Wadden Sea Specific Eutrophication Criteria

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WADDEN SEA ECOSYSTEM No. 14

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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.

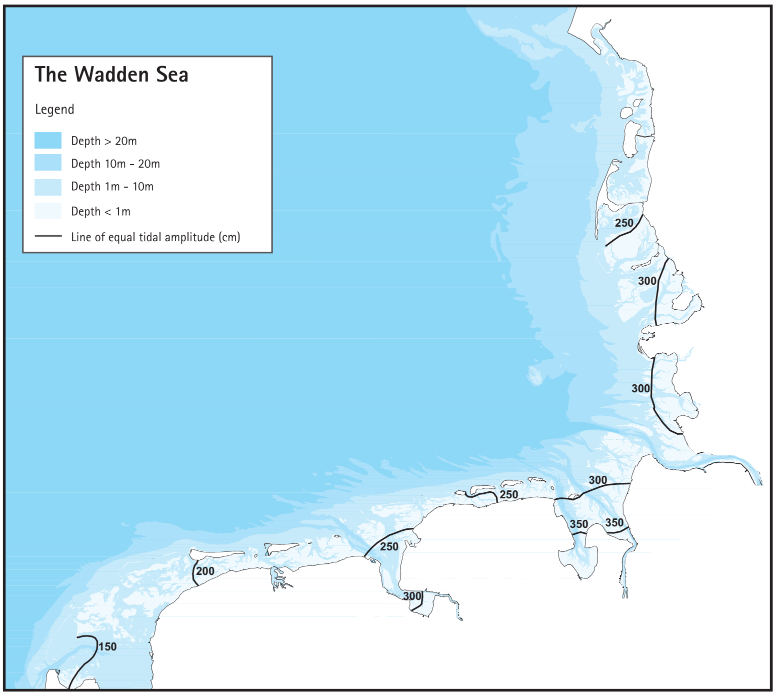

Figure 2.1:
Map of the Wadden Sea showing eu- and sublittoral areas and lines of equal tidal amplitude.

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.

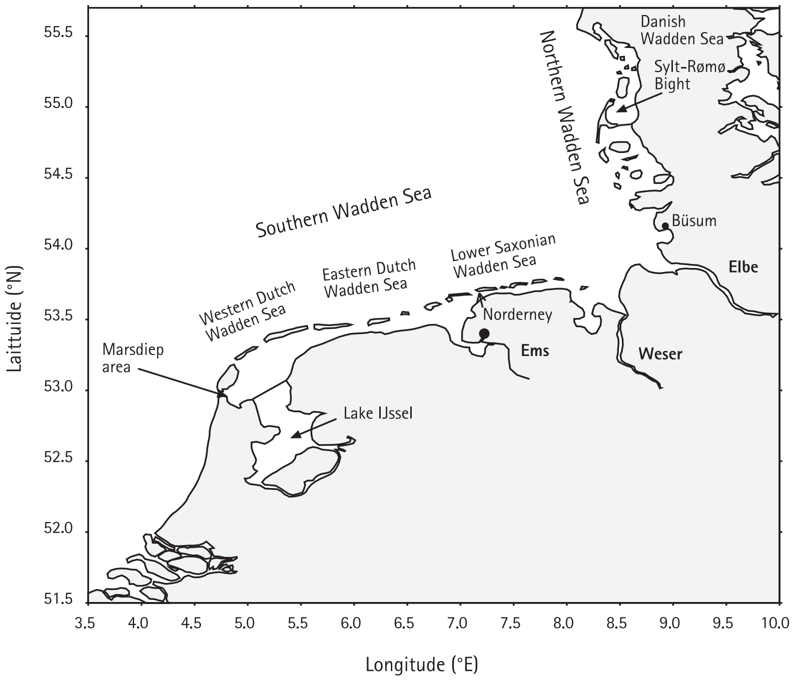

Figure 2.3: **Map of the Wadden Sea with the main subareas used in the data analysis.**

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 longterm 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.

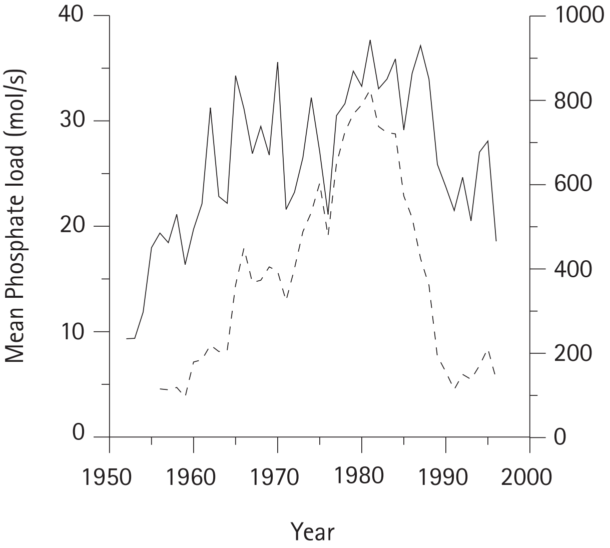

Figure 3.1: Mean annual load of PO_4 (dashed line) and Dissolved Inorganic Nitrogen (solid line) at Lobith.

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).

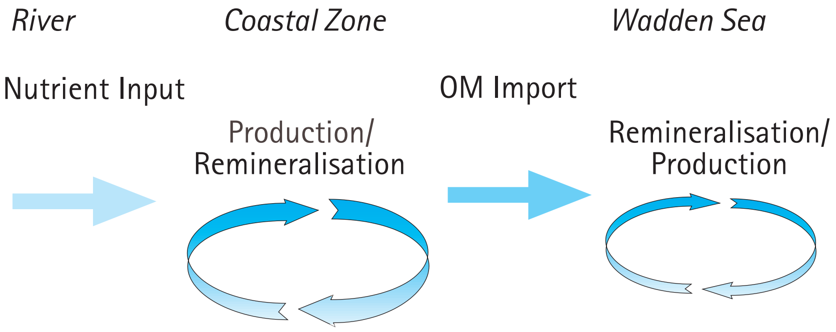

Figure 3.2: Conceptual model linking nutrient input via rivers with the nutrient seasonal cycle within the Wadden Sea.

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.

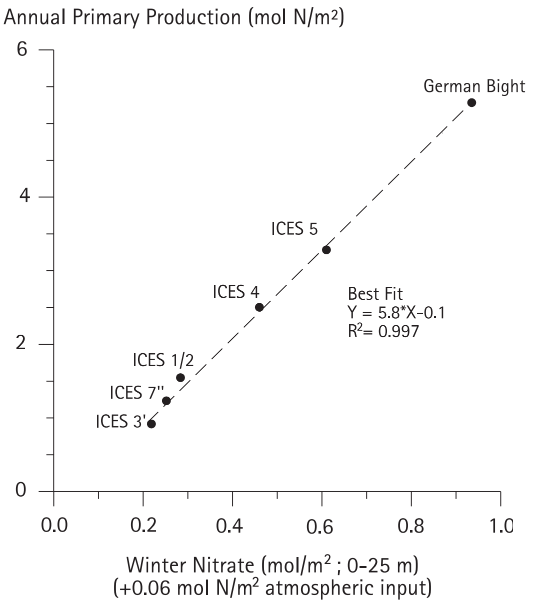

Figure 3.3: Relation between nitrate stock in winter and annual primary production. Data: Joint and Pomry (1993), van Beusekom and Diel-Christiansen (1994), German Bight: van Beusekom et al. (1999) and Rick et al. (1998).

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.

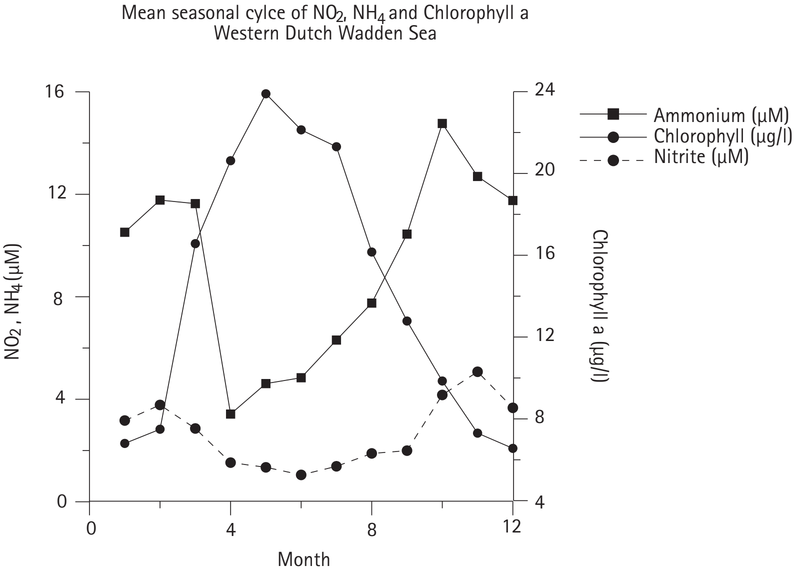

Figure 3.4: Mean seasonal cycle of ammonium, nitrite and chlorophyll a in the western Dutch Wadden Sea.