in the 1950s, reached a maximum in the mid of the 1980s and only slightly decreased since. Because of the changes in the P and N loading the N:P ratio has strongly increased since the end of the 1980s. The high N:P ratio and the relatively (compared to P and N) reduced Si loads (Admiraal and van der Vlugt, 1990) , but also selective feeding by secondary producers, pollution and increased water temperatures, are factors which may have contributed to the general shift in the phytoplankton species composition in favor of Si-independent flagellates (van Beusekom and Diel-Christiansen, 1996).

Timing. The reproductive success of bivalve species like *Macoma balthica* is particularly determined by body condition in winter (Honkoop and van der Meer, 1998). Increased nutrient loads in winter will not improve the food supply for overwintering bivalves since during winter the phytoplankton is light limited.

Pollution. High loads of heavy metals, organochlorine compounds etc. may influence the macrofaunal production. Declining metal contamination levels have been observed since the early 80s.

Climate. Climatic conditions have a strong impact on macrofaunal production, recruitment, abundance and biomass (Diel-Christiansen and Christiansen, 1999, and references therein). The „severity" of winter acts as large scale synchronising factor on macrofauna populations (e.g., Beukema et al., 1996). Local windfields can determine the magnitude of coastal benthic secondary production. The coastal benthic energy flow may be physically regulated (Emerson, 1989).

Analysis of Species Composition, Abundance and Biomass

Species Composition

A shift in species composition during the last decades has been reported from several subareas of the Wadden Sea. These changes include the introduction of species such as *Ensis americanus* (1978, Beukema and Dekker, 1995), *Marenzelle-*

ria spp. (1983, Essink and Kleef, 1993; Essink et al., 1998b) and *Crassostrea gigas* (1990s, Reise, 1998), the decline or disappearance of species such as the whelk, *Buccinum undatum* (e.g., de Jonge et al., 1993b), the oyster, *Ostrea edulis*, and reefs of *Sabellaria spinulosa* (Reise et al., 1989), the bivalves *Nassariaus reticulatus*, *Scrobicularia plana* and *Cerastoderma lamarcki* (Lauckner, 1990) and the growing relative importance (in terms of biomass or abundance) of small polychaetes such as *Heteromastus filiformis*, *Scoloplos armiger*, and *Nereis diversicolor* in the western Dutch Wadden Sea (Beukema, 1991) and in the North Frisian Wadden Sea (Reise, 1982; Reise et al., 1989). A trend of increasing abundance of polychaetes was also observed in the Danish Wadden Sea (Jensen, 1992). No changes were found in the eastern Dutch Wadden Sea (de Jonge and Essink, 1991) and in the East Frisian Wadden Sea (Rhode, 1985; Dörjes et al., 1986). Subtidal and intertidal mussel beds increased in parts of the North Frisian and East Frisian Wadden Sea between the 1920s and the early 1980s (Reise et al., 1989 and references therein) but intertidal mussel beds strongly decreased since the mid of the 1980s (Dankers et al., 1999). .

Of these changes, only the increasing importance of polychaetes can probably be attributed to indirect effects of eutrophication. Consequently, the stability of the macrofaunal community in the eastern Dutch Wadden Sea and in the East Frisian Wadden Sea could indicate that these areas are not subject to enhanced nutrient loads as supported by Essink et al. (1998a). The alien species have arrived either with ballast water or have been released accidentally (Reise, 1994). Fisheries and sediment erosion are probable reasons for the epifaunal losses in the North Frisian Wadden Sea (Reise et al., 1989). The decline or disappearance of the whelk has been caused by TBT pollution (Ten Hallers-Tjabbes et al., 1993). Parasitic infestations may lead to mass mortality and have caused, e.g., the disappearance of the bivalves *Nassariaus reticulatus*, *Scobicularia plana* and *Cerastoderma lamarcki* (Lauckner, 1990). The increase of mussel beds in some parts of the Wadden Sea which took place until the beginning of the 1980s may be related to an improved food supply (Reise et al., 1989). However, the heavy exploitation of mussels in most parts of the Wadden Sea has probably been the main cause for the decline of intertidal beds that has occurred since. The species composition is usually expressed on the basis of the individual species´ abundances. As the reproduction and settlement time varies from species to species, species composition based on abundance changes in the course of the season. For the comparability of data it is therefore necessary to standardize the sampling time to a particular phase in a benthic communities population development, and not to a particular time of the year. Furthermore, the differential sensitivity of species to winter conditions leads to a high inter-annual variability of species composition. Consequently, possible effects of eutrophication can only be detected on, at least, decadal scales.

Abundance

The absolute abundance of polychaetes more than doubled in the western Dutch Wadden Sea (Beukema, 1989; Beukema, 1991) and increased considerably in the North Frisian (Reise, 1982; Reise et al., 1989) and Danish Wadden Sea (Jensen, 1992). No trends were observed in the East Frisian Wadden Sea (Dörjes et al., 1986). No data are available for the eastern Dutch Wadden Sea.

The increasing abundances of polychaetes are probably linked to an enhanced food supply due to eutrophication.

Biomass

Macrofaunal biomass in the western Dutch Wadden Sea increased considerably after 1980 (Beukema and Cadée, 1997). In the eastern Dutch Wadden Sea no significant changes were observed (de Jonge et al., 1993b; Essink et al., 1998a). In the intertidal of the East Frisian Wadden Sea no clear temporal trend for total biomass was found, but the biomass of polychaetes and crustaceans increased (Essink et al., 1998a) whereas the biomass of the major species except *Mytilus* remained stable over the past 30 years (Anon. 1996, cited after Delafontaine and Flemming, 1997). In the subtidal, Kröncke et al. (1998) found an increase in macrofaunal biomass since 1989. No comparable data are available for the other subareas.

The biomass increase in the western Dutch Wadden Sea, which followed the nutrient enrichment with a 2 years time lag, is probably related to an improved food supply. The relationship between nutrient load and macrofaunal biomass in the East Frisian Wadden Sea is not clear. The picture could be severely biased because the production of *Mytilus* was not included in most investigations. In the subtidal of the East Frisian Wadden Sea the observed biomass increase is linked to mild winters, but is probably enhanced by a eutrophication-related food enrichment (Kröncke et al., 1998).

General Judgement of the Criteria

According to current knowledge, none of the above criteria (species composition, abundance, biomass) seem suitable to characterize the indirect impact of eutrophication-related changes on the macrobenthic fauna of the inter- and subtidal Wadden Sea. Possible effects appear to be regional or local rather than Wadden Sea wide, and the complexity of interactions with other forcing factors (climate-related variations in mortality, reproduction, predation, temperature, wave action, ice-shear, sediment stability, turbidity etc.) may camouflage possible links. As Heip (1995) pointed out, possible effects of eutrophication on macrozoobenthos are expected to be detectable only on long-term, i.e. decadal, scales.

The only Wadden Sea region where the intertidal macrobenthic biomass increased, is the western Dutch Wadden Sea. However, this area is different from the other Wadden Sea subareas in some respects (Reise, 1994): Its macrofaunal biomass used to be lower than in the other areas, possibly due to large scale hydrologic effects of the closure of the Zuiderzee in 1932 which took 30-40 years to come to a new geomorphological and hydrological equilibrium (Misdorp et al. 1990, cited after Reise, 1994).

Alternative Indicators of Eutrophication

Diversity Indices
Diversity is not sensitive to small changes in the environment. Effects can only be expected after considerable impacts. Climate-induced fluctuations and mass mortality after parasitic infestations can strongly influence species richness. Most diversity indices depend strongly on sample size and on taxonomic expertise.

The observed changes in the species composition of the Wadden Sea macrofauna in the last decades may probably be expressed in changed diversity indices. However, most changes cannot be solely attributed to eutrophication.

Growth Rates, Productivity and P/B Ratios
The individual or population biomass increase in a certain unit of time could be a useful indicator for the reaction of macrobenthos to eutrophication-related changes in food availability (e.g., Madsen and Jensen, 1987). These parameters integrate varying food qualities and quantities over a rather long time and reflect the local growth conditions, provided the species investigated is not highly mobile and opportunistic. The increasing production of *Mytilus edulis*, expressed as higher landings (Meixner, 1992), could be an indicator of a eutrophication-induced food enrichment.

On the other hand, growth rate and production are strongly influenced by parameters other than food, such as physical forcing (Wanink, 1993) and competitors. Emerson (1989) found that local wind fields determine the coastal benthic secondary production and that the coastal benthic energy flow is mainly physically regulated.

Condtion Index
The condition index in bivalves appears to be related to food availability (Madsen and Jensen, 1987), but it shows a strong seasonal variability and is also dependant on other environmental factors and thus site-specific.

Indicator Species
The Wadden Sea is a habitat with a high natural variability of environmental parameters, including food supply. Species living in this habitat are thus adapted to a wide range of environmental conditions. Besides showing a differential sensitivity to anoxia it is most unlikely that any of these species could serve as indicator of a low to moderate eutrophication. Parasite infestations can have severe effect on single species (Lauckner, 1990; Lauckner, 1994).

Parasites
Lauckner (1990) proposed that the increasing infestation rates by trematodes in benthic invertebrates may be caused by eutrophication, either via the higher stocks of birds acting as intermediate host, or by the better food conditions for the benthos. Since no data on parasitic infestations exist from before 1970, this explanations es still speculative.

Assessment

It is concluded that at the present state of knowledge neither species composition, abundance or biomass seems to be suitable to characterize the indirect impact of eutrophication-related changes on the macrobenthic fauna of the inter- and subtidal Wadden Sea (see Annex 3 for an overview). Possible effects appear to be regional or local rather than Wadden Sea wide, and the complexity of interactions with other forcing factors (climate-related variations in mortality, reproduction, predation, temperature, wave action, ice-shear, sediment stability, turbidity etc.) may camouflage possible links. As Heip (1995) pointed out, possible effects of eutrophication on macrozoobenthos are expected to be detectable only on long-term, i.e. decadal, scales. Despite its potential indicative value, further research is required to precisely define the role of eutrophication for Wadden Sea macrozoobenthos. Höpner (1991) warned not to be comforted with the absence of a Wadden Sea wide, clear-cut relation between eutrophication and changes in the benthos. He suspects that the ecological state of the Wadden Sea might be subject to sudden changes (without notice), as opposed to the generally assumed gradual changes. A drastic increase of nutrient loads, leading to catastrophic scenarios with exceptional algal blooms, subsequent decay and large-scale anoxic conditions, would certainly affect the macrozoobenthos severely.

In addition to the indices mentioned in the „Common Procedure" some alternative indices have been addressed. Neither one of these has proven to be applicable.

5.5.5 Ecosystem structure

Ecosystem structure change comprises changes in (the interaction of) physical, chemical and biological aspects of the system. For the assessment of the impact of nutrient enrichment it is essential to define the temporal and spatial scales of the changes.

For the purpose of this study it is assumed that large-scale anthropogenic eutrophication started in the beginning of the 1950s. In the past 50 years important physical, chemical and biological changes have occurred in the Wadden Sea.

Physical changes

The main parameters belonging to this category which are relevant for the Wadden Sea are:

- Climate and weather. The relevance of these parameters has been comprehensively described in sections 2.6 and 5.3.3.
- Coastal protection and land reclamation. There have been considerable changes in the hydrology and geomorphology of the Wadden Sea system as a result of large embankments, such as the closure of the former Zuiderzee in 1932 (the effects of which can still be measured), the embankment of the Lauwersmeer in 1969 and the embankment of the Nordstranderbucht in 1987. Also the deepening of the major rivers has greatly influenced hydrological patterns.

Changes in hydrology and geomorphology are likely to influence biological processes in the system. Reise (1995) concluded that the higher dynamics of the system, caused by the embankments and straightening of the coastline, have resulted in a reduced transparency of the water and consequently have counteracted the potential for higher primary production through nutrient enrichment.

Chemical changes

Considerable changes have occurred in the past 50 years in the loading of the system with nutrients and polluting substances. A strong increase in anthropogenic inputs took place in the period 1965 to 1985 after which inputs and concentrations generally declined. Several heavy metals and organohalogens are, however, still above natural background levels and/or ecotoxicological assessment criteria levels (Bakker et al., 1999).

A wide array of impacts of these substances on the biota has been documented in the scientific literature. Impacts which are directly relevant for effects of nutrient enrichment are, amongst others, a reduction of zooplankton grazing ability (see 5.3.4.), decline of seegrass (see 5.4.2) and inhibition of photosynthesis.

Biological changes

Reise et al. (1989) and Michaelis (1987) have pointed to changes in species composition which occurred this century. The decline of eelgrass beds for example led to a loss of specialized species (for example several snails) (Reise,1994). Evidence of increases and changes in species composition of benthos and phytoplankton were given in the corresponding sections of this text. However, at present, there is no comprehensive description of whole-ecosystem changes considering present and pre-eutrophication conditions.

Assessment

The above discussion on the effects of eutrophication on the different compartments of the Wadden Sea ecosystem only rarely shows a clear relation between nutrient enrichment and response to the enrichment. Sometimes the effects are overridden by other factors like climate. Sometimes eutrophication is only one of the several factors that explain the observed phenomena. This is clearly illustrated by de Jonge et al. (1993b) who comprehensively described many different changes which occurred in the Dutch Wadden Sea in a study entitled „The Dutch Wadden Sea, a changed ecosystem".

These complex interactions are hardly understood at present and, as long as this is the case, it is too early for a discussion on possible effects of eutrophication on the ecosystem structure. Generally speaking, no overall conceptual framework is available yet that allows a system-wide analysis of the impact of nutrient enrichment. This assessment is in accordance with the Workshop conclusion (see Annex 2).

5.5.6 Other Possible Effects: Algal toxins

Toxic algal blooms have a long known history in coastal areas. At the eastern coast of the USA toxic blooms have been known for hundreds of years (Horner et al., 1997). Detailed guidelines for commercial mussel purification were already given by Dodgson (1928) in the 1920s. This and traditional rules ("Only eat mussels in months with a ‚R' !") indicate that toxicity of algae evidently occurred in the pre-eutrophication era, too.

However, mechanisms for the development of toxicity in harmful algae are still widely unknown. Bacteria are assumed to play an important role, either acting as additional toxicants or supplying essential compounds to algal toxicity (Dantzer and Levin, 1997; Landsberg, 1997). Furthermore, high N:P ratios are assumed to play a role (Zevenboom et al.,1997).

The application of algal toxins as an effect parameter for eutrophication requires more research effort. At present, algal toxins are only of little indicative value. This assessment is in accordance with the Workshop conclusion (see Annex 2).

5.5.7 Summary

The results of the above analysis of the parameters from the Checklist have been summarized in Table 5.2.

Table 5.2: Summary of analysis of suitability of parameters from the Checklist of the Comprehensive Procedure for application in the assessment of the eutrophication status of the Wadden Sea. The suitability is indicated by: Y = suitable; P = potentially suitable; N = not suitable Parameters not contained in the checklist, but considered suitable for the assessment, are indicated in bold.

Parameter		Suitability	Remarks
1. CAUSATIVE FACTORS			
DIN, DON, TN, DIP, DOP, TP, Si	Nutrient enrichment, concentrations.	Y	
	Sources	Y	
	Ratios	Y	
	Fluxes and cycles	P	Calculation of fluxes is problematic.
	Annual cycles	Y	There have been considerable changes in the annual cycle of nutrients in the past decades.
2. SUPPORTING FACTORS			
Light availability	Irridiance	Y	
	Turbidity	Y	
	Suspended load	Y	
Hydrodynamics	Stratification	N	Not relevant for the Wadden Sea because of tidal mixing.
	Flushing time	Y	
	Retention time	Y	
	Retention time of particles	P	
	Accumulation of particles	P	
	Salinity	Y	
	Upwelling	P	
	Gradients	Y	
	Deposition		
Weather	Wind	Y	
	Temperature	Y	
Climate		Y	Effects of changes in the NAOI on benthos have been documented.
Biotic interactions	**Parasites**	P	Insufficient data.
	Zooplankton grazing	P	Insufficient data.
	Benthic suspension feeding	Y	
	Benthic grazing	Y	
3. DIRECT EFFECTS			
Phytoplankton biomass	Chl a	Y	
	Biomass, org. C.	Y	
	Cell numbers	Y	
Phytoplankton blooms	Frequency	Y	
	Duration	Y	
	Intensity	Y	

Table 5.2 (continued)

Parameter		Suitability	Remarks
Phytoplankton Primary Production		Y	
Phytoplankton Shifts in species composition		Y	
Macrophytes	**Eelgrass coverage**	**P**	Eutrophication may stimulate growth of epiphytic algae on eelgrass, leading to deterioration of eelgrass stands. A toxic relationship to ammonia is known, probably also to nitrate. Long-time data series are lacking.
	Macroalgal coverage	**Y**	
	Shifts in species composition	N	Different *Enteromorpha* species are hardly distinguishable.
	Reduced depth distribution	N	Intertidally not relevant. For subtidal no sufficient data. Is probably more dependent on turbidity than on eutrophication.
Microphytobenthos Biomass	Chl a	P	Insufficient data
Microphytobenthos Primary Production		P	Insufficient data
4. INDIRECT EFFECTS			
Organic carbon	DOC and POC	P	Insufficient data.
	POC	P	Insufficient data.
	Foam and slime	N	No time series.
	OC in sediments	N	No time series.
Oxygen	Concentrations	N	Measurement of daily cycle considered more important.
	Consumption rate	N	Insufficient data.
	Depth of sediment oxic layer	Y	
Zoobenthos and fish	Mortality	N	Very irregular phenomenon.
Macrozoobenthos	Abundance	Y	
	Species composition	Y	
	Biomass	Y	
Ecosystem structure	E.g. carbon cycling, biogenic structures (eelgrass stands)	P	No overall conceptual framework available for analyzing effects of eutrophication on ecosystem.
5. OTHER POSIBLE EFFECTS			
Algal toxins		P	Lack of data and basic knowledge.

6. Developing a Methodology for Assessment

6.1 Introduction

The overall assessment of the eutrophication status is defined here as the combined evaluation of all suitable parameters with the aim of arriving at an unequivocal determination of the status of the area under consideration as Non-Problematic, Potentially Problematic or Problematic with regard to undesirable effects of anthropogenic nutrient enrichment.

The idealized steps in this exercise are first to describe eutrophication, then to link the eutrophication related undesired phenomena to a certain input of nutrients and, finally, to decide at which levels of nutrient enrichment problems will not occur.

In the foregoing part of this report the suitability of individual parameters for their usefulness as indicator of eutrophication was comprehensively discussed. The criteria used were the indicative value of the parameter for eutrophication processes and eutrophication related phenomena, and the applicability of the parameter. The latter was mainly dependent upon data availability. This evaluation, which is summarized in Table 5.2 resulted in the following parameters which were considered principally suitable for use in an assessment of the eutrophication status of the Wadden Sea (see also Annex 2, Appendix 1):

CAUSATIVE FACTORS
Riverine nutrient loads
TN, including PN, DIN and DON
TP, including PP, DIP and DOP
Si
Nutrient Ratios
DIRECT EFFECTS
Nutrient Annual cycles
Phytoplankton biomass (Chlorophyll a; organic C; cell numbers);
Phaeocystis blooms (frequency; duration; intensity);
Phytoplankton primary production;
Phytoplankton species composition;
Macroalgal coverage
INDIRECT EFFECTS
Depth oxic sediment layer
Macrozoobenthos (abundance; species composition; biomass).

An integrated assessment should, ideally, be based upon causal links between causative factors and direct and indirect effects, taking into account the supporting environmental factors.

Whereas eutrophication can be described in an objective way, the definition of problems is to a large extent subjective. Moreover, it has been demonstrated in the previous Chapters that only a few direct links between nutrient enrichment (riverine input) and effects could be established. Although for most phenomena, such as increased macrobenthic biomass, increased anoxia in sediments (Black Spots), increased macroalgal cover or decreased eelgrass stands, a certain role of eutrophication could be observed, a direct link that quantifies the effect of eutrophication on the undesired effects could not be established. Many other factors, in particular climate and weather related parameters, influenced the occurrence or even triggered the outbreak of certain phenomena.

For these reasons, two principally different approaches are followed in this Chapter, as a basis for developing methodologies for assessing the eutrophication status.

The first approach, described in 6.2, is based upon a comparison of the present and past eutrophication status in terms of concentrations and inputs, and applies the above listed parameters from the category "causative factors".

The second approach, described in 6.3, aims at applying the direct and indirect eutrophication effect parameters by linking these to inputs, concentrations and/or ratios.

6.2 The "Causative Factor" Approach [Model I]

In Chapters 3 and 4 of this study it has been shown, that eutrophication of the Wadden Sea (the enhanced turnover of organic matter) can be described by the shape of the seasonal cycle of nitrogen and, in particular, by the autumn concentrations of nitrite and ammonium. It was proposed to use these concentrations as a measure of eutrophication.

The analysis of causative factors was based upon a conceptual model of the Wadden Sea presented in Chapter 3. Briefly, this model states that Wadden Sea eutrophication depends on the import of primary produced organic matter from the adjacent North Sea. Evidence was presented that at present the annual primary production in the coastal zone depends on the available amount of nitrogen. In the Southern Wadden Sea eutrophication could be linked to river input of nutrients. In the Northern Wadden Sea a more general link with offshore nitrate concentrations was proposed.

Available data for the Dutch Wadden Sea cover about four decades. Analysis of these data suggested that several sources are responsible for Wadden Sea eutrophication. Major sources are riverine and atmospheric inputs. At present, variation in the annual riverine nitrogen load amounts to almost 50%. The maximum effect on the variability on the Wadden Sea eutrophication is less: about 30%. The role of nitrogen input via the atmosphere contributes up to 25% to eutrophication (Chapter 4.9). In a historic perspective the changed denitrification potential in estuaries was stressed. At present, denitrification is low but could have been much higher during the sixties and seventies when oxygen content was lower and organic matter loading was much higher.

Based on the data and literature analysis and the outcome of the expert Workshop, it is proposed that at present the seasonal cycle of nitrogen and in particular, the autumn values of NH_4 and NO_2 are the best indicators of the eutrophication status of the Wadden Sea. If background concentrations for ammonium and nitrite in autumn are available, the degree of the present day eutrophication can be quantified. In Chapter 4.9 a background value for the western Dutch Wadden Sea of 3±1µM was proposed. This value implies that the eutrophication status of the Wadden Sea has increased by at least a factor of five as compared to a "pristine" situation.

6.3 The "Eutrophication Effects" Approach [Model II]

As already stated in the introduction to this Chapter, the relationship between direct effects and causative factors is generally unclear. Only for the western Dutch Wadden Sea a significant relation between nitrogen input and mean summer chlorophyll was found. The most comprehensive phytoplankton data series in the Wadden Sea is the one for *Phaeocystis* in the Marsdiep. Significant negative correlations could be established between the duration of the bloom and the relative importance of ammonium in the Rhine. During the past two decades the relative contribution of ammonium has been very low and bloom duration has been long. During this period the Si load by the river Rhine was negatively correlated and the N:Si ratio positively correlated with bloom duration of *Phaeocystis*. In conclusion, although the major part of the bloom duration could be explained by the data analysis presented above, no dose - response relation between nitrogen input and bloom duration exists.

Also for the other direct and indirect effects no direct dose - response relation could be established. It must, therefore, be concluded that the cause of events from nutrient enrichment, via primary production, to secondary production and the direct and indirect effects resulting from changes in primary and secondary production, is generally not a straightforward one and that the effect pa-

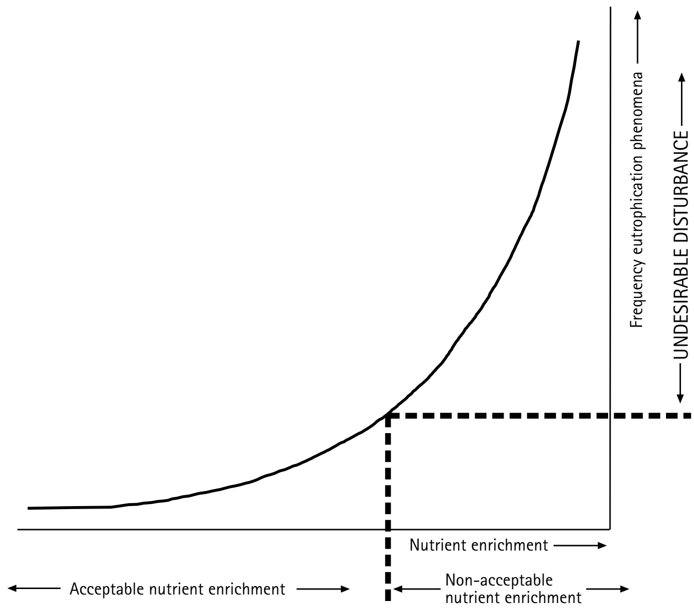


Figure 6.1: Schematic presentation of the relation between nutrient enrichment and eutrophication effects and the inference of acceptable and non-acceptable enrichment conditions.

rameters are determined by a range of factors. It is important to note that these factors may influence each other negatively or positively and at various temporal and spatial scales. Further examples of such multi-factorial processes were given in 5.5 for macrozoobenthos.

Although in most cases no direct relationships between inputs, concentrations and specific effects could be established, it is possible to apply eutrophication event in an assessment methodology using a probability approach, according to which it is assumed that the chances of eutrophication-related phenomena will increase with increasing nutrient loading. An essential question in the evaluation of eutrophication events is how to value "undesirable disturbance". The participants in the Workshop generally felt that the Wadden Sea is, also in a pristine state, a eutrophic system. In such a system there will always be a chance for eutrophication phenomena to occur. Such phenomena, for example a relatively high abundance of macroalgae, are a natural feature of the Wadden Sea and can, as such, not be judged as undesirable. Instead, however, the frequency and intensity of eutrophication events can be applied as the main criteria for determining whether certain events must be regarded as undesirable or not.

This is illustrated in Figure 6.1 where the X-axis represents nutrient enrichment and the Y-axis the relative incidence and/or intensity of phenomena directly or indirectly related to nutrient enrichment. According to this simple model undesirable disturbance may be defined as the exceedance of a certain frequency and/or intensity of the event. The corresponding nutrient concentration value on the X-axis would then demarcate the borderline between acceptable and non-acceptable nutrient enrichment situations.

7. Applying the Assessment Models to the Wadden Sea

7.1 Introduction

In this Chapter the Models proposed in the previous Chapter will be applied to arrive at a quantification of the eutrophication status and a classification of the Wadden Sea in terms of Problem Areas, Potential-Problem Areas and Non-Problem Areas. The first Model allows the description of the eutrophication status, but without a link to eutrophication problems. The second Model focuses on the relation between a certain eutrophication status and the co-occurrence of problems. In accordance with the expert Workshop the transition from Non-Problem to Potential-Problem conditions is reached when the ambient concentrations surpass the background concentrations. Based on Model II a proposal for the transition between Potential-Problem conditions and Problem conditions will be made. Based on Model I these conditions will be quantified for the different subregions of the Wadden Sea and a division into Problem Areas, Potential-Problem Areas and Non-Problem Areas will be made.

7.2 Assessment According to Model II

At the Workshop an approach was started to separate Non-Problem Area, Potential-Problem Area and Problem Areas, on the basis of Model II.

As a basic starting point the Workshop agreed that natural background ranges for nutrients as recently elaborated for the Dutch Wadden Sea by Van Raaphorst et al. (2000) (Table 7.1) represent non-problematic conditions. In principle, this was considered to represent the transition between Non-Problematic and Potentially Problematic conditions.

A second starting point was that at the right hand end of the scale the maximum values for nutrients monitored in the Wadden Sea would be used and that these values would depict Problem Area conditions.

The result of these deliberations is illustrated in Figure 7.1 for DIN for which the background range for Dutch waters is 4 to 7 μM and maximum values observed are 80-100 μM.

According to the Model the most important difference between the three eutrophication categories is given by the frequency and/or intensity of eutrophication related events. In order to establish the transition range between Potentially Problematic and Problematic conditions, the Workshop proposed to carry out an inventory of all observed outstanding eutrophication related phenomena and incidents (with emphasis on the parameters identified as suitable indicators), together with the specific circumstances accompanying these events, i.e. all nutrient parameters and essential co-factors (temperature, transparency). These data would then have to be pooled and an assessment would have to be carried out whether these events could be linked to a certain range of nutrient concentrations and/or ratios, taking account of the co-factors. This range would then be representative of the category Problem Area.

Such an analysis was not possible within the time-window of the project and this proposal is therefore put forward as the most important follow-up activity of this project.

A tentative option for establishing the transition range between the categories Potential-Problem Area and Problem Area is derived from the apparent change in the system which took place in the 1970s. In an analysis of the nutrient status of the German Bight, Radach (1998) distinguished four stages of nutrient enrichment, the earliest one already starting in the 1960s. He called it the period of "starting eutrophication" (1962 - 1970). In this period the rate of change in his ecological development index (EDI-index) according to physics and inorganic nutrients was higher than for the biology involved in the analysis. In the second period 1970 to 1977 (the "increasing eutrophication"-period), the rate of change for biology was already faster than for physics and nutrients. In the "maximum eutrophication"-period (1977-1985), the rate of change for the biological parameters was three times higher than for physics and chemistry. Afterwards, a slight decrease in the nutrient status was observed, not reaching the pre-1977 conditions. For biological parameters no change was observed.

The analysis of Radach leads to two conclusions :

(1) Eutrophication by means of enrichment and ecological effects started before 1970;

(2) The most severe change in effects occurred after 1977.

Table 7.1: Natural background ranges for nutrients in the Dutch coastal water and in the Dutch Wadden Sea (van Raaphorst et al., 2000).

Part 1: Natural background concentrations of TP and TN estimated for the total of the Marsdiep and Vlie (M+V) basins. The estimates are based on conservative mixing of water from the North Sea (NS) boundary at the tidal inlets with water from IJsselmeer. Values at the two tidal inlets of the basins are taken as representative for the NS boundary.

	Winter	Spring	Summer	Autumn
NS boundary salinity	28 - 32	28 – 32	29 - 32	30 - 33
NS boundary TP (μM)	0.9 ± 0.3	0.7 ± 0.3	0.7 ± 0.3	0.8 ± 0.4
NS boundary TN (μM)	15 ± 5	14 ± 5	9 ± 3	8 ± 4
M+V basins salinity	24 - 27	26 – 29	27 - 30	27 - 30
% IJsselmeer water	16	9	6	10
M+V basins TP (μM)	0.9 ± 0.3	0.7 ± 0.3	0.7 ± 0.3	0.8 ± 0.4
M+V basins TN (μM)	17 ± 7	16 ± 6	10 ± 4	9 ± 5
M+V basins TN:TP	~ 19	~ 23	~ 14	~ 11
M+V basins DIP (μM)	~ 0.5	~ 0.1	~ 0.2	~ 0.4
M+V basins DIN (μM)	~ 7	~ 4	~ 3	~ 3
M+V basins DIN:DIP	~ 14	~ 40	~ 15	~ 8

Part 2: Annual mean background TP and TN concentrations in Lauwersmeer, the river Ems and the Westerwoldsche Aa + Eemskanal, and the corresponding discharges into the Wadden Sea. For the water discharge of the Westerwoldsche Aa and Eemskanal no estimate for the standard deviation of the mean was available.

		Lauwersmeer	River Ems	Westerwoldsche Aa + Eemskanal
water discharge	m≈ s^{-1}	41 ± 8	100 ± 50	18
TP concentration	μM	1.4 ± 0.6	1.8 ± 0.8	1.8 ± 0.8
TN concentration	μM	41 ± 18	45 ± 25	45 ± 25
TP discharge	mol s^{-1}	0.06 ± 0.03	0.2 ± 0.1	0.04 ± 0.02
TN discharge	mol s^{-1}	1.7 ± 0.8	4.5 ± 2.3	0.08 ± 0.05

Part 3: Natural background concentrations of phosphate and nitrate in the English Channel, the river Rhine and the Dutch coastal area during winter.
Concentrations in the English Channel and Dutch coastal area were obtained from Laane et al. (1992). Concentrations for the river Rhine are the annual mean values. Salinities in the English Channel and the Dutch coastal waters are from Laane et al. (1992). The concentrations for the Dutch coast were calculated by theoretical mixing Channel water and Rhine water according to the salinities in the areas under consideration. For references see van Raaphorst et al. (2000).

Area	Salinity	Phosphate	Nitrate	N:P
English Channel	35.3	0.45 ± 0.05	5.5 ± 0.5	12
River Rhine	app. 0	1.8 ± 0.8	45 ± 25	25
Dutch coast	32 ± 1	0.57 ± 0.13	9.1 ± 3.1	16

Part 4: Natural background TP and TN concentrations estimated for the Dutch coastal zone of the North Sea.
Four seasons considered. Winter: Dec-Jan-Feb; Spring: Mar-Apr-May; Summer: Jun-Jul-Aug; Autumn: Sep-Oct-Nov. The concentrations were calculated by combining background values estimated for the winter months with the annual cycles shown in the text (not shown here). Ratios are relative to the annual mean.

	Winter	Spring	Summer	Autumn
TP ratio	1.1 ± 0.3	0.9 ± 0.2	0.9 ± 0.2	1.1 ± 0.3
TP conc. μM	0.8 ±0.3	0.6 ± 0.3	0.6 ± 0.3	0.8 ± 0.3
TN ratio	1.3 ± 0.3	1.2 ± 0.2	0.7 ± 0.2	0.8 ± 0.3
TN conc. μM	13 ± 5	12 ± 5	7 ± 3	8 ± 4
N:P	16	20	12	10

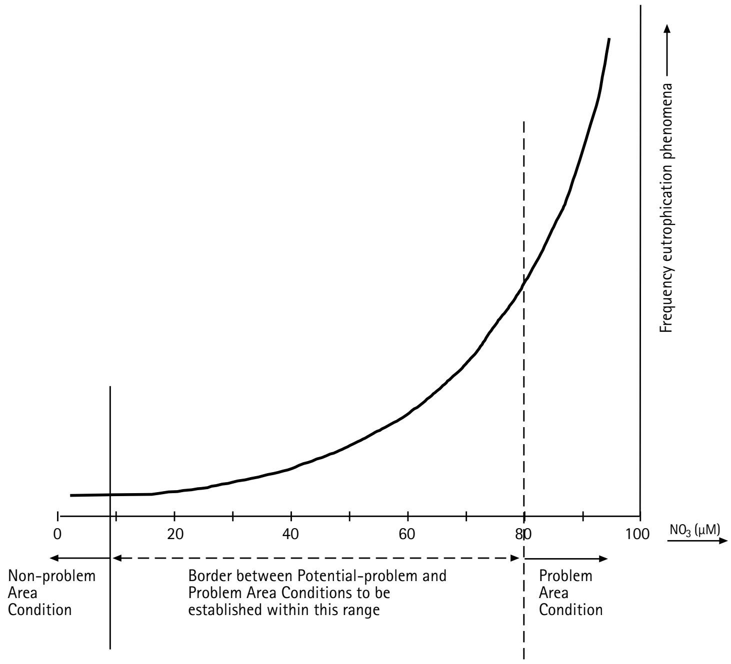


Figure 7.1: Schematic presentation of the development of the border ranges between non-problematic, potentially problematic and problematic eutrophication conditions for the example of nitrate.

Actually, most phenomena in the Wadden Sea which may be linked to nutrient enrichment (probably except for the more or less continuous decline of eelgrass in the southern Wadden Sea) occurred after 1977: The increase in length of *Phaeocystis* blooms, the increase in primary production to nearly 500 g C m^{-2} y^{-1} in the Marsdiep, the occurrence of Black Spots, the mass occurrence of macroalgae and a series of algal blooms (tabulated in Zevenboom, 1997).

The shift during the seventies was accompanied by a doubling of inorganic nitrogen nutrients in the German Bight. Especially nitrate increased. A similar shift occurred in the Dutch Wadden Sea (see Chapter 4). The sudden increase in nitrogen was not only due to increased nitrogen loads by rivers but also due to increased atmospheric nitrogen input and a change in the denitrification capacity due to reduced waste water discharge and increased waste water treatment (Billén et al., 1985; see Chapter 4.9). All available data (Chapters 3 and 4) suggest that during the seventies the organic matter turnover in the Wadden Sea doubled. It is suggested here that the increase by a factor of 2 demarcates the transition from a Potential-Problem Area to a Problem Area.

7.3 Assessment According to Model I

According to Model II, the border between Non-Problem and Potential-Problem conditions is defined by the background concentrations. In Chapter 4.9 a background range for NH_4 + NO_2 of 3±1µM was proposed for the western Dutch Wadden Sea for 1932. Values for a pristine Wadden Sea might be even lower. The transition between Potential-Problem and Problem conditions for the Wadden Sea can, as a first approximation, be defined on the basis of a reduction of the mean annual organic matter after 1980 by 50%. For the western Dutch Wadden Sea this corresponds with mean autumn values of NH_4 + NO_2 of 8.3 µM. As for the above background concentration an uncertainty range of ±1µM should be added to this value.

The background concentrations for the other subareas have been estimated on the basis of the above estimate for the western Dutch Wadden Sea, assuming that in all areas the autumn concentrations have increased proportionally. Data from the 1990s have been used for this comparison because only for this period comparable data are available. The results are shown in Table 7.2.

The transition between Potential-Problem and Problem conditions was defined on the basis of a reduction of the mean annual organic matter by 50% after 1980 . Since the monitoring programs for the other subareas do not cover this period, the autumn concentrations have been estimated by using data from the 1990s. The Dutch Wadden Sea data suggest that during these years the organic matter loading was 21-25% lower than during the entire period (1980-present). Therefore, the transition for the other areas was set at 63% of the mean values during the 1990s. The results are shown in Table 7.2.

Table 7.2: Classification of the Wadden Sea into Non-Problem, Potential-Problem and Problem Areas based on autumn concentrations of $NH_4 + NO_2$ (µM). The division in subregions is based on the availability of seasonal data. The present autumn values refer to values during the 1990s.

Area	Non-Problem conditions	Potential-Problem conditions	Problem conditions	'Present' values (1990s)
Western Dutch Wadden Sea	<3.0 µM	3.0 µM <> 8.3 µM	> 8.3 µM	12.3 µM
Eastern Dutch Wadden Sea	<4.0 µM	4.0 µM <>10.2 µM	> 10.2 µM	16.7 µM
Lower Saxonian Wadden Sea	<3.2 µM	3.2 µM <> 8.2 µM	> 8.2 µM	13.0 µM
Sylt Rømø Bight	<3.1 µM	3.1 µM <> 7.4 µM	> 7.4 µM	11.8 µM
Danish Wadden Sea	<2.5 µM	2.5 µM <> 6.5 µM	> 6.5 µM	10.3 µM

The values given in Table 7.2 should be seen as a first proposal enabling a check whether nutrient reduction programs will have the expected effect on the turnover of organic matter in the Wadden Sea. As for the background values derived for the western Dutch Wadden Sea, an uncertainty range of ±1µM should be added to the threshold values presented in Table 7.2.

It should be noted that a 50% reduction of the eutrophication of the Wadden Sea can only be accomplished if also the atmospheric deposition is reduced. Meanwhile, research should be carried out, especially to quantify the effect of eutrophication on eelgrass. The Workshop agreed that these severely threatened habitats are an important characteristic of the Wadden Sea. Under the present conditions reestablishment of eelgrass is very slow. If a nutrient level could be defined that enables the return of eelgrass, this level should be applied as an indicator of the transition between Potential-Problem and Problem conditions.

7.4 Subdivision

The subdivision shown in Table 7.2 is based on the availability of seasonal nutrient data. A comparison of present day levels shows some regional differences (see Chapter 4). In the eastern Dutch Wadden Sea the highest values are found (16.7 µM), but the other regions are quite comparable despite the different hydrographic settings (Northern and Southern Wadden Sea) and despite the different proximity to freshwater and nutrient sources. The lowest values are found in the Danish Wadden Sea (10.3 µM). All parts of the Wadden Sea are to be classified as Problem Areas.

7.5 Summary

The assessment of the eutrophication status of the Wadden Sea is based on the autumn values of ammonium plus nitrite. These values reflect the amount of organic matter that was turned over during the previous summer. The transition from Non-Problem conditions to Potential-Problem conditions was defined by the Workshop as autumn values exceeding the background concentrations. Background concentrations of ammonium plus nitrite were developed for the western Dutch Wadden Sea and amount to 3±1µM. The transition from Non-Problem conditions to Potential-Problem conditions was set at 50% of the autumn values after 1980. The transition is based on the observation that after about 1970 the organic matter turnover in the Wadden Sea doubled and that after 1970 most problems associated with the Wadden Sea eutrophication occurred. For the western Dutch Wadden Sea the transition to Problem Conditions corresponds to autumn values of 8.3 µM.

The threshold concentrations developed for the western Dutch Wadden Sea, were extrapolated to the other areas, proportionally to the present day autumn values. It is concluded that the entire Wadden Sea is a Problem Area. For the Wadden Sea to reach the status of a Non-Problem Area a 50% reduction of riverine nitrogen loads is not sufficient. Atmospheric input has to be reduced as well.

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Annex 1

Oslo and Paris Conventions for the Prevention of Marine Pollution
Joint Meeting of the Oslo and Paris Commissions
Brussels: 2- 5 September 1997
Annex 24
(Ref. § 8.1)

Common Procedure for the Identification of the Eutrophication Status of the Maritime Area of the Oslo and Paris Conventions

Preface

This document defines a common procedure for the identification of the eutrophication status of the maritime area of the Oslo and Paris Conventions (the "Common Procedure"). The Common Procedure will be an integral part of a Strategy to Combat Eutrophication. The purpose of the Common Procedure is to characterise the maritime area in terms of problem areas, potential problem areas and non-problem areas with regard to eutrophication. Action with respect to measures required following the identification of the eutrophication status of the maritime area will be specified within a Strategy to Combat Eutrophication.

The procedures specified in this document are without prejudice to existing and future legal requirements, including European Community legislation where appropriate.

1. Introduction

The Common Procedure comprises a stepwise process. The purpose of the Common Procedure is to characterise the maritime area in terms of problem areas, potential problem areas and non-problem areas with regard to eutrophication and to enable regional comparisons of eutrophication status on a Convention-wide basis. The intention of the Common Procedure is to enable regional comparisons of eutrophication status on a common basis.

The first step in the Common Procedure comprises a screening procedure. This is a preliminary ("broad brush") process which is likely to be applied once only in any given area. The screening procedure is intended to identify those areas which in practical terms are likely to be non-problem areas with regard to eutrophication, but for which there is insufficient information to apply the comprehensive procedure.

Following the application of the screening procedure, all areas which are not identified as non-problem areas with regard to eutrophication shall be subject to the comprehensive procedure and monitoring shall be undertaken in accordance with the minimum monitoring requirements for potential problem areas with regard to eutrophication in accordance with the Nutrient Monitoring Programme[1].

The second step in the Common Procedure is the comprehensive procedure. The comprehensive procedure is an iterative procedure and may be applied as many times as necessary. The outcome of the comprehensive procedure should enable a classification of the maritime area in terms of problem areas, potential problem areas and non-problem areas with regard to eutrophication.

The screening procedure is to be applied to all areas for which there is insufficient information to apply the comprehensive procedure. The selection of the size of the area to be assessed using the screening procedure is critical. Selection of areas should take into account hydrodynamic characteristics and proximity to nutrient sources. It is for the Contracting Parties concerned to decide on the size of the areas to be assessed.

2. Aim

The purpose of the Common Procedure is to characterise the maritime area in terms of problem areas, potential problem areas and non-problem areas with regard to eutrophication in accordance with the assessment procedure specified at Section 4. These areas are defined as follows:

a. problem areas with regard to eutrophication are those areas for which there is evidence of an undesirable disturbance to the marine ecosystem due to anthropogenic enrichment by nutrients;
b. potential problem areas with regard to eutrophication are those areas for which there

[1] The Nutrient Monitoring Programme was adopted by OSPAR 1995 (cf. OSPAR 95/15/1, Annex 12).

are reasonable grounds for concern that the anthropogenic contribution of nutrients may be causing or may lead in time to an undesirable disturbance to the marine ecosystem due to elevated levels, trends and/or fluxes in such nutrients;

c. non-problem areas with regard to eutrophication are those areas for which there are no grounds for concern that anthropogenic enrichment by nutrients has disturbed or may in the future disturb the marine ecosystem;

3. The Screening Procedure

In their assessment of eutrophication status Contracting Parties are invited to obtain information to the extent possible for the following types of information, *inter alia*:

a. demographic/hydrodynamic/physical information
   - demographic data: population and waste water treatment;
   - agriculture and industry;
   - hydrodynamic/physical features (for example fronts, upwelling, turbidity, flushing rates, residence times, water transport and currents);

b. optical observations
   - relevant optical observations made by ship, aircraft or satellite (for example the presence of, or evidence to the contrary of, algal blooms or fish kills);

c. nutrient-related information
   - voluntary data held by ICES, such as nutrient concentrations from international research cruises. ICES data is useful for screening large areas, but in coastal areas, fjords and small estuaries other data may be more appropriate (although such data may not be easily available);
   - input data (for example, atmospheric inputs, riverine inputs or direct discharges);
   - nutrient budgets (including the total nutrient component and the anthropogenic nutrient component);
   - information from monitoring carried out under European Community Directives (where applicable).

When applying the screening procedure Contracting Parties are encouraged to use the sequence of information types specified at points a-c above. Reporting procedures are specified at Section 5.1.

4. The Comprehensive Procedure

4.1 Scope of the comprehensive procedure

The comprehensive procedure should be applied to all areas except those classified as non-problem areas with regard to eutrophication following the application of the screening procedure described in Section 3. Repeated applications of the comprehensive procedure should identify any change in the eutrophication status of a particular area.

4.2 Principles of the comprehensive procedure

The comprehensive procedure consists of a set of assessment criteria that may be linked to form an holistic assessment of the eutrophication status of the maritime area. The biological, chemical and physical assessment criteria may be organised into five categories of information.
These categories comprise:

a. the causative - nutrient enrichment related - factors;

   and

b. the supporting environmental factors;

   which together produce

c. the direct effects of nutrient enrichment;

d. the indirect effects of nutrient enrichment;

   and

e. other possible effects of nutrient enrichment.

It should be noted however that some anthropogenic activities other than those leading to nutrient enrichment may result in a number of these effects. The different assessment parameters in each category are listed at Section 4.2.1, the assessment process that links the assessment parameters is described at Section 4.2.2 and the application of quantitative assessment criteria is described at Section 4.2.3.

4.2.1 Checklist for an holistic assessment

The qualitative assessment parameters are as follows:

a. the causative factors

   the degree of nutrient enrichment
   - with regard to inorganic/organic nitrogen
   - with regard to inorganic/organic phosphorus
   - with regard to silicon

taking account of:

- sources (differentiating between anthropogenic and natural sources)
- increased/upward trends in concentration
- elevated concentrations
- increased N/P, N/Si, P/Si ratios
- fluxes and nutrient cycles (including across boundary fluxes, recycling within environmental compartments and riverine, direct and atmospheric inputs)

b. the supporting environmental factors, including:
- light availability (irradiance, turbidity, suspended load)
- hydrodynamic conditions (stratification, flushing, retention time, upwelling, salinity, gradients, deposition)
- climatic/weather conditions (wind, temperature)
- zooplankton grazing (which may be influenced by other anthropogenic activities)

c. the direct effects of nutrient enrichment
i. phytoplankton;
- increased biomass (e.g. chlorophyll a, organic carbon and cell numbers)
- increased frequency and duration of blooms
- increased annual primary production
- shifts in species composition (e.g. from diatoms to flagellates, some of which are nuisance or toxic species)

ii. macrophytes, including macroalgae;
- increased biomass
- shifts in species composition (from long-lived species to short-lived species, some of which are nuisance species)
- reduced depth distribution

iii. microphytobenthos;
- increased biomass and primary production

d. the indirect effects of nutrient enrichment
i. organic carbon/organic matter;
- increased dissolved/particulate organic carbon concentrations
- occurrence of foam and/or slime
- increased concentration of organic carbon in sediments (due to increased sedimentation rate)

ii. oxygen;
- decreased concentrations and saturation percentage
- increased frequency of low oxygen concentrations
- increased consumption rate
- occurrence of anoxic zones at the sediment surface ("black spots")

iii. zoobenthos and fish;
- mortalities resulting from low oxygen concentrations

iv. benthic community structure;
- changes in abundance
- changes in species composition
- changes in biomass

v. ecosystem structure;
- structural changes

e. other possible effects of nutrient enrichment
i. algal toxins (still under investigation - the recent increase in toxic events may be linked to eutrophication)

4.2.2 Principles for using the qualitative assessment parameters

4.2.2.1 selection of the qualitative assessment parameters

Regional differences with respect to demographic and hydrodynamic conditions will influence the selection of assessment parameters for different areas. Since it is the intention of the Common Procedure to enable regional comparisons of eutrophication status on a common basis, Contracting Parties shall harmonise the selection of assessment parameters to the extent possible. The basic assessment parameters to be used for assessment throughout the whole maritime area are those contained in the Nutrient Monitoring Programme. Additional parameters (e.g. the list at appendix 1) may be applied where necessary to aid the assessment process and to increase our current understanding. Assessments can take account of information supplied from monitoring, research and modelling.

4.2.2.2 links between the assessment parameters

The overall assessment of the eutrophication status of an area will take into account the interaction of the causative - nutrient-enrichment related - factors and the supporting environmental factors (cf. 4.2.1). For example, apart from nutrients, sufficient light is required to allow phytoplankton to grow and reduced zooplankton grazing could allow increased phytoplankton biomass. Linking these categories of information will enable the cause of the direct and indirect effects of nutrient enrichment to be established and will allow appropriately targeted measures to be applied where necessary. Control measures are generally applied to the causative - nutrient-enrichment related - factors as these are the factors most directly influenced by anthropogenic activities.

4.2.3 Application of the quantitative assessment criteria

All relevant assessment parameters should be considered when applying the comprehensive procedure, although there is a need to recognise that regional differences (for example in terms of hydrography) and differences in data availability are likely to affect the assessment parameters actually used in the assessment procedure. It should also be noted that although the assessment tools (eg. background/reference concentrations) may be region-specific the methodology for applying the assessment criteria is based on a common approach.

Many areas are likely to be assessed using a stepwise approach: a preliminary investigation using the screening procedure followed by the comprehensive procedure. The stepwise approach has several advantages including *inter alia*:

a. the outcome of the screening procedure applied as a broad brush technique to a large area may, in some cases, indicate areas for which more detailed investigations using the comprehensive procedure would be appropriate;

b. the outcome of the screening procedure may help focus the selection of assessment parameters for use in the comprehensive procedure;

c. the outcome of the screening procedure may be of use in helping to refine particular assessment criteria.

Areas for which there is much existing information (for example parts of the North Sea) are likely to be subject to the comprehensive procedure at an earlier date than areas for which there is little information. Nevertheless the first iteration of the comprehensive procedure should be undertaken soon after applying the screening procedure. This is particularly important for areas which will be identified as problem areas and potential problem areas with regard to eutrophication, since it will be necessary to start rapidly appropriate monitoring activities and to initiate action programmes in these areas.

It should be pointed out that despite large anthropogenic nutrient inputs and high nutrient concentrations an area may exhibit few if any adverse effects. However, Contracting Parties should take into account the risk that nutrients input may be transferred to adjacent areas where they can cause detrimental environmental effects and Contracting Parties shall recognise problem areas and potential problem areas with regard to eutrophication outside their national jurisdiction.

5. Reporting

5.1 Screening Procedure

When reporting on their application of the screening procedure Contracting Parties are required to explain their selection of areas and information types. For each selected area, the responsible Contracting Party should prepare a statement which summarises the relevant information available and concludes whether, on the basis of that information, the area can be classified as a non-problem area or is an area which will need to be subject to the comprehensive procedure. Such statements should be examined within OSPAR no later than at OSPAR 1999.

Information available by the third quarter of 1998 may be used in the preparation of the regional quality status reports, with a view to its inclusion in the QSR 2000.

5.2 Comprehensive Procedure

In principle, reporting on the implementation of the comprehensive procedure although later in time should be in accordance with that for the screening procedure. For a given area, the outcome of the screening procedure may affect the implementation of the comprehensive procedure.

6. Timing

The timing of the implementation of the screening procedure and the comprehensive procedure is likely to vary for the Contracting Parties concerned; this reflects variations in the availability of relevant information. Nevertheless Contracting Parties shall as a minimum implement the screening procedure in accordance with the following schedule:

1. A first progress report on the implementation of the screening procedure shall be prepared, with a view to ASMO 1998 examining progress.
2. A final report on the results of applying the screening procedure shall be submitted to OSPAR 1999 for consideration.

Appendix 1

Additional assessment parameters

The additional assessment parameters may include the following:

- total nitrogen
- organic nitrogen
- organic phosphorous
- dissolved organic carbon
- dissolved organic nitrogen
- dissolved organic phosphorous
- sedimentation rate
- nutrients in sediments
- microphytobenthos (biomass and primary production)
- zoobenthos mortality
- fish mortality
- ecosystem structure
- algal toxins

Report of the Workshop on Wadden Sea Specific Eutrophication Criteria

List, Germany, 26-28 October 1999, AWI Wadden Sea Station Sylt

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1. Background and Opening of the Workshop

The meeting was held at the Wadden Sea Station Sylt of the Alfred Wegener Institute from 26 to 28 October 1999 at the kind invitation of the Alfred Wegener Institute, and welcomed by Karsten Reise, director of the Wadden Sea Station Sylt.

Folkert de Jong of the Common Wadden Sea Secretariat (CWSS) introduced the background of the meeting. At the 7th Trilateral Wadden Sea Conference in 1994 ecological Targets had been defined and, regarding nutrients and water quality, a Target had been defined to attain a Wadden Sea which can be regarded as a eutrophication Non-Problem Area. This formulation was in accordance with the OSPAR Common Procedure for the Assessment of the Eutrophication Status of the maritime area. The Common Procedure consists of the Screening Procedure and the Comprehensive Procedure for the final assessment of the eutrophication status. Taking this procedure into account, the Trilateral Wadden Sea Working Group (TWG) instructed the Common Wadden Sea Secretariat to coordinate a trilateral study aiming at developing Wadden Sea specific eutrophication criteria. The study started in late 1997 as a pilot study for the application of the Common Procedure and will be finalized by the end of 1999. It was jointly financed by the Danish Ministry of Environment and Energy, the German Ministry for the Environment, Nature Protection and Nuclear Safety and the Dutch Ministry of Transport and Public Works.

Folkert de Jong requested the participants to work on the following terms of reference :

(a) to discuss the results of the analysis of causative factors and related assessment criteria for the eutrophication status of the Wadden Sea;

(b) to define a priority list of Wadden Sea specific eutrophication criteria based on the checklist of direct and indirect effects provided by the Comprehensive Procedure within the framework of the Common Procedure;

(c) to discuss a scoring system in which these direct and indirect effects can be quantified with respect to eutrophication and therefore can be applied to assess and evaluate the eutrophication status of the Wadden Sea.

2. The Results of the Analysis of Causative Factors and Related Assessment Criteria

The first phase of the project had been carried out by Justus van Beusekom, who presented the results of his analysis of causative factors for eutrophication in the Wadden Sea area, as well as, related eutrophication assessment criteria, based on available data sets. The participants had received a copy of the analysis in advance.

The analysis is based upon the conceptual model that eutrophication in the Wadden Sea depends on the import of organic matter from the North Sea and adjacent coastal waters. After the imported organic matter has been remineralized, the regenerated nutrients can support local primary production in the Wadden Sea. A relationship between riverine TN loads before and during the growing season and remineralized N-species in autumn (chlorophyll as a covariate) was shown for the western and eastern Dutch Wadden Sea. For the Lower Saxonian Wadden Sea a similar seasonal and temporal pattern for remineralized N-species was found as for the eastern Dutch Wadden Sea, but no significant relationship between riverine loads from the Rhine and remineralized N-species. For the Northern Wadden Sea a relationship between winter nitrate concentrations in the German Bight and autumn remineralization was suggested. Earliest values of remineralized N-species (1960-1961; Postma, 1966) were presented for the Dutch Wadden Sea. Although these values do not represent a real background situation, they can serve as an indication. Special attention was given to the duration of *Phaeocystis* blooms in the Marsdiep as a potential indicator of the eutrophication status. It was shown that during the 80s and 90s the Si-load from river Rhine and the N/Si-ratio could sufficiently explain the length of *Phaeocystis*-blooms in the Dutch Wadden Sea. The very short bloom duration during the 70s is probably related to the high share of NH_4 to total N input.

Heinz-Jochen Poremski addressed the necessity to satisfy political demands within this study by means of defining Non-Problem, Problem and Potential-Problem Areas and to provide practical guidelines for, amongst others, the assessment of effects and the quantification of nutrient concentration ranges. This would be especially important for the implemenation of the EU Water Framework Directive, according to which water quality will have to be quantified into five categories. Poremski furthermore argued that for management purposes it would be important to distinguish between controllable and non-controllable factors in the analysis of eutrophication effects. Folkert de Jong answered that working on the Checklist of the Comprehensive Procedure would be a step in achieving this goal.

In the discussion Victor de Jonge asked whether resuspension from the benthos could raise the levels of chlorophyll in the water column and by this mask the amount of chlorophyll contributed by the phytoplankton. Justus van Beusekom suggested that resuspension is not that important. In a reply V. de Jonge argued that resuspension can be regionally of high importance, e.g. in the Dutch Wadden Sea. For the eutrophication debate it is however less important whether the chlorophyll is derived from benthic populations or from the phytoplankton.

3. Evaluation of the OSPAR Comprehensive Procedure Checklist

During the first day the workshop separated into two subgroups. Chairs were held by Justus van Beusekom and Victor de Jonge The results of the subgroups were reported to the plenary by the two rapporteurs Joop Bakker and Heino Fock. On the second day the subgroups rejoined and work was continued in a plenary session, chaired by Folkert de Jong and with Heino Fock as rapporteur.

The selection in the first subgroup was carried out according to the following two-step procedure :

- A first criterion for selecting a parameter from the Checklist was the availability of relevant data sets (Criterion AVAILABILITY).
- Secondly, it was considered whether this parameter was applicable for the assessment of the eutrophication status of the Wadden Sea (Criterion APPLICABILITY).

The selected parameters were assigned to three categories of importance : Fully applicable, potentially and not applicable. The value 'potentially applicable' was assigned to those parameters:

- for which data (e.g. time series data) were unsufficient or lacking but knowledge indicated a strong interplay with eutrophication or
- for which knowledge on the interplay with eutrophication was weak but could be anticipated.

The second subgroup concentrated on the relevance of the parameters from the checklist of the OSPAR Comprehensive Procedure (the Checklist for eutrophication problems).

The results of the work of both groups have been summarized in Appendix 1.

Additional statements have been summarized in the following.

3.1 Inputs

The conclusion from the data analysis that import of organic matter produced in the adjacent coastal zone supports the Wadden Sea eutrophication was supported. Additionally, in both subgroups the item of direct inputs of nutrients into the Wadden Sea was discussed. It was evident that only little information on direct inputs is available. It was suggested to run a model exercise, for example based upon data from the Schleswig-Holstein SWAP project ("Sylter Wattenmeer Austauschprozesse") , to investigate the relationships between changing imports of organic matter, directs inputs of nutrients and intensity of remineralization of nutrients and to improve calculation models for fluxes between rivers, Wadden Sea and adjacent coastal waters.

The 1999 Quality Status Report (QSR) for the Wadden Sea summarizes river nutrient loads and Wadden Sea nutrient concentrations for the time period 1985 to 1996. Considerable reductions have been achieved for phosphate, leading to significant decreasing trends in phosphate concentrations in most parts of the Wadden Sea. A decrease for N-compounds was not found in most of the areas.

3.2 Supporting Factors

It was stated that often a critical combination of supporting factors is a prerequisite for undesirable eutrophication related effects (e.g. Black Spots).

The item "zooplankton grazing" was extended to "biotic interactions", including also grazing by benthic filter feeders on phytoplankton and benthic grazing, as well as, the effects of parasites on the development of phytoplankton blooms.

The interplay between eutrophication and heavy metal pollution has to be considered, since an increased primary production may change the bioavailability of heavy metals e.g. by dilution through an increased biomass.

Furthermore the effects of contaminants on grazing intensity must be taken into consideration.

3.3 Direct Effects

It was concluded that phytoplankton is an indicator of eutrophication effects. It was stated that in general phytoplankton is recently showing blooms almost continuously throughout the season, indicating an acceleration of the production/remineralisation system. This was considered another sign of eutrophication, which enhances the risk of derailing of the production-remineralisation system. Justus van Beusekom stressed that except for the Western Dutch Wadden Sea, it is not possible to relate nitrogen input to chlorophyll levels.

3.4 Indirect Effects

Considering macrozoobenthic biomass, the Wadden Sea QSR 1999 states that climatological impacts (e.g. severe winters) have to be regarded as major determinants of the structure of benthic communities. However, locally, food limitation and availability are seen to influence community structure as a response to eutrophication.

Considering organic matter, increased POC contents of sediments had not been observed on a geological time scale. On a biological time scale however, temporary increased POC contents occur in the top few millimeters of sediments, probably due to increased sedimentation of detritus and microphytobenthos biomass. Analytical techniques in geological research, such as sieving and other pretreatment operations, may prevent the observation of recent, labile and fragile organic matter. The large proportion of detrital organic matter associated with the clay fraction possibly masks the observation of recent labile organic matter.

4. Further Specification and Quantification of Relevant Parameters

This section was carried out on the second day of the workshop, having Folkert de Jong as chairperson and Heino Fock as rapporteur.

In the beginning of the discussion Karsten Reise suggested to develop specific assessment criteria for each of the subregions of the Wadden Sea. He suggested to do this for a southern, central and northern part, depending on coastal morphology. Eike Rachor and Wolfgang Hickel suggested to additionally include tidal range, renewal time and river impact, in order to define subareas. It was concluded that finding a proper subdivision for the Wadden Sea in terms of eutrophication is a research item.

Focussing on nutrients, Victor de Jonge stated that before it is agreed upon that N is the major driving factor behind the Wadden Sea eutrophication, it has to be shown explicitly that P is presently of less importance. Based on his analysis Justus van Beusekom stated that nitrogen is presently the major nutrient compound to assess the eutrophication status of the Wadden Sea. Joop Bakker argued that also losses to the atmosphere by means of denitrification need to be taken into account. However, only little is known about denitrification rates in the Wadden Sea area as a whole. Ragnhild Asmus summarized results from the Sylt-Rømø area showing that denitrification rates were comparably low for that particular intertidal area. It was agreed that ammonia is a useful indicator of eutrophication and remineralization, probably reflecting short-term processes. On the other hand, Harald Asmus argued that nitrate is a better indicator of long-term processes.

Next, questions concerning nutrient measurements and background values were addressed. Michael Hanslik expressed the need for a standardized water sampling methodology so that each sample can be related to the same tidal phase. Furthermore, samples need to be standardized to salinity. Joop Bakker suggested to focus on inorganic compounds during winter time and to focus on organic compounds during summer. Uli Claussen added that knowledge of the seasonal P-cycle is very important to assess changes in phosphate-related effects. Karl-Jürgen Hesse suggested to also take into account the P-contents of the sediment. In this context Justus van Beusekom explained that P depicts a complex dynamics in the Wadden Sea, being either organic-particulate, inorganic(Fe)-particulate or soluble. No clear eutrophication signal is found in Wadden Sea sediment cores.

It was agreed not to define ranges for riverine inputs, but rather to focus on Wadden Sea features. However, Victor de Jonge argued that the present correlation between river loads and Wadden Sea nutrient concentrations can be used to investigate the magnitude of response of a nutrient compound in relation to changing riverine inputs. Furthermore, in some cases input values can be used to run model calculations in order to simulate nutrient concentrations. It was agreed to distinguish between nutrient concentrations in the Wadden Sea and the coastal water.

Victor de Jonge presented a table on background values from the 50s of total Phosphorus (TP) and total nitrogen (TN) for the Dutch Wadden Sea (Appendix 4). Assuming that the Northern Wadden Sea generally has lower values (about 4 μM) than the Southern Wadden Sea (about 7 μM), a range of salinity standardized wintertime background values of 4 to 7 μM DIN was accepted. This range was defined by the meeting to represent the upper border of Non-Problem Areas.

However, this must be regarded as a rough estimate and Harald Asmus suggested to do some careful calculations instead of using an estimate.

As an approach to defining border ranges between Potential-Problem Areas and Problem Areas it was agreed to start an inventory of years in which certain eutrophication related phenomena had been observed and to compare nutrient concentrations in such years with years in which no events had occurred. For this analysis participants were requested to present data of eutrophication-related phenomena[1]. If ranges of nutrient concentrations or nutrient ratios could be found which would correlate with observed problems, this range could be taken as the threshold between the categories Potential-Problem Area and Problem Area.

5. Conclusions

In summary, the workshop agreed on the following points:

- Importance of organic matter import from the North Sea.
- Relative importance of OM import versus locally supported OM production remains a research item.
- Symptoms of eutrophication are often due to a combination of supporting factors.
- The interplay between eutrophication and heavy metal pollution deserves attention.
- Phytoplankton is an –albeit problematic- indicator of eutrophication. It was discussed that present day bloom intensity indicates an acceleration of the production/remineralisation system.
- Macrozoobenthos is determined primarily by climatological factors, but food availability and other human impacts (f.e. fisheries) also play an important role.
- Finding a proper subdivision for the Wadden Sea in terms of eutrophication remains a research item.
- In addition to the significant relation between Wadden Sea nutrient dynamics and river input, the not-significant effect of P has to be shown.
- The role of denitrification deserves further attention.
- Despite the possibly subordinate role of P in Wadden Sea eutrophication, the seasonal P cycle deserves future attention in order to be able to asses changes in P related effects.
- The workshop agreed not to define riverine input ranges but rather to focus on Wadden Sea features.
- Background values presented by V. de Jonge were accepted as representing the upper range of the category "Non-Problem Wadden Sea".
- The Wadden Sea is a naturally eutrophic area. If Wadden Sea concentrations are above the background range, the area should be regarded as a Potential-Problem Area.
- If ranges of nutrient concentrations or nutrient ratios can be found which correlate with observed problems, this range can be taken as the threshold between the categories Potential-Problem Area and Problem Area. The NH_4 toxicity level for seagrass growth could be such a threshold value

[1] A first series of data and some preliminary analyses are presented in Appendices 2 and 3. There were, however, not yet sufficient data to carry out a full analysis necessary for determining the border range between potential problem and problem areas.

Appendix 1: Modified Checklist

Wadden Sea Specific Eutrophication Criteria: Modified checklist. NL=Netherlands; DK= Denmark; LowSax=Lower Saxony; p.=present; WS=Wadden Sea; LOD=Lack of Data. Parameters in Bold were added by the workshop.

Parameter from Checklist	Parameter specification	Data availability	P applicability full	potential	not	
CAUSATIVE FACTORS						
DIN, DON, TN	Nutrient enrichment, c_o	NL: WS-monitoring	X			Only scarce data on DON and DOP. In former times P was supposed to be the main factor - . N and P loads are at present uncoupled.
DIP, DOP, TP		D: WS-monitoring	X			The relevance of silicate is mainly restricted to diatom blooms, but considering ratios, probably also for the development of *Phaeocystis* blooms.
S_i		D	X			
	S_o	NL: long-term data sets, D: long-term data sets, DK: only TN TP Si, Atmospheric inputs D: long-term deposition data sets Norderney and W				and inputs via the English Channel have to be considered. Limited information on direct inputs into the Wadden Sea. At present all models indicate an initial input into the coastal waters, which then contributes to the input into the Wadden Sea. The Wadden Sea naturally depends on organic matter import from the coastal waters and therefore has to be regarded as a naturally eutrophic ecosystem. For N and P different kinetics have to be considered, since P
	Ratios	See concentrations	X			Derived from concentrations. Laboratory results indicate importance for phytoplankton community structure.
	Fluxes and cycles		X			Problems exist in calculating fluxes from rivers to estuaries, from estuaries to coastal waters, from lagoons to coastal waters (SWAP.) **Research item**
	Annual cycles	Marsdiep, Sylt-Rømø, Büsum, Norderney	X			Cycling dynamics differ from year to year
SUPPORTING FACTORS (interplay eutrophication - heavy metal pollution has to be considered)						
L_{ig}						
	T_u					
	Suspended load	Netherlands, LowSax, Sylt	X			
H_v						
	Flushing time	NL, Northern WS (Sylt-Rømø), and 1 station in DK	X			In NL available as freshwater flushing time.
	Retention time	NL, Northern WS (Sylt-Rømø), and 1 station in DK	X			
	Retention time of particles	NL	X			Indirectly by means of sediment budgets based on soundings
	Particle accumulation	D: 1 transect Eiderstedt - Sylt	X			
	S_a		X			
	Upwelling				X	
	Gradients		X			
	Deposition					

. DK (not fo

ortant due t

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Parameter from Checklist	Parameter specification	Data availability	applicability full	potential	not	
W						
	T_e					
Climate		Data bases available	X			E.g. NAOI
Biotic interactions	Parasites	No time series.		X LOD		
	Zooplankton grazing	Few data in NL and for northern WS		X LOD		Grazing can be considered one of the factors controlling controlling phytoplankton standing stocks. Grazing can also be influenced by heavy metal pollution. **Research Item**
	Benthic suspension feeding	*Mytilus*-beds in LowSax 1940-p., WS-wide bypass data from fisheries, *Cerastoderma*-biomass in NL, intertidal data, subtidal estimates in northern WS, inter- and subtidal data in DK (5 yrs duration)	X			**Research Item** Often subtidal distributions of mussel beds unknown, the same for culture lots.
	Benthic grazing	Few data in Northern WS	X			**Research Item**
DIRECT EFFECTS						
P_h Biomass	a	NI, D, DK	X			Biomass itself is not a eutrophication effect, but has to be considered in relation to grazing and light climate.
	Biomass, org. C.	DK	X			
	Cell numbers	Marsdiep, DK, LowSax	X			Consistent bloom definition required, intensity by means of peak values.
P_h B_l	**and intensity**		X			*Phaeocystis* a distinction must be made between single cell blooms and colonial blooms, the latter ending up as detritus.
		Aerial surveys		X LOD		Where possible, areal surveys should be included in the description of phytoplankton blooms.
P_h Primary Production		DK 1990-97 Northern WS (Sylt-Rømø) 1992-p.	X			Is a better parameter than phytoplankton biomass, since biomass depends on at least two processes : import from coastal zone and *in situ* produced cells.
Phytoplankton Shifts in species composition		Marsdiep 1974-p. Sylt-Rømø longer series DK 2 station 1987(1989-)-p. Northern WS. ALGFES 1990-p. LowSax 1990-p. NL 4 Stations in the WS 1987-p.	X			Sylt-samples are net-samples. Shifs regarded as relevant both for species and functional groups. At present the analysis of species shifts is not completed. There is a Dutch analysis in coming (pers. comm. Cadée).

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Parameter from Checklist	Parameter specification	Data availability	P applicability full	potential	not	
Macrophytes	**Coverage**	NL no suff. time series Sylt-Rømø, Northern WS- 2 stations and aerial su LowSax 1988-p. DK 1992-p.	Macro-algae	X Eelgrass		Eutrophication may stimulate growth of epiphytic algae on eelgrass, leading to deterioration of eelgrass stands. A toxic relationship to ammonia is known, probably also to nitrate. should be treated as a descriptive eutrophication parameter, since no comprehensive data sources exist.
	Shifts in species composition				X	Different *Enteromorpha* species hardly distinguishable.
	Reduced depth di				X	Intertidally not relevant, subtidal no sufficient data - probably more
Microphytobenthos Biomass	Chl a	No ongoing time series available		X LOD		Some historical data allow comparison. Due to lack of time series only descriptive analysis possible.
Microphytobenthos Primary production		No ongoing time series available		X LOD		Some historical data sets allow comparison. Due to lack of time series only descriptive analysis possible.
INDIRECT EFFECTS						
Organic carbon	DOC and POC	Marsdiep		X LOD		W
	Pn	ømø selected years		X LOD		W
	Foam and slime	No time series			X	
	OC in sediments	No time series			X	
O		NL: 7 station and 3 surveys LowSax : short time series in the 80s				Measurement of daily cycle important : The diurnal cycle has changed under eutrophic conditions. Massive oversaturation at daytime and severe undersaturation during night. Maxima stand for elevated production rates, whereas minima indicate consumption and remineralisation.
	Consumption rate	NL: short time series in the Ems-estuary		X		
	Depth of sediment oxic layer	LowSax: 1970s -p. DK: 1980-p. NL: 1989-p.	X			Visual measurements, including Black Spots. Regarded as highly valuable approach, since the benthos integrates effects over longer periods of time.
		-p.			X	W ater column meas

Parameter from Checklist	Parameter specification	Data availability	P applicability full	potential	not	[illegible]
Zoobenthos and fish	Mortality				X	Not regarded relevant. However, probably links to the Botulismus-phenomenon exist.
Macrozoobenthos	A	ømø, Marsdiep, Balgzand, Norderney, Leybucht, Hobucht, Weser	X			Analysis presented in QSR 1999. It was stated that especially 'opportunistic' species take advantage of eutrophic conditions. In the Dollart a shift from short-lived opportunistic species to long-lived species was observed in response to the sanitation of organic waste input. Probably effects on a rather local scale visible.
	Species composition	See above	X			
	B					
Ecosystem structure	E.g. carbon cycling, biogenic structures (eelgrass stands)			X		Applicable in case studies : Westerschelde, green algae, Black Spots, Dollard pollution.It was stated, that the microbial food web becomes abundant under eutrophied conditions. A narrative approach should be applied to this point. General: lack of sufficient knowledge.
OTHER POSSIBLE EFFECTS						
Algal toxins		No time series		X		Lack of knowledge.

Appendix 2: Comparative Analysis

Comparative Analysis of Classified *Phaeocystis* sp.-incidents

Objective

In this analysis two time series of *Phaeocystis* data provided by workshop participants (Belgian Monitoring Station 330 (=BMS330) and Norderney Monitoring Station (=NMS)) were analyzed in order to define ranges for Problem, Non-Problem and Potential-Problem nutrient conditions for this potential eutrophication effect. The data sets can be regarded as supplements to the Marsdiep data set for which an analysis was presented during the workshop.

Data preparation and data sets

The data sets differed with regard to temporal coverage of the different variables. Depending on availability, for N-compounds in the BMS330 only nitrate values were used, whereas DIN was used for the NMS data set. Missing values were interpolated. In cases where ratio-calculation - either N:P or N:Si - was numerically impossible (denominator values =0) ratio-values were set at 100. For the Norderney data series, data from three monitoring stations were merged and averaged. Both series were run on a weekly schedule.

Both data sets contain very different categories of *Phaeocystis* sp. Whereas the Belgian data set presented cell numbers, in the Norderney data set colony numbers were counted.

Data analysis

Previous investigations have shown, that pre-bloom conditions (pers. comm. V. Rousseau), as well as, inter-annual variability have to be considered. Therefore two different analyses were carried out : the intra-annual analysis focussing on the relevance of pre-bloom conditions and the inter-annual analysis focussing on average conditions at different bloom intensities.

Classification

For the separation of bloom and non-bloom conditions a new variable was introduced, bearing a code value for *Phaeocystis* sp. abundance. For the Belgian data set code values were set '1' for densities > 10^6 cells l^{-1} and '0' otherwise. For the Norderney data set values were set '1' for colony abundance > 1300 (mean of the presented data set) and '0' otherwise. The relationship to pre-bloom conditions was obtained by lagging nutrient variables. For the BMS330 data set each year was separately lagged. Lags of up to 7 weeks length were applied for the NMS data set. Due to the smaller temporal extent of the BMS330 data set (only spring season covered) lags of a maximum of 3 weeks were applied.

For the analysis of inter-annual variability years were classified according to the frequency of '1'-incidents per year. Since the number of measurements in the Belgian data set varied greatly between years, both the frequency of '1'-incidents and the proportional frequency of '1'-incidents was used to classify different years. By this the classification refers to bloom duration.

Results

Both data sets (Tables 2 and 3) depict a comparable figure in the intra-annual analysis of pre-bloom conditions (Figure 1), whereas great differences can be seen in the analysis of inter-annual variability (Figure 2).

Intra-annual analysis of pre-bloom conditions

Whereas the nutrient concentration values for the BMS330 data set are lower than for the NMS data set, the values for the ratios (N/P resp. NO_3/P and N/Si resp. NO_3/Si) are in the same order of magnitude. Both data series indicate excess nitrogen availability in the pre-bloom phase (under extrapolation for BMS330 data), which is depleted in advance of the bloom. Both series indicate low phosphate values in the pre-bloom phase. Accordingly N to P ratios are high in the pre-bloom phase, but decrease as the bloom advances due to depletion of N-compounds and then reach values obtained under non-blooming conditions. This is

Table 1 : Features of the data sets used in the comparative analysis of Phaeocystis. Originators : (1) V. Rousseau, Ecologie des Systèmes Aquatiques, Belgium; (2) M. Hanslik, Forschungsstelle Küste, Germany

Data series	Duration	Average distance between two measurements (days)	Comments
(1) Belgian Monitoring Station 330 (BMS330)	1988 - 1997	8	Only spring season covered
(2) Norderney Coastal Monitoring Stations 0, 1, 2 (NMS)	1985 - 1996	7.9	Complete annual cycle

not the case for the N to Si ratio. These are considerably higher in the pre-bloom phase and do not reach the non-bloom level as the bloom advances. However, the difference is rather small for the NMS data set.

Inter-annual analysis of bloom duration

Despite the comparable pre-bloom conditions in both data series the analysis of inter-annual variability shows no concordant pattern for both series. In some cases N to P ratio situations are contrasting in both data sets. This is shown in Figure 2 for complete data series and in Table 4 for the months covered in both series representing the spring season. In both series no relationship is seen to excess N-compounds. Furthermore, the clear relationship of N to P and N to Si found in the intra-annual analysis is not reflected at the inter-annual level. The negative relation between phosphate and silicate and year class values, i.e. bloom duration, in the NMS data set is in concordance with the intra-annual analysis.

Due to the high variability and low indicative value of the data, only for phosphate ranges can be - tentatively - defined in the NMS data set. It shows (Table 3) that phosphate levels under 'low'-bloom conditions (class value = 1) are higher than under 'high'-bloom conditions (class values 2 and 3). The relevant values have been framed in Table 4.

N-P reduction scenario

Finally in a multiple regression analysis on inter-annual level for the NMS data set phosphate and DIN were found to be significant factors to determine year class values of bloom duration. However, for both data sets, less than 10 % of data set variability is expressed by this relationship. It was indicated that N-compounds higher than 50 µM for the NMS data set and higher 30 µM for the BMS330 data set coincided with increased bloom duration. However, these values are higher than the average and median values already recorded in the data sets (Table 4).

Conclusion

From a comparison of intra- and inter-annual dynamics of data sets from two different locations it is concluded that intra-annual conditions seem to be more important for the formation of *Phaeocystis*-blooms, than pre-bloom conditions such as excess nitrogen and high N:P and N:Si ratios in the pre-bloom phase. Thus, for these locations *Phaeocystis* has only limited value to indicate the eutrophication status on an annual scale. The different inter-annual dynamics for the NMS and BMS330 data sets indicate that regional analyses of this phenomenon are required.

Critical points

Critical points of this analysis are :

(1) Different duration of presented time series, starting in 1985 and 1988.

(2) Both series do not cover the time period before 1980. Therefore the change in dynamics found in the Marsdiep data set from the 70's to the 80's could not be checked for the locations covered in this analysis.

(3) Different definitions of bloom intensity according to different ways of counting of *Phaeocystis*-abundance.

(4) Due to limited time no full time series analysis was applied, i.e. no analysis of residuals, adjustment to seasonal values etc.

Table 2
Classification of the BMS330 data set

Year	'0'-incidents	'1'-incidents	Total counts per year	Classification acc. to frequency of incidents	proportion of '1'-incidents	Classification acc. to prop. frequency
1988	12	5	17	2	0.29	2
1989	3	7	10	3	0.70	3
1990	11	3	14	1	0.21	2
1991	4	4	8	2	0.50	3
1992	8	4	12	2	0.33	2
1993	12	8	20	3	0.40	3
1994	17	3	20	1	0.15	1
1995	9	6	15	3	0.40	3
1996	14	2	16	1	0.13	1
1997	12	7	19	3	0.37	2

Table 3:
Classification of the NMS data set

Year	'0'-incidents	'1'-incidents	Classification acc. to frequency of incidents	Total counts per year
1985	28	0	1	28
1986	32	5	2	37
1987	35	4	2	39
1988	42	3	2	45
1989	35	5	2	40
1990	43	10	3	53
1991	30	11	3	41
1992	43	2	1	45
1993	42	2	1	44
1994	63	8	3	71
1995	49	5	2	54
1996	47	2	1	49
1997	51	1	1	52

Table 4 :
Nutrient values and ratios for different categories of Phaeocystis bloom duration considering the months 1 to 6 in both data series. Nutrient values in µM. CI=Confidence interval. Class refers to year class values of bloom duration (see Tables 2 and 3)

	Norderney				Belgian Coastal Waters St. 330		
Class	1	2	3	Class	1	2	3
	phosphate			phosphate			
Median	1.1	0.8	0.8	Median	0.5	1.0	0.5
Mean	1.2	0.9	0.8	Mean	0.6	1.1	0.7
95% CI Upper	1.3	1.1	0.9	95% CI Upper	0.7	1.3	0.8
95% CI Lower	1.0	0.8	0.8	95% CI Lower	0.4	0.9	0.5
	silicate				silicate		
Median	9.6	11.5	7.6	Median	3.2	1.2	3.4
Mean	18.5	19.2	13.3	Mean	8.3	4.3	6.3
95% CI Upper	22.3	22.7	15.9	95% CI Upper	11.1	6.0	8.2
95% CI Lower	14.7	15.8	10.7	95% CI Lower	5.5	2.6	4.4
	DIN				NO3		
Median	37.4	41.0	30.8	Median	12.7	21.8	10.8
Mean	43.9	43.9	41.2	Mean	15.0	23.5	14.6
95% CI Upper	52.7	50.3	47.9	95% CI Upper	18.2	29.5	18.1
95% CI Lower	35.3	37.7	34.3	95% CI Lower	11.7	17.4	11.2
	N:P				NO3:P		
Median	39.6	44.8	45.5	Median	25.9	19.7	21.9
Mean	59.6	53.1	81.4	Mean	49.5	25.0	32.3
95% CI Upper	74.9	61.6	110.9	95% CI Upper	67.5	32.0	39.8
95% CI Lower	44.3	44.7	51.8	95% CI Lower	31.5	18.0	24.7
	N:Si				NO3:Si		
Median	1.7	2.5	2.8	Median	2.2	7.9	2.1
Mean	9.1	5.6	8.1	Mean	7.0	21.2	7.1
95% CI Upper	16.3	8.1	10.9	95% CI Upper	10.9	31.0	11.5
95% CI Lower	1.9	3.0	5.3	95% CI Lower	3.2	11.4	2.7

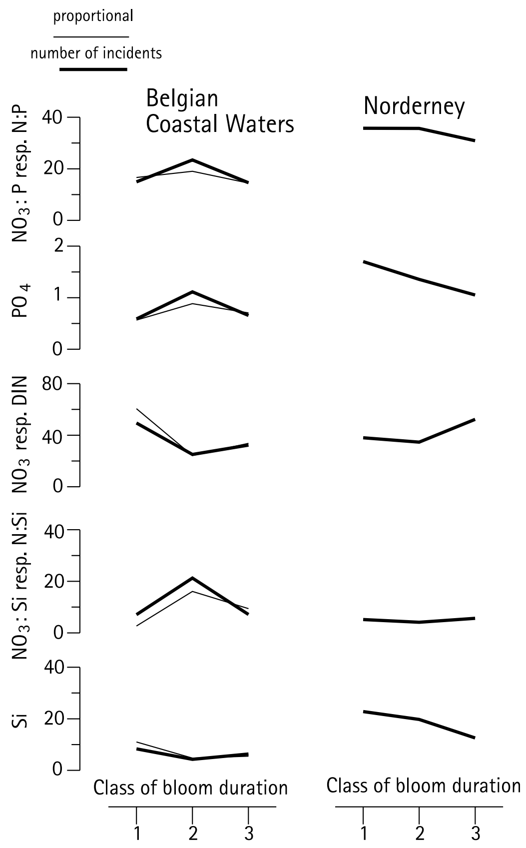

Figure 1 :
Intra-annual analysis of pre-bloom conditions. Bold lines indicate non-blooming conditions, thin lines and circle symbols indicate blooming conditions. Time lag refers to weeks before bloom occurred (pre-bloom phase) under both conditions. Only average values are indicated without standard deviations.

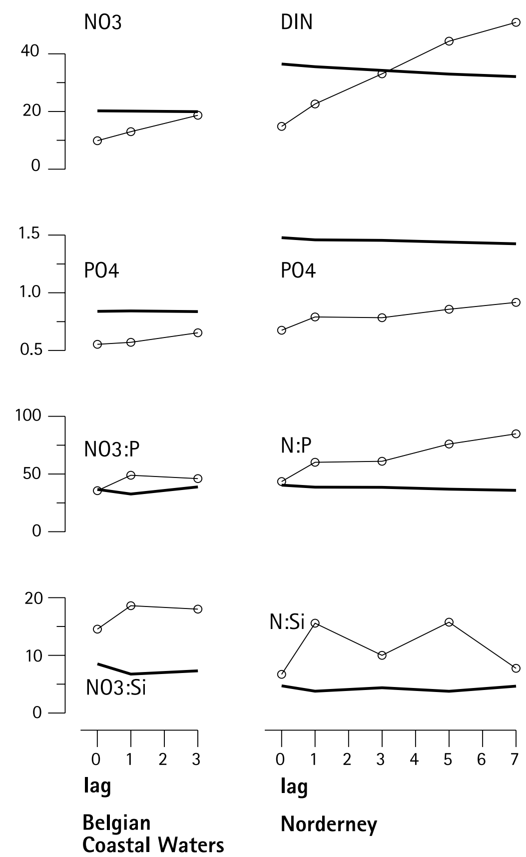

Figure 2:
Analysis of inter-annual variability according to year-classes of bloom duration. Complete data series analyzed. For the BMS330 data series values according to frequency of incidents (bold lines) as well as according to proportional frequencies (thin lines) are shown. Only average values are indicated without standard deviations.

Appendix 3: Events

Events Probably Related to Eutrophication in the Wadden Sea

Events which may be related to eutrophication in the Wadden Sea (source: Reise, pers. com.)

	Ecosystem structure	Phenomenon
1.	*Zostera marina*	Disease and irreversible decline of subtidal stands in 1933-34 at Sylt.
2.	*Zostera noltii*	Königshafen/Sylt: *Z. noltii* dominated in discrete patches in the 1970s. Following the severe winter 1978/79, this species became more wide spread but scattered, and *Z. marina* gradually achieved dominance throughout the 1980s. Total coverage of seagrass was higher than in the decade before. This reversed gradually since 1988 and in the 1990s *Z. noltii* dominated again but also declined and attained an all-time low in 1999. There is evidence, that this pattern was similar throughout the entire northern Wadden Sea, although the decline in the 1990s may be only local.
3.	Mussel beds	Königshafen/Sylt: Few mussel beds until the winter 1962/63. Ice scouring in 1969,1979 and 1996 caused a decline but beds recovered and maintain a larger coverage than earlier this century.
4.	Macrophytes	Königshafen/Sylt: Green algae were rare but occurred in a few lagoons and higher tidal zones until 1979. Since then explosive growth of *Enteromorpha* in June/July has led to the formation of thick algal mats. The extent declined again since 1992 but green algal mats are still more extensive than prior 1979.
5.	Macrophytes	German and Danish Wadden Sea: First observations of large-scale *Enteromorpha* mats in summer 1989, peak development in 1990-91, thereafter gradual decline but a very recent increase again in summer 1999.

Appendix 4: Background Concentrations

Background Concentrations in Dutch Coastal Waters

Background concentrations for the Dutch Wadden Sea (W. van Raaphorst, V.N. de Jonge, D. Dijkhuizen, B. Frederiks, 2000. Natural background concentrations of phosphorus and nitrogen in the Dutch Wadden Sea. RIKZ 2000-013).

Table 1 : Natural background concentrations of TP and TN estimated for the total of the Marsdiep and Vlie (M+V) basins. The estimates are based on conservative mixing of water from the North Sea (NS) boundary at the tidal inlets with water from IJsselmeer. Values at the two tidal inlets of the basins are taken as representative for the NS boundary.

	Winter	Spring	Summer	Autumn
NS boundary salinity	28 - 32	28 - 32	29 - 32	30 - 33
NS boundary TP (µM)	0.9 ± 0.3	0.7 ± 0.3	0.7 ± 0.3	0.8 ± 0.4
NS boundary TN (µM)	15 ± 5	14 ± 5	9 ± 3	8 ± 4
M+V basins salinity	24 - 27	26 - 29	27 - 30	27 - 30
% IJsselmeer water	16	9	6	10
M+V basins TP (µM)	0.9 ± 0.3	0.7 ± 0.3	0.7 ± 0.3	0.8 ± 0.4
M+V basins TN (µM)	17 ± 7	16 ± 6	10 ± 4	9 ± 5
M+V basins TN:TP	~ 19	~ 23	~ 14	~ 11
M+V basins DIP (µM)	~ 0.5	~ 0.1	~ 0.2	~ 0.4
M+V basins DIN (µM)	~ 7	~ 4	~ 3	~ 3
M+V basins DIN:DIP	~ 14	~ 40	~ 15	~ 8

Table 2 : Annual mean background TP and TN concentrations in Lauwersmeer, the river Ems and the Westerwoldsche Aa + Eemskanal and the corresponding discharges into the Wadden Sea. For the water discharge of the Westerwoldsche Aa and Eemskanal no estimate for the standard deviation of the mean was available.

		Lauwersmeer	River Ems	Westerwoldsche Aa + Eemskanal
water discharge	$m^3 s^{-1}$	41 ± 8	100 ± 50	18
TP concentration	µM	1.4 ± 0.6	1.8 ± 0.8	1.8 ± 0.8
TN concentration	µM	41 ± 18	45 ± 25	45 ± 25
TP discharge	$mol s^{-1}$	0.06 ± 0.03	0.2 ± 0.1	0.04 ± 0.02
TN discharge	$mol s^{-1}$	1.7 ± 0.8	4.5 ± 2.3	0.08 ± 0.05

Table 3: Natural background concentrations of phosphate and nitrate in the English Channel, the river Rhine and the Dutch coastal area during winter.

Area	Salinity	Phosphate	Nitrate	N:P
English Channel	35.3	0.45 ± 0.05	5.5 ± 0.5	12
River Rhine	app. 0	1.8 ± 0.8	45 ± 25	25
Dutch coast	32 ± 1	0.57 ± 0.13	9.1 ± 3.1	16

Concentrations in the English Channel and Dutch coastal area were obtained from Laane et al. (1992). Concentrations for the Rhine are the annual mean values. Salinities in the English Channel and the Dutch coastal waters are from Laane et al. (1992). The concentrations for the Dutch coast were calculated by theoretical mixing Channel water and Rhine water according to the salinities in the areas under consideration. For references see Van Raaphorst et al., (2000).

Table 4: Natural background TP and TN concentrations estimated for the coastal North Sea. Four seasons considered. Winter: Dec-Jan-Feb; Spring: Mar-Apr-May; Summer: Jun-Jul-Aug; Autumn: Sep-Oct-Nov. The concentrations were calculated by combining background values estimated for the winter months with the annual cycles shown in the text (not shown here). Ratios are relative to the annual mean.

	Winter	Spring	Summer	Autumn
TP ratio	1.1 ± 0.3	0.9 ± 0.2	0.9 ± 0.2	1.1 ± 0.3
TP conc. (µM)	0.8 ±0.3	0.6 ± 0.3	0.6 ± 0.3	0.8 ± 0.3
TN ratio	1.3 ± 0.3	1.2 ± 0.2	0.7 ± 0.2	0.8 ± 0.3
TN conc. (µM)	13 ± 5	12 ± 5	7 ± 3	8 ± 4
N:P	16	20	12	10

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Annex 3: Eutrophication Effects

A. Intertidal macrofauna

Table 1: Possible eutrophication effects in benthic macrofauna. WDWS: Western Dutch Wadden Sea; EDWS: Eastern Dutch Wadden Sea; EFWS: East Frisian Wadden Sea; NFWS: North Frisian Wadden Sea; DWS: Danish Wadden Sea.

Area	Changes evident?	Appli-cable?	Observations/reasons	References
1. Species Composition				
a) Wadden Sea as a whole	Only locally	No	Species composition varies locally due to sediment characteristics, exposure.	Beukema, 1988
			Nutrient enrichment differs locally.	de Jonge and Essink, 1991 van Beusekom, 1999 Essink et al., 1998a
			"Severity" of winter is large scale synchronizing factor, overriding signs of eutrophication, but: local departures may indicate disturbing factors, e.g. eutrophication.	Beukema and Essink, 1986 Beukema et al., 1996
			Climate (winter conditions) have a differential direct or indirect impact on the species (mortality, reproductive success, predation etc).	Beukema et al., 1978 Beukema, 1993 Beukema, 1979 Beukema and Cadée, 1996 Beukema et al., 1998 Beukema, 1990 Beukema, 1991a Beukema, 1992a Beukema, 1992b Dörjes et al., 1986
			Species immigration and emigration point to highly dynamic system: *Ensis americanus* (1978) *Marenzelleria* spp.(1983) *Crassostrea gigas* (1990s)	Beukema and Dekker, 1995 Armonies, 1998 Essink and Kleef, 1993 Essink et al., 1998b Reise, 1998
			Sampling is problematic because of migrations of more mobile organisms (*Macoma*, *Cerastoderma*, *Ensis*, *Corophium* etc.).	Armonies, 1998
			Impact of storms/wave action is locally different and species dependant. Harvest of target and non-target species by fisheries (*Crangon*, *Mytilus*, *Cerastoderma*, by-catch) influences species composition.	Nehls and Thiel, 1993 Dörjes et al., 1986 Piersma and Koolhaas, 1997 cited in QSR1998, Reise and Schubert, 1987
			Parasites may be responsible for large oscillations in species abundances, mass mortality and thus species composition.	Michaelis, 1981 Lauckner, 1990 Lauckner, 1994

Table 1 (continued): Possible eutrophication effects in benthic macrofauna. WDWS: Western Dutch Wadden Sea; EDWS: Eastern Dutch Wadden Sea; EFWS: East Frisian Wadden Sea; NFWS: North Frisian Wadden Sea; DWS: Danish Wadden Sea.

A. Intertidal macrofauna (continued)

Area	Changes evident?	Applicable?	Observations/reasons	References
1. Species Composition				
b) WDWS	Yes	Probably yes	Long-term (1979-90) increase in deposit feeders, decrease in carnivores, no trend in suspension feeders; small sized species increased more than large sized: particularly *Heteromastus filiformis*, *Scoloplos armiger, Nereis diversicolor*	Beukema, 1991b
c) EDWS	No	?	No changes observed	de Jonge and Essink, 1991
d) EFWS	No	?	No change in species composition observed (1973-1985)	Dörjes et al., 1986 Rhode, 1985
e) NFWS	Yes	No	increase of polychaetes, decrease of Porifera, Coelenterata, Bivalvia (mostly subtidal). Reason most probably, besides food enrichment, effect of erosion and fisheries, as well parasite infestations.	Reise, 1982 Reise et al., 1989 Lauckner, 1990
f) DWS	No	?	Species composition on intertidal mudflats did not change 1930/40s-1980s.	Jensen, 1992
2. Biomass				
a) Wadden Sea as a whole	Only locally	No	Growth rates of bivalves dependant on exposure time, sediment type (site), and predators rather than available food.	Wanink and Zwarts, 1993
			Local windfields can determine the magnitude of coastal benthic secondary production; coastal benthic energy flow is physically regulated.	Emerson, 1989
			Long-lasting trend of polychaete biomass increase cannot be related to eutrophication.	Essink et al., 1998a
			Strong predatory effect on macrobenthos biomass: birds take up to 25 % of the mean annual biomass of macrobenthos - predatory impact on macrofauna depends on climate-related population development (and fisheries).	Scheiffarth and Nehls, 1997 Beukema et al., 1993 Beukema, 1993 Piersma et al., 1993

Table 1 (continued): Possible eutrophication effects in benthic macrofauna. WDWS: Western Dutch Wadden Sea; EDWS: Eastern Dutch Wadden Sea; EFWS: East Frisian Wadden Sea; NFWS: North Frisian Wadden Sea; DWS: Danish Wadden Sea.

A. Intertidal macrofauna (continued)

Area	Changes evident?	Appli cable?	Observations/reasons	References
2. Biomass (continued)				
b) WDWS	Yes	Probably yes	Biomass increase observed after 1980 related to improved food supply due to nutrient enrichment with 2 y time lag. But: food limitation only locally (favourable environmental conditions) effective.	Beukema and Cadée, 1997
c) EDWS	No	?	No significant change in biomass observed - area considered not to be enriched with nutrients.	de Jonge et al., 1993 Essink et al., 1998a
d) EFWS	No	?	No clear temporal trend for total biomass, but increase of polychaete and crustacean biomass; biomass of major species except *Mytilus* remained stable over the past 30 ys.	Essink et al., 1998a Anon. 1996, cited after Delafontaine and Flemming,1997
e) NFWS	?	?	Data insufficient	
f) DWS	?	?	Only limited data on cockles available	Jensen, 1992
3. Abundance				
a) Wadden Sea as a whole	Only locally	No	Densities of macrofauna very variable, synchronized over vast areas, dependant on site, on climate-related recruitment success and impact of predation.	Beukema et al., 1998 Beukema and Cadée, 1997 Beukema et al., 1996
b) WDWS	Yes	Yes?	Small, mostly deposit-feeding polychaetes more than doubled in abundance 1970-1990.	Beukema, 1989 Beukema, 1991b
c) EDWS	?	?	No data available.	
d) EFWS	No	Yes?	No significant trends observed.	Dörjes et al., 1986
e) NFWS	Yes	Probably yes	Polychaetes more abundant in the 1980s than in the 1930s (incl. *Scoloplos*, *Nereis*, *Scolelepis*), probably linked to organic enrichment.	Reise, 1982 Reise et al., 1989
f) DWS	Yes	Probably yes	Deposit feeding polychaetes (*Scoloplos*, Capitellidae) show considerably higher abundances in 1980s as compared to 1930s. Maybe related to food availability.	Jensen, 1992

Table 1 (continued): Possible eutrophication effects in benthic macrofauna. WDWS: Western Dutch Wadden Sea; EDWS: Eastern Dutch Wadden Sea; EFWS: East Frisian Wadden Sea; NFWS: North Frisian Wadden Sea; DWS: Danish Wadden Sea.

B. Subtidal macrofauna

Area	Changes evident?	Appli-cable	Observations/reasons	References
1. Species composition				
a) Wadden Sea as a whole	Locally yes	No	Instability of substrate leads to sporadic and/or highly fluctuating occurrence of species, trends hardly detectable.	Dörjes et al., 1986
			Variability in species numbers and abundances (winter types - summer fauna) is climate-related, eutrophication is only minor modifying factor.	Kröncke et al., 1998
			„Severe" winters cause great losses which can be traced for several years.	Dörjes et al., 1986 Rachor and Gerlach, 1978
			Species-dependant locally varying impact of wave action due to strong gales.	Dörjes et al., 1986 Madsen, 1984
			Added impact and differential sensitivity to suspended matter (dredging, extraction of sand and gravel) and pollution.	Michaelis and Reise, 1994 Dörjes, 1992
			Trawling for shrimp and flatfish kills sessile and slow-moving epifauna (bycatch), thus shifts species composition.	Buhs and Reise, 1997
b) WDWS	Probably yes	No	Insufficient database; disappearance of species not related to eutrophication.	Dekker, 1989
c) EDWS	?	?	No data available.	
d) EFWS	Yes	No	Long-term changes (1974-1987) related to impact of dredging/sedimentation. Species number dependant on climatic factors.	Dörjes, 1992 Kröncke et al., 1998
e) NFWS	Yes	No	Long-term changes related to impact of dredging and trawling.	Riesen and Reise, 1982 Reise and Schubert, 1987 Buhs and Reise, 1997
f) DWS	?	?	No data available.	
2. Abundance				
a) Wadden Sea as a whole	?	No	Insufficient data base; constrictions as shown above.	
b) WDWS	?	No	Insufficient data base.	Dekker, 1989
c) EDWS	?	No	No data available.	
d) EFWS	No	No	Variability in abundance related to climate, no temporal trend observed.	Kröncke et al., 1998
e) NFWS	Yes	No	Decline of sessile and slow-moving animals, fast-moving crustaceans persisted, increase of infaunal abundance related to combination of fisheries, dredging and eutrophication.	Buhs and Reise, 1997 Riesen and Reise, 1982 Reise and Schubert, 1987 Reise et al., 1989
f) DWS	?	No	No data available.	
3. Biomass				
a) Wadden Sea as a whole	?	No	Insufficient data base; constrictions as shown above.	
b) WDWS	?	No	Insufficient data base.	Dekker, 1989
c) EDWS	?	No	No data available.	
d) EFWS	Yes	No	Increase in total biomass since 1989 due to mild winters (possibly enhanced by eutrophication-related food increase).	Kröncke et al., 1998
e) NFWS	?	No	Insufficient database.	
f) DWS	?	No	No data available.	

Table 1 (continued): Possible eutrophication effects in benthic macrofauna. WDWS: Western Dutch Wadden Sea; EDWS: Eastern Dutch Wadden Sea; EFWS: East Frisian Wadden Sea; NFWS: North Frisian Wadden Sea; DWS: Danish Wadden Sea.

C. Other parameters

Taxon. group	Changes evident?	Appli-cable?	Observations/reasons	References
1. Indicator species				
a) *Macoma balthica*				
	Yes	Pro	Stockforming species which should profit from increased food supply.	Beukema and Cadée, 1991
			Reduction in organic enrichment of Dollard led to decrease in *Macoma* density.	Rijsdijk, 1995
			Density of *Macoma* is related to food availability/sediment load; *Macoma* growth rates are correlated to pelagic diatom abundance.	Beukema and Cadée, 1991
			Biomass increase in western Dutch Wadden Sea reflects extent of freshwater/nutrient input.	Beukema et al., 1996
			Fluctuations in abundance follow same pattern all over the Wadden Sea, synchronized by climatic factors; local deviations from overall pattern may reflect eutrophication	Beukema and Essink, 1986 Beukema et al., 1996
		Contra	Staple food (diatoms) is usually not enhanced by eutrophication.	Beukema and Cadée, 1991
			Growth rates: not only food, but also other factors such as exposure time, wave action etc.	Beukema and Cadée, 1997
			Highly mobile; seasonal migrations.	Armonies, 1998 Beukema, 1973
			Highly affected by Trematode infestations which may lead to mass mortality.	Lauckner, 1990 Lauckner, 1994
b) Hydrobia ulva				
	Yes	No	Highly affected by Trematode infestations which may lead to mass mortality.	Lauckner, 1990 Lauckner, 1994
b) *Corophium volutator*				
	Yes	Pro	Recommended as indicator of organic pollution. Sensitive to low oxygen contents.	Essink et al., 1989 Esselink et al., 1989
			Should profit of increased microphytobenthos production because selective deposit feeder.	Newell, 1979
		Contra	Highly mobile. Topulation fluctuations for unknown reasons.	Esselink et al., 1989 Essink and Kleef, 1993
			Highly affected by Trematode infestations which may lead to mass mortality.	Lauckner, 1990 Lauckner, 1994
			Distribution indirectly dependant on climate.	Beukema and Flach, 1995
2. Condition index				
a) Bivalvia	Yes	Probably not	Appears to be related to food availability, but: strong seasonal variation, dependant also on other environmental factors and thus site-specific.	Madsen and Jensen, 1987
3. Production, P/B ratio, growth rate				
a) Bivalvia	Yes	Probably	Appears to be related to food availability, but: dependant also on food quality and on other environmental factors, and thus site-specific; for single species competition has to be considered.	Madsen and Jensen, 1987 Beukema and Cadée, 1991 Wanink and Zwarts, 1993 Meixner, 1992
b) Macro-benthos	?	No	Local windfields can determine the magnitude of coastal benthic secondary production; coastal benthic energy flow is physically regulated.	Emerson, 1989

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