The hydrochemical and biological impact of the river Vistula on the pelagic system of the Gulf of Gdańsk in 1994. Part 1. Variability in nutrient concentrations*

OCEANOLOGIA, No. 37 (2)
pp. 181–205, 1995.
PL ISSN 0078–3234

Baltic Sea
Nutrients
Vistula impact
Seasonal/spatial variability

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Manuscript received April 18, 1995, in final form July 11, 1995.

Abstract

The paper discusses the physical and biological factors as well as the water/nutrient discharges by the river Vistula affecting nutrient distribution in the Gulf of Gdańsk in 1994. Seasonal and spatial variability in nutrient distribution is discussed with reference to the biological cycle in the coastal marine ecosystem and with respect to seasonal variability in water/nutrient discharges by the river. The greatest discharge of nutrients, with extremely high concentrations of nitrates, was recorded in April 1994. Powerful water dynamics, mainly wind-induced, are depicted as a factor responsible for the transport/transformation of riverine water. Separate mini-ecosystems, characterised by distinguishable chemical, physical and biological parameters, were found. High concentrations of ammonia in July may have been related to its regeneration by abundant zooplankton. Low silicate concentrations in November may have resulted from a diatom bloom.

* The study was supported financially by: grant No. 6P20504304 from the State Committee for Scientific Research, Republic of Poland; funds from the State Committee for Scientific Research, Republic of Poland for the statutory activity of the Institute, and within that for studies of 'The impact of eutrophication on trophic relations in different coastal areas of the south-eastern Baltic'; European Community grant No. CIPA CT–903–0146.

1. Introduction

Eutrophication in the Baltic Sea, in its coastal zones in particular, and also the observed effects of this process, have been tackled by numerous scientists (Baden *et al.*, 1990; Cederwall and Elmgren, 1990; Granéli *et al.*, 1990; Hansson and Rudstam, 1990; Rosenberg *et al.*, 1986, 1990; Trzosińska, 1990).

Of the seven subregions of the Baltic Sea (Ehlin, 1981), the Baltic Proper is the largest one with respect to its own area and its drainage area. The latter is 568 973 km^2 and of this as much as 311 900 km^2 belongs to Poland (HELCOM, 1993). The Vistula (Wisła) is the largest Polish river as regards discharges of water, nutrients, suspended and dissolved organic matter into the Baltic (Majewski, 1990; Niemirycz, 1994a; Niemirycz and Borkowski, 1993, 1995; Niemirycz and Makowski, 1992; Niemirycz and Markiewicz, 1993; Niemirycz and Żebrowska, 1992; Niemirycz *et al.*, 1991, 1994, 1995; Rybiński and Makowski, 1991; Rybiński and Niemirycz, 1991; Rybiński *et al.*, 1990).

The surface layer of the sea is supplied with nitrogen and phosphorus compounds originating from mineralisation, regeneration, gaseous-nitrogen fixation, as well as deposition from the atmosphere and the land. Terrestrial nutrient discharges are an important cause of eutrophication in the coastal zones of the Baltic Sea. It is estimated that approximately 60% of nitrogen and 90% of phosphorus is derived directly from land areas, including point sources (Cederwall and Elmgren, 1990). Therefore, it is hardly surprising that nutrient concentrations are much higher in the coastal zones than in the open sea (Bolałek *et al.*, 1993; Falkowska *et al.*, 1993; Nowacki, 1994; Pastuszak, 1985; Pastuszak *et al.*, in preparation). The degradation of the marine environment, resulting from excessive loads of nitrogen and phosphorus, is reflected in intensive algal blooms, higher concentrations of chlorophyll *a*, increased primary production and decreased water transparency, increased sedimentation of organic matter to the bottom, a greater frequency and severity of oxygen deficiency in bottom waters and, in consequence, the formation of areas with hydrogen sulphide; this last has a negative effect on the bottom fauna.

It is estimated that primary production has doubled and chlorophyll *a* concentrations have increased by 50% in the Baltic Proper since the 1970s (Renk *et al.*, 1988). A rise in chlorophyll *a* has also been reported for the Pomeranian Bay and the Gulf of Gdańsk (Renk, 1990; Renk and Wiktor, 1984).

The external supply of nitrogen (N) and phosphorus (P) to the Baltic from rivers, point sources and atmospheric deposition is estimated to have been 980×10^3 tonnes (N) and 50×10^3 tonnes (P) per year at the beginning

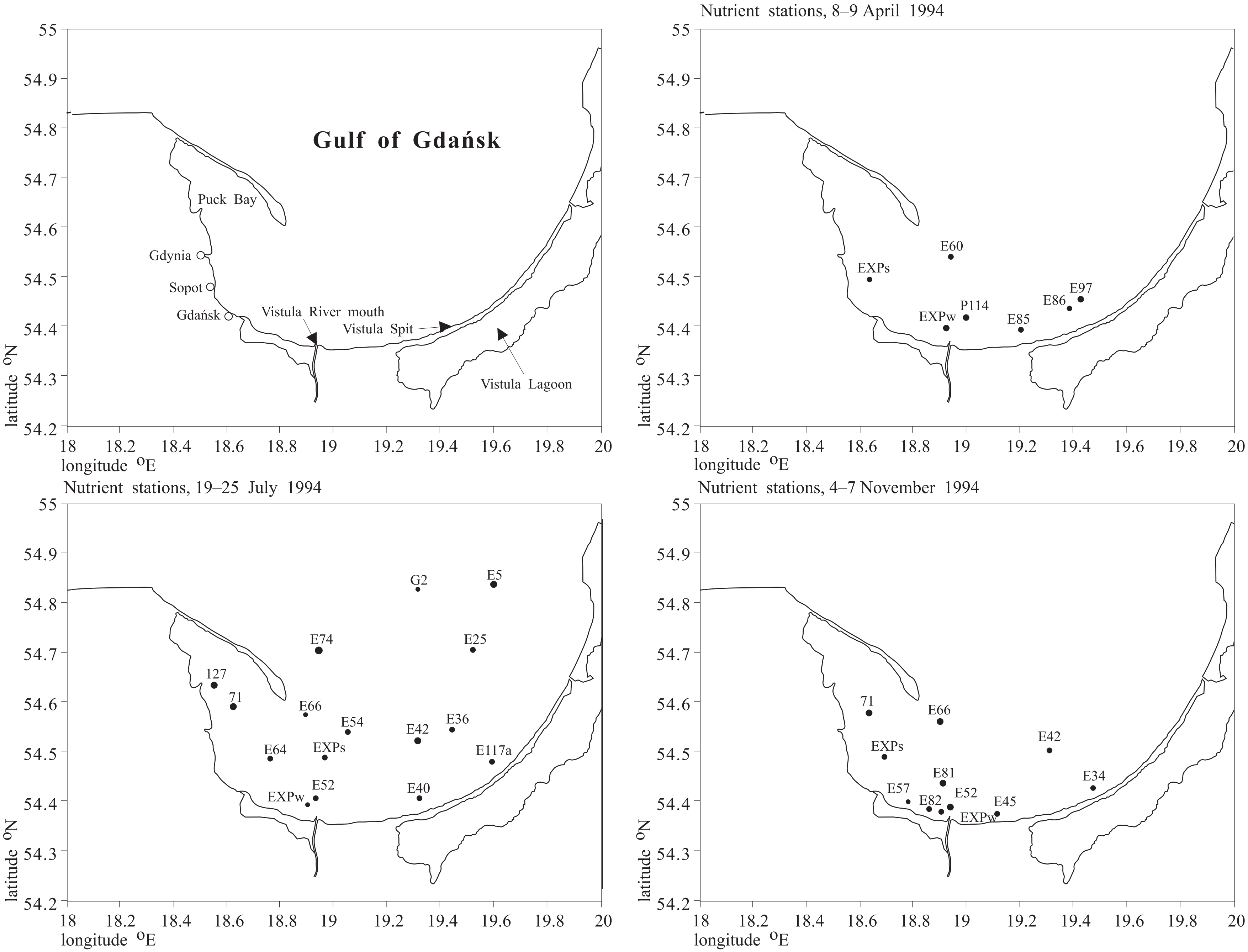

Fig. 1. Area of study and location of stations at which nutrients were analysed in the Gulf of Gdańsk in April, July, November 1994

of this century (Larsson *et al.*, 1985). The same authors state that the respective nitrogen and phosphorus discharges are at present four and eight times higher.

The aim of this study, conducted by an interdisciplinary team (see the paper by Ochocki *et al.*, published below under the same general title), was to estimate the impact of the Vistula discharge on the distribution of nutrients and chlorophyll *a*, and on the level of primary production and its utilisation in the Gulf of Gdańsk ecosystem. This paper (subtitle: Part 1. 'Variability in nutrient concentrations') discusses nutrient concentrations and their variability in the part of the Gulf studied in 1994.

2. Materials and methods

This paper is based on the materials collected during three cruises of r/v 'Baltica' in the Gulf of Gdańsk on 8–9 April, 19–25 July, and 4–7 November 1994 (Fig. 1). The strategy of each cruise was to obtain a synoptic picture of physical parameters (temperature, salinity) based on a dense grid of stations (Grelowski and Wojewódzki, in press). This enabled the Vistula waters penetrating the Gulf of Gdańsk to be identified in relation to hydrological/meteorological conditions. In the Vistula river plume and in the waters beyond the direct impact of the river a new series of CTD measurements was carried out and was accompanied by the determination of the following nutrients: nitrates, nitrites, ammonia, phosphates, silicates, total nitrogen and total phosphorus. The chemical analyses were performed using manual methods on board the vessel directly after sampling. The spectrophotometric measurements were done with a BECKMAN (model 26) spectrophotometer. The following analytical methods (Grasshoff, 1976; Grasshoff *et al.*, 1983; UNESCO, 1983;) were applied to determine particular species: phosphates were determined by the Murphy and Riley method modified by Koroleff; nitrates by the Morris and Riley method; nitrites by the Bendschneider and Robinson method; silicates by Mullin and Riley's blue method; ammonia by Koroleff's blue indophenol method; total N and total P by the Koroleff method involving simultaneous persulphate oxidation of phosphorus and nitrogen compounds. The dissolved oxygen content was determined by the Winkler method (Grasshoff *et al.*, 1983).

3. Results

April 1994

The horizontal distributions of nitrates, ammonia, phosphates, silicates, total nitrogen and phosphorus at the surface produced a similar picture for all the parameters, showing that the highest concentrations of nutrients

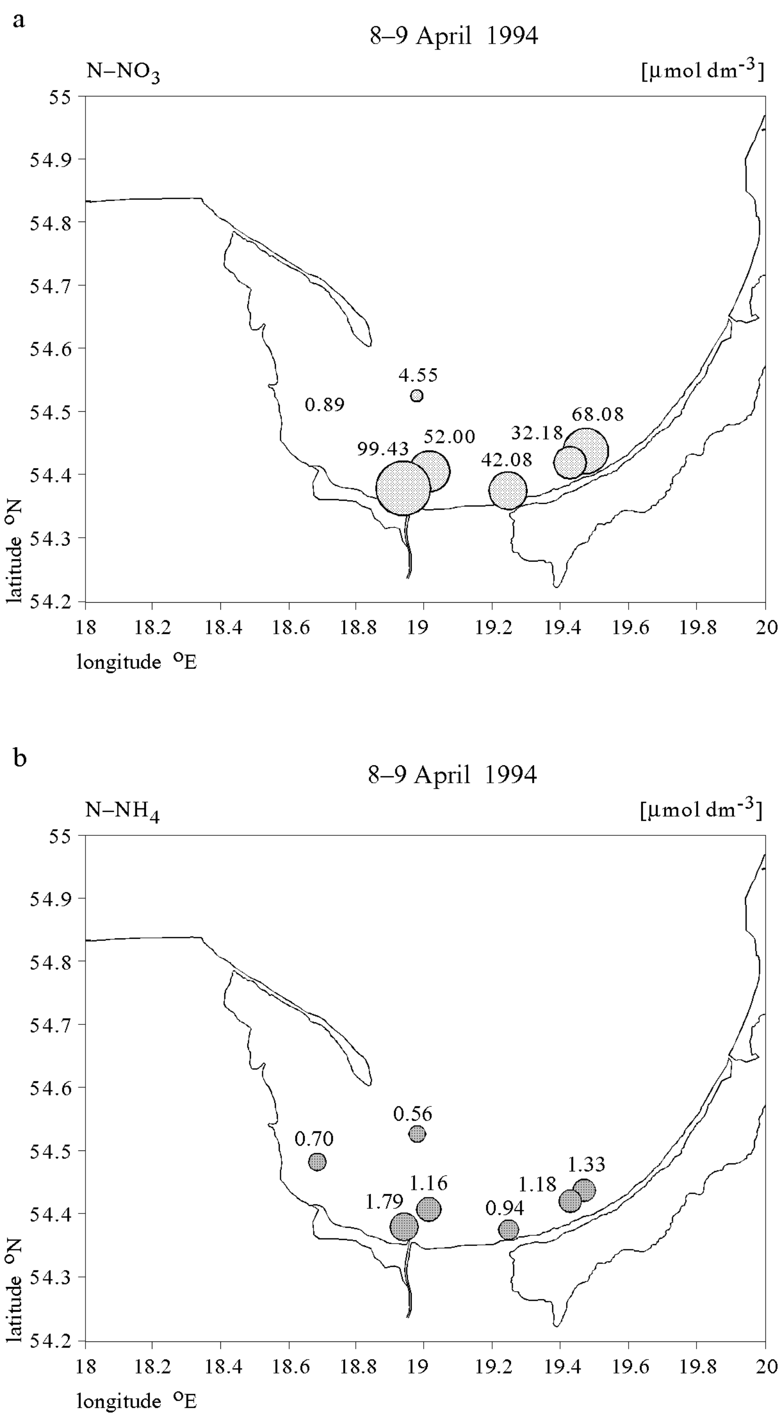

Fig. 2. Distribution of nitrates and ammonia at 0 m (April 1994)

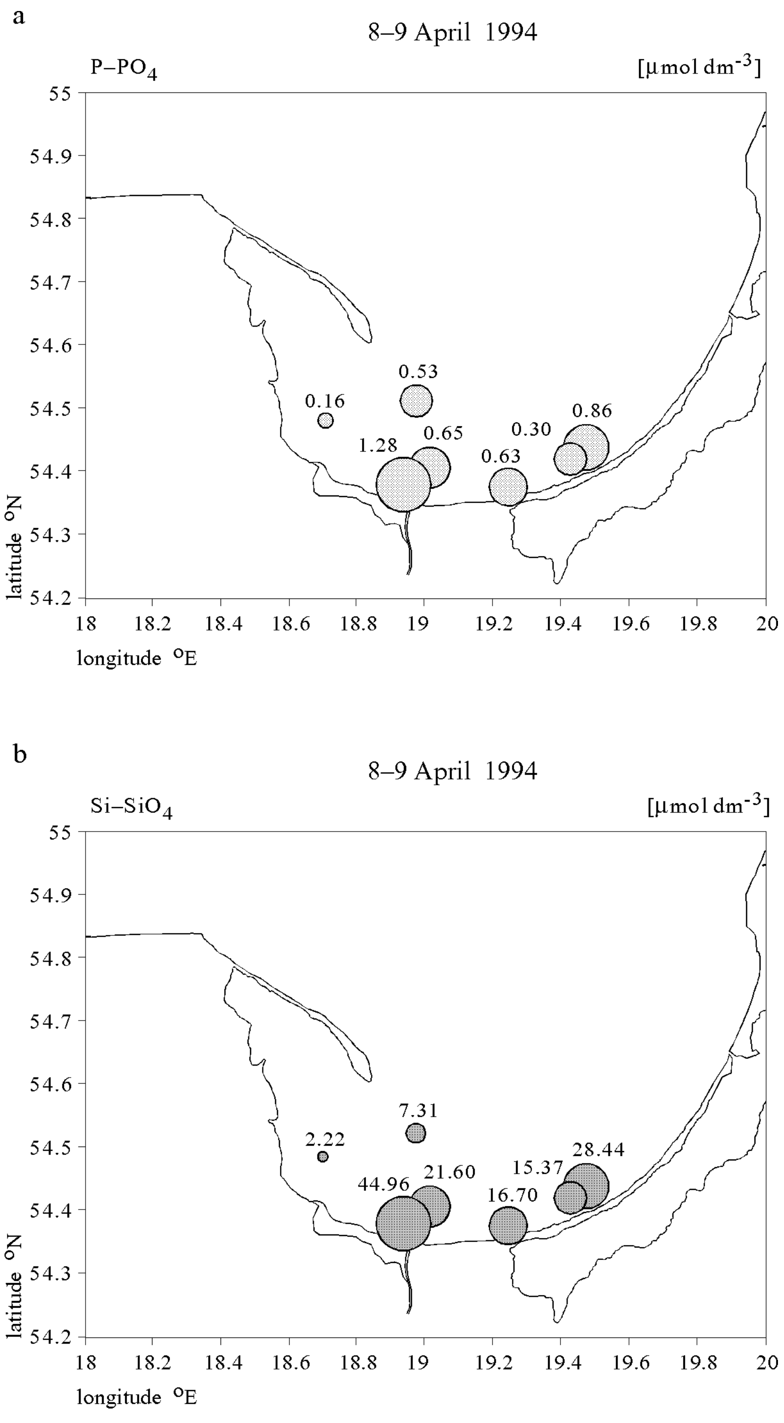

Fig. 3. Distribution of phosphates and silicates at 0 m (April 1994)

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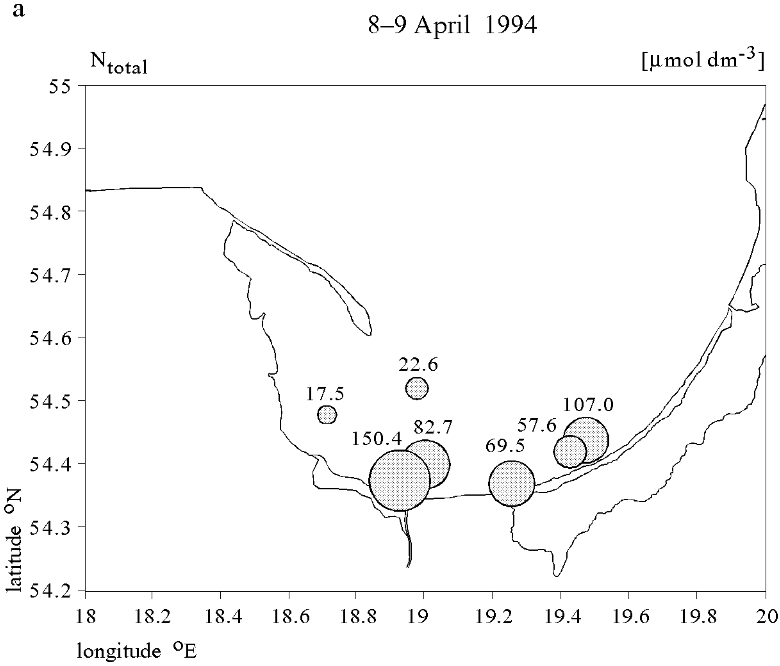

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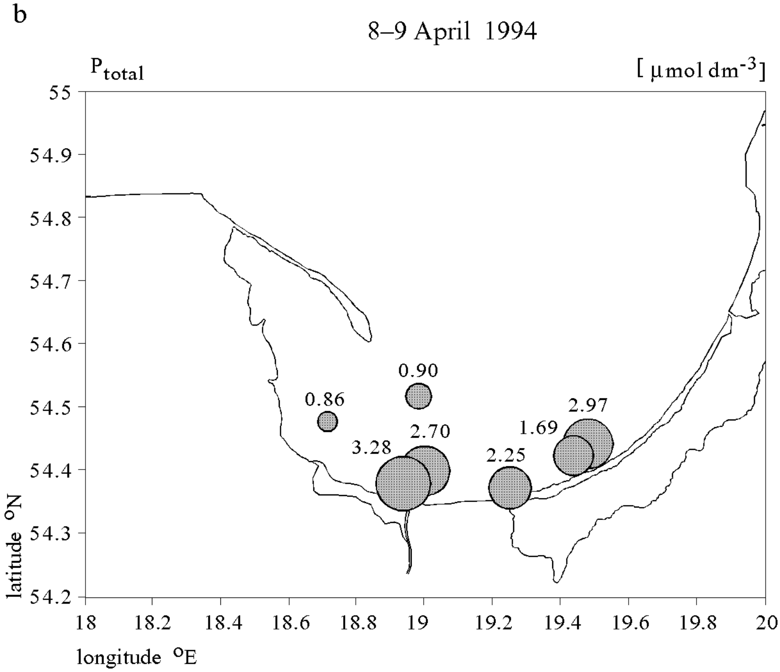

Fig. 4. Distribution of total nitrogen and total phosphorus at 0 m (April 1994)

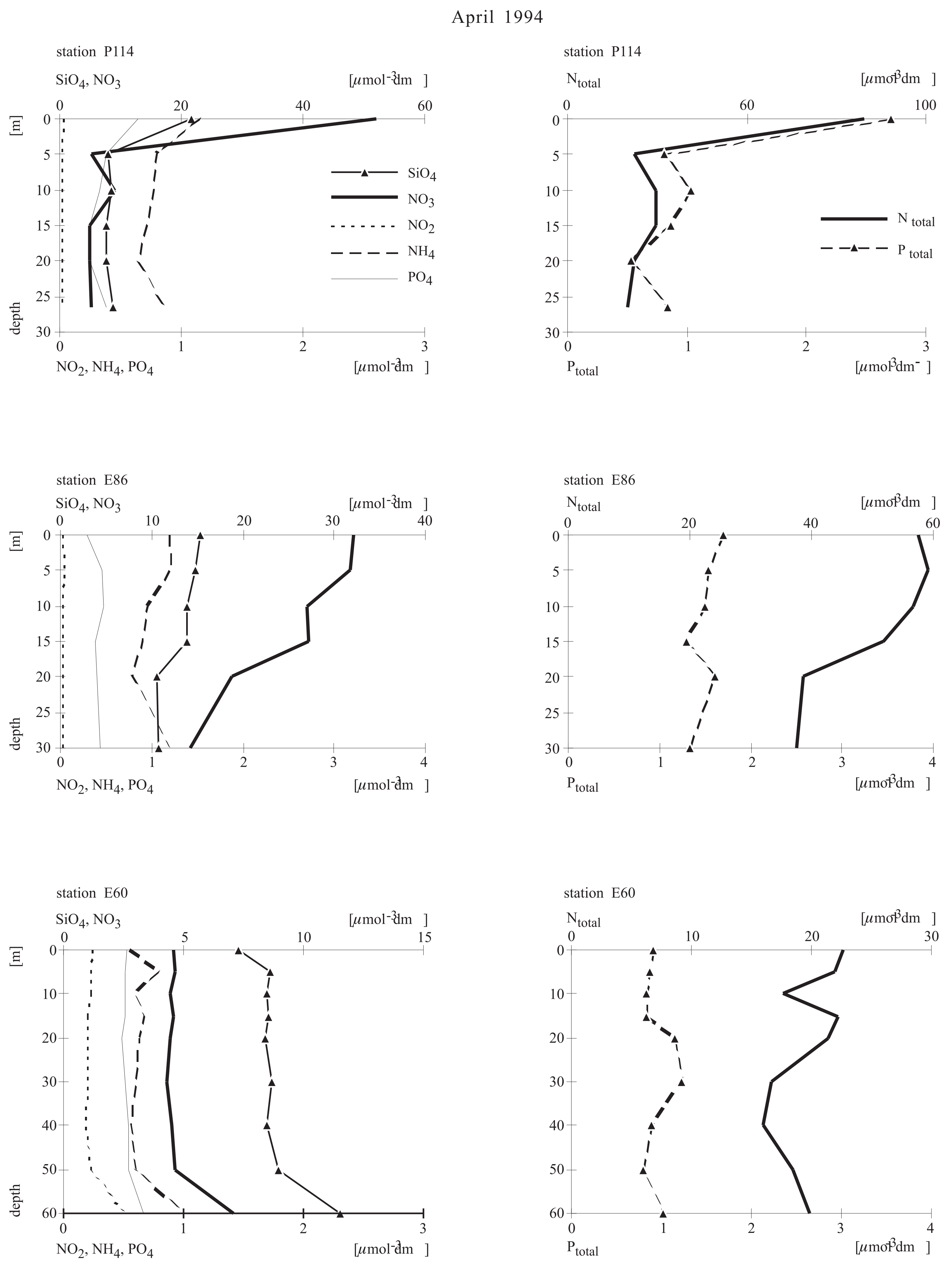

Fig. 5. Vertical profiles of nutrients at selected stations (April 1994)

were recorded in the Vistula estuary and to the north of the river mouth (station P114); a second nutrient maximum was found at station E97 (the easternmost one near the Vistula Spit). These two maxima were separated by a water mass with lower nutrient concentrations, which is visible in all the horizontal distributions at stations E85 and E86. The lowest concentrations of all the nutrients were recorded at the westernmost (EXPs) and the northernmost (E60) stations (Figs. 2, 3, 4). Spatial differences in nutrient concentrations were considerable: *ca* 98 μmol dm^{-3} for nitrates, *ca* 1 μmol dm^{-3} for ammonia and phosphates, and *ca* 42 μmol dm^{-3} for silicates (stations EXPw, EXPs). The greatest spatial variability, between the same two stations, was also expressed by total nitrogen and total phosphorus, these concentrations differing by about 133 μmol dm^{-3} and 2.40 μmol dm^{-3} respectively.

Vertical distribution of parameters

Analysis of the vertical profiles of the chemical parameters measured showed considerable concentrations of N–NO_3 at the surface and their abrupt decrease (even by 50 μmol dm^{-3}) within the 0–5 m layer (stations P114, E85, E97) or within the 0–20 m layer (station E86) at the estuarine stations as well as at those off the Vistula Spit (Fig. 5). A similar pattern, although with an incomparably gentler vertical gradient, was displayed by the other parameters, *e.g.* ammonia, phosphates, silicates. The shapes of the vertical $N_{tot.}$ profiles were similar to those of $P_{tot.}$, and their respective variabilities in the water column were similar to those of N–NO_3 and P–PO_4. Concentrations of nitrites at all the stations ranged from 0.2 μmol dm^{-3} to 0.7 μmol dm^{-3}, higher values being observed near the Vistula mouth and at the surface at P–114, *i.e.* the station most strongly affected by the Vistula plume. E60 was the only deep-water station where the vertical distribution of chemical parameters did not seem to be directly affected by the Vistula discharge, although there was a characteristic vertical distribution of $N_{tot.}$ and $P_{tot.}$ with alternating maxima and minima.

July 1994

In July the study area was much larger and included the south-eastern part of the Gulf of Gdańsk. An almost total depletion of surface N–NO_3 was observed, except at stations E5, E66 and E64, where the respective concentrations of this species were 0.11 μmol dm^{-3}, 0.14 μmol dm^{-3}, and 0.31 μmol dm^{-3}. It is characteristic that nitrates and ammonia were completely exhausted at the station closest to the Vistula mouth. Ammonia was also exhausted at E64, while at the remaining stations the concentrations ranged from 0.35 to 2.19 μmol dm^{-3}, with the highest value being found at E52,

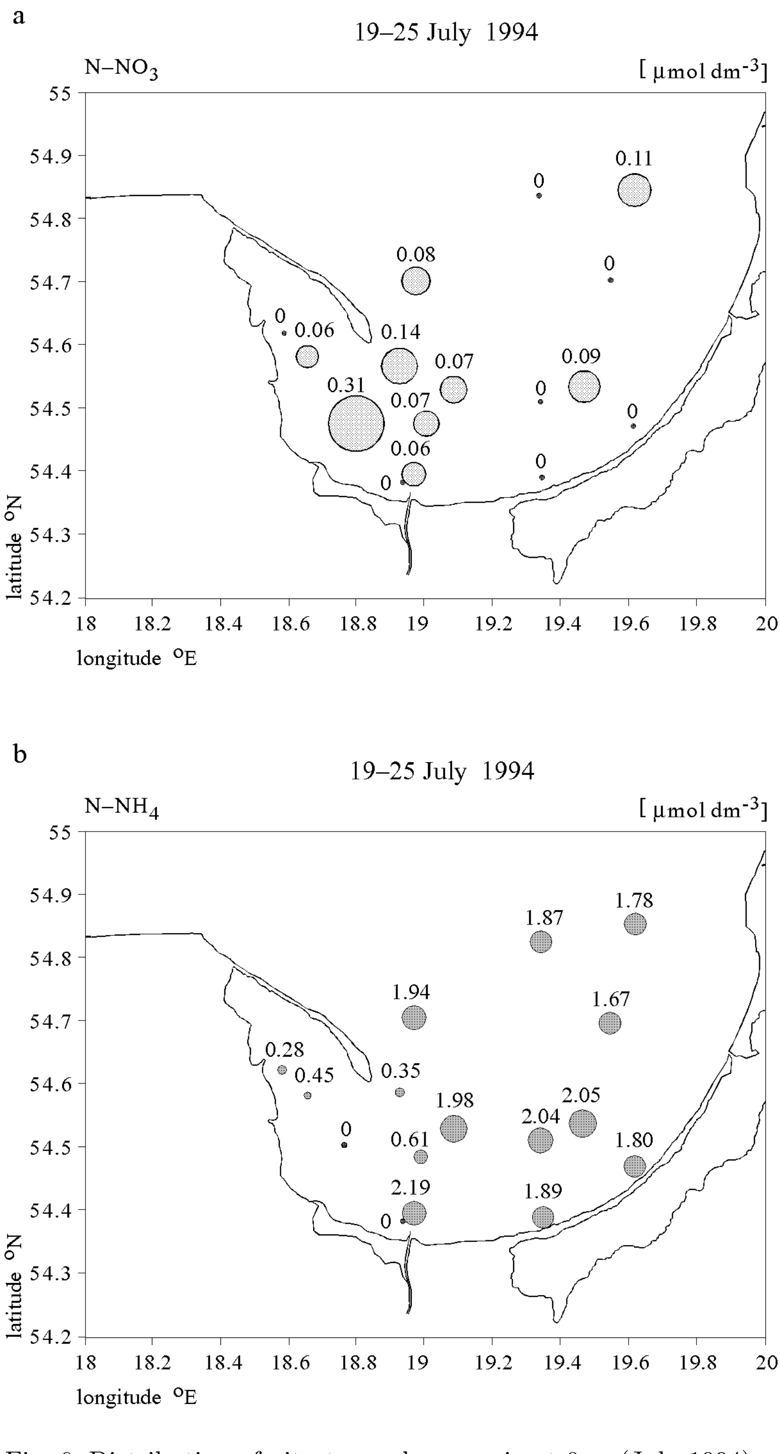

Fig. 6. Distribution of nitrates and ammonia at 0 m (July 1994)

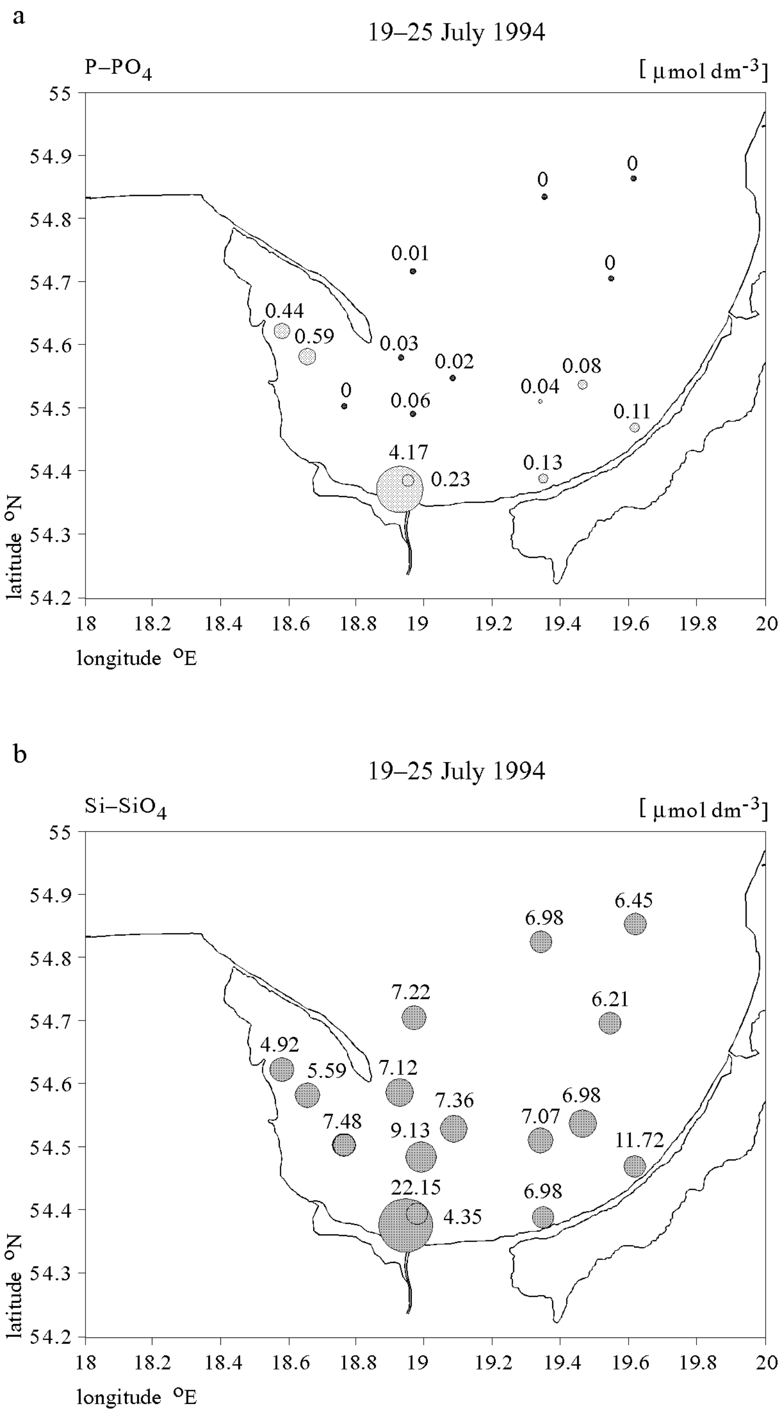

Fig. 7. Distribution of phosphates and silicates at 0 m (July 1994)

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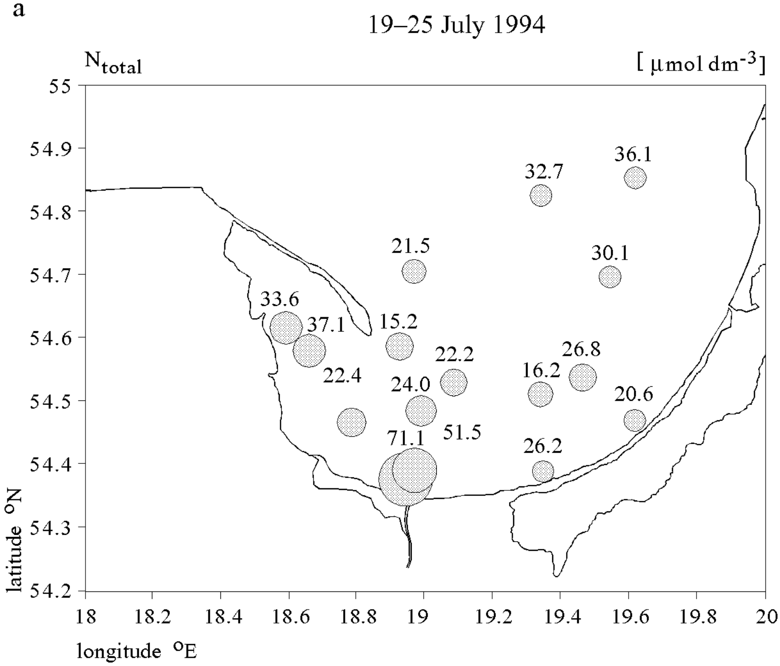

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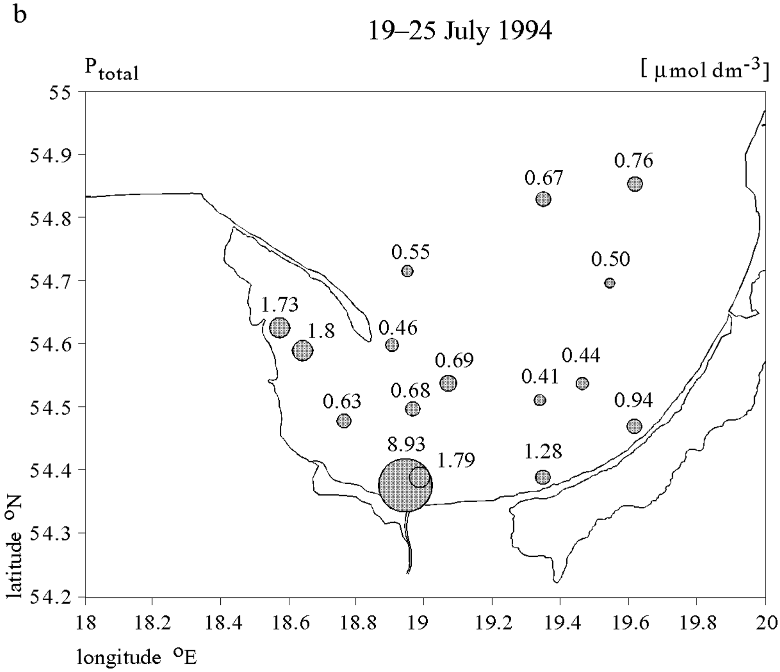

Fig. 8. Distribution of total nitrogen and total phosphorus at 0 m (July 1994)

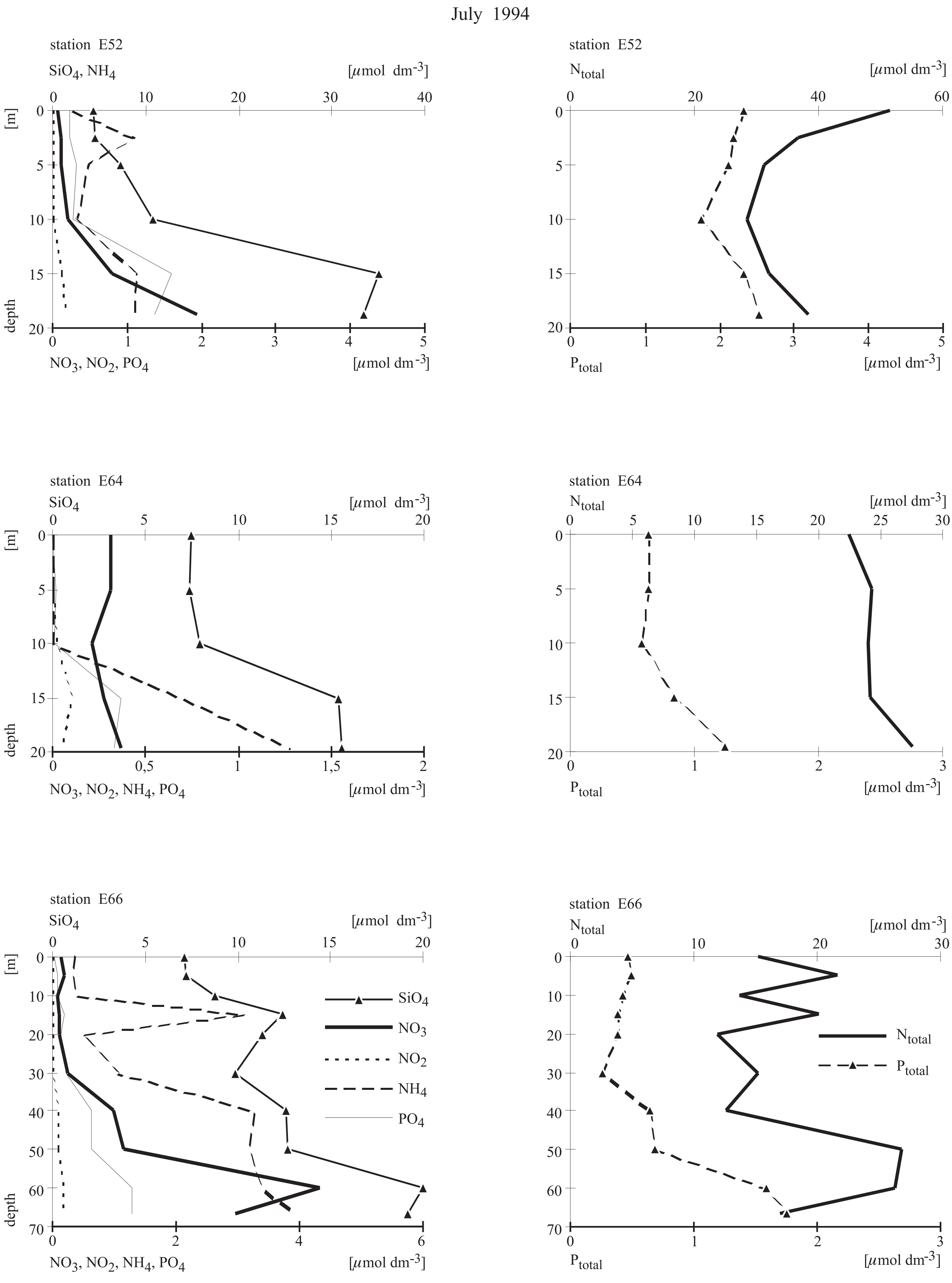

Fig. 9. Vertical profiles of nutrients at selected stations (July 1994)

just north of the Vistula mouth (Fig. 6). Concentrations of $P–PO_4$ were equal to zero in the north – western part of the area or close to zero in the central part of the area studied; higher concentrations were observed in the Vistula estuary (4.17 μmol dm^{-3}), in Puck Bay (0.44–0.59 μmol dm^{-3}) and off the Vistula Spit (0.11–0.13 μmol dm^{-3}). Silicates showed a horizontal distribution at 0 m similar to that of ammonia; the only exception was a $Si–SiO_4$ maximum (22.15 μmol dm^{-3}) found in the Vistula plume. Concentrations of silicates in the remaining part of the area ranged from 4.92 to 11.72 μmol dm^{-3} (Fig. 7). The highest concentrations of $N_{tot.}$ and $P_{tot.}$ were found at the station closest to the Vistula mouth (71.1 μmol N dm^{-3} and 8.93 μmol P dm^{-3}) and at E52 (51.5 μmol N/l and 1.79 μmol P/l). At the remaining stations, the respective $N_{tot.}$ and $P_{tot.}$ concentrations ranged within 15–37 μmol dm^{-3} and 0.46–0.59 μmol dm^{-3} (Fig. 8).

Vertical distribution of parameters

The vertical profiles (Fig. 9) show that at nearly all stations $N–NO_3$, $N–NO_2$, $P–PO_4$ were exhausted from the surface to the bottom at shallow stations, or from the surface down to 40–50 m at deeper ones. Ammonia was present in the entire region, except at E64, where in the uppermost 15 m layer the concentrations were below the detection limit. Concentrations of $N–NH_4$ in the remaining part of the area ranged from 0.3 μmol dm^{-3} to about 8 μmol dm^{-3}. Moreover, numerous vertical profiles showed alternating $N–NH_4$ maxima and minima, and the depths of these extreme values differed between stations. The most disturbed vertical distribution of $N–NH_4$ and $Si–SO_4$ is visible at E66. Silicates in the area studied ranged from a few to over 10 μmol dm^{-3}. The vertical distributions of $N_{tot.}$ and $P_{tot.}$ demonstrated that total nitrogen at most stations (except for E52 and E64) and total phosphorus at some stations showed alternating maximum and minimum concentrations, but there was no agreement either in the depth of occurrence of the extreme values, or in the absolute values of the concentrations.

November 1994

In November the surface distribution of chemical parameters showed a well-pronounced maximum at the station closest to the Vistula mouth, expressed by the following parameters: $N–NO_3$ (78.44 μmol dm^{-3}), $N–NH_4$ (6.20 μmol dm^{-3}), $P–PO_4$ (2.45 μmol dm^{-3}), $Si–SiO_4$ (136.91 μmol dm^{-3}) (Figs. 10, 11, 12). Elevated values of these parameters occurred towards Puck Bay and to the east of the Vistula mouth (E45). The respective concentrations in these two areas lay within the following ranges: $N–NO_3$ – 9.98–1.63 and 1 μmol dm^{-3}; $N–NH_4$ – 2.13–0.73 μmol dm^{-3} and

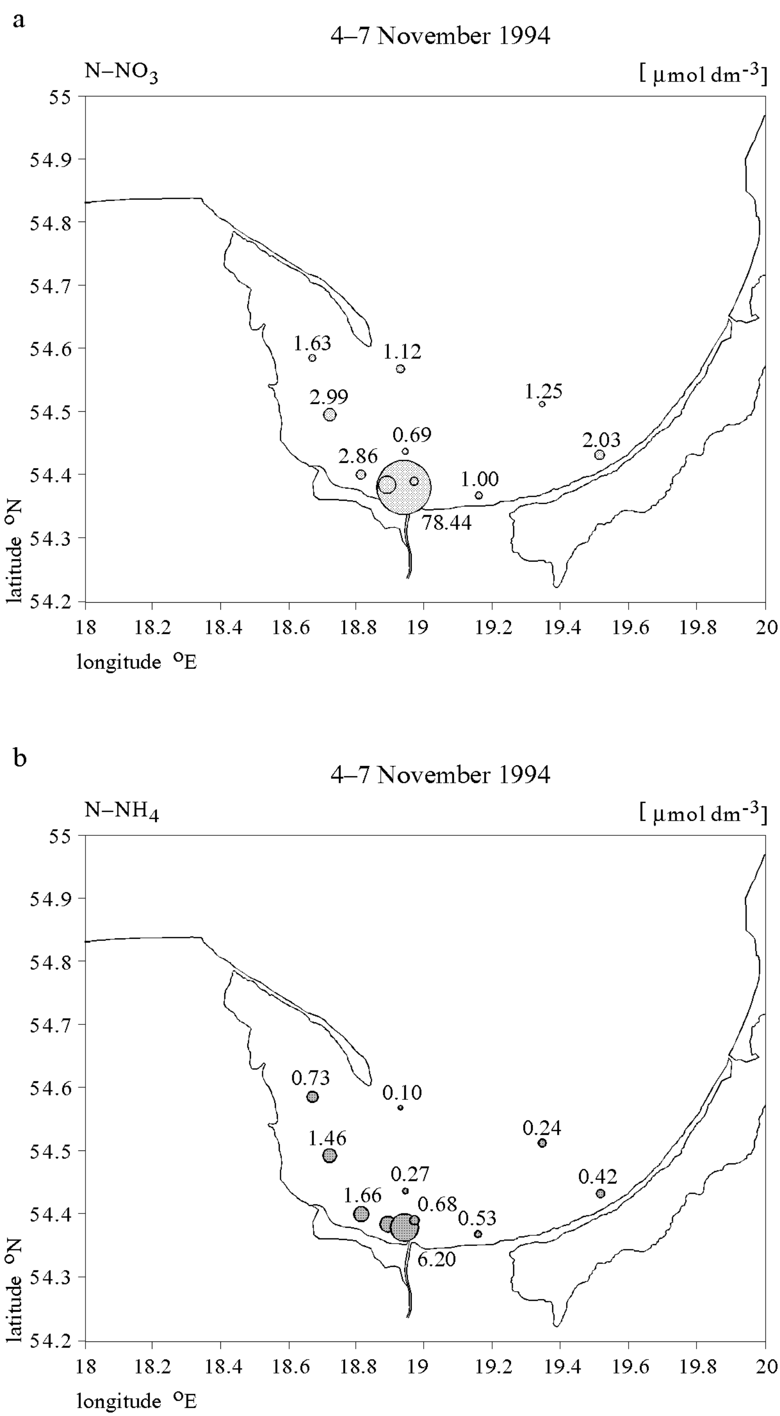

Fig. 10. Distribution of nitrates and ammonia at 0 m (November 1994)

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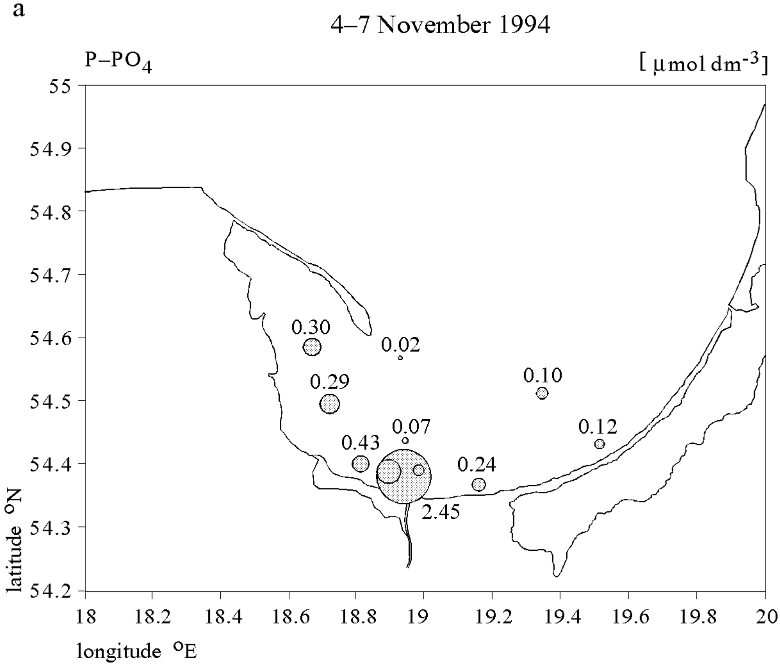

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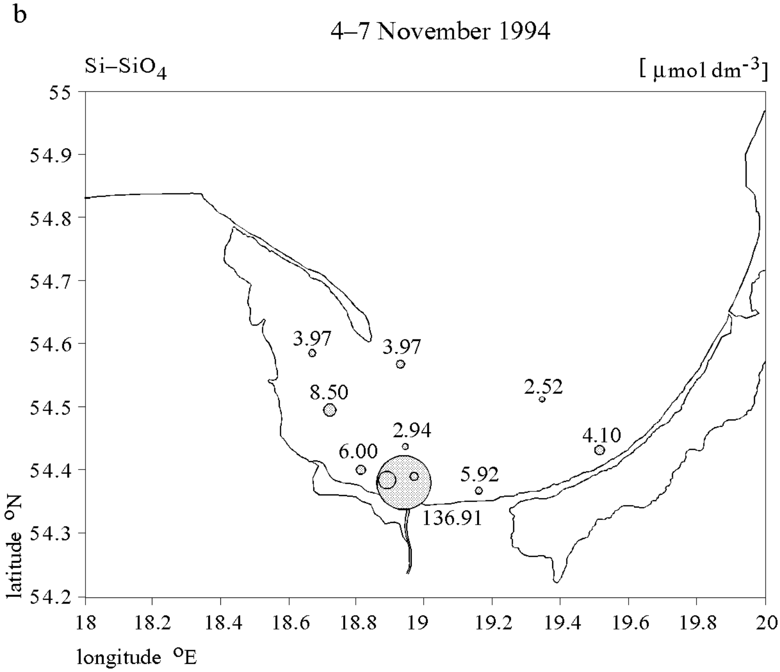
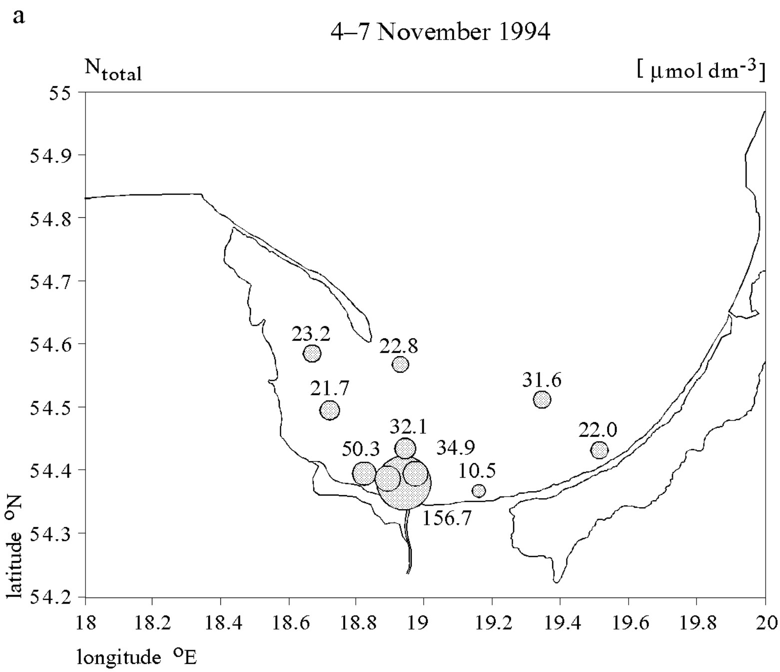


Fig. 11. Distribution of phosphates and silicates at 0 m (November 1994)



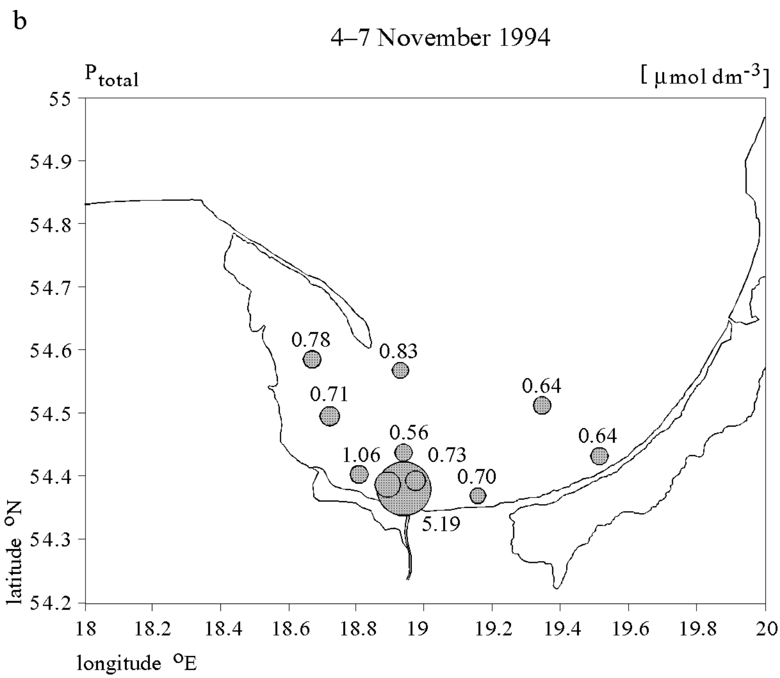


Fig. 12. Distribution of total nitrogen and total phosphorus at 0 m (November 1994)

November 1994

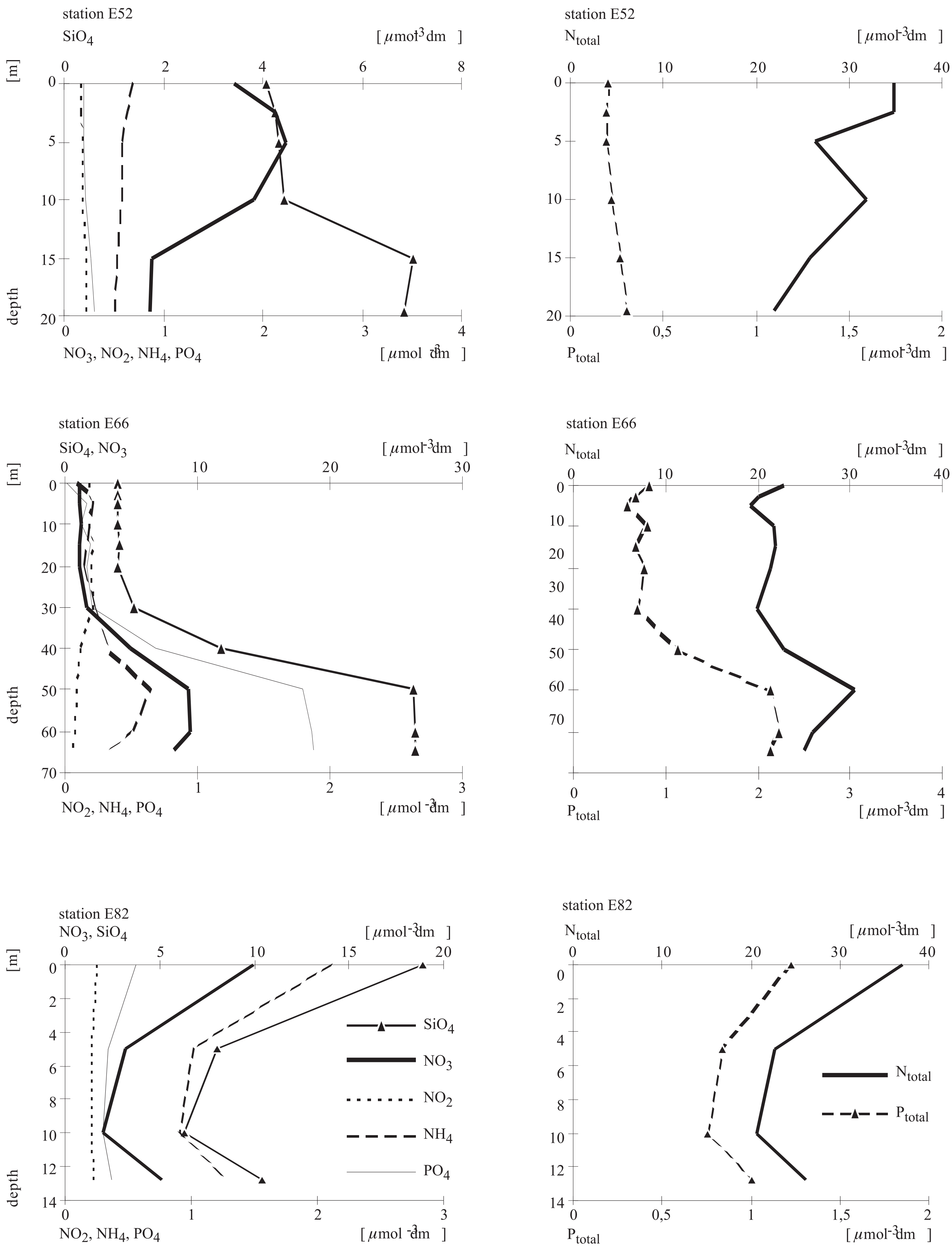


Fig. 13. Vertical profiles of nutrients at selected stations (November 1994)

0.53 μmol dm^{-3}; P–PO$_4$ – 0.56–0.30 μmol dm^{-3} and 0.24 μmol dm^{-3}; Si-SiO$_4$ – 18.91–3.97 μmol dm^{-3} and 5.92 μmol dm^{-3}. Although located close to the Vistula mouth, station E52 seems to be only slightly influenced by riverine waters (a N–NO$_3$ maximum of 2.41 μmol dm^{-3} in the 2.5–10 m layer). The highest surface concentrations of N$_{tot.}$ occurred at stations close to the Vistula mouth (156.7-32.1 μmol dm^{-3}). The highest surface concentrations of P$_{tot.}$ were found at the station nearest to the Vistula mouth (EXPw; 5.19 μmol dm^{-3}) and at stations E57 and E82 (1.06 and 1.23 μmol dm^{-3} respectively).

Vertical distribution of parameters

The steepest vertical gradient in the surface layer, most clearly visible in N–NO$_3$ concentrations, occurred at E82. Stations E57 and E52 exhibited a subsurface (5 m) N–NO$_3$ maximum (Fig. 13). There was a vertical gradient of parameters at deep-water stations E66 and E42, where the concentrations of all the parameters increased abruptly at 30 m and continued to do so down to the bottom (N–NO$_3$ changed from about 1 μmol dm^{-3} to 7–8 μmol dm^{-3}; P–PO$_4$ – from 0.5–1 μmol dm^{-3} to nearly 2 μmol dm^{-3}, and Si–SiO$_4$ – from 2–3 μmol dm^{-3} to 26–27 μmol dm^{-3}).

4. Discussion

4.1. The seasonal, interannual and spatial variability of Vistula discharges

The Gulf of Gdańsk is fed mainly by the rivers Vistula, Pregel and Neman; its drainage area consists of the drainage areas of the river Vistula (193 911 km^2), the Vistula Lagoon (23 439 km^2) and of the direct drainage area of the Basin (about 3000 km^2) (Majewski, 1990). Niemirycz (1994b) ascribes a slightly larger drainage area (194 424 km^3) to the river Vistula; other data published by that author indicate that the mean Vistula flow, calculated for a long-term period, is equal to 1000 m^3 s^{-1}, which yields an annual discharge to the Gulf of Gdańsk of 32 km^3 of water.

The Vistula discharge varies both seasonally and interannually (Figs. 14, 15). Seasonal variations are related to the variable annual water supply, which reaches a maximum in March/April as a result of snowmelt, and also to variations in annual precipitation. The minimum discharge of Vistula waters takes place from August to November (Majewski, 1990; Niemirycz, 1994b; Niemirycz and Borkowski, 1995 (in press).

The discharge of water, as well as of nitrogen and phosphorus, show fluctuations in the long term (Fig. 15, 16). The highest loads of N and P – *ca* 130 000 ton N/year and *ca* 7 000 ton P/year – introduced into

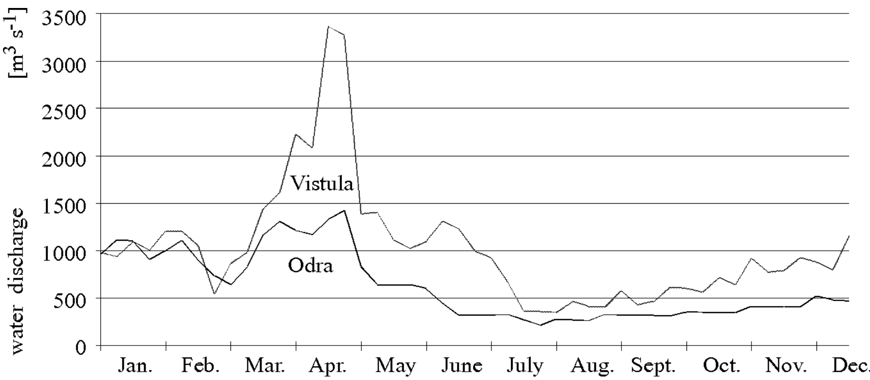


Fig. 14. Water discharge of the rivers Vistula and Odra during 1994 (after Niemirycz and Borkowski, 1995)

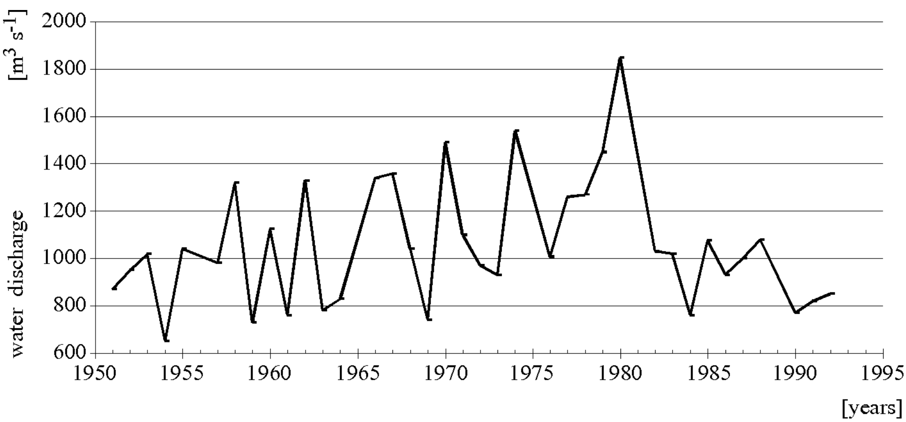
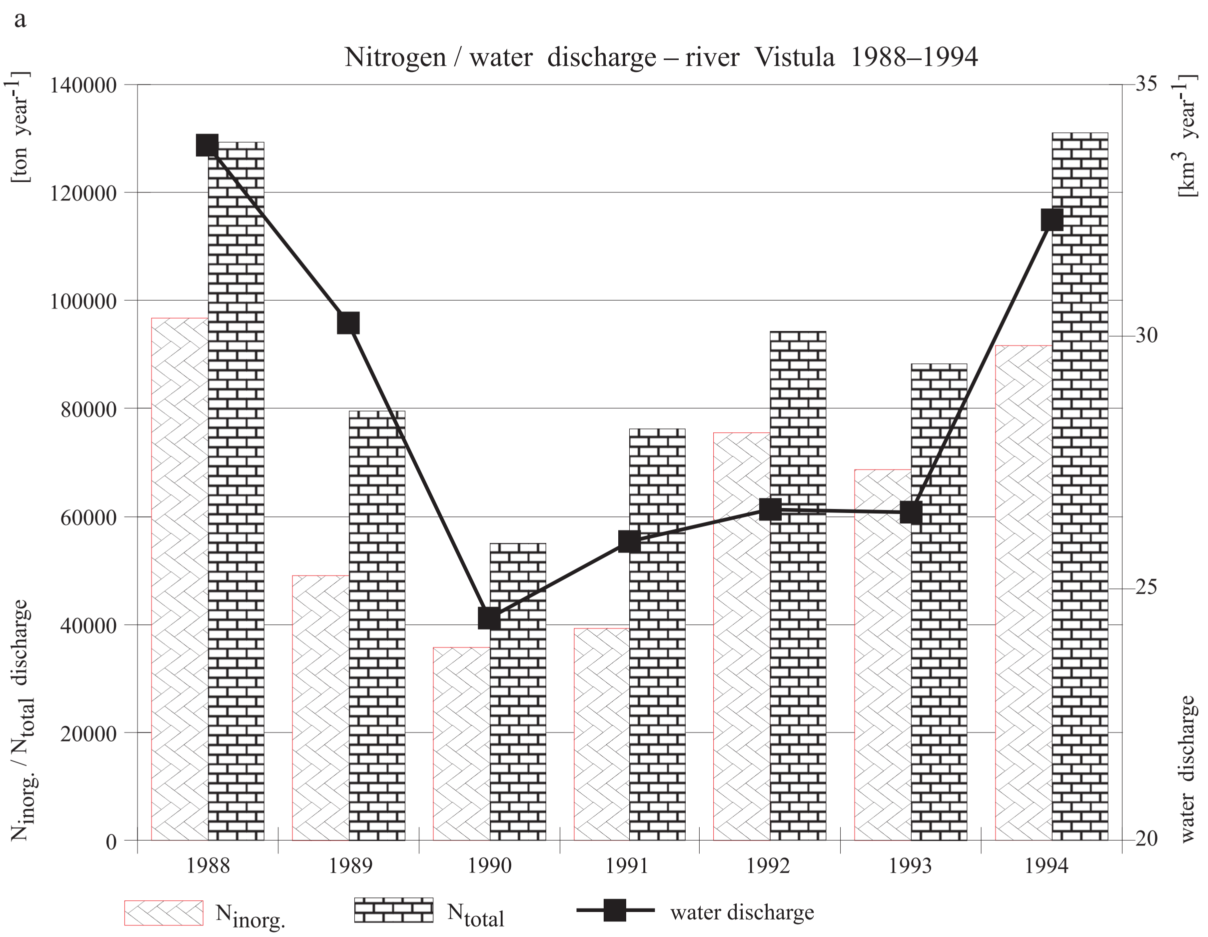


Fig. 15. The average annual water discharge of the river Vistula in 1951–1992 (after Niemirycz, 1994b)

the Gulf of Gdańsk during the past seven years were observed in 1988. A considerable decrease in the discharge of nitrogen, down to 55 000 ton N/year, was noted in 1990 as a result of a smaller water discharge in that year; the economic crisis in Poland at the beginning of the transformation period also contributed to this situation. Nitrogen discharges are well correlated with the Vistula outflow, but there is no such clear-cut relationship with respect to phosphorus.

The discharge of nutrients was highly variable during 1994 and seemed to be well correlated with the amount of water discharged by the Vistula in that year (Figs. 14, 17). All the peaks in the curve representing the



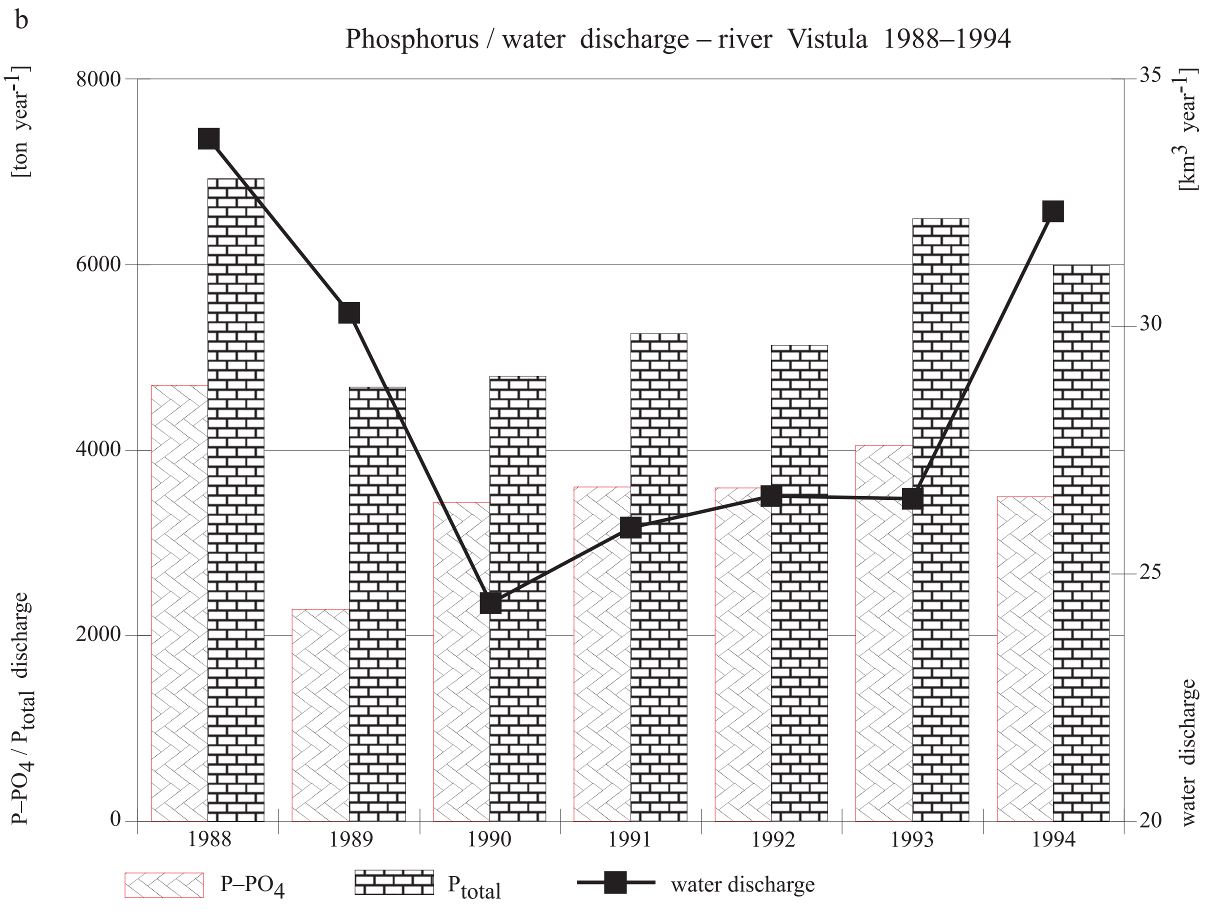


Fig. 16. Nitrogen, phosphorus and water discharged by the river Vistula in 1988-1994 (figure based on data published by Niemirycz, 1994a; Niemirycz and Borkowski, 1993, 1995; Niemirycz and Makowski, 1992; Niemirycz and Markiewicz, 1993; Niemirycz and Żebrowska, 1992; Niemirycz *et al.,* 1991, 1994, 1995; Rybiński and Markiewicz, 1991; Rybiński and Niemirycz, 1991; Rybiński *et al.,* 1990)

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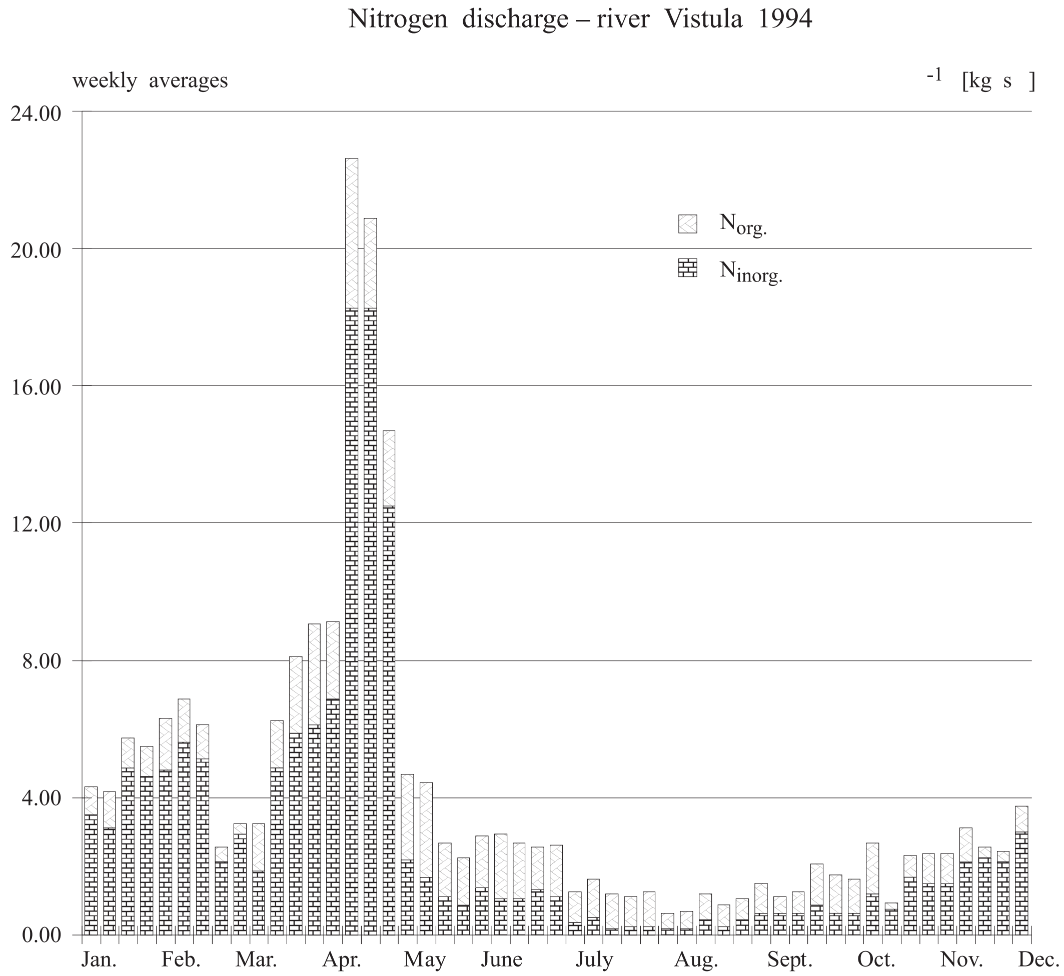

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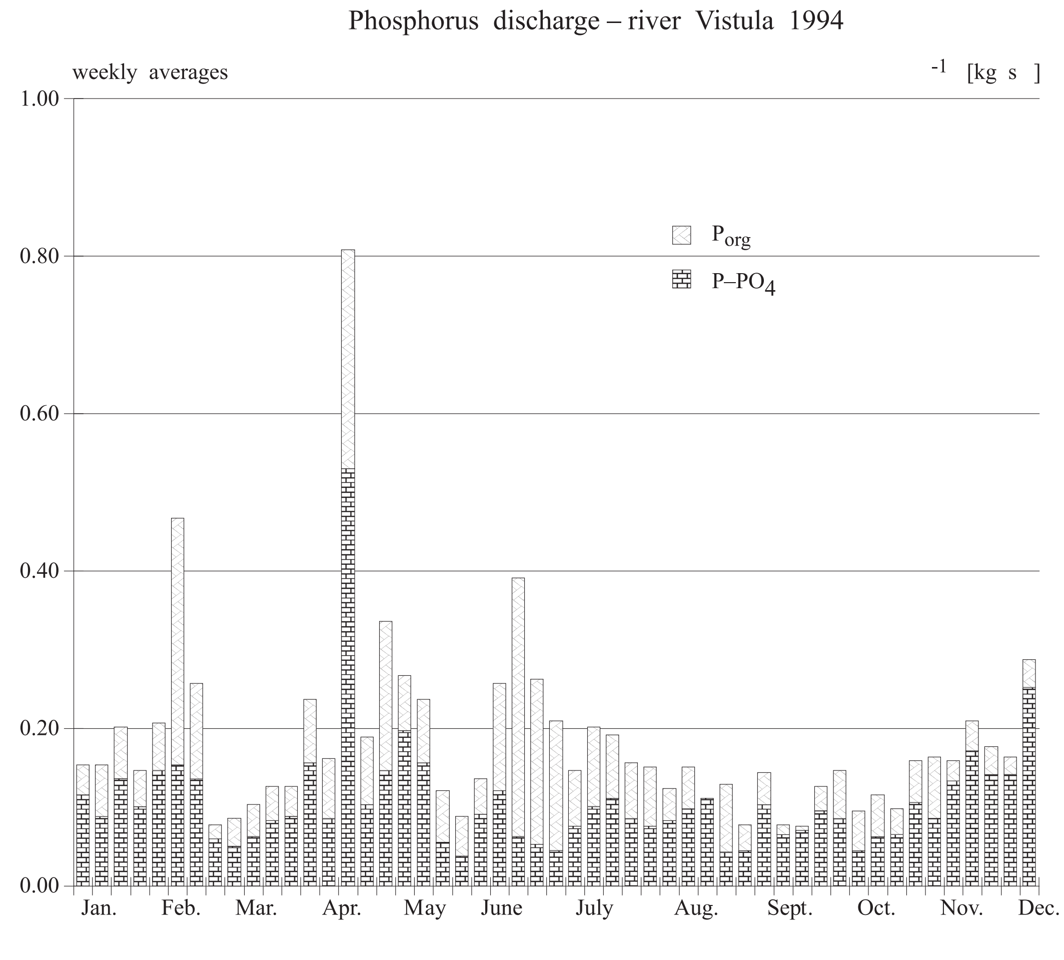

Fig. 17. Nitrogen and phosphorus discharged by the river Vistula during 1994 (after Niemirycz *et al.*, 1995)

water discharge were reflected in the increased average weekly discharges of inorganic nitrogen and phosphorus compounds.

Although the hydrological conditions have a great impact on nutrient concentrations in the Vistula, finding a mathematical correlation, *e.g.* between nitrogen concentrations and the river flow is, according to Niemirycz (1994b), rather difficult. Rybiński (1994) is of a similar opinion, and states that the quantity of nutrients discharged is positively correlated with the amount of outflowing water, but in any individual year, or even over shorter time periods, the correlation may be very variable in terms of the correlation coefficient range.

The amount of water discharged by the Vistula influences the extent of the river plume, whilst concentrations of nutrients in the river greatly affect nutrient concentrations in the Gulf of Gdańsk (Cyberska and Krzymiński, 1988; Nowacki, 1994). Studies carried out in the Gulf of Gdańsk (Nowacki, 1994) during 1981–1985 led to the finding of a relationship between the annual mean concentrations/masses of inorganic nitrogen/phosphorus and both the distance from the coast and the water depth. Nowacki demonstrated that the highest concentrations of the species studied occurred in the surface layer (down to 10–20 m) of the estuarine zone. The coastal belt of highest concentrations is 12–13 km wide. He also demonstrated that the Gdańsk port canal discharges a greater quantity of phosphates into the Gulf of Gdańsk than the Vistula does.

4.2. Spatial and seasonal variability in the parameters measured in 1994

The distribution of temperature and salinity (Grelowski and Wojewódzki, in press) indicates that the northern horizontal and vertical extent of the Vistula plume in 1994, expressed in absolute values, was as follows: in April, before strong NW winds blocked the outflow, the horizontal extent was 12 NM (22 km) and the vertical 10–12 m; after the blocking of the outflow the horizontal spread was 6 NM and the vertical 5–10 m. In July the horizontal extent was about 8 NM, the vertical 5–7 m; in November two separate pockets of riverine water were found, each of them 10 m thick and a few NM in diameter.

The time-variable discharges of Vistula water were reflected in both the concentrations and the vertical gradient of nutrients in the estuarine zone. In April the highest N–NO_3 concentrations, in excess of 50 μmol dm^{-3}, were observed at the stations closest to the river mouth; an abrupt drop in values, down to a few μmol dm^{-3} was recorded in the 0–5 m layer; the gradient diminished with the offshore distance (Fig. 5). The closest range of the river plume, observed in July 1994, was accompanied by much lower nutrient concentrations in the estuarine zone in comparison with April and November 1994 (Figs. 9, 13). The seasonal increase in nutrient concentrations observed in November 1994 did not result exclusively from the intensified Vistula discharge, but also from the lower biological production (Ochocki *et al.*, 1995) and higher mineralisation in the Gulf. The increased nutrient discharge in November 1994 was due to nitrates, phosphates, and particularly to silicates. The surface concentrations of silicates at the station closest to the Vistula mouth exceeded 136 μmol dm^{-3}, while in the area beyond the direct riverine impact they were lower than in July 1994. This latter value must have resulted from the autumn bloom of diatoms, which accounted for as much as 90% of the phytoplankton biomass, dominated by large forms (82–144 μm in diameter) of the genus *Coscinodiscus* (Kownacka, personal communication).

These outstanding features, observed in the estuarine zone, were not only demonstrated by the physical and chemical parameters but also by the biological ones. Particularly great differences in chlorophyll *a* concentrations between the estuarine zone and the remaining part of the area were recorded in April 1994 (a bloom stimulated by introduced nutrients); they were less pronounced but nevertheless detectable in July 1994 (increased amounts of phytoplankton brought in with the Vistula waters) (Ochocki *et al.*, 1995). The month of April was also marked by great spatial differences in potential primary production, reaching *ca* 50 mgC m^{-3} h^{-1} (Ochocki *et al.*, 1995). The surface distribution patterns of chlorophyll *a*, potential primary production and nutrients showed great similarity in April 1994. The relatively low regional variability in the distribution of the above parameters (arising partly from their lower values, *e.g.* nutrients depleted on occasion) in July and November 1994 did not produce so clear a correlation. The variable spatial distribution of nutrients and primary production in July 1994 could have been an effect of a very complex distribution of temperature at the surface and at 10 m depth (Grelowski and Wojewódzki, in press). Generally, the surface temperature in July 1994 was *ca* 3–5°C higher than the long-term mean. The isotherms formed numerous closed fields at the surface, and the exceptionally calm weather conditions did not favour wind-induced mixing.

It seems that when describing the spatial distribution of nutrients and organic matter in the Gulf one more factor, decisive with respect to the transport of water masses and therefore of nutrients in the Gulf, should be taken into consideration: water dynamics. The southern, shallow part of the Gulf of Gdańsk is highly susceptible to wind-induced transport/mixing, which has been proven for April 1994. The hydrochemical and biological investigations carried out on 8–9 April 1994 were preceded by CTD measurements conducted on 5–6 April 1994 (Grelowski and Wojewódzki, in press).

The CTD measurements indicated an undisturbed outflow of riverine water. A sudden and strong north-westerly wind (8° B) on 7 April 1994 not only blocked the outflowing water, but also inhibited its eastward transport. As a result, there appeared two areas of increased temperature and lower salinity, separated by a water mass of lower temperature and higher salinity; the first separate pocket of water was found north-east of the Vistula mouth, while the second remained off the central part of the Vistula Spit. Both of these water masses displayed elevated nutrient concentrations (Figs. 2, 3, 4) and much higher chlorophyll *a* contents and primary production values (Ochocki *et al.*, in press). For this reason they formed 'mini-ecosystems' living their own life. Such a phenomenon was also observed in the Pomeranian Bay in 1993 (Pastuszak *et al.*, in preparation).

A northward transport of the surface water mass, generated by strong southerly winds, was observed in November 1994, and that resulted in the compensatory upwelling of cold subsurface waters in the narrow coastal zone (Grelowski and Wojewódzki, in press). The intensified water dynamics also resulted in the formation of separate pockets of water, identified by their different temperature and salinity, which were found east and west of the Vistula mouth. The location of the sampling stations did not completely coincide with those centres, so the identification of the 'mini-ecosystems' was hindered, though still possible. Elevated concentrations of ammonia, phosphates, silicates were recorded east and west of the Vistula mouth (Figs. 10, 11).

These substantial, though short-lived changes in the distribution of water masses are evidence of the powerful dynamics of the area studied. They are in agreement with the observations of Kwiecień (1990), who has shown that winds with a northerly component drive the water into the southern Gulf of Gdańsk, while the winds with a southerly component drive the water out of that area. The former case, most frequent in spring and summer, results in blocking; the latter, most frequent in autumn and winter, produces enhanced Vistula outflow. The prevailing winds in the Gulf of Gdańsk have a westerly component, *i.e.* SW, W, NW, and make up from 40 to 50% of the annual wind rose. Winds blowing from the E to S sector also make a substantial contribution – from 30 to 40% (Kwiecień, 1990).

Although the studies in 1994 were carried out only in three months of the year, a seasonal pattern can be identified in the discharge of water and nutrients by the Vistula, well pronounced in April, less so in July; there is also a seasonal pattern in biological activity leading, on occasion, to nutrient depletion in the area. The efficiency of phytoplankton production, expressed by the assimilation number, was highest in summer but much lower in spring and autumn (Ochocki *et al.*, 1995). The considerable decrease in nutrient concentrations in July 1994 affected mainly N–NO_3 and P–PO_4. In that month ammonia remained at a relatively high level at most of the stations; such high values had been reported earlier by Trzosińska (1990).

The surface concentrations of N–NH_4 in July 1994 displayed considerable spatial variability, greater than that in April or November 1994; the concentrations were about 0.3 μmol dm^{-3} higher than those in April 1994 (Figs. 2, 6). This difference might have arisen from the greater regeneration of ammonia in the microbial loop during intensive plankton growth. This, in turn, is associated with the presence of the small organisms mainly responsible for ammonia regeneration (Sahlsten, 1987). It seems that in July 1994 the abundant zooplankton (Krajewska, personal communication) and the higher bacterial activity (Maciejowska, personal communication) greatly contributed to the fact that ammonia regeneration prevailed over its uptake in the Gulf of Gdańsk.

Studies conducted by Sahlsten (1987), Sahlsten *et al.* (1988), Selmer (1988), and Sahlsten and Sorensson (1989) demonstrate that primary production is based to a great extent on regenerated forms of nitrogen, and that ammonia and urea play a key role in that process. These authors have found that the respective ammonia and urea uptakes in summer may make up 50% and 30% of the total nitrogen uptake. Nitrates are preferred only during blooms, owing to their quantitative predominance in spring and to the presence of larger organisms which take up N–NO_3 more readily, their metabolic processes requiring a higher expenditure of energy.

Analysis of the $N_{tot.}$ and $P_{tot.}$ vertical profiles showed them to be very irregular, with alternating maxima and minima (Figs. 5, 9, 13). Such curve shapes must have resulted from both the transformation of riverine water, which brought in not only inorganic but also organic forms of nitrogen and phosphorus, and the thermal stratification affecting biological processes. Chlorophyll *a* also showed numerous maxima and minima in the vertical profiles. The lack of comprehensive biological data (their analysis is time-consuming) does not allow a more exact interpretation of the data presented.

The great interest scientists have shown in the coastal zones of the Baltic Sea stems not only from the environmental degradation observed there, but also from the impact of these eutrophicated regions on the entire Baltic. A disturbed marine ecosystem requires more time to recover than one would expect. As a result of the lack of respect for the laws of nature, increased nitrates and phosphates are recorded even in the Gotland Basin, well away from the direct impact of land (Nehring and Matthäus, 1994). An increase in nitrates, observed in the surface, intermediate and bottom layers of the Gdańsk Deep in 1965–1990, has also been reported by Trzosińska

(1994). This enrichment with nutrients has led to excessive primary production (Renk, 1990) and, therefore, elevated concentrations of organic matter, which has resulted in a considerable increase in oxygen demand for its decomposition and an oxygen deficiency below the halocline.

5. Conclusions

- The seasonal and spatial variability in concentrations of the nutrients studied (nitrates, ammonia, phosphates, silicates, $N_{tot.}$, $P_{tot.}$) were recorded in the Gulf of Gdańsk in April/July/November, 1994;
  - seasonal variability was manifested as an accumulation of nutrients, also in the euphotic layer beyond the direct impact of the river Vistula. This accumulation was detected in April and November, while in July there was a depletion of nutrients. The Vistula estuary displayed the highest concentrations of nitrates in April 1994, which was in line with the river's increased seasonal discharge of water and nutrients,
  - spatial variability was expressed as the most extensive range of nutrient-rich water in April 1994 (north-east and east of the Vistula mouth); a reduced but nonetheless well-pronounced extent of this water was observed in November 1994. It was demonstrated that the spatial variability depended not only on the volume of fresh, nutrient-rich water discharged, but also on the water dynamics in the area. In April 1994, blocking/transport of Vistula waters towards the east by strong N–W winds was observed. In November 1994 the prevailing S wind aided the Vistula outflow and the transport of these waters northwards.
- The Gulf of Gdańsk is a highly dynamic area. To a great extent, the dynamics control the transport of water masses, and in consequence that of nutrients and dissolved/suspended organic matter to distant regions of the Gulf. In April and November 1994 this process led to the formation of separate pockets of estuarine water. Though undergoing transformation, they formed temporary mini-ecosystems living their own life. At the initial stage of transformation these pockets were characterised by lower salinity and elevated concentrations of nutrients and chlorophyll *a* as compared with surrounding waters.
- The elevated nutrient and chlorophyll *a* concentrations, as well as the higher primary production yielded very similar surface distribution patterns in April 1994, an indication of well-pronounced links between the presence of nutrient-rich water and the increased biological production in the estuarine zone.

- Analysis of the vertical profiles of chemical/physical parameters showed that the Vistula waters, rich in nutrients and in dissolved/suspended organic matter, entered the Gulf of Gdańsk in the surface (0–20 m) layer. The most pronounced vertical gradient, best expressed by nitrates, was found in April (a drop from over 50 to a few μmol dm^{-3} in the 0–5 m layer).
- Both the horizontal and the vertical distribution of ammonia indicates its higher concentrations in July than in April or November. This most probably resulted from higher regeneration of ammonia in the water column by heterotrophic organisms and from intensified bacterial processes under the thermal conditions obtaining.

Acknowledgments

I would like to express my sincere gratitude to Dr. Elżbieta Niemirycz from the Institute of Meteorology and Water Management, Maritime Branch, Gdynia, for allowing me access to her data on discharges of nutrients and water into the Gulf of Gdańsk in 1994 prior to her own publication. Special thanks are also due to Leszek Frankowski (from Gdańsk University) and Hanna Wróblewska for their help in the determination of chemical parameters at sea, to Mariusz Zalewski for his assistance in the chemical analyses at sea and for plotting the graphs, and to Dr. Zbigniew Witek for his valuable suggestions and remarks on the manuscript.

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