Nutrients (P, N, Si) in the Channel and the Dover Strait: seasonal and year-to-year variation and fluxes to the North Sea

Nutrients
Fluxes
North Sea
Channel
Trends

Nutriments
Flux
Mer du Nord
Manche
Tendances

Remi W.P.M. LAANE [a], Gerard GROENEVELD [a], Arie DE VRIES [a], Johan VAN BENNEKOM [b] and Sjoerd SYDOW [c]

[a] RIKZ/Tidal Waters Division, P.O. Box 20907, 2500 EX 's-Gravenhage, the Netherlands.

[b] Netherlands Institute for Sea Research, P.O. Box 59, 1790 AB Den Burg, the Netherlands.

[c] Rijkswaterstaat, North Sea Directorate, P.O. Box 5807, 2280 HV Rijswijk, the Netherlands.

ABSTRACT

Recent measurements (1986-1988) of the distribution of the concentration of different nutrients (nitrogen, phosphorus and silicate) in the Dover Strait have been used, combined with older results, to calculate the total flux (dissolved and particulate) of nutrients into the North Sea. Special efforts are made to take into account in the fluxes the tidal, geographical and temporal variations in the concentrations of the different nutrients. No vertical gradients in the concentration of the different nutrients were found. Increased nutrient concentration was found in the coastal zones of England and France, compared to the Atlantic water in the central part of the Dover Strait.The variation within a single year and between different years in the data available (1930-1988) for the different nutrients was rather large and no clear annual trends could be distinguished. Average yearly fluxes are, for ammonium, nitrate, nitrite and total nitrogen respectively: 156 ± 29, 364 ± 68, 26 ± 6 and 1411 ± 209 ktonnes N; for ortho-phosphate and total phosphorus, 79 ± 13 and 192 ± 32 ktonnes P per year and for dissolved silicate 492 ± 80 ktonnes Si per year. These fluxes are higher than those published before, because in this study the particulate fraction and the dissolved organic fraction of the nutrients (except Si) are also taken into account.

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RÉSUMÉ

Nutriments (P, N, Si) dans la Manche et le Pas-de-Calais : variations saisonnières et inter-annuelles et flux à la Mer du Nord

Des mesures récentes (1986-1988) de la répartition des teneurs en divers nutriments (azote, phosphore et silicium) dans le Pas de Calais ont été utilisées, combinées avec des résultats antérieurs, pour évaluer le flux total (dissous et particulaire) de nutriments dans la Mer du Nord. Les flux prennent particulièrement en compte les variations qui relèvent de la marée et les variations géographiques et temporelles des teneurs des différents nutriments. Aucun gradient vertical des concentrations des différents nutriments n'a été trouvé. Une augmentation dans la teneur en nutriments a été observée en zones côtières anglaises et françaises comparativement à l'eau atlantique dans la partie centrale du Pas de Calais. Les données disponibles (1930-1988) pour les différents nutriments présentent des variations annuelles et inter-annuelles assez grandes, et aucune tendance annuelle ne peut être mise en évidence. Les flux moyens annuels sont respectivement de: 156 ± 29, 364 ± 68, 26 ± 6 et 1411 ± 209 kT d'azote pour l'ammonium, les nitrates, les nitrites et l'azote total, 79 ± 13 et 192 ± 32 kT de phosphore par an pour les ortho-phosphates et le phosphore, 492 ± 80 kT de silicium par an pour les silicates dissous. Ces flux sont plus élevés que ceux publiés précédemment parce que, dans cette étude, la fraction particulaire et la fraction organique dissoute des nutriments (excepté pour Si) ont été prises en compte.

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INTRODUCTION

During the last thirty years the concentrations of nutrients containing nitrogen and phosphorus have increased in nearly all rivers that discharge into the North Sea (Anonymous, 1987). In the North Sea itself, especially in restricted areas such as coastal zones, the German Bight and the Wadden Sea, the anthropogenic contribution to the various nutrient loads has increased considerably (de Jonge and Postma, 1974; Gerlach, 1984; Anonymous, 1985). The coastal ecosystem of the North Sea has been affected by this eutrophication (van Bennekom *et al.*, 1975; Nelissen and Stefels, 1988). Long-term measurements (1968-1985) in the western part of the Dutch Wadden Sea indicate that both algal biomass and primary production roughly doubled during this period (Cadée, 1984 and 1986; Cadée and Hegeman, 1986).

At station Helgoland Reede the phytoplankton biomass almost tripled in the period between 1962 and 1984 (Radach and Berg, 1986). This was mainly because of a ten- to fifteenfold increase in the biomass of flagellates, whereas the biomass of diatoms decreased slightly. A gradual change in phytoplankton species composition and seasonal succession in the North Sea during the last thirty years has also been confirmed by the results from the Continuous Plankton Recorder (Gieskes and Kraay, 1977; Reid, 1977 *a* and *b*).

The increase in algal biomass and production (Cadée, 1984 and 1986; Cadée and Hegeman, 1986) and an increase in the biomass and production of macrobenthos were observed simultaneously in the western part of the Wadden Sea during the years 1979-1984 (Beukema and Cadée, 1986 and 1987). The hypothesis of a causal relation with eutrophication ("the more algae, the more food"), is plausible but has not yet been proven.

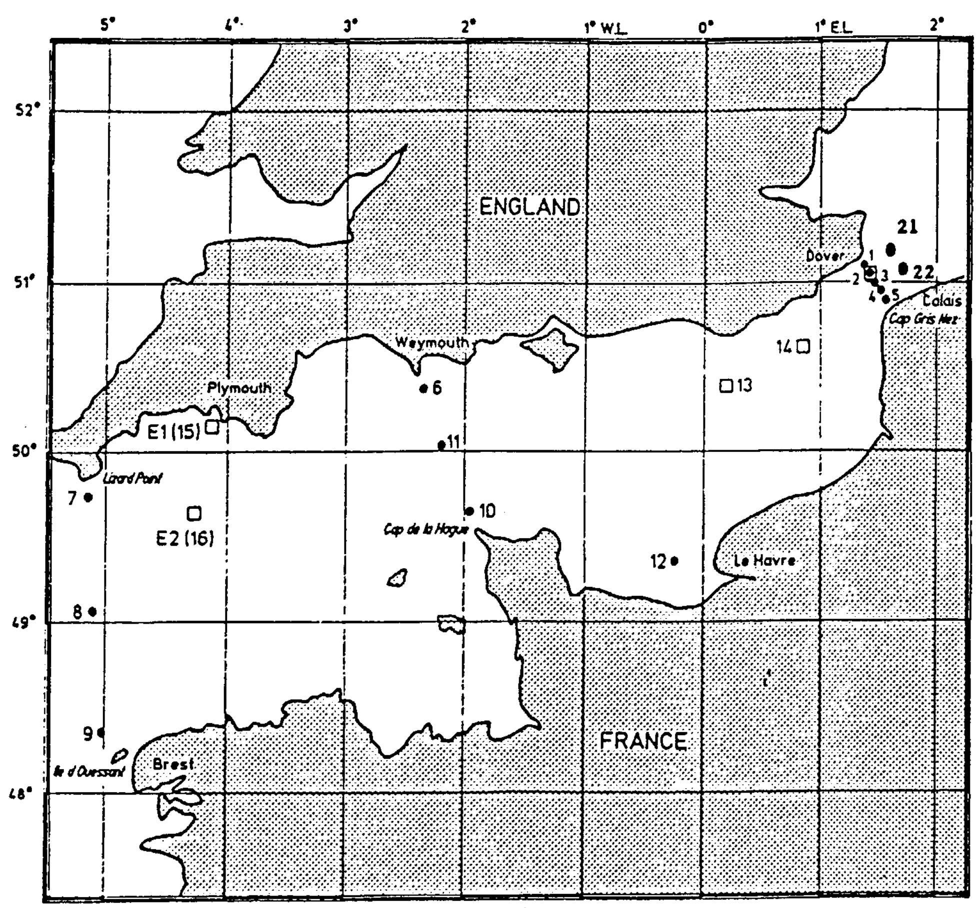


Figure 1

Map of the Channel and the Dover Strait showing the different sampling locations ●: 1-12 visited during 1987-1988. ❑: stations from literature Cooper (1933) and Butler (1979) and from Laane (unpublished 2, 13, 14). Stations 21 and 22 NERC program (Hydes and Edmunds, 1989).

Rachor (1980; 1985) also related the decrease in macrobenthic biomass in a silty area and the increase in biomass in a more sandy area in the German Bight during the years 1969 and 1983 to eutrophication. The observed decrease in macrobenthic biomass is a result of low oxygen concentrations near the bottom in the German Bight, caused by a surplus of imported and locally produced decaying organic matter and the temporary occurrence of stratified conditions (Gerlach, 1984). In addition, extreme algal blooms may damage mussels and other aquacultures.

These effects of eutrophication on the coastal ecosystem have provoked political action. In the Rhine Action Plan (RAP), the ministers of various countries agreed to strive to reduce the concentrations of certain substances in the Rhine (such as compounds of phosphorus and nitrogen) by 50 % before 1995. During the second North Sea Ministerial Conference in London in 1987, international agreement was also reached on a reduction (in the order of 50 %) of the nutrient flux to areas where eutrophication is a major problem (Laane *et al.*, 1989).

The North Sea receives an enormous amount of nutrients and metals from different sources *e.g.* the rivers, the atmosphere and the Atlantic Ocean. Atlantic waters enter the North Sea in the North and through the Dover Strait in the South. Although the concentrations in the Atlantic water are relatively low, the amount of water is enormous compared to the river output. The nutrients in the incoming Atlantic water determine in the first place the background concentration in the North Sea (Fig. 1).

Estimations of the input of nutrients from the Channel into the North Sea have been made by several scientists. Postma (1973) found $240*10^3$ tonnes N and $40*10^3$ tonnes P entering yearly the North Sea in the south. Anonymous (1985) calculated that $975*10^3$ tonnes N and $120*10^3$ tonnes P per year enters the North Sea through the Dover Strait. Brockmann *et al.* (1988) calculated an annual input through the Dover Strait of $705*10^3$ tonnes N, $82*10^3$ tonnes P and $371*10^3$ tonnes Si.

These amounts are difficult to compare with each other because the range is enormous: for nitrogen $240\text{-}975*10^3$ tonnes and for phosphorus $40\text{-}120*10^3$ tonnes per year. This is mainly due to the fact that these calculations are based on a few data and that it is often unclear in the papers which part of the nutrients is taken into account; mostly only the dissolved inorganic nutrient flux is calculated.

Nutrients in water are present in dissolved and particulate (adsorbed to and incorporated into suspended matter) and in organic (biomolecules like proteins) and inorganic form (*e.g.* ammonium, phosphate). Nitrogen, for instance, occurs as organic N in solution and in suspension and as ammonium (NH_4^+), nitrite (NO_2^-) and nitrate (NO_3^-). Phosphorus (P) is present in sea water as dissolved inorganic phosphate (PO_4^{3-}), dissolved organic phosphate compounds, particulate organic phosphate and adsorbed inorganic phosphate on particles. Silicon occurs in the sea in dissolved form and in suspension.

In this paper the total flux of nutrients (dissolved and particulate together) is calculated from recent measurements (1986-1988) in the Channel (mainly in the cross-section Dover-Calais), taking into account the tidal, vertical and horizontal variations during different seasons. Special attention is given to the contribution of the dissolved organic and particulate nitrogen and phosphorus to the total flux of nitrogen and phosphorus.

MATERIALS AND METHODS

Six surveys were carried out in the Channel (mainly in the cross-section Dover-Calais) during the years 1986-1988: November 1986, stations 1-5; April 1987, stations 1-12; November-December 1987, stations 1-5; February 1988, stations 1-5; August 1988, stations 1-5, 11, 12; November-December 1988, stations 1-5, 11, 12 (Fig. 1).

The water samples have been analyzed on the following parameters: total nitrogen (unfiltered) and dissolved nitrogen (filtered) and ammonium, nitrate and nitrite; total phosphorus (unfiltered) and dissolved phosphorus (filtered) and ortho-phosphate); and dissolved silicate. Particulate nitrogen and phosphorus were calculated by subtracting the unfiltered concentration from the concentration in the filtrate. Dissolved organic nitrogen and phosphorus comprises the difference between dissolved nitrogen and phosphorus and the different inorganic nitrogen and phosphate respectively.

At all sampling locations water samples were collected at the surface, half-depth and 1 m above the bottom by means of a Rosette sampler (Go-flow bottles). Temperature, conductivity and depth were continuously registrated over the vertical by means of a CTD-sensor coupled to the Rosette-sampler.

As an indication, the different sampling-depths are given for stations 1-5 (Fig. 2). To obtain an insight into tidal variations of the different compounds along this transect also 13-hour tidal measurements were carried out at locations 1, 3 and 5. The water samples were immediately filtered (0.45 μm) and cooled (4°C) on board. Further analyses were performed on shore according to standard procedures (Strickland and Parsons, 1968; Fig. 2).

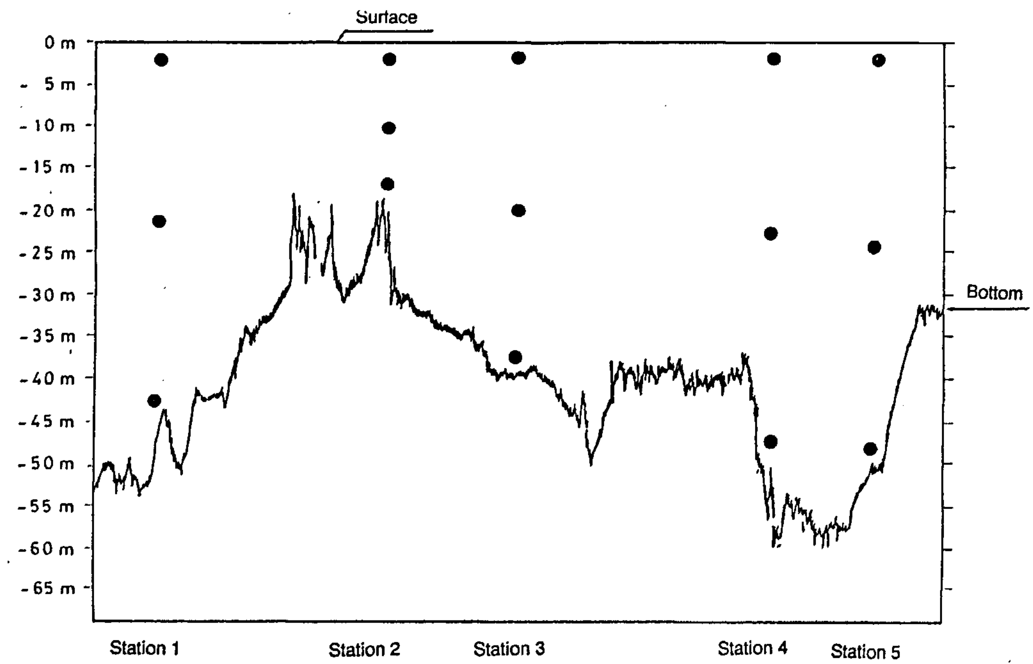
SUPPLEMENTARY DATA FROM LITERATURE AND OTHER MEASUREMENTS

Data from 1986-1988 were mainly collected in winter periods. In this period nutrients can be regarded as "conservative", meaning that their production and consumption is minimal (Laane *et al.*, 1989; Zevenboom *et al.*, 1987 *a* and *b*). To obtain an insight into the seasonal and year-to-year variations, published and unpublished data in different periods of one year and different years have been collected. Atkins (1924), Cooper (1933) and Kalle (1937) summarized the horizontal and vertical distribution and seasonal variation of different nutrients in the English Channel.

Johnston and Jones (1965) collected and summarized data concerning inorganic nutrients (N and P) in the North Sea in the early 1950s (1953) and early 1960s (1961-1962).

Figure 2

Depth-profile echo-sounder and sampling locations (●) in the Channel.



The nutrient concentrations reported by Johnston and Jones (1965) are long-term averages and are presented in the form of contour maps for two-month periods. For the relevant locations (transect Dover-Calais and E_1 = location 15, Fig. 1) their data were interpreted and used for trend studies (period 1951-1962). Armstrong *et al.* (1974) presented nutrient data collected during different surveys in the western English Channel during 1965 and 1966 in contour maps for a number of months. These data were collected in the area between Ile d'Ouessant and Lizard Point, and are thus representative for locations 7, 8 and 9 (*see* also Armstrong and Butler, 1962 *a* and *b*; 1970). Butler (1979) gives monthly means of dissolved inorganic nutrient concentrations obtained during the period 1968-1974 in the western English Channel, especially in 1974 for station E_1 (location 15, Fig. 1).

Data of dissolved and particulate nutrients (organic and inorganic) collected in the Dover Strait in February and July 1987 have been used to calculate roughly the contribution of organic nitrogen and phosphorus to total nitrogen and phosphorus (Butler *et al.*, 1979; Laane, unpublished). Finally dissolved inorganic nutrient data in the English Channel collected by the MAFF laboratory at Lowestoft (obtained through courtesy of Dr. R.R. Dickson; to be called MAFF (Fig. 3) data of the period 1960-1977) and NIOZ data (van Bennekom and Wetsteijn, 1990) were used. Results of this compilation were checked with the data published recently by Hydes and Edmunds (1989) and Kremling and Pohl (1989).

RESULTS AND DISCUSSION

Tidal variation

During winter, when biological activity in the North Sea is at a minimum, an inverse linear relation between the nutrient concentrations and salinity exists (van Bennekom and Wetsteijn, 1990). This indicates that the nutrient concentrations in the rivers are highest and that they decrease because of dilution with seawater. If salinity varies under the influence of the tidal movement the nutrient concentrations also do so in winter.

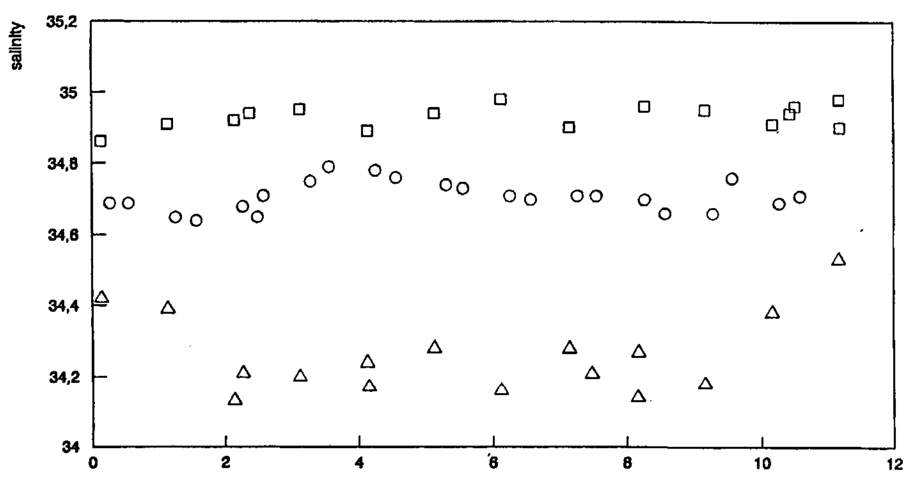


Figure 3

Variation in salinity over a tidal cycle for three stations in the Dover Strait: station 1 (□: English coastal zone) and station 5 (Δ: French coastal zone): 26-28 November 1986; station 3 (○ : central part of the Dover Strait):27-30 April 1987.

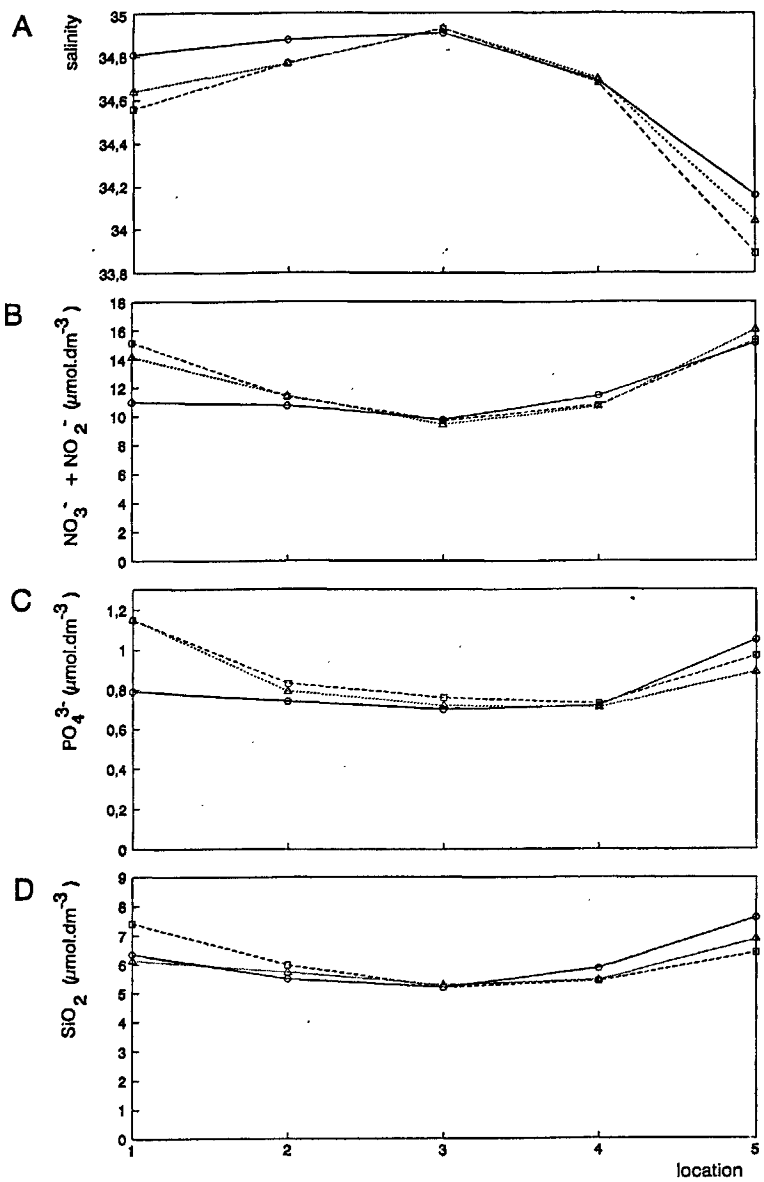


Figure 4

Horizontal and vertical distribution of salinity (A), nitrate and nitrite (B), orthophosphate (C) and silicate (D) at three different depths (○: surface, □: 1/2 depth and △: bottom) averaged at five different locations in the Dover Strait (1: English and French coasts) averaged for the years 1986-1988 (December-February).

Figure 3 shows the results of the variation of salinity during a tidal cycle at three stations (1-Dover, 3-centre, 5-Calais; Fig. 1). In the central part the salinity variations vary from 34.7 to 34.8. This is within the range given by van Bennekom and Wetsteijn (1990): 35.0 ± 0.3. The largest salinity variation (*ca.* 0.4) is found along the French coast (location 5, Fig. 1).

The thirteen-hour measurements at locations 1 and 5 were carried out in the same period (November 1986). However, measurements at location 3 were carried out in April 1987. This probably explains why the salinity at location 3 is lower than at location 1 (Fig. 3).

The variation in salinity during a tidal cycle is small, therefore concentrations of the different nutrients are not normalized for salinity(Fig. 4).

Horizontal and vertical variation

Almost no vertical changes in salinity and nutrient concentration were found at the different stations in the Dover Strait during each of the cruises. This in agreement with the results of Cooper (1933) who also found no significant variations in nutrients in the period 1930-1932.

As an example, the horizontal and vertical distribution of the average of all winter data (1986-1988) of salinity (A), nitrate (B), ortho-phosphate (C) and silicate (D) at three different depths in the Dover Strait are given in Figures 4 A-D. The horizontal distribution for the different nutrient compounds is inverse to the salinity distribution. For all compounds, higher concentrations are found near the English (station 1) and French coast (station 5) compared to the central part (station 3). This is in agreement with the observations of van Bennekom and Wetsteijn (1990) who found higher concentrations, especially for nitrate, along the French and English coasts. The vertical variation is highest at the coastal stations.

Because the horizontal variation of the different compounds over the Dover Strait is large compared to the vertical variation, the latter is not taken into account in the budget calculation. For budget studies it is necessary to take into account the horizontal differences in the concentrations of the different compounds. Therefore the Dover Strait is divided into four sections: section 1 = station 1; section 2 = station 2; section 3 = station 3 and 4; section 4 = station 5 (*see* Fig. 1).

Seasonal variations

To establish a seasonal variation in the concentration of the different nutrients the results of the period 1986-1988 are not sufficient because these six cruises were mainly carried out in the winter period.

Published and unpublished nutrient data were combined with data from the different cruises to describe the seasonal variation of the different nutrients in the Dover Strait. It was not possible to describe the seasonal (Fig. 5) variation at a certain salinity, because often no salinity data were published in the different papers. However for all nutrients a clear seasonal variation is found (Fig. 5 A-C).

For all nutrients highest concentrations were found during the winter and lowest in summer (Fig. 5 A-C). Nitrate is presented as an example of the nitrogenous nutrients (Fig. 5A), because nitrate was the most abundant dissolved inorganic nitrogen compound. This was also found by Cooper (1933) in the English Channel in the early 1930s.

The seasonal variation of nitrate combined out of the data from 1960-1988 (Fig. 5A) is remarkably similar to that in the 1930s by Cooper (1933).

Recently, Kremling and Pohl (1989) published nutrient concentrations in the Dover Strait in March (7 µmol.dm^{-3}

nitrate and 0.5 μmol.dm^{-3} phosphate) and June 1987 (concentrations below detection limit). This is in fairly good agreement with the interpolated values in Figures 5 A and B for nitrate and phosphate.

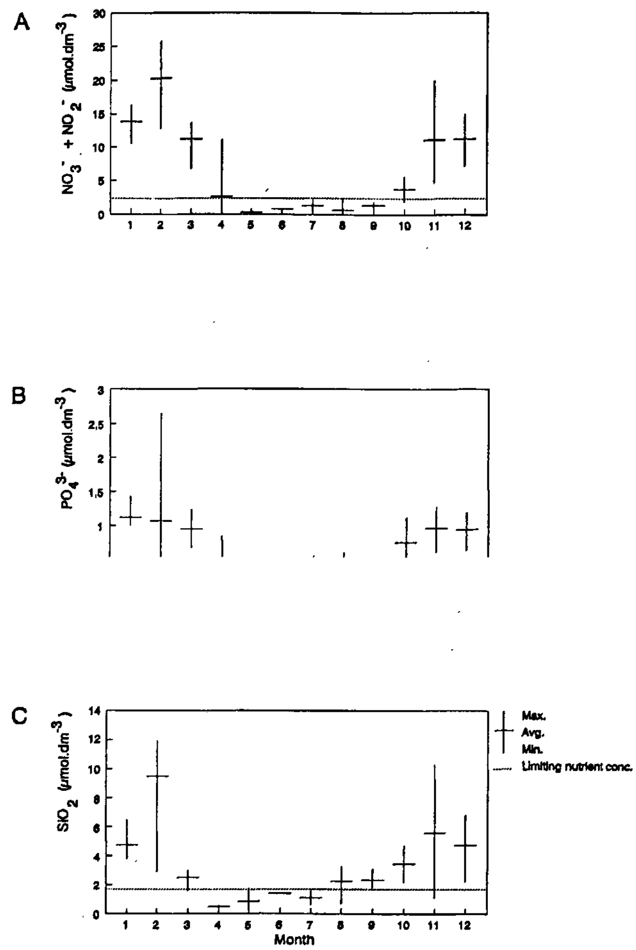


Figure 5

Seasonal variation of nitrate and nitrite (A), orthophosphate (B) and silicate (C) of all stations in the Channel and in the Dover Strait (data from literature and this study).

In Figures 5 A-C the ranges in which the nutrients are potentially limiting phytoplankton growth, are indicated by a dotted line (Peeters and Peperzak, 1990). Silicate and ortho-phosphate are potentially limiting in April whereas nitrate is limiting one month later in the coastal sections as well as in the central sections (Fig. 5).

Figures 6 A and B show the seasonal variation in the measured concentration of total nitrogen and phosphates in 1987 and 1988. It appears that the average winter concentrations of total nitrogen and phosphorus are higher than the summer values. This is not in agreement with the conclusion in some papers (*e. g.* Cooper, 1933; Armstrong *et al.*, 1974) in which it is suggested that the total concentration of phosphorus and nitrogen is constant over the year. During the summer dissolved inorganic nutrients were supposed to be transferred to particulate organic matter. Probably due to increased wave action and associated resuspension of bottom material, the concentrations of particulate nitrogen and phosphorus increase during winter. These results are taken into account in the budget calculations (*see* Tab. 1; Fig. 6).

LONG-TERM VARIATIONS

It is known that during the winter months nutrient concentrations are highest and virtually no chemical and biological processes occur to alter the concentration. Changes in the concentration are in that period mainly due to mixing processes (Laane *et al.*, 1989). In summer, however, the nutrient concentrations are difficult to predict. They are highly variable, because the concentration is changed by the primary production and mineralization of organic matter. So, only the winter values have been used for trend analyses.

Long-term variations (1930-1988) for the average winter concentrations, from November to February, of nitrate +

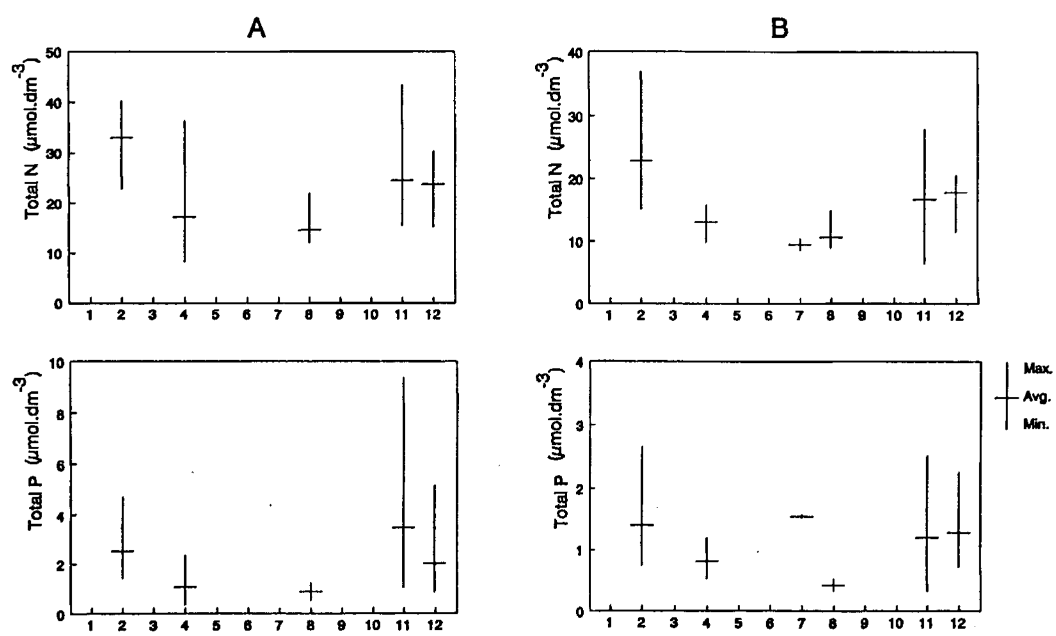


Figure 6

Seasonal variation in the concentration of total nitrogen and phosphorus in the coastal zones (locations 1, 5, 6, 7, 9, 10, 12, 15, 22; A) and in the central part (locations 2, 3, 4, 8, 11, 13, 14, 16, 21; B) in the Dover Strait in 1987-1988.

Table 1

Averaged monthly water flow (10^3 $m^3.s^{-1}$*) and monthly fluxes with their standard deviations for different nutrients (*10^3 tonnes per year) through the Dover Strait into the North Sea. * Data taken from Prandle (1978; 1984).*

	Flow *	NH_4-N	NO_2-N	NO_3-N	N-tot	PO_4-P	P-tot	SiO_2
Jan	181 ±70	20 ±8	3 ±2	67 ±30	237 ±92	12 ±5	31 ±12	95 ±40
Feb	142 ±65	13 ±15	1 ±1	71 ±36	190 ±93	8 ±5	17 ±10	50 ±36
Mar	134 ±49	10 ±4	1 ±.4	37 ±14	131 ±51	5 ±2	12 ±4	31 ±15
Apr	114 ±49	6 ±4	.8±.4	6 ± 4	61 ±33	2 ±1	7 ±5	13 ± 6
May	124 ±55	4 ±2	.6±.3	3 ±10	38 ±17	2 ±1	9 ±4	10 ± 5
Jun	135 ±33	4 ±1	.4±.1	3 ±.6	37 ± 9	4 ±1	13 ±3	8 ± 2
Jul	153 ±58	6 ±2	.5±.2	3 ± 1	60 ±23	6 ±2	17 ±7	13 ± 8
Aug	162 ±44	13 ±6	.6±.2	1 ±2	76 ±25	2 ±1	6 ±2	24 ± 9
Sep	168 ±55	21 ±7	1 ±.4	12 ±4	95 ±31	4 ±1	12 ±4	38 ±12
Oct	164 ±62	12 ±8	3 ±1	34 ±13	120 ±45	8 ±3	18 ±7	49 ±19
Nov	182±106	20 ±14	5 ±4	58 ±35	164±107	12 ±7	25 ±20	63 ±40
Dec	205 ±70	18 ±12	8 ±4	70 ±26	197 ±82	15 ±6	25 ±14	77 ±31
Averaged monthly flow	155 ±21							
Yearly flux		156 ±29	26 ±6	364 ±68	1411 ±209	79 ±13	192 ±32	492 ±80

nitrite (A), ortho-phosphate (B) and silicate (C) in the coastal zones and in the central part of the Dover Strait and of the Channel are presented in Figures 7 A-C and 8 A-C, respectively.

A distinction between the coastal and central zone is made because the concentrations of the different nutrients in the coastal zone are increased (*see* Fig. 4). Eutrophication and trend analysis on the existing nutrient data of the coastal zone of France, Belgium, the Netherlands, Germany and England have been described by Weichart (1986), Dickson *et al.* (1988), Baeteman and Vincke (1989), van Bennekom and Wetsteijn (1990), Joanny *et al.* (1990), Mommaerts (1990 *a* and *b*) and van der Meijden (1992). The general conclusion in all these papers is that no obvious trend has been discernible in the coastal waters of the Channel and the North Sea in the last ten to twenty years. After an impressive increase of, for instance, ortho-phosphate in the Dutch coastal zone and the German Bight between 1930 and 1970 (Weichart, 1986; van der Meijden, 1992) the concentration in the seventies and eighties stabilizes. A decreasing concentration of ortho-phosphate in the Dutch coastal zone has been recently found by van der Meijden (1992), mainly due to the decreasing concentration in the river Rhine.It seems that the concentration of nitrate and nitrite and ortho-phosphate have indeed increased in the coastal zone and to a lesser extent in the central part of the Channel and Dover Strait between the years 1930-1990 (Fig. 7 A-B, 8 A-B). However, it must be kept in mind in the interpretation of possible trends in the data of Figures 7 and 8, that data from the Channel [most data are before 1975 (Fig. 7)] have been mixed with data from the Dover Strait (most of the data after 1975). Also, that the data are not corrected for salinity; the salinity in the Channel is higher then in the Dover Strait. An increase of inorganic nutrients in the northern part of the southern Bight during the year 1961 to 1978 was found by van Bennekom and Wetsteijn (1990) which could be related to the increase in nutrients in the Rhine.

In the Dover Strait also an increase in the concentration of nutrients was observed during 1961-1978, probably caused by the increase in nutrients in the river Seine (van Bennekom and Wetsteijn, 1990).

However all correlation lines between nutrients and salinity converge to the average nutrient concentration for inflowing Atlantic water given by Pingree *et al.* (1977).

So, the increase in the coastal zone of the Channel and of the Dover Strait for nitrate and nitrite and ortho-phosphate (Fig. 7 A-B) and to a lesser extent in the central part of the Dover Strait (Fig. 8 A-B) is mainly due to the increase in the concentrations in the fresh water end members. This is in agreement with van Bennekom and Wetsteijn (1990) who also concluded that the increase in concentration was not caused by the incoming Atlantic water but by river water. Background values of the nutrients in the Atlantic water entering the North Sea *via* the Channel, are the average winter values in the English Channel in the 1930s for nitrate, ammonium, ortho-phosphate and silicate 5-6, 2.0, 0.43-0.56, and 2.5-7 $\mu mol.dm^{-3}$ respectively at a salinity of 35.21 (Cooper, 1933; Laane, 1992).

The increase in the extrapolated concentrations of nutrients in the fresh water end members between 1930 and 1990 have been clearly demonstrated by different authors (Laane *et al.*, 1989 and cited references). However, Laane *et al.* (1989) also showed that the changes in the nutrient concentrations in the coastal zone are hard to establish from the existing monitoring data (Fig. 8). In the French rivers a year-to-year variation has recently been described (Joanny *et al.*, 1990).

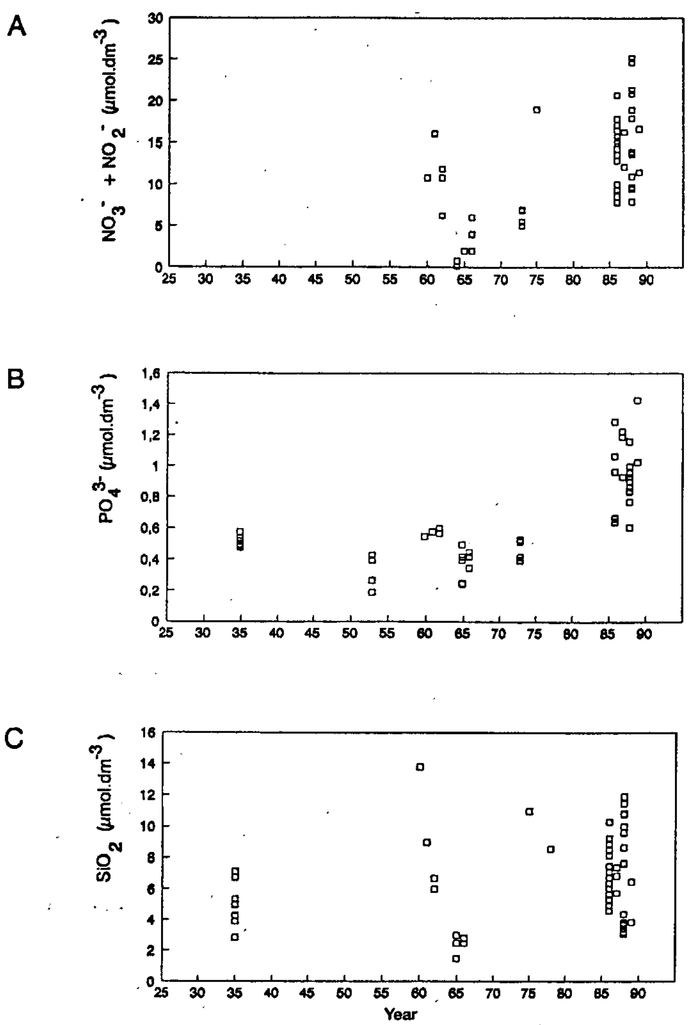


Figure 7

Long-term variation in the concentration of nitrate and nitrite (A), phosphate (B) and silicate (C) during winter for different years in the coastal zone of the Dover Strait and in the Channel (locations: 1, 5, 6, 7, 9, 10, 12, 15 (E1), 22; see Figure 1, data from the literature and this paper).

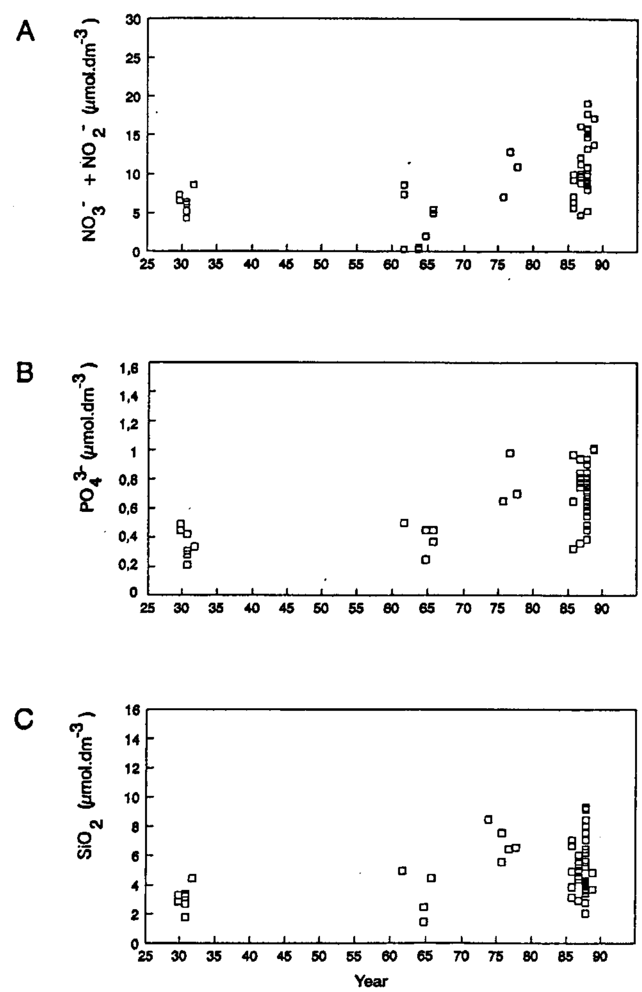


Figure 8

Long-term variation in the concentration of nitrate and nitrite (A), phosphate (B) and silicate (C) during winter for different years in the central-part of the Dover Strait and in the Channel (locations: 2, 3, 4, 8, 11, 13, 14, 16, 21; see Figure 1, data from the literature and this paper).

In general, it seems that the concentrations of nitrate + nitrite, ortho-phosphate and silicate are, in the coastal zones of the Channel and of the Dover Strait, higher in winter 1988 compared to the average values in 1932-1973. Silicate shows the smallest increase. How much higher is impossible to answer, because a lack of data, the use of "old" data and the absence of salinity corrections. For the central part it is not valid to draw this conclusion, because insufficient data are available.

Average winter concentrations are in the period 1986-1988 in the English coastal zone for nitrate, ammonium, ortho-phosphate and silicate 18, 2.2, 1.1 and 8.8 µmol.dm^{-3} at a average salinity of 34.77 (33.97-35.26). The values are higher than those in the incoming Atlantic water as published by Cooper (1933, *see* above) and Pingree *et al.* (1977).

The upward trend in the central part of the Channel and in Dover Strait indicates that the increased anthropogenic influence in the English and French coastal zones (Fig. 7 A-C) increases also the concentrations of nitrate and ortho-phosphate in the central part of the Channel and in the Dover Strait (Fig. 8 A-C). So probably due to the influence of local low salinity waters (van Bennekom and Wetsteijn, 1990), the concentration of nitrate and phosphate in the English coastal zone of the Channel and in the Dover Strait has increased. For the French coast no "old" data were available.

FLUX OF NUTRIENTS

Postma (1990) recently discussed the variability in the water fluxes through the Dover Strait. Prandle (1978; 1984) has made an estimate of the mean value of residual flow through the Dover Strait for each month over the period from 1949 to 1980. The estimates are based on results from a modelling investigation where it was shown that the residual flow consists of three components, a tidal, a wind-driven residual and a flow due to a long term gradient in mean sea level. The first and last components are assumed to be constant and the value of the wind-driven part is deduced using wind-data recorded by Dutch lightvessels located in the southern North Sea. According to Prandle the mean Channel flow over the whole period (1949-1980) amounts to $155*10^3$ m^3.s^{-1} $21*10^3$ m^3.s^{-1} into the North Sea. The average monthly residual water flow through the

Table 2

Inputs of nutrients from different sources to the North Sea (10^3 tonnes per annum) (Quality Status Report of the North Sea, 1987; **, van Bennekom* et al., *1975; ***, Laane, unpublished results; ****, only dissolved ortho-phosphate, Laane, unpublished results).*

Sources	Phosphorus	Nitrogen	Silicate
Rivers	76*	1000*	450**
Atmosphere	5*	5*	-
Channel	192	1411	492
Atlantic	1044****	4059***	5389***

Dover Strait, together with the standard deviation, as described by Prandle (1978; 1984) are used to calculate the monthly flux of the different nutrients through the Dover Strait into the North Sea.

Strong horizontal gradients in the dissolved and particulate nutrient concentrations are found in the Dover Strait (*e. g.* for the dissolved compounds in Fig. 4): relatively high concentrations in the English and French coast compared to the middle part of the Channel and the Dover Strait. To take this variation into account for the flux calculations, it is necessary to estimate the water flux through different sections (coastal- and central sections).

van Alphen (1989) assumed that the contribution of the volume of the coastal sections is small (20 %) compared to the central section of the Dover Strait (80 %). The fluxes are calculated using the relation: flux = concentration x residual water flow. Monthly average fluxes of the different nutrients have been estimated by taking the average concentration for each month (Fig. 5 A-C). These averaged interpolated concentrations are multiplied with the residual water flow for that month (Tab. 1).

The standard deviations in the fluxes in Table 1 are based on the standard deviations in the monthly residual water flows according to Prandle (1978; 1984) and the standard deviations in the concentrations of the different nutrients. The variance of the product of the residual flow and the concentration is calculated by first order approximation as follows (van Alphen, 1989): variance flux = (residual flow)^2 * variance (conc.) + conc.^{2} * variance (residual flow).

From this the standard deviation for the different nutrients is calculated as the square root of the variance flux. The standard deviation of the yearly averaged flux is derived from the square root of the sum of the monthly variances of the different fluxes (Tab. 1).

The total fluxes of total nitrogen, total phosphorus and silicate are higher than the values published (Postma, 1973; Anonymous, 1985; Brockmann *et al.*, 1988) because in Table 1 the fluxes of particulate and dissolved organic nutrients are, except for silicate, also taken into account.

The Dover Strait is one of the nutrient sources of the North Sea. Other sources are the rivers, atmospheric deposition and the Atlantic water entering in the north. Comparison of inputs from these major sources are shown in Table 2.

The fluxes of nitrate, ortho-phosphate, silicate and total nitrogen from the Atlantic Ocean entering the North Sea in the north are high compared the other sources. The input of silicate through the Dover Strait is comparable with the amount entering the North Sea by the rivers. However although the concentrations are much lower in the Dover Strait compared to the rivers, the fluxes of nitrogen and phosphorus through the Dover Strait are larger than those from the rivers.

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