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Review

The North Sea: source or sink for nitrogen and phosphorus to the Atlantic Ocean?

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Abstract. Annual nitrogen and phosphorus budgets for the whole North Sea taking into account the most recent data available were established. The area considered has a total surface of approximately 700,000 km^2 and corresponds to the definition by OSPARCOM (Oslo and Paris Commission) with the exclusion of the Skagerrak and Kattegat areas. Input and output fluxes were determined at the marine, atmospheric, sediment and continental boundaries, and riverine inputs based on river flows and nutrient concentrations at the river–estuary interface were corrected for possible estuarine retention. The results showed that the North Sea is an extremely complex system subjected to large inter-annual variability of marine water circulation and freshwater land run-off. Consequently, resulting total N (TN) and P (TP) fluxes are extremely variable from 1 year to another and this has an important influence on the budget of these elements. Total inputs to the North Sea are 8870 ± 4860 kT N $year^{-1}$ and 494 ± 279 kT P $year^{-1}$. Denitrification is responsible for the loss of $23 \pm 7\%$ of the TN inputs while sediment burial is responsible for the retention of only of $2 \pm 2\%$ of the TP input. For TN, due to the large variability on marine and estuarine fluxes, and to the uncertainty related to the denitrification rate, it was concluded that the North Sea could either be a source (1930 kT N $year^{-1}$) or a sink (1700 kT N $year^{-1}$) for the waters of the North Atlantic Ocean. For TP it was concluded that the North Sea is mostly a source (-4 to 52 kT P $year^{-1}$) for the waters of the North Atlantic Ocean.

Introduction

Continental shelf ecosystems in the North Atlantic Ocean have been presented as important sinks for nutrients (Nixon et al. 1996). For nitrogen, they are believed to retain all inputs from atmosphere and rivers (597–760 Gmol $year^{-1}$) arriving to the system and even to represent a net sink of about 12–37% of the DIN supplied onto the shelf by onwelling from the deeper ocean by denitrification. For phosphorus, they act more as a filter, reducing the terrestrial inputs to the North Atlantic by as much as 40% (24 Gmol $year^{-1}$) through sedimentation and long-term burial into sediments.

Note that throughout the article the term 'retention' will include processes of storage within a system (for example, N and P burial in sediments) and removal processes (as denitrification), as used by many authors.

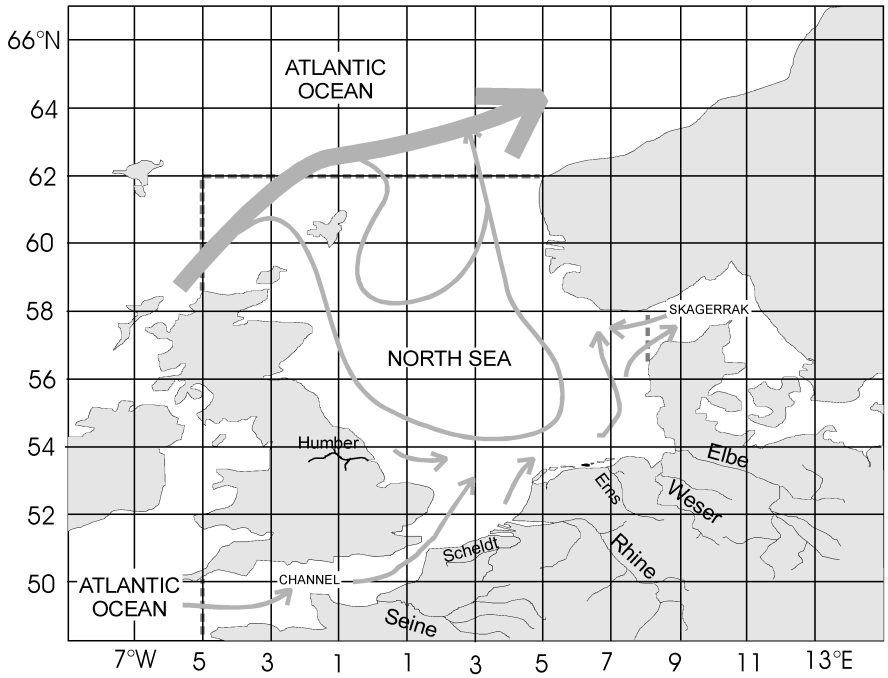

Figure 1. The North Sea and its major river contributors. Arrows present the general water circulation in the area. Dotted lines represent the limit of the surface considered to calculate the N and P budgets.

Nutrients (mainly nitrogen and phosphorus) fluxes to shelf ecosystems are largely influenced by human activity in the catchment area of the rivers and watershed. They are generated through various processes and enter the shelf systems via rivers, direct wastewater discharge and the atmosphere. Anthropogenic nitrogen in rivers mainly originates from the leaching of fertilised agricultural soils, from domestic wastewater discharge, and from atmospheric deposition while phosphorus is mainly linked to domestic wastewater. Nitrogen as NO_x (oxidised forms) and NH_y (reduced forms) in the atmosphere originates from domestic and industrial combustion processes and from intensive farming practises (manure). Moreover, nitrogen also enters the ecosystem by biological fixation of atmospheric N_2 and via marine water circulation.

Representing an important area of the shelves of the North Atlantic Ocean, the North Sea ecosystem (Figure 1) is located in one of the world's most industrial and densely populated watersheds. From all man induced changes, the increase over the past decades of the nutrient load to the North Sea due to anthropogenic activities is probably one of major's. Radach (1992) estimated that the riverine N and P inputs to the North Sea between 1950 and 1980 increased by a factor 7 and 5, respectively, while atmospheric inputs of nitrogen increased by a factor 3 in the same period. Whether the North Sea shelf acts as a source or a sink for nitrogen and phosphorus

for the waters of the North Atlantic Ocean was only rarely investigated in recent years, and results are controversial. Radach and Lenhart (1995) in their extensive modelling of nutrient cycling in the North Sea found a net export of N and P to the North Atlantic (710 kT N year^{-1} and 59 kT P year^{-1}). On the contrary, Hydes et al. (1999) published recently results from nutrient balance calculations suggesting that the North Sea is an important sink for nitrogen from North Atlantic Ocean waters. These authors found that 'A net flow of ocean water onto the shelf equivalent to 0.6×10^6 m^3 s^{-1} containing nitrate at the winter concentration of 7.5 μM is required to maintain the nitrogen balance in the North Sea'. This corresponds to a net inflow of 1990 kT N year^{-1} from North Atlantic Ocean waters to the North Sea shelf. However, none of these authors considered the variability on their fluxes estimates.

The objective of this paper is to establish annual nitrogen and phosphorus budgets for the whole North Sea taking into account the most recent (>1990) data available. The various inputs and output fluxes at the boundaries of the system are identified and quantified including their inter-annual variability and an attempt is made to answer the controversial question whether the system is a source or a sink for N and P to the North Atlantic Ocean.

The North Sea system we consider is the one defined by the Oslo and Paris Commission as the Greater North Sea (OSPARCOM 2000c) with the exclusion of the Skagerrak and Kattegat areas because of their geographical isolation from the main North Sea basin. The area considered is presented in Figure 1 and has a total surface of 698000 km^2 (750,000 km^2 for the Greater North Sea according to OSPARCOM (2000c) minus the 52,000 km^2 of the Skagerrak and Kattegat). Turning clockwise, this system is limited by the southern and eastern continental borders of the United Kingdom, the 50 °W and 62 °N lines (limit with the North Atlantic between Scotland and Norway), the western continental border of Norway, the 10 °E longitude line (limit with the Skagerrak), the western continental border of Denmark, Germany, The Netherlands, Belgium and northern France and the 5 °W line (limit with the Atlantic Ocean at the entry of the Channel).

There are 4 types of boundaries where nitrogen and phosphorus can be exchanged: sea–continent, sea–sea, air–sea and sea–sediment interfaces. At each of these interfaces, nutrients can either enter or leave the system by physical and/or biogeochemical processes. Note that in this study, the sea–continent border corresponds to the marine–estuary interface unlike many other budget studies where this border is considered to be located at the freshwater–estuary interface.

Calculation of fluxes

Exchanges at the marine boundaries

Inputs at the open sea interfaces can be estimated knowing water fluxes distributions and nutrient concentration distribution at the boundaries of the system.

The general water-mass circulation in the North Sea was extensively described by Otto et al. (1990) and is presented in Figure 1. The mean current distribution of

Table 1. Mean annual nutrient concentration integrated over the depth of the water column at the northwestern (NW), eastern (E) and southern (S) marine boundaries of the North Sea. NO_3: nitrate, DON: dissolved organic nitrogen, PON: particulate organic nitrogen, PO_4: phosphate, DOP: Dissolved organic phosphorus, POP: particulate organic phosphorus, TN: total nitrogen; TP: total phosphorus.

Boundary	NO_3[1] (μM)	DON[2] (μM)	PON[2] (μM)	PO_4[1] (μM)	DOP[2] (μM)	POP[2] (μM)	TN (μM)	TP (μM)
NW (Atlantic)	8.5 ± 2.2	3–5	0.02–1	0.7 ± 0.2	0.2	0.01–0.05	13.0 ± 2.2	0.9 ± 0.2
E (Skagerrak)	7.2 ± 3.3	3–5	0.02–1	0.6 ± 0.2	0.2	0.01–0.05	11.7 ± 3.3	0.8 ± 0.2
S (Channel)	4.4 ± 2.8	3–5	0.02–1	0.3 ± 0.1	0.2	0.01–0.05	8.9 ± 2.8	0.5 ± 0.1

[1]From Radach et al. (1995).
[2]Values reported in Michaels et al. (1996) for North Atlantic waters.

Table 2. Mean annual total N (Tot N) and P (Tot P) concentrations integrated over the depth of the water column, water flows (Fw) and total N and P fluxes (FTN and FTP) at the northwestern (NW), eastern (E) and southern (S) marine boundaries of the North Sea. Values are presented with standard deviations illustrating the inter-annual variability. Negative values present fluxes going out of the North Sea system.

Boundary	TN[1] (μM)	TP[1] (μM)	Fw[2] (Sv)	FTN[3] $kT\,year^{-1}$	FTP[3] $kT\,year^{-1}$
NW (Atlantic)	13.0 ± 2.2	0.9 ± 0.2	1.035 ± 0.565	6190 ± 3540	430 ± 250
E (Skagerrak)	11.7 ± 3.3	0.8 ± 0.2	-0.054 ± 0.029	-290 ± 180	-20 ± 10
S (Channel)	8.9 ± 2.8	0.5 ± 0.1	0.042 ± 0.087	170 ± 360	10 ± 20

[1]As described in Table 1.
[2]Data reported by Laane et al. (1996).
[3]Calculated by multiplying concentrations with water fluxes using the appropriate unit conversion factors.

the North Sea forms a cyclonic circulation. Water from the North Atlantic enters the North West and follows the British coastline to the South were it meets water-masses coming from the Atlantic that passed through the Channel and the Strait of Dover. From there, water masses circulate to the Northeast following the coastlines of Belgium, The Netherlands, Germany and Denmark. Part of the water-mass is there deviated East to the Skagerrak while the rest continues to the North along the Norwegian coastline where it re-enters the Atlantic Ocean. Moreover, Westerly winds enhance the cyclonic circulation while Easterly winds weaken the circulation. As a result, year to year variations in mean annual water fluxes at the marine boundaries of the North Sea are extremely important (Laane et al. 1996; OSPARCOM 2000c).

The water fluxes at marine boundaries can rarely be measured directly and water balances for the North Sea are mainly based on model results. The average annual water flux (averaged over a 20 year period) $\pm$ standard deviation at each of the boundaries of the North Sea computed with the NORWECOM model are reported in the publication of Laane et al. (1996) (Table 2). The calculations concern the period 1976–1995 and are described in detail in the article by Laane et al. (1996). At the northwestern boundary with the Atlantic, water flows are 1.035 ± 0.565 Sv

(Sv = Sverdrup, $1\,\mathrm{Sv} = 10^6\,\mathrm{m^3\,s^{-1}}$). At the eastern boundary with the Skagerrak, water flows are $-0.054 \pm 0.029\,\mathrm{Sv}$ and enter the Skagerrak. At the southern boundary with the Atlantic, water flows are $0.042 \pm 0.087\,\mathrm{Sv}$ and are thus either flowing in or out of the Channel. Note that positive flows are to be regarded as incoming flows while negative flows are outgoing flows.

Nutrient fluxes associated with these water flows (Table 2) can be calculated by multiplying mean annual water flows (Table 2) with mean annual nutrient concentrations (Table 1) at the boundaries of the system, assuming that both are normally distributed over the year.

Mean annual dissolved inorganic nutrient concentration integrated over the depth of the water column in the North Atlantic Ocean and Skagerrak waters at the boundaries of the system (Table 1) were from a technical report published by Radach et al. (1995) who used the ECOMOD and ICES data base covering the time period 1950–1994. In this report, average monthly nutrient concentrations are given for each month of the year with their standard deviation covering the year to year variations. From these data we selected the regions located at the boundaries of our system and calculated for each a yearly average (by averaging the monthly averages) and a pooled standard deviations.

Unfortunately, no similar information is available for the organic forms of N and P. According to Michaels et al. (1996), there are very few data reported for dissolved (DON) and particulate organic N (PON) and P in the waters of the open Northern Atlantic Ocean. Typical concentrations for DON are believed to be between 3 and 5 μM with only small variations with depth and PON varies between 0.02 and 1 μM as integrated over the water column (Michaels et al. 1996). As ammonium is biologically very reactive, its contribution to the total nitrogen (TN) concentration can be considered as negligible in Oceanic waters. For organic phosphorus, typical dissolved organic P concentrations are believed to be around 0.02 μM and particulate organic P between 0.01 and 0.05 μM (Michaels et al. 1996). By lack of direct measurements, these estimates will be used as the mean annual depth integrated organic N and P concentrations at the marine boundaries of our system (Table 1). This gives TN concentrations of $13.0 \pm 2.2\,\mu\mathrm{M}$ at the northwestern boundary with the Atlantic, $11.7 \pm 3.3\,\mu\mathrm{M}$ at the eastern boundary with the Skagerrak and $8.9 \pm 2.8\,\mu\mathrm{M}$ at the southern boundary with the Atlantic (Channel). For total phosphorus (TP), these concentrations are 0.9 ± 0.2, 0.8 ± 0.2 and $0.5 \pm 0.1\,\mu\mathrm{M}$ for the same boundaries, respectively.

The range of TN and TP flows at the marine boundaries of the North Sea can thus be calculated by multiplying the average annual concentrations (Table 2) with the average annual water fluxes (Table 1). Estimated input fluxes from the Atlantic to the North Sea at the NW boundary are $5950 \pm 3250\,\mathrm{kT\,N\,year^{-1}}$ and $430 \pm 230\,\mathrm{kT\,P\,year^{-1}}$. The output flux to the Skagerrak is $260 \pm 140\,\mathrm{kT\,N\,year^{-1}}$ and $17 \pm 9\,\mathrm{kT\,P\,year^{-1}}$. The nutrient input flux through the Channel is of $160 \pm 340\,\mathrm{kT\,N\,year^{-1}}$ and $10 \pm 20\,\mathrm{kT\,P\,year^{-1}}$.

Output-fluxes to the North Atlantic along the Norwegian coast, which are not assessed, will be estimated later assuming that the system is in balance (sum of all nutrient fluxes = 0).

Table 3. Drainage area (S), mean annual freshwater residence time (tres), mean annual river flow (Q) and mean annual N and P retention in the estuaries of the seven major rivers discharging in the North Sea. NI: no information.

Estuary	S(km^2)	Tres (days)	Q (m^3 s^{-1})	Element	Retention (%)	Data from
Rhine	185,000	2[2]	2220[2]	N	NI	
				P	NI	
Seine	73,190	8[3]	413[3]	N	7	AESN (1994)
				P	7	AESN (1994)
Weser	46,300	11[5]	325[5]	N	NI	
				P	NI	
Elbe	148,270	13[4]	865[4]	N	~20[1]	Schroeder et al. (1996) and
				P	NI	Wolter et al. (1985)
Humber	27,000	40[6]	246[6]	N	25	Barnes and Owens (1998)
				P	86	Sanders et al. (1997)
Ems	13,150	40[2]	88[2]	N	25	Van Beusekom and de Jonge (1998)
				P	40	Van Beusekom and de Jonge (1998)
Scheldt	20,300	75[2]	108[2]	N	25	Heip and Herman (1995)
				P	52	Billen and Servais (1991)

[1]Gross estimate: 40% in summer according to Schroeder et al. (1996), and in winter reduction of denitrification by a maximum factor 3–5 according to Wolter et al. (1985). Estimates were 40% for the three summer months, (40/3)% for the six spring and autumn months and (40/5)% for the three winter months and the average was calculated from these values.
[2]From Middelburg and Nieuwenhuize (2000).
[3]From Brion et al. (2000).
[4]From Goosen et al. (1995).
[5]From Grabemann et al. (1999).
[6]From Barnes and Owens (1998).

The large standard deviations of the N and P exchange fluxes mirror the extreme inter-annual variability of the water flows (between 60 and 200% depending on the boundary) with weakest flows reported during years of low cyclonic circulation (as in 1977, 1979, 1985) and strongest flows during years with high cyclonic circulation (as in 1990, 1991 and 1994) (Laane et al. 1996; OSPARCOM 2000c). The variability on the nutrient concentration is much lower (around 20%).

Exchange at the continent-sea interface

River inputs

The North Sea is the outlet of a watershed of 731,520 km^2 with a mean freshwater discharge of 5600 m^3 s^{-1}. Seven major river basins cover more than 70% of the total watershed surface and contribute to more than 60% of the total freshwater discharge. These are the Rhine, the Elbe, the Seine, the Humber, the Weser, the Scheldt, and the Ems Rivers (Figure 1 and see Table 3 for their hydrologic characteristics).

Table 4. Estimation of the relative error (error%) made on riverine nutrient fluxes presented in the OSPARCOM reports. Errors are estimated from the calculation method used and the number of measurements made per year (n) according to De Vries and Klavers (1994) (see text). The equation numbers correspond to the equations used for the load calculation (see text). B: Belgium; UK: United Kingdom; F: France; G: Germany; NL: The Netherlands; DK: Denmark; N: Norway. NI: no information.

	n	Equation no.	Error%
Scheldt (B)	14–86	2–3	5–20
Other rivers (B)	7–12	NI	NI
Humber (UK)	12	1–2	20
Other Rivers (UK)	12	1–2	15–20
Seine (F)	24–43	1	20
Ems (G)	12	1	20
Weser (G)	12	1	20
Elbe (G)	24–52	2	10–20
Other rivers (G)	12–27	1	20
Rhine (NL)	12–27	2	20
Other rivers (NL)	12–27	2	20
Rivers (DK)	16–20	NI	NI
Rivers (N)	12–19	2	20

The annual TN and TP loads to the North Sea were extracted from the data reported by each country in the OSPARCOM reports on riverine and direct inputs (OSPARCOM 1992, 1994, 1995a,b, 1996, 1997, 1998a, 2000a,b). These reports present nutrient flux data for the years 1990–1998 that result from national monitoring programmes. River discharge, nitrate, ammonium, TN, phosphate, and TP concentrations were monitored between 7 and 52 times a year (see Table 4) at the outlet of the rivers, before mixing with marine waters. The flux-data reported in the OSPARCOM reports include information on the number of observations and the equation used to calculate the annual TN and TP loads at each river–estuary interface (see Table 4). Fluxes were calculated using one of the following equations:

$$\text{Load} = \sum_{i=1}^{n} C_i Q_i \tag{1}$$

$$\text{Load} = \frac{\sum_{i=1}^{n} C_i Q_i}{\sum_{i=1}^{n} Q_i} \times \sum_{j=1}^{m} Q_j \tag{2}$$

$$\text{Load} = \sum_{i=1}^{n} C_i Q_i^{\text{GAI}} \tag{3}$$

with C_i: concentration measured on day i; Q_i: discharge measured on day i; Q_j: discharge measured on day j; Q_i^{GAI}: average discharge for the 10 days around day i; n: number of concentration measurements per year; m: number of discharge measurements per year.

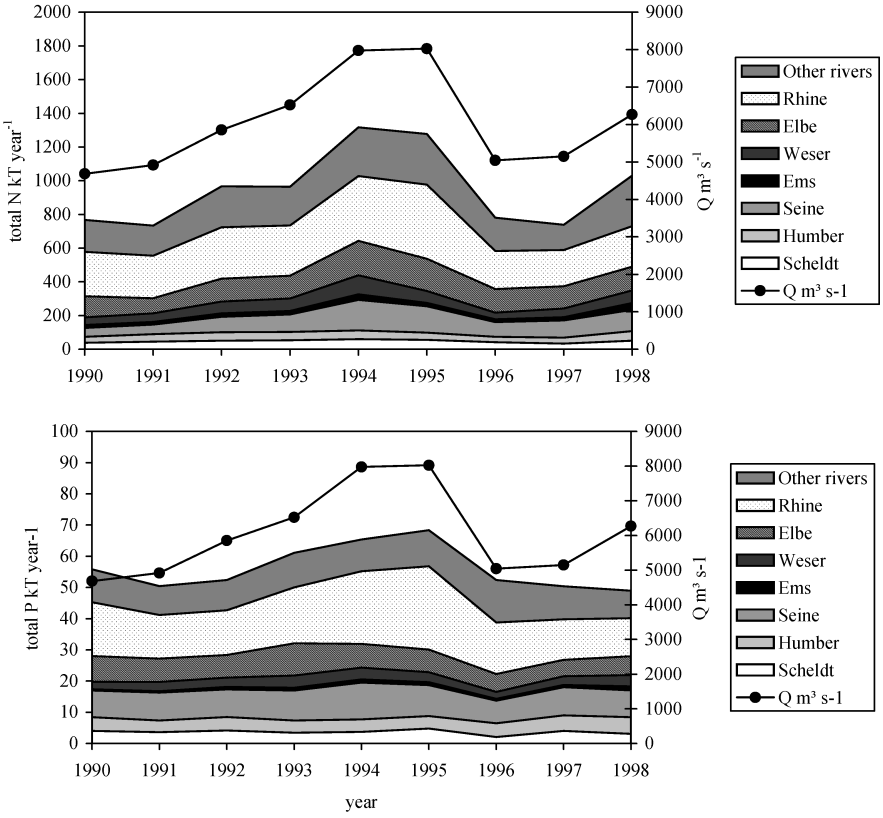

Figure 2. Total nitrogen (top) and total phosphorus (bottom) annual riverine fluxes and mean annual total freshwater discharge from 1990 to 1998. Coloured areas represent the contribution of the major rivers as indicated in the legend.

This information can be used to make an estimation of the relative error of the calculated fluxes by comparison to the study of De Vries and Klavers (1994). For the Rhine and Maas rivers, these authors compared different annual load calculation methods for ammonium, using concentration and discharge data with various sampling frequency. These results were compared to a reference method using loads obtained from daily measurements. The relative error of the flux was shown to be dependent on the sampling frequency and calculation method used. Applying these results to the OSPARCOM data, it is possible to estimate that the relative error made on the OSPARCOM fluxes lays between 5 and 20% as shown in Table 4.

Figure 2 presents the annual freshwater inputs, TN inputs and TP inputs from rivers to estuaries as reported in the OSPARCOM reports. Freshwater inputs range between 4680 and 8030 $m^3 s^{-1}$, TN inputs between 730 and 1320 kT $year^{-1}$, and TP inputs between 45 and 68 kT year. The large inter-annual variability in the TN flux from 1990 to 1998 is comparable to the inter-annual variability of the freshwater

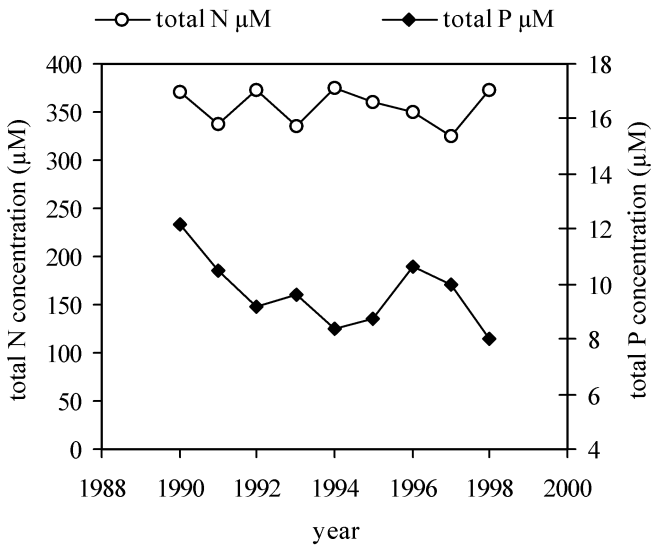

Figure 3. Mean annual concentrations of total N and P in rivers discharging in the estuaries of the North Sea from 1990 to 1998. Calculated by dividing total annual N and P loads from rivers by the total annual freshwater discharge.

discharge (Figure 2, top), indicating that mean annual concentrations in the discharging rivers were relatively stable over the past 9 years. The relationship between the TP flux and the freshwater discharge is less evident (Figure 2, bottom). Indeed, it appears that the average annual TN concentration for all rivers discharging in the North Sea (Figure 3), calculated as the TN flux divided by the freshwater discharge do not show any variation trend over the 9 years. But the average annual TP concentration (Figure 3) decreased by about 30% (from 10.2 to 7 µM). This is on-line with results reported in the QSR 2000 (OSPARCOM 2000c) and in the Fifth North Sea Conference (2002) reports. They are linked to the large efforts made in the treatment of urban wastewater in the catchment of North Sea rivers, that reduced significantly sewage N and P loads to rivers. This decrease had a direct effect on P concentrations in rivers as wastewater is one of the major P source for river waters. However, as the major N contributor for rivers is linked to agricultural practises (fertilisation) which are, politically, much more difficult to constrain, this N reduction had a limited effect with no visible decrease in river water N concentrations.

The average annual freshwater input to the estuaries is $6051 \pm 1269\,m^3\,s^{-1}$, TN input is $953 \pm 224\,kT\,year^{-1}$ and TP input is $56 \pm 7\,kT\,year^{-1}$. Major single contributor is the Rhine River representing $31 \pm 4\%$ of the TN load and $31 \pm 5\%$ of the TP load (Figure 2). We can see that, as for the nutrient exchanges at the marine boundaries, riverine nutrient input fluxes also show a strong inter-annual variability which is higher than the estimated 20% error on flux calculations.

Riverine nutrient fluxes as presented in the OSPARCOM reports do not take into account the role of estuaries on the possible retention or release of nutrients, and can thus not be used directly in the calculation of North Sea budgets. As a matter of fact, nitrogen compounds can be denitrified to gaseous forms and be lost to the atmosphere, while phosphorus can be released from or stored in sediments. Nixon et al. (1996) showed for estuaries and lakes that the 'percentage of TN and TP input from land that is exported' was directly correlated with the logarithm of the freshwater residence time of the systems. The relation made by Nixon et al. (1996) are mainly based on American estuaries with only two European estuaries considered: the Danish Norsminde Fjord and the Belgian–Netherlands Scheldt.

Table 3 gives the TN and TP retention in the estuaries of the seven major rivers entering the North Sea. We can see that the retention of TN varies between 7 and 25% and that of TP between 7 and 86%. Estuaries with the longest residence time generally also show the highest retention of both TN and TP. Plotting these data in the same way as in Nixon et al. (1996) (% TN or TP exported as a function of the freshwater residence time in logarithmic scale), shows a quite good agreement between the correlation line established by Nixon et al. (1996) and North Sea estuaries data (Figure 4) except for exceptionally high P retention in the Humber estuary.

Retention percentages were applied to the riverine OSPARCOM data set in order to account for the effect exerted by estuaries on riverine TN and TP fluxes. For estuaries where no data for this factor were available, retention percentages were extrapolated from the freshwater residence times given in Table 3. For the Rhine, given the extremely short residence time we considered that there was no retention of TN and TP. For the Weser, a retention of 15% for the TN load and of 10% of the TP load was estimated. For the Elbe, a retention of 10% of the TP load was extrapolated. In addition to the seven major rivers, the estuaries of the other smaller rivers will most probably have relatively long residence times. Therefore, we used a mean retention of 25% for TN and of 50% for TP like for the Scheldt and Ems estuaries.

Using these factors allows us to obtain the following estimates for the estuarine TN and TP loads to the North Sea: 805 ± 237 kT N year^{-1} and 42 ± 8 kT P year^{-1}.

Direct inputs

Nitrogen and phosphorus can also enter the North Sea by direct wastewater discharge from coastal cities and industries. The data covering the period 1990–1998 were found in the same OSPARCOM reports as the river input data and are presented in Figure 5.

According to the country, direct discharges were monitored at the outlet of wastewater discharges, estimated from population density or given directly by those responsible for the sewage effluents. A large error probably exists on those values as the monitoring was often incomplete or even absent for several countries (France and Belgium). Only the UK (major contributor with more than 4000 km North Sea coastline), Denmark and Norway (minor contributors with less than 400 km North Sea coastlines) provided a complete and detailed data set

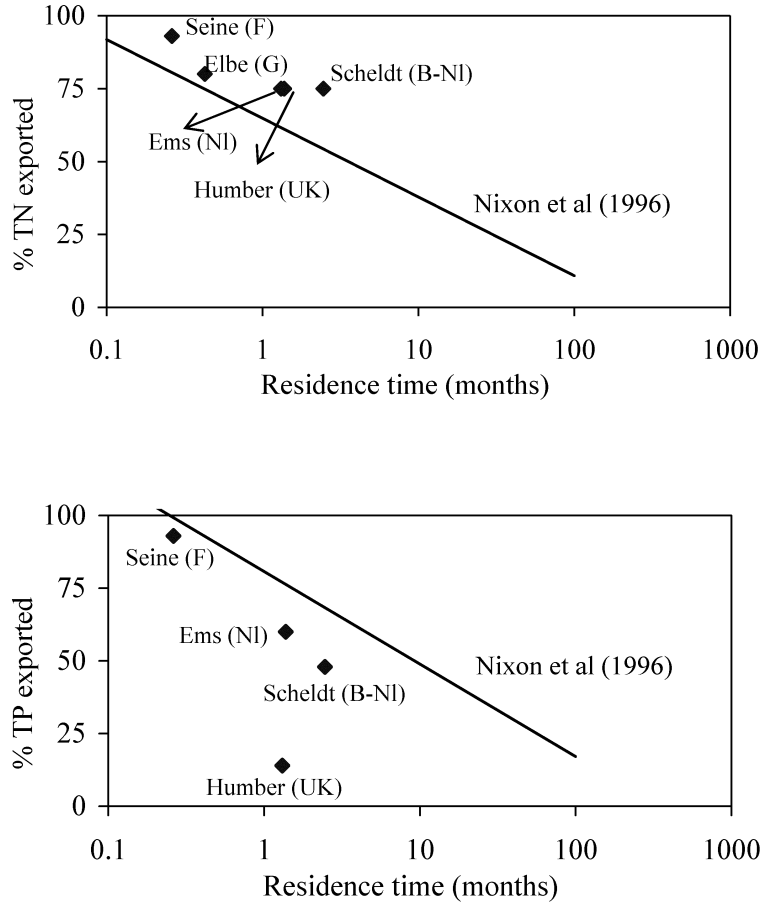

Figure 4. Fraction of the total nitrogen (TN, top) and total phosphorus (TP, bottom) arriving in North Sea estuaries that is exported to the North Sea as a function of the freshwater residence time in the estuaries. Plain line represents the relationship founded by Nixon et al. (1996). Nl: The Netherlands; UK: United Kingdom; F: France; G: Germany; B: Belgium.

for the 9 years. The Netherlands also presented a quite complete data set except for the years 1993 and 1994. The contribution of Belgium is probably negligible regarding its very short coastline (66 km), however, the contribution of France could be important (more than 1000 km North Sea coastline). Hence, values should then be considered as minimum values. Direct inputs of TN to the North Sea vary between 58 and 95 kT year^{-1} with an average of 70 ± 12 kT year^{-1} (Figure 5, top) and of TP between 11 and 14 kT year^{-1} with an average of 12 ± 1 kT year^{-1} (Figure 5, bottom). The observed decreasing trend for N and P inputs mostly reflects the decrease observed in UK sewage waters probably as a result of more efficient sewage treatment.

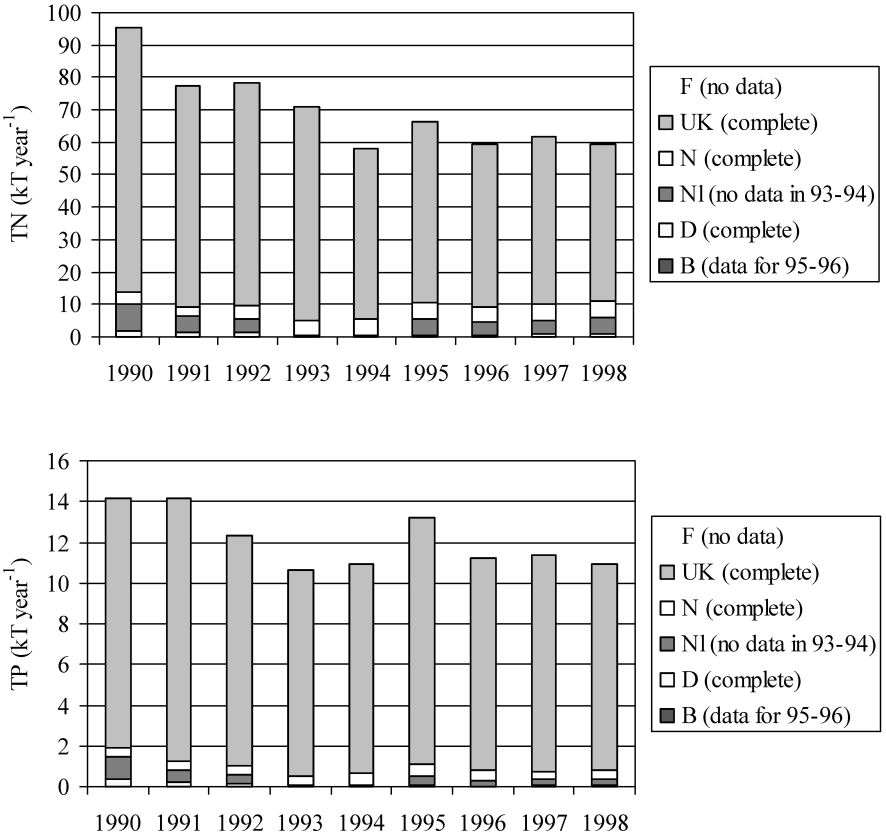

Figure 5. Annual direct inputs of total nitrogen (TN, top) and total phosphorus (TP, bottom) in the North Sea by bordering countries between 1990 and 1998. Note that the contribution of Germany is not presented as no direct inputs are made to the North Sea by this country. Nl: The Netherlands; UK: United Kingdom; F: France; B: Belgium; N: Norway; DK: Denmark.

Exchange at the air–sea interface

Atmospheric inputs

Atmospheric deposition only deals with nitrogen. Data between 1990–1995 were collected by the Comprehensive Atmospheric Monitoring programme (CAMP) from the Paris Commission (OSPARCOM 1998b) but they only consider wet deposition of inorganic N and are thus underestimated. A detailed literature review made by van Boxtel et al. (1991), including data of dry deposition of N, reported deposition rates (wet + dry) of inorganic nitrogen of 150–320 mmol N m^{-2} $year^{-1}$ for coastal areas and of 20–80 mmol N m^{-2} $year^{-1}$ for the open areas of the North Sea. Considering that about 1/3 of the North Sea area corresponds to coastal areas, this gives an average deposition rate of 63–160 mmol N m^{-2} $year^{-1}$ which correspond to an annual flux of 615–1560 kT N $year^{-1}$. This is considerably higher than

the OSPARCOM estimates which are between 310 and 370 kT N year^{-1}. It seems thus obvious that only using wet deposition rates greatly underestimates the magnitude of atmospheric N inputs. Therefore the deposition rates presented by van Boxtel et al. (1991) will be preferred. However, the study of van Boxtel does not include the eventual contribution of organic N and its deposition rates should thus still be considered as minimum values. Cornell et al. (1995) reported two times higher DON than DIN concentrations in rain. This would mean that the wet deposition rates reported by van Boxtel et al. (1991) are still underestimated by a factor of 2. Taking this into account, TN deposition fluxes could be as high as 922–2340 kT year^{-1} (or 1631 ± 709 kT year^{-1}).

Biological N_2-fixation

To our knowledge, no biological N_2-fixation was ever measured in the North Sea and in general there is little information about the importance of biological N-fixation in eutrophic coastal areas. It is generally believed to be a minor source of TN in marine systems, although recent estimations obtained in warm, oligotrophic regions of the North Atlantic (Sargasso Sea, for example) suggest that this source can be very important (Lipshultz and Owens, 1996). For regions located north to latitude 50 °N (like the North Sea), these authors estimated that the N_2-fixation in the water column amounted to 0.012 mol N km^{-2} year^{-1}. However, recent measurements made in the Baltic Sea by Ohlendieck et al. (2000) using ^{15}N tracers yield summer rates of 0.3–3.9 nmol N_2 l^{-1} h^{-1}. Considering that these rates only occur in summer during cyanobacterial blooms (Rolff 2000) and assuming a photic layer of about 20 m (Rahm et al. 2000), this corresponds to an N_2-fixation of 88–1140 mol N km^{-2} year^{-1}. As the North Sea, unlike the Baltic, is not a system where N_2-fixing cyanobacterial blooms are common, these values are probably by far too high for the North Sea. We will thus refer to the value recommended by Lipshultz and Owens (1996), which multiplied by the North Sea area (698,000 km^2) gives an input of 125 kg N year^{-1}. It is clear that the uncertainty on this value is very large, but as N-fixation is several orders of magnitude lower than the other quantified TN inputs to the North Sea, this flux can be neglected.

Denitrification

Denitrification rates for the North Sea reported by various authors (see Table 5) are extremely variable (from 0.9 to 255 mmol m^{-2} year^{-1}) according to season, station and method used. According to Lohse et al. (1995), denitrification rates measured in the North Sea with the classical acetylene inhibition method may greatly underestimate the *in situ* rates. Indeed, acetylene is known to inhibit nitrification, reducing the nitrate availability to denitrifying organisms. Taking this information into account and only considering studies covering yearly cycles and large parts of the North Sea (Seitzinger and Giblin 1996; Smith et al. 1997; Hydes et al. 1999), reasonable estimates of denitrification rates in the North Sea vary between 130 and 255 mmol N m^{-2} year^{-1} with an average of 201 ± 64 mmol N m^{-2} year^{-1}. This means for the whole North Sea area a total loss of 2080 ± 662 kT N year^{-1}.

Table 5. Denitrification rate (DNIT rate in mmol m^{-2} $year^{-1}$) measurements made in North Sea sediments and reported in recent literature (after 1990). PP: primary production.

Author	DNIT rate	Area	Method and period
Lohse et al. (1993)	0.9–71.8	Southern North Sea	Acetylene block – August and February
Seitzinger and Giblin (1996)	219	North Sea	Extrapolation from PP values – Annual cycle
Kieskamp et al. (1991)	110	Wadden Sea	Acetylene block – Annual cycle
Law and Owens (1990)	3.5–109.5	North Sea	Acetylene block – July
van Raaphorst et al. (1992)	7–101.6	Southern North Sea	Acetylene block – Annual cycle
Lohse et al. (1995)	85.8–115.6	Central North Sea	Isotope pairing technique – July
Hydes et al. (1999)	255	Southern North Sea	Budget approach – Annual
Smith et al. (1997)	130	Southern North Sea	Budget approach – Annual
van Raaphorst et al. (1990)	55.2–85.8	Dogger Bank	Pore-water concentrations + model – Summer

Exchange at the sea–sediment interface

The sedimentation of refractory organic material to the bottom and its burial could represent a permanent storage of N and P. To our knowledge, values of this permanent storage in the sediments were never determined directly for the North Sea. The Quality Status Report 2000 (OSPARCOM 2000c) reports values of suspended matter deposition rates of 39,000–46,000 kT year^{-1} for the North Sea. This deposition occurs preferentially in some specific areas like the Oyster Ground, Norwegian Trench, Wadden Sea and German Bight. By considering that approximately 1% of this sediment correspond to organic C as determined in sediments accumulating in the Norwegian Trench by Van Weering et al. (1987), a C/N molar ratio of 10 (Nixon et al. 1996) and a C/P molar ratio of 250–500 (Nixon et al. 1996) we estimate a permanent N and P burial in the North Sea of 46–54 kT N year^{-1} and from 2 to 5 kT P year^{-1}. These values can be compared to data reported by Nixon et al. (1996) for coastal areas: 5–36 kT N year^{-1} and 2–19 kT P year^{-1}.

Discussion

Anthropogenic inputs versus natural inputs

Direct, estuarine and atmospheric inputs to the North Sea are strongly related to the anthropogenic activity in its watershed. In order to estimate the contribution of anthropogenic activity to the inputs in the North Sea area, we used background data summarised by Laane (1992). Background concentrations of TN and TP in rivers of the North Sea Basin are in the range 20–71 μM and 0.7–4.5 μM, respectively. These values reflect concentrations measured in rivers of the North Sea Basin before 1940 and are thus not real pristine situations (which are virtually impossible to asses in the North Sea Basin). Pristine conditions are probably closer to the lower values of the given range. Multiplying these concentrations with the annual river water discharges gives us the range of the background riverine TN and TP fluxes by rivers to the North Sea: 41–250 kT N year^{-1} and 3–35 kT P year^{-1}. This means that anthropogenic activities (i.e., intensive use of fertilisers, use of phosphates in washing powders, increasing demography) multiplied the riverine N input by a factor 3–20 and the P input by a factor 2–14 since the 1940's. This range is rather large, but Radach (1992) estimated that the TN and TP inputs by rivers to the North Sea between 1950 and 1980 increased by a factor 7 and 5 respectively, which fall well inside our range.

In the same way, Laane (1992) reported that the background atmospheric inputs of N to the North Sea were around 7.1 mmol N m^{-2} year^{-1}. Levy and Moxim (1989) report even lower values for remote locations of the world (0.2–1.9 mmol m^{-2} year^{-1}). These are average values reported for pristine areas in the world, as there are no 'ancient' data on atmospheric deposition in the North Sea. By multiplying these deposition rate by the North Sea area we find a background atmospheric deposition of N between 2 and 70 kT year^{-1} meaning that inputs increased by a factor 20–800 (!) due to increased anthropogenic N emissions to the

Table 6. Annual N and P budget in the North Sea. Fluxes and error on fluxes are described in text. Flux to the North Atlantic via the north east (NE) was calculated by budgeting. Negative values present output fluxes.

	Flux TN kT year^{-1}	Flux TP kT year^{-1}
NW (Atlantic)	6190 ± 3540	430 ± 250
E (Skagerrak)	-290 ± 180	-20 ± 10
S (Channel)	170 ± 360	10 ± 20
NE (Atlantic)	-6476 ± 5715	-464 ± 298
Estuaries	805 ± 237	42 ± 8
Direct inputs	70 ± 12	12 ± 1
N-fixation	125×10^{-6}	–
Atmospheric deposition	1631 ± 709	–
Denitrification	-2080 ± 662	–
Sediment burial	-20 ± 15	-10 ± 9
Net exchange with Atlantic	-116 ± 1815	-24 ± 28

atmosphere by human activity. This is much more than the factor 3 increase reported by Radach (1992) between 1950 and 1980 which is not surprising since we used here pristine deposition rates.

N and P budgets in the North Sea

By combining all determined fluxes it is possible to establish a nitrogen budget for the entire North Sea (Table 6) taking into account the variability on each of the fluxes as described previously. As already pointed out all of the defined fluxes were subject to a very large variability (between 20 and 200%) with maximum variabilities observed for marine (between 60 and 200%) and estuarine (30%) fluxes.

Total inputs of N and P to the North Sea are 8870 ± 4860 kT N year^{-1} and 494 ± 279 kT P year^{-1}. Major contributor for N are the waters flowing from the NW Atlantic ($70 \pm 40\%$) followed by atmospheric deposition ($18 \pm 8\%$) and estuaries ($9 \pm 3\%$). Direct sewage inputs ($1 \pm 0.1\%$) and waters flowing from the Channel ($2 \pm 4\%$) represent only a minor fraction of the total input. From these we can conclude that fluxes which are influenced by human activity (estuaries, atmosphere and sewage) represent $28 \pm 11\%$ of the total TN inputs.

For P the situation is a little different with major contributor being waters flowing from the NW Atlantic ($87 \pm 50\%$) followed by estuaries ($8 \pm 2\%$). Direct sewage inputs ($2 \pm 0.2\%$) and waters flowing from the Channel ($2 \pm 4\%$) represent only a minor fraction of the total input. In this case, fluxes under the influence of anthropogenic activities only represent $11 \pm 2\%$ of the total inputs. It is thus obvious, from these observations, that fluxes which are regulated by human activity are especially important for N but that the general nutrient dynamics in this system is dominated by the very dynamic marine circulation. In other words, changing the human-influenced nutrient inputs to the North Sea will have a significant impact on the global N-cycling

of the North Sea but only a very limited effect on the global P cycling. Note that this is only true considering the global scale and is not applicable to a regional scale.

Comparing N and P sinks (denitrification and sediment burial) to these input fluxes allows to estimate the importance of the North Sea shelf as a nutrient filter for the waters of the North Atlantic. Denitrification, for example, is responsible for the loss of $23 \pm 7\%$ of the TN inputs while sediment burial is responsible for the retention of only $0.2 \pm 0.1\%$ of the TN input and of $2 \pm 2\%$ of the TP input. More interesting is the comparison of these sinks to the N and P inputs linked to human activity (estuaries, atmosphere and sewage). In this case we can see that denitrification is able to eliminate $83 \pm 26\%$ of the human-influenced N inputs in the North Sea. It is clear that changing the magnitude of N inputs will most probably also change the impact of the denitrification process.

To respond to the question whether the North Sea is a net source or sink of nutrients for the adjacent marine waters, we calculated the net exchange of N and P between the North Sea and the North Atlantic Ocean and found a net export of $116 \pm 1815\,\mathrm{kT\,N\,year^{-1}}$ and $24 \pm 28\,\mathrm{kT\,P\,year^{-1}}$. The extremely high variability on fluxes (1560% for N and 120% for P) is linked to the fact that they result from the sum of variables with very large standard deviations.

For N we can conclude that the North Sea system is on the average a nearly balanced ecosystem with Atlantic N inputs balanced by an almost equal marine N output. However according to the extremely high variability on N (1560% !) exchange fluxes, the system could either be a net sink or a net source for N. These findings are very important as they allow to reconsider the work done by Radach and Lenhart (1995) and Hydes et al. (1999) who found opposite conclusions regarding the nitrogen. Radach and Lenhart (1995) in their extensive modelling of nutrient cycling in the North Sea found a net export of N to the North Atlantic of $710\,\mathrm{kT\,N\,year^{-1}}$. This value lays well in the range determined in this study. The values published by Hydes et al. (1999) suggesting a net sink of $1990\,\mathrm{kT\,N\,year^{-1}}$ for nitrogen from North Atlantic Ocean is very high compared to our range. However we have to relate this high value to the fact that Hydes et al. (1999) determined this net import for a North Sea shelf area of $1{,}095{,}734\,\mathrm{km^2}$ defined in Seitzinger and Giblin (1996), which is 1.6 times larger than the surface we considered ($698{,}000\,\mathrm{km^2}$). By introducing this surface correction factor to the value of Hydes et al. (1999) we find a value of $1{,}270\,\mathrm{kT\,N\,year^{-1}}$, which is close to the higher end of our estimated range.

For P, we can conclude that the North Sea system is a generally a net source of P for the North Atlantic Ocean. Net output fluxes of phosphorus from the North Sea reported by Radach and Lenhart (1995) ($59\,\mathrm{kT\,P\,year^{-1}}$) are also close to our estimated range.

Conclusion

From this study, the North Sea appears as an extremely complex system subject to large inter-annual variability of marine water circulation and freshwater land run-off.

Consequently, TN and TP fluxes resulting from marine circulation and from freshwater inputs are extremely variable from one year to another influencing strongly the budget of these elements. The values range from a net import of 1699 kT N year^{-1} to a net export of 1931 kT N year^{-1} to the North Atlantic Ocean. For P the variability is less important and the conclusion is that the North Sea generally exports P to adjacent marine areas in a range -4 to 52 kT P year^{-1}.

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