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Natural background concentrations of phosphorus and nitrogen in the Dutch Wadden Sea

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1 Summary

Policy plans and subsequent measures to reduce nutrient concentrations in coastal waters require realistic historical information on nutrient concentrations. The main goal of the present report was to develop and apply a practical, but scientifically sound strategy to assess the background concentrations of nutrients in the Dutch Wadden Sea. Given the changes in the area (*e.g.* the closing of the former Zuiderzee) and the availability of only a restricted set of historical data, we decided to modify this goal in: the development and application of a practical hindcasting method to estimate nutrient concentrations that would have occurred in the Dutch Wadden Sea under the present conditions, given the nutrient concentrations in the rivers and in the adjacent North Sea in the period prior to the early 1930s.
Two subtasks were defined: (1) the assessment of the nutrient concentrations in the adjacent North Sea area representing the period before circa 1930, as well as freshwater discharges, nutrient concentrations, and nutrient loads by the fresh water inputs to the Dutch Wadden Sea (2) the estimation of the seasonal fluctuations in the nutrient concentrations in the basins of the Dutch Wadden Sea.

Considered were the river Rhine (at Lobith/Spijk), the river IJssel (at Kampen), the IJsselmeer, the Lauwersmeer, the river Ems, the Westerwoldsche Aa and the Eemskanaal.
Attention was focused to the nutrients ammonium, nitrate, phosphate, total nitrogen and total phosphorus.
Important steps in the calculation procedure were the assessment of freshwater discharge, the estimation of present and past nutrient concentrations in river water, the nutrient retention in between the rivers and the sea, the nutrient loads at freshwater discharge points and the assessment of the concentrations in the Wadden Sea prior to the early 1930s. Based on these calculation, the seasonal cycles in the phosphorus and nitrogen loads and concentrations at Den Oever and Kornwerderzand were assessed as well as the seasonal cycles of the background phosphorus and nitrogen concentrations in the Dutch Wadden Sea.

The natural background concentrations of total phosphorus (TP) and total nitrogen (TN) for the total of the Marsdiep and Vlie (M+V) basins are given in the table below and are based on conservative mixing of water from the North Sea (NS) boundary at the tidal inlets with water from IJsselmeer.

		winter	spring	summer	autumn
NS boundary salinity	PSU	28 - 32	28 - 32	29 - 32	30 - 33
NS boundary TP	µM	0.9 ± 0.3	0.7 ± 0.3	0.7 ± 0.3	0.8 ± 0.4
NS boundary TN	µM	15 ± 5	14 ± 5	9 ± 3	8 ± 4
M+V basins salinity	PSU	24 - 27	26 - 29	27 - 30	27 - 30
% Ijsselmeer water		16	9	6	10
M+V basins TP	µM	0.9 ± 0.3	0.7 ± 0.3	0.7 ± 0.3	0.8 ± 0.4
M+V basins TN	µM	17 ± 7	16 ± 6	10 ± 4	9 ± 5
M+V basins TN:TP		~19	~23	~14	~11
M+V basins DIP	µM	~ 0.5	~ 0.1	~ 0.2	~ 0.4
M+V basins DIN	µM	~ 7	~ 4	~ 3	~ 3
M+V basins DIN:DIP		~14	~40	~15	~ 8

2 Recommendations

It is recommended to carry out an analysis as presented here also for other coastal areas. If possible, it would be of interest to get an even more detailed picture of the 'background' situation as well as the historical developments. Finally, we are the opinion that the available information is usable in 'river continuum models' and 'land use models' and combinations as aimed in global programmes like Land Ocean Interactions in the Coastal Zone (LOICZ).

3 Acknowledgements

We are greatly indebted to W.A. de Kloet and H. Postma for supplying indispensable data which were not yet published before.

4 Introduction

4.1 The Dutch Wadden Sea

The Wadden Sea is a shallow and sheltered coastal area with extensive tidal flats (approximately 15% to 80% of the total area depending on the tidal basin) which is separated from the North Sea by a girdle of barrier islands. The tidal basins are separated from each other by tidal watersheds (high elevated tidal flats).

The Dutch part of the Wadden Sea, the Ems estuary included, covers approximately 2700 km², and can be subdivided into three parts (fig. 4.1A):

1. The western part, including the tidal basins "Marsdiep", "Eijerlandse Gat" and "Vlie";
2. The eastern part, with the basins "Borndiep", "Pinkegat", "Friesche Zeegat", "Eilanderbalg", "Lauwers" and "Schild";
3. The Ems estuary.

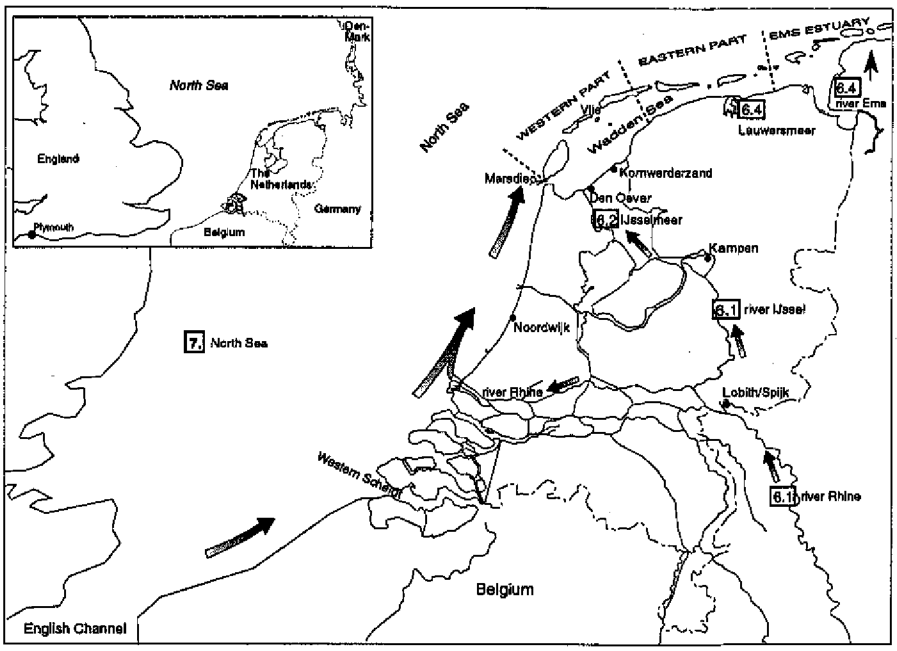
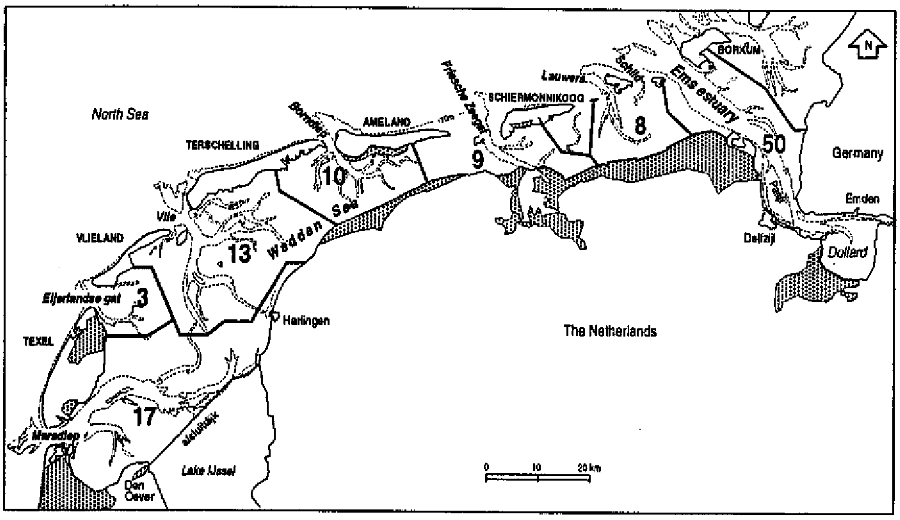


Figure 4.1a
Map of Dutch coastal waters including the Dutch Wadden Sea. Given are the residual coastal current and the nutrient sources (arrows). Framed numbers refer to report chapters.

All basins are in open connection to the North Sea to which water is exchanged by tidal movement. Turn-over times of the basins (defined as the time interval necessary to reduce the mass present in a basin to a fraction e^{-1} of the original mass) vary between 3 tidal periods in the Eijerlandse Gat to 17 tidal periods in the Marsdiep basin (Ridderinkhof *et al.*, 1990) (Fig. 4.1B).

Figuur 4.1b
Map of the Dutch part of the Wadden Sea with the different tidal basins and land reclamation works since circa 1200 (*cf.* Dijkema, 1987). Turn-over times of the water are given in tidal periods (*cf.* Ridderinkhof *et al.*, 1990.



The turn-over time of the Ems estuary is much longer and approximately 50 tidal periods (Helder and Ruardij, 1982).

Freshwater inputs are most important in the Marsdiep and Vlie basin (discharges from IJsselmeer at Den Oever and Kornwerderzand), the Friesche Zeegat (freshwater supply from Lauwersmeer at Lauwersoog), and the Ems estuary (the river Ems). Apart from these main inputs, there are several local freswater discharges, but these are of minor importance for the freshwater balance of the basins (Van Meerendonk *et al.*, 1988).

Major nutrient sources are the North Sea, the main freswater inputs and the atmosphere. Substantial amounts of nutrients are also discharged at Den Helder in the Marsdiep basin, and from the Eemskanaal and the Westerwoldsche Aa in the Ems estuary (Van Meerendonk *et al.*, 1988).

4.2 Objectives

The general objective is to gain insight in the background concentrations of nutrients in the Wadden Sea, representing the 'natural' reference level under the present geographical and morphological situation. This insight is important to define the optimal concentrations ('target levels') under anthropogenic influence. Only with this insight, (new) management measures such as further reduction of nitrogen and phosphorus loads can be evaluated. In this document we do not deal with the management measures but we restrict ourselves to the scientific main problem:

To develop and apply a practical, but scientifically sound strategy to assess the background concentrations of nutrients in the Dutch Wadden Sea

The definition of background or natural concentrations may be subject to some dispute. We have adopted the definition that was used in a similar study for the North Sea (Laane *et al.*, 1992):

Natural background concentrations are defined as those concentrations that could be found in the environment in the absence of any human activity.

Stricktly speaking, this definition implies that concentrations have to be estimated that occurred before the presence of mankind in the Wadden Sea area. This is an impossible task.
Alternatively, background concentrations could be assessed by determining the concentrations due to solely natural processes, *i.e.* the estimation of these natural processes and the calculation of the concentrations in the Wadden Sea resulting from these processes. Again, this seems an impossible task since most of these processes are influenced somehow by human activities.
For the management of the Wadden Sea it is, however, most important to know the concentrations representing the situation prior to current disposal practice and prior to present eutrophic conditions. Thus, for practical reasons we interpret the above definition as follows:

Natural background concentrations are approximated by those concentrations that could be found in the environment before the early 1930s, viz. before the massive introduction of artificial fertilizers and detergents and the wide-spread connection of sewage systems to open waters.

The disadvantage of this working definition is that nutrient levels in the Wadden Sea in the early 1930s certainly were already influenced by human activities. This period corresponds, however, to the period for which the first reliable data on nutrient concentrations in sea water were available (see *e.g.* Laane *et al.*, 1992, 1993 and references therein). Further, the strongest increase in nutrient loads to the Wadden Sea took place after the early 1930s, even after the early 1950s due to the introduction of artificial fertilizers and detergents.

One further complication is that the Wadden Sea in its present form did not exist before approximately 1970, *i.e.* after the closure of the former Zuiderzee by the Afsluitdijk (1932) and the closure of the former Lauwerszee by the Lauwerszee-dijk (1969). Further, extensive land reclamation works were carried out within these areas (Dijkema, 1987; De Jonge, Essink & Boddeke, 1993)(*cf.* Fig. 4.1B). Consequently, the total surface area of the several basins has decreased substantially since 1932. Additionally, the hydrological regime of some main freshwater tributaries has changed during the last decades. Keeping in mind that water quality managers have to deal with the present coastline and freshwater discharges, this means that background concentrations are needed, representing a situation that in reality never existed (present geographic boundaries and morphology, past nutrient loads). This means a necessary change in our objective to:

The development and application of a practical hindcasting method to estimate nutrient concentrations that would have occurred in the Dutch Wadden Sea under the present conditions, given the nutrient concentrations in the rivers and in the adjacent North Sea in the period prior to the early 1930s.

5 Strategy

Two subtasks were distinguished to meet the objective formulated:

1. To assess the nutrient concentrations in the adjacent North Sea area representing the period before circa 1930, as well as nutrient concentrations and loads by the fresh water inputs to the Dutch Wadden Sea;
2. Subsequently, to estimate the nutrient concentrations in the basins of the Dutch Wadden Sea from the above concentrations and loads of rivers and adjacent North Sea area.

Background concentrations in the main north-west European rivers and the North Sea were analysed by Laane *et al.*, 1992, 1993. For our purpose one serious shortcoming of that analysis is that mainly winter values were considered.
For any conservative tracer introduced in a tidal basin at a certain time, the mass present after a time interval t can be approximated by $M = M_0\, e^{-t/\tau}$, where M_0 is the original mass and τ is the turn-over time of the basin. At $t = 3 \times \tau$, M has reduced to < 5% of M_0. Thus, typical time-constants ('memory') of the Wadden Sea basins can be approximated by $3 \times \tau$, *viz.* 3 x 50 = 150 tidal periods (~75 days) in the Ems Estuary at average fresh water discharge, less than 3 x 17 = 51 tidal periods (~26.5 days) in the Marsdiep basin, and even shorter in the other basins.
The above means that winter values in the coastal North Sea have no direct relation with spring and summer conditions (including phytoplankton blooms) in coastal areas as the Wadden Sea. Therefore, information is needed on the seasonal cycle of nutrient concentrations in relevant parts of the North Sea as well as the nutrient supplying freshwater tributaries.

To estimate the past loads from the freshwater sources we had to rely on historical data (*cf.* Laane *et al.*, 1992, 1993). In this way we estimated the background input of the river IJssel into what nowadays is IJsselmeer. Since IJsselmeer did not exist in 1930, we could not use historical data representing the nutrient discharge of IJsselmeer into the Wadden Sea. Instead, we had to search for simple relations between loads of the rivers Rhine and IJssel and the discharge of the lake (*e.g.* retention models) to the coastal waters, taking into account the past changes in the flushing time of the lake. Lauwersmeer is, as far as possible, treated in a similar way.

The most simple approach to estimate the background concentrations in the Wadden Sea basins is to combine North Sea concentrations and freshwater inputs in mixing models, that are based on the present average salinities of the basins. These salinities can be calculated from the seawater *vs.* freshwater ratio. For our purpose this was judged to be sufficient. For detailed studies on the effects of different concentrations, more complicated ecosystem models are required (*e.g.* EcoWasp; Brinkman, 1993). In these ecosystem models the often substantial nutrient consumption and production processes in the basins are taken into account.

The Ems estuary is the only basin in the Dutch Wadden Sea with true estuarine properties (*e.g.* a full and stable salinity gradient and turbidity maximum). Here, simple mixing models to arrrive at one single background value for the entire estuary may be not sufficient. Although, in principle the same strategy as for the other basins can be followed to estimate background inputs into the estuary. Use of these inputs in models including physical mixing and advection, as well as the most important chemical and biological transformations may result in background distributions of nutrients in the estuary. These models exist and can be applied to the Ems estuary, either directly ('BOEDE' model; Baretta & Ruardij, 1988) or after some modifications (EcoWasp; Brinkman, 1993).

In this report we will not deal with these model applications, but we will restrict ourselves to the simple mixing approach to exemplify the strategy to assess background concentrations of nutrients in the Wadden Sea. As a case study, the procedure to determine the natural background concentrations in the western Wadden Sea basins will be described in detail.

Looking back further in time, back to the period preceding those of having reliable analytical techniques and monitoring programmes, inevitably leads to increasing levels of uncertainty. Defining these levels of uncertainty is not always a straightforward procedure. It may be subject to some dispute. Nevertheless the uncertainties should be given as accurate as possible given the purpose of this study. In the following sections all results are given as a mean value ± standard deviation. The standard deviation is either calculated directly when data from a longer period were available or estimated from a given range (SD = 0.5 x range) when no more information was available. Common rules were applied to account for propagation of errors in estimates, treating the data as independent.
It should be noted that the standard deviations obtained largely reflect the model calculations applied to reconstruct the past and that they do not likely represent the natural variability in the past. Also the models used not necessarily are the best possible and, in any case, give only an approximation of reality. Thus, one could argue that the final estimates are subject to much speculation. Therefore, and to present more confidence in the hindcasted results, we will compare our findings with data available from the literature whenever possible.

We did not make any attempt to calculate e.g. confidence intervals or levels of significance when e.g. differences between water bodies, years or nutrients were addressed. In general, we feel that such an extensive statistical treatment of the data is beyond the scope of this study. It could, however, be part of a follow-up project.

6 Natural background levels of nutrients in the freshwater sources

6.1 The river Rhine, the river IJssel and IJsselmeer

The river Rhine at Lobith/Spijk

Data on annual nutrient discharges from the river Rhine at Lobith/Spijk are available since the early 1950s, with several missing years before 1965. Reliable data on total P and N (TP, TN) are available only since the early 1970s. Van der Veer *et al.* (1989) estimated the loads in the missing years by interpolation and extrapolation of the trends in the TN:TP ratio, the ratios in (DIP):TP and the ratios in (DIN):TN.
Taking the applicability of this approach for granted, a continuous time series of the annual loads since the fifties was obtained. In Fig. 6.1 and 6.2 the TP and TN loads at Lobith/Spijk are given, including the loads obtained by interpolation and extrapolation.

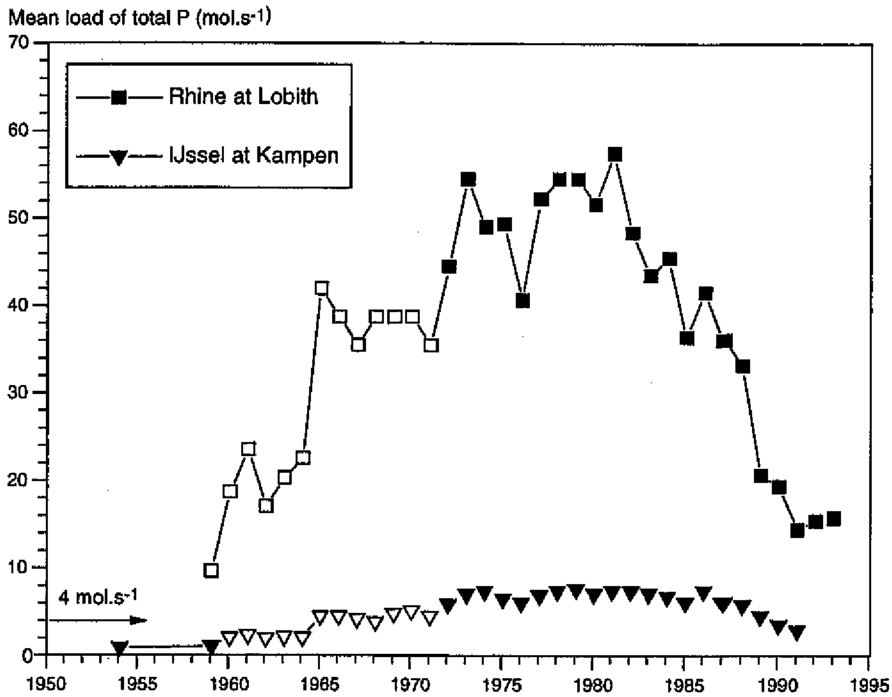


Figure 6.1
Time series of the annual TP discharges ($mol.s^{-1}$) of the river Rhine at Spijk/Lobith and the river IJssel at Kampen. Data from Rijkswaterstaat and after Van der Veer et al. (1989). Interpolated and extrapolated loads are indicated by open symbols. Arrow indicates the estimated background TP discharge of the Rhine.

In the 1950s, the annual mean loads of TP and TN were ca. 10 and 500 $mol.s^{-1}$, respectively. These loads were estimated assuming an atomic DIP:TP ratio of 0.40 and an atomic DIN:TN ratio of 0.75. Uncertainties in these ratios were estimated by Van der Veer *et al.* (1989) at ~10%. After the 1950s, nutrient loads of the river Rhine increased considerably until maxima were reached in the early (TP) and late (TN) 1980s.

The maximum load occurred in the period 1978-1981 when the annual river Rhine load of TP at Lobith/ Spijk was ~55 $mol.s^{-1}$ (Fig. 6.1), *viz.* 5.5 times the load in 1959. In the early 1990s the TP discharge had decreased to ~15 mol.s^{-1} which is even less than the load in the 1960s.

The maximum TN load of the river Rhine at Lobith/ Spijk was ~1300 mol.s^{-1} between 1985 and 1988, *viz.* a factor 2.5 larger than the load in the 1950s. At present, the TN discharge at Lobith/ Spijk has decreased to ~600 mol.s^{-1}, a value slightly above the estimated value for 1959 (Fig. 6.2).

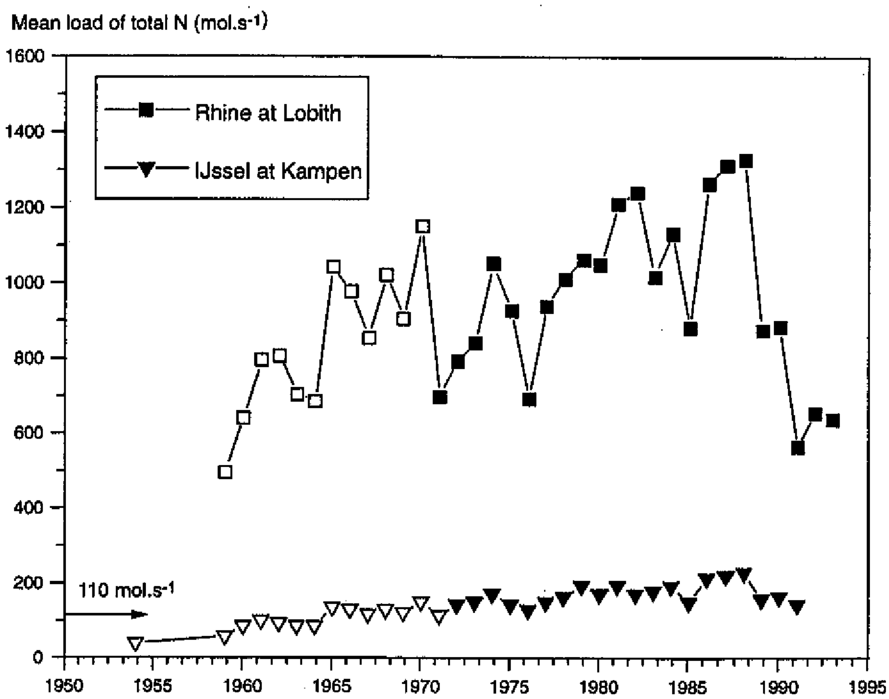
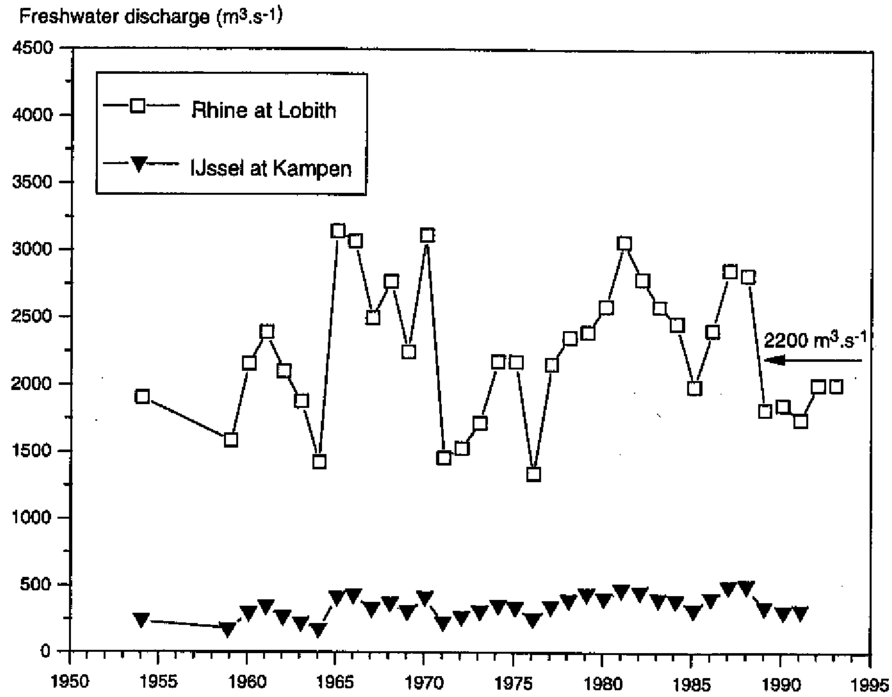


Figure 6.2
Time series of the annual TN discharges (mol.s^{-1}) of the river Rhine at Spijk/Lobith and the river IJssel at Kampen. Data from Rijkswaterstaat and after Van der Veer et al. (1989). Interpolated and extrapolated loads are indicated by open symbols. Arrow indicates the estimated background TN discharge of the Rhine.

A rough visual extrapolation of the temporal trends in Fig. 6.1 and 6.2. back to the 1930s yields annual mean loads of < 5 and < 200 mol.s^{-1} for TP and TN, respectively.

Laane *et al.* (1992) followed another approach based on general information and historical data from the European continental rivers. Those authors arrived at TP concentrations ranging from 0.7 - 4.5 µM and TN concentrations that ranged from 20-71 µM. Combining these numbers with the annual mean water discharge of the Rhine (2200 m^3.s^{-1}, RIWA 1994, Fig. 6.3) yields background loads of 1.5-10 mol.s^{-1} for TP and 45-160 mol.s^{-1} for TN.

Figure 6.3
Time series of the annual mean water discharges ($m^3.s^{-1}$) of the river Rhine at Spijk/Lobith and the river IJssel at Kampen. Data from Rijkswaterstaat. Arrow indicates the long-term mean water discharge of the Rhine.



These values agree well with the above estimated values obtained by the extrapolations. We will use the results of Laane *et al.* (1992) as the basis for further estimates.

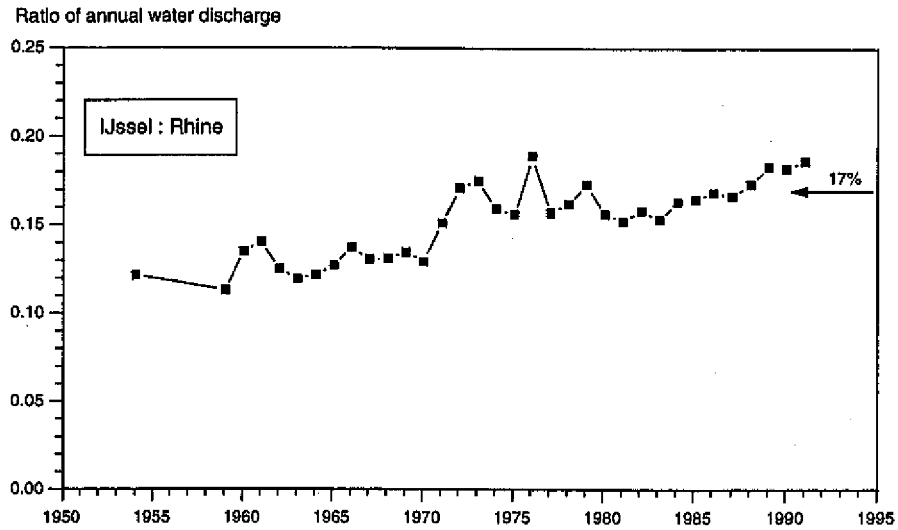
The relative range given by Laane *et al.* (1992) for TP background concentrations in river water (max:min = 6.4) is much larger than for TN (max:min = 3.6). The relative range in TP is also larger than the range in the pristine TP concentrations as estimated by Ahl (cited by Laane *et al.*, 1992) and the relative annual variation in TP concentrations in the period 1970-1991 (see *e.g.* De Jonge and Van Raaphorst, 1995). In 1990 and 1991, TP concentrations in the Rhine varied between 4 and 10 µM, without a clear seasonal trend. Therefore, a background TP concentration as high as 4.5 µM seems suspect. Thus, for TP we slightly deviate from Laane *et al.* (1992), constraining the range of TP background concentrations as being between 1 and 2.5 µM. Based on the above information we assess the background annual mean TP load of the river Rhine at 4 ± 2 $mol.s^{-1}$ (Table 1), *i.e.* approximately 3.5 times lower than the load in the early 1990s.

Both the water discharge and the nutrient concentrations of the Rhine show distinct annual cycles. Highest TN concentrations in the river Rhine occur at highest discharges in winter (De Jonge and Van Raaphorst, 1995). This correlation implies that the annual average TN discharge is larger than the product of the annual mean water discharge and the annual mean TN concentration. We have, however, no good information to quantify this effect. We here directly follow Laane *et al.* (1992) and re-estimate the annual mean TN background discharge of the Rhine at 110 ± 50 $mol.s^{-1}$ (Table 1). Loads in the early 1990s are approximately 5.5 times larger than this value (Fig. 6.2).

The river IJssel at Kampen

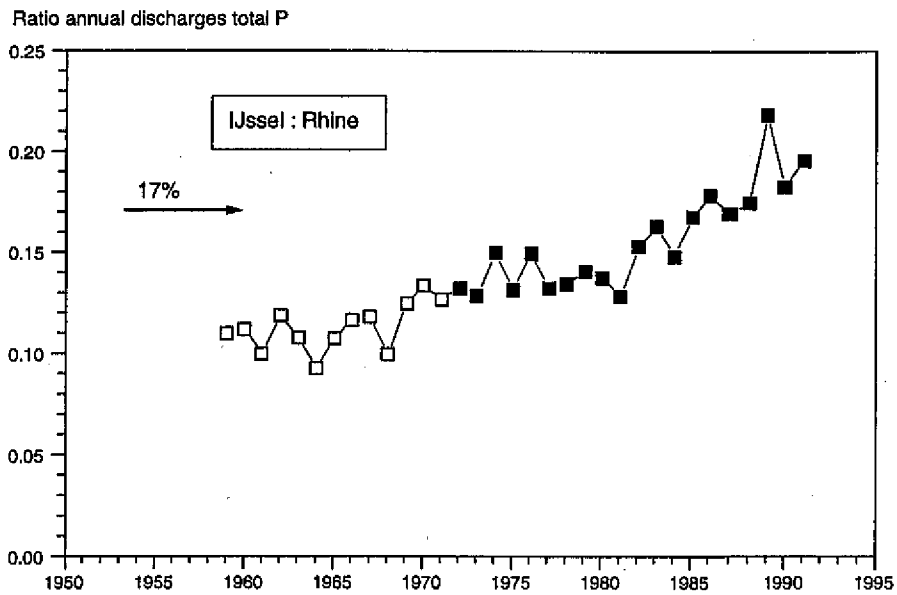
According to Van der Veer *et al.* (1989) the annual nutrient loads of the river IJssel at Kampen showed a similar increase in the period 1954 - 1980 as the loads of the river Rhine (Figs. 6.1 and 6.2). In the period prior to 1970, the annual water, TP and TN discharges at Kampen were 12-14% the discharges of the river Rhine at Lobith/Spijk (Figs. 6.4, 6.5 and 6.6).
In 1970, the flushing regime of the river tributaries in The Netherlands changed by management measures. Since that year (Fig. 6.4) the annual water discharge at Kampen is 17% of that at Lobith/Spijk.

Figure 6.4
Time series of the ratio of the annual mean water discharges of the IJssel at Kampen and the Rhine at Lobith/Spijk. Arrow indicates the mean ratio (as percentage) since 1970.



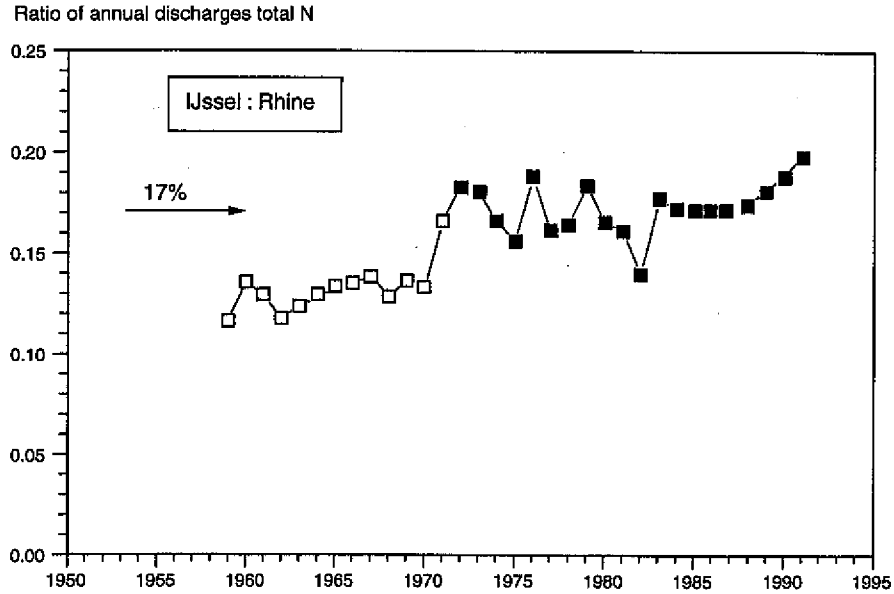
Due to the increased water volume passing the river IJssel, the TP load at Kampen (with an observed lag period during the late 1970s) increased (Fig. 6.5). Since 1980 this value amounts to 17 ± 2% that of the load of the river Rhine at the Dutch-German border.

Figure 6.5
Time series of the ratio of the annual TP discharges of the IJssel at Kampen and the Rhine at Lobith/Spijk. Ratios obtained from interpolated and extrapolated loads are indicated by open symbols. Arrow indicates the mean ratio (as percentage) corresponding to the ratio of the water discharges after 1970.



According to these findings, the background TP load of the IJssel was consequently adjusted at 4 x 0.17 = 0.7 ± 0.3 mol.s^{-1} (Table 1).
The development of the ratio of the TN loads in the rivers Rhine and IJssel followed that of the water discharge even more closely than TP did (Fig. 6.6). The TN loads even included the 'jump' in 1970 when the ratio between the loads of both rivers increased from 12-13% to 17 ± 2%.

Figure 6.6
Time series of the ratio of the annual TN discharges of the IJssel at Kampen and the Rhine at Lobith/Spijk. Ratios obtained from interpolated and extrapolated loads are indicated by open symbols. Arrow indicates the mean ratio (as percentage) corresponding to the ratio of the water discharges after 1970.



From this latter percentage, we calculated the background annual mean TN load of the river IJssel at 110 x 0.17 = 19 ± 9 mol.s^{-1} (Table 1).

Table 1
Estimates of the natural background water discharges and nutrient loads of the major fresh water sources relevant to the western Dutch Wadden Sea. All numbers refer to annual means.

	Water discharge ($m^3.s^{-1}$)	TP load ($mol.s^{-1}$)	TN load ($mol.s^{-1}$)
River Rhine (Lobith/Spijk)	2200 ± 500	4 ± 2	110 ± 50
River IJssel (Kampen)	370 ± 65	0.7 ± 0.35	19 ± 9
Ijsselmeer (Den Oever + Kornwerderzand)	520 ± 90	0.33 ± 0.17	14 ± 7

6.2 IJsselmeer

The long-term trends of the nutrient concentrations in IJsselmeer close to the Afsluitdijk (De Wit 1980, Van der Veer *et al.* 1989) and, consequently, of the discharges into the Wadden Sea (Figs. 6.7 and 6.8) differ considerably from the trends in the rivers Rhine and IJssel. Data of the 1950s and 1960s were obtained from Postma (1954, 1966, 1967, and unpublished), Duursma (1961) and De Kloet (1971). More recent data are borrowed from Helder (1974), De Jonge & Postma (1974) and the Rijkswaterstaat monitoring programme. The analysis of the time series is given below.

Figure 6.7
Time series of the annual TP discharges ($mol.s^{-1}$) of the river IJssel at Kampen and IJsselmeer at Den Oever and Kornwerderzand (DO + KZ). Data from Rijkswaterstaat and after Van der Veer et al. (1989). Interpolated and extrapolated loads are indicated by open symbols. Arrows indicate the estimated background TP discharges of the IJssel (left) and IJsselmeer the (right), respectively.

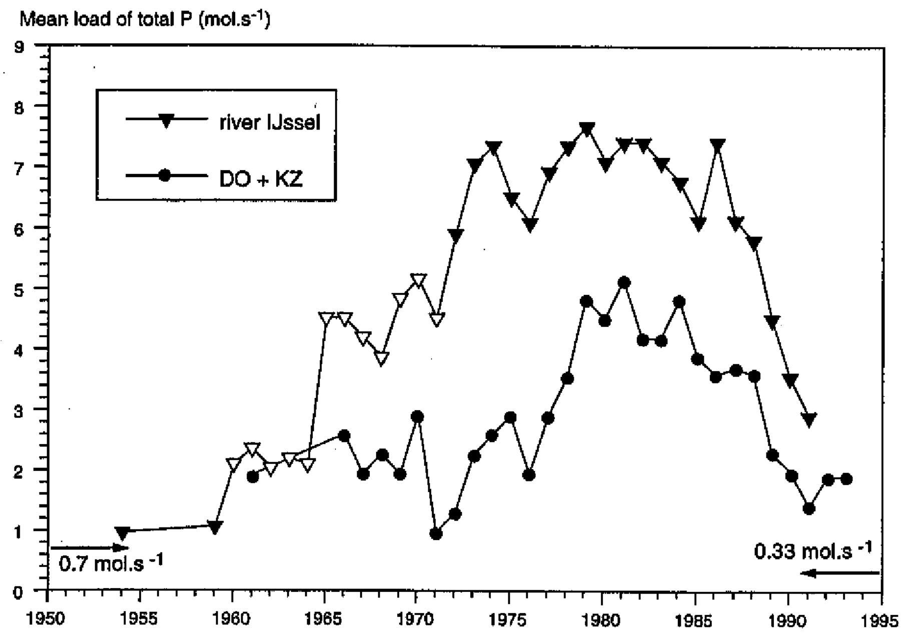
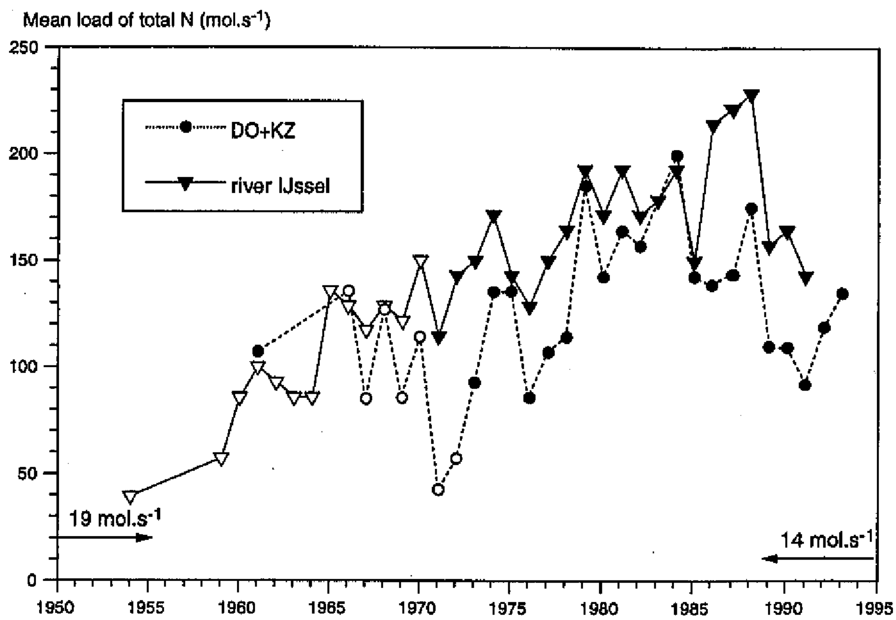


Figure 6.8
Time series of the annual TN discharges ($mol.s^{-1}$) of the river IJssel at Kampen and IJsselmeer at Den Oever and Kornwerderzand (DO + KZ). Data from Rijkswaterstaat and after Van der Veer et al. (1989). Interpolated and extrapolated loads are indicated by open symbols. Arrows indicate the estimated background TN discharges of the IJssel (left) and IJsselmeer (right), respectively.



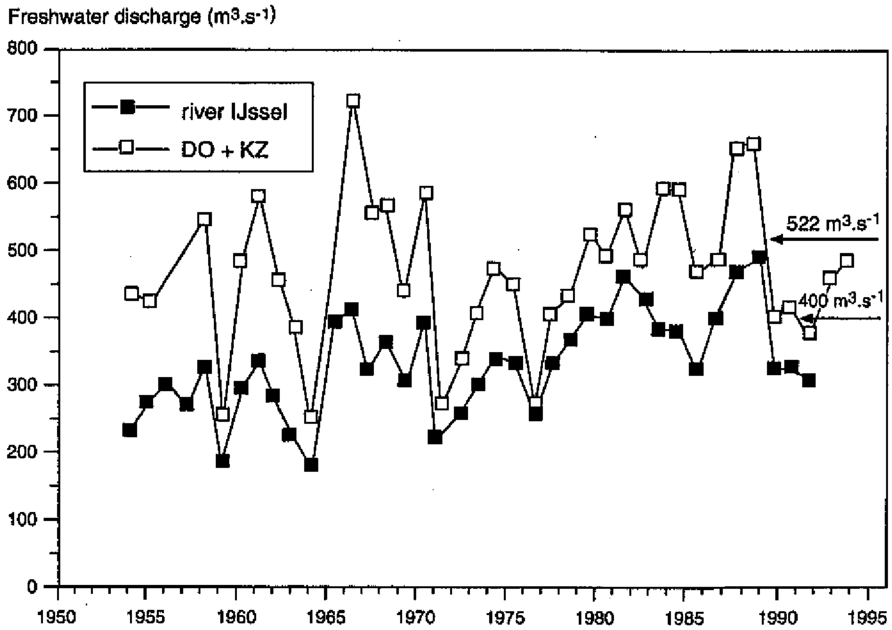
Water discharges

The difference in water discharges between river IJssel and lake (IJsselmeer) is partly explained by the contribution of other tributaries to the water and nutrient budgets of the lake *(Fig. 6.9)*.

In 1969, the river IJssel contributed approximately 60% of the total water input to IJsselmeer, 30% originated from other rivers *e.g.* the Amsterdam area and polderwaters, while 10% entered the lake by precipitation (De Kloet, 1978). Since 1970, the quantitative water management of the lake and it's tributaries has been changed. As a result, the river IJssel contributed between 75% and 80% to the total water input of the lake in the second half of the 1970s (data obtained from the former 'werkgroep sanering IJsselmeer', RIZA, Lelystad; see also De Wit, 1980).

The water output of the lake almost completely occurs through the sluices at Den Oever (DO) and Kornwerderzand (KZ), *i.e.* to the Marsdiep basin and the Vlie basin in the Wadden Sea. In 1969 approximately 85% (De Kloet, 1978), and between 1975 and 1979 approximately 78% ('werkgroep sanering IJsselmeer', De Wit, 1980) was sluiced out to the Wadden Sea. The rest flew to the northeastern part of The Netherlands. Some care should be taken, however, when using these percentages (and those of the inputs), because of the problems in determining well-balanced water budgets of the lake: the difference between total water input and output in the budget can be as large as 23% of the total input ('werkgroep sanering IJsselmeer').

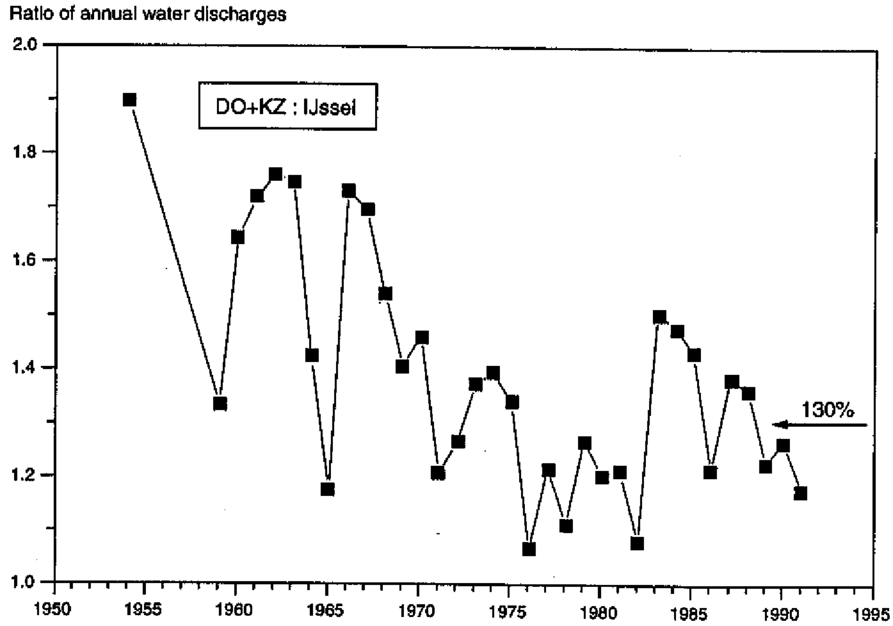
Figure 6.9
Time series of the annual mean water discharges ($m^3.s^{-1}$) of the river IJssel at Kampen and IJsselmeer at Den Oever and Kornwerderzand (DO + KZ). Data from Rijkswaterstaat and after Van der Veer et al. (1989). Arrows indicate the estimated background discharges of the IJssel (left) and IJsselmeer (right), respectively.



To circumvent problems in establishing close and confident water budgets of the lake, we directly compared the most important water input by the river IJssel at Kampen with the most important output by the sluices in the Afsluitdijk (DO + KZ). During all years, when considering the period 1954 to 1991 the output at DO + KZ was larger than the discharge of the river IJssel (Fig. 6.9). This was due to the contribution of the other water sources of the lake. Before 1970 the difference between the water discharge at DO +KZ and Kampen was larger than after 1970. The ratio between both discharges (DO+KZ : IJssel at Kampen) gradually decreased from 1.2 - 1.9 before 1970 to 1.3 ± 0.2 since 1980 (Fig. 6.10).

The corresponding annual water discharge into the Wadden Sea is 520 ± 90 $m^3.s^{-1}$ since 1980. This value is used in further calculations to estimate the background conditions in the lake (Table 1).

Figure 6.10
Time series of the ratio of the annual mean water discharges of IJsselmeer at Den Oever and Kornwerderzand (DO + KZ) and the IJssel at Kampen. Arrow indicates the mean ratio (as percentage) since 1970.



An important parameter controlling the retention percentage of lakes for nutrients is the flushing time (τ). Accepting that the fresh water discharge at DO + KZ is approximately 80% of the total output of the lake, and further assuming that on the average the total input of water equals the total output, we calculated the flushing time (τ) of the lake for the different years from:

$$\tau = 0.8 \times (\text{volume of the lake}) / (\text{water output at DO + KZ})$$
$$= V / Q_{out} \qquad (1)$$

Before 1957, the volume of IJsselmeer was 9.0×10^9 m^3, while in the late 1950s and early 1960s it was 8.5×10^9 m^3. In 1967 the volume decreased to 7.6×10^9 m^3 due to the closure of the polder Zuidelijk Flevoland, while it further decreased to 5.4×10^9 m^3 in 1975 due to the construction of the dam separating the Markermeer from the IJsselmeer (calculated from data in Berger, 1987). As a consequence the flushing time (τ) decreased fom 250 $\pm$ 100 days before 1967 to 215 $\pm$ 65 days between 1967 and 1975. Averaged over the period 1980 - 1993 the flushing time was 125 $\pm$ 30 days or approximately 4 months, a value that is applied in further estimates of the background conditions.

Phosphorus and nitrogen retention of IJsselmeer

Before the 1970s (1969), the river IJssel contributed 60% of the TP input to the lake. Smaller rivers, the Amsterdam sewage system and polderwaters together contributed an additional amount of almost 40% (De Kloet, 1978). In the early 1970s the input of the Amsterdam sewage system stopped. Between 1975 and 1979, the relative contribution of the river IJssel increased to 80-90% of the TP input to IJsselmeer and 80% of the TN input, while the discharge of the Zwolse Diep with 7% and 8% was the second contributor (data obtained from the former 'werkgroep sanering IJsselmeer', see also De Wit, 1980).

The discharge at DO+KZ contributed 80% to the total output of TP in 1969 (De Kloet, 1978) and 75-80% between 1975 and 1979 (former werkgroep sanering IJsselmeer, De Wit, 1980). In the 1970s the relative contribution in the TN output was 80-85%.

In the further calculations it is assumed that the river discharge at Kampen represents 60% of the TP and TN input of IJsselmeer before 1971, and 80% in the years thereafter. The discharge at DO+KZ is assumed to account for 80% of the total TP and TN output of the lake during the entire period between 1950 and 1995.

If the ratio of the loads at DO+KZ and Kampen for background conditions is known, the annual mean TP and TN discharge at DO+KZ can be calculated from the background loads of the river IJssel. The evolution of the observed ratios over time is strongly influenced, however, by the past changes in TP and TN inputs to IJsselmeer from other sources than the river IJssel and by the repeated decrease in flushing time of the lake. To account for these changes, a simple annual mean retention model is applied in which the losses of TN and TP are formulated as a first order process (Van Straten, 1986). Further assuming a step-wise year-to-year steady state, the model yields the following annually averaged mass balance:

$$0 = L_{in} - Q_{out} x C - K x C x A \Rightarrow C = L_{in} / (Q_{out} + K x A) \qquad (2)$$

In which L_{in} is the annual mean load at the entrance and $Q_{out}xC$ is the annual mean nutrient loads at the outlet of the lake ($mol.s^{-1}$). Q_{out} is the annual mean water discharge at DO+KZ ($m^3.s^{-1}$), C is the average concentration of TN or TP in the lake ($mol.m^{-3}$), A is the surface area (m^2), and K is the apparent first order loss rate ($m.d^{-1}$).

The retention R is defined as

$$R = K x C x A / L_{in} = 1 - (L_{out} / L_{in}) \qquad (3)$$

Combining (2) and (3) yields:

$$R = K x A / (Q_{out} + K x A) \qquad (4)$$

which, after inserting the definition of the flushing time (1) results in:

$$R = K x \tau / (H + K x \tau) \Rightarrow \qquad (5)$$

$$L_{out} / L_{in} = H / (H + K x \tau) \qquad (6)$$

where H = V/A is the average depth of IJsselmeer (4.5 m; Berger, 1987).

Although the above presented model undoubtly is too simple to account for all the processes affecting the retention of phosphorus and nitrogen in lakes, it correctly predicts that retention decreases at decreasing flushing time (CUWVO 1980, Van Straten, 1986). The only free parameter K is a true 'rest' parameter including the concerted action of several sinks and sources, e.g. sedimentation and burial, denitrification and release from the sediments. Taking into account the relative contribution of the discharge at Kampen and at DO+KZ to the total loads L_{in} and L_{out} over the years, we estimated the parameter K by fitting eq. (6) to the measured ratios DO+KZ : IJssel between 1960 and 1993 as given in Figs. 6.11 and 6.12.

Figure 6.11
Time series of the ratio of the annual TP discharges of IJsselmeer at Den Oever and Kornwerderzand (DO+KZ) and the IJssel at Kampen. Ratios obtained from interpolated and extrapolated loads are indicated by open symbols. Lines are based on best fits of a simple retention model with first order loss rates (K). Solid line is the result of the model with K = 0.033 m.d.$^{-1}$ for all years between 1961 and 1993. Broken lines are based on K = 0.040 m.d^{-1} for the years 1961 to 1978 and 1986 to 1993, and K = 0.022 m.d^{-1} from 1979 to 1985. Arrow indicates the mean ratio (as percentage) estimated for background conditions.

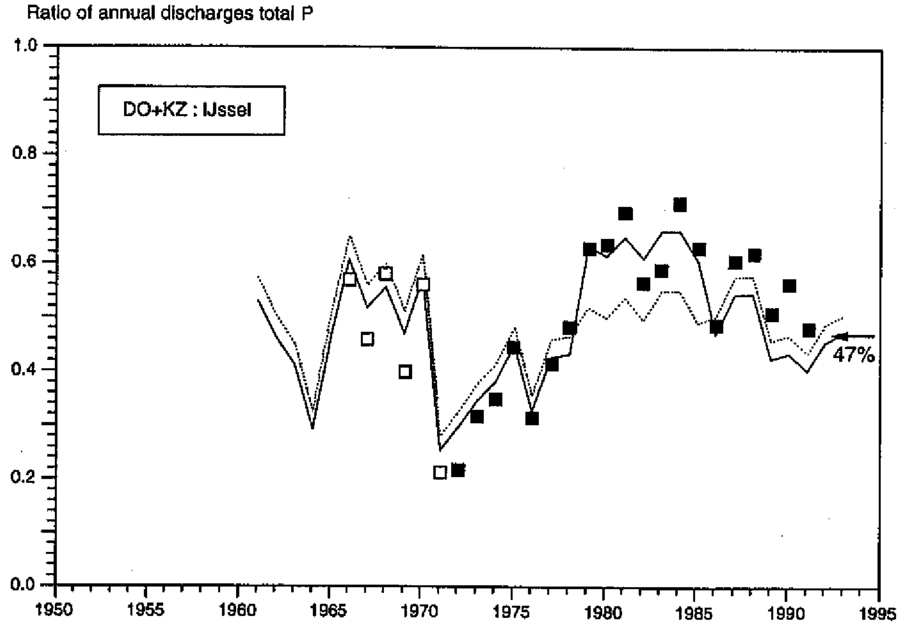
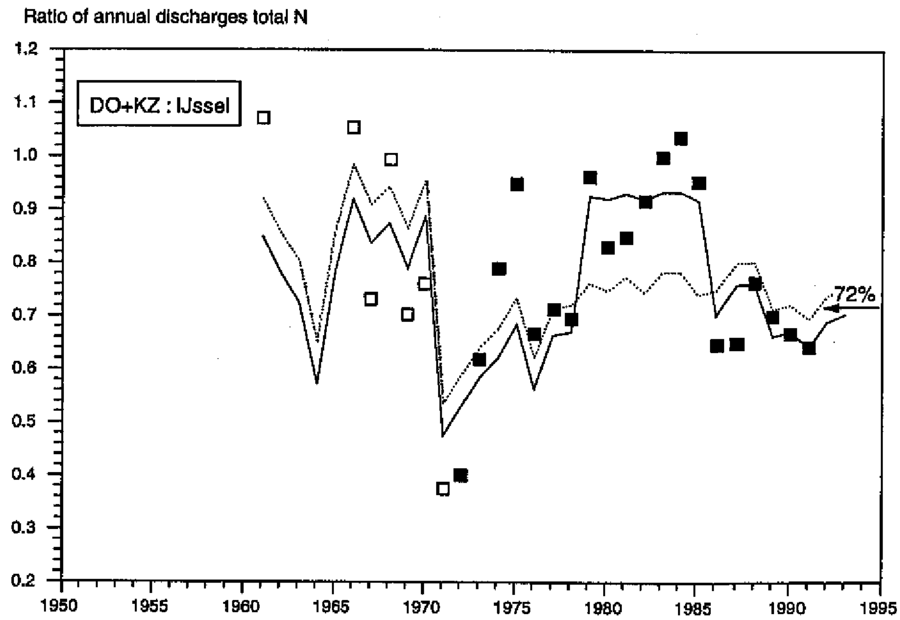


Figure 6.12
Time series of the ratio of the annual TN discharges of IJsselmeer at Den Oever and Kornwerderzand (DO+KZ) and the IJssel at Kampen. Ratios obtained from interpolated and extrapolated loads are indicated by open symbols. Lines are based on best fits of a simple retention model with first order loss rates (K). Solid line is the result of the model with K = 0.012 m.d^{-1} for all years between 1961 and 1993. Broken lines are based on K = 0.015 m.d^{-1} for the years 1961 to 1978 and 1986 to 1993, and K = 0.003 m.d^{-1} from 1979 to 1985. Arrow indicates the mean ratio (as percentage) estimated for background conditions.



Reasonably good fits were obtained with K = 0.033 ± 0.011 m.d^{-1} for TP and K = 0.012 ± 0.008 m.d^{-1} for TN for the entire period between 1961 and 1993 (dotted lines in Figs. 6.11 and 6.12). The low ratios between the nutrient discharges at DO+KZ compared to the loads at Kampen in the early 1970s, corresponding to high retentions, are adequately reproduced by the model (dotted lines in Figs. 6.11 and 6.12). We conclude that the high nutrient retention of IJsselmeer in the 1970s is caused by the relatively long flushing times during that period. Since the flushing time is controlled by hydrological parameters only, the dependency of nutrient retention from flushing times demonstrates the strong influence of water quantity management on the nutrient budget of the lake, and consequently on the nutrient output to the Wadden Sea.

In a similar way, separation of the Markermeer has decreased the volume and the flushing time of the remaining smaller lake. Consequently, also the nutrient retention decreased which (compared to the input from the river IJssel) has led to an increase in the discharge of TP and TN to the Wadden Sea.

Inspection of the model outcome indicates that the model substantially underestimates the ratios in the early 1980s. Therefore, we improved the model by applying lower apparent loss rates for the years between 1979 and 1985 than in the other years (solid lines in Figs. 6.11 and 6.12). We have no explanation for the decreased loss rates in the first half of the 1980s. Nevertheless, from the good fits we are confident that, apart from this half decade, the estimated loss rates can be applied to calculate the background retention of IJsselmeer and the TP and TN discharges at DO+KZ.
From the data in Table 2 and taking into account error propagation in the estimates we arrive at a ratio of the TP loads at DO+KZ and Kampen of 0.47 ± 0.08 under background conditions, corresponding to a natural background TP retention under present hydrological conditions of 53%. Estimates for TN are 0.72 ± 0.07 for the natural background ratio DO+KZ : IJssel and consequently 28% for the natural background retention of N in the lake.
The retention mechanisms for nitrogen and phosphorus basically differ. Phosphorus retention includes deposition and burial while nitrogen retention is possibly mainly caused by denitrification.

Table 2
Background parameters of IJsselmeer (DO+KZ). The apparent loss rates are based on the values obtained for the periods 1961-1978 and 1986-1993. For the further explanation see text.

water discharge (DO+KZ) Q_{out}	520 ± 90	$m^3.s^{-1}$
flushing time τ	125 ± 30	days
apparent loss rate K, *TP*	0.040 ± 0.009	$m.d^{-1}$
apparent loss rate K, *TN*	0.015 ± 0.007	$m.d^{-1}$
retention R, *TP*	53	%
retention R, *TN*	28	%
L_{out} / L_{in}, *TP*	0.47 ± 0.08	-
L_{out} / L_{in}, *TN*	0.72 ± 0.07	-
mean TP concentration	0.63 ± 0.34	µM
mean TN concentration	26 ± 13	µM
mean background load of TP	0.33 ± 0.17	$mol.s^{-1}$
mean background load of TN	14 ± 7	$mol.s^{-1}$

Annual mean background loads of total phosphorus and total nitrogen and concentrations at Den Oever and Kornwerderzand

The TP and TN loads from IJsselmeer into the Wadden Sea were derived from the background loads at Kampen (Table 1) combined with the results of the above section. The annual mean background load at DO+KZ is estimated at (0.7 ± 0.3) x (0.47 ± 0.08) = 0.33 ± 0.17 $mol.s^{-1}$ for TP, and (19 ± 9) x (0.72 ± 0.07) = 14 ± 7 $mol.s^{-1}$ for TN (Table 1, Figs. 6.7 and 6.8).

In 1961, the annual TP discharge at DO+KZ was ~6 times larger than the background load, and the TN discharge was ~8 times larger. Around 1980 when the TP discharge was at maximum, the input of phosphorus through the sluices of the Afsluitdijk was ~23 times larger than what may be expected for background conditions. In the early 1990s the TP load had returned to the level of the early 1960s, thus 6-fold the background. The highest TN discharge occurred in 1984 at a level ~15 times the background load. Subsequently, in the early 1990s the TN load at DO+KZ decreased to a 9-fold level compared with the background situation.

The annual mean background concentrations are calculated from dividing the loads by the annual mean water discharge at DO+KZ = 520 ± 90 $m^3.d^{-1}$ (Table 1). Thus, the background TP concentration is estimated at 0.33 / 520 x 1000 = 0.63 ± 0.34 μM, and the TN concentration is calculated at 14 / 520 x 1000 = 26 ± 13 μM (Table 2).

The above concentrations were compared with available 'old' data. Hutchinson (1957 p. 729 table 94) summarises the avarage TP concentrations in surface waters in 9 regions in the USA, Japan, Austria and Sweden between 1930 and 1940. The mean concentration in these regions was 0.67 ± 0.26 μM. Based on the work of Mortimer, Hutchinson (1957 p. 845 table 120) gives average TN concentrations in 3 'productive' and 6 'less productive' water bodies of the English Lake District in the thirties. In the productive lakes the mean TN concentration was 37 ± 14 μM, in the less productive lakes 21 ± 9 μM. The calculated natural background concentrations in this paper are very close to these historical data, thus strongly supporting the correctness of the estimates.

Dissolved nutrients (ammonium, nitrate and phosphate)

Up till here, we developed and applied a strategy to assess the background loads and concentrations of TP (total phosphorus) and TN (total nitrogen) at the outlets of IJsselmeer, starting from the river Rhine as the major resource of the lake.
This strategy can not be followed for the inorganic dissolved phosphorus and the different nitrogen compounds (mainly ammonium and nitrate) since these are strongly affected by chemical and biological processes in the water bodies. Nevertheless, some insight in the background concentrations of phosphate, ammonium and nitrate is desired for management purposes.

To start with, some general remarks can be made. The water of IJsselmeer near the Afsluitdijk seems phosphorus limited with a TN:TP ratio above 40 mol/mol under background conditions (data given above). As a consequence, in 1930 most of the phoshorus probably was present as particulate organic P and a minor fraction as dissolved (organic an inorganic) phosphate. Nitrogen, however, was available in excess. This excess was likely present in the form of nitrate or ammonium. Hutchinson (1957, p. 731 table 95) discusses the fractionation of TP in lakes of North Wisconsin (USA) and Linsley Pond (UK) in the 1930s. As a mean value, he arrives at phosphate concentrations ranging between 0.05 and 0.1 μM, i.e. 10-15% of TP. In the English Lake District the mean nitrate concentration was 6 ± 3 M, i.e. 30% of TN (Hutchinson 1957, p. 845 table 120). For unpolluted lakes, Hutchinson (1957) indicates that both ammonium and nitrate can have been the dominant forms of dissolved inorganic nitrogen. Taking these values (Hutchinson 1957, p. 853-854) for granted, mean ammonium concentrations between 1 and 20 μM may have occurred in freshwater lakes in 1930. Unfortunately, TN levels are not mentioned for these lakes.

Further historical information is obtained from Havinga (1941, 1954). For April 1934 Havinga (1954) reports zero ammonium concentrations in the northern IJsselmeer and 32 µM nitrate. For 5 stations in IJsselmeer in June 1938, Havinga (1941) measured phosphate concentrations of 6 µM, 3 x traces and 0 µM, respectively. Corresponding nitrate concentrations were 8, 5, 8, 3 and 29 µM. Neglecting the high phosphate concentration which probably has been the result of some form of contamination, the data of Havinga point at mean phosphate concentrations close to zero and mean nitrate concentrations between 3 and 30 µM in the 1930s. Apparently, the values given by Hutchinson (1957) are valid for IJsselmeer too. For ammonium, the historical data of Havinga are inconclusive.

Loads at Den Oever versus loads at Kornwerderzand

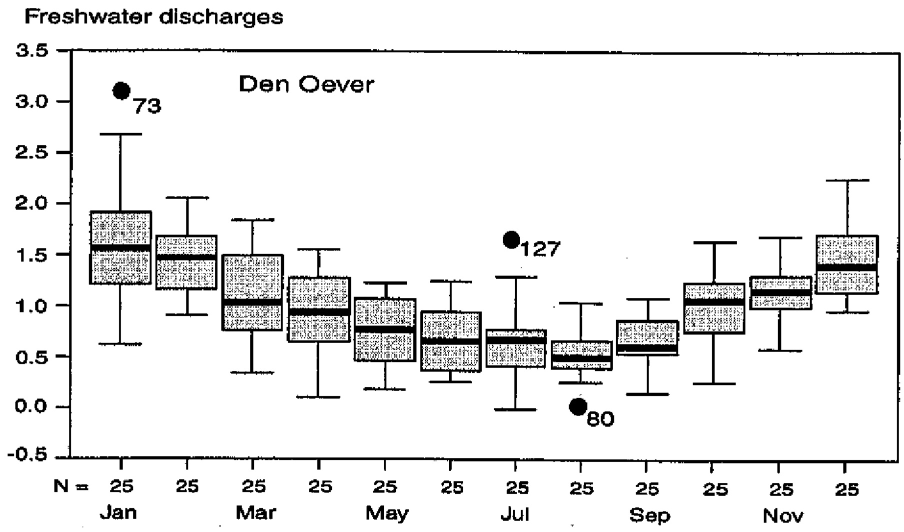
The individual TP and TN discharges at the two sluices of the Afsluitdijk can be estimated from the water discharges and the combined loads defined in the preceding sections. For the present day situation (1980-1994), the annual mean water discharge at DO is 310 $m^3.s^{-1}$, and at KZ 210 $m^3.s^{-1}$. Hence, the background TP load at DO is calculated at 310/520 x 0.33 = 0.20 $mol.s^{-1}$, and the background TN load at 310/520 x 14 = 8 $mol.s^{-1}$. The corresponding loads at KZ are estimated at 0.13 and 6 $mol.s^{-1}$ for TP and TN, respectively.

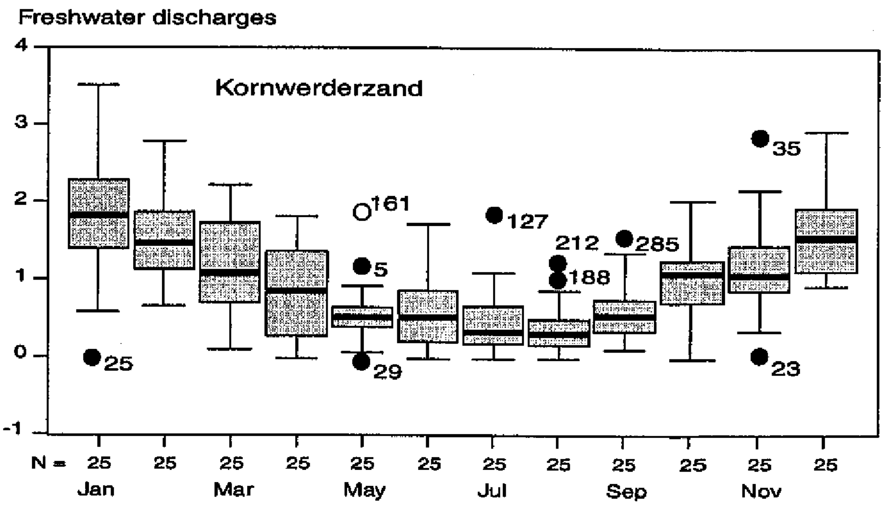
Seasonal cycles in the phosphorus and nitrogen loads and concentrations at Den Oever and Kornwerderzand.

The output of water and nutrients from IJsselmeer into the Wadden Sea is not evenly distributed over the year. In Fig. 6.13 to 6.15 we plotted normalized long-term average seasonal cycles of the water discharge of the lake, and the TP and TN concentrations in the fresh water near the Afsluitdijk, respectively. The cycles were constructed separately for DO and KZ by first calculating the ratio between the monthly values and the annual mean of each year from 1970 to 1995, and subsequently averaging these monthly ratios over the entire period. For the water discharge the cycles are based on the full 25 year period. For TP and TN data were available for 13 to 21 years. There was no obvious trend in the monthly ratios over the years, indicating that the seasonal cycles remained essentially unchanged between 1970 and 1995. Based on this observation, we assume that the cycles can be extrapolated, even to the natural background conditions.

Highest water discharges occur from December to February, lowest between June and August (Fig. 6.13). To estimate the expected monthly background discharges under the present hydrological conditions, the plotted ratios between monthly and annual water discharges in Fig. 6.13 are multiplied with the annual mean discharges at DO and KZ (see section above). For example, the maximum background discharge at DO is expected in January at a rate of 1.5 x 310 = 465 $m^3.s^{-1}$, the corresponding January discharge at KZ approximates 380 $m^3.s^{-1}$. In this way the expected mean discharges were calculated for the 4 seasons of the year: December-February (winter), March-May (spring), June-August (summer), and September-November (autumn) (Table 3).

Figure 6.13
Box-whisker plots of the ratios between monthly and annual mean water discharges at Den Oever and Kornwerderzand.
N denotes the number of years for which the ratios were calculated.





Highest TP concentrations at DO and KZ occur in January, lowest in May (Fig. 6.14). The seasonal variability of TP is, however, not very strong with average monthly ratios between 0.6 and 1.2. The seasonal cycle of the TP load at DO+KZ is almost completely determined by the variability in the water discharge (Table 3). The cycles of the TN concentration, on the other hand, are very pronounced with maxima in March and minima in September (Fig. 6.15). As a result, TP:TN ratios are very high in spring and relatively low in autumn (Table 3). The combined cycles of water discharges and TN concentrations yield background loads of TN being 2-4 times larger in winter and spring than in summer and autumn.

Table 3
Seasonal variation of the average background water discharge, natural background TP and TN loads and TP and TN concentrations of water in the IJsselmeer for DO+KZ.
Winter: December, January, February;
Spring: March, April, May;
Summer: June, July, August;
Autumn: September, October, November.
Levels of uncertainty are not included for clarity, on average these are 20-30% of the mean for water discharge, 60-80% for TP concentration and load, and 50-70% for TN concentration and load.

		winter	spring	summer	autumn
water discharge	$m^3.s^{-1}$	811	464	316	496
mean TP conc.	µM	0.7	0.6	0.6	0.6
mean TN conc.	µM	30	36	20	17
mean TP load	$mol.s^{-1}$	0.6	0.3	0.2	0.3
mean TN load	$mol.s^{-1}$	24	17	6	8
TN:TP ratio	-	42	60	34	29

Figure 6.14
Box-whisker plots of the ratios between monthly and annual mean discharges of TP at Den Oever and Kornwerderzand.
N denotes the number of years for which the ratios were calculated.

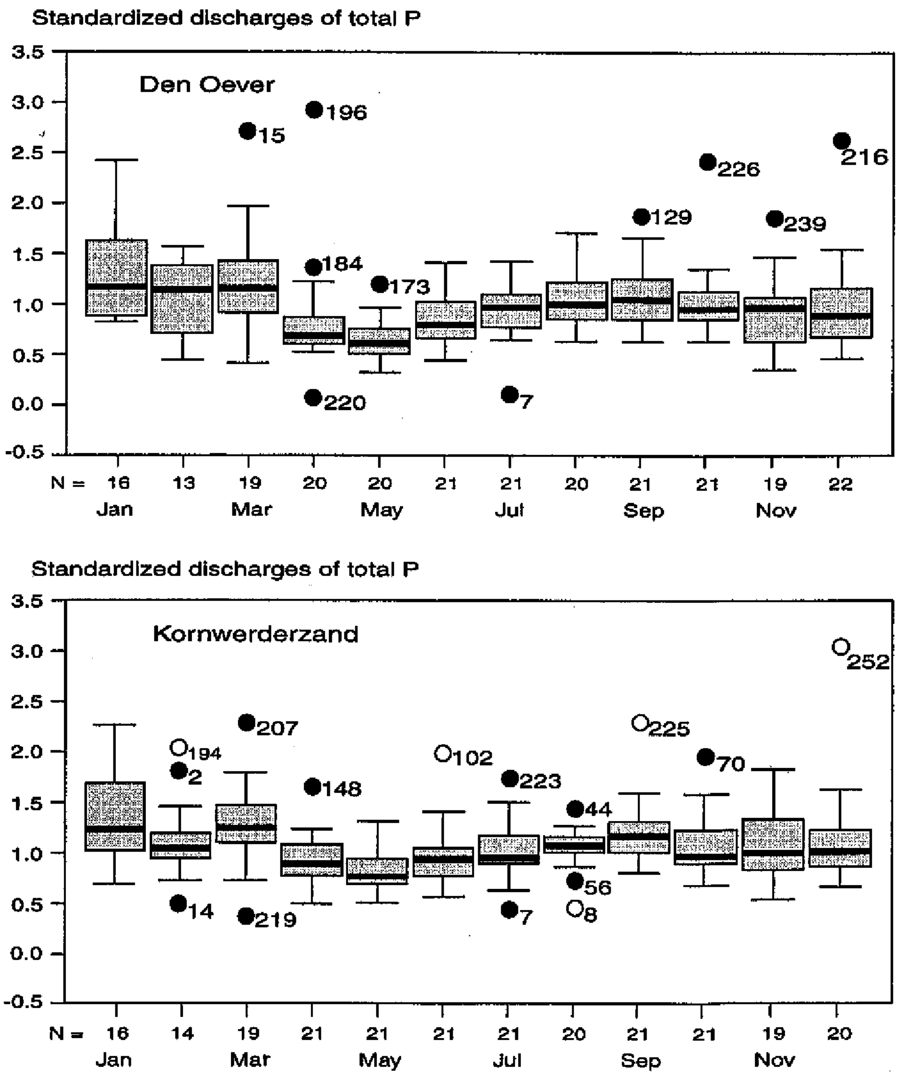
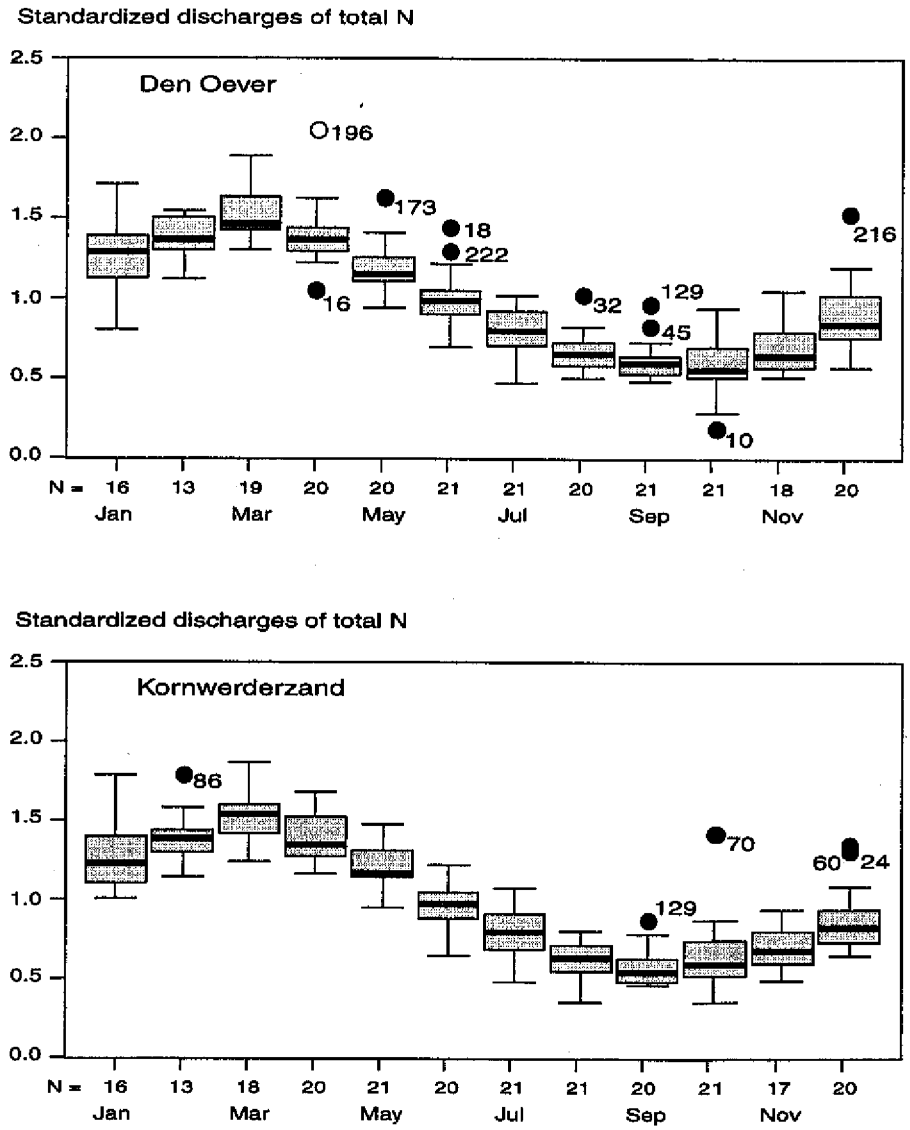


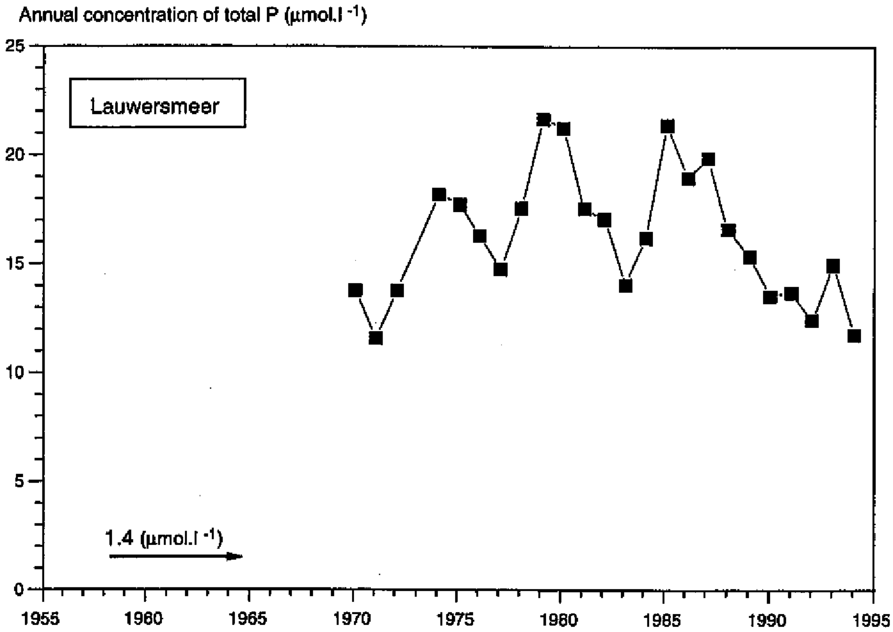
Figure 6.15
Box-whisker plots of the ratios between monthly and annual mean discharges of TN at Den Oever and Kornwerderzand.
N denotes the number of years for which the ratios were calculated.



6.3 Lauwersmeer

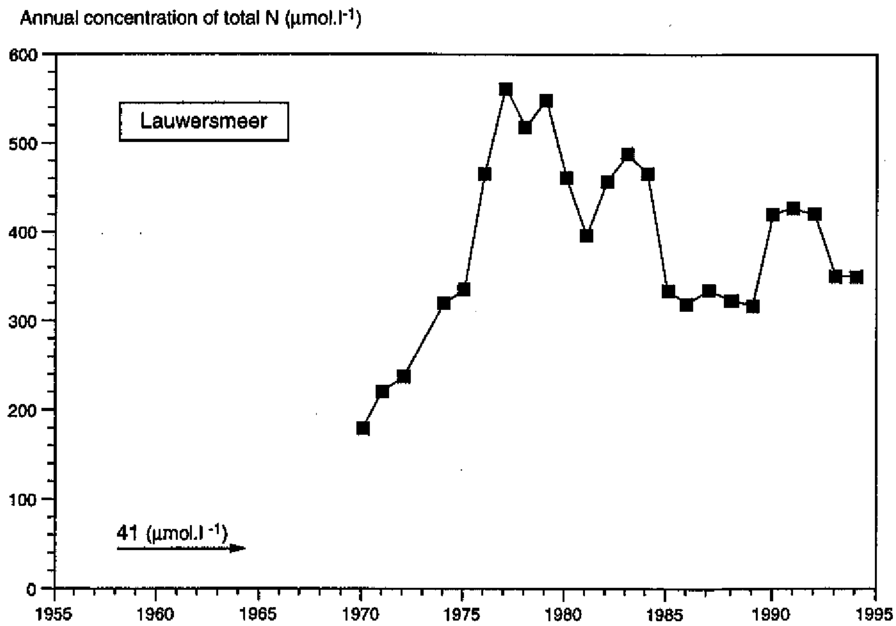
Based on data from the province of Groningen, the annual mean freshwater discharge of Lauwersmeer (Table 4) was ~30 $m^3.s^{-1}$ between 1970 and 1978, increasing in 1979 to 41 ± 8 $m^3.s^{-1}$. Compared to the output of IJsselmeer the water discharge of Lauwersmeer is approximately 11.5 times smaller. Using the depth (2.3 m), surface area (20 x 10^6 m^2) and volume of the lake (46 x 10^6 m^3) (Berger & Bij de Vaate, 1974; Berger, 1987), the annual mean flushing time of the Lauwersmeer has been calculated. It has been 21 days in the 1970s, and 16 ± 4 days from 1979 onwards. The annual mean hydraulic load (water discharge per unit of surface area) of the lake is 41 x 86400 / 20x10^6 = 0.17 $m.d^{-1}$ since 1979. During the first few years after its separation from the Wadden Sea the average TP concentration in Lauwersmeer was 12-14 µM. Unexpectedly, the values increased to 15 to 20 µM in 1974-1989 (Fig. 6.16).

Figure 6.16
Time series of the annual mean TP concentration (µmol.l^{-1}) in Lauwersmeer. Arrow indicates the estimated background TP concentration in the lake.



In the 1990s TP had returned to its original concentrations of 13 ± 1 µM. In contrast, the development of TN concentrations showed a gradual increase from 200 µM in the early 1970s to a first maximum of 550 µM in 1977 and a second maximum of 490 µM in 1983. Subsequently, TN concentrations decreased to < 400 µM since 1985 (Fig. 6.17). The combined patterns of TP and TN resulted in variable TN:TP ratios in the lake being as low as 13 in 1970 and as high as 38 in 1977 and 35 in 1983. At present the annual average TN:TP is ~30, i.e. close to the ratio estimated for freshwater background conditions.

Figure 6.17
Time series of the annual mean TN concentration (µmol.l^{-1}) in Lauwersmeer. Arrow indicates the estimated background TN concentration in the lake.



The annual mean TP discharge of Lauwersmeer into the Wadden Sea initially was ~0.4 mol.s^{-1}, sharply increasing to 0.8 ± 0.1 mol.s^{-1} between 1979 and 1988, and subsequently decreasing again to 0.5 ± 0.1 mol.s^{-1} since 1989 (Fig. 6.18). For TN the annual mean loads were ~6 mol.s^{-1} in the early 1970s, increasing to ~24 mol.s^{-1} in 1979 followed by a decrease to 14 ± 3 mol.s^{-1} in the early 1990s (Fig. 6.19). Compared to IJsselmeer, the 1988 nutrient output of Lauwersmeer was 4.5 times less for TP and 10 times less for TN.

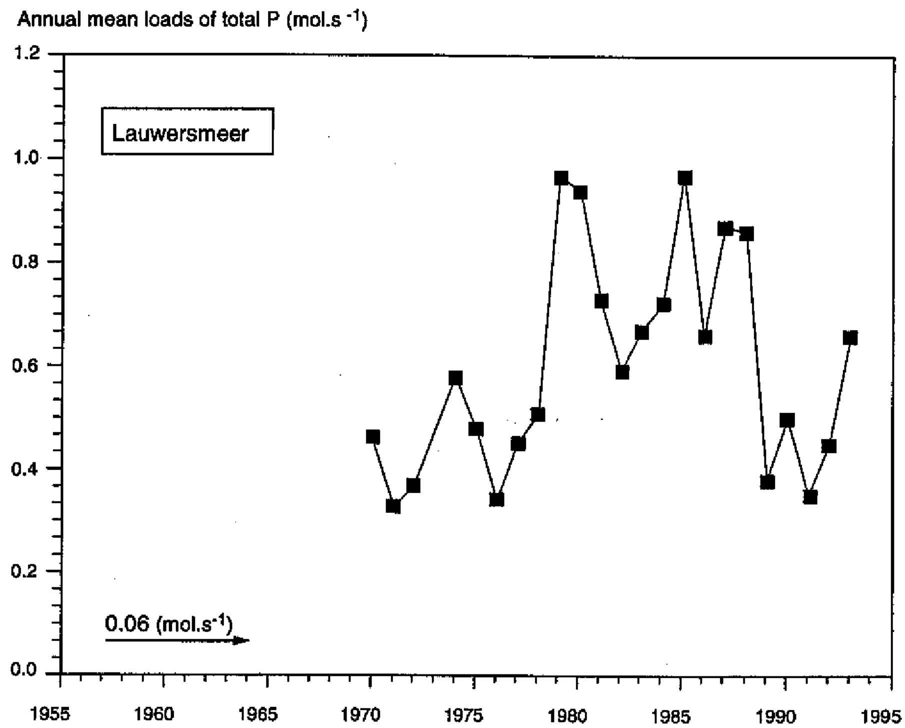


Figure 6.18
Time series of the annual mean TP load (mol.s^{-1}) from Lauwersmeer into the Friesche Zeegat. Arrow indicates the estimated background discharge of TP.

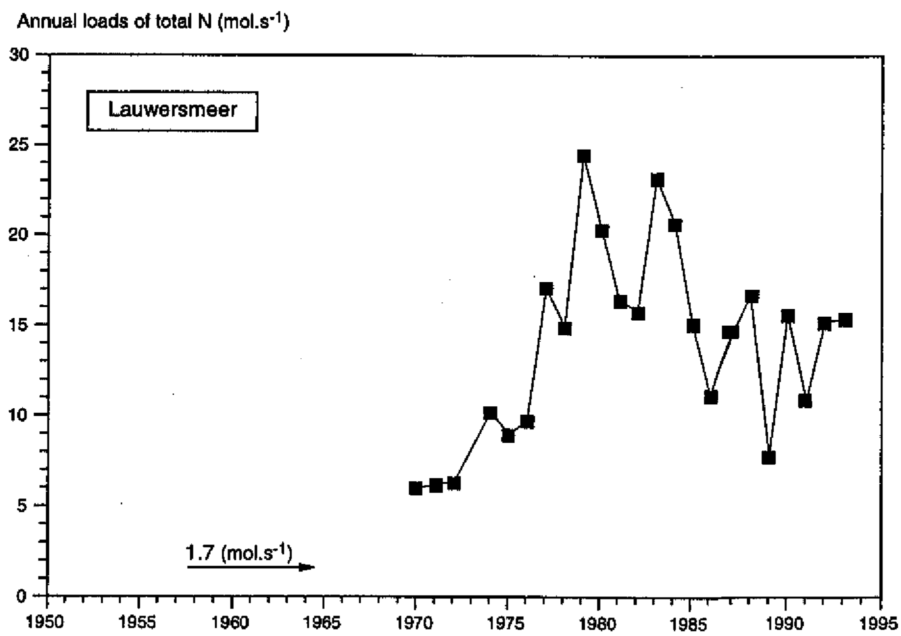


Figure 6.19
Time series of the annual TN load (mol.s^{-1}) from Lauwersmeer into the Friesche Zeegat. Arrow indicates the estimated background discharge of TN.

For background conditions we assume the same annual mean concentrations in the tributaries of Lauwersmeer as in the river Rhine: TP = 1.8 ± 0.8 μM, TN = 50 ± 23 μM. To arrive at the concentrations in the water flowing out the lake, the same retention formula as for IJsselmeer was applied (eq. 5). Van Straten (1986) summarizes the apparent loss rates (K) for several Dutch lakes. For lakes with hydraulic loads > 0.01 $m.d^{-1}$, he calculated loss rates > 0.01 $m.d^{-1}$ and slightly higher retentions for TP than for TN. For simplicity we applied the apparent loss rates estimated for IJsselmeer (Table 2) to Lauwersmeer. These estimates are in line with the general findings of Van Straten (1986). Better estimates can be made after collecting detailed data on the development of the TP and TN inputs into the lake.

Our estimate of the retention R of Lauwersmeer is 20 ± 5% for TP and 10 ± 5% for TN. The relatively low nutrient retention estimated for Lauwersmeer corresponds to the short flushing time of the lake which is the result of the relatively large water masses that pass the area.

Application of the above estimated retention results in an annual mean background concentration in the outflow of the lake of 0.8 x 1.8 = 1.4 ± 0.6 μM for TP, and 0.9 x 45 = 41 ± 18 μM for TN (Table 4). The corresponding background loads are 41 x 1.4 / 1000 = 0.06 ± 0.03 $mol.s^{-1}$, and 41 x 41 / 1000 = 1.7 ± 0.8 $mol.s^{-1}$ for TP and TN, respectively (Table 4).

Compared to the output of IJsselmeer, the background concentrations in Lauwersmeer are substantially higher due to its much lower estimated retention for TP and TN. The loads of this much smaller lake are, however, approximately 5.5 (TP) and 7.5 (TN) times lower than those at DO+KZ.

Table 4
Annual mean background TP and TN concentrations in Lauwersmeer, the river Ems and the Westerwoldsche Aa + Eemskanaal, and the corresponding background discharges into the Wadden Sea. For the water discharge of the Westerwoldsche Aa and Eemskanaal no estimate for the standard deviation of the mean was available.

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

6.4 The river Ems, the Westerwoldsche Aa and the Eemskanaal

The water discharge of the river Ems is highly variable. On an annual basis the discharge varies between 50 and 150 $m^3.s^{-1}$, with a mean of 100 $m^3.s^{-1}$ (De Jonge, 1988; De Jonge & Essink, 1991). Assuming similar background concentrations as for the Rhine (TP = 1.8 ± 0.8 μM, TN = 45 ± 25 μM), annual mean background loads are estimated at 0.2 ± 0.1 $mol.s^{-1}$ for TP and 4.5 ± 2.3 $mol.s^{-1}$ for TN (Table 4). The adoption of the background concentration of the river Rhine is justified seen the results of the discussion in that section.

The annual mean water discharges of the Westerwoldsche Aa is only 10% that of the river Ems (De Jonge, 1988; De Jonge & Essink, 1991) and that of the Eemskanaal is slightly lower (Van Meerendonk *et al.* 1988). For calculating natural background loads of these freshwater sources we assume the water discharges to be 10 and 8 $m^3.s^{-1}$, for the Westerwoldsche Aa and Eemskanaal, respectively. Further assuming approximately similar background concentrations in all the freshwater sources of the Ems estuary, we conclude that, for natural background conditions, the Westerwoldsche Aa and the Eemskanaal play only a minor role compared to the river Ems. For this reason we did no attempt to better constrain the estimate. From these considerations we estimate the background loads of both the Westerwoldsche Aa and the Eemskanaal to amount to 0.02 ± 0.01 $mol.s^{-1}$ for TP, and 0.4 ± 0.25 $mol.s^{-1}$ for TN (Table 4).

The combined freshwater input of nutrients under natural background conditions into the Ems estuary is estimated at 0.24 ± 0.12 $mol.s^{-1}$ for TP, and 5.3 ± 2.8 $mol.s^{-1}$ for TN. Compared to the loads from IJsselmeer into the Wadden Sea the inputs to the Ems estuary are approximately 1.5 (TP) and 2.5 times lower (TN).

7 Natural background concentrations in the North Sea

The basins of the Wadden Sea are largely filled with water from the North Sea, and to a much lesser extent with freshwater. The North Sea, in turn, is controlled by the Atlantic Ocean, the southern North Sea mainly by the input via the English Channel and the Strait of Dover. The inputs to the North Sea are modified by the inputs of the continental rivers (Brockmann *et al.*, 1990). Thus, Laane *et al.* (1992) in their extensive analysis of background concentrations of natural compounds distinguished between the following areas in the North Sea.
(1) Waters inflowing from the ocean.
(2) Coastal waters with riverine influence.
(3) Waters in the central part of the North Sea.
From the coastal waters, the water near the Dutch coast (area C in Laane *et al.*, 1992) is the direct source of both water and nutrients for the Dutch Wadden Sea. We have adopted the background concentrations estimated by Laane *et al.* (1992) for area C as the basis for our further analysis.

Winter concentrations of phosphate and nitrate

The salinity of Laane's area C (Dutch coastal waters) is between 31 and 33, while the salinity of the Atlantic water flowing in through the western English Channel has a salinity of ~35.3 (Laane *et al.*, 1992, area 'A'). In the English Channel and the Strait of Dover fresh water from *e.g.* French rivers and English rivers are mixed with ocean water. Further north water from the rivers Schelde, Meuse and Rhine is added. This implies that the coastal water in area C consists for 6-12% of fresh water, mainly from continental rivers the river Rhine included. Laane *et al.* (1992) only estimated background concentrations of dissolved phosphate, nitrite and nitrate for the winter months. For area C their estimates are based on observations by Kalle (1937) during cruises in January 1935 and February 1936, and by Folkard & Jones (1978) during cruises in 1961 and 1962. Laane *et al.* (1992) give a range between 0.5 and 0.9 μM for phosphate and 20 - 33 μM for nitrite + nitrate. The latter values are, however, solely based on the data of Folkard & Jones (1974, 1978). Since the river Rhine was already considerably enriched with both P and N compounds in the early 1960s (Figs. 6.1 and 6.2), the results of Laane *et al.* (1992) presumably provide an over-estimate for natural background conditions as defined for our study. For phosphate the data of Kalle (1937, stations 61, 71, 16, 16A) span a range of 0.49 - 0.63 μM which is at the lower part of the range of values given by Laane *et al.* (1992).

We can constrain the above estimates for the Dutch coastal waters (area C) by calculating the phosphate and nitrate winter-concentrations from the background levels in the river Rhine (and other continental rivers) and the English Channel. A few assumptions have to be made. We have only background winter-values in the sea water in area C, and annual mean concentrations for the river Rhine (*cf.* section 6.1). It takes several months for a water parcel to travel from the English Channel through the Strait of Dover to the Dutch coast (Otto *et al.*, 1990). According to Prandle (1993) the flushing time of the southern North Sea (south of 56N) is 240 days. The flushing time of the area between the Belgian-Dutch and English coast is calculated to be 108 days or 3½ month. Hence, the seasonal cycle in the input in the south is strongly attenuated upon entering the North Sea and this cycle may show up along the Dutch coast with a considerable phase-shift. In other words, winter concentrations in the English Channel and the Strait of Dover are not directly linked to those in area C. We assume, however, that the winter concentrations of phosphate and nitrate (nitrite << nitrate and is ignored) in the English Channel represent the annual mean levels of all P and N compounds in the input from the Atlantic Ocean that, eventually, can be converted into phosphate and nitrate in the southern North Sea during the winter months.

The time of a water parcel needed to travel from the mouth of the Rhine to the northern boundary of area C is only a few weeks. This would imply that winter values in the river Rhine, better than annual means, should be used to estimate winter concentrations in Dutch coastal waters. Along the eastern part of the English Channel, Strait of Dover and Southern Bight of the North Sea, we are also dealing with river inputs from France, Belgium and The Netherlands of which the transport time of the most southern fresh water source is considerably longer than several weeks. Our range of the annual mean TP background concentration for the river Rhine (1-2.5 μM) includes the phosphate concentrations of 1.24-1.34 μM measured by Kalle (1937) at virtually zero salinity off the mouth of the Rhine during winter. From these considerations and because of lack of appropriate data, we assume that the annual mean background concentrations of TP and, also, TN in the river Rhine may be applied as the basis for a crude estimate of the freshwater contribution to the background phosphate and nitrate concentrations in area C during winter.

As mentioned above, the river Rhine is not the only fresh water source for Dutch coastal waters. However, the other rivers probably have natural background concentrations of nutrients close to those of the Rhine. Therefore, we have used the river Rhine as being representative for all fresh water inputs to area C in the southern North Sea.

The concentrations in the English Channel and the river Rhine from which we calculated the natural background winter-concentrations of phosphate and nitrate in area C along the Dutch coast are summarised in Table 5.
Assuming conservative mixing, the background phosphate winter concentration in area C becomes 0.57 ± 0.13 μM. This estimate very well fits the range given by Kalle (1937) in 1935 and 1936 (average 0.58 ± 0.05). The calculated background concentration for nitrate is 9.1 ± 3.1 μM. and is considerably lower than the value given by Laane *et al.* (1992) based on data from the 1960s.
As an additional check for the validity of our estimates we calculated the nitrate to phosphate ratio in area C under background conditions. Taking the data from Laane *et al.* (1992: table 4) this ratio would have been 25 : 0.7 = 36, *i.e.* even larger than the background TN : TP ratio in the river Rhine itself. This seems not a realistic result. Use of the estimates in Table 5 yield a nitrate to phosphate ratio of 16, which is similar to the ratio encountered in unpolluted coastal waters (Redfield, 1958).

We conclude that the values in Table 5 are the best possible estimates of natural background winter-concentrations of phosphate and nitrate in Dutch coastal waters. Moreover, these values are consistent with the background levels estimated for the Atlantic inflow and the freshwater sources.

Table 5
Natural background concentrations of phosphate and nitrate in the English Channel (area A in Laane *et al.*, 1992), the river Rhine and the Dutch coastal area (area C in Laane *et al.*, 1992) during winter. Concentrations in the English Channel were obtained from Laane *et al.* (1992), concentrations in the Rhine are the annual mean TP and TN values (see text). Salinities in the English Channel and in the Dutch coastal waters are from Laane *et al.* (1992). The concentrations for the Dutch coast were calculated by theoretical mixing Channel water and Rhine water according to the salinities in the areas under consideration.

area	Salinity PSU	Phosphate (DIP) ($\mu mol.l^{-1}$)	Nitrate ($\mu mol.l^{-1}$)	N:P
English Channel	35.3	0.45 ± 0.05	5.5 ± 0.5	12
River Rhine	~0	1.8 ± 0.8	45 ± 25	25
Dutch coast	32 ± 1	0.57 ± 0.13	9.1 ± 3.1	16

Winter concentrations of TP and TN

Estimates of natural background concentrations of TP and TN were not evaluated by Laane *et al.* (1992). For winter conditions they may be determined from the phosphate (DIP) and nitrate concentrations, because outside the phytoplankton growing season these compounds form the largest portion of TP and TN.
In winter and unpolluted conditions, ammonium is present in much lower concentrations than nitrate (see for data in the English Channel in 1931 *e.g.* Cooper, 1933). From the data given for Dutch coastal waters by Klein & Van Buuren (1992), we calculated the winter TP:DIP and TN:DIN ratios. This value was 1.4 for both compounds in the period 1976-1991. Application of this ratio, under neglection of ammonium, results in background concentrations in the coastal North Sea, during winter, of 0.8 ± 0.3 µM for TP and 13 ± 5 µM for TN (Table 6).

The above given estimates can be compared with the 5 observations of Kalle (1937) for TP at 4 stations near the Dutch coast with a salinity of 31 - 33 in January 1935 and February 1936. These concentrations range from 0.8 to 1.1 µM with an average of 0.95 µM. These observations by Kalle (1937) do not significantly differ from our estimate in Table 6 for the winter period, although we realize that the number of observations is low.

Seasonal cycles of the background phosphorus and nitrogen concentrations in Dutch coastal waters

To estimate the seasonal cycle of TP and TN in the coastal North Sea we applied the same procedure as was followed for IJsselmeer. Thus, for each year for which sufficient data were available we calculated the annual mean concentration, divided the individual monthly values by the annual mean to arrive at monthly ratios, and subsequently determined the average of these ratios for the 12 months of the year (Figs. 7.1 and 7.2). The so determined average seasonal cycles are based on data from the Rijkswaterstaat monitoring station Noordwijk-20 (*e.g.* Klein & Van Buuren, 1992) measured during 7 years between 1980 and 1993. Since we have no further information we assume that these cycles can be applied to approximate the background seasonal cycles in the Dutch coastal zone.

Figure 7.1
Box-whisker plots of the ratios between monthly and annual mean concentrations of TP in the coastal North Sea at the Rijkswaterstaat monitoring station Noordwijk-20. N denotes the number of years for which the ratios were calculated.

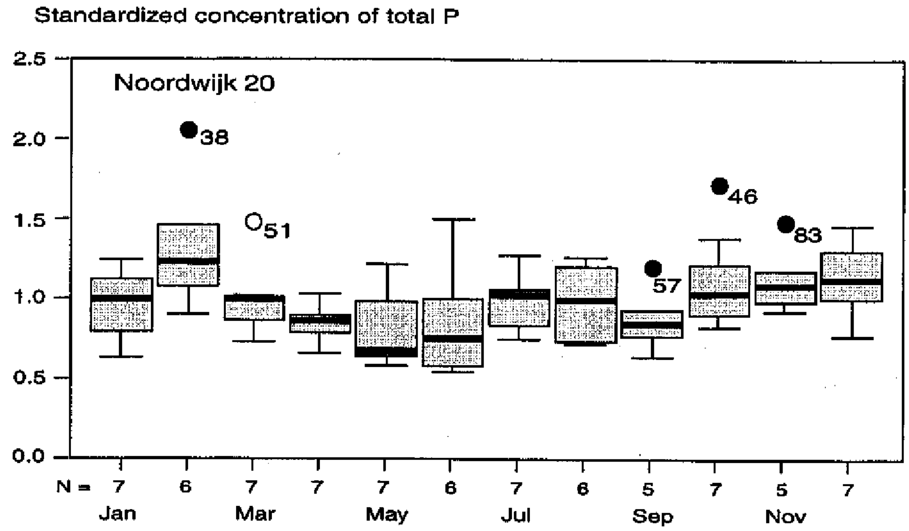
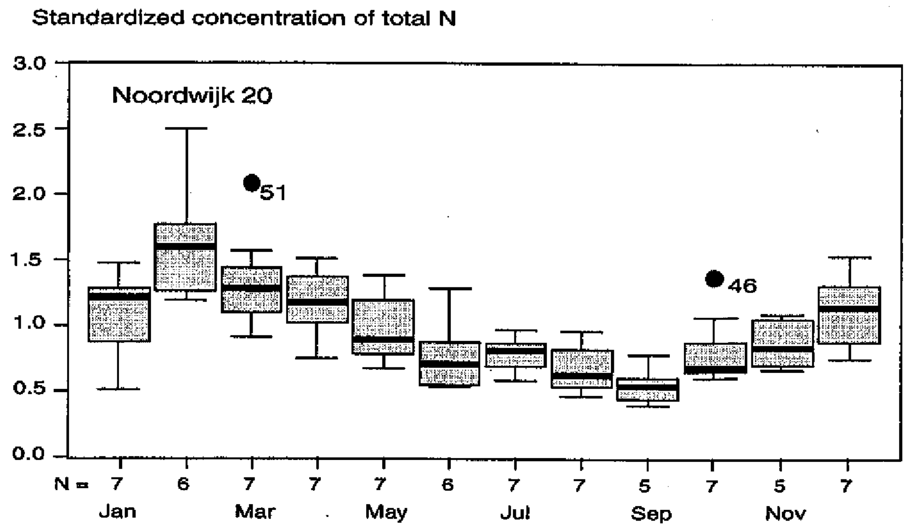


Figure 7.2
Box-whisker plots of the ratios between monthly and annual mean concentrations of TN in the coastal North Sea at the Rijkswaterstaat monitoring station Noordwijk-20.
N denotes the number of years for which the ratios were calculated.



On average, winter concentrations of TP are 1.1 ± 0.3 times the annual mean concentration (Fig.7.1, Table 6). Consequently, the annual mean background concentation of TP in the Dutch coastal zone is estimated at 0.8 / 1.1 = 0.7 ± 0.3 µM. Winter concentrations of TN are 1.3 ± 0.3 times the annual mean background concentration (Fig. 7.2, Table 6), which is estimated at 13 / 1.3 = 10 ± 4 µM.

The background concentrations of TP and TN as estimated for the 4 seasons of the year are listed in Table 6. As for IJsselmeer, the annual cycle of TP reveals minor seasonal variability with slightly higher concentrations in winter and autumn (0.8 µM) than in spring and summer (0.6 µM). The variation in TN is more pronounced with the highest concentrations in winter and spring (1.2-1.3 µM) and considerably lower levels in summer and autumn (0.7-0.8 µM). As a consequence, the TN:TP ratio shows an annual cycle as well, with values well above the Redfield ratio (16) in spring, and below in summer and autumn.

There are not many historical observations reported on TP and TN to confirm our estimates. In marine waters reliable data for TN are probably not available from the period before the 1960s. For TP, however, a few seasonal cycles have been measured before that time. Armstrong & Harvey (1950) give data of TP for the period 1947 to 1949 at a station 20 miles off shore Plymouth in the English Channel. Their winter values range from 0.4 to 0.5 μM, and their summer values from 0.3 to 0.4 μM. Logically, the concentrations at this Atlantic station (salinity ~35) are lower than we have estimated for the Dutch coast which is heavily influenced by the different continental rivers. The moderate seasonal variability of the station investigated by Armstrong & Harvey (1950), however, is similar to the moderate seasonal amplitude we estimated for the Dutch coastal zone. Closer to the coast (5-15 miles), Armstrong & Harvey (1950) measured TP concentrations between 0.5 and 0.7 μM in January 1949. Our estimate for TP during winter is close to these values. Redfield *et al.* (1937) presented data for the Gulf of Maine in the mid 1930s. In February 1936 they measured a TP concentration of 1.1 μM in the surface water, in August 1935 they found a TP concentration close to 0.7 μM. Finally, Postma (1954) gives an annual average TP concentration of 0.94 M for a station in the North Sea 15 km of Texel (salinity = 32) between 1949 and 1951. Taking into account the probable increase in TP concentrations in the coastal area between the 1930s and the early 1950s, and the relatively large errors involved in our estimates, but also in the averaged values measured, we conclude that the background values listed in Table 6 are in good agreement with the few observational data available from the literature.

Table 6
Natural background TP and TN concentrations in the coastal North Sea estimated for the 4 seasons of the year. Winter: December, January and February; Spring: March, April, May; Summer: June, July, August; Autumn: September, October, November. The concentrations were calculated by combining background values estimated for the winter months with the annual cycles shown in Figs. 7.1 and 7.2. Ratios are relative to the annual mean.

	winter	spring	summer	autumn
TP ratio	1.1 ± 0.3	0.9 ± 0.2	0.9 ± 0.2	1.1 ± 0.3
TP conc. μM	0.8 ± 0.3	0.6 ± 0.3	0.6 ± 0.3	0.8 ± 0.3
TN ratio	1.3 ± 0.3	1.2 ± 0.2	0.7 ± 0.2	0.8 ± 0.3
TN conc.μM	13 ± 5	12 ± 5	7 ± 3	8 ± 4
N:P	16	20	12	10

8 Natural background concentrations in the Wadden Sea basins

Nutrients in the Wadden Sea and the estuaries intersecting this area show non-conservative distribution patterns which is caused by production and loss processes in different periods of the year (Postma, 1954, 1966; Duursma, 1961; Helder, 1974; De Jonge & Postma, 1974; De Jonge & Van Raaphorst, 1995; Van Beusekom & De Jonge, 1995, 1997, 1998; De Jonge *et al.* 1996; De Jonge, 1997). De Jonge & Van Raaphorst (1995) analysed the TP-salinity distributions in the Marsdiep basin for the winter and summer period, respectively, of 1949-1951, 1970-1971 and 1986, and showed that TP is 'consumed' in the basin during winter and 'produced' during summer. This pattern reflects the deposition of phosphorus compounds in the Wadden Sea interior in the winter months and subsequent release from the sediments in summer (Postma, 1954; De Jonge & Postma, 1974; Van Raaphorst & Kloosterhuis, 1994). There is no doubt that these processes also occurred under natural background conditions. These processes can, however, only be quantified 'reliably' by means of ecosystem modelling (*e.g.* Baretta & Ruardij, 1988; Brinkman, 1993), applying the background concentrations in the fresh water sources and the coastal North Sea (as estimated above) as boundary conditions. To quantify the non-conservative behaviour of the nutrients is, however, beyond the scope of our present analysis, and we will restrict ourselves to some qualitative remarks.

All background concentrations presented below are based on simple theoretical and conservative mixing of fresh water and North Sea water. The error introduced by this simple approach can not easily be quantified. However, compared to the much higher present day average concentrations in the different basins, we expect that this error will turn out to be of minor importance for management purposes.

The conservative mixing approach implies that background concentrations in the Wadden Sea basins deviate from the North Sea values only in case of substantial fresh water inputs. Therefore, only the Marsdiep and Vlie basin, the Friesche Zeegat and the Ems estuary will be treated below. The other basins are assumed to have natural background concentrations close to the values estimated for the North Sea.

TP and TN in the Marsdiep and Vlie basins.

The total surface area of the Marsdiep and the Vlie basins is 1380 10^6 m^2 (De Jonge & Van Raaphorst, 1995) of which 25-30% consists of tidal flats. The load of freshwater via the sluices in the Afsluitdijk dam is 520 $m^3.s^{-1}$ for background conditions (Table 1), *viz.* 520 / 1380 10^6 x 86400 = 0.03 $m.day^{-1}$ when expressed per unit of surface area (hydraulic load). The background loads of TP and TN from the IJsselmeer are estimated from Table 1 at 0.02 and 0.9 $mmol.m^{-2}.day^{-1}$, respectively.

The salinity in the two western most basins of the Wadden Sea is highly variable. Postma (1954), for instance, mentioned a range between 16 and 31. This variability is determined by the sluicing regime at Den Oever and

Kornwerderzand (freshwater input), but also by the salinity of the coastal North Sea which is not constant under influence of varying current patterns and discharges of the main rivers. To assess the salinity in the basins and the portion of water from IJsselmeer present we used the definition of the flushing-time (Ridderinkhof *et al.*, 1990):

$$\tau_{ij} = (V / Q)_{ij}$$

where τ is the flushing time (days) of the volume of freshwater V (m^3) present in the basins, discharged at a rate Q ($m^3.day^{-1}$) out of IJsselmeer (subscript ij). Values of the flushing time, taken from Ridderinkhof *et al.* (1990), amounted to 10 and 12 days for water discharged into the Marsdiep and Vlie basins from Den Oever (DO) and Kornwerderzand (KZ), respectively. The volumes V_{ij} were calculated from the above equation using the average discharges at DO and KZ in the four seasons of the year over the period 1980-1993, and were subsequently divided by the tidal mean volume of the basins (4.66 10^9 m^3, Ridderinkhof, 1990; De Jonge & Van Raaphorst, 1995). These calculations yield contributions of water from IJsselmeer to the total volume of the basins varying from 6% in summer to 16% in winter (Table 7).

The flushing-times reflect the average time needed for a water parcel from IJsselmeer to be flushed out of the basin, *i.e.* to be transported through one of the tidal inlets to the coastal North Sea. In other words, the tidal inlets are treated as the seaward boundaries of the basins. As a consequence, in the further calculations the salinities and concentrations directly outside the inlets were considered as the seaward end member in the conservative mixing model. As a starting point we used the salinities and concentrations in the coastal North Sea (salinity 31 - 32, section 6), representative for the Rijkswaterstaat monitoring station Noordwijk-20 (see *e.g.* Klein & Van Buuren 1992). At this station, the average salinity (period 1975 - 1993) is 31.8 in winter, 31.4 in spring, 31.5 in summer and 32.6 in autumn. The salinities at the inlet of the Vlie basin are assumed to be similar to these coastal North Sea values. Salinities at the Marsdiep inlet are, however, clearly lower (Ridderinkhof, 1990) with annual averages between 27 and 30 between 1977 and 1990 (*c.f.* also Klein & Van Buuren, 1992 and De Jonge, 1997) and mean winter values between 25 and 30. The coastal North Sea concentrations, however, are also here within the range given by the confidence limits of the Marsdiep and Vlie basin estimates (*cf.* Table 7).

Concentrations at the North Sea boundary are derived from the background values of TP and TP in the coastal North Sea after a correction for salinity and using river Rhine water as the freshwater end member. The correction resulted in slightly higher concentrations in the tidal inlets as compared to those estimated for the coastal North Sea (Table 7).

Finally, we calculated the average salinities and background concentrations of TP and TN in the Marsdiep and Vlie basins by mixing IJsselmeer water with North Sea boundary water, according to the relative volumes and salinities listed in Table 7. Thus, we arrived at salinities between 24-27 in winter, 26-29 in spring and 27-30 in summer and autumn. With the natural background TP and TN concentrations estimated for the discharge of IJsselmeer (Table 3), the annually mean natural background concentrations in the two Wadden Sea basins are calculated at 0.8 µM for TP and 13 µM for TN. The seasonal cycle shows highest TP background concentrations in winter and lowest in spring and summer. Highest TN concentrations are estimated for winter and spring, and lowest for summer and autumn. As a consequence of the different annual cycles of the nutrients, the TN:TP ratio is close to the Redfield ratio (16) in summer, well above this ratio in winter and spring, and considerably below in autumn.

Some care should be taken when interpreting the annual cycles. The reasons are following.
(1) The level of uncertainty in the estimates of the concentrations is relatively large.
(2) Non-conservative behaviour of the nutrients may have a strong impact on the annual variability.
According to the data of Postma (1954) for the years 1949 - 1951, De Jonge & Postma (1974) for 1970 - 1971, and the data for 1986 appearing in De Jonge & Van Raaphorst (1995: fig. 9), TP during winter may be a few tens of µM lower than indicated by conservative mixing, and an approximately similar amount higher during summer. This implies that, in agreement with Postma (1954) and De Jonge & Postma (1974), true background concentrations of TP are probably lowest in winter (0.7 µM) and highest in summer (0.9 µM). It should be noted, however, that these 'non-conservative' estimates are still within the uncertainty intervals of the 'conservative' TP values. For TN the effect of non-conservative behaviour is less clear.

Compared to the background concentrations in IJsselmeer (Table 3), the TP values in the Wadden Sea are somewhat higher, but the values still are within the range of the given confidence intervals. The background concentrations of TN estimated for the Wadden Sea are lower than those calculated for IJsselmeer. Compared to the coastal North Sea (Table 6) both the TP and TN background concentrations in the Wadden Sea are higher. The coastal North Sea concentrations are, however, also within the range given by the confidence limits of the Marsdiep and Vlie basin estimates.

Table 7
Natural background concentrations of TP and TN estimated for the total of the Marsdiep and Vlie (M+V) basins. The estimates are based on conservative mixing of water from the North Sea (NS) boundary at the tidal inlets with water from IJsselmeer. Values at the 2 tidal inlets of the basins are taken as representative for the NS boundary (see text).

		winter	spring	summer	autumn
NS boundary salinity	PSU	28 - 32	28 - 32	29 - 32	30 - 33
NS boundary TP	µM	0.9 ± 0.3	0.7 ± 0.3	0.7 ± 0.3	0.8 ± 0.4
NS boundary TN	µM	15 ± 5	14 ± 5	9 ± 3	8 ± 4
M+V basins salinity	PSU	24 - 27	26 - 29	27 - 30	27 - 30
% Ijsselmeer water		16	9	6	10
M+V basins TP	µM	0.9 ± 0.3	0.7 ± 0.3	0.7 ± 0.3	0.8 ± 0.4
M+V basins TN	µM	17 ± 7	16 ± 6	10 ± 4	9 ± 5
M+V basins TN:TP		~19	~23	~14	~11
M+V basins DIP	µM	~ 0.5	~ 0.1	~ 0.2	~ 0.4
M+V basins DIN	µM	~ 7	~ 4	~ 3	~ 3
M+V basins DIN:DIP		~14	~40	~15	~ 8

The oldest data in the literature with which our estimates can be compared are the phosphorus data of Postma (1954) indicating that the annually averaged TP concentration in the Marsdiep basin was ~1.6 µM for the years 1949-1951 (Postma 1954: table 23). This value is higher than our findings, which is apparently caused by the much higher TP concentrations measured by Postma

(1954: fig. 48) in IJsselmeer (1 - 3 μM) between 1949 and 1951, as compared with our estimate of 0.63 μM for background conditions (Table 2). As an additional source, the Noord Hollandsch Kanaal discharged water with an average TP concentration of ~27 μM (!) into the harbour of Den Helder in the early 1950s (Postma 1954: table 18). This high concentration was caused by the sewage supply from Den Helder and connected area. Actually, the TP input from the Noord Hollandsch Kanaal into the Wadden Sea was more than twice as large as the input from IJsselmeer in 1951. Probably this was also the case in January 1935, when Kalle (1937) measured a TP concentration of 1.9 μM at "Den Helder Reede". Since we are confident in our estimates of the background concentrations in the freshwater sources, we conclude that the data of Postma (1954) represent conditions already strongly enriched with phosphorus. It also means that in the relation between phosphate loads from IJsselmeer and primary production in the Marsdiep tidal inlet (De Jonge, 1990) the phosphate load for 1951 was significantly underestimated.

The oldest data on TN in the Wadden Sea were presented by Postma (1966) for October 1960 to March 1962, when the nitrogen concentrations were substantially elevated compared to background conditions: ~110 μM in winter, 75 μM in spring, and 60 μM in summer and autumn. Clearly, these oldest data are not sufficiently old to serve as a reference level in eutrophication studies.

Maximum winter concentrations in the basins were reached for TP around 1980 with values of ~8 μM, and for TN some years before with values of ~200 μM (Van Raaphorst & Mom, 1995; data representing first quarter). In summer (third quarter) maximum TP concentrations were measured in the early 1980s (6 - 10 μM) and maximum TN levels in 1977 (160 - 180 μM). In 1978 TN concentrations suddenly dropped to ~50 μM. Compared to the natural background concentrations, the maximum TP concentrations were 8 - 9 times higher in winter and 9 - 14 times higher in summer. The maximum TN concentrations were 11-12 times higher in winter and approximately 17 times higher in summer. Apparently, the basins were relatively stronger enriched with nitrogen compared to phosphorus in the summers before 1978.

In the early 1990s, TP was close to 4 μM in winter and 2.5 - 3 μM in summer (Van Raaphorst & Mom, 1995), *viz.* 4.5 and 3.5 - 4 times higher than the background concentrations in winter and summer, respectively. For TN the present concentrations are 70 - 110 μM (4 - 6 times the background) in winter and 30 - 40 μM (3 - 4 times the background) in summer.

Phosphate and Nitrate + Ammonium in the Marsdiep and Vlie basins.

For comparison with the background concentrations estimated for the North Sea by Laane *et al.* (1992) it is useful to assess the natural background concentrations of phosphate (DIP) and nitrate + ammonium (DIN) in the Marsdiep and Vlie basins. Unfortunately, these can not be quantified in a similar way as the TP and TN values as they are largely controlled by non-conservative processes. Therefore, we rely on the relationships between the dissolved inorganic compounds and the TP and TN concentrations established in the oldest data sets available. Based on the data of Postma (1954: fig. 53), the relative contribution of DIP to TP was 45 - 55% in autumn and winter and 10 - 25% in spring and summer (1949 - 1951). Similarly, the data of Postma (1966) reveal that DIN contributed 40% to TN in the winter and 25 - 35% in the summer of 1960-1962. Accepting these relative contributions, we arrive at average mean natural background DIP concentrations of ~0.3 M, with the highest values in winter and autumn (Table 7). For DIN the annual mean background concentration is ~6 M, with the highest concentration to be expected in winter (Table 7). The often quoted DIN:DIP ratio amounts to ~14, 40, 15 and 7,5 in winter, spring, summer and autumn, respectively, under background conditions. Together with the corresponding TN:TP ratios (Table 7), these estimates for background conditions point at a relative shortage of P compared to N for the phytoplankton production in spring, and a relative shortage of N in autumn.

TP and TN in the Friesche Zeegat

The Friesche Zeegat has a surface area of 195 10^6 m^2 of which 70% is in the form of tidal flats. The background discharge of freshwater from Lauwersmeer is estimated at 41 $m^3.s^{-1}$ (Table 4), corresponding to a surface load of 41 / 195 10^6 x 86400 = 0.02 $m.day^{-1}$. The associated background TP and TN loads (Table 4) are ~0.03 and ~0.8 $mmol.m^2.day^{-1}$. These numbers indicate that the natural areal input of nutrients from Lauwersmeer into the Friesche Zeegat is approximately equal to that from IJsselmeer into the Marsdiep and Vlie basins.

The flushing time of water from Lauwersmeer in the Friesche Zeegat is, to our knowledge, not known. Therefore, we use the turn-over time (4.5 days) given by Ridderinkhof *et al.* (1990) as a approximation for the flushing time. Using the definition of the flushing time (see above), and with a tidal mean volume of the basin of 0.2 10^9 m^3 (De Jonge & Van Raaphorst, 1995), we calculated the amount of freshwater present in the Friesche Zeegat at 8% of the total volume (annual average). It may be expected that this percentage is larger in winter, and lower in summer (for comparison see Table 7). Further assuming a salinity of 32 at the seaward boundary of the basin, the annual mean background salinity in the Friesche Zeegat is estimated at 29-30.

The background concentrations of TP and TN in the Friesche Zeegat are calculated from the concentrations in Lauwersmeer (Table 4) and the coastal North Sea, respectively. For the latter winter concentrations (Table 6) were divided by 1.1 (TP) and 1.3 (TN, see chapter 7). Applying conservative mixing, the annual mean natural background concentration of TP in this part of the Wadden Sea is calculated at 0.08 x 1.4 + 0.92 x 0.8 / 1.1 = 0.8 ± 0.3 μM. Similarly, the annual mean natural background TN concentration is estimated at 13 ± 6 μM.

TP and TN in the Ems estuary

The Ems estuary is characterised by a well developed salinity gradient from the river Ems to the open sea and by the presence of a turbidity maximum at low salinity (e.g. Van Beusekom & De Jonge, 1995, 1998). Data of Postma from 1954 (Postma, 1960) indicate that TP was produced in the estuary in July 1954, similarly to what has been found for the Marsdiep and Vlie basins (see above). Since TP is a conservative property in itself, this summer production should be compensated for by a net loss during winter (Postma, 1954). De Jonge & Villerius (1989) showed a production of phosphate at salinities between 5 and 20 in April, May, June, July and December of 1981. Helder *et al.* (1983) demonstrated an annual mean production of nitrate at the expense of ammonium in the Ems estuary in 1970-1972. The main part of the nitrate production occurred in summer. These data demonstrate that calculating the natural background concentrations from a conservative mixing concept can yield crude estimates only.

The conservative mixing concept implies that the TP and TN concentrations in the estuary are intermediate to those at its end members, *i.e.* the river Ems, the Westerwolsdche Aa and the Eemskanaal, and the coastal North Sea. Annual mean background concentrations in the freshwater sources are taken from Table 4: TP = 1.8 ± 0.8 µM and TN = 45 ± 25 µM. For the North Sea we apply the values given in Table 6 representing coastal waters at salinities between 31 and 33. Annually averaged TP = 0.8 / 1.1 = 0.7 ± 0.3 µM and TN = 13 / 1.3 = 10 ± 4 µM in the coastal North Sea. Consequently, in the estuary annual mean background TP concentrations decrease from 1.8 to 0.7 µM and TN from 45 to 10 µM along the salinity gradient.

To give a single value representing the average situation in the estuary we used the flushing-time concept in a similar way as we did for the Marsdiep and Vlie basins in the western Wadden Sea. Approximating the flushing time of all freshwater inputs by the average flushing time of water from the river Ems (38 days; Helder & Ruardij 1982), the total fresh water discharge of 120 $m^3.s^{-1}$ from Table 4 and the tidal mean volume of the estuary of 1.76 10^9 m^3 from Helder & Ruardij (1982), we calculated the mean volume of freshwater present in the estuary at 0.39 10^9 m^3, or 22% of the total volume. From this percentage the typical, annual mean background concentration of TP amounts to 0.22 x 1.8 + 0.78 x 0.7 = 0.9 ± 0.4 µM.
The corresponding TN concentration is estimated at 0.22 x 45 + 0.78 x 10 = 18 ± 8 µM.

General conclusion for the Wadden Sea basins

Comparing the estimates for the Friesche Zeegat and the Ems estuary with those for the western Wadden Sea basins (Table 7) indicates that they are similar within their limits of confidence. Thus, although differences between the basins of the Wadden Sea may occur under background conditions, these are smaller than we can predict within the uncertainty constraints of our estimates. From this consideration we conclude that the natural background concentrations estimated for the Marsdiep and Vlie basins and listed in Table 7 can be applied as a crude estimate for all basins receiving substantial amounts of nutrient containing fresh water. The only exception may be the Ems estuary, that probably needs more sophisticated modelling to better constrain the background conditions.

Conversely, background concentrations in the basins are close to the estimates made for the coastal North Sea. Thus, with the precaution of the assumption of conservative mixing, for the Wadden Sea basins without substantial freshwater discharges, the natural background concentrations may be approximated safely by those in the coastal North Sea (Table 6).

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