

# Patterns and trends in nutrients and phytoplankton in Dutch coastal waters: comparison of time-series analysis, ecological model simulation, and mesocosm experiments

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In the Dutch coastal zone, nutrient and chlorophyll concentrations show gradients of up to one order of magnitude perpendicular to the coast within the first 30–50 km offshore. Time-series analysis reveals significant decreasing trends for dissolved inorganic phosphorus (40%) and total phosphorus (35%) and an increase in the dissolved inorganic N:P ratio from 25–30 to 40–55 over the period 1988–1995. Trends in nitrogen (–15%), silicate (stable), and chlorophyll are smaller and generally not statistically significant. The trends in phosphorus reflect a proportional and immediate response to decreasing riverine inputs. The observed trends, spatial gradients, and long-term seasonal patterns are simulated quite well with a coupled physical–ecological model with high spatial resolution for the coastal zone. The model results indicate no effect of decreasing phosphorus, but an important role for both nitrogen and light climate in primary production and algal biomass. These results have been reproduced in mesocosm experiments. Moreover, these experiments indicate a strong response of primary production and chlorophyll to nitrogen load, whereas secondary production (macrobenthos) remains relatively stable. Ecological efficiency of secondary production increases from 7% to >10%, with a decrease in nitrogen loading by 50% from the present level. In the absence of a significant nitrogen reduction in coastal waters, the mesocosm results cannot be related to field data as yet. However, the expectation is that reducing nitrogen inputs will not affect productivity at higher trophic levels to any great extent.

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**Key words:** coastal eutrophication, ecological efficiency, mesocosm experiments, model simulation, nutrients (phosphorus, nitrogen, N:P ratio), productivity, riverine inputs, trend analysis.

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## Introduction

The North Sea is part of the north-west European Shelf and is open to the Atlantic Ocean in the north, to the English Channel in the south, and to the Baltic in the east. The circulation is counter-clockwise and is strongly influenced by the inflow through the open boundaries. Consequently, Dutch coastal waters are subject to the transport of nutrients through the Channel. With a mean residual current through the Channel to the southern North Sea of  $114.10^3 \text{ m}^3 \text{ s}^{-1}$  (Salomon *et al.*, 1993)

and nutrient concentrations according to Laane *et al.* (1993), the annual transport amounts to 400 ktonnes DIN (dissolved inorganic nitrogen), 1000 ktonnes total-N, 60 ktonnes DIP (dissolved inorganic phosphorus), 140 ktonnes total-P, and 360 ktonnes DISi (dissolved inorganic silicate). These inputs into the southern North Sea are comparable to the local supply of nutrients from the river systems debouching into the Dutch coastal waters. The annual loads (average 1975–1995) of Schelde, Maas, and Rijn amount to 380, 22, and 206 ktonnes DIN, DIP, and DISi, respectively

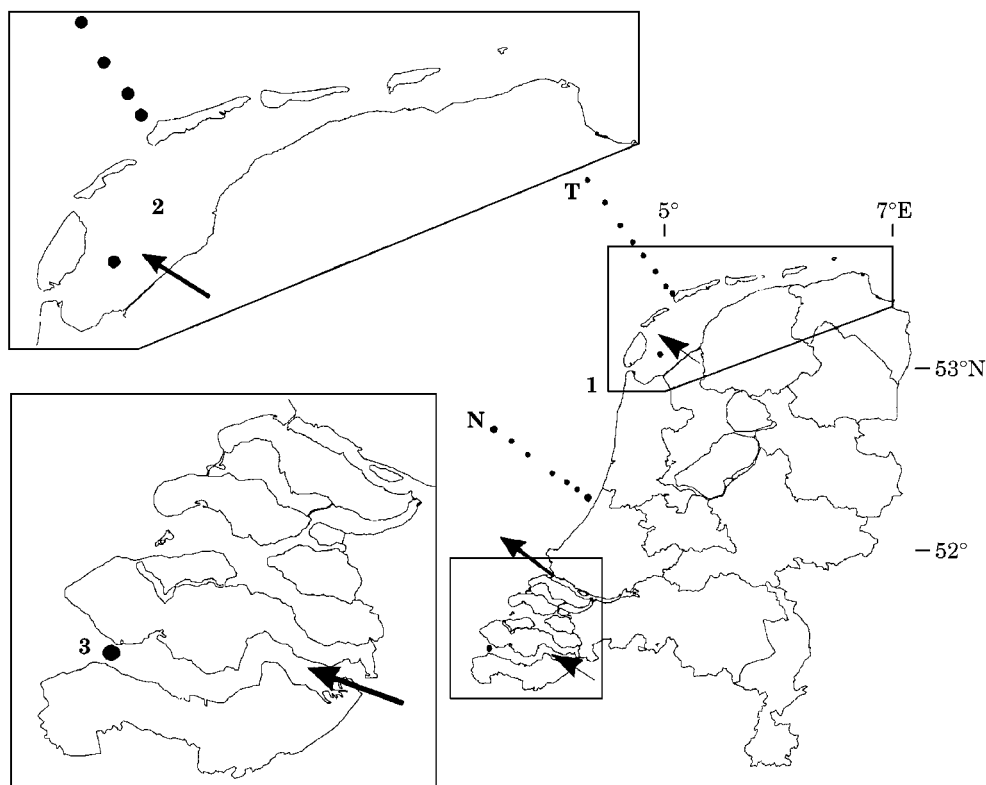


Figure 1. Study area and main sampling locations: (1) coastal zone with Noordwijk (N) and Terschelling (T) transects; (2) Wadden Sea; and (3) Westerschelde estuary. Arrows indicate local nutrient supply from freshwater inputs.

(data Rijkswaterstaat). This paper focuses on the influence of oceanic and riverine inputs on the eutrophication of Dutch coastal waters, in particular on nutrient concentration patterns, their variability, and long-term trends, and the effects of these on phytoplankton concentration (chlorophyll), and primary and secondary production.

## Material and methods

### Study area and data

The study area (Fig. 1) includes the Dutch coastal waters of the North Sea, the western part of the Wadden Sea, and the Westerschelde estuary. The coastal zone receives local supply of nutrients from the rivers Rijn and Maas combined via the discharge sluices of the Haringvliet and the canalized river-mouth of the Rijn, the Nieuwe Waterweg. The western Wadden Sea receives coastal water via the Marsdiep tidal inlet and a local freshwater and nutrient input from the IJsselmeer. The water in this lake originates mainly from the Rijn, but its quality is influenced by the long hydraulic residence time of the lake. The Westerschelde receives freshwater and nutrient input from the Schelde river.

Data on dissolved inorganic nitrogen (sum of ammonium, nitrite, and nitrate), phosphate, and silicate (DIN, DIP, and DISi) and chlorophyll for a 20-year period (1975–1995) are available from the monitoring programme by Rijkswaterstaat. These include (1) two transects in the coastal zone perpendicular to the coast, the Noordwijk transect near the Rijn/Maas outflow, and the Terschelling transect to the north, with emphasis on the stations near the coast (2–4 km), (2) six stations in the western Wadden Sea with emphasis on the central station, and (3) nine stations along the salinity gradient in the Westerschelde with emphasis on the station at the mouth of the estuary. The main stations are depicted in Figure 1. Riverine inputs are calculated from daily-weekly water discharge data and biweekly monthly freshwater quality data.

### Time-series analysis

The available data set for 1975–1995 contained bi-weekly (summer) and monthly (winter) data. The time series were made equidistant in time by linear interpolation of the dissolved nutrients and of the log-transformed values of chlorophyll and the particulate substances.

The trend analysis is based on a linear regression model which includes trend, salinity, seasonal component, and correction for the autoregressive error. The correction is needed because the data are serially correlated, which violates the statistical assumptions of the ordinary regression analysis. The following model was used:

$$y_{it} = \beta_{0,i} + \beta_{1,i} \times \text{time} + \beta_{2,i}(\text{sal}_{i,t} - \overline{\text{sal}_i}) \\ + \gamma_{i,j} \times \text{month}_j + v_{i,t}, \\ v_{i,t} = \varepsilon_{i,t} + \varphi_{i,1}v_{i,t-1} + \dots + \varphi_{i,m}v_{i,t-m}, \\ \varepsilon_{i,t} \sim \text{NI}(0, \sigma_\varepsilon^2),$$

with  $y_{it}$  as the variable at location  $i$  and time  $t$ ,  $\beta_{0,i}$  a constant for location  $i$ ,  $\beta_{1,i}$  the trend coefficient of location  $i$ , the variable time is in years,  $\beta_{2,i}$  the coefficient which gives the correlation with the salinity at location  $i$  ( $\text{sal}_{i,t}$ ),  $\gamma_{i,j}$  the deterministic month coefficient at location  $i$  and  $\text{month}_j$  a dummy value with 1 if  $\text{month}_j = j$  and 0 otherwise. The error term  $v_{i,t}$  is modelled as an  $m$ th-order autoregressive process with  $\varepsilon_t$  normally (N) and independently (I) distributed. To meet the assumptions of  $\varepsilon_{i,t}$ , the dissolved nutrients and particulate variables had to be transformed by taking the square root and the logarithm, respectively.

Data on dissolved nutrients are available for 1975–1995. A segmented trend with a breakpoint in 1986 was included in the variable time, because this breakpoint gave the best explanation of the total variation in DIP. The variable salinity was included in the equation because part of the variation in the concentrations was due to local differences in salinity other than the average seasonal pattern.

Unfortunately, the particulate variables (chlorophyll, total-P, and total-N) were measured correctly only from 1988 onwards. Also, some sampling locations were excluded from the monitoring programme during 1983–1987. Therefore, comparison of trends between all variables was only possible for the period 1988–1995. A separate analysis of the dissolved nutrients revealed that the trends for 1986–1995 and for 1988–1995 were not significantly different, and that all trends for the period 1975–1985 were not significantly different from zero. Therefore only results for 1988–1995 are presented.

### Ecological model simulation

For model simulation, the North Sea BLOOM water quality model has been applied to a fine resolution grid of the Dutch coastal region (Peeters *et al.*, 1992). The freshwater version of the model has been applied to various shallow Dutch lakes (Los *et al.*, 1984; Los and Brinkman, 1988; van der Molen *et al.*, 1994). For modelling of the near field (i.e. coastal) effects of eutrophication, resolution of the steep spatial and temporal gradients is considered necessary. The model

area is a band with a width of approximately 70 km extending from the Westerschelde estuary in the south up to and including the western Wadden Sea in the north (Fig. 2). The grid and transport are derived from a 3D hydrodynamic model of the Dutch coast (Kok *et al.*, 1995). Residual flows computed for average wind conditions, with a dispersive correction factor for other wind directions, are used as input to the water quality calculations, i.e., a quasi-actual wind forcing is used. The water quality model uses a 2D (vertically averaged) horizontally aggregated schematization. The grid consists of over 2000 elements with varying sizes of about  $1 \times 1$  km near the coast up to a few square kilometres at the open sea boundaries. Nutrient cycles (N, P, Si) and phytoplankton are calculated for the 20-year period (1975–1994) using monthly riverine loads as input. The light climate in the water is calculated explicitly, including extinction by detritus, algae, suspended matter, and yellow substance. The algal community is distinguished into four functional groups possessing dynamically varying C:N:P:Si ratios and adaptive affinity to light: diatoms, flagellates, dinoflagellates, and *Phaeocystis*. Model results on species composition are not presented here. The limiting factors for algal growth (N, P, Si, or light) are also calculated.

### Mesocosm experiments

The mesocosm experiments were carried out in six land-based black polyethylene tanks (height 3 m, volume 3000 l) flushed with sea water (residence time of 30 days). Water was continuously mixed and fouling of the walls was prevented. Each tank contained 150 l artificial sediment and was connected to benthos chambers, enabling solute and particle exchange between the pelagic system and the benthos. Fluorescence, oxygen, pH, temperature, and conductivity were measured continuously. Water samples were taken twice a week, and analysed for particulate and dissolved carbon and nutrients and phytoplankton biomass and composition. Primary and bacterial production and zooplankton were measured weekly. The growth rate of the benthos was calculated from the weight increase during the experiments (Escaravage *et al.*, 1995, 1996; Prins *et al.*, 1995a, b).

The experiments reported here were carried out from March to September 1995, with a preceding acclimation period of one month. Three different treatments (high, medium, and low nutrient loads) with replicates of daily additions of inorganic nutrients were used. The high treatment (average daily additions, including input by flushing, of  $11.7 \text{ mmol m}^{-2}$  DIN,  $0.31 \text{ mmol m}^{-2}$  DIP and  $2.85 \text{ mmol m}^{-2}$  DISi) resembles the present (1990–1995) situation in the Dutch coastal zone at approximately 10 km offshore.

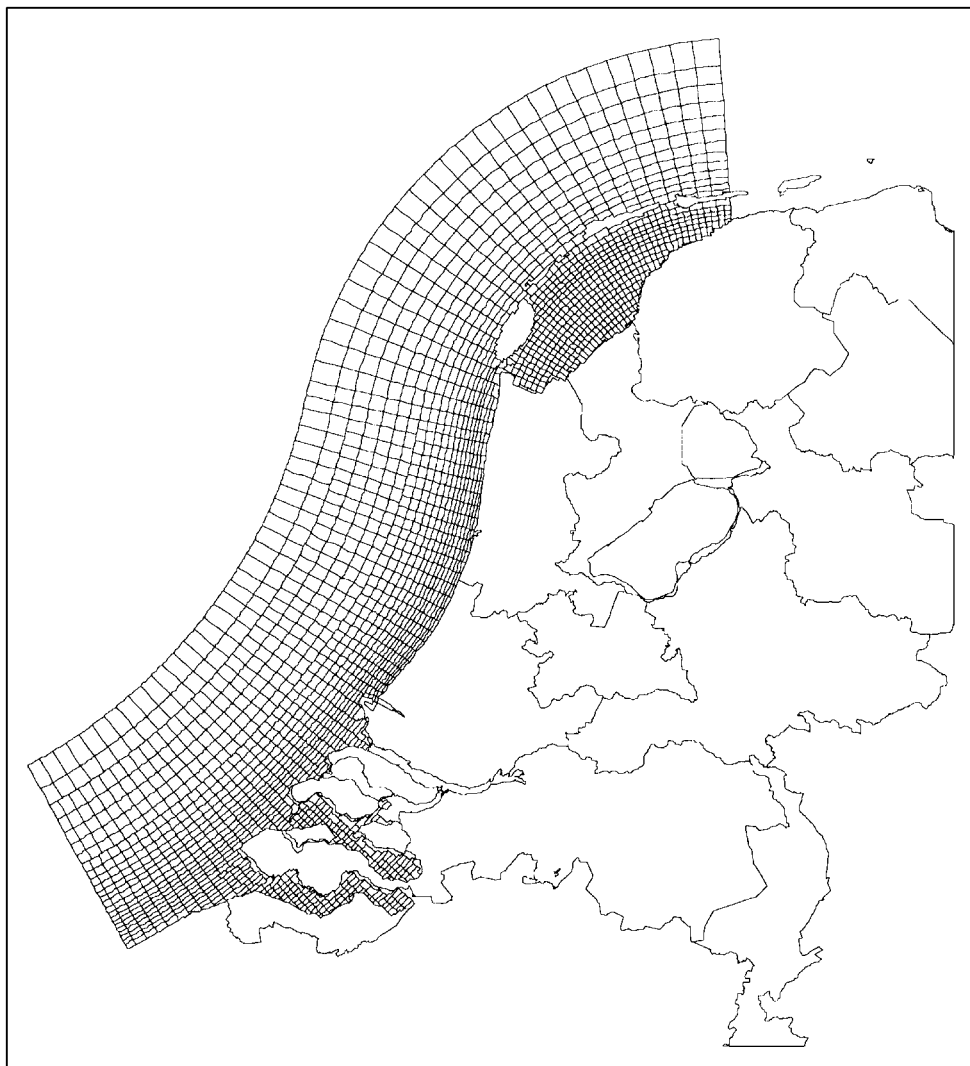


Figure 2. Area and grid of the 2D simulation model.

## Results and discussion

### Observed seasonal patterns and nutrient–salinity relations

Figs 3–6 show the long-term seasonal behaviour of concentrations in fresh water and coastal waters and the nutrient–salinity relations for the winter concentrations. The seasonal patterns of DIN (Fig. 3) in fresh water and coastal waters are fairly comparable, but the spring depletion, caused by phytoplankton uptake, is faster and deeper in the coastal waters. The winter concentrations show a linear relation along the salinity gradients including the freshwater end members, indicating conservative behaviour. Only the winter concentrations in the Wadden Sea are lower than expected from simple dilution. This may be explained by nitrogen removal

through denitrification (Seitzinger, 1988; Pitkänen and Tamminen, 1995).

For DIP (Fig. 4), there is no resemblance at all between the seasonal patterns in freshwater and coastal waters, and they also differ from DIN. The relationship with salinity shows distinct deviations from conservative behaviour along the salinity gradient. The differences between coastal and freshwater DIP, compared to DIN, can be explained by the phosphate buffer mechanism in relation to suspended matter dynamics (Froelich, 1988; van Beusekom and de Jonge, 1994) and by the higher mobility of phosphate in marine sediments (Caraco *et al.*, 1990). Thus, the spatial and seasonal patterns of DIP in shallow coastal waters are not only influenced by biological uptake and regeneration, but also by sorption dynamics. DIP starts decreasing already in December–

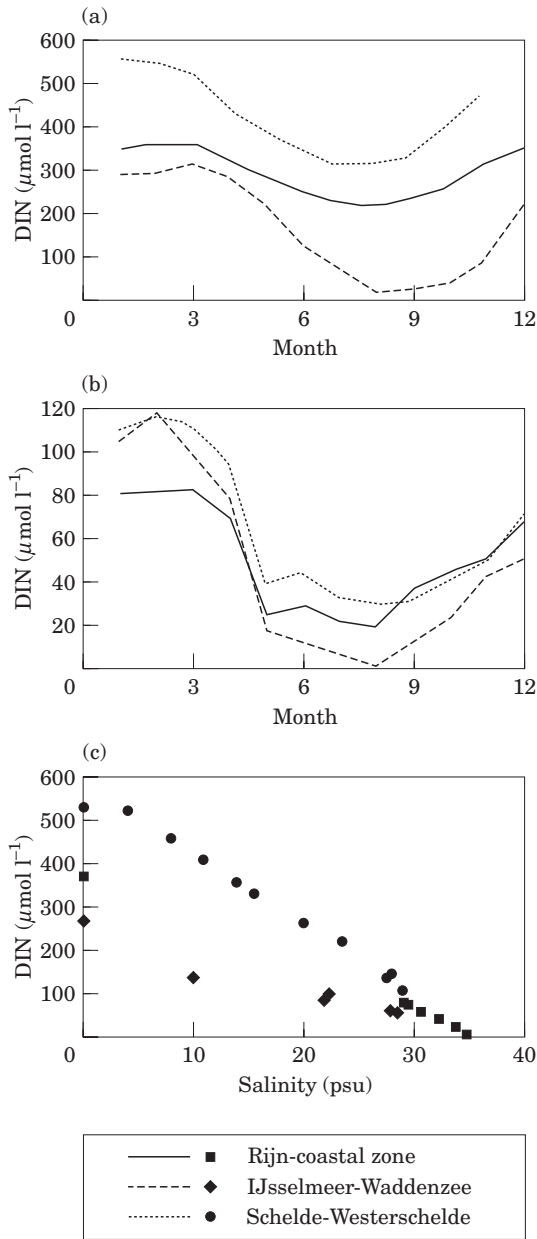


Figure 3. Dissolved inorganic nitrogen (DIN): long-term average seasonal pattern in three freshwater sources (a) and the three adjacent coastal areas (b) and relationship with salinity during winter (c; means over December, January, February), 1975–1995.

January, i.e. several months before the biological uptake and the DIN decrease. The DIP increase starts in May immediately after the spring bloom, whereas biological uptake and DIN depletion continues for several months. The winter decrease of DIP is probably caused by adsorption due to the increasing oxygen content of the sediment. Similarly, the summer increase may be caused

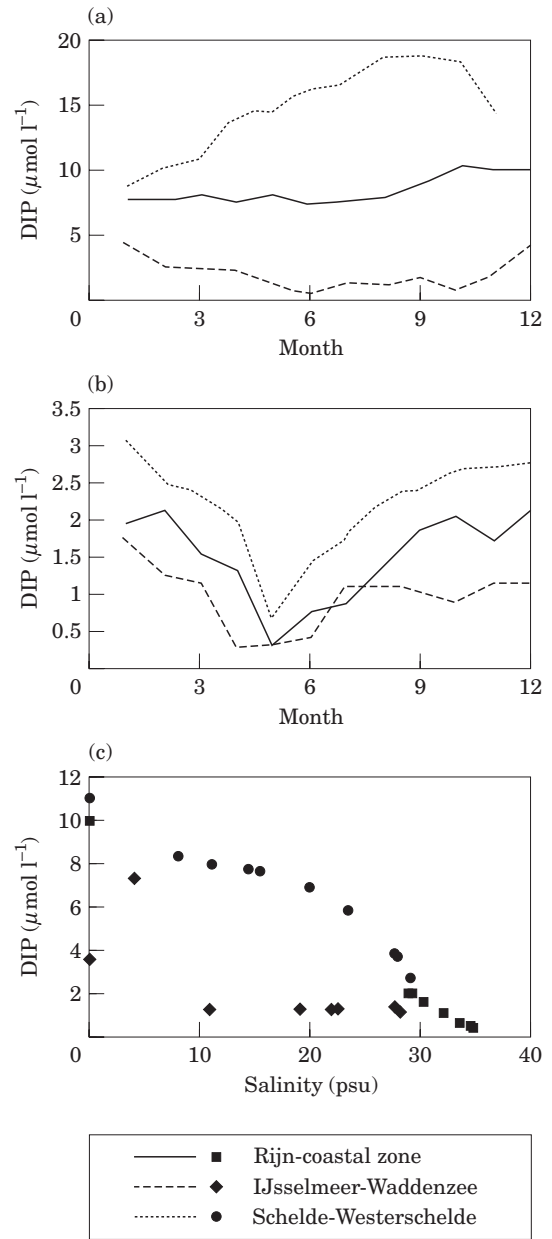


Figure 4. Dissolved inorganic phosphorous (DIP): as Figure 3.

by desorption due to the decreasing oxygen content of the sediment, induced by the oxygen demand of detritus from the spring bloom.

The differences between the two nutrients are further illustrated by the seasonal patterns in the N:P ratio (Fig. 5). The freshwater values are well above the ratio of 16 for marine phytoplankton uptake (Redfield *et al.*, 1963), especially during winter, when water discharges are highest. The coastal waters develop an even higher N:P ratio compared to fresh water during winter and spring, due to P-adsorption to the sediment and

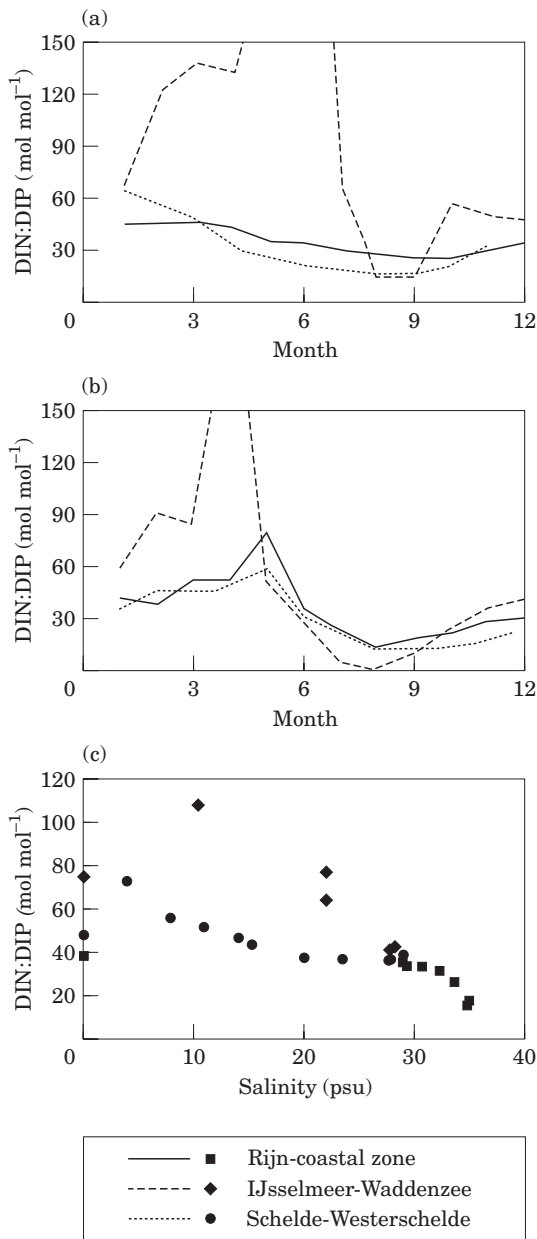


Figure 5. DIN:DIP ratio: as Figure 3.

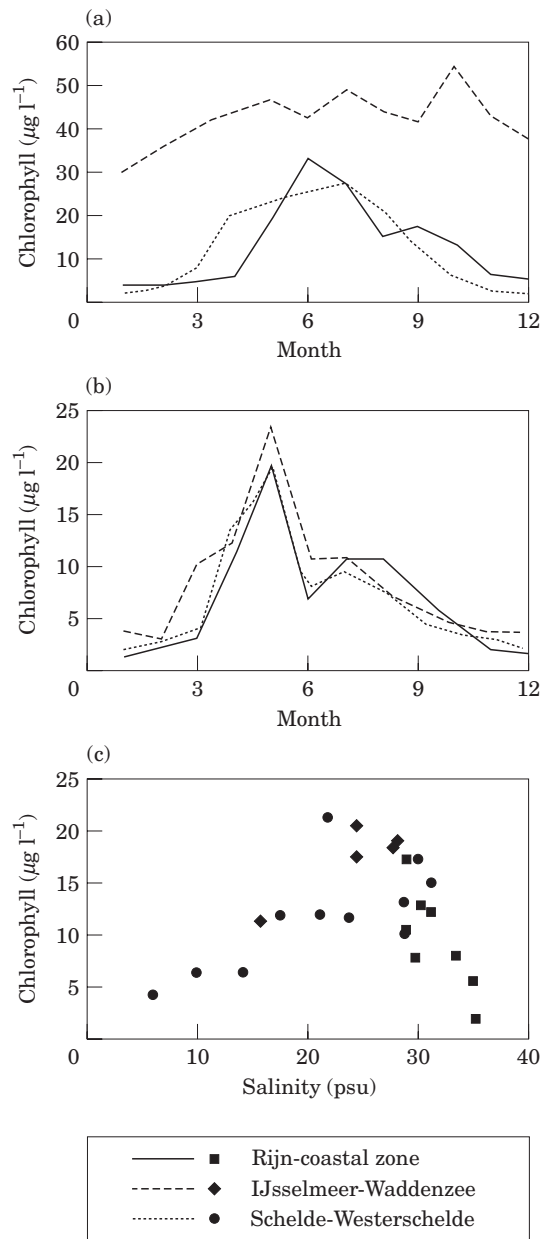


Figure 6. Chlorophyll concentration: long-term average seasonal pattern in three freshwater sources (a) and the three adjacent coastal areas (b) and relationship with salinity during summer (c; means over May, June), 1975–1995.

P-depletion by the spring bloom. During summer, however, i.e. during most of the growing season, the N:P ratio in the coastal waters decreases to values below the Redfield ratio. This is caused by the combination of P-desorption from the sediment and continued N-depletion by biological uptake. These results clearly demonstrate some fundamental dynamical properties of estuaries and coastal waters with long residence times, which are induced by non-conservative behaviour of nutrients and result in non-linear gradients against salinity:

- the capacity to either mobilize or immobilize phosphate by sorption processes
- the tendency towards lower N:P ratios by denitrification and biological uptake
- the transition from potential P-limitation of algal biomass during the spring bloom to potential N-limitation during summer (see also de Vries *et al.*, 1996).

The phytoplankton biomass dynamics measured as chlorophyll are largely similar in the three coastal water systems considered here (Fig. 6). As expected, the behaviour is independent of freshwater chlorophyll. An interesting feature is the high concentration in the IJsselmeer during winter when water discharge is highest. This chlorophyll represents a readily degradable organic load to the Wadden Sea equivalent to  $>1 \mu\text{mol P l}^{-1}$ , which is considerable compared to the DIP concentration (Fig. 4).

The peak of the spring bloom is in early May in all three water systems, which is 1–2 months later than in offshore areas of the southern Bight (Joint and Pomroy, 1992). The light climate is the decisive factor for the timing of the spring bloom, i.e. the combination of depth, turbidity, and the amount of solar radiation during the preceding months (Cadée, 1986). The reduced light conditions by increased turbidity is also the cause of decreasing chlorophyll at lower salinities (Fig. 6).

This is further illustrated in Figure 7, showing long-term averaged data for the salinity range 28–35 in the Dutch coastal zone. The nutrient–salinity relations are perfectly linear in this area and agree, when extrapolated to zero salinity, with the freshwater end members of the relation (cf. Figs 3 and 4). Apparently, this conservative behaviour of the winter concentrations is related to the absence of estuarine conditions. The canalization of the river mouth in the Rijn/Maas–North Sea transition zone and the rapid flushing may have contributed to this situation.

Chlorophyll increases with decreasing salinity to  $15\text{--}20 \mu\text{g l}^{-1}$  at 32 and levels off at lower salinities and concomitant higher nutrient concentrations. This suggests that other factors, viz. the light climate, limit phytoplankton biomass when nutrient availability increases above winter levels of  $1\text{--}1.5 \mu\text{mol l}^{-1}$  DIP and  $30\text{--}40 \mu\text{mol l}^{-1}$  DIN. An extrapolation to annual primary production is possible because chlorophyll has been found to be a good predictor for primary production, when the factors governing light climate are taken into account (Bot and Colijn, 1996). Van Beusekom and Diel-Christiansen (1994) found good agreement between winter nitrate concentrations and annual production for different parts of the North Sea. Compiled average data range from  $75 \text{gC m}^{-2} \text{year}^{-1}$  coinciding with  $6 \mu\text{mol l}^{-1}$  winter DIN concentration for the northern UK coast to  $250 \text{gC m}^{-2} \text{year}^{-1}$  and  $22 \mu\text{mol l}^{-1}$  DIN for the German Bight. This range agrees well with a levelling off of the production up to  $300 \text{gC m}^{-2} \text{year}^{-1}$  ( $185\text{--}440$ ; Peeters *et al.*, 1991) at  $\geq 30 \mu\text{mol l}^{-1}$  DIN in the nearshore area of the Dutch coast (Fig. 8).

#### Relation between river loads and concentrations at sea

Figure 9 is an example of the results of time-series analysis for one station. The structured statistical model

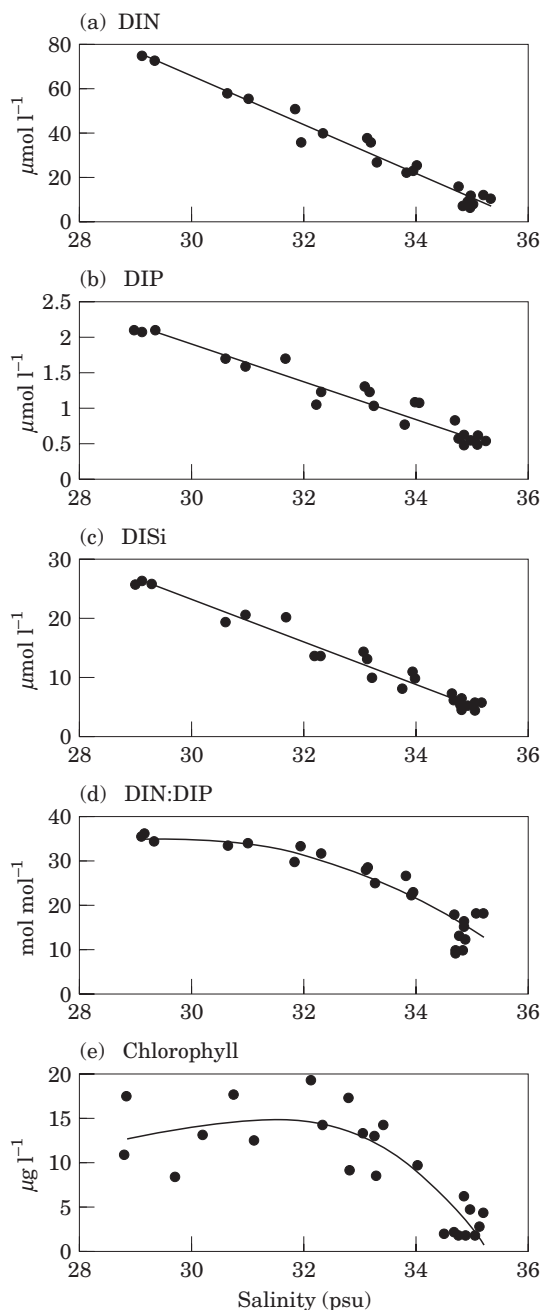


Figure 7. Long-term average winter nutrients and summer chlorophyll against salinity along the Noordwijk and Terschelling transects in the Dutch coastal zone, 1975–1995.

explains in general  $>80\%$  of the variation in the original data. No significant increasing or decreasing trends were found for the period 1975–1985 at any of the stations. Table 1 presents the linearized trends since 1988 for the main sampling stations in the three coastal water systems. The main finding is that DIP and total-P decreased

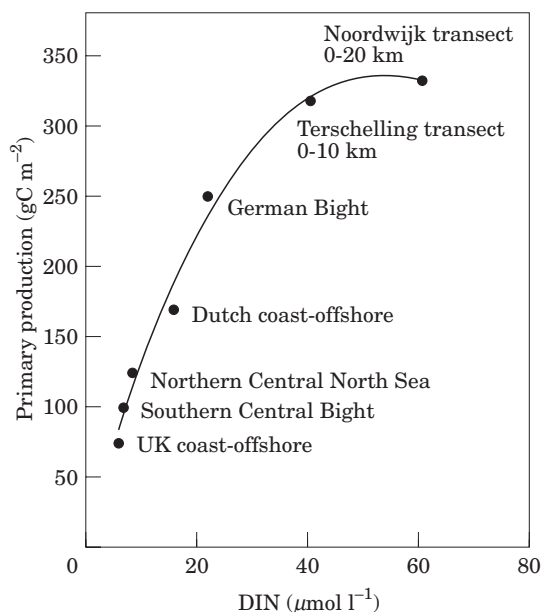


Figure 8. Relation between annual primary production and winter DIN concentration in different locations within the North Sea (after van Beusekom and Diel-Christiansen, 1994; data for Noordwijk and Terschelling transect from Peeters *et al.* 1991).

Table 1. Trends for the period 1988–1995 expressed as percentage change of the January values (nutrients) and the summer values (chlorophyll) in 1995 compared to 1988. Non-significant trends are indicated by 'ns', other trends are significant at  $p < 0.05$ .

	Coastal zone	Wadden Sea	Westerschelde
Total N	-15	-35	-13
Total P	-38	-36	-38
Tot N/totP	+32	-7 ns	+39
DIN	-17	-18 ns	-18
DIP	-53	-42	-23
DIN/DIP	+89	+41 ns	+4 ns
DISi	-2 ns	+16 ns	-17
Chlorophyll	+5 ns	-10 ns	+35 ns

significantly in all cases by 25–50% for DIP and >35% for total-P over 8 years. For DIN and total-N, smaller and not always significant trends were detected. The differences between P and N cause considerable and statistically significant increases of inorganic dissolved and total N:P ratios in the coastal zone. No significant trends were found for silicate and chlorophyll, with the exception of a silicate decrease at the mouth of the Westerschelde. Figure 10 illustrates spatial differences in the trends for the Noordwijk transect in the coastal zone. The decreasing trend for DIP by approximately

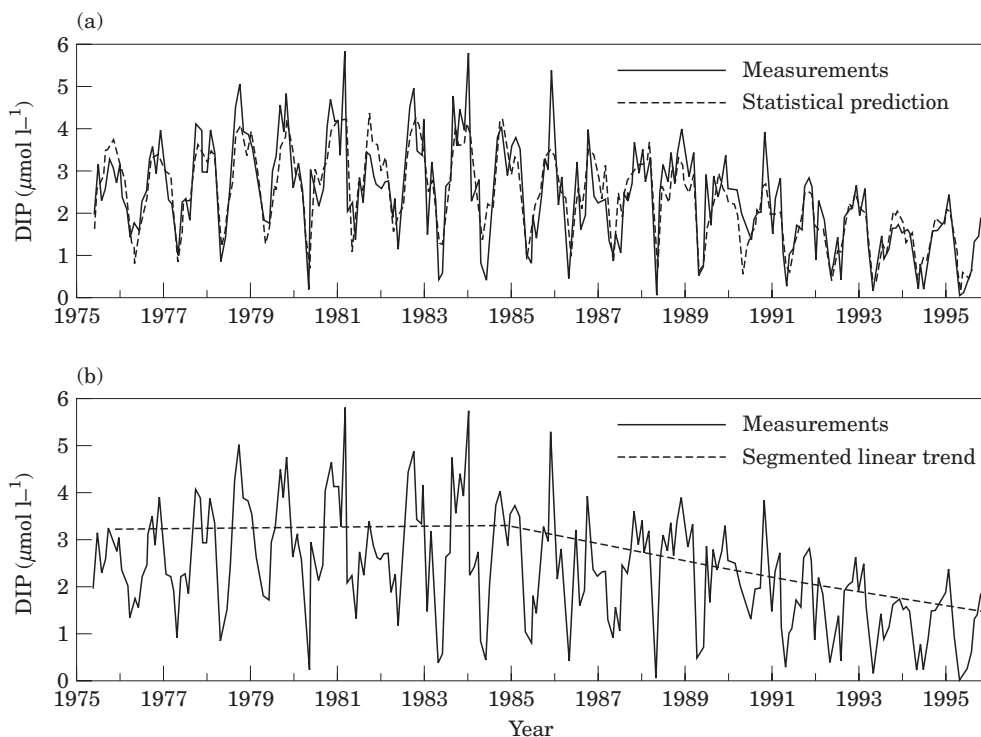


Figure 9. Example of results of time-series analysis: DIP measurements at the Noordwijk transect <10 km off the coast, compared with the statistical prediction of the concentration (a) and the segmented linear trend (b) for the January concentration (see text).



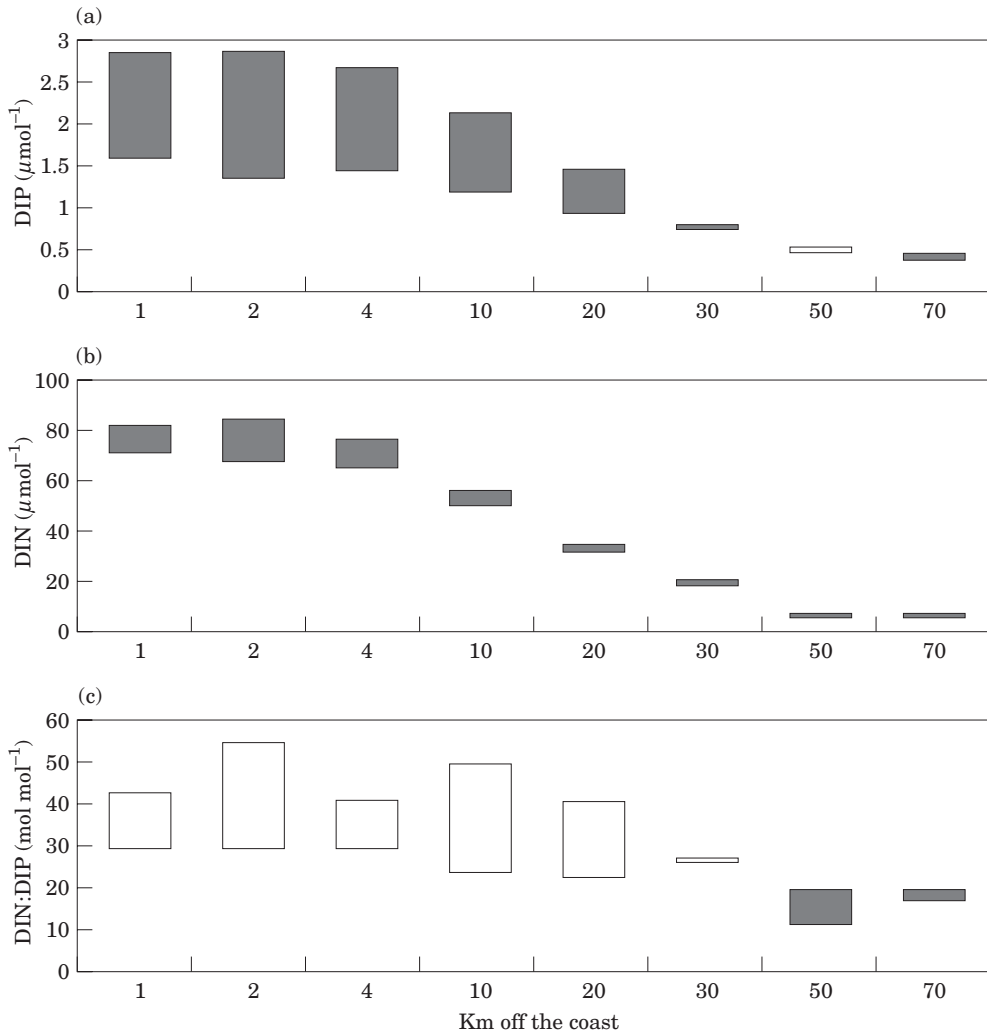


Figure 10. Spatial pattern in trends in DIP (a), DIN (b), and DIN:DIP ratio (c) along the Noordwijk transect. Boxes indicate the difference in winter concentrations (open: increase; hatched: decreases) between 1988 and 1995.

40% was apparently restricted to the elevated concentrations within 20 km distance from the coast. The low concentrations further offshore remained virtually unchanged. The smaller (10–20%) DIN decreases are also restricted to the elevated nearshore concentrations. The ratio of the two nutrients, which was already well above the Redfield ratio of 16, has increased further to 40–55 in the nearshore area.

In the case of conspicuously decreasing trends (i.e., DIP in the three systems), the correlation between the annual nutrient loads from fresh water and the concentration in the receiving coastal water during the succeeding winter months is significant (Fig. 11). The y-intercepts for DIP ( $1\text{--}1.5\ \mu\text{mol l}^{-1}$ ) are comparable to the winter concentrations at coastal stations in the Channel (Laane *et al.*, 1993), indicating the background concentration induced by the Channel inflow including

the river water component originating from the River Seine (van Bennekom and Wetsteijn, 1990).

In general, these results indicate (1) local supply of nutrients from fresh water as the main if not the only factor for elevated concentrations in nearshore coastal areas (see also van Bennekom and Wetsteijn, 1990) and (2) an immediate and proportional response of nutrient concentrations in nearshore coastal areas to decreasing riverine inputs. It is surprising that the non-conservative behaviour of DIP in the transient zone and the independent seasonal patterns do not cause a delay in the response beyond the seasonal cycle. The absence of substantial internal loading after reduction of the external input was only expected for the Wadden Sea, because most of the sedimentary phosphorus seems to be associated with Ca (Raaphorst *et al.*, 1988; de Jonge *et al.*, 1993; Danen-Louwerse *et al.*, 1995).

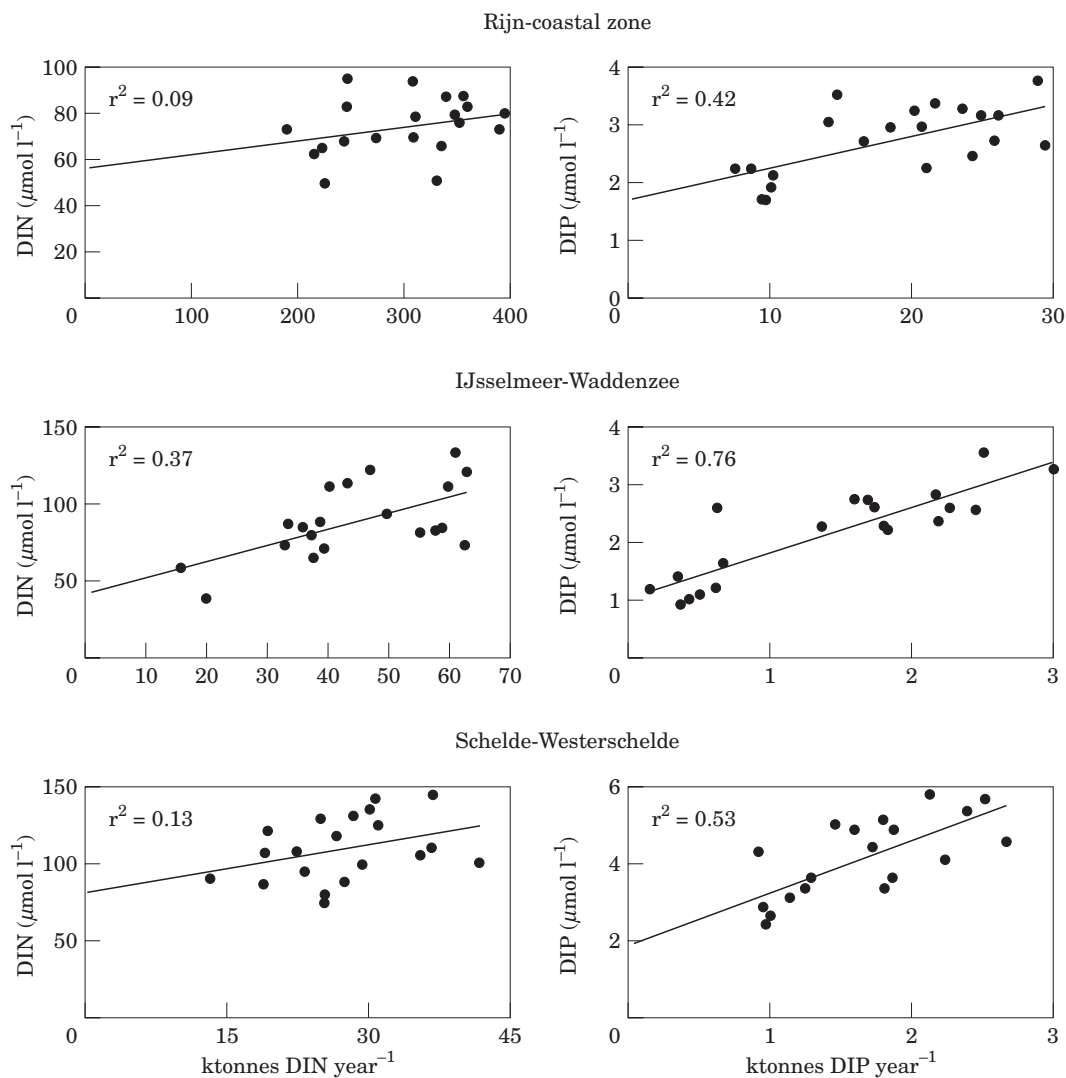


Figure 11. Correlations between annual loads (ktonnes year<sup>-1</sup>) of DIN and DIP from freshwater input and concentrations (μmol l<sup>-1</sup>) during the succeeding winter in the three coastal areas.

The highest concentrations encountered in the coastal zone around 1980 (Fig. 9) are a factor 3–5 (DIP) and 4–7 (DIN) above the background induced by the Channel input. Compared with background estimates for the Atlantic Ocean (0.75 and 10 μmol l<sup>-1</sup> for DIP and DIN, respectively; van Beusekom and Diel-Christiansen, 1994), offshore concentrations in the North Sea (0.5 and 10 μmol l<sup>-1</sup>, respectively; Fig. 10) and coastal waters in more pristine conditions (<1 μmol l<sup>-1</sup> DIP; Kalle, 1937), the elevations are a factor 4–7 (DIP) and 9–14 (DIN). The present DIP concentrations are comparable to the highest concentrations at coastal stations in the Channel, but are still a factor 2–3 above the marine background values. Also, they are slightly higher than the level at which limitation

of the algal biomass could be expected (Fig. 7). In conclusion, the actual DIP concentrations in the near-shore coastal zone of the North Sea and in other Dutch coastal waters can still be considered as being elevated by anthropogenic nutrient supply through freshwater discharges.

Other studies of trends in nutrients and eutrophication in other coastal areas, e.g. Skagerrak-Kattegat (Aure *et al.*, 1996; Andersson, 1996) describe increasing trends at much lower concentration levels, but do not reveal decreasing trends as yet. Only Hickel *et al.* (1993) describe comparable developments for the German Bight, i.e. decreasing phosphate concentrations, no conspicuous changes in nitrate and no downward trend in phytoplankton.

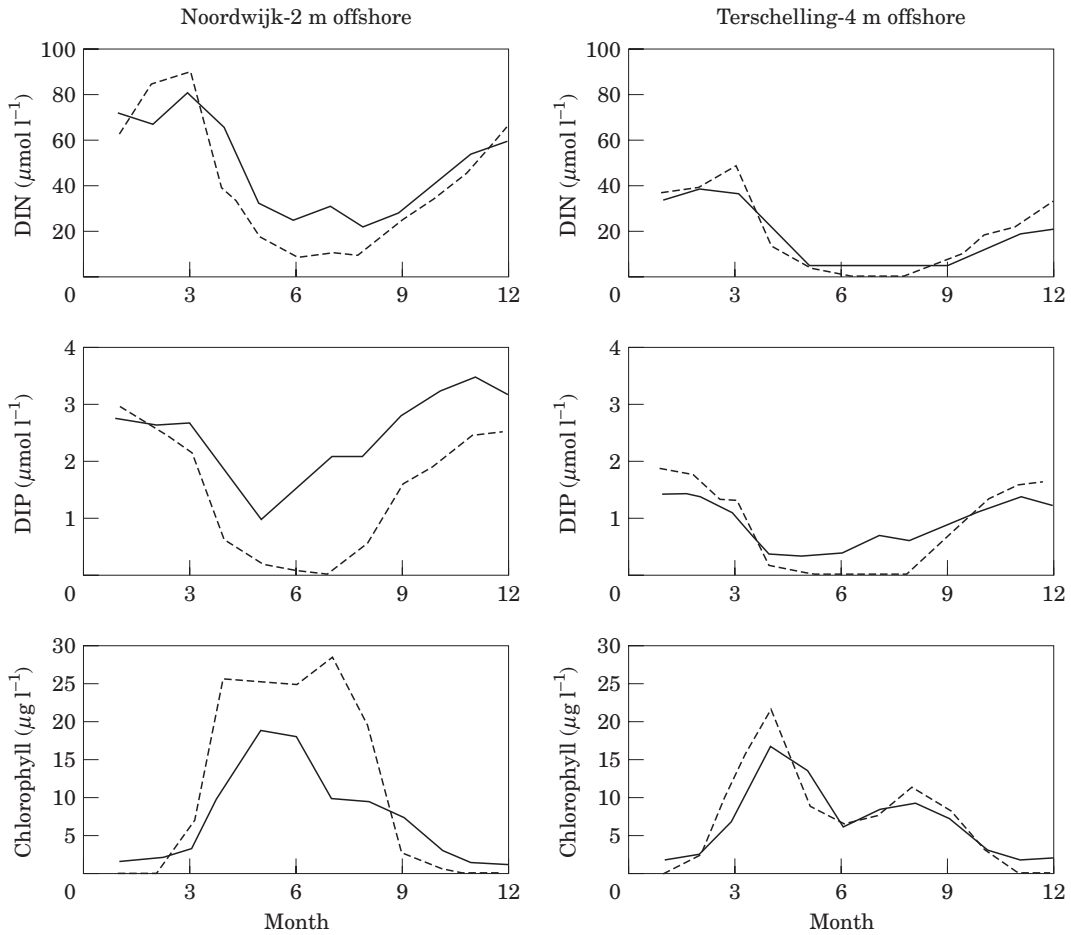


Figure 12. Data (solid lines) – model (broken lines) comparison of long-term monthly averages of DIN, DIP, and chlorophyll at nearshore stations (Noordwijk – 2 km offshore; Terschelling 4 km offshore), 1975–1995.

### Model simulation

Model–data comparisons for seasonal patterns, spatial patterns, and long-term trends are presented in Figs 12–14. Model results for long-term seasonal patterns agree very well with available measurements for DIN at both nearshore stations and for chlorophyll at the Terschelling station (Fig. 12). The overprediction for chlorophyll at the Noordwijk station is caused by the light climate in the model forcing which differs from the real situation, i.e., the water in the model is too transparent. The underprediction of DIP is partly due to the overprediction of chlorophyll at this station. However, the main cause is the absence of sorption dynamics in the model (see, e.g., Ruardij and van Raaphorst, 1995). Besides transport, the model only includes biological uptake, and transformation and regeneration processes. The deviation thus illustrates the importance of sediment–water exchange of DIP by sorption dynamics

in shallow coastal waters, as described in the previous section on seasonal patterns.

Overall, a good agreement was found between model results and measurements with respect to the long-term annually averaged spatial patterns along the Noordwijk transect (Fig. 13). The model resolves the steep spatial gradient in the nearshore coastal region. Deviations at the nearshore stations (<10 km offshore) are due to the overprediction of chlorophyll (light climate) and the absence of sorption dynamics in the model formulation as mentioned above.

The strong decrease of DIP, the smaller decrease of DIN, and the absence of a trend in chlorophyll over 20 years is also simulated quite well by the model (Fig. 14). Some higher frequency events, caused by large differences in river discharge between years are also reproduced by the model, e.g., the elevated concentrations caused by high river discharges in 1987 and 1993. Other anomalies, such as the low DIP and

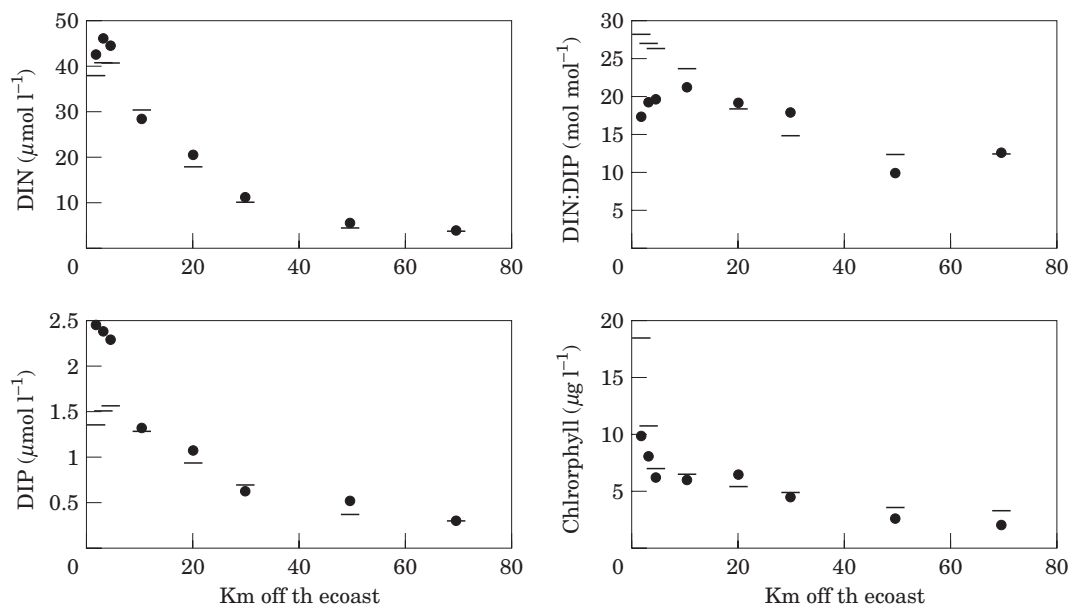


Figure 13. Data (dots) – model (bars) comparison of long-term annual averages of DIN, DIP, DIN:DIP ratio, and chlorophyll along the Noordwijk transect.

DIN concentrations at the Noordwijk station in 1981, a year with a high Rijn discharge, are not reproduced by the model and must be due to as yet unknown sources of variation not included in the model forcing. A clear difference is the enormous interannual variability in observed chlorophyll which is almost absent in the model results, especially at the Noordwijk station. A possible explanation is variability in factors like suspended particulate matter. The quality of the data set may provide an additional explanation. Because of the low sampling frequency, phytoplankton blooms may have passed undetected in some years.

The overall conclusion is that the simulations confirm the results of the statistical time-series analysis for DIN and DIP. However, the conclusion that chlorophyll has not decreased in the nearshore coastal waters cannot be validated.

#### Mesocosm nutrient reduction experiments

The effects of nitrogen input reduction on pelagic primary production (PP) and secondary benthic production (BSP) in the mesocosms are shown in Figure 15. The effects of phosphate input reduction (not shown) on PP were less pronounced and restricted to the spring bloom, and there was no effect of phosphate on BSP. Varying nitrogen input has a more or less linear effect on PP within the range of the experiment. However, the large difference between the replicates of the high-input treatment should be noted. The effect on BSP is significantly different. BSP changes marginally between

medium and high nitrogen input, and is only moderately lower in the low input treatment. As a consequence, the BSP:PP ratio ('ecological efficiency') increases from 7% at high nitrogen input to  $\geq 10\%$  at reduced inputs.

These results cannot be related to field data as yet, because of the absence of a conspicuous decreasing nitrogen trend in the coastal waters. Comparison with other mesocosm studies is also difficult. Oviatt *et al.* (1986) observed comparable responses, but only for much larger differences between low and high treatments and without distinction between effects of P and N. Egge and Heimdal (1994) found the highest increase in PP for balanced nutrient additions (N:P=16) and for excess phosphate (N:P=3.2), and less stimulation for excess nitrogen (N:P=80), i.e. a stronger response to phosphorus. However, their range of nutrient ratios is much broader than the range in the experiments reported here (18–38).

There is partial circumstantial evidence that our mesocosm results, indicating a decisive role of nitrogen, are applicable to the Dutch coastal waters. Firstly, potential limitation of algal biomass by phosphate is restricted to the spring bloom, whereas nitrogen potentially limits the algal biomass during summer. Secondly, Fransz and Gieskes (1984) suggested that the pelagic secondary production depends on the summer production of phytoplankton rather than on the spring production. Thirdly, primary production, macrobenthos biomass, and the meat content of mussels in the western Wadden Sea did not decrease with reduced inputs of phosphorus and decreasing concentrations (Cadée and Hegeman,

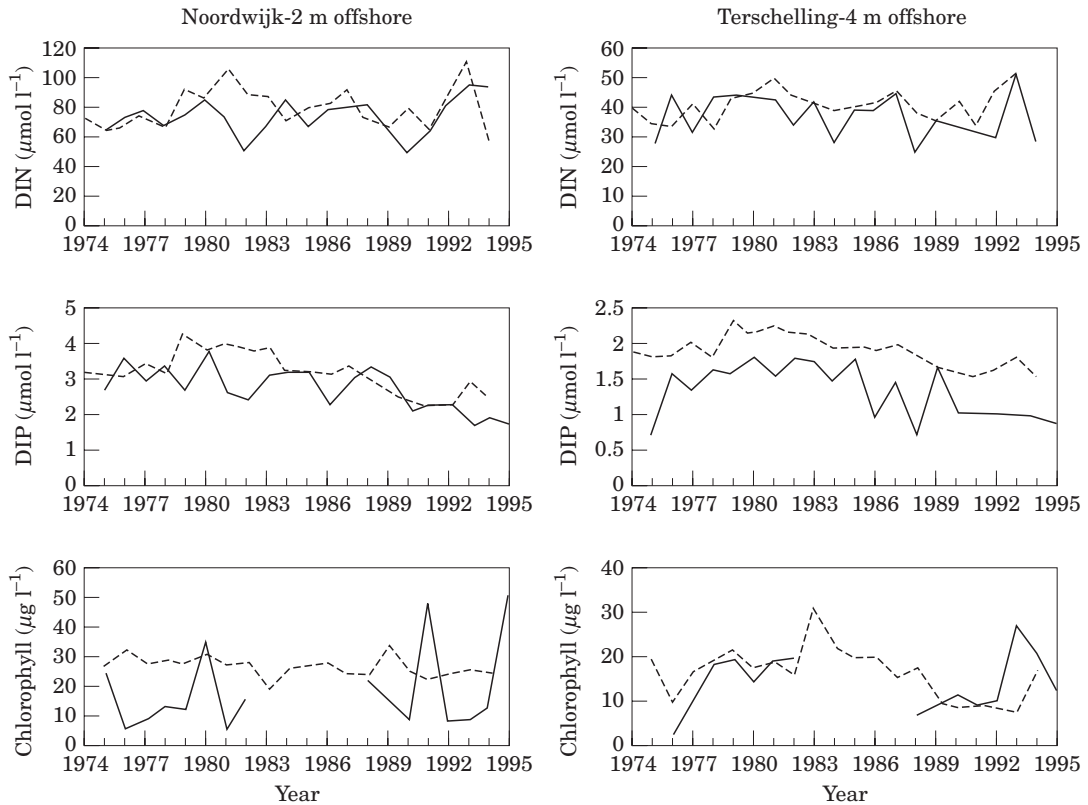


Figure 14. Data (solid lines) – model (broken lines) comparison of winter concentrations of DIN and DIP and summer concentrations of chlorophyll at nearshore stations (Noordwijk – 2 km offshore; Terschelling 4 km offshore). Winter 1975 = December 1975, January– February 1976; etc.

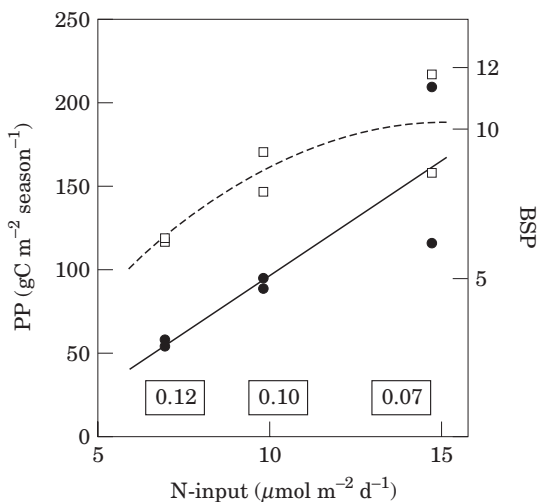


Figure 15. Results of mesocosm experiments: relation between primary production (PP, dots, left axis) and benthic secondary production (BSP, squares, right axis) and N-input. Numbers in the boxes indicate the associated BSP/PP ratio.

1993; de Jonge *et al.*, 1996). Van Stralen and Dijkema (1994) found a positive correlation between the annual primary production and the meat content of mussels in the Oosterschelde.

### Concluding remarks

Phosphate loads from freshwater discharges into Dutch coastal waters have declined by approximately 50% since 1985. The decrease in nitrogen loads is much smaller. Winter concentrations of DIP in the coastal waters have responded immediately and proportionally to the declining inputs and N:P ratios have increased. These results indicate that the local supply of nutrients from fresh water is the main factor for elevated concentrations in the nearshore areas of the North Sea, the mouth of the Westerschelde, and the western Wadden Sea. DIP and DIN concentrations in these areas are still a multiple of the background level, and above the level considered to be limiting for primary production and algal biomass. It is thus not surprising that as yet algal biomass (chlorophyll), primary production, and macrobenthos do not show any downward trend in these areas.

The mesocosm results indicate that reduction of the nitrogen input into the coastal waters may be more effective in reducing algal biomass and primary production, possibly without large effects on the productivity at higher trophic levels.

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