Natural and human impacts on the eutrophication status of the western Wadden Sea

A literature survey

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1. Introduction

This study of the past changes is motivated by the project seaward extension of Rotterdam harbors, the so-called Maasvlakte II, and by the need to anticipate on eventual impacts on the Wadden Sea.
This report aims to identify the origins of the past changes in the eutrophication status of the Wadden Sea. Special attention is given to changes in light regime, nutrient elimination and retention, which may have resulted from human interventions along the Dutch coast. Starting point for the assessment is that model calculations expect that 10% less fresh water and 15% less suspended matter will enter the western Wadden Sea as a result of the Maasvlakte II extension.

The analysis of the past is based on long-term records, which have been collected in a systematic and in a consistent way by Rijkswaterstaat and the Royal NIOZ. Additional data and information are gained from an extensive literature research. No additional calculations have been made.

Most impacts of the Maasvlakte are expected in the direct vicinity or northward from the interventions, because of the northward direction of the residual current and the material fluxes along the Dutch coastal zone. This report deals with the natural and human impacts on the eutrophication status of the western Wadden Sea. Special focus is on the relation between the Dutch coastal zone and the western Wadden Sea.

No comparison is made between the observed impact on the eutrophication status of the western Wadden Sea and impacts and related causes in other estuaries. The reason is that the observed reactions of various aquatic ecosystems on changed nutrient concentrations were quite different from each other (Elliot and De Jonge, 2002).

The changes and possible causes in the turbidity (light climate) and suspended matter concentration in the Dutch coastal zone and the western Wadden Sea have been described by Dronkers (2005). He concluded that the long-term impact of the Maasvlakte II extension will be perceptible in the morphological evolution of the Wadden Sea. Also, that the impact of Maasvlakte extension on the suspended matter concentration will be much smaller than the fluctuations of a factor of two or more, which have occurred in the period 1970-1990.

2. Conclusions

Various useful long-term data sets on nutrient concentrations exist. Many authors have interpreted the impact of eutrophication on the Dutch coastal zone and western Wadden Sea. Various hypotheses regarding the response of the phytoplankton biomass and production have been investigated. The major conclusions are:

- The inter-annual variability in nutrient loading via the Dutch coastal zone of the western Wadden Sea is mainly affected by the variability in the concentration and water discharge of the river Rhine and by the Atlantic Ocean,
- There are no indications that former extensions in the Dutch coastal zone between 1950-2000 had a major impact on the nutrient load of the Dutch coastal zone and on the western Wadden Sea,
- The inter-decadal trend of nutrient loads via the IJsselmeer to the western Wadden Sea is strongly affected by land reclamation in the IJsselmeer and changes in hydrological retention before 1975,
- Nutrient loading is an important driving force for the ecology of the western Wadden Sea and there is a significant relation between the nutrient loads of the Rhine and the IJsselmeer and the nutrient loads of the western Wadden Sea.
- Models for the Maasvlakte II extension predict an overall reduction of 10% fresh water concentration through the Marsdiep; according to a strongly simplified model this results in a reduction of nutrient loads from the Dutch coastal zone into the western Wadden Sea of about 4% for phosphorus and 5% for nitrogen. No major impact on the ecology of the western Wadden Sea is expected.

3. Starting Point

Eutrophication

Weber (1907) was the first to use the adjective eutrophe to describe the nutrient conditions of a plant community. Later on the term was used to classify the nutrient status of lakes. Eutrophication of freshwater became widely recognized by the scientific community in the 1940s and 1950s (Harper, 1992; Gray, 1992). Political attention for coastal and marine eutrophication appeared in the 1980s.

Eutrophication has been referred to as the term that describes biological effects or changes induced at the ecosystem level by an increased load of nutrients from external sources. Brockmann et al. (1988). Postma (1985) and Nixon (1995) defined eutrophication as any increase in the rate of supply of nutrients or organic matter to an ecosystem. OSPAR (1997) described eutrophication as an undesirable disturbance to the marine ecosystem due to anthropogenic enrichment by nutrients. The Common Procedure for the identification of the eutrophication status of a marine area (OSPAR, 1997) was followed by various criteria to harmonize the assessment of the eutrophication status. These criteria were adopted for the Wadden Sea and used to assess the eutrophication status of the Wadden Sea (Essink et al., 2005).

Background concentration of nutrients

Background concentration is defined as the concentration that is present in the natural environment without human activities (Laane, 1992). Average background values for total nitrogen (TN) and phosphorus (TP), dissolved inorganic nitrogen and phosphorus for the North Sea boundary and for the basin of the western Wadden Sea were estimated by Van Raaphorst et al. (2000). To cope with the estuarine character of the western Wadden Sea, they defined background values for four different salinity classes during the four seasons (Table1).

Table 1. Comparison between the natural background and the present concentration of total phosphorus (TP) and total nitrogen (TN) (μM) for the Marsdiep and Vlie basins during winter months. Salinity ranges from 28 to 32 (extracted from Van Raaphorst et al., 2000)..

Variable	**concentrations**	
	background	**present (2003)**
TP	0.9 ± 0.3	1.97
TN	17 ± 7	70

It is well established that the present concentration of nitrogen and phosphorus compounds in the western Wadden Sea is above the natural background concentration ((De Jong et al., 1999; Raaphorst et al., 2000; Van Beusekom et al., 2001; Essink et al., 2005)

Driving forces

Various factors have an influence on the eutrophication status of the western Wadden Sea. Here the focus will be on the factors that affect the nutrient concentrations in the western Wadden Sea:

- Human activities in the catchment areas of the Rhine, Meuse and Scheldt,
- Land reclamation. More specific the reclamation in the

  - IJsselmeer; 1932 (AF), 1942 (NO), 1957 (OFL), 1967 (ZFL), 1975 (MM) (Fig.1)
  - Coastal zone; 1974 (MA-I) (Fig.1)
- Hydrological retention in the
  - IJsselmeer; 1971 (discharge IJssel >400 $m^3.s^{-1}$)
  - Coastal zone; 1967 (IJM), 1970 HA, 1972 (GR), 1985 (ES), 1985 (ZE) (Fig.1)
- Climate variability:
  - NAOI (1965, 1980)
  - Rainfall (1975, 1978, 1979, 1981, 1982, 1983; 1993, 1995 Q > 3000 $m^3.s^{-1}$ discharge Rhine/Meuse).
  - Temperature; 1970, 1979, 1982, 1985-1987 (Dec-Jan, $T<0^{o}C$)
- Exploitation
  - Fishing activities
  - Dredging activities
  - Mussel and cockle culture (1988-1990).

Marsdiep and western Wadden Sea

The Marsdiep is the inlet of the Dutch coastal zone into the western Wadden Sea. Samples of the Marsdiep for the long-term time series of nutrients, chlorophyll and primary production are taken around high tide from the NIOZ pier located in the south of the island Texel. The western Wadden Sea covers approximately 1500 km^2 and is a well mixed estuary. The annual averaged residence time of the freshwater in the Dutch coastal zone and the western Wadden Sea is about 70-80 and 12 days respectively (Zimmerman, 1976).

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Figure 1. Map of the Netherlands, Dutch coastal zone and Wadden Sea.
AF=Afsluitdijk; NO=Noordoostpolder; OFL=Oost Fleveland; ZFL=Zuid Flevoland MM= Markermeer; MA-I=Maasvlakte-I; IJM=harbor extension IJmuiden; GR=closing dam Grevelingen; HA=Haringvliet ES=half open dam Eastern Scheldt and ZE=Zeebrugge.

Possible relations between changes in nutrient loading, eutrophication symptoms and consequences have been identified by Elliot and De Jonge (2002) and De Jonge et al. (2002) (Fig. 2).

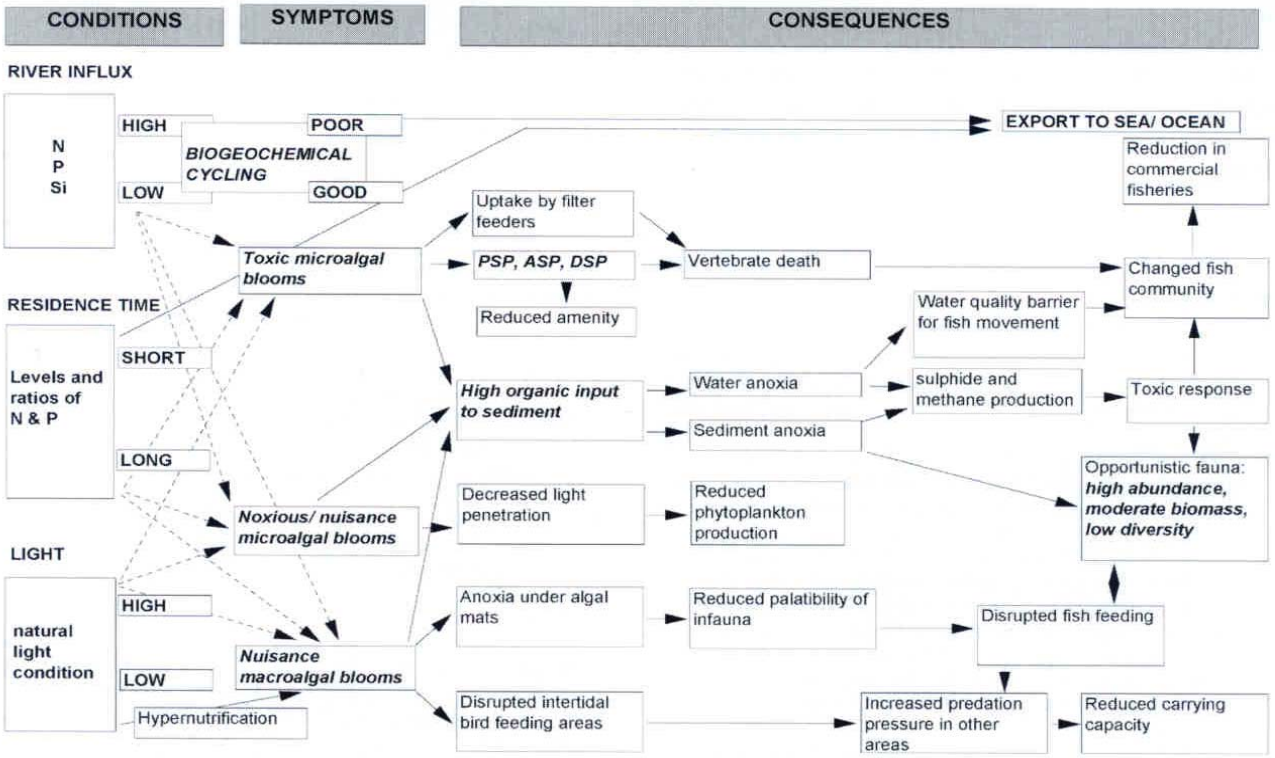


Figure 2. Relations between conditions, symptoms and consequences of eutrophication in estuarine environments (From Elliot and De Jonge, 2002).

From this chart it can be inferred that a linear reaction is not likely between increased nutrient loading and changes in the biological and chemical status of an aquatic system.

4. Nutrient sources and sinks

The main external transport routes of dissolved and particulate nutrients (nitrogen and phosphorus compounds and silicate) into the western Wadden Sea are the rivers Rhine-Meuse, via the Dutch coastal zone and via the IJsselmeer, the Atlantic Ocean water that enters the North Sea in the south, and atmospheric deposition (De Leeuw, 2001; Van Raaphorst and De Jonge, 2004).

Internal sources are the mineralisation of locally produced and imported particulate organic matter and sediment water exchange (Rutgers van der Loeff et al., 1981; De Wilde & Beukema, 1984; Van Beusekom et al., 2001; Van Beusekom, 2005). Other important processes that need to be taken into account are the trapping of dissolved phosphate in the Wadden Sea in the mineral apatite and denitrification releasing nitrogen gas to the atmosphere (Van Beusekom et al., 1999; 2001; Phillippart et al., 2000) (Fig. 3).

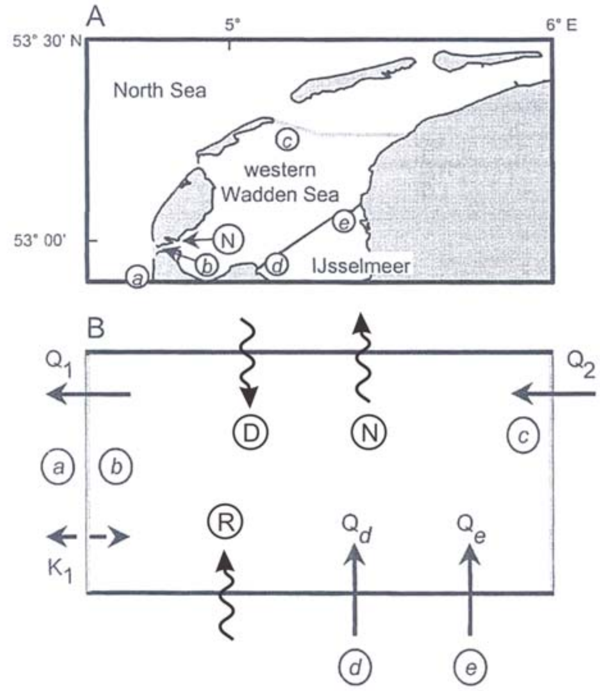


Figure 3. Geographical (A) and box (B) presentation of the western Wadden Sea. Arrows represent tidally averaged advective water transport (Q_1 and Q_2) and major freshwater inputs (Q_d and Q_e), dashed arrow (K_1) represents the dispersive exchange with the North Sea. D: atmospheric deposition, R: mineralisation and sediment-water exchange. B: burial of phosphate and N: denitrification (adapted from Philippart et al., 2000).

The main sources for nitrogen in the catchment of the Rhine are: industry, wastewater treatment plants, agriculture with inorganic fertilizers and combustion of fossil fuel

(Peeters et al., 1999; Anonymous, 2000; Van Beusekom et al., 2005). The main phosphorus sources in the Rhine catchment are: wastewater treatment plants, industry and agriculture.

The waters passing through the Marsdiep contain on average 15 % freshwater (Zimmerman, 1976). The average relative contribution of major freshwater sources to the nutrient input into the Dutch part of the Wadden Sea (1977-2002) are given by Van Beusekom et al. (2005) (Table 2).

Table 2. The averaged relative contribution of major freshwater sources to the nutrient input into the Dutch part of the Wadden Sea (1977-2002) (from Van Beusekom et al., 2005).

source	discharge	total nitrogen	total phosphorus
Haringvliet	28	27	22
Maassluis	47	47	57
Noordzeekanaal	3	3	5
IJsselmeer	19	18	14
Ems	3	5	2

The annual averaged salinity of the western Wadden Sea (Marsdiep area) varied between 24.5 (30% freshwater; 1994) to 30 (14% freshwater; 1977 and 1990) during the years 1977-1995 (De Jonge, 1997). About 40% of the freshwater is supplied by the Ijsselmeer and about 60% from the coastal zone. In general, the year-to-year variability in the annual averaged salinity of the Marsdiep resembles the variability in the water discharges of the IJsselmeer and Rhine.

The contribution of the riverine input of nitrogen, phosphorus and silicate into the Dutch coastal zone is relatively high, and extends up to 30 - 40 km offshore (Rutgers van der Loeff, 1980). He noticed that the relative influence of the nutrients from the Channel increases going further offshore and that the sea floor contributes significantly to the total amount of phosphorus and silicate in the Dutch coastal zone (Fig. 4).

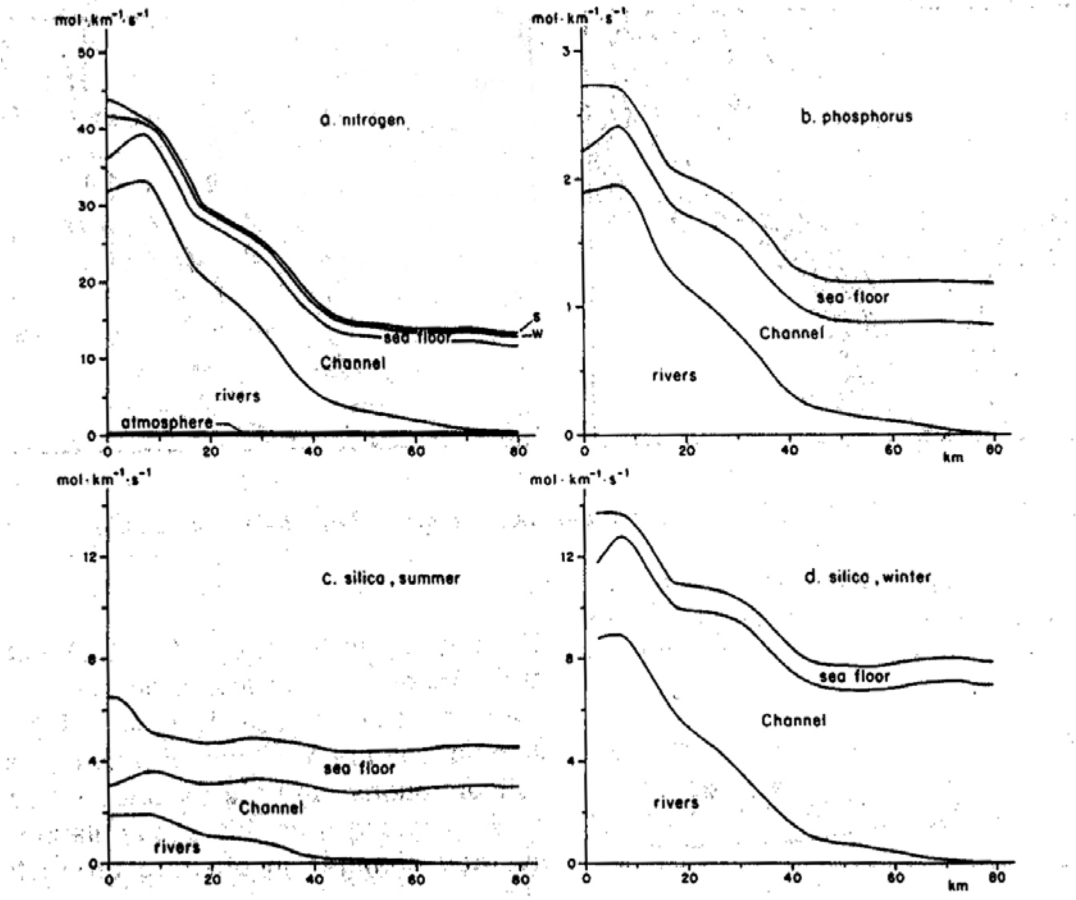


Figure 4. Composition of nutrient inputs (M.km^{-2}.s^{-1}) to the Dutch coastal zone as a function of offshore distance (from Rutgers van der Loeff, 1980).

Conclusions

- **The western Wadden Sea receives nutrients from the Dutch coastal zone, IJsselmeer, atmosphere and from the sediments,**
- **The western Wadden Sea imports particulate organic matter from the North Sea that serves as a food source or is mineralized within the Wadden Sea,**
- **On average 15% (14-30%) of the water in the western Wadden Sea is freshwater,). About 40% of the freshwater is supplied by the IJsselmeer and about 60% comes from the coastal zone.**
- **The major part of the Dutch coastal water entering the western Wadden Sea origins from the Atlantic Ocean,**
- **The annual average salinity in the Marsdiep is highly variable. This is mainly determined by the variability of the river discharge of the Rhine.**

River Rhine

The river Rhine is the main freshwater source for the Dutch coastal zone (Van Bennekom et al., 1975; Van Bennekom and Wetsteijn, 1990; De Jonge and Essink, 1991; De Jonge and Raaphorst, 1994; Cadée and Hegeman, 2002 and De Jonge et al., 1996). The annual mean water discharge at Lobith, Europoort and Haringvliet sluices between 1975 and 2004 are presented in Fig. 5.

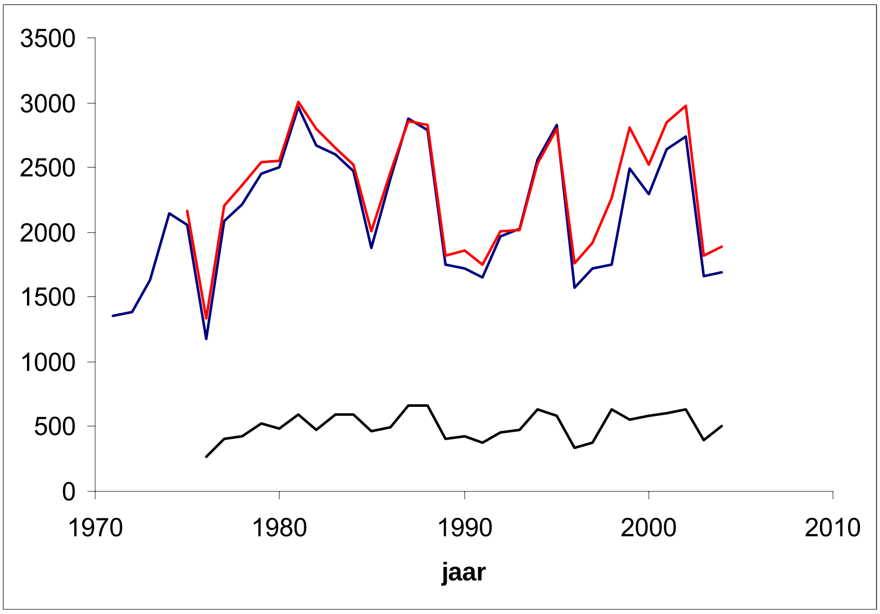


Figure 5. Annual averaged water discharge (m^3.s^{-1}) from the river Rhine at Lobith (red line), the Europoort channel and Haringvliet sluices (lower line) between 1975 and 2004.

The variability in the water discharges during the years 1975-2004 is mainly caused by wet and dry years in the Rhine and Meuse catchment (e.g. Van der Weijden and Middelburg, 1989).

The total nitrogen and total phosphorus load from the Rhine to the IJsselmeer and Dutch coastal zone increased from 1954 onwards (Van Bennekom and Salomons, 1981; Van Bennekom & Wetsteijn 1990; Van Raaphorst et al., 2000; Van Beusekom et al., 2001). The loading increased till 1981 (5-7 times for total phosphorus and 2-3 times for total nitrogen). Since 1982, there is a decreasing trend (Van der Veer et al., 1989; Schaub and Gieskes, 1991; Van Beusekom et al., 2001).

Concentrations of dissolved nitrogen remained rather stable in the Rhine in the period 1972-1986 (Schaub and Gieskes, 1991), with the exception of the ammonia concentration which showed a steep decline in the same period from 5 to 1 mg.l^{-1} (Schaub and Gieskes, 1991).

Nowadays, 80% of the riverine nitrogen compounds that enter the Dutch coastal zone are dissolved (Van Beusekom et al., 2001). Dissolved loads of inorganic nitrogen compounds increased already in the 1950s, remained high until 1985 decreased in 1990 to values as in the 1960s (Van Beusekom et al., 2001; Van Bennekom & Wetsteyn, 1990).

For phosphorus the picture is different; here between 35-40% occurs in particulate form (Van Beusekom et al., 2001).

The dissolved phosphate load of the Rhine increased due to human activities from the 1960s to 1980 and decreased afterwards until 1990 due to banning phosphate from washing powders.

The rather sharp decrease in the total phosphorus concentration and a lesser decrease in the total nitrogen concentration have resulted in an increase in the total N-total P molar ratio in the Rhine water from annual average values around 20 in 1979 to 30 in 1990 (Klein and Van Buuren, 1992; De Vries et al. 1998).

Focus has been mainly on nitrogen and phosphorus loads of the river Rhine in relation to eutrophication of the Dutch coastal zone and the western Wadden Sea. Schaub and Gieskes (1991) showed that also the silicate load of the Rhine-Meuse varied considerably during 1972-1986, with possible consequences for diatom growth and on the phytoplankton composition (diatom-flagellate ratios).

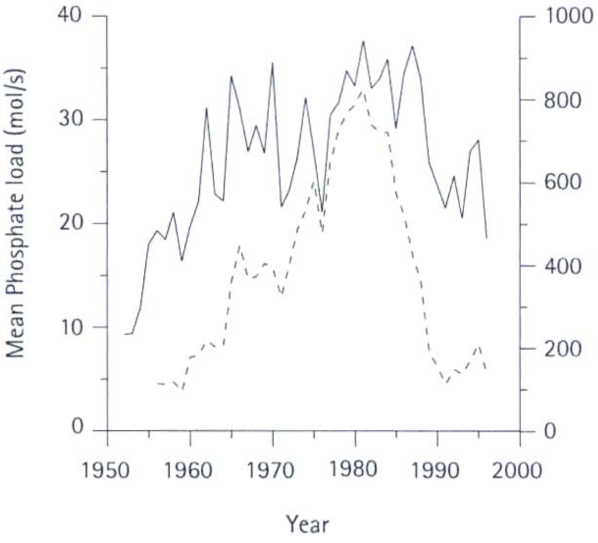


Figure 6. Annual average load of dissolved phosphate (dashed line) and dissolved inorganic nitrogen compounds (solid line) at Lobith (from Van Beusekom et al., 2001).

In general, the fluctuations in the discharge of total nitrogen and phosphorus compounds by the Rhine to the Dutch coastal zone are approximately proportional to the water discharge (Van der Weijden and Middelburg, 1989; Schaub and Gieskes, 1991). Annual mean discharge loads show a gradual decrease in TN and TP loads since the early 1980's (Van Beusekom et al., 2005).

Nutrient load data, presented here and by others, are the loads at Lobith or Europoort (e.g. Fig. 6). However, it must be recognized that these loads do not entirely represent the quantities arriving in the coastal zone. The actual quantities reaching the coastal zone are less due to estuarine retention (Billen et al. 1985; Billen and Garnier, 1997; Laane, 2005). It is assumed that there is proportionality between the nutrient load at the head of the Rhine-Meuse estuary and the amount discharged by these rivers in the Dutch coastal zone.

The nutrient input of the Scheldt estuary into the Dutch coastal zone is not taken into account here, because the absolute contribution in nutrient loads from the Scheldt, compared to the Rhine-Meuse, is relatively small (Lacroix et al., 2004). Soetaert et al. (2005) investigated the long-term trends (1965-2002) in the nutrient concentrations from the Scheldt river to the Dutch coastal zone. The same interannual pattern is observed as in the Rhine: the concentrations of dissolved inorganic nitrogen and phosphorus increased strongly till the mid 1970s after which they declined again. The total N-total P ratio doubled in the Scheldt estuary in the period 1980-2002.

Conclusions

- **The annual average nutrient load of the Rhine to the Dutch coastal zone is as a first approximation proportional to the annual mean water discharge, but there is a gradual decrease in specific nutrient load,**
- **Nutrient loads increased due to human activities in the Rhine catchment already in the 1950 till the 1980s,**
- **Between 1980-1990 the annual average total phosphorus and total nitrogen load decreased to 1960s values, TP faster than TN,**
- **The total N-P molar ratio increased between 1970-1990,**
- **Nutrient inputs to the coastal zone are based on riverine data. The precise amounts of riverine nitrogen and phosphorus carried into the Dutch coastal zone are not well known.**

IJsselmeer

The annual mean water discharge and nutrient loads of the IJsselmeer to the western Wadden Sea are presented in Figure 7. From 1950 until 1981 there was an increase in the total load of phosphorus (from 0.03 to 0.16 $kg.s^{-1}$) and in total nitrogen (from 0.6 to 2.3 $kg.s^{-1}$) (Van der Veer et al., 1989). The main increase in N and P loads from the IJsselmeer to the western Wadden Sea took place in the 1970s (Van der Veer et al., 1989).

The patterns in nutrient loading from the IJsselmeer (Figure 7) agreed well with those of the river Rhine at Lobith. However, a time lag of about 15-20 years has been observed between the increase in nitrogen and phosphorus loads in the Rhine to the Dutch coastal zone and the nitrogen and phosphorus loads from the IJsselmeer to the western Wadden Sea (Van der Veer, 1989). From the 1950s to 1970s the IJsselmeer acted as a trap for phosphorus compounds (Van der Veer et al., 1989).

The decrease in phosphorus concentration in the Rhine water and the trapping of phosphorus in the IJsselmeer have resulted in a sharp increase in the N-P molar ratio of the water entering the western Wadden Sea through the sluices from 34 in 1981 to values above 50 in the years around 1990 (Van der Veer et al., 1989; Klein and Van Buuren, 1992; Van der Veer et al., 1995b; Philippart et al., 2005).

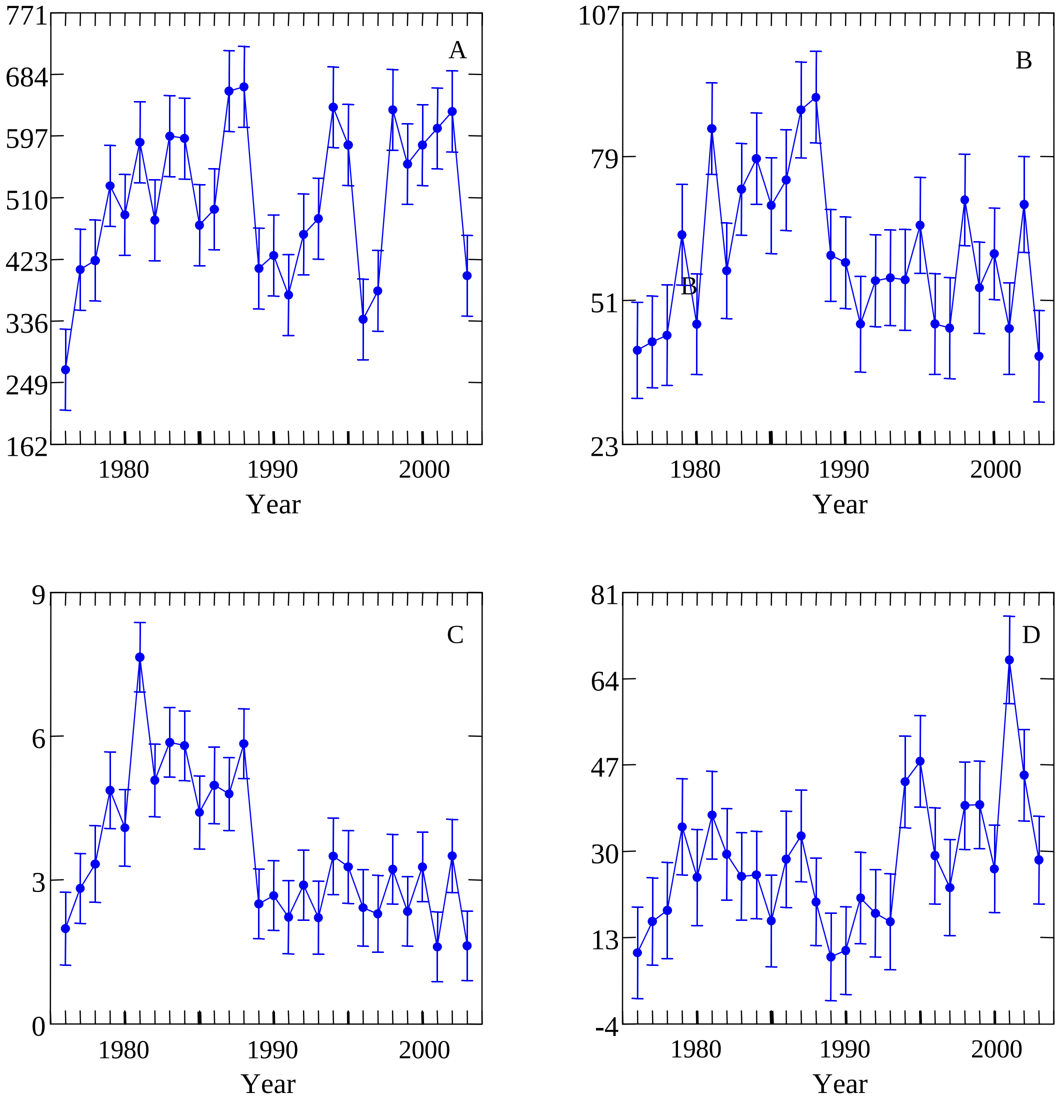


Figure 7. Annual averaged water discharge of the IJsselmeer (A: $m^3.s^{-1}$) and annual averaged loads of total nitrogen (B; μM $N.s^{-1}$), phosphorus (C; μM $P.s^{-1}$) and silicate (D) (μM $Si.s^{-1}$). (with permission from Philippart et al.,2005).

Van Raaphorst and de Jonge (2004) reconstructed the total nitrogen and phosphorus inputs from the IJsselmeer into the western Wadden Sea between 1935 and 1998. They noticed that before 1975 the concentration of total nitrogen and phosphorus at the sluices in the IJsselmeer changed in time, compared with those at Lobith,. Changes in discharge where attributed to changes in surface area of the IJsselmeer due to land reclamation (1942, 1957, 1967) and 1975 (due to the Houtribdike) by which the hydraulic retention changed from about 600 days in 1940 to less than 300 days in 2000.
Also the loads of nitrogen and phosphorus to the western Wadden Sea were strongly modified by addition of nutrients from other sources and retention of water and nutrients in the IJsselmeer (Van der Veer et al., 1989; Van Raaphorst and De Jonge, 2004).

The total freshwater discharge into the western Wadden Sea changed slightly in time due to manipulation of the discharge of the IJssel to a minimum of 300 $m^3.s^{-1}$, which is necessary for shipping purposes.

The trend in phosphorus loads from land in 1975 to 1988 is reflected in the total phosphorus and dissolved inorganic phosphate concentration in the Marsdiep area (Philippart et al., 2000). However, they found that the increase in nitrogen loading was not reflected in the total nitrogen concentration in the Marsdiep area, but only in the nitrate and nitrite concentration. They concluded that this disparity suggests a non-linear response of the Marsdiep system to enhanced nutrients inputs.

Conclusions

- **The discharge of nutrients from the IJsselmeer to the Wadden Sea has significantly changed due to land reclamation in the IJsselmeer before 1975,**
- **The water discharge of the IJsselmeer to the western Wadden Sea is highly variable in the period 1975-2003 and resembles the variability of the Rhine,**
- **The decrease in nutrient loads from the IJsselmeer since 1988 is mainly caused by a decrease in concentrations,**
- **Nitrogen and phosphorus loads in the period 1989-2003 are smaller than in the period 1975-1988, due to lower concentrations. In the period 1989-2003 the concentrations were fairly constant, and the loads followed the variability in the water discharge,**
- **Dissolved silicate loads from the IJsselmeer increased from 1989 to 2003.**

Coastal zone

The Dutch coastal zone is a source for nutrients for the western Wadden Sea due to tide induced mixing processes (Philippart et al., 2000). However, the Wadden Sea also imports particulate organic matter from the IJsselmeer and the Dutch coastal zone of the North Sea; a process that is often found in other coastal areas (Smith and Hollibaugh, 1993; Heip et al., 1995). Postma (1954) underlined the importance of the import of particulate organic matter from the Dutch coastal zone into the western Wadden Sea. Once trapped in the Wadden Sea this organic matter is mineralized (Brockmann and Kattner, 1997; Philippart et al., 2000; Van Beusekom et al., 2001).

De Jonge and Postma (1974) estimated that the particulate organic matter input from the Dutch coastal zone to the western Wadden Sea had increased by a factor three during the years between 1954 and 1970. Nearly no data are available in the literature for changes in the input of particulate organic matter from the IJsselmeer. It can be expected that due to eutrophication in the IJsselmeer more particulate organic matter is discharged to the western Wadden Sea.

De Wilde and Beukema (1984) estimated, based on calculations by Cadée (1980), a marine input of particulate organic matter of 330 $gC.m^{-2}\cdot y^{-1}$ for the western Wadden Sea and 130 $gC.m^{-2}\cdot y^{-1}$ from the IJsselmeer. Van Beusekom et al. (1999) estimated a lower amount of about 100 $gC.m^{-2}\ y^{-1}$ (see also Hoppema cited in Van Beusekom, 1999).

Van Beusekom and De Jonge (2002) and Van Beusekom (2005) used the increased nitrite and ammonium concentrations in autumn in the western Wadden Sea to estimate the mineralization and associated particulate organic matter input.

Van Beusekom and De Jonge (2002) showed that more organic matter was imported from the Dutch coastal zone and remineralized in the western Wadden Sea in the years with high riverine nitrogen load than in the years with relatively low nitrogen load. Almost 50% of the inter-annual variability in the autumn concentrations of ammonium and nitrite in the western Wadden Sea could be explained by the riverine total nitrogen load.

The increase in the nitrogen and phosphorus compound concentrations and load in the Rhine during 1950 till 1980, later followed by a decrease, is clearly reflected in the Dutch coastal zone (Van der Veer et al., 1989).
Van Raaphorst and Van der Veer (1990) noticed that the exchange of dissolved phosphorus compounds between the western Wadden Sea and the Dutch coastal zone is very important. Based on their phosphorus budget for the western Wadden Sea they observed a decrease in the amount of phosphorus retained or trapped. During the start of the eutrophication 75% of the incoming phosphorus was trapped, decreasing to 25-30% in the 1980s.

The increasing N-P molar ratio in the Rhine water resulted also in an increase in the ratio in the Dutch coastal zone (Klein and Van Buuren, 1992; De Vries et al., 1998). The average N-P molar ratio of the dissolved inorganic compounds in the winter months decreased from the 1960 from 35 to 15 in the 1970s and increased afterwards slowly to values around 40 in the 1990s (Klein and Van Buuren, 1992).

Conclusions

- **The western Wadden Sea imports about 100 gC.m^{-2}.y^{-1} of particulate organic matter from the IJsselmeer and from the Dutch coastal zone,**
- **This organic matter is mineralized in the western Wadden Sea and adds in this way dissolved nutrients to the water phase,**
- **Dissolved nutrients are exported from the western Wadden Sea to the Dutch coastal zone,**
- **The amount of imported particulate organic matter increased threefold in the 1970s due to eutrophication of the Dutch coastal zone,**
- **The amount of imported particulate organic matter from the Dutch coastal zone to the western Wadden Sea is related to the nitrogen load of the Rhine (wet and dry years),**
- **The N-P molar ratio of the dissolved nutrient compounds increased from 15 to 40 in the western Wadden Sea in the last decades.**

Atmosphere

Various estimations have made for the atmospheric deposition of nitrogen on the Wadden Sea (e.g. De Leeuw, 2001; Van Beusekom, 2005). The nitrogen emission from ships is an important source for the atmospheric deposition of nitrogen in the coastal zone (De Leeuw, 2001).
A four-fold increase in the load of atmospheric nitrogen on the North Sea in time is found when old model results are compared with recent field and model data (Laane unpublished results). This increase is also found in a 20-year record of atmospheric deposition of nitrogen in North Carolina (Paerl, 2002). The most reliable data are based on field measurements and model results (Bleeker and Duyzer, 2004). The total annual average deposition of nitrogen was 2.2 gN.m^{-2} for the western Wadden Sea for the year 2000.

Van Beusekom et al. (2001) and Van Beusekom (2005) calculated that the atmospheric deposition of nitrogen in the Wadden Sea is responsible for about 25% of the local primary production.

Conclusions

- **Atmospheric deposition of nitrogen is an important additional source of nitrogen to the water phase,**
- **Atmospheric deposition of nitrogen has increased due to human activities.**

Atlantic ocean

The contribution of nutrients (N, P and Si) in the Atlantic Ocean water to the total nutrient concentration in the Dutch coastal waters is presented by Rutgers van der Loeff (1980) (see figure 2). The influence of the Atlantic Ocean to the total nutrient concentration in the Dutch coastal zone is smaller along the coast than offshore. Laane et al. (1993; 1996a,b) showed that the inter-annual variability of the nutrient fluxes (N, P and Si) through the Channel is large (up to a factor of five) and is during the years 1930-1988 related to the variability in the water flow through the Channel (Fig. 8). This is reflected in a large standard deviation around the annual averaged loads; for instance for nitrate the annual averaged load through the Channel to the North Sea is 147±197 kT N.y^{-1} for the period 1955 -1995. No clear inter-annual trend was observed in the averaged winter nutrient (N, P and Si) concentration in the incoming Atlantic water through the Strait of Dover in the period 1930-1988 (Laane et al., 1993). However, there is a slight indication that the concentrations of dissolved ortho-phosphate (from 0.4 to values between 0.4 and 1.0 μM) and nitrate (from values between 1-5 to values between 5 and 20 μM) increased from 1965 till 1985 in the coastal water of the Channel (Laane et al., 1993). De Jonge et al. (1996) suggested from Laane's data that the concentration of dissolved inorganic nitrogen compounds and dissolved phosphate had increased two to three times in the period of the 1960s to the 1990s. Based on the same data it was concluded by De Jonge (1990) and De Jonge and Van Raaphorst (1995) that there was a clear increase (2-3 times) in the winter concentration of dissolved inorganic phosphate in the Strait of Dover.

Due to the increased contribution of dissolved phosphate in the Atlantic water to the Marsdiep presumed by De Jonge and Van Raaphorst (1995) it was necessary to compensate the decreasing riverine load of phosphorus to the western Wadden Sea. The total phosphorus load of the Rhine and IJsselmeer decreased after 1980 by a factor of 3.5; the load of dissolved inorganic phosphate decreased by a factor of 10 (De Jonge et al., 1996). However, the decrease in the Marsdiep values was only a factor of two over the same period and primary production and algae biomass remained at the same level afterwards (Cadée and Hegeman, 2002).

During transport from the Channel to the Marsdiep several processes influence nutrient levels, changing the characteristic patterns. The average transit time for water from the Channel to the Marsdiep area is estimated to be about half a year (Visser et al., 1996). No tele-connection is found between the variability in the monthly average concentration of dissolved phosphate in the English Channel and the Dutch coastal zone, meaning that during transport the concentrations have been changed by various biogeochemical processes (Laane et al.,1996b; Fig. 9).

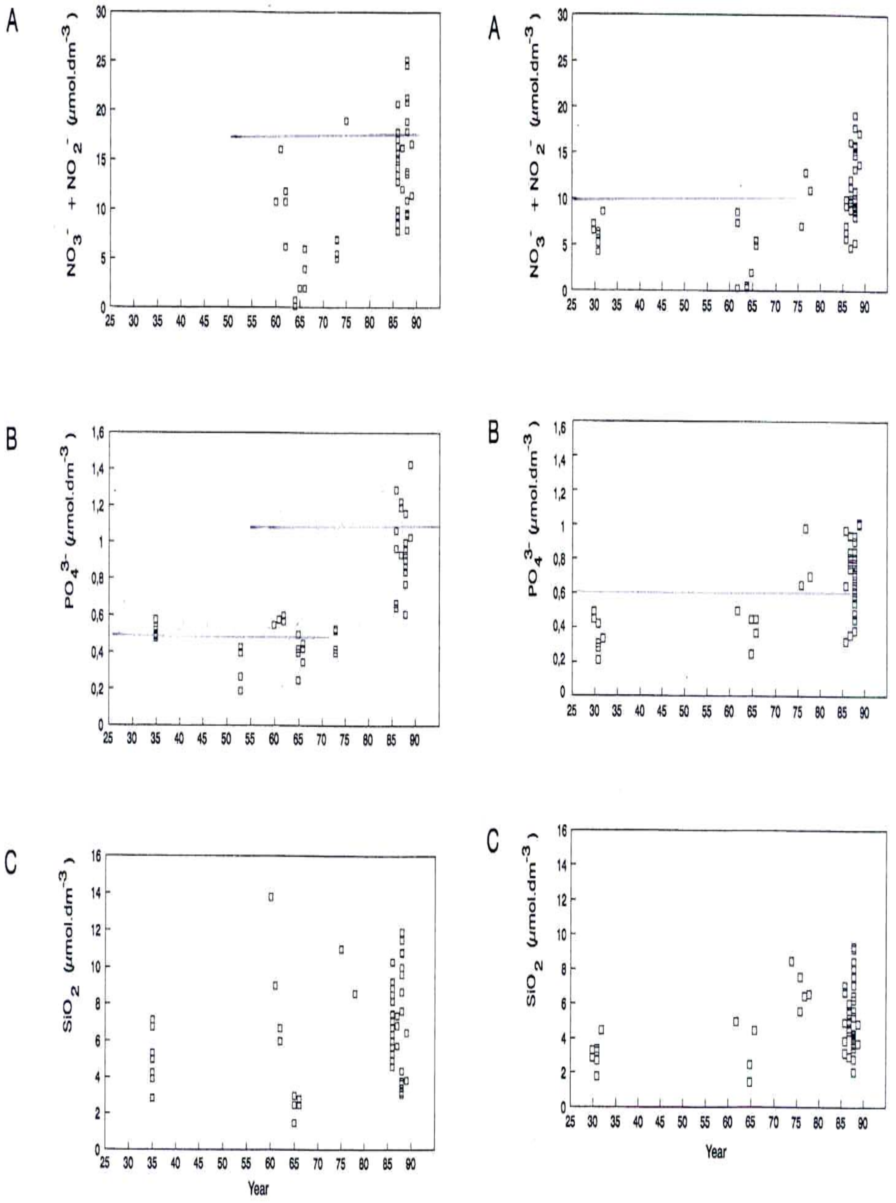


Figure 8. Long-term variation in the concentration of nitrate and nitrite (A), phosphate (B), and silicate (C) during the winter for different years in the coastal zone of the Channel (three figures left) and in the central part of the Channel (three figures right) (from Laane et al., 1993).

The annual averaged N-P ratio in the Atlantic water entering the North Sea through the Channel was rather constant during 1935-1990: 18.4 (Laane et al., 1993).

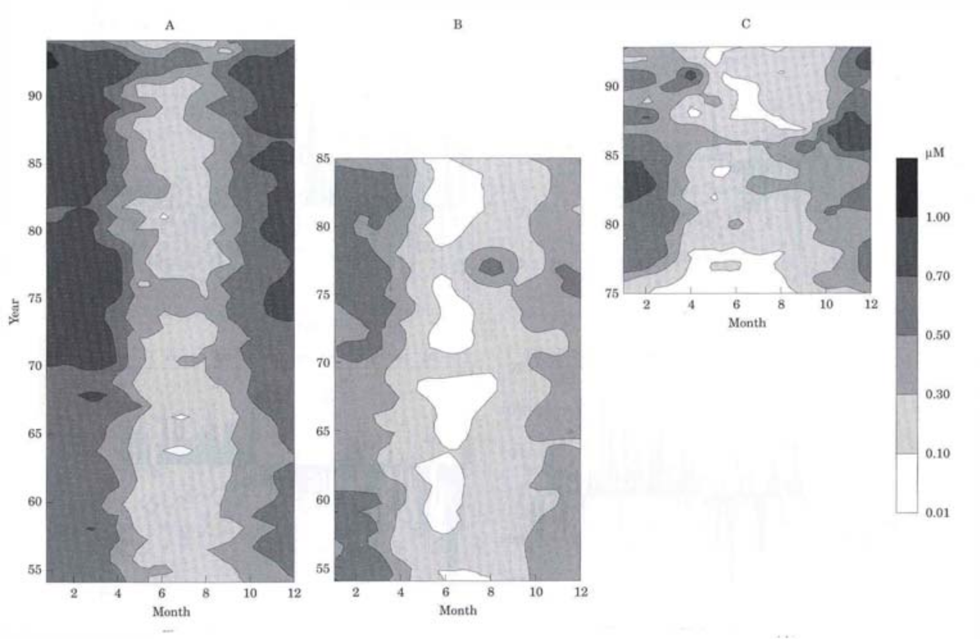


Figure 9. Monthly average dissolved phosphate concentration in the English Channel (A), Irish Sea (B) and Dutch coastal zone for different years (from Laane et al., 1996b).

Conclusions

- **The nutrient concentration (N, P and Si) in the Channel is highly variable in the period 1930-1988,**
- **No clear trend could be observed in the nitrogen and phosphorus concentrations in the Channel in the period 1930-1988,**
- **No clear tele-connection could be observed between the variability in the dissolved phosphate concentration in the Channel and the Dutch coastal zone,**
- **Biogeochemical processes alter the nutrient concentrations during transport from the Channel to the Dutch coastal zone.**

Nutrient sinks

Denitrification is an important sink for nitrogen compounds in the Wadden Sea (Van Beusekom and De Jonge, 2002; Van Beusekom et al., 2001). It is estimated that 19-35% of the total nitrogen input into the Wadden Sea is denitrificated (Lohse et al., 1993; Van Beusekom et al, 2001).

About 25% of the imported phosphorus into the Wadden Sea is trapped as a Ca-P mineral (apatite) (Van Beusekom et al., 2001). De Jonge et al. (1993) and De Jonge and Engelkes (1993) showed for the beginning of the 1990s that the bioavailability of phosphorus released from the sediments can substantially contribute to the primary production in the western Wadden Sea. Recently, it is suggested that this pool of phosphorus is limiting phytoplankton growth in the western Wadden Sea (Kuipers and

Van Noort, pers. comm.). However, the data show that only during a very short time, dissolved phosphate reaches limiting concentrations.

Conclusions

- **Denitrification of nitrogen compounds is an important nitrogen sink in the western Wadden Sea,**
- **Part of the dissolved phosphate is trapped in the surface sediments and partly released again to the water phase,**
- **It is suggested that the sediment water exchange of dissolved phosphate decreased during the last years and is limiting phytoplankton growth at the moment.**

Nutrient and carbon budgets

Van Raaphorst and Van der Veer (1990) constructed a phosphorus budget for the western Wadden Sea. They confirmed that there is an import of particulate phosphorus from the Dutch coastal zone and that there is an export of dissolved inorganic phosphate to the coastal zone. They assumed that the phosphorus import from the North Sea is less important than previously thought (De Jonge and Postma, 1974). 50% of the particulate phosphorus comes from riverine sources, and 45% from the adjacent Vlie basin leaving only 5% for import via the Marsdiep. They demonstrated that the phosphorus import changed over the years; a gradual increase to 30% import during 1950-70s and then from 1975 onwards the import changed to an export in the 1980s. Van Raaphorst and Van der Veer (1990) suggested that this output of phosphorus compounds may have considerable impact on the eutrophication status of adjacent coastal areas and other parts of the Wadden Sea.

Philippart et al. (2000) constructed a nitrogen and phosphorus budget for the western Wadden Sea for three different periods: 1975-1977, 1978-1987 and 1988-1993. Their findings for phosphorus were in agreement with those of Van Raaphorst and Van der Veer (1990). They assumed that denitrification of nitrogen compounds in the western Wadden Sea became important during the last two periods; 35% of the total nitrogen input is denitrified in the western Wadden Sea.

Table 2. Annual averaged carbon budget (gC.m^{-2}.y^{-1}) for the western Wadden Sea. DCZ = Dutch coastal zone. 1: Van Beusekom et al. (2005); 2: Van den Hoek et al. (1979); 3: De Wilde and Beukema (1984).

	Pre-industrial <1930	**Present >1990**	**Ref.**
Phytoplankton	55-86	200	1
Phytobenthos	100	200	2
Sea grass	30	-	2
Offshore primary production	63	322	1
Import DCZ	22	110 330	1 3
Import IJsselmeer		65	3
Remineralisation	77-108	419	1

Import of particulate organic matter

De Wilde and Beukema (1984) calculated the particulate organic matter import to the western Wadden Sea and assumed that it was mainly refractory organic detritus. However, the degradable part is probably higher than assumed because of the high eutrophication status of the Dutch coastal zone and the IJsselmeer (Nelissen and Stefels (1988). The degradable part of the organic matter in the surface sediments of the western Wadden Sea has been measured to be more than 50% in spring and summer and below 20% in autumn and winter (Etcheber et al., 1993).
Seagrass production in the western Wadden Sea appeared to be important during pre-industrial times (Van der Hoek et al., 1979). The relatively high pre-industrial phytoplankton production, estimated by Van den Hoek et al. (1979) is a consequence of the better light climate before 1932, but it ignores the possible limiting role of nutrients.

The contribution of particulate organic import to the nutrient budget of the western Wadden Sea can be roughly estimated as follows. Basic assumptions are: (1) the average winter fresh water fraction in the western Wadden Sea is 25%, (2) the TN concentration of the winter fresh water fraction is approximately 10 times the background concentration of the Atlantic water (i.e. 170 vs. 17 µM) and the TP concentration is approximately 4 times the background concentration (i.e. 3.6 vs. 0.9 µM), (3) the present average winter concentrations are 70 µM N and 2 µM P (see Table 1). The contribution of particulate P, N input into the western Wadden Sea is the difference between the total P, N load minus the contributions of the fresh water fraction (25%) and the Atlantic water fraction (75%). The result is that the particulate organic matter import (due to other transport mechanisms than tidal mixing) contributes approximately 20% of the total P load and N load of the western Wadden Sea. The particulate import of P, N is of the same order of magnitude as the P, N import from the IJsselmeer and consistent with the estimate of 100 $gCm^{-2}y^{-1}$ (Van Beusekom, 1999).

The contribution of the fresh water fraction to the P,N load of the western Wadden Sea according to the above crude model is approximately 45% for P and 60% for N. Recent model simulations on the extension of the Maasvlakte indicate a decrease of 10% of the freshwater input into the western Wadden Sea from the coastal zone. This decreases the fresh water fraction by approximately 6% and increases the Atlantic water fraction by about 2%. The P and N concentrations will then decrease by about 2 and 3% respectively. If the particulate import is also reduced by 10% the P and N concentrations in the western Wadden Sea will decrease by about 4 and 5% respectively.

Conclusions

- **The annual amount of produced primary pelagic and benthic carbon increased after pre-industrial times in the Dutch coastal zone and western Wadden Sea,**
- **The remineralisation of particulate imported and produced organic matter in the western Wadden Sea increased,**
- **A crude model indicates that a decrease of 10% of the input of fresh water and particulate carbon from the coastal zone will result in a decrease of phosphorus and nitrogen concentrations in the western Wadden Sea by about 4 and 5% respectively.**

5. Nutrient Concentration

Dutch coastal zone

The year-to-year variation in the monthly average dissolved phosphate concentration in the Dutch coastal zone shows an increase from the 1950s with highest winter values in the beginning of the 1980s and a decrease afterwards (Nelissen and Steffels, 1988; Van der Veer et al., 1989; Van Bennekom and Wetsteijn,1990; Klein and Van Buuren, 1992; Laane et al. ,1996b and Visser et al.,1996). The annual trends in dissolved nitrate and silicate in the Dutch coastal zone show a decrease after 1988 and is very similar as found for the Belgium coast in the years 1975-1993 (Visser et al., 1996). However, it should be noticed here that, due to the Rhine input, the nitrate concentration in the Dutch coastal zone is about 50% higher than in the Belgium coast (Visser et al. 1996).

Bot et al. (1996) studied the seasonal cycle of monthly averaged nitrate, phosphate and silicate concentrations in the Dutch coastal zone and compared the patterns with the cycles at seven places in and around the North Sea in 1980-1984. Highest concentrations of nitrate (75 μM), phosphate (3 μM) and silicate (34 μM) were found in winter time in the Dutch coastal zone compared to the other coastal locations. The concentration of nitrate and phosphate in the open North Sea was respectively 8 to 4 times lower than in the coastal waters. Hardly any difference was found between the silicate concentration in the Dutch coastal zone and the offshore values.

Along the Belgium, Dutch and German coast the changes in the length of the periods with relatively low nitrate concentrations are more pronounced than in open sea water (Bot et al., 1996). The number of months with nitrate concentrations below 20 μM is almost zero in the 1970s and early part of the 1980s. From 1987 onwards this period increased to 4 months in the 1990s (Bot et al., 1996).

A decrease in the period for low dissolved inorganic phosphate (values below 1 μM) is found in the Dutch coastal zone from 9 months in the 1960s to zero months in the 1970s and early 1980s. From 1982 onwards there is a gradual increase to about 5 months in the 1990s (Bot et al., 1996).

Visser et al. (1996) compared the variability in the dissolved inorganic nutrient concentration (N, P and Si) and salinity in the Dutch coastal zone (1954-1993), with the variability of these compounds along the Belgium coast (1975-1993) and in the English Channel ((1958-1993). From these data they concluded that the level and variability in the salinity and nutrient concentration in the Dutch coastal zone is mainly caused by the Rhine discharge.

The dissolved inorganic N-P molar ratio in the Dutch coastal zone is fairly constant in the period (values below 20) and increases (values above 20) after 1986 due to the reduction of phosphate input (Visser et al., 1996). The seasonal cycle of this N-P ratios shows that the Dutch coastal waters have the highest annual averaged ratios compared to other stations in and around the North Sea in 1980-1984 (Bot et al., 1996). Winter values are around 24 and highest values are found in May dropping to values below 10 in September and October (Bot et al.,1996). The monthly averaged values for the N-P ratio in the Channel (1980-1984) remained under 16 indicating a potential nitrogen limitation (Bot et al., 1996).

Conclusions

- **N and P nutrient concentrations increased till 1980s and decreased afterwards in the Dutch coastal zone (<20km): P decrease was more pronounced than N,**
- **Annual variability in concentration N and P nutrient concentrations in the Dutch coastal zone (< 20 km) is related to salinity and mainly caused by variations in nutrient concentrations and nutrient loads of the Rhine.**

Western Wadden Sea

The long-term nutrient series for the western Wadden Sea are from the sampling station Marsdiep at the border of the western Wadden Sea and sampling locations within the western Wadden Sea. The Marsdiep data are representative for the incoming coastal water and the data from the western Wadden Sea are a result of loading from external sources and local biogeochemial processes (Helder, 1974).
The seasonal variation in the monthly averaged values for 1999 and 2000 combined showed an increase in the concentration of dissolved phosphate, nitrate, dissolved inorganic nitrogen compounds and silicate compared to the values in 1950 in the Marsdiep (Cadée and Hegeman, 2002) (Fig. 10).

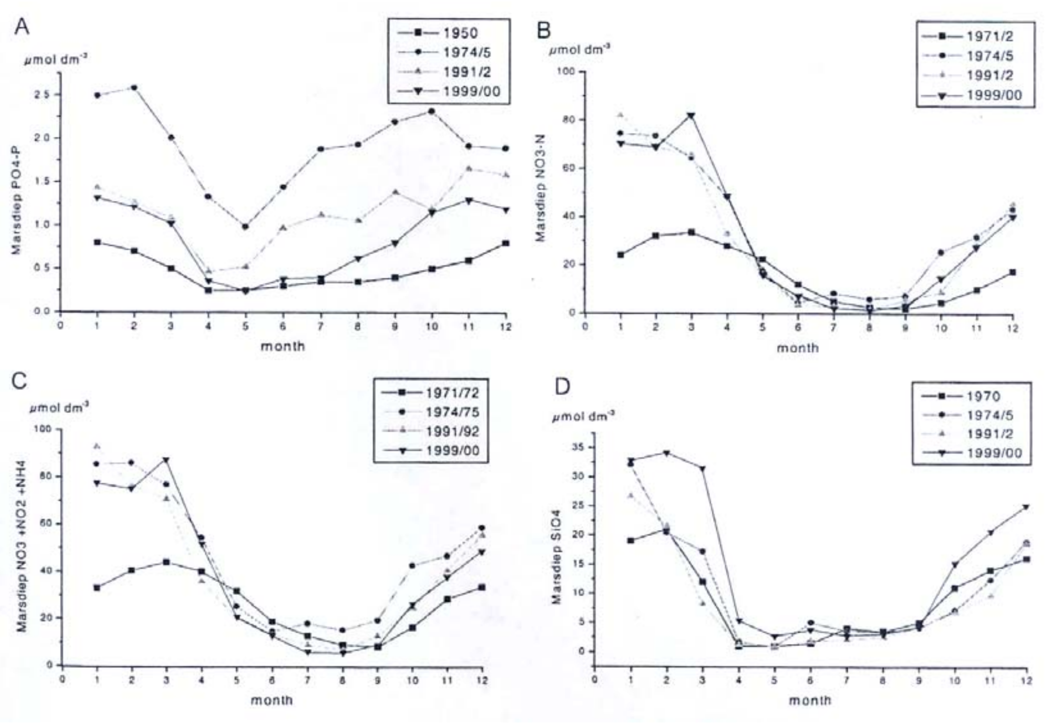


Figure 10. Seasonal variability in the monthly average concentration (µM.dm^{-3}) of dissolved phosphate (A), nitrate (B), dissolved inorganic nitrogen compounds (C) and silicate (D) for two years combined, compared wilt the values in 1950, in the Marsdiep area (from Cadée and Hegeman, 2002).

The general picture is that the winter concentration of nutrients increased during the 1950s to the 1970s and that the summer concentrations of phosphorus in the 1990s are back at the level observed in 1950. Winter values also decreased in the 1990s compared to 1970, but are still above the 1950 values. Dissolved phosphate concentrations in the 1970s did not reache the 1950 values in the summer period, as did the nitrogen nutrients and silicate. A similar pattern is observed in the Rhine river.

The mean winter concentration of dissolved ortho phosphate in the western Wadden Sea is relatively high up to 1986 and dropped to lower values in a few years. From 1990 to 2003 the concentration decreases slightly to rather stable level (Fig.11).

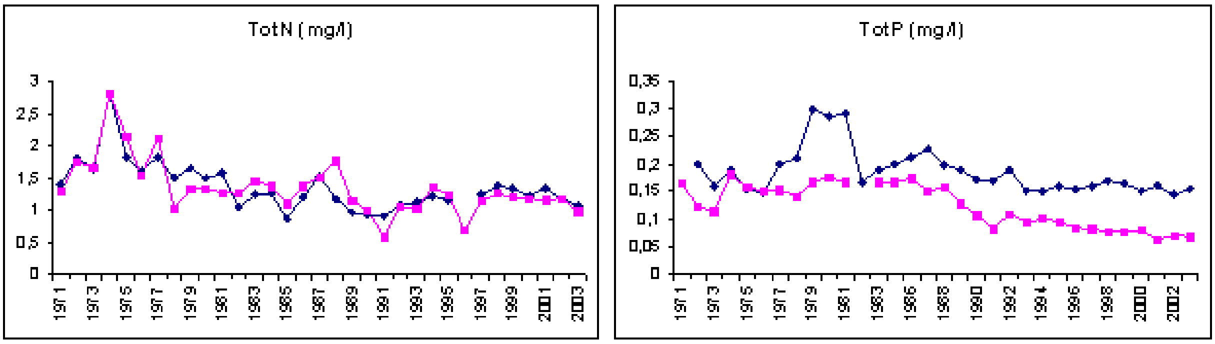


Figure 11. Annual variation in the total nitrogen and total phosphorus concentration (mg.l^{-1}) in the western (black line, ■) and in the eastern Dutch Wadden Sea (pink line, ▲) during 1971 to 2003.

The mean winter concentration of dissolved inorganic nitrogen compounds (ammonia, nitrate and nitrite) is rather constant during the years 1975-2003

Van der Veer et al. (1989) showed that the inter-annual variability in the nutrient concentrations in the western Wadden Sea could be explained mainly by the discharges of the IJsselmeer. They concluded that the IJsselmeer and not the coastal zone and Marsdiep is the main nutrient source for the western Wadden Sea.

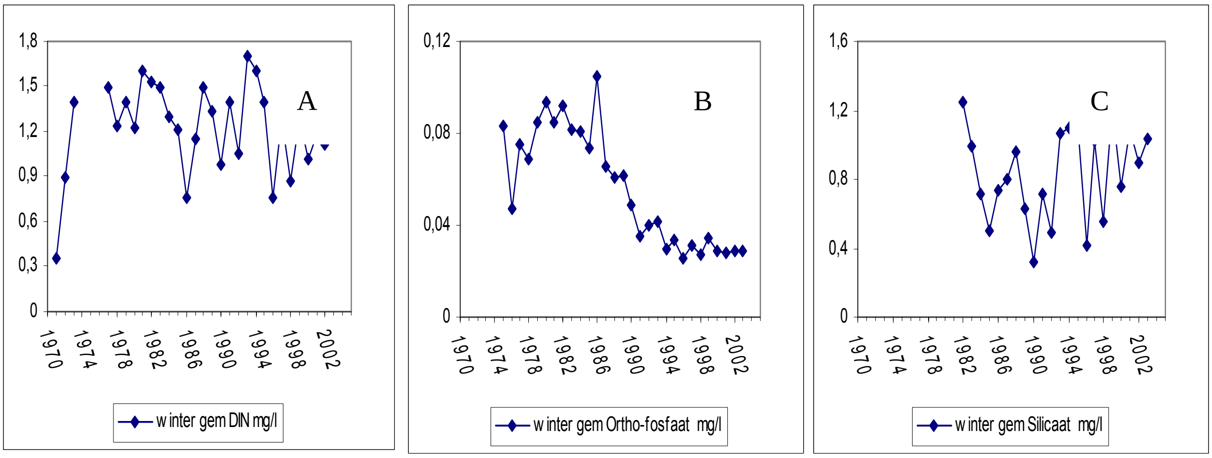


Figure 12. Annual variation in the winter concentration of dissolved nitrogen compounds (A), dissolved phosphate and silicate (mg.l-1) in the western Wadden Sea during 1974 to 2003.

The annual average N-P molar ratio increased from 12 (1972) to values above 40 in the period 2000-2003 (Philippart et al., 2005), see Fig. 13.

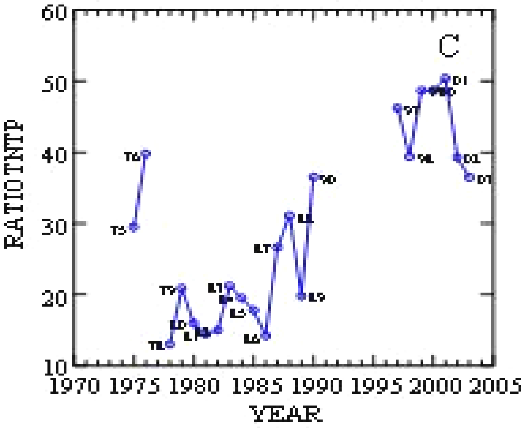


Figure 13. Increase in annual average N-P molar ratio in the Marsdiep during 1975-2003.

Conclusions

- **The inter-annual variability in the winter N and P concentration in the Marsdiep is partly caused by the inter-annual variability in the Rhine concentrations and Rhine loads,**
- **The inter-annual variability in the winter N and P concentration in the western Wadden Sea is similar to the IJsselmeer but is changed also by local biogeochemical processes,**
- **The N-P molar ratio has increased in the Marsdiep in the period 1975-2004.**

6. (In)direct effects

6.1. Chlorophyll-a

Dutch coastal zone

Chlorophyll-a often has been used as an indicator for phytoplankton biomass in aquatic systems. However, it must be recognized that there is a wide range in the conversion factor (between 30-200) between chlorophyll-a and phytoplankton carbon (Parsons et al., 1977). Beside that, the concentration of chlorophyll-a is a steady state concentration and a result of various physical, chemical and biological processes.

In the Dutch and Belgium coastal zone the spring bloom (characterized with chlorophyll-a) is rather late (May) compared to the more offshore stations in the period 1980-1984 (Lancelot, 1989; Bot et al., 1996). This delay is supposed to be caused by reduced light availability in the coastal zone during winter and early spring.
In the Dutch coastal zone an increasing and decreasing trend in chlorophyll-a have been observed with highest values in the mid 1980s (Visser et al., 1996). They could not find any trend in the chlorophyll-a concentration offshore (>50km) in the Dutch coastal zone.

River discharges of nutrients did not influence the chlorophyll concentration in the Dutch coastal zone between October and April, if it is assumed that light is the limiting factor for phytoplankton (Schaub and Gieskes, 1991). During the growing season, April-September) the amount of Rhine-Meuse water discharge was correlated positively with chlorophyll concentrations in the Dutch coastal zone (Schaub and Gieskes, 1991).

Wadden Sea

The chlorophyll-concentrations in the Marsdiep showed a clear year-to-year variation with highest values in spring and early summer. Maximum values are between 20 and 35 with an exception of 1986 which reaches 45 $\mu g.l^{-1}$ (Colijn and Cadée, 2003). Annual mean Chlorophyll-a concentration in the Marsdiep (Fig.14) increased from values around 5 $\mu g.l^{-1}$ in 1975 to values around 10 $\mu g.l^{-1}$ in 1980 and remained rather constant in the following years (Cadée , 1986; Cadée and Hegeman, 2002).
Relative high annual average values (>12 $\mu g.l^{-1}$) were observed in 1978 and 1986 ind coincide with relatively high fresh water discharge from the Rhine. Lowest values were observed in 1984 and 1996; both years with a relatively low water annual average fresh water discharge (Cadée and Hegeman, 2002). Cadée (1992a) found a correlation between nitrogen load of the Rhine/Meuse and phytoplankton biomass in the Marsdiep. These results are confirmed by Van Beusekom et al. (2001).

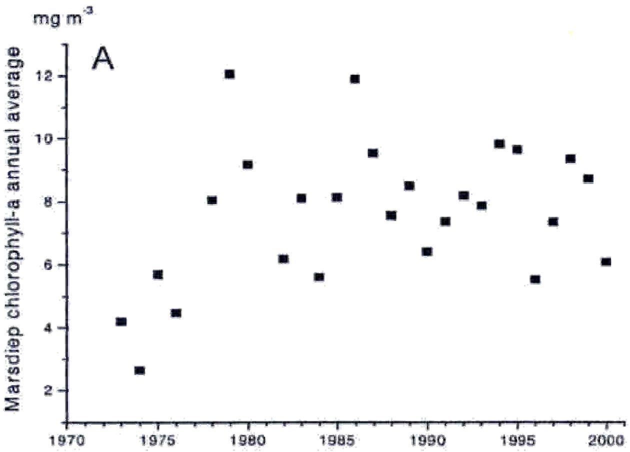


Figure 14. Annual average chlorophyll-a values between 1973 and 2000 in the Marsdiep (from Cadée and Hegeman, 2002).

6.2 Primary production

Dutch coastal zone

Steele's estimate of the annual averaged primary production of 130 gC.m^{-2}.y^{-1} in the North Sea (Steele, 1974) was upgraded by Jones (1984) to 160 gC.m^{-2}.y^{-1}. Gieskes and Kraay (1984) measured an annual averaged primary production of 250 gC.m^{-2}.y^{-1} offshore and 200 gC.m^{-2}.y^{-1} in the Dutch coastal zone between 1971 and 1981. They found a clear difference between coastal and offshore waters, which they attributed to light limitation.

Peeters et al. (1991) estimated the annual primary production at several stations in the Dutch coastal zone in 1990: ranging from 100-500 gC.m^{2}.y^{-1}. Highest values were found just offshore the 10 km line: the area where the suspended matter concentration decreased drastically and light limitation is not important anymore.

Such an estuarine eutrophication maximum in the Dutch coastal zone is suggested by Postma (1979), Colijn (1984; Ems estuary) and by Spitser et al. (1990): relatively high nutrient concentrations due to diffusion and no light limitation due to relatively low suspended matter concentrations.

Van Beusekom et al. (2001) summarized annual primary production data for the Dutch coastal zone and concluded that the annual average primary production increased from pre-industrial times to present from 63 to 322 gC.m^{-2}.y^{-1}. Schaub and Gieskes (1991) found a relation between the river discharge of nutrients and the chlorophyll concentration in the Dutch coastal zone during the years 1972-1986. DeGroodt et al. (1995) showed with a mathematical model that the increased chlorophyll-a concentrations and primary production in the Dutch coastal zone is related to the elevated nutrient concentrations.

Conclusions

- **Annual mean primary production in the Dutch coastal zone increased during the 1970s to the 1990s,**
- **A maximum in annual primary production is observed just outside the 10 km line where light is not limiting anymore and sufficient nutrients are available.**

Western Wadden Sea

Primary production increased from 20-40 gC.m^{-2}.y^{-1} in 1954 to values of 125 gC.m^{-2}.y^{-1} in the years 1965 -1975 and increased to 300 - 500 gC.m^{-2}.y^{-1} in the 1980 in the Marsdiep (fig. 15) (Cadée and Hegeman, 2002; Van Beusekom et al., 2001). Cadée and Hegeman (2002) suggested a slight decrease in primary production in the Marsdiep area in 1995-2000. Unlike the seasonal behavior of chlorophyll-a, primary production is generally highest in summer in the western Wadden Sea (Colijn and Cadée, 2003).

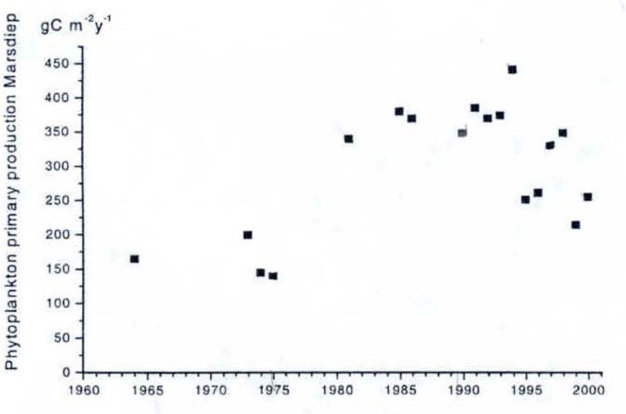


Figure 15. Annual primary production (gC.m^{-2}.y^{-1}) in the Marsdiep between 1964 and 2000 (from Cadée and Hegeman, 2002).

Only few primary production data are available for the western Wadden Sea. Based on the available data, Van der Veer et al. (1989) concluded that the pelagic primary production increased also from values of 100-150 in the 1970s to 165-300 gC.m^{-2}.y^{-1} in 1986 in the western Wadden Sea.

Benthic primary production in the western Wadden Sea doubled from about 100 gC.m^{-2}.y^{-1} in 1968 to 200 gCm^{-2}.y^{-1} in 1982 (Cadée, 1984). A two- to threefold increase in phytoplankton and phytobenthos production has also been found in the northern Wadden Sea (Asmus et al., 1998; Beusekom, 2005).

Several explanations have been published to relate the increase in phytoplankton production with nutrient loading. De Jonge (1990) related the annual average chlorophyll-a and primary production data (before 1987) in the Marsdiep area with the dissolved phosphate load of the IJsselmeer. Cadée and Hegeman (1993) noticed that, despite the decrease in the dissolved phosphate input to the western Wadden Sea and the decreasing concentrations in that area, primary production remained at a relatively high level. They suggested that the nitrogen load of the river Rhine was the driving force behind the primary production in the Dutch coastal zone (Cadée, 1992a; Cadée and Hegeman, 1993). De Jonge et al. (1996) and De Jonge (1997) argued that the increase in nutrient loading via the Channel to the Marsdiep has compensated the decreased phosphorus input of the IJsselmeer.

Conclusions

- **Primary production in the western Wadden Sea has increased from 1975 till 1995; a slight decrease is noticed afterwards,**
- **Benthic production increased twofold in the western Wadden Sea**

6.3 Mineralisation

De Jonge and Postma (1974) were the first to mention a possibly increased mineralisation rate in the western Wadden Sea due to an increased primary production in the coastal zone and an associated increased input of particulate organic matter into the western Wadden (Van Beusekom et al. 2001). The import of particulate organic matter has been estimated indirectly. The increase in the nitrite and ammonium concentration in autumn in the western Wadden Sea is taken as an indicator for the amount of imported particulate organic matter into the western Wadden Sea (Van Beusekom et al., 2001).

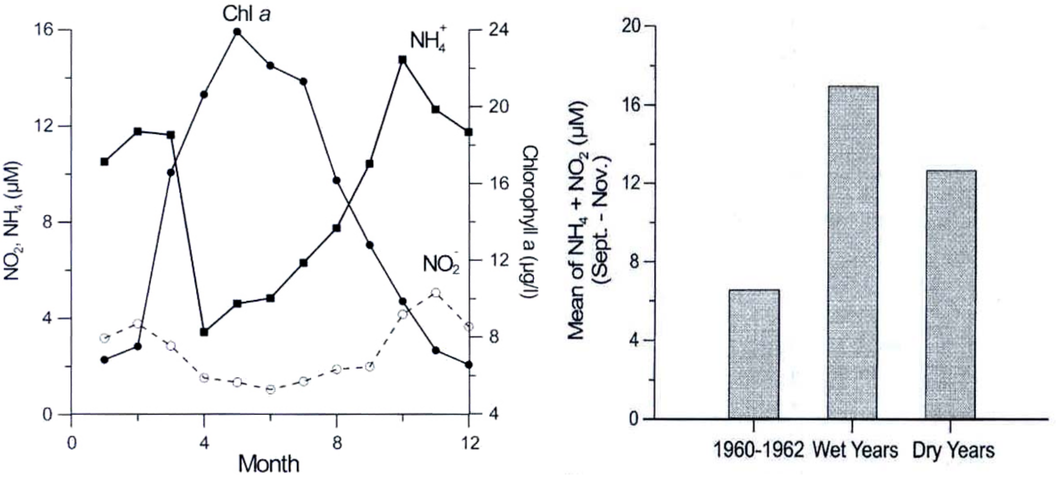


Figure16. Averaged seasonal cycle of ammonium, nitrite and chlorophyll-a in the western Wadden Sea (A) and long-term comparison of the autumn values of ammonium and nitrite during wet and dry years in the western Wadden Sea (from Van Beusekom et al., 2001).

These results of Van Beusekom et al. (2001, 2005) indicate that the import of particulate organic matter from the Dutch coastal zone to the western Wadden Sea is higher during wet years than during dry years (Fig.16).

Chlorophyll-a concentrations were positively correlated with nitrogen loss rates in the Marsdiep area, suggesting enhanced benthic denitrification through increased deposition of phytoplankton biomass (Philippart et al., 2000).

Conclusions

- **Particulate organic matter is imported via the Marsdiep into the western Wadden Sea,**
- **This amount of organic matter has increased probably due to eutrophication and is higher during wet years than dry years.**

6.4 Algae species

Cadée (1989) and Cadée and Hegeman (1991) found that the blooming period of the colonial flagellate *Phaeocystis globosa* in the Marsdiep increased from about 30 days in the period 1897-1975 to more than 120 days in the late 1980s. Riegman et al. (1992) concluded from experimental research, that this phenomenon was attributed to a shift from phosphorus to a nitrogen controlled system.

The species composition of the pelagic phytoplankton community in the Marsdiep changed drastically in the nutrient controlled months (July-August) between 1976 and 1978 and between 1987 and 1988 (Philippart et al., 2000). These changes coincide with changes in the N-P ratio. It was concluded, based on principal component analysis, that the Marsdiep area shifted from a phosphorus to a nitrogen controlled system in 1977 and reshifted to a phosphorus controlled system between 1987 and 1988 (Philippart et al., 2000).

The observed increase in algae biomass was particular due to an increase in the abundance of larger algae (Riegman et al., 1992; Philippart et al., 2000).

Conclusions

- **The blooming period of *Phaeocystis globase* in the Marsdiep changed from 30 to 120 days in the late 1980s,**
- **Species composition of phytoplankton in the Marsdiep changed between the seventies and the eighties,**
- **The increase in algae biomass in the Marsdiep is due to an increase in larger algae.**

6.5 Oxygen concentration

Locally anoxic sediments have always existed in the Wadden Sea (Höpner and Michaelis, 1994). However, an increase in black spots at the surface sediments has been observed in the Wadden Sea (Höpner and Michaelis, 1994; Heip, 1995 and Böttcher, 2003).

Rusch et al. (1998) showed that the severity of the black spots depends on the amount of buried organic matter. They calculated a critical load of less than 400 $gC.m^{-2}.a^{-1}$. This value is close to the primary produced amount of organic carbon of over 300 $gC.\ m^{-2}$.

Beukema et al. (1999) studied the recovery of zoobenthos populations after possible large scale mortality due to black spots. They found that settlement occurred already after 6 months and the total richness and number of animals recovered after several years.

6.6 Benthic production

Van der Veer (1989) noticed that since the 1950s, two large changes took place in the western Wadden Sea: eutrophication and the exploitation of extensive sub tidal mussel cultures. Between 1950 and 1970 the impact of eutrophication on mussels cannot be assessed. However, the intertidal macrozoobenthos biomass in the western Wadden Sea (Balgzand) doubled from the 1970s to the 1990s (Beukema et al., 2002). This change is in agreement with the increase in annual primary production (Cadée and Hegeman, 2002). However, it was noticed that the response was not proportional to the variation in primary production, suggesting that other factors also play a role (De Jonge et al., 1996). The meat content of the blue mussel also increased slowly since the beginning of the 1970s to 1992; no clear relation with primary production was found (De Jonge et al., 1996). Van der Veer 1989) hypothesized that the macrofauna biomass decreased in the western Wadden Sea in the period 1950-1970s, due to the introduction of mussels (*Mytillus edulis*) and the associated competition for food. Eutrophication after the 1970s increased the amount of food and resulted in an increase in macrobenthos and mussel biomass. During 1988-1990 the stocks of mussels declined to low values due to failing recruitment after intensive fishing for seed mussels (Beukema et al., 1993). No effect of eutrophication could be detected on settlement and growth of flatfish and shrimps on the tidal flats in the western Wadden Sea in the period 1974-1993 (Van der Veer et al., 1995a).

The exploitation of benthic organisms started already in the beginning of the last century (Brinkman and Smaal, 2003; Wolff, 2005). The stock of many anadromous fishes as sturgeon, allis shad, twaite shad and lampern decreased or even got extinct in the Wadden Sea due to human activities (Wolff, 1988, 2005). This process started already centuries ago and cumulated in the first half of the twentieth century. Bottom trawling activities also reduced the stock of many demersal fishes in the North Sea (De Vooys et al., 1991). Effects of changing fish stocks in the North Sea are reflected in the Wadden Sea because most fishes migrate between the Wadden Sea and North Sea (Zijlstra, 1979).

Van der Veer et al. (1985) showed that dredging activities in the western Wadden Sea affected the macrobenthic fauna.

De Jonge and Essink (1991) concluded that the impact of the nutrients from the Rhine is restricted to the Dutch coastal zone and the western Wadden Sea and is not extended to other parts of the Wadden Sea. In the eastern Wadden Sea no increase in neither macrozoobenthos biomass nor in the mean chlorophyll-a concentration was found as was for the western Wadden Sea (De Jonge and Essink, 1991; Van Beusekom et al. 2001; Essink et al., 2005).

The impact of increased chlorophyll-a concentrations and increased primary production on benthic organisms is difficult to assess. Beside strong winters, the interaction between phytoplankton and benthic organisms may change.
First of all, it is clear that, due to eutrophication, larger algae become more abundant. It is not clear if these larger algae are consumed by the benthic organism, or they die and are mineralized.
So, the ratio between the amount of organic matter that serves as food (grazing path) compared to the amount of organic matter that is directly mineralized (detritus path) may change during eutrophication and due to natural circumstances. Also the intensity of filtering capacity of the area may change from pelagic zooplankton to benthic organisms.

Conclusions

- **The impact of the nutrients from the Rhine is restricted to the Dutch coastal zone and the western Wadden Sea and does hardly extend to other parts of the Wadden Sea.**
- **The intertidal macrozoobenthos biomass in the western Wadden Sea (Balgzand) doubled from the 1970s to the 1990s**

7. Limiting conditions

Liebigs law of the minimum states that there is always one factor that limits growth (e.g one specific nutrient or light) (De Baar, 1994). Limiting conditions may have an effect on biomass, nutrient uptake and primary production.

7.1 Nutrients

Generally it is assumed that coastal and marine algae are nitrogen limited. It is well recognized that in coastal waters, due to eutrophication, other nutrients can become limiting. Brockmann & Kattner (1997) proposed phosphorus as a possible limiting factor during summer in the German Bight. Peeters and Peperzak (1990) used a bioassay approach and found that silicate and phosphorus are the limiting nutrients in the Dutch coastal zone (in 1988) and nitrogen offshore.

Riegman et al. (1990) found in an experimental study in the Wadden Sea that silicate was the limiting factor after the spring bloom, while later on nitrogen limitation could be possible. Bot et al. (1996) also suggested a silicate limitation for the spring bloom in the Southern Bight of the North Sea. Van Bennekom et al. (1974) concluded from the seasonal cycle of silicate that from April to September silicate was limiting diatom growth.

Van Beusekom et al. (2001) focused more on nitrogen. They stated that nitrogen is the limiting factor for primary production in the Wadden Sea because: 1) nitrogen is the limiting factor in the North Sea (Cadée and Hegeman, 1993) and therefore limits the potential amount of organic matter that can be accumulated in the Wadden Sea, 2) primary production remains at the same level despite decreasing loads and concentrations of phosphate (Cadée and Hegeman, 2002). The linear relation between riverine TN-input into the coastal zone and the amount of ammonium and nitrite in autumn in the Wadden Sea as indicators of remineralisation activity support that nitrogen regulates the organic matter dynamics in the Wadden Sea.

Philippart et al. (2000) concluded that the increase in phytoplankton production and phytoplankton biomass in the Marsdiep during 1976-1978 occurred from a phosphate-limited to a nitrogen limited system, and that later on the system became phosphate controlled in the period 1988-1994.

7.2 Light

Gieskes and Kraay (1984) found a clear light limitation in the Dutch coastal zone between 1971 and 1981: offshore higher annual averaged primary production values were measured, They concluded that nutrients are not the limiting factor in the Dutch coastal zone and that the excess of nutrients will diffuse towards open water, with a result that production will be increased there (Gieskes and Kraay, 1975; Fransz and Gieskes, 1984; Fransz and Verhagen, 1985). Colijn and Cadée (2003) applied the model of Cloern (1990) on data from the Marsdiep (1995-1996) to show the dominance of light limitation and primary production. From May to July they showed a slight nutrient limitation, probably caused by nitrogen. A decrease in annual averaged Secchi disc visibility in the Marsdiep between 1973 and 2000 is observed by Cadée and Hegeman (2002). Borkman and Smayda (1998) observed the same phenomena in twelve

eutrophic coastal areas all over the world.
Van Beusekom et al. (1999) suggested also that light limitation plays a role in the Wadden Sea. They cite Heip et al (1995) who argue that import of organic matter only supports local primary production if enough light is available. Heip et al (1995) tentatively distinguish between light limited systems (primary production below 160 $gC.m^{-2}.y^{-1}$) and light sufficient systems, where additional input of organic matter stimulates primary production. According to Van Beusekom et al. (1999), the Wadden Sea is not strictly light limited and extra input of organic matter enhances local primary production. However, the response of the Wadden Sea to import of organic matter is lower than in other areas suggesting that the light conditions are suboptimal.

Visser et al. (1996) described a decreasing concentration of suspended matter in the Dutch coastal zone in the period 1977-1993, with a strong decrease in the period 1985-1990.
They observed that the development of chlorophyll is correlated with changes in the suspended matter concentrations in the Belgium and Dutch coastal waters.

De Vries et al. (1998) established a relation between the winter concentration of dissolved inorganic nitrogen compounds and the annual amount of primary produced organic matter in different parts of the North Sea and Wadden Sea. They show that in the Dutch coastal zone light is the limiting factor.

The increasing and decreasing trend in suspended matter, found by De Jonge et al. (1996) is in contradiction with the decreasing trend of the annual mean Secchi disc visibility in the Marsdiep during 1975-2000 (Cadée and Hegeman, 2002). This could be caused by differences in sampling time in the tidal cycle and different methods (Secchi disk and filtration). However, Cadée and Hegeman argued, based on the findings of Postma (1954, 1961) that there is not a simple straightforward relation between the suspended matter concentration, measured by filtration, and the turbidity or under light climate.

Based on the relation between phytoplankton community structure and N-P molar ratio it was concluded that despite the relatively high concentration of nutrients, nutrients have a regulatory impact on species composition (Philippart et al., 2000). This colimitation of nutrients and light in the western Wadden Sea has been found also in other coastal areas (Riegman et al., 1990; Cloern et al., 1995).

7.3 Temperature

The temperature in the Dutch coastal waters had maximum values in 1982 and 1990 and lowest values in 1979 and 1986 in the period 1975-1993 (Visser et al., 1996).). Sündermann et al. (1996) found a cycle of 8 to 9 years. Between 1978 and 1987 a remarkable shift to higher temperatures was noticed in the Belgium and Dutch coastal waters between 1987 and 1989 (Sündermann et al., 1996; Visser et al., 1996). This was related to the increase in atmospheric temperature in that period due to a relatively high North Atlantic Oscillation Index (Mann and Lazier, 1991; Hurrell, 1995). Nicholls et al. 1996). These observations are in agreement with a significant higher heat content of the North Sea in the years 1988-1992 compared to the period 1983-1987 (Pohlmann, 1996). Lindeboom et al. (1995) concluded from various long-term time series of various organisms that not only in the Marsdiep and in the western Wadden Sea rather sudden changes occurred in the years at the end of the1970s and 1980s, but also in other areas. Weijerman et al (2005) analyzed these sudden changes and concluded that large-scale natural effects could explain the regime shift during the1970s in salinity and weather conditions and that the predominant factor for the shift in the 1980s was temperature and weather conditions.

In the Marsdiep area no trend in the length of the growing season of phytoplankton was observed for the period 1973-2000 (Cadée, 1989; Cadée and Hegeman 2002). They found a relation between the start of the *Phaeocystis* growth (the first data cell numbers are above 10^{-6} cells per liter) and day number. It is suggested by Cadée and Hegeman (2002) that this phenomenon could be related to the observed higher spring temperatures of the Marsdiep water (Van Aken, unpubl. results).

A strong decadal variability in the temperature in the open North Sea has been found by Lafit et al., 1996). A prominent period of 17 years was found with highest temperatures around 1960s and 1980s and lowest around 1973 (difference of about 1.7°C). These observations strongly correlate with the signal of the Northern Atlantic Oscillation Index (NAOI) with relatively high values in the sixties and eighties and lower values in the seventies (Rogers, 1985; Loewe, 1998).

It is assumed that a higher summer temperature of the water facilitates a higher grazing pressure by zooplankton as well as macrobenthos in shallow areas (Colijn and Cadée, 2003).

Beukema et al. (1992) and Beukema et al. (1995, 1996 and 1999) showed that part of the variability in the long-term time series in zoobenthos in the western Wadden Sea could be explained by extreme cold winters: 1979, 1985-1987 and 1996. Fransz and Gieskes (1984) observed that dense populations of zooplankton in the western Wadden Sea developed during periods of mild winters (1973-1975, 1988-1990).

Nutrient reduction

How big must the reduction in nutrient load be to reduce the impacts of eutrophication in coastal and marine areas? The concept that the impact responds in a predictable, often linear way, with proposed nutrient load reduction is controversial (Anonymous, 2000; Pelly, 2005). De Vries et al. (1998), Escaravage et al. (1998) and Prins et al. (1999) demonstrated in mesocosm studies that a substantial reduction (>75%) in nitrogen and phosphorus was necessary to have any effect on phytoplankton biomass and production. This was confirmed by model studies where Lenhart (2001 and 2004) calculated that a 50% reduction in nutrients did not resulted in a similar decrease in chlorophyll-a and primary production in the Dutch coastal zone. A significant response was present with nitrogen and phosphorus reductions of >80%.

Conclusions

- **The response of the Wadden Sea to import of organic matter is lower than in other areas suggesting that the light conditions are suboptimal**.
- **A reduction in nutrients does not result in a similar decrease in chlorophyll-a and primary production in the Dutch coastal zone.**

8. Implication for the impact assessment of the proposed Maasvlakte extension

Coastal ecosystems, like the Wadden Sea, are subject to continuous and ongoing changes and never reach a steady state irrespective the time frame considered. There are trends in sea level, climate and nutrient supply, interspersed by particular events such as severe winters, warm summers and regime shifts caused by the North Atlantic Oscillation Index (NAOI) that can trigger these changes.

The Dutch part of the Wadden Sea receives inorganic nutrients and particulate organic matter from the Dutch coastal zone and the IJsselmeer. Although the major part of the Dutch coastal water entering the Wadden Sea originates from the Atlantic Ocean, riverine nutrient sources are important. The impact of this input on the ecology is greatest in the western Wadden Sea and much less in the other Dutch parts of the Wadden Sea. The fluxes of water and nutrients from the Atlantic ocean, rivers and atmosphere show strong, natural inter annual variability.

Increased riverine nutrient loads in the second half of the past century have led to increased import of nutrients and particulate organic matter. The total phosphorus and nitrogen loads in the river Rhine increased in the period from 1950 to 1980 by a factor of 6 and 3, respectively. These imports resulted most probably in an increased primary production and an increased intensity of the nutrient and organic matter turnover, larger algal blooms and the appearance of black spots in the surface sediment. In other words, the western Wadden Sea had become eutrophic. A policy-driven reduction of riverine nutrient loads during the past decades resulted in a reduction of the mean annual loads of nutrients into the western Wadden Sea. Although not in a one to one relation, it appears that this reduction has resulted in a decrease in primary production, a reduction in the occurrence of black spots, and a reduction of chlorophyll concentrations (Fig.17 a.b.c.). The recent concentration of phosphorus is twice the natural background value and the nitrogen concentrations exceed the background by a factor of about five. So, despite the ongoing reduction of nutrient loads, the Western Wadden Sea is still eutrophic.

From the literature survey we conclude that apart from natural variations, nutrient loading is a major driving force for the ecology of the western Wadden Sea and that there is a significant relation between the nutrient loads of the Rhine and the IJsselmeer and the nutrient loads for the western Wadden Sea. Available data do not indicate that the constructional work carried out along the Dutch coast in the 1970s and 1980s (Maasvlakte I and the closure of sea arms in the Delta area) interfered substantially with the riverine nutrient loads and the transport of nutrients along the Dutch coast to the western Wadden Sea.

Recent model simulations show that an extension of the Maasvlakte may lead to a dilution of the riverine fresh water along the Dutch coast. This may result in a decrease of 10% in the suspended matter import into the western Wadden Sea via the Marsdiep. It is also suggested that less freshwater (10%) would enter the Wadden Sea from the coastal zone. However, it is not expected that this reduction will have major impact on the ecology of the western Wadden Sea. Based on the freshwater content in the western

Wadden Sea, the nutrient load from the IJsselmeer and riverine nutrient concentrations, the reduction of nutrient loads from the Dutch coastal zone into the western Wadden Sea is roughly estimated at about 4% for phosphorus and 5% for nitrogen.

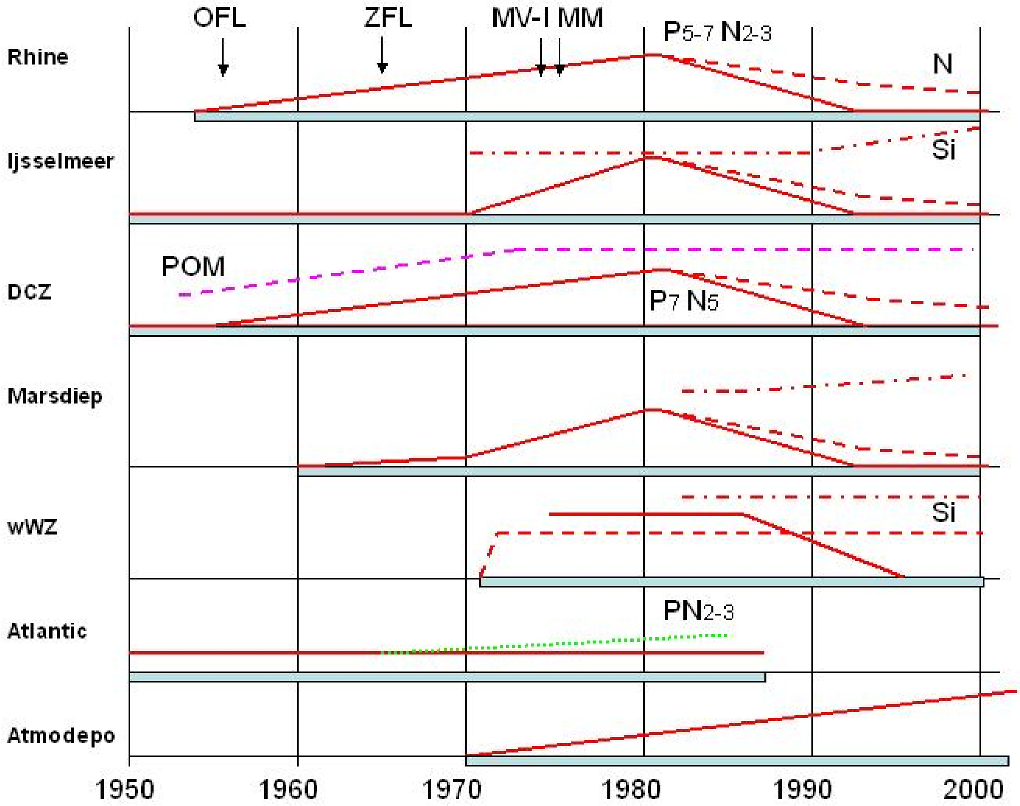
Conclusions

- **Apart from natural variations, nutrient loading is a major driving force for the ecology of the western Wadden Sea; there is a significant relation between the nutrient loads of the Rhine and the IJsselmeer and the nutrient loads for the western Wadden Sea.**

- **The recent concentration of phosphorus is twice the natural background value and the nitrogen concentrations exceed the background by a factor of about five. So, despite the ongoing reduction of nutrient loads, the Western Wadden Sea is still eutrophic.**

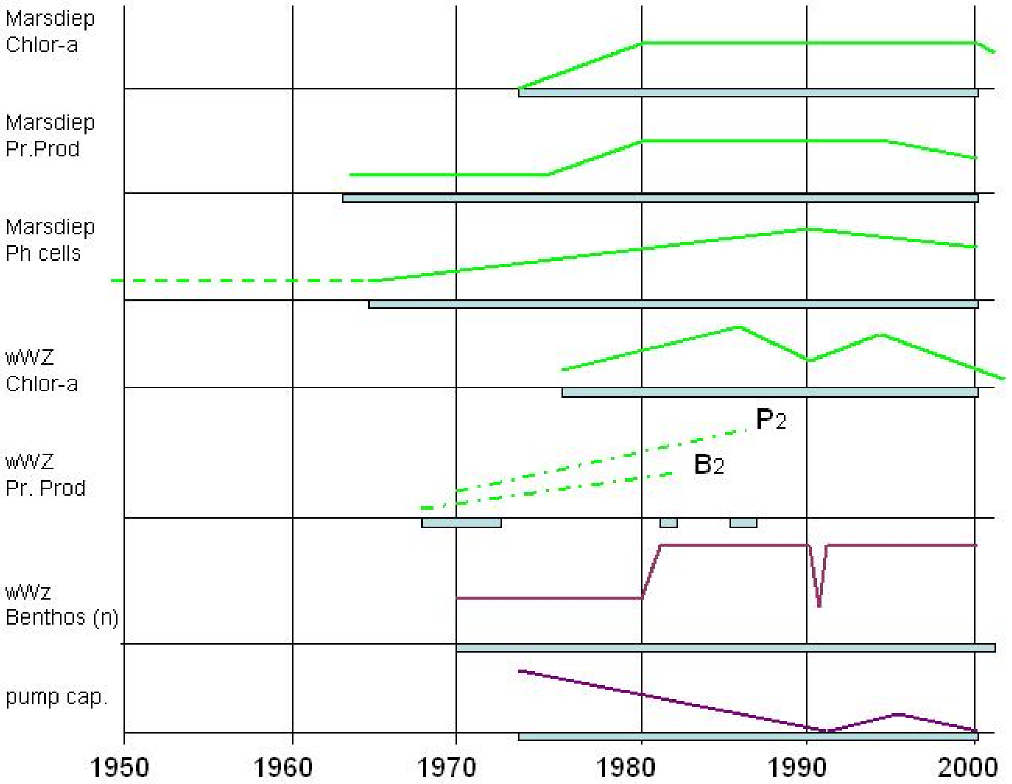
- **Available data do not indicate that major constructional works carried out along the Dutch coast in the 1970s (Maasvlakte I and the closure of sea arms in the Delta area in the 1970s and 1980s) strongly interfered with the riverine nutrient loads and the transport of nutrients along the Dutch coast to the western Wadden Sea.**

- **A decrease of 10% of the input of fresh water and particulate organic matter from the coastal zone will result in a decrease of phosphorus and nitrogen concentrations in the western Wadden Sea by about 4 and 5% respectively.**

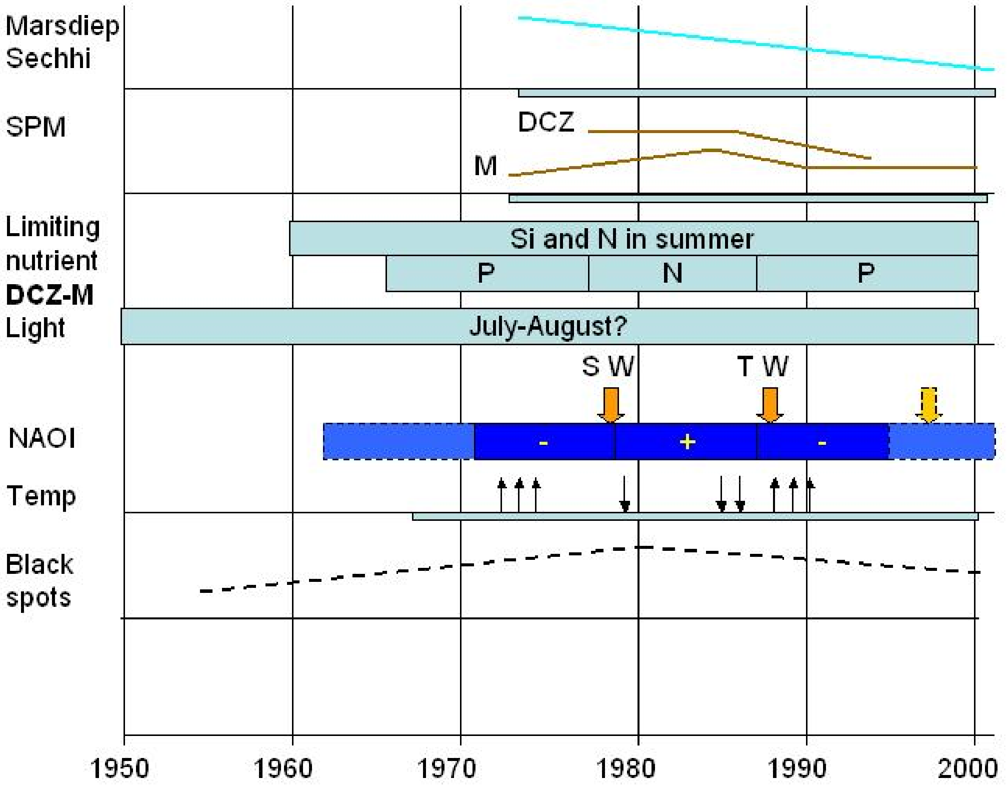


17a Schematic overview of the long-term changes in the input of nutrients (N, ------; P, _____ and Si, -.-.-.-.- .-., numbers e.g 5-7 indicate times increase compared to background values) from the Rhine, IJsselmeer, Dutch coastal zone (DCZ), the Atlantic Ocean and Atmospheric deposition to the western Wadden Sea (wWZ). Blue balk represent the period of sampling. Dotted green line: suggested change. POM and pink line: Particulate organic matter.

Arrows indicate the years when coastal interventions and extensions took place: OFL and ZFL = Oost and Zuid Felvoland, 2 polders in the IJsselmeer, MVI = Maasvlakte I, coastal extension just south of Rotterdam; MM = Markermeer, closer of Houtribdijk in IJsselmeer



17b Schematic overview of possible impact of increased nutrient concentration on the concentration of chlorophyll-a, the annual averaged amount of primary production, the number days the amount of *Phaeocystis* cells are above 10^6 cells per liter , the number of zoobenthos and its pumping capacity in the Marsdiep area and in the western Wadden Sea.



17c Schematic overview of physical circumstances that could have an impact on the status of an aquatic ecosystem. Secchi disk visibility, SPM = concentration suspended matter after filtration, Suggested periods for nutrient limitation, indicated is the limiting nutrient: DCZ-M = Dutch coastal zone and Marsdiep, NAOI = Northern Atlantic Oscillation Index, temperature and the area of black spots in the Wadden Sea

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