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Reconstruction of the total N and P inputs from the IJsselmeer into the western Wadden Sea between 1935–1998

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Abstract

In this paper we reconstruct the Total Nitrogen (TN) and Total Phosphorus (TP) inputs into the western Wadden Sea from its major freshwater source the lake IJsselmeer between 1935–1998. The reconstruction is based on the TN and TP loads of the river Rhine at the German/Dutch border and follows the aquatic continuum approach to calculate loads further downstream in (1) the river IJssel feeding the IJsselmeer, and (2) the discharge of this lake into the western Wadden Sea. Our objectives are to determine (1) how the signal of changing nutrient loads of the Rhine is transferred downstream, and (2) how hydrological changes in the rivers-and-lake system affected the TN and TP discharges into the western Wadden Sea. Observational data from which TN and TP loads of the river Rhine could be calculated date back to the 1960s and we used background loads for European rivers for the period before World War II. The period in between was interpolated using the historic scenarios of watershed land use and management tested for the hypothetical Phison river (Billen and Garnier, 1997, Aquat. Microb. Ecol. 13, 3–17), adapted for the hydrology of the Rhine. The interpolations were constrained by loads of dissolved inorganic N and P compounds, for which data go back to the 1930s. Using the reconstructed loads of the river Rhine, TN and TP loads of the river IJssel and the lake IJsselmeer were calculated with simple mass balance models that were calibrated against data available from 1972–1993 onwards. Results show a gradual 12-fold increase of the TN discharge of the IJsselmeer into the Wadden Sea from 1935 to 1988, after which it decreased to levels still ~ 5 fold those in 1935. The discharge of TP increased more abruptly in the early 1960s to values in 1983 ~ 10 fold those before 1965, followed by a sharp decrease to values still ~ 2.5 fold those before 1965. These patterns resemble those in the river Rhine, but are modified due to (1) variability of other sources to the lake, and (2) reduction of the retention capacity of the lake due to enormous land reclamation. TN:TP atomic ratios in the freshwater input to the Wadden Sea as high as 100 in 1995 were caused by successful P reduction programmes, less successful N reduction and N-rich inputs from smaller rivers and land runoff into the lake IJsselmeer. Land reclamation caused the lake's retention of TN to decrease step-wise from ~ 70% to ~ 45–50% and that of TP from 85% to 55–60% between 1950 and 1980.

Keywords: TN; TP; Time series; Nutrient reconstruction; Western Wadden Sea

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[1] During the processing of this manuscript for publication, Dr. W. van Raaphorst died in an accident. This tragic event marked the end of the life of a devoted and widely appreciated oceanographer who made important contributions to our understanding of the geochemistry of coastal sediments.

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1. Introduction

As many other coastal waters (Gray, 1992; Nixon, 1995; Richardson and Jørgensen, 1996) the Wadden Sea has been subjected to strong anthropogenic eutrophication during the last 50 years (Postma, 1985; Van der Veer et al., 1989; Van Raaphorst and Van der Veer, 1990; De Jonge and Van Raaphorst, 1995, Philippart et al., 2000). Several changes in the ecosystem have been attributed to the increase of nutrient resources, for example increased phytoplankton concentrations and productivity (De Jonge and Essink, 1991; Cadée and Hegeman, 1993, 2002) as well as doubling of the macro-zoobenthic stock (Beukema and Cadée, 1997; Beukema et al., 2002). Relative changes in the nitrogen and phosphorus resources (N:P ratios) stimulated alteration of the phytoplankton species composition (Riegman et al., 1992; Philippart et al., 2000). These effects are still within the initial stages of eutrophication (Gray, 1992), and later stages such as mass growth of certain species, mortality of others and extended hypoxia (e.g., Rosenberg et al., 1990; Baden et al., 1990) have not been reported for the western Wadden Sea. In the 1980s, phosphates in washing powders were banned and this resulted in a considerable reduction of P-loads via the freshwater sources. In 1990, the governments of the countries bordering the North Sea agreed upon the reduction of nitrogen and phosphorus inputs to the North Sea by 50% relative to those in 1985. Furthermore, P-removal and to a lesser extent N-removal have been effectuated at many sewage treatment plants in western Europe during the past two decades. As a consequence, phosphorus loads of the river Rhine have decreased (De Jonge and Van Raaphorst, 1995) and the phosphorus concentrations in the Wadden Sea have dropped strongly since 1980–1985. The nitrogen loads of the Rhine have decreased much less and nitrogen concentrations in the western Wadden Sea were only slightly lower in the 1990s than in the 1980s (De Jonge, 1997; Philippart et al., 2000).

To put the history of eutrophication in proper perspective it is important to have insight in base-line nutrient inputs and concentrations. The most fundamental approach to define such reference levels is to assess them from pristine conditions. Attempts to do so have been conducted by Nixon (1997) for Narragansett Bay. He defined pristine as the period before European settlement and used historic information from sediment cores and model outcomes to estimate prehistoric nitrogen deposition from the atmosphere. Data from modern 'minimally disturbed' temperate forested watersheds were used to estimate the nutrient runoff from land. Billen and Garnier (1997) applied coupled models of the idealized Western European drainage networks including their stagnant annexes (the Riverstrahler model, Billen et al., 1994) and river impacted coastal zones, to assess the chronological succession from pristine to present-day conditions in an imaginary river-coastal zone system, typical for Western Europe. Although sometimes crude assumptions had to be made in both studies, they provide a historic perspective in which recent developments can be evaluated. For example, the results of Billen and Garnier (1997) indicate that (based on Nixon, 1997) molar N:P ratios in the Western European freshwater sources may have varied under pristine conditions with forested watersheds from about 60:1 down to about 18:1 in the 19th and 20th century. These ratios are to be compared with about 26:1 measured in the Rhine in 1985 (Klein and Van Buren, 1992) and 16:1 typifying coastal marine phytoplankton assemblages (Redfield, 1958).

While the concept of pristine conditions provides a scientifically valid framework it is not very meaningful from a management perspective. The major reason is that pristine conditions are far too distinct from the present-day situation. It is not easy to see how the effects of management measures to be taken in heavily urbanised and industrialised European societies with modern agriculture can be compared with prehistoric settings. Another reason is that drainage networks on the watershed as well as coastal systems themselves have been altered near-irreversibly by human activities. The western Dutch Wadden Sea in its present form exists only since 1932 when the brackish Zuiderzee was closed off by the Afsluitdijk, thereby creating the freshwater lake IJsselmeer (Figs. 1 and 2).

The complete history of nutrient enrichment of the western Wadden Sea and its tributaries has not been evaluated up to now. Philippart et al. (2000) restricted their time-series analysis of the western part of the Wadden Sea to the period 1974–1994, for which an extensive and reliable data set exists, thus missing the

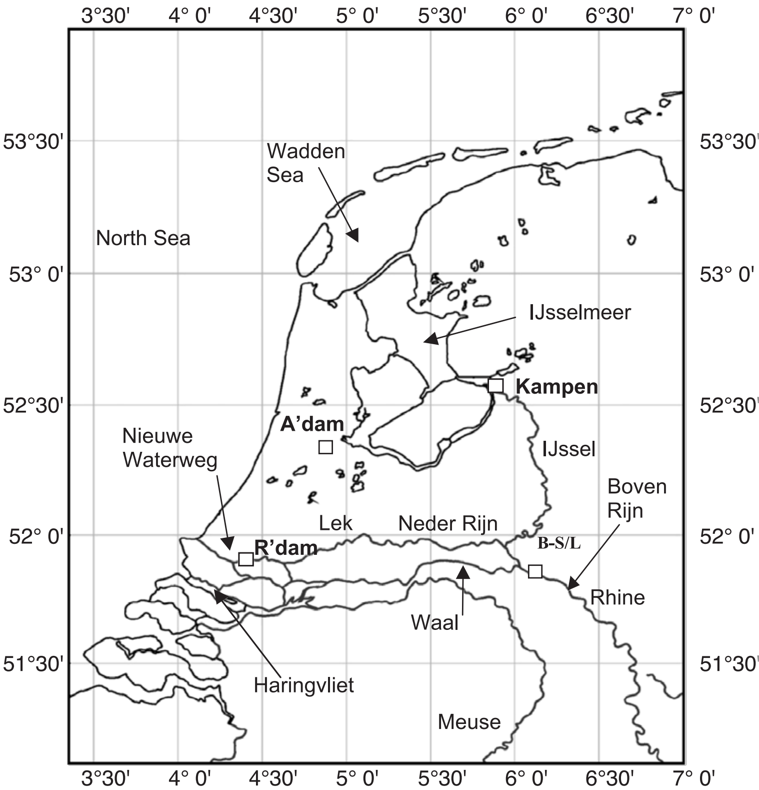

Fig. 1. Map showing the course of the Rhine and its branches in the Netherlands after passing the German/Dutch border at Bimmen-Spijk/Lobith (B-S/L). Indicated are: the major branch along the Bovenrijn and Waal towards the Nieuwe Waterweg and Haringvliet from which the Rhine drains in the North Sea; the branch along the Bovenrijn, Nederrijn and Lek to the Nieuwe Waterweg and Haringvliet; and the route from the Bovenrijn via the IJssel into the IJsselmeer (near the town of Kampen) and to the northern discharge points into the Wadden Sea. The plume of the Rhine off the Nieuwe Waterweg and the Haringvliet flows northward in a narrow zone parallel to the Dutch coast.

onset of modern eutrophication before 1970 (Nixon, 1995; Billen and Garnier, 1997). Van der Veer et al. (1989) went back as far as 1950 and tried to link the development of nutrient concentrations in the western Wadden Sea to nutrient loads of the Rhine, but their study contains several gaps and uncertainties. Because the river Rhine is the main freshwater source to Dutch coastal waters, others (Van Bennekom et al., 1975; Van Bennekom and Wetsteijn, 1990; De Jonge and Essink, 1991; Cadée and Hegeman, 1993; De Jonge et al., 1996) have used the discharge of the Rhine to explain the available long-term observations in the coastal North Sea and the western Wadden Sea. Data from the Rhine at the German/Dutch border provide probably one of the best-documented historical nutrient data sets in the world. However, nutrient elimination and retention as well as additional inputs during transfer from the German/Dutch border to the western Wadden Sea influence the final loads into the western Wadden Sea. It is unclear how these underway gains and losses have changed over time.

In this paper we will reconstruct the freshwater total nitrogen (TN) and total phosphorus (TP) inputs to the western part of the Dutch Wadden Sea between 1935–1998. We selected TN and TP as target variables rather than dissolved inorganic compounds because those allow us to set up whole-system mass balances more easily and are the most robust indicators of available N and P to support algal growth (Guildford and Hecky, 2000). We admit that additional knowledge on the availability of silicid acid would be needed to fully evaluate the effects of changing nutrient inputs on phytoplankton production and species composition. However, concentrations and loads

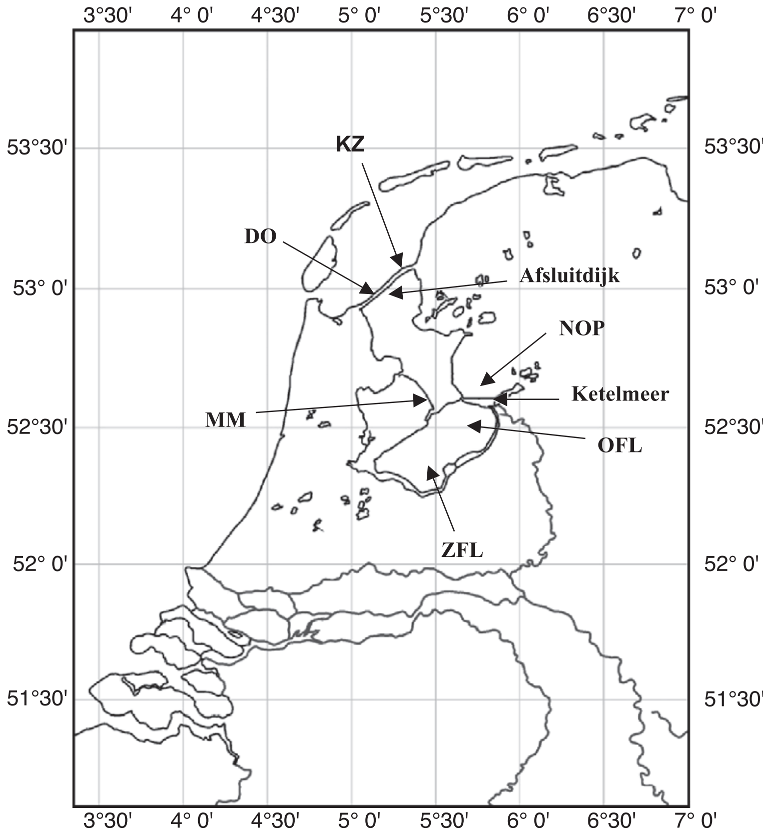

Fig. 2. Map focusing on the northern branch of the Rhine along the IJssel and the IJsselmeer towards the Wadden Sea. The IJssel branches off the Bovenrijn and flows into the Ketelmeer, the most eastern part of the IJsselmeer. The IJsselmeer drains into the westernmost Wadden Sea through the sluices in the Afsluitdijk at Den Oever (DO) and Kornwerderzand (KZ). Polders that were constructed in the lake after its construction in 1932 are the Noordoostpolder (NOP), Oostelijk Flevoland (OFL) and Zuidelijk Flevoland (ZFL). Also indicated is the dyke (MM) separating the Markermeer (west of this dike) from the IJsselmeer proper.

of silicid acid are not documented as well as those of nitrogen and phosphorus. Furthermore, data on total Si, including biogenic opal that may become available for diatom growth upon dissolution, are not available for the rivers Rhine and IJssel and the lake IJsselmeer.

We will follow the aquatic continuum approach (Billen et al., 1991) and derive the inputs to the western Wadden Sea from TN and TP concentration levels in the river Rhine at the German/Dutch border. In our calculations we will take into account gains and losses when going downstream from the river Rhine via the river IJssel and the lake IJsselmeer to the western Wadden Sea (Fig. 1). Main objectives of this study are (1) to determine the elimination and retention of TN and TP during transfer from the river Rhine to the western Wadden Sea, and (2) how hydrological changes downstream of the German/Dutch border have affected their discharges into the western Wadden Sea. We selected 1935–1940 as the period of reference, shortly after the closure of the Afsluitdijk in 1932 and corresponding to the onset of modern eutrophication due to large-scale use of fertilisers, detergents and a steep increase in population density in Western Europe (De Jonge and Postma, 1974; Van der Veer et al., 1989; Nixon, 1995; Billen and Garnier, 1997). Our analysis depends directly on the time series that will be reconstructed for the river Rhine and subsequently will serve as an input to all further calculations. The reconstruction will be based on concentrations regularly measured in the Rhine since the 1960s and background loads of European rivers representing the period before 1940 (Laane, 1992).

The period in between will be interpolated applying the scenarios of watershed land use and management tested by Billen and Garnier (1997) for their hypothetical river Phison and adapted to the Rhine as a guidance. All downstream time series will be calculated with simple mass balance models, using data on discharge and concentrations available from 1972 onwards to calibrate and confirm the model results.

2. Study area

The densely populated drainage basin of the Rhine (~ 270 inhabitants per km^2 at present, International Commission for the Protection of the Rhine, Koblenz, Germany) comprises an area of ~ 160 10^3 km^2 upstream of the German-Dutch border and receives water from both snow melting in the Alps and rain. We use data collected at the German-Dutch border at Bimmen-Spijk/Lobith (B-S/L) as starting point for all further calculations. This location is upstream of the major branches into the rivers Nederrijn/Lek, Waal and IJssel. The first two branches (together with the river Meuse) drain into the North Sea, at present mainly via Rotterdam along the Nieuwe Waterweg and for a minor portion through the sluices in the dam of the Haringvliet slightly further south (Fig. 1). The climatological mean discharge at B-S/L is 2300 m^3 s^{-1}, but seasonal and year-to-year variations are large (International Commission for the Protection of the Rhine, Koblenz, Germany). The river IJssel flows northwards to the IJsselmeer and has an average discharge of ~ 400 m^3 s^{-1} since 1980 (data obtained from the Dutch Ministry of Transport, Public Works and Water Management, The Hague, The Netherlands). The distance from B-S/L to the entrance of the IJsselmeer near the town of Kampen is ~ 120 km. The additional drainage area of the IJssel downstream of B-S/L is ~ 3500 km^2 with a present-day population density of ~ 150 inhabitants per km^2 (data from the Dutch Statistical Bureau, CBS, Voorburg, The Netherlands).

After its creation in 1932, the surface area and volume of the IJsselmeer has decreased stepwise due to the construction of three large polders in 1942, 1957 and 1967, as well as a dike separating the southwestern edge from the main lake in 1975. In its present form the lake has a volume of 5.4 10^9 m^3, a surface area of 1.2 10^9 m^2 and a mean depth of 4.4 m. Water enters the lake mainly in the southeast where the IJssel discharges. The contribution of other sources draining into the lake has decreased during the past decades from about 35–45% during 1940–1970 (Rijkswaterstaat/DZW, 1942–1969; Havinga, 1954; De Kloet, 1971, 1978) to some 20–30% since the 1970s (De Wit, 1980). Water leaves the lake in the north mainly through two sluices in the Afsluitdijk at Den Oever (DO) and Kornwerderzand (KZ, Fig. 2) into the western basins of the Wadden Sea. The average total discharge at DO and KZ is ~ 470 m^3 s^{-1}. Some additional 50–100 m^3 s^{-1} is not discharged into the western Wadden Sea directly, but diverted to the drainage network in the surrounding main land (Rijkswaterstaat/DZW, 1942–1969; De Kloet, 1978, De Wit, 1980).

3. Data sets

3.1. Rhine and IJssel

Data on water discharges and nutrient concentrations for the rivers Rhine at B-L/S and IJssel at Kampen where it discharges into the IJsselmeer were obtained from several sources. Discharges were taken from the annual reports of the International Commission for the Protection of the Rhine (Koblenz, Germany), and from three data sources of the Dutch Ministry of Transport, Public Works and Water Management: the yearbooks on the water quality in Dutch waters 1965–1971 published by the 'Rijksinstituut voor Zuivering van Afvalwater' (Lelystad, The Netherlands), the three-monthly announcements of the 'Dienst der Zuiderzeewerken' (Rijkswaterstaat/DZW, 1942–1969), and the water quality database (DONAR). TN and TP have been determined regularly in the Rhine since 1966 and 1969, respectively, regular data on DIP and DIN go back to the early 1950s. Nutrient concentrations in the Rhine before 1972 were all taken from the written sources published by Dutch Ministry of Transport, Public Works and Water Management. Data from later than 1972 (both Rhine and IJssel) were obtained from the DONAR database. Total phosphorus (TP) includes dissolved inorganic phosphate (DIP), dissolved organic phosphorus (DOP), and particulate P compounds.

Total nitrogen (TN) is the sum of ammonium, nitrite, nitrate (DIN), dissolved organic nitrogen (DON) and particulate N. Annual discharges of TN and TP were estimated by multiplying monthly water discharges with monthly mean concentrations (1–2 data points) and subsequently summing the 12 months in a year. Data from before 1966 (Rhine) and 1972 (IJssel), which will be used for comparison only, were obtained from Clarke (1920), Biemond (1940, 1948), Havinga (1954), Postma (1966, 1967, unpubl. data), Van Bennekom et al. (1975) and De Kloet (1969, 1971, 1978).

3.2. IJsselmeer

Monthly water discharges at the two sluices (DO, KZ) in the Afsluitdijk were obtained from the Ministry of Transport, Public Works and Water Management (see above). Nutrient concentrations (TN, TP) at stations near the two sluices in the DONAR database go back to 1972 and will be used for calibration of our models. Some older nutrient data are available, but these will be used for comparison only. For 1970–1971 we used the data of De Jonge and Postma (1974; TP), for 1967–1970 De Kloet (1971; TP), for 1960–1962 Postma (1966, TN), for 1957–1958 Postma (1967 and unpubl. data; TP), for 1958 Duursma (1961; TP), and for 1949–1951 Postma (1954; TP). Inserting concentrations measured by the Provincial Water Company (PWN, Bloemendaal) at their inlet near Andijk filled in missing data of DIN and DIP between 1966–1972 (Van Der Veer et al., 1989). Additional data referring to DIN and/or DIP were obtained from Havinga (1941, 1954), Dresscher (1951), Duursma (1961), De Kloet (1971) and Helder (1974).

3.3. Data quality

Quality assurance and data consistency are major points of concern when using different data sets that span long periods of time and in which many institutes and techniques are involved. Our major data source is the DONAR database of the Dutch Ministry of Transport and Public Works. Although analytical methodologies have changed slightly over time in the labs providing the data to DONAR, they were always based on standard techniques. Ammonium was determined photometrically upon titration with 0.02 NH_2SO_4 (Berthelot reaction, detection limit 0.3 μM, precision 5%). Nitrite plus nitrate was measured photometrically with sulfuric amide (detection limit 0.7 μM, precision >2%) and TN (detection limit 0.3 μM, precision 5%) was determined as $NO_3 + NO_2$ plus NH_4 upon Kjeldahl destruction (Strickland and Parsons, 1972). DIP (detection limit 0.03 μM, precision 2%) was measured photometrically using the molybdate blue method (Strickland and Parsons, 1972) and TP was measured as DIP upon destruction with boiling sulfuric acid and persulfate (detection limit 0.3 μM, precision 2%). The consistency of the analytical procedures has been checked regularly by the Ministry including inter-calibration and cross-calibration. The nutrient data from DONAR are the basis for most, if not all, larger-scale eutrophication studies in the Netherlands (e.g. De Wit, 1980; Klein and Van Buren, 1992; Cadée and Hegeman, 1993; De Jonge and Van Raaphorst, 1995; De Jonge, 1997; Philippart et al., 2000).

We are fairly confident that most other data measured by specialised labs have been accurate since about the early 1960s (Weichart, 1990; Laane, 1992). There may, however, still be some inconsistencies between different data sets, while the earliest data are likely to contain inaccuracies due to sub-optimal analytical procedures. To avoid inconsistencies we will make use only of the DONAR data set (1972–1998) plus the written sources (yearbooks on water quality) from the Ministry of Transport, Public Works and Water Management (1966–1972) to reconstruct the TN and TP loads of the river Rhine at the German/Dutch border from 1966 onwards. For calibration of the mass balance models of the river IJssel and the lake IJsselmeer we will use the DONAR data from 1972 onwards. All other nutrient data are given for what they are, without any attempt to assess their accuracy. We feel this is justified as in this paper the older data serve for qualitative comparison only, and not for calibration purposes.

4. Reconstruction of TN and TP loads

The basis for our study is the reconstruction of the TN and TP loads of the river Rhine at B-S/L. The next step is to calculate the loads of the downstream river IJssel from the time series at B-S/L, using simple mass balance models. The river IJssel discharges into the lake IJsselmeer (Fig. 1). We will use time series of the water discharges of the IJssel as well as other measured water inputs to and outputs from the IJsselmeer to set up 2-monthly water budgets of the lake. As the final step, we will apply mass balance models of the IJsselmeer to reconstruct the discharge of TN and TP from the lake into the western Wadden Sea, using the calculated loads of the IJssel as the major nutrient source of the lake.

4.1. Rhine at B-S/L

Annual mean water discharges of the Rhine at B-S/L varied from ~1500 to ~3000 m^3 s^{-1} between 1928 and 1998 (Fig. 3a). Calculation of the annual means from January to December may have introduced some unrealistic year-to-year variability, i.e. a year with high discharge followed by one with minor discharge, particularly when maximum winter run-off occurred in January and December of the same year. To remove this variability we smoothed this and all other time series with a three-year running mean. The smoothed data show relatively high discharges in most years before 1940, between 1965 and 1970, as well as in several years after 1980, whereas a longer period with lower annual discharges occurred from 1940 to 1965. Both the year-to-year variability and the decadal variability in the water discharge follow variations in precipitation in Western Europe and are correlated to the NAO winter index (Sündermann et al., 1996).

The available data show high TN loads, 1000–1400 mol s^{-1}, between 1966 and 1988 followed by a decrease to ~800 mol s^{-1} since 1990 (Fig. 3b). TP loads were as high as ~50 mol s^{-1} between 1969

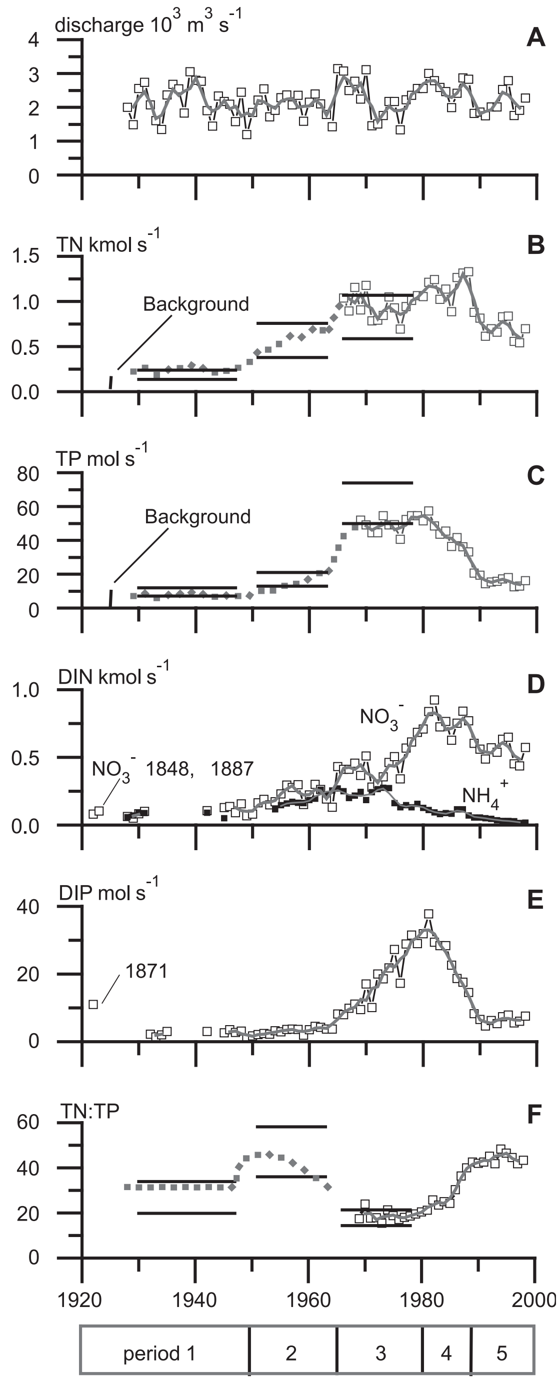

Fig. 3. Time series of the annual loads of the Rhine at the German/Dutch border at B-S/L between 1928 and 1998. Open squares indicate measured values and solid lines are 3-y moving averages of these measured values. Pairs of horizontal lines are the Phison scenarios (Billen and Garnier, 1997) extrapolated to the Rhine, with (lower line) and without retention in the river system (upper line). Dotted lines indicate 3-y moving averages of our reconstructions not directly based on observational data. Periods 1 to 5 are explained in the text. (A) Water discharge. (B) Load of TN; background load represents that of European rivers as estimated by Laane (1992). (C) Load of TP; background load as for TN. (D) Loads of the dissolved inorganic nitrogen (DIN) compounds NO_3^- and NH_4^+. The data for 1848 and 1887 are from Clarke (1920). (E) Load of dissolved inorganic phosphorus (DIP). The data for 1871 are from Clarke (1920). (F) TN:TP atomic ratio in the load of the Rhine.

and 1980, decreased steeply during the 1980s to reach ~ 20 mol s^{-1} in 1990 and stabilised in recent years (Fig. 3c). Loads in the period before 1940 were calculated from the background concentrations as estimated for rivers draining into the North Sea by Laane (1992). In their analysis, Laane (1992) apply results from statistical models and extrapolations from present-day situations to assess nutrient concentrations in the rivers under pristine conditions, and compare these with early observations representing the period 1920–1940. The statistical models first estimate phosphorus concentrations after which a fixed TN:TP (of 28) is applied to assess the background TN concentrations. Thus, their range of TP background concentrations (0.7–4.5 μM) appears more accurate than that of TN. Taking into account the annual mean discharge by the Rhine of ~ 2500 m^3 s^{-1} between 1930–1940 (Fig. 3a) and the observation that high concentrations represent winter conditions with high discharges, we arrived at TP loads ranging from 5 to 10 mol s^{-1} with an average of 8.7 mol s^{-1} between 1930 and 1940. Adopting the assumptions by Laane (1992) we estimate that background TN concentrations in European rivers range between 20 and 125 μM, from which we calculate a TN load by the Rhine of 100–315 mol s^{-1} between 1930 and 1940.

Using the background loads for the period before 1940 and the measured loads from 1966 (TN) and 1969 (TP) onwards, a data gap of 2.5–3 decades remains to be interpolated. Billen and Garnier (1997) discuss scenarios for 5 distinct periods in eutrophication history, which are relevant to our study (Fig. 3, Table 1). Period-1 spans the first 50 years of the 20th century with a lowered industrial load compared to the 19th century (Billen et al., 1999) and about half the population density at the end of the 20th century. In period-2, between 1950 and 1965, the use of N-fertilisers increased steeply together with population density (see also Nixon, 1995). Period-3 (1965–1980) is characterised by extensive use of fertilisers and polyphosphates in washing powders, as well as a further increase of population. In period-4 (1980–1990) polyphosphates were banned from washing powders and P was removed from many sewage treatment plant effluents. In period-5 from 1990 onwards, N-removal from sewage effluents and reduction of N-runoff from agricultural land resulted in decreased TN loads. Thus, we expect only a minor increase in TN loads between 1940 and ~ 1950 followed by a gradual increase until the mid-1960s. For TP we expect a moderate increase between ~ 1950 and 1965 and a steep increase afterwards due to the introduction of polyphosphates in washing

Table 1
Annual mean TN and TP inputs to the Rhine extrapolated from the Phison scenarios (Billen and Garnier, 1997) and compared to results of similar input models (Scholte Ubing, 1980; Behrendt et al., 1999) as well as computed (periods 1,2) and measured (periods 3,4,5) loads

Period	Characteristics	Phison scenarios mol s^{-1}	Scholte Ubing (1980) mol s^{-1}	Behrendt et al. (1999) mol s^{-1}	*Computed*/ Measured loads mol s^{-1}
1: 1935–1950	F: 5; D: 110; I: 55	TN = 242 TP = 12			*TN = 150–350* *TP = 5–10*
2: 1950–1965	F: 100; D: 155; I: 70	TN = 692 TP = 21			*TN = 350–900* *TP = 10–45*
3: 1965–1980	F: 140; D: 220; I: 110 Use of poly-P	TN = 1070 TP = 74	TN = 900–1000 TP = 45–60		TN = 900–1100 TP = 45–55
4: 1980–1990	F: 175; D: 220; I: 110 Ban of poly-P + P-treatment	TN = 1078 TP = 74 down to 10		TN = 1290 TP = 52	TN = 900–1300 TP = 50 Down to 25
5: 1990–1998	F: 175; D: 220; I: 110 N and P treatment	TN = 928 TP = 10		TN = 900 TP = 21	TN = 570–790 TP = 15–17

For the extrapolation from the Phison scenarios we assumed 25% forest, 25% grassland and 50% cereals as land use in the Rhine drainage area for all periods. F: fertiliser use in kg N ha^{-1} y^{-1}, D: domestic inputs in inhabitant equivalents per km^{-2}, I: industrial inputs in inhabitant equivalents km^{-2}. To account for denitrification in the soil in the model of Scholte Ubing (1980) we applied a 50% reduction of non-point TN sources similar to Billen and Garnier (1997).

powders. A cautious interpretation of the nutrient data from before the mid-1960s shows that the expected trends in TN and TP loads between 1940 and 1970 are in accordance with the measured trends of loads of the inorganic dissolved nutrients DIN and DIP (Fig. 3d, e).

The discharge of N and P compounds by the Rhine is approximately proportional to the water discharge (Van der Weijden and Middelburg, 1989). Therefore, concentrations in the river rather than the loads themselves were interpolated. In accordance with the expected trends we assume that annual mean concentrations for TN at B-S/L remained unchanged until the end of perod-1 and that they increased linearly (from 115 to 340 μM) between 1948 and 1966. For TP we selected an exponential model to account for the expected steep increase after 1965. Thus, *annual mean TP concentration in* $year(i) = 2.5 + 0.5e^{0.123\ (year(i)-1940)}$ mmol m^{-3}, where year(i) runs from 1948 to 1969. Annual loads were then calculated by multiplying the interpolated TN and TP concentrations by the annual mean water discharges (Fig. 3b, c). As a consequence, the variation in the annual water discharge of the Rhine is directly apparent in the estimated nutrient loads. The reconstruction suggests TN:TP ratios of 31 in perod-1 (close to the ratio assumed by Laane, 1992), increasing to 48 in 1950–1955 and subsequently decreasing to less than 20 in perod-3 (Fig. 3f). During the last 20 years, TN:TP has again increased to values >40. The reconstruction yields DIN/TN ratios between 0.5 and 0.9 and DIP/TP between 0.2 and 0.5 before 1970, which is comparable to the measured ratios after 1970 (Fig. 4).

To provide a check on our interpolations, we extrapolated the scenarios that Billen and Garnier (1997) elaborated with the Riverstrahler model for their hypothetical Phison river to the Rhine at B-S/L. In their approach, point source and non-point source inputs are calculated depending on land use, level of fertiliser application, population density and industrialisation, as well as on the status of sewage networks, sewage treatment plants and natural retention processes in the drainage network. We took into account that the drainage area of the Rhine is ∼ 2.45 times larger than that of the hypothetical river Phison and that its population density is ∼ 1.4 times larger. The extrapolations are compared to measured loads and to estimates from other input models (Scholte Ubing, 1980; Behrendt et

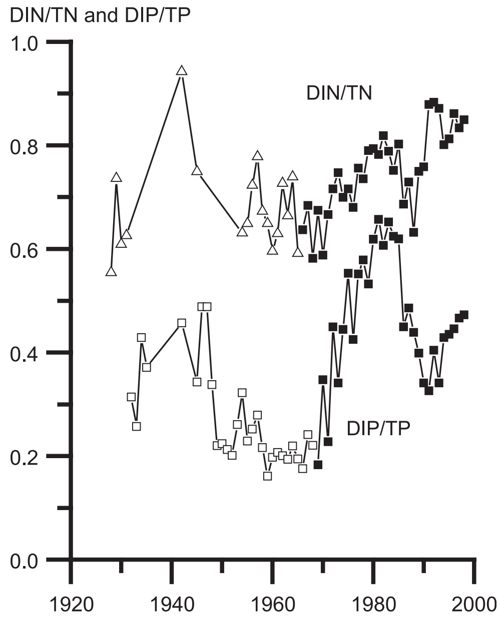

Fig. 4. Ratios between the dissolved and total nutrients DIN/TN and DIP/TP in the Rhine at the German/Dutch border at B-S/L between 1928 and 1998. Closed symbols are measured data, open symbols are based on measured DIN, DIP values and reconstructed TN and TP loads. All data and reconstructed values are annual means.

al., 1999) for periods 3–5 in Table 1. From this comparison we conclude that extrapolating the Phison scenarios to the Rhine provides TN and TP inputs to the Rhine that are well in line with both the other input models and the measured loads for 1965–1998. For perod-1, the extrapolated inputs into the Rhine are close to the TN and TP loads that were estimated on the basis of the analysis by Laane (1992). For perod-2, the Phison scenario predicts mean inputs that are at the high end, but still within of the range of TN and TP loads that we obtained through interpolation (Table 1, Fig. 3b, c).

Billen et al. (1991) indicate that ∼ 35% of the input of nitrogen into the Rhine is removed in the river system before being delivered to the sea. Billen and Garnier (1997) assume that 43–50% of the TN input is retained in the river and 29–46% of the TP input. In Fig. 3b and c both the inputs as calculated from the Phison scenarios and the corresponding loads of TN and TP are plotted, using the retention percentages given by Billen and Garnier (1997) for periods 1–3. From these plots, we conclude that our reconstructions are consistent with the chronological succession of land use and management scenarios in Western European countries. Ideally, we should have applied the Riverstrahler model directly to the Rhine, while discussing the history of diffuse and point loadings and taking into account what is known of the history of human activity in the watershed. Then, we should have run the model and determined retention processes in the (changing) Rhine system upstream of B-S/L. Although in principle this may be a feasible piece of work, we consider it beyond scope of our study. Our major objective is to determine the retention of nutrients downstream of B-S/L and to assess how changes in the hydrological system affected the transfer of TN and TP from the Rhine at B-S/L to the western Wadden Sea. For this purpose, an 'input signal' at B-S/L that is in accordance with the general historical trends is sufficient.

4.2. IJssel

The water discharge of the IJssel depends directly on that of the Rhine. Before 1971, ~ 11% of the discharge at B-S/L was diverted into the Ijssel, to which was added the net precipitation (~ 248 mm per year) in its ~ 3500 km^2 drainage area. Since then, the discharges of the three major branches of the lower Rhine (Waal, Neder-Rijn, IJssel) have been manipulated through dams and weirs in the Neder-Rijn to guarantee a minimum discharge of 300 m^3 s^{-1} in the IJssel necessary for shipping purposes. Thus, the annual mean discharge of the IJssel near Kampen increased from 200–350 m^3 s^{-1} before 1971 to ~ 400 m^3 s^{-1} thereafter (Fig. 5a).

TN and TP inputs to the IJssel were calculated from the discharges of the Rhine at B-S/L, corrected for the percentage diverted into its northern branch (Fig. 5b), and the local point as well as non-point sources. Historical data concerning the latter sources are not available. Therefore, we quantified them by using the Phison scenarios, assuming population den-

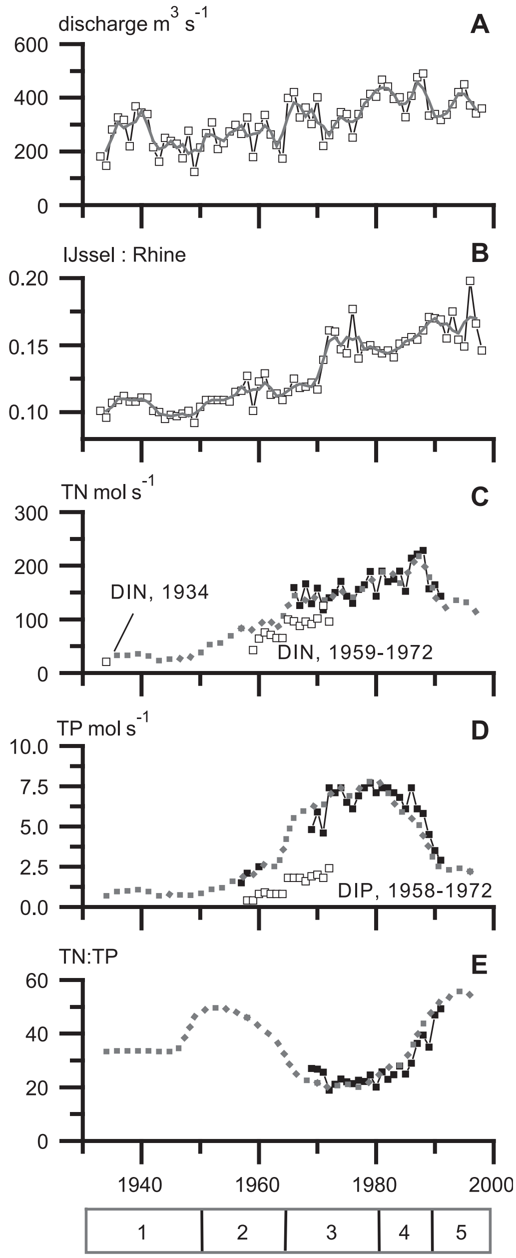

Fig. 5. Time series of the annual loads of the IJssel at Kampen between 1935 and 1998. Open squares in panels A, B indicate measured values. Open squares in panels C and D are measured loads of the dissolved components DIN and DIP, respectively. Closed squares in panels C, D, E are measured loads of TN, TP and the TN:TP ratio in these loads, respectively. Thick solid lines are 3-y moving averages of the measured annual loads. Dotted lines are 3-y moving averages of the reconstructed loads. Periods 1–5 are described in the text. (A) Water discharge. (B) Ratio of the annual discharges of the IJssel at Kampen and the Rhine at B-S/L. (C) Load of TN; loads of DIN in 1934 (based on Havinga, 1954) and 1959–1972 are given for comparison. (D) Load of TP; load of DIP during 1958–1972 is given for comparison. (E) TN:TP atomic ratio in the load of the IJssel.

sities of 80, 110 and 160 inhabitants per km^2 in the periods 1, 2 and 3–5, respectively, and further parameter settings similar to the Rhine (Table 1). We are aware that this approach involves some uncertainty. However, local sources contribute < 15% to the total TN and TP inputs and, therefore, associated errors are most likely to be of minor importance. To calculate the loads at the entrance to the IJsselmeer near Kampen we applied a simple retention model:

$$\text{Load}_i = \text{Input}_i \times (1 - \text{Retention}_i) \quad (1)$$

where the subscript i denotes TN or TP. The values of the retention factor were estimated by fitting Eq. (1) to the measured annual TN and TP loads of the IJssel between 1972 and 1992, using the Microsoft Excel® solver routine for minimising the sum of squared residuals between measured and calculated loads. The obtained retention factors are 0.04 ± 0.003 for TN and 0.15 ± 0.01 for TP. The computed time series of the annual TN and TP loads are given in Fig. 5c and d, respectively. In general the loads follow the same trend as those of the Rhine, with some deviation in the early 1970s due to increase in water discharge since 1971. Although the model was fitted to the data after 1972, the model outcomes agree well with the few measured TN and TP loads before 1972 as well as with the trends suggested by the early loads of DIN and DIP (Fig. 5c, d). We regard the good agreement of particularly the TP loads in 1957–1960, for which years no data were available for the Rhine, as a validation of our reconstruction approach.

Due to a different TN:TP ratio in the input from its watershed compared to the Rhine and the preferred retention of TP, the TN:TP ratio in the discharge of the IJssel is slightly higher than in the Rhine (Fig. 5e). The general pattern with a first maximum in the early 1950s (TN:TP = 50) declining to a minimum in the 1970s (TN:TP = 20) and a second maximum in the most recent years (TN:TP = 55) is similar to that in the Rhine.

4.3. IJsselmeer

4.3.1. Water budgets

Water entering the IJsselmeer comes from the discharges of the IJssel and some smaller rivers, precipitation and drainage from the surrounding polders (Fig. 6a). Output of water is mainly to the Wadden Sea in the north. The water level in the lake is manipulated such that the polders drain into the lake during winter and occasionally take in water during summer months. To construct closed annual water budgets of the lake we first quantified the outputs to the Wadden Sea on the basis of monthly discharges published by the Ministry of Transport, Public Works and Water Management. The same Ministry has published net outputs to the surrounding polders for 1933–1969 and 1976–1978, respectively, which amounted to < 1% of the total output before 1945, ~ 5% from 1945–1968 and ~ 8% in 1976–1978. The annual intake by the polders was estimated, by interpolation, at 6% of the total output for 1970–1975 and, by extrapolation, at 8% for the years after 1978. Annual net precipitation on the lake contributes < 5% to the total input and was assumed to equal the climatological average of 248 mm y^{-1}. Year-to-year storage of water in the lake was < 1% of the annual output. The budgets were closed by calculating the total inputs from smaller rivers and surrounding polders as the difference between the discharge of the IJssel + precipitation and total outputs (Fig. 6d). Results show that the IJssel contributed ~ 55% to the total water input into the lake until 1971. The increased discharge of the IJssel since 1971 (Fig. 6d) was compensated for by a decrease of the other inputs to the IJsselmeer. As a consequence, the IJssel contributed ~ 70% to the total water input after 1971.

An important parameter controlling the potential of the lake to modify the nutrient input signal is the average residence time of a water parcel or hydraulic retention (τ), defined as $\tau = V\,Q^{-1}$ where V is the volume of the lake (m^3) and Q is the total output of water ($m^3\ s^{-1}$). The surface area of the lake has decreased step-wise due to the construction of polders in 1942, 1957 and 1967, respectively, and a dam in 1975 (Fig. 6b). Given its almost homogeneous depth, the volume of the lake decreased proportionally and the annual mean hydraulic retention decreased from ~ 1 y before 1942 to ~ 4 mo after 1975. Both Q and, to a lesser extent, V show considerable seasonal variability and so should τ. To account for this, we calculated time series of τ_2 at a 2-mo resolution, using 2-mo average values of water

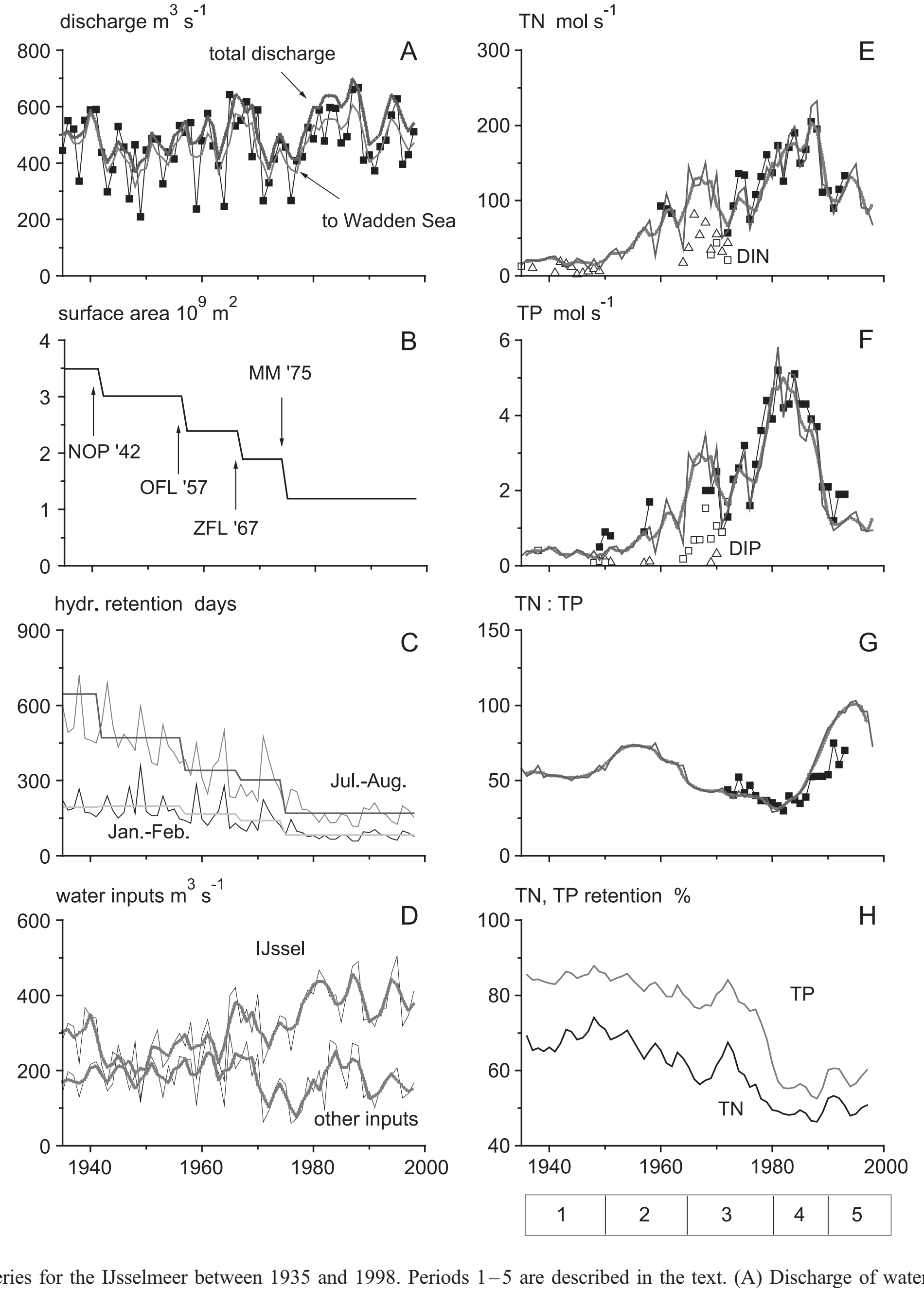

Fig. 6. Time series for the IJsselmeer between 1935 and 1998. Periods 1–5 are described in the text. (A) Discharge of water from the lake. Symbols and lower thick solid line are measured annual mean discharge and 3-y moving averages into the Wadden Sea, respectively. The upper dotted line is the 3-y moving average of the total discharge including the surrounding polders. (B) Step-wise decrease of the surface area of the lake due to the construction of the polders Noordoostpolder (NOP) in 1942, Oostelijk Flevoland (OFL) in 1957, Zuidelijk Flevoland (ZFL) in 1967, and the dyke separating the Markermeer (MM) from the IJsselmeer proper in 1975. (C) Hydraulic retention time of the lake in January-February and July-August. (D) Input of water into the lake from the IJssel separately and from other sources. Dotted lines are 3-y moving averages. (E) Annual mean discharge of TN from the lake into the Wadden Sea. Solid squares are measured TN discharges, solid and dotted lines are the reconstructed annual mean load and its 3-y moving average, respectively. Measured loads of DIN are given by the open symbols for comparison. (F) As panel E, but for TP and DIP. (G) TN:TP atomic ratio in the discharge into the Wadden Sea. (H) Calculated retention (output/input $\times$ 100%) of TN and TP in the IJsselmeer.

depth to assess V_2 and a de-convolution function f_2 to calculate Q_2 from the annual mean Q_y:

$$(Q_2)_j = (f_2)_j Q_y \text{ and } 1/6\Sigma(f_2)_j = 1 \quad (2)$$

in which j = 1 denotes January/February, j = 2 March/April, and so on. The climatological mean function f_2 was determined on the basis of monthly discharges and varies between 1.5 in January/February and 0.5 in July/August for the discharge into the Wadden Sea (Fig. 7a) and between 0.3 in November-February and 1.7 in May-August for the discharges into the surrounding polders (Fig. 7b).

Fig. 6c shows the seasonal variability of the hydraulic retention of the IJsselmeer. For January/February τ_2 decreased from ~ 200 d until 1957 to ~ 85 d after 1975. A more dramatic decrease occurred in July/August, from ~ 645 d before 1942 to 300–350 d between 1957 and 1975, and finally to ~ 170 d in most recent years. Thus, during July/August a fraction (62 d)/$\tau_2 \times 100 = 9\%$ of the lake

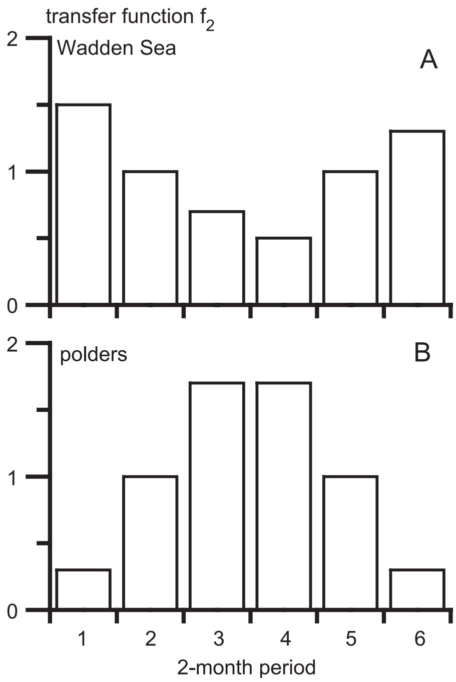

Fig. 7. Transfer function f_2 used for the de-convolution of the annual mean water discharges of the IJsselmeer into 2-mo averaged discharges (Eq. (2)). (A) Discharge into the Wadden Sea. (B) Discharge into the polders surrounding the lake.

volume was flushed into the Wadden Sea before 1942 and as much as 35% after 1975. For January/February these percentages are 30% and 70%, respectively. For the other 2-mo periods they are in between those of January/February and July/August.

4.3.2. TN and TP inputs

The major source of TN and TP to the IJsselmeer is the IJssel. Additional inputs are from (1) smaller rivers and the surrounding polders, (2) atmospheric deposition, and (3) sewage discharge from the city of Amsterdam. Consistent time series of nutrient loads of the smaller rivers and polders draining into the lake are not available. Therefore, we extrapolated the Phison scenarios (Billen and Garnier, 1997) to estimate their combined annual inputs. Atmospheric deposition, estimated on the basis of values listed by Rendell et al. (1993) and De Jong et al. (1993) for the coastal North Sea and Wadden Sea, contributed less than 2% to the total inputs of TN and was negligible for TP. Starting in 1913 the city of Amsterdam discharged sewage of ~ 500 10^3 inhabitants (Dresscher, 1951) directly into first the Zuiderzee, then at the same spot in the IJsselmeer and, after 1975, into the Markermeer. Since 1982, the sewage is being treated and the effluent diverted towards the North Sea (Wismeijer and Weenink, 1982). The contribution of this source to the inputs of TN and TP into the IJsselmeer until 1975 was calculated by using the loads per inhabitant given by Billen et al. (1991). Due to the low TN:TP ratio in domestic discharges (~ 6:1) relative to the other sources, the impact of the input from the Amsterdam sewage system is largest for phosphorus.

The calculated inputs of TN and TP can be compared with those estimated by De Kloet (1978 and unpublished) for 1969 and by the Ministry of Transport, Public Works and Water Management for 1976–1978 (Table 2). The inputs of TP calculated here for the IJssel and the polders plus smaller rivers are slightly higher than those of De Kloet (1978). Also, polders and smaller rivers provide more TP and TN than indicated by the Ministry for 1976–1978. Because we do not know the exact background of these discrepancies and because our as well as the other inputs may be subject to considerable uncertainties (De Wit, pers. comm.), we did not attempt to find a better match.

Table 2
Comparison between inputs of TP and TN to the IJsselmeer as calculated in this study and in earlier budget studies

Year	Source	Calculated in this study mol s^{-1}	Estimated in earlier studies mol s^{-1}	Reference
I: TP				
1969	IJssel	6.4	4.7	De Kloet, 1978 and unpubl. data
	Polders + small rivers	3.5	2.6	
	Amsterdam	0.6	0.5	
1976–1978	IJssel	7.3	7.2	T,PW&WM
	Polders + small rivers	1.9	1.2	
II: TN				
1976–1978	IJssel	147	155	T,PW&WM
	Polders + small rivers	48	38	

A distinction is made between inputs from the river IJssel, polders plus small rivers and the Amsterdam sewage system. T,PW&WM is the Ministry of Transport, Public Works and Water Management.

4.3.3. TN and TP discharges into the Wadden Sea

To calculate TN and TP concentrations in the water discharged into the Wadden Sea a simple model was constructed that expresses the mass balance of a well-mixed single-compartment basin:

$$\frac{dVC_i}{dt} = \Sigma L_i P_i A - \Sigma Q_{out} C_i - k_i V C_i \quad (3)$$

Which after some rearranging can be written as:

$$\frac{dC_i}{dt} = \frac{\Sigma L_i}{V} + \frac{P_i}{h} - \frac{(1 + (k_i + dV/dt)\tau)}{\tau} C_i \quad (4)$$

Where C_i is the lake-average concentration of TN or TP (mol m^{-3}), ΣL_i stands for the total input of TN or TP (mol s^{-1}), P_i for the atmospheric input rate (mol m^{-2} s^{-1}), A for the surface area (m^2), $h = V/A$ for the depth of the lake (m), ΣQ_{out} for the total output rate of water (m^3 s^{-1}), and k_i for the first order removal rate of TN or TP (s^{-1}) due to, e.g., sedimentation and denitrification. The term dV/dt (m^3 s^{-1}) accounts for storage due to changes of water level. The dynamics of C_i in response to variations in the external loadings are determined by the last term of Eq. (4) in which the retention time τ equals $V/\Sigma Q_{out}$ and ranges between ~ 3 mo and ~ 2 y, depending on year and season. Because of these relatively short time scales, Eq. (4) was solved analytically for subsequent intervals of 2 mo while assuming constant parameters during these intervals. The term dV/dt was calculated from the difference in water level at the start and the end of the 2-mo periods. Two-mo average loadings of TN and TP were, analogously to Eq. (2), calculated from the annual inputs by the use of a climatological mean transfer function f_2 (Fig. 8). Annual mean values were used for the relatively minor atmospheric inputs.

We are aware that the assumption of well-mixed conditions that underlies our model is not strictly valid for the IJsselmeer. Normally, concentrations are highest in the Ketelmeer where the IJssel flows into the lake (Fig. 2) and lowest in the northern part (De Kloet, 1971; De Wit, 1980). Also, most of the retention of TN and TP probably occurs in the Ketelmeer where deposition of particles transported by the IJssel is favoured due a decrease in current velocity. However, further compartmentalisation would both complicate the model and add statistical uncertainty through the addition of new fit-parameters. To minimise the error associated with the single-compartment assumption

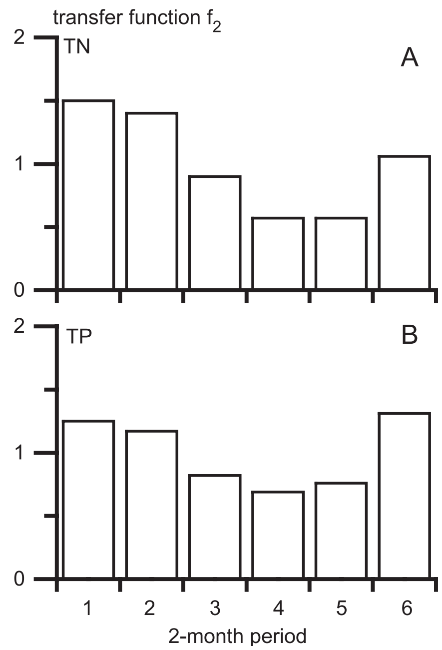

Fig. 8. Transfer function f_2 used for the de-convolution of the annual mean loads (ΣL_i in Eqs. (3) and (4)) of (A) TN and (B) TP into the IJsselmeer into 2-mo averaged loads (Eq. (2)).

and because we are mainly interested in the TN and TP output into the Wadden Sea, we did not calibrate the model on measured concentrations in the lake but directly on measured discharges through the sluices at DO and KZ.

Eq. (4) contains one unknown parameter k_i, which was estimated by calculating the 2-mo average discharges into the Wadden Sea from the model as $L_{Wad,i} = < Q_{Wad} \times C_I >_2$, where $< >_2$ denotes 2-mo averages, and fitting these outputs to the data available for the years 1974–1994. Initial fits were performed with time-invariant removal rates. For TN this resulted in modelled discharges that were slightly out of phase (~ 2 mo) with the data. The balance of burial plus denitrification in the sediment and refluxes from the sediment to the water column determines the removal of TN. In summer, a larger fraction of the TN deposited onto the sediment may be denitrified due to higher temperatures together with a larger supply of labile organic matter that both favour microbial activity. As a consequence, oxygen penetration in the sediment is less during summer and anoxic mineralisation pathways are stimulated, including denitrification as long as nitrate availability is sufficient. The model could be improved by assuming an annual cycle in the removal rate of TN:

$$k_{TN,j} = < k_{TN} > (1 - \beta\cos(2\pi(j-1)/6)) \quad (5)$$

Where $< k_{TN} >$ is the annual mean removal rate, 2β is the amplitude of the seasonal cycle, and $j = 1$ indicates January/February, $j = 2$ March/April, and so on. Eq. (5) implies minimum removal rates in January/February and maximum rates in June/July. The best fit of the model (Microsoft Excell® solver routine), obtained with $< k_{TN} > = 9.00 \pm 0.05 \ 10^{-8}$ s^{-1} ($7.8 \ 10^{-3} \ d^{-1}$) and $\beta = 0.8 \pm 0.02$, reproduces the data well, both the year-to-year variations and the annual cycles (Fig. 9a, b).

For TP using a removal rate that was constant over the year could fit the measured annual cycles, probably because burial is the major loss mechanism of TP. It was impossible, however, to obtain a reasonable fit by applying the same removal rate before and after 1980 when external loadings of TP and concentrations in the lake started to decline. This may reflect increased internal loadings from the sediment upon desorption of phosphate from iron oxy-hydroxides that were loaded with phosphate during previous years with high TP concentrations (Van der Molen and Boers, 1994). Best fit (Fig. 9c, d) was obtained with $k_{TP} = 2.25 \pm 0.05$ 10^{-7} s^{-1} ($1.9 \ 10^{-2} \ d^{-1}$) for the years before 1980 and $1.20 \pm 0.05 \ 10^{-7}$ s^{-1} ($1.0 \ 10^{-2} \ d^{-1}$) thereafter.

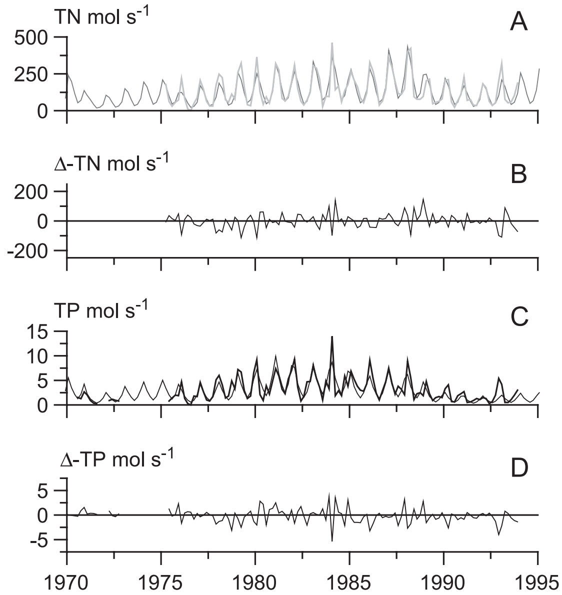

Fig. 9. Time series of 2-mo averaged output of TN and TP from the IJsselmeer into the Wadden Sea during 1970–1993. Thick solid lines in panels A and B are measured outputs, thin lines are model results. (A) Output of TN. (B) Difference Δ-TN between measured and modelled output of TN. (C) Output of TP. (D) As panel B but for TP.

Modelled annual discharges of TN and TP into the Wadden Sea compare well with discharges calculated from monthly measurements (Fig. 6e, f), albeit modelled TP outputs may be slightly too low for the years before 1960. The model indicates that TN inputs to the Wadden Sea increased from ~ 15 to 25 mol s^{-1} before 1950 to a maximum of ~ 230 mol s^{-1} in 1988, with relatively high inputs from 1965–1971 due to large water discharges from the IJssel (Fig. 6d). After 1988, TN discharges into the Wadden Sea have decreased to less than 100 mol s^{-1}. Annual discharges of TP were 0.3 to1 mol s^{-1} until 1965, increased steeply to a maximum of 5.1 mol s^{-1} in 1983, and decreased as steeply to 1to 1.8 mol s^{-1} after 1990.

TN:TP ratios in the lake decreased from ~ 55 until 1950 to a minimum of ~ 30 in 1980, and then rose sharply to a maximum of ~ 100 in 1995 (Fig. 6g). These ratios are considerably higher than those in the Rhine (Fig. 3f) due to the preferential removal of TP over TN, particularly in the IJsselmeer. The retention of TN by the IJsselmeer was ~ 70% of the total TN input until 1950, but only 45–50% after 1980. The main reason for this decrease in removal efficiency is the stepwise reduction of the hydraulic retention time as a consequence of the construction of polders in the lake, and particularly the dike in 1975. Retention of TP was ~ 85% until 1950 and decreased to 55–60% after 1980. Compared to TN, the retention of TP has decreased more sharply after 1975 due to its lower removal rate after 1980 associated with increased internal loading. The calculated retention percentages fit well with similar data listed by Billen et al. (1991) for lakes on the European and American continent.

5. Discussion

5.1. TN and TP in the IJsselmeer

Data to confirm the modelled time-series of TN and TP discharges of the Rhine, which form the basis of all further reconstructions, were available for the period since the second half of the 1960s only. Furthermore, TN and TP inputs to the IJsselmeer from other sources than the IJssel rely on assumptions rather than observational data. This puts constraint on the reliability of the calculated final TN and TP outputs from the IJsselmeer. We conducted some sensitivity analysis with our models by varying the interpolated loads of the Rhine at B-S/L between 1950 and 1966 (TN) and 1969 (TP). From this we estimated the uncertainty in annual discharge into the Wadden Sea at ~ 15% for TN and ~ 25% for TP in individual years earlier than the 1970s. For later years, major inputs and outputs were calibrated against the available data. However, loads calculated from measured concentrations and water discharges bear some uncertainty, too. We calculated the loads by the rivers from monthly mean water discharges and 1 or 2 concentration data per month, which causes a relative error in the 'measured' annual loads of the Rhine and IJssel of ~ 5 to ~ 30% (Wulffraat et al., 1993). The relative error in the 'measured' annual water budgets of the IJsselmeer is ~ 5 to ~ 15% (De Wit, pers. comm., 2000). From this, we estimate that the relative error in the 'measured' annual TN and TP budgets of the lake could amount to ~ 5 to ~ 35%, with an average of 15%.

Further confirmation of the reliability of the reconstructed time-series comes from a direct comparison of observational and modelling data earlier than the 1960s (IJssel) and the 1970s (IJsselmeer). Our model agrees excellently with the TP loads of the IJssel in 1957–1960 as estimated by Postma (1966, 1967), and also with the TN discharge from the IJsselmeer into the Wadden Sea in 1960–1962 as estimated by Postma (1966). Reasonable fits were obtained with the TP discharges of the IJsselmeer in 1949–1951 as given by Postma (1954) and with those in 1957–1958 (Duursma, 1961; Postma, 1967).

Finally, we compared modelled TN and TP concentrations in the IJsselmeer in 1935–1940, 38 ± 12 μM and 0.71 ± 0.10 μM, respectively, with early data available for other lakes. Hutchinson (1957, Table 120) summarises results of the work of Mortimer, who measured mean TN concentrations of 37 ± 14 μM in 'productive' lakes and 21 ± 9 μM in 'less productive' lakes in the English Lake District in the 1930s. For TP, Hutchinson (1957; Table 94) gives concentrations of 0.67 ± 0.26 μM for surface waters in 9 regions in the USA, Japan, Austria and Sweden between 1930 and 1940. Although the lakes discussed by Hutchinson (1957) may differ in many respects from the IJsselmeer, the estimated TN and TP concentrations agree surprisingly well.

5.2. Base-line discharges of TN and TP

As stated in the Introduction, insight into base-line loads is necessary to put past eutrophication and possible future developments into perspective. The choice for a particular year or period assumed to represent base-line conditions is somewhat arbitrary. We selected the period 1935–1940 for reference, i.e. before the onset of modern eutrophication (Nixon, 1995; Billen and Garnier, 1997; Cloern, 2001) and after increased nutrient discharges by European rivers associated with early-industrial inputs at the end of the 19th century (Billen et al., 1999). Determination of the proper reference levels for the discharge of the IJsselmeer into the Wadden Sea is, however, not straightforward. As a first estimate we calculated the annual mean discharges in 1935–1940, which amounted to 20 mol TN s^{-1} and 0.37 mol TP s^{-1}, at a TN:TP ratio of 55 (Table 3), corresponding to 7.3% of the TN load of the Rhine and 4.3% of its TP load. However, present-day hydrology of both the Rhine-IJssel and the IJsselmeer differ considerably from that in 1935–1940 and this has a large effect on the discharges into the Wadden Sea. Therefore, we also calculated the annual mean TN and TP discharges of the IJsselmeer assuming concentrations and loads as in 1935–1940, but taking into account the increased flow of the IJssel since the 1970s (Fig. 5a, b), the reduced water input into the lake from other sources (Fig. 6d) and the reduced surface area of the lake (Fig. 6b). Thus calculated reference discharges are almost twice as high as those representing 1935–1940 proper (Table 3) and correspond to 13.1% of the reference TN load of the Rhine and 9.2% of its reference TP load. Finally, we have to take into account that the Amsterdam sewage system provided a major source of nutrients to the IJsselmeer until 1975. Excluding this source yields reference discharges of 34 mol TN s^{-1} and 59 mol TP s^{-1} (Table 3), i.e. 12.4% and 6.8% of the loads of the Rhine. We regard these latter values as the most realistic baseline discharges of the present-day lake into the Wadden Sea (Fig. 10).

5.3. How important were sources other than the Rhine and IJssel?

Although, via the IJssel, the Rhine is the major source of nutrients to the IJsselmeer and thus to the Wadden Sea, it is not the only one. Local sources downstream of the German-Dutch border contribute < 15% to the TN and TP loads of the IJssel and are not further discussed here. More important are the inputs from the Amsterdam sewage system and the drainage from the surrounding polders and mainland into the IJsselmeer. The input from the Amsterdam sewage system was about 4.7 mol TN s^{-1} and 0.75 mol TP s^{-1}, which for TN is not very large compared to the inputs of the IJssel, but it is considerable for TP until the 1970s. Thus, the relatively low TN:TP ratio in the sewage (~ 6:1, Billen et al., 1991) caused the ratio in the lake to decrease substantially from ~ 75–95, as it would have been without the input of sewage from Amsterdam, to ~ 50–70 (Fig. 11). In other words, the input of sewage from Amsterdam has prevented TN:TP ratios in the discharge into the Wadden Sea prior to the 1960s being as high in the 1980s and 1990s, albeit at much lower concentrations of both TN and TP.

Sources other than the IJssel provided substantial amounts of water to the IJsselmeer, particularly before 1971 when the discharge regime of the IJssel was changed (Fig. 6d). To demonstrate the importance of these sources (polder drainage, small rivers), nutrient outputs to the Wadden Sea were calculated while keeping the TN and TP concentrations in the additional sources at the levels of perod-1 (< 1950). Results of these calculations (Fig. 10) show that reduced inputs from other sources would have reduced the nutrient outputs of the lake by ~ 40% in the 1960s and 20–30% between1971 and 1985 for both TN and TP. In most recent years, however, TP concentrations in the IJssel were only slightly higher than before 1950 and the TP inputs from the other

Table 3
Modelled reference annual mean discharges (1935–1940) of TN and TP in the Rhine at B/S-L and from the IJsselmeer into the Wadden Sea at DO + KZ

		Rhine	From IJsselmeer into Wadden Sea		
			1) 1935–1940	2) modern hydrology	3) excluding Amsterdam
TN	mol s^{-1}	274 ± 50	20 ± 3	35 ± 6	34 ± 6
TP	mol s^{-1}	8.7 ± 1.6	0.37 ± 0.07	0.80 ± 0.20	0.59 ± 0.15
TN:TP		31	55 ± 3	46 ± 2	59 ± 5

1) refers to discharges calculated for 1935–1940, 2) uses the inputs of TN and TP into the lake from 1935–1940 but takes into account modern hydrology (increased discharge of water by the IJssel, reduced surface area), and 3) as 2) but without TN and TP inputs from the Amsterdam sewage system. Numbers are given as 5-y mean ± standard deviation.

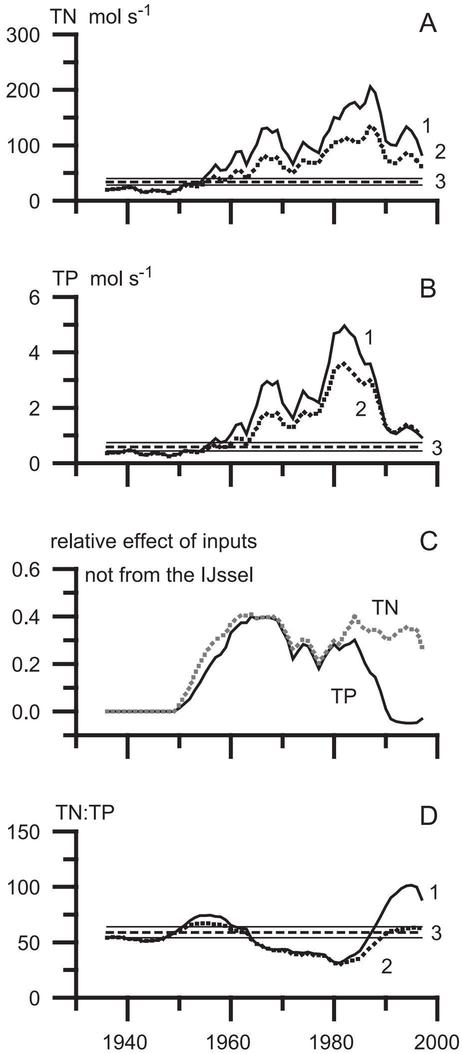

Fig. 10. Modelled time series (3-y moving averages) of the TN and TP outputs from the IJsselmeer into the Wadden Sea between 1935–1998. In all panels, line 1 is the standard model (Fig. 6), line 2 is the output without taking into account nutrient sources to the lake other than the IJssel, and line 3 is the baseline output ($\pm 1\sigma$) into the Wadden Sea (Table 3). (A) Output of TN. (B) Output of TP. (C) relative effect of sources to the lake other than IJssel for the TN (dotted line) and TP (solid line) output. The relative effect is calculated as *(output with–output without)/output with other sources*. (D) TN:TP atomic ratio in the output.

sources appeared even lower than before 1950. As a consequence, the time series of TP output to the Wadden Sea 'with and without other sources' are very close to each other after 1985 (Fig. 10b). For TN, reduced input from other sources would have reduced the output of the lake by ~ 35% in 1985–1998, very similar to earlier years. Thus, the strongly increased TN:TP ratio in the lake in most recent years appears to be due to high TN:TP ratios in smaller rivers and surrounding polders draining into the lake. Without elevated TN concentrations in these additional down-stream sources, the TN:TP ratio in the IJsselmeer in the 1990s would have been close to base-line levels (Fig. 10d).

5.4. Effect of land reclamation in the IJsselmeer

The construction of 3 major polders and a dyke in the IJsselmeer has reduced the surface area of the lake considerably (Fig. 6b), and thereby its hydraulic retention time (Fig. 6c). As a consequence, the retention of both TN and TP has decreased, most strongly after closure of the dyke in the southwest corner of the lake in 1975 (Fig. 6h). We calculated time series of the TN and TP discharges of the IJsselmeer into the Wadden Sea without reduction of its surface area and compared these to the 'real' time series and base-line discharges (Fig. 12). As expected, outputs of TN and TP modelled for the original surface area are lower than with polders. Particularly in the 1980s when eutrophication was at maximum (perod-4) the discharge of both nutrients from the lake into the Wadden Sea appears strongly enhanced due to the successive reductions of surface area. The portion of the increase in nutrient loads that can be attributed to the reduction of surface area increased stepwise from

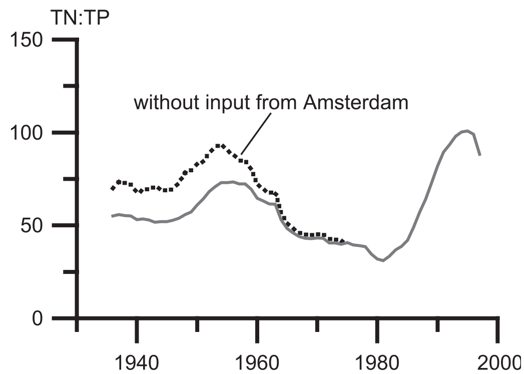

Fig. 11. Modelled TN:TP atomic ratio in the discharge of the IJsselmeer into the Wadden Sea during 1935–1998 with (solid line) and without (dotted line) input from the Amsterdam sewage system into the lake. Both lines are 3-y moving averages.

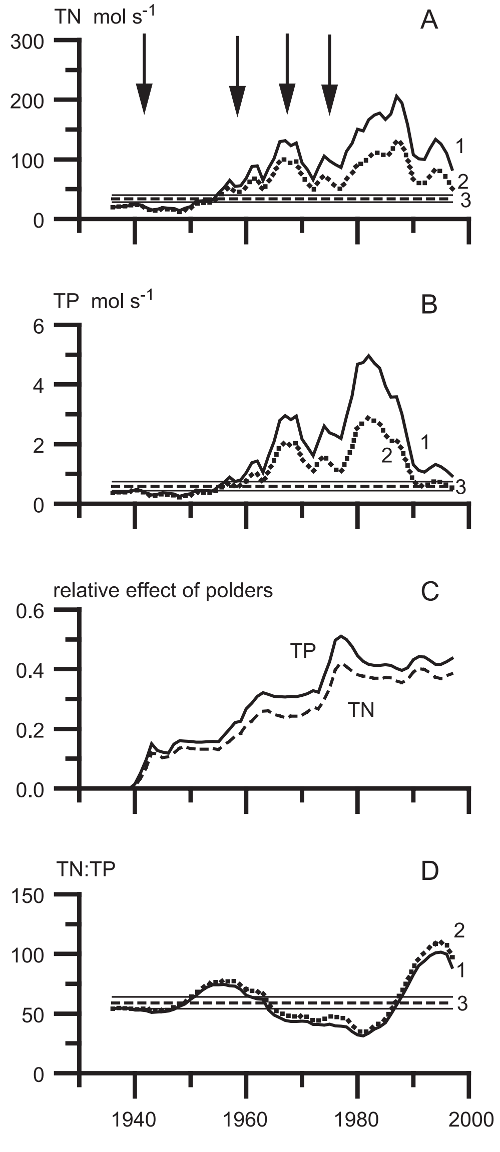

Fig. 12. Modelled time series (3-y moving averages) of the TN and TP outputs from the IJsselmeer into the Wadden Sea between 1935–1998. In all panels, line 1 is the standard model (Fig. 6), line 2 is the output without reduction of the surface area of the lake due to the construction of the three polders and dyke after 1940 (indicated by the arrows), line 3 is the baseline output ($\pm 1\sigma$) into the Wadden Sea (Table 3). (A) Output of TN. (B) Output of TP. (C) Relative effect of the reduction of surface area on the outputs of TN (dotted line) and TP (solid line). The relative effect is calculated as *(output with−output without)/output with polders and dyke*. (D) TN:TP atomic ratio in the output.

~ 15% in 1942 to ~ 50% after the closure of the dyke in 1975. Because the decreased hydraulic retention had a similar effect on TN and TP, the TN:TP ratio was not strongly affected.

5.5. Transfer function relating Rhine and IJsselmeer discharges

The effects discussed above imply that the changes in TN and TP loads of the Rhine as they occurred over time are not transferred linearly to the discharge of the IJsselmeer into the Wadden Sea. We plotted the modelled discharges of TN and TP by the IJsselmeer as a function of the loads of the Rhine at B/S-L and observed power relations with exponents >1 (Fig. 13a, b). This suggests that variations in the loads of the Rhine were amplified further downstream, in accordance with the parallel increasing nutrient inputs and decreasing retention capacity of the IJsselmeer until 1975. This, as well as the relative importance of sources other than the IJssel to the IJsselmeer may explain the scattered and hysteresis-type relationships in Fig. 13a and b.

To take into account the reduced volume of the IJsselmeer we evaluated the ratio between the discharges from the IJsselmeer and the loads of the Rhine as a function of the hydraulic retention time of the lake (Fig. 13c and d). These plots show that the output of TN from the lake increased from ~ 5% of the TN load of the Rhine in 1935 to ~ 18% in 1995, as the annual mean hydraulic retention decreased from ~ 400 d to ~ 100 d. The corresponding increase in the relative TP output from the lake was from ~ 3% in 1935 to a maximum of ~ 10% in the mid-1980s and ~ 8% in 1995. These observations have important implications for the nutrient budgets of the Wadden Sea. Based on the data of Postma (1954), Van Raaphorst and Van der Veer (1990) calculated the inputs of particulate organic P from the North Sea to the western Wadden Sea at ~ 0.4 mol s^{-1} in 1950, about equal to the input of TP from the IJsselmeer (~ 0.5 mol s^{-1}) at that time. Nutrient concentrations in North Sea off the Dutch coast are strongly determined by the Rhine outflow (Van Bennekom et al., 1975; Van Bennekom and Wetsteijn, 1990). The inputs of TP and TN from the North Sea into the Wadden Sea are proportional to their concentrations in the coastal North Sea (Van Raaphorst and Van der

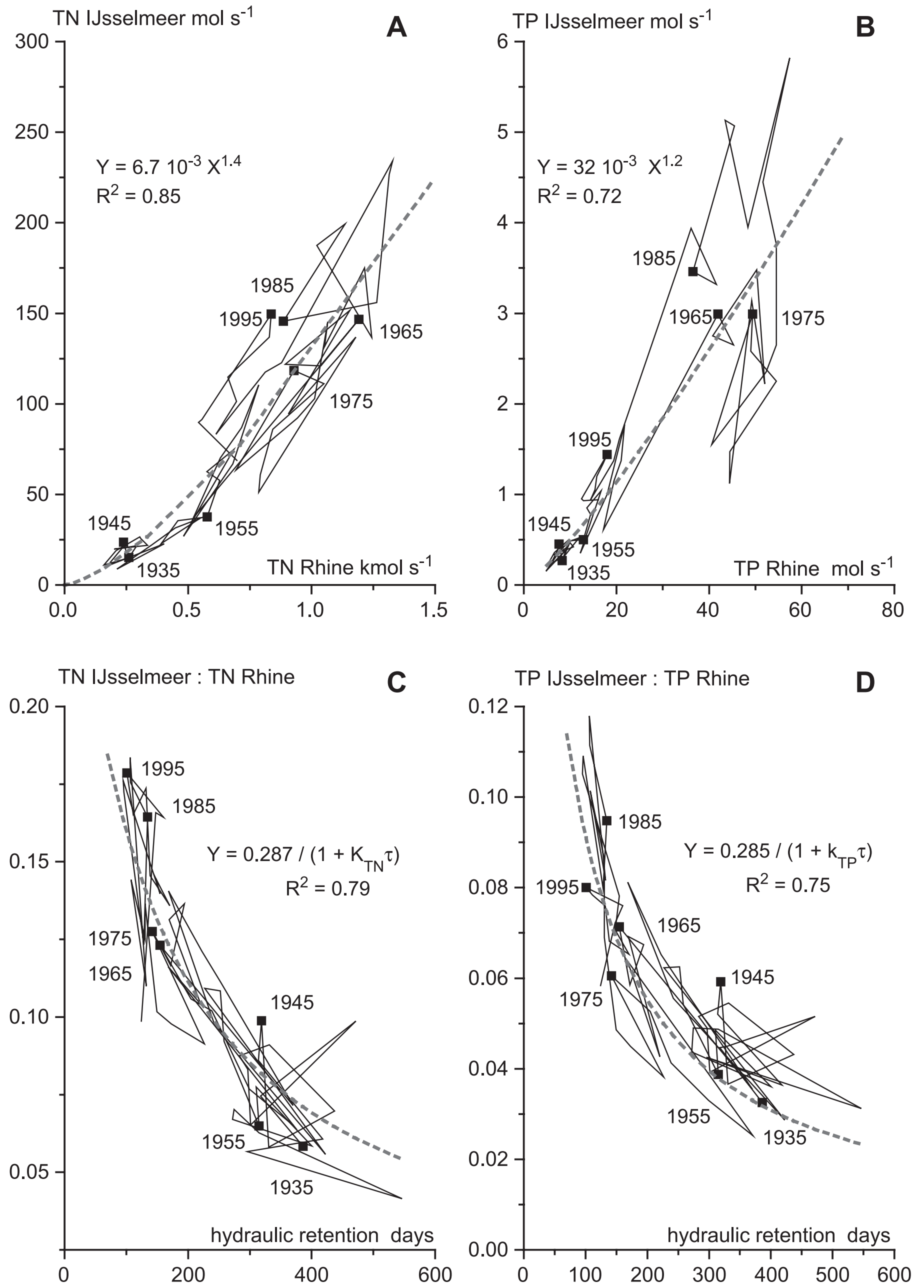

Fig. 13. Relation between the annual nutrient discharge of the Rhine at the German/Dutch border at B-S/L and the annual output of the IJsselmeer into the Wadden Sea. Thin solid lines connect individual years between 1935 and 1998. Solid squares mark 10-y intervals. Dotted lines are regressions as indicated in the panels. (A) IJsselmeer output of TN as a function of the Rhine discharge of TN. (B) As panel A but for TP. (C) Ratio between the IJsselmeer output of TN and the Rhine discharge of TN, as a function of the annual mean hydraulic retention time of the IJsselmeer. (D) As panel C but for TP.

Veer, 1990; De Jonge, 1997; Philippart et al., 2000). Thus, to first order, the inputs from the North Sea will have followed a similar trend with time as the loads by the Rhine. Indeed, De Jonge and Postma (1974) showed that the input of TP from the North Sea tripled from 1950 to 1970, parallel to the increase of the TP load of the Rhine. In this same period, however, the input of TP from the IJsselmeer increased 4–5 fold due to the reduced retention capacity of the lake. After 1975 the relative importance of the IJsselmeer as a source of nutrients for the Wadden Sea increased further and since the 1980s the input of TP from the IJsselmeer has been ~2 times larger than the input from the North Sea (Philippart et al., 2000). For TN, the IJsselmeer provides 70–75% of the total input to the western Wadden Sea since 1978 (Philippart et al., 2000).

The inverse relationships in Figs. 13c and d can be used to predict the effect of a further decrease in hydraulic retention of the IJsselmeer, for instance due to increased river runoff as a consequence of global climate change. The relationships can be described with the simple Vollenweider-type model (Vollenweider, 1969)

$$(\text{Load IJsselmeer}/\text{Load Rhine})_i = \gamma_i/(1 + k_i\tau_i) \quad (6)$$

Where the loss rates k_i are the average values of 7.8 10^{-3} d^{-1} for TN and 1.9 10^{-2} d^{-1} for TP. The factor γ_i incorporates the ratio of the water discharges of the IJsselmeer and the Rhine and is estimated at 0.29 for both TN and TP. The fact that this estimate is higher than the actual average ratio (470/2300 = 0.20) reflects the contribution of other nutrient sources than the Rhine-IJssel to the lake. Using this model, it is estimated that a further decrease of the hydraulic retention time of the lake from 100 d at present to, say, 75 or 50 d would result in an increase of the TN output from 16 to 18 and 21% of the load of the Rhine, respectively. For TP this increase would be from 10 to 12 and 15%, respectively. Our analysis shows that future higher annual runoff without proportional increase in the volume of the lake will inevitably result in relatively higher TN and TP outputs from the IJsselmeer to the Wadden Sea, thereby counteracting ongoing de-eutrophication measures and stimulating coastal eutrophication. Periods with high water discharges of the Rhine, for example in the second half of the 1960s (Fig. 3a) resulted in lowered TN and TP retention of the IJsselmeer (Fig. 6h) and large TN and TP outputs to the western Wadden Sea (Fig. 6e, f). Relatively high retention and low outputs of TN and TP occurred in the 1970s when annual discharges of the Rhine were low. Thus, further reduction of TN and TP inputs to the Rhine and the IJsselmeer will be necessary if existing policy targets on nutrient levels in the Wadden Sea are to be reached under changed climate conditions with higher precipitation and runoff in the watershed of the Rhine.

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References

Baden, S.P., Loo, L.-O., Pihl, L., Rosenberg, R., 1990. Effects of eutrophication on benthic communities including fish. Swedish West Coast. Ambio 19, 113–122.

Behrendt, H., Huber, P., Ley, M., Opitz, D., Schmoll, O., Scholz, G., Uebe, R., 1999. Nährstoffbilanzierung der Flussgebiete Deutschlands. UBA-texte 75/99, 288.

Beukema, J.J., Cadée, G.C., 1997. Local differences in macrozoobenthic response to enhanced food supply caused by mild eutrophication in a Wadden Sea area: food is only locally a limiting factor. Limnol. Oceanogr. 42, 1424–1435.

Beukema, J.J., Cadée, G.C., Dekker, R., 2002. Zoobenthic biomass limited by phytoplankton abundance: evidence from parallel changes in two long-term data series in the Wadden Sea. J. Sea Res. 48, 111–125.

Biemond, C., 1940. Rapport inzake de watervoorziening van Amsterdam. Stadsdrukkerij Amsterdam.

Biemond, C., 1948. Rapport 1948; de watervoorziening van Amsterdam. Stadsdrukkerij Amsterdam.

Billen, G., Garnier, J., 1997. The Phison River plume: coastal eutrophication in response to changes in land use and water management in the watershed. Aquat. Microb. Ecol. 13, 3–17.

Billen, G., Lancelot, C., Meybeck, M., 1991. N, P, and Si retention along the aquatic continuum from land to ocean. In: Mantoura, F.C.A., Martin, J.-M., Wollast, R. (Eds.), Ocean margin processes in global change. John Wiley & Sons, Chichester, pp. 19–44.

Billen, G., Garnier, J., Hanset, P., 1994. Modelling phytoplankton development in whole drainage networks: The Riverstrahler model applied to the Seine river system. Hydrobiologia 289, 119–137.

Billen, G., Garnier, J., Deligne, C., Billen, C., 1999. Estimates of early-industrial inputs of nutrients to river systems: implication for coastal eutrophication. Sci. Tot. Environm. 243/244, 43–52.

Cadée, G.C., Hegeman, J.J., 1993. Persisting high levels of primary production at declining phosphate concentrations in the Dutch coastal area (Marsdiep). Neth. J. Sea Res. 31, 147–152.

Cadée, G.C., Hegeman, J.J., 2002. Phytoplankton in the Marsdiep at the end of the 20th century; 30 years monitoring biomass, primary production and *Phaeocystis* blooms. J. Sea Res. 48, 97–110.

Clarke, F.W., 1920. The data of geochemistry. Bulletin 695. Department of the Interior – United States Geological Survey, Washington.

Cloern, J.E., 2001. Our evolving conceptual model of the coastal eutrophication problem. Mar. Ecol. Prog. Ser. 210, 223–253.

De Jong, F., Bakker, J.F., Dahl, K., Dankers, N., Farke, H., Jäppelt, W., Kossmagk-Stephan, K., Madsen, P.B., 1993. Quality Status Report of the North Sea, subregion 10, The Wadden Sea. Common Wadden Sea Secretariat. FRG, Wilhelmshaven.

De Jonge, V.N., 1997. High remaining productivity in the Dutch western Wadden Sea despite decreasing nutrient inputs from riverine sources. Mar. Poll. Bull. 34, 427–436.

De Jonge, V.N., Essink, K., 1991. Long-term changes in nutrient loads and primary and secondary producers in the Dutch Wadden Sea. In: Elliott, M., Ducrotoy, J.-P. (Eds.), Estuaries and Coasts: Spatial and Temporal Intercomparisons. ECSA 19 Symposium. Olsen & Olsen, Fredensborg, pp. 307–316.

De Jonge, V.N., Postma, H., 1974. Phosphorus compounds in the Dutch Wadden Sea. Neth. J. Sea Res. 8, 139–153.

De Jonge, V.N., Van Raaphorst, W., 1995. Eutrophication of the Dutch Wadden Sea (Western Europe), an estuarine area controlled by the river Rhine. In: McComb, A.J. (Ed.), Eutrophic Shallow Estuaries and Lagoons. CRC Press, Boca Raton, pp. 129–149.

De Jonge, V.N., Bakker, J.F., Van Stralen, M., 1996. Recent changes in the contributions of river Rhine and North Sea to the eutrophication of the western Dutch Wadden Sea. Neth. J. Aq. Ecol. 30, 27–39.

De Kloet, W.A., 1969. Phosphaat eutrofiering van het IJsselmeer. Contactbl. Oecol. 5 (3), 45–49.

De Kloet, W.A., 1971. Het eutrofieringsproces van het IJsselmeergebied. Meded. Hydrobiol. Ver. 5 (1), 23–38.

De Kloet, W.A., 1978. Study of the phosphorus loading and retention in IJsselmeer. Verh. Internat. Limnol. 20, 1619–1623.

De Wit, J.A.W., 1980. Aspecten van de waterkwaliteit in het IJsselmeergebied. H_2O 13, 251–256.

Dresscher, Th.G.N., 1951. De invloed van het Amsterdamse rioolwater op het IJsselmeer vroeger, nu en in de toekomst. Ned. Cent. Org. Toegep. Natuurwet. Onderz.

Duursma, E.K., 1961. Dissolved organic carbon, nitrogen and phosphorus in the sea. Neth. J. Sea Res. 1, 1–148.

Gray, J.S., 1992. Eutrophication in the sea. In: Colombo, G., Ferrari, I., Ceccherelli, V.U., Rossi, R. (Eds.), Marine Eutrophication and Population Dynamics. Olsen & Olsen, Fredensborg, pp. 3–15.

Guildford, S.J., Hecky, R.E., 2000. Total Nitrogen, total phosphorus, and nutrient limitation in lakes and oceans: Is there a common relationship? Limnol. Oceanogr. 45, 1213–1223.

Havinga, B., 1941. De veranderingen in de hydrographischen toestand en in de macrofauna van het IJsselmeer gedurende de jaren 1936–1940. De biologie van de Zuiderzee tijdens haar drooglegging. Meded. Zuiderzeecomm. Ned. Dierk. Ver. 5.

Havinga, B., 1954. Hydrografie van het IJsselmeer. In: De Beaufort, L.F. (Ed.), Veranderingen in de Flora en Fauna van de Zuiderzee (thans IJsselmeer) na de Afsluiting in 1932. Ned. Dierk. Ver., pp. 1–24.

Helder, W., 1974. The cycle of dissolved inorganic nitrogen compounds in the Dutch Wadden Sea. Neth. J. Sea Res. 8, 154–173.

Hutchinson, G.E., 1957. A Treatise on Limnology. Geography, Physics and Chemistry, vol. I. Wiley & Sons, New York.

Klein, A.W.O., Van Buren, J.T., 1992. Eutrophication of the North Sea in the Dutch coastal zone 1976–1990. Report WS-92.003. Ministry of Transport, Public Works and Water Management, Tidal Waters Division, The Hague.

Laane, R.W.P.M., 1992. Background concentrations of natural compounds in rivers, seawater, atmosphere and mussels. Report DGW-92.033. Ministry of Transport, Public Works and Water Management, Tidal Waters Division, The Hague.

Nixon, S.W., 1995. Coastal marine eutrophication: a definition, social causes, and future concerns. Ophelia 41, 199–219.

Nixon, S.W., 1997. Prehistoric nutrient inputs and productivity in Narragansett Bay. Estuaries 20, 253–261.

Philippart, C.J.A., Cadée, G.C., Van Raaphorst, W., Riegman, R., 2000. Long-term phytoplankton-nutrient interactions in a shallow coastal sea: nutrient loadings, algal community structure and denitrification potential. Limnol. Oceanogr. 45, 131–144.

Postma, H., 1954. Hydrography of the Dutch Wadden Sea. Archs. néerl. Zool. 10, 405–511.

Postma, H., 1966. The cycle of nitrogen in the Wadden Sea and adjacent areas. Neth. J. Sea. Res. 3, 186–221.

Postma, H., 1967. Observations on the hydrochemistry of inland waters in The Netherlands. In: Golterman, H.L., Clymo, R.S. (Eds.), Chemical Environment in the Aquatic Habitat. Proc. IBP Symp. Amsterdam and Nieuwersluis, pp. 30–38.

Postma, H., 1985. Eutrophication of Dutch coastal waters. Neth. J. Zool. 35, 348–359.

Redfield, A.C., 1958. The biological control of chemical factors in the environment. Am. Sci. 46, 205–222.

Rendell, A.R., Ottley, C.J., Jickells, T.D., Harrison, R.M., 1993. The atmospheric input of nitrogen species to the North Sea. Tellus 45B, 53–63.

Richardson, K., Jørgensen, B.B., 1996. Eutrophication: definition, history and effects. In: Jørgensen, B.B., Richardson, K. (Eds.), Eutrophication in Coastal Marine Ecosystems. Coastal and Estuarine Studies, vol. 52. Am. Geophys. Uni., Washington, DC, pp. 1–19.

Riegman, R., Noordeloos, A.A.M., Cadée, G.C., 1992. *Phaeocystis* blooms and eutrophication of the continental coastal zones of the North Sea. Mar. Biol. 112, 479–484.

Rijkswaterstaat/DZW, 1942–1969. Driemaandelijksch bericht betreffende de Zuiderzeewerken, vol. 23–50. Rijksuitgeverij, Departement van Waterstaat, Den Haag.

Rosenberg, R., Elmgren, R., Fleischer, S., Jonsson, P., Persson, G., Dahlin, H., 1990. Marine eutrophication case studies in Sweden. Ambio 19, 102–108.

Scholte Ubing, D.W., 1980. Nutriënten in de Rijn. H_2O 13, 97–104.

Strickland, J.D.H., Parsons, T.R., 1972. A practical handbook of seawater analysis. Fish. Res. Bd, 167.

Sündermann, J., Becker, G., Damm, P., Van Den Eynde, D., Frohse, A., Laane, R., Van Leussen, W., Pohlmann, T., Van Raaphorst, W., Radach, G., Shultz, H., Visser, M., 1996. Decadal variability on the Northwest European shelf. German J. Hydrogr. 48, 365–400.

Van Bennekom, A.J., Wetsteijn, F.J., 1990. The winter distribution of nutrients in the Southern Bight of the North Sea (1961–1978) and in the estuaries of the Scheldt and the Rhine/Meuse. Neth. J. Sea Res. 25, 75–87.

Van Bennekom, A.J., Gieskes, W.W.C., Tijssen, S.B., 1975. Eutrophication of Dutch coastal waters. Proc. R. Soc. Lond. B. 189, 359–374.

Van der Molen, D.T., Boers, P.C.M., 1994. Influence of internal loading on phosphorus concentration in shallow lakes before and after reduction in external loading. Hydrobiologia 275/276, 379–389.

Van der Veer, H.W., Van Raaphorst, W., Bergman, M.J., 1989. Eutrophication of the Dutch Wadden Sea: external nutrient loadings of the Marsdiep and Vliestroom basin. Helgoländer Meeresunters 43, 501–515.

Van der Weijden, C.H., Middelburg, J.J., 1989. Hydrochemistry of the river Rhine: long term and seasonal variability, elemental budgets, base levels and pollution. Wat. Res. 23, 1247–1266.

Van Raaphorst, W., Van der Veer, H.W., 1990. The phosphorus budget of the Marsdiep tidal basin (Dutch Wadden Sea) in the period 1950–1985: importance of the exchange with the North Sea. Hydrobiologia 195, 21–38.

Vollenweider, R.A., 1969. Possibilities and limits of elementary models concerning the budget of substances in lakes. Arch. Hydrobiol. 66, 1–36.

Weichart, G., 1990. On the value of "pld" phosphate data. ICES paper MCWG 1990/7.3.4/1, 1–7.

Wismeijer, A.A., Weenink, J., 1982. Amsterdam en z'n afvalwater. H_2O 15, 155–158.

Wulffraat, K.J., Smit, Th., Groskamp, H., De Vries, A., 1993. De belasting van de Noordzee met verontreinigende stoffen 1980–1990. Report DGW-93.037, Ministry of Transport, Public Works and Water Management, Tidal Waters Division, The Hague.