Variability in nutrient distribution in the Pomeranian Bay in September 1993

OCEANOLOGIA, No. 38 (2)
pp. 195–225, 1996.
PL ISSN 0078–3234

Baltic Sea
Nutrients
Odra impact
Spatial variability

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Manuscript received November 27, 1995, in final form February 2, 1996.

Abstract

Physical and biological factors as well as water/nutrient discharges from the river Odra (via the Szczecin Lagoon and the rivers connecting the Lagoon with the Pomeranian Bay) were found to affect nutrient distribution in the Pomeranian Bay in September 1993. Other factors influencing this distribution included the eutrophic waters of the Greifswalder Bodden, and physical phenomena such as upwelling and the pulsating nature of the river Świna's outflow. The dynamics of the water are thought to be a significant factor in the transport/transformation of riverine water. A separate 'mini-ecosystem', characterised by distinct chemical, physical and biological parameters, was recorded.

1. Introduction

The Baltic Sea is surrounded by highly industrialised countries with a total population of over 70 million people. Its drainage area is roughly four times as large as its surface area of 373 000 km^2 (Wulff *et al.*, 1990). Highly diversified with respect to physical, chemical and biological parameters, the Baltic has been divided into seven subregions, of which the Baltic Proper is the largest (Ehlin, 1981). The drainage area of the Baltic Proper is 568 973 km^2, and of this no less than 311 900 km^2 belongs to Poland (HELCOM, 1993).

The Vistula and the Odra (German – Oder) are the two largest Polish rivers carrying nutrients, and suspended and dissolved matter into the Baltic (Dojlido *et al.*, 1994; Falkowska *et al.*, 1993; Niemirycz and Makowski, 1992; Niemirycz and Markiewicz, 1993; Niemirycz and Żebrowska, 1992; Niemirycz *et al.*, 1994; Rybiński and Niemirycz, 1991). These rivers differ not only in the volumes of water and pollutant loads they discharge into the bays, but also in their estuaries: the Vistula enters the Gulf of Gdańsk directly while the Odra flows into the Pomeranian Bay (Pommersche Bucht) via the Szczecin Lagoon (Oderhaff). Monitoring studies show that 35% of river waters and 40% of waste waters in Poland flow through lagoons and coastal lakes before entering the sea. These reservoirs, with retention times of several weeks, are influenced by periodic inflows of seawater. The decomposition and accumulation of pollutants resulting from the long retention time in such reservoirs permit a significant decrease in the pollution loads carried into the sea (HELCOM, 1993; Robakiewicz, 1993).

Excessive loads of nitrogen and phosphorus have led to the degradation of the Baltic Sea environment, and the question 'How much more can the ecosystem take?' is being raised ever more frequently. The changes taking place in the Baltic Sea have prompted all the Baltic countries to conduct investigations focused not only on the functioning of the ecosystem in the Baltic Proper, but also on the coastal zones, which are particularly exposed to the adverse effects of discharges of anthropogenic substances (Baden *et al.*, 1990; Cederwall and Elmgren, 1990; Granéli *et al.*, 1990; Hanson and Rudstam, 1990; Nehring, 1991; Nehring and Matthäus, 1994; Nowacki, 1994; Ochocki *et al.*, 1995b; Pastuszak, 1995; Rosenberg *et al.*, 1986, 1990; Rydberg *et al.*, 1990; Trzosińska, 1994; Witek, 1993). The Gulf of Gdańsk and the Pomeranian Bay are the two regions which have become study areas in the Polish economic zone. Generally speaking, it seems that in the past few decades much more has been done in the Gulf of Gdańsk region, where a number of scientific institutions are located, than in the Pomeranian Bay. The present Polish – German interdisciplinary pilot study, carried out in the Pomeranian Bay in September 1993, provided the impetus for the first comprehensive programme to cover chemical, physical and biological investigations in this region. The pilot study was conducted on board the following research vessels: the Polish r/v 'Baltica'[1],

[1]These studies were carried out within the framework of project O/114: 'The impact of eutrophication on trophic relations in different coastal areas of the south-eastern Baltic' financed by the State Committee for Scientific Research, Republic of Poland, the funds having been provided for the statutory activity of the Institute.

r/v 'Oceania' and the motorboat 'Stynka'[2], and the German r/v 'A. v. Humboldt' and r/v 'Prof. A. Penck'. The main objective of the programme was to study the processes responsible for the transport and transformation of nutrients, as well as suspended and dissolved organic matter carried into the Pomeranian Bay by the river Odra.

The importance of chemical measurements has arisen for three reasons: firstly, nutrients control the autochthonous primary formation of organic matter; secondly, the interpretation of biological processes requires an interdisciplinary environmental background which includes both physics and chemistry; and finally, the chemical parameters, together with the biological and physical ones, are indicators of the processes under scrutiny in the pilot and main studies. The aim of the present paper is to discuss nutrient concentration variability with reference to the physical and biological factors recorded in the Pomeranian Bay in September 1993. Nutrient variability is also discussed with reference to the literature on discharges from the river Odra in 1993, which not only allows the reader to compare the observed nutrient concentrations to discharges in September 1993, but also provides a picture of the annual and interannual variability in nitrogen and phosphorus discharges, the latter depending to a great extent on variable riverine water discharge.

2. Materials and methods

This paper is based on the materials collected during cruises of r/v 'Baltica', r/v 'A. v. Humboldt' and the motorboat 'Stynka' in the Pomeranian Bay on 22–30 September 1993 (data in the Świna mouth were collected until 7 October 1993) (Fig. 1).

In order to characterise the short-term variations in the hydrological, hydrochemical and biological parameters, two sampling runs were done by r/v 'A. v. Humboldt' at the same grid of stations, with a time lapse of 3 days; the first on 24–27 September 1993, the second on 27–30 September 1993. The task of 'Stynka' was to collect water in the mouth of the river Świna and at some selected shallow stations in the coastal zone which were inaccessible to large research vessels but very important with respect to the discharge and distribution of pollutants. The CTD measurements on r/v 'Baltica' were done with the help of a Neil Brown Mark III CTD combined with a General Oceanic rosette sampler. The temperature and salinity measurements

[2]The offshore measurements on 'Stynka' (a motorboat belonging to the Świnoujście branch of the Sea Fisheries Institute) were done within the framework of a separate grant: 'Bottom fauna as an element allowing determination of the environmental state of the Szczecin Lagoon and the Pomeranian Bay', project 5 S311 006 05, conducted by Dr. N. Wolnomiejski and J. Grygiel of the SFI.

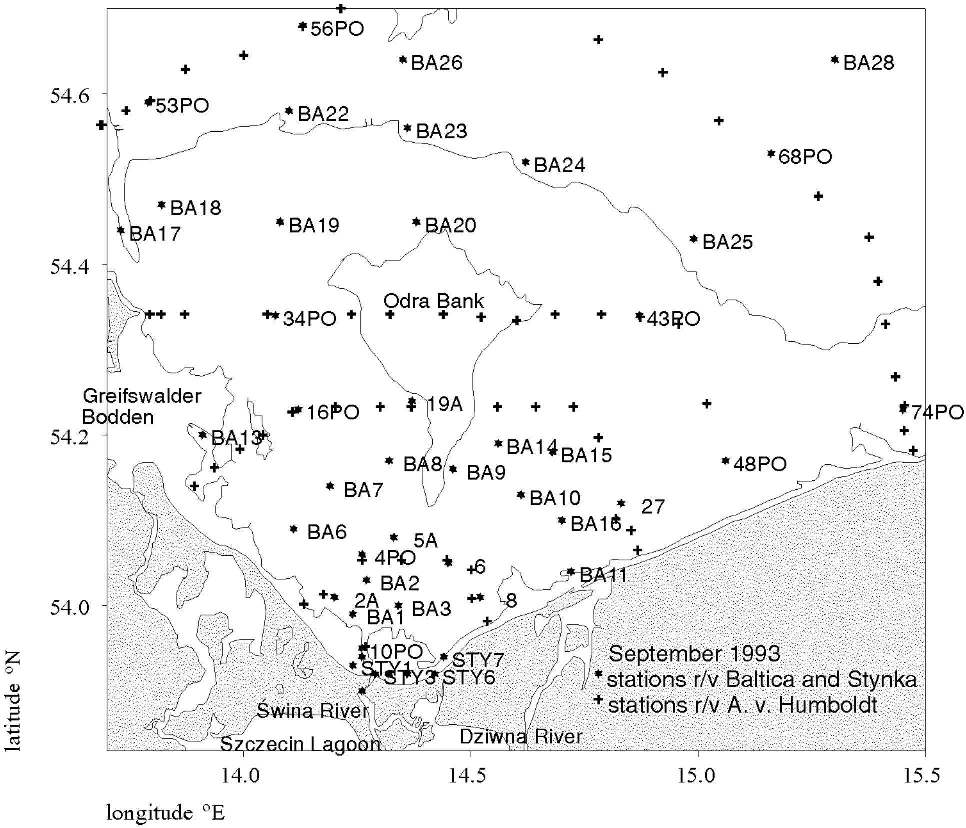


Fig. 1. Study area and the location of sampling stations at which measurements were carried out by r/v 'Baltica', r/v 'A. v. Humboldt' and the motorboat 'Stynka' in the Pomeranian Bay on 22–30 September 1993 (measurements in the Świna mouth were conducted until 7 October 1993)

on 'Stynka' were made with reversing thermometers and a Plessey Environmental Systems 6230N salinometer. Water samples were collected at the following depths: 0, 3, 5, 10, 15, 20, 30, 40 m; the near-bottom level was as close to the bottom as possible. On the two Polish vessels nutrient analyses were performed manually, and the following spectrophotometers were used: a Beckman 26 on r/v 'Baltica' and a Spekol 11 (Carl Zeiss Jena) at the SFI Branch in Świnoujście. 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; ammonia by the blue indophenol method of Koroleff; silicates by the blue method of Mullin and Riley; total N and total P with the Koroleff method involving the simultaneous persulphate oxidation of phosphorus and nitrogen compounds. The dissolved oxygen content was determined by the Winkler method (Grasshoff *et al.*, 1983).

Nutrient analyses on board r/v 'A. v. Humboldt' were performed with an Alliance Instruments five-channel autoanalyser system using standard methods adapted for continuous flow systems (Grasshoff *et al.*, 1983).

3. Results

Temperature

The surface temperature in the central part of the investigated region of the Pomeranian Bay ranged from 13.0 to 13.5°C, and remained unchanged from the surface to the bottom. Markedly lower values were observed in the northern part of the region, where they varied from 12.5°C at the surface to 8.5°C near the bottom. The temperature of a separate pocket of water at stations 5A and 4PO was lower by about 0.6°C as compared with the surrounding waters (Fig. 2).

Salinity

The surface salinity in most parts of the region studied lay within the 7.6–7.8 PSU range. Two 'patches' with lower salinity were recorded, one in the vicinity of stations 5A and 4PO, the other in the Świna estuary. In the former area the salinity was lower by 0.4 PSU while in the latter it was lower by 1.8 PSU as compared with the values found in the surrounding waters (Fig. 3).

Oxygen content

The waters of the central and eastern parts of the Pomeranian Bay contained from 7.0 to 7.4 $cm^3\ dm^{-3}$ oxygen. Four areas with a pronounced horizontal gradient were recorded:

1) the northern part of the region with a tongue of less oxygenated waters at 10 m depth;
2) the area east of the Greifswalder Bodden with an oxygen content lower by 0.6 $cm^3\ dm^{-3}$ in the inshore waters;
3) the Świna estuary, where the oxygen content dropped to 6.0 $cm^3\ dm^{-3}$;
4) stations 5A, 6 and 4PO, characterised by a maximum oxygen content at the surface (values higher by 0.2 $cm^3\ dm^{-3}$) coinciding with temperature and salinity minima and total nitrate depletion (Fig. 4).

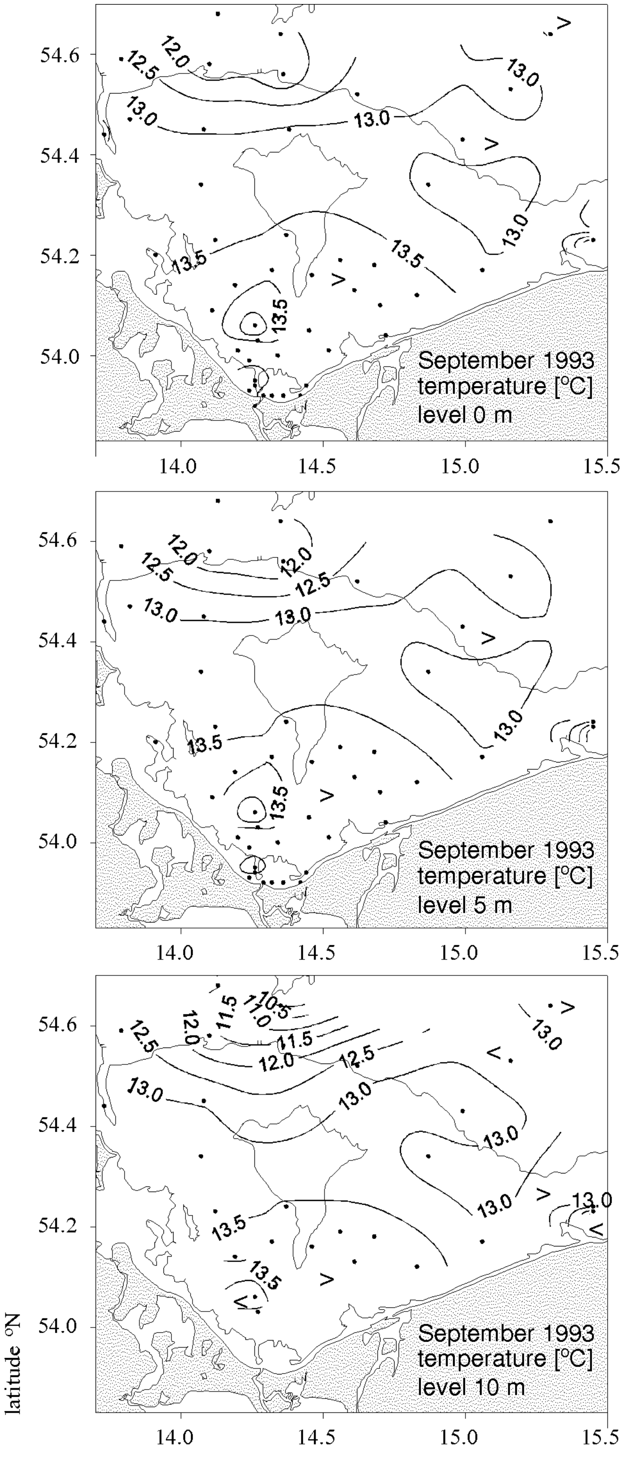


Fig. 2. Distribution of temperature at 0, 5 and 10 m depths on 22–30 September 1993

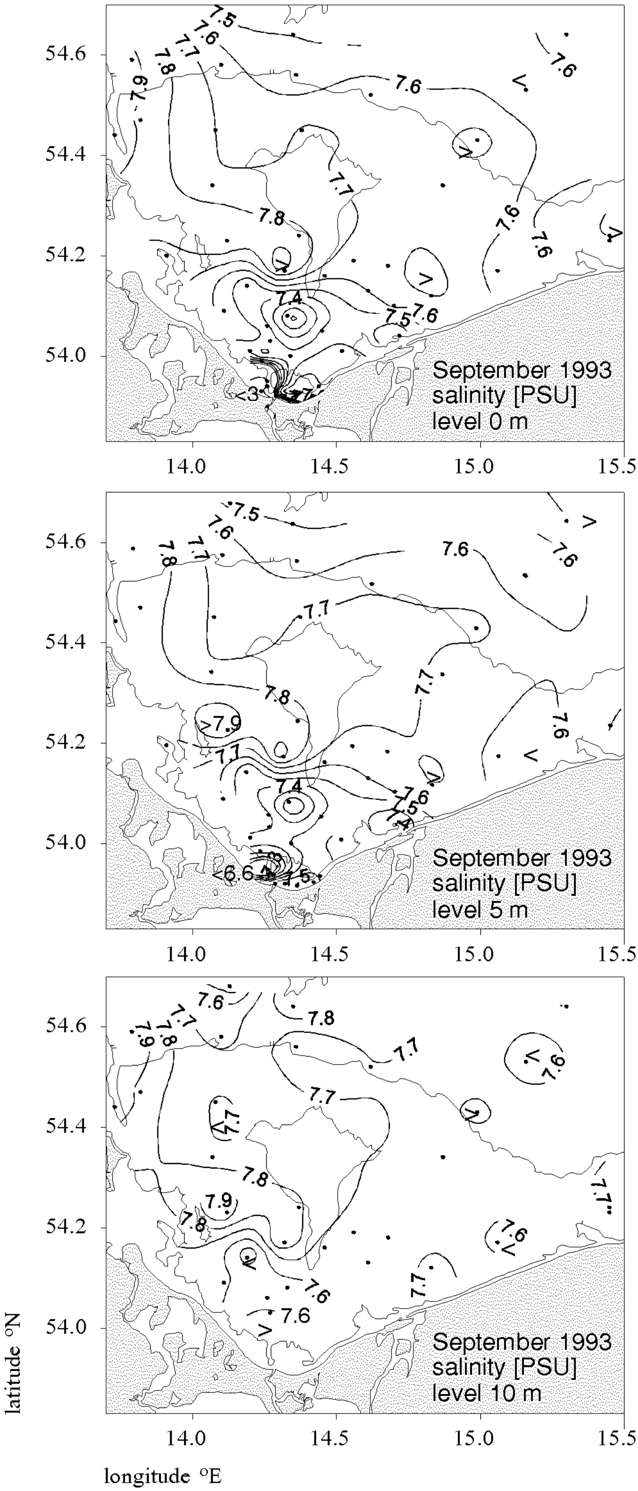


Fig. 3. Distribution of salinity at 0, 5 and 10 m depths on 22–30 September 1993

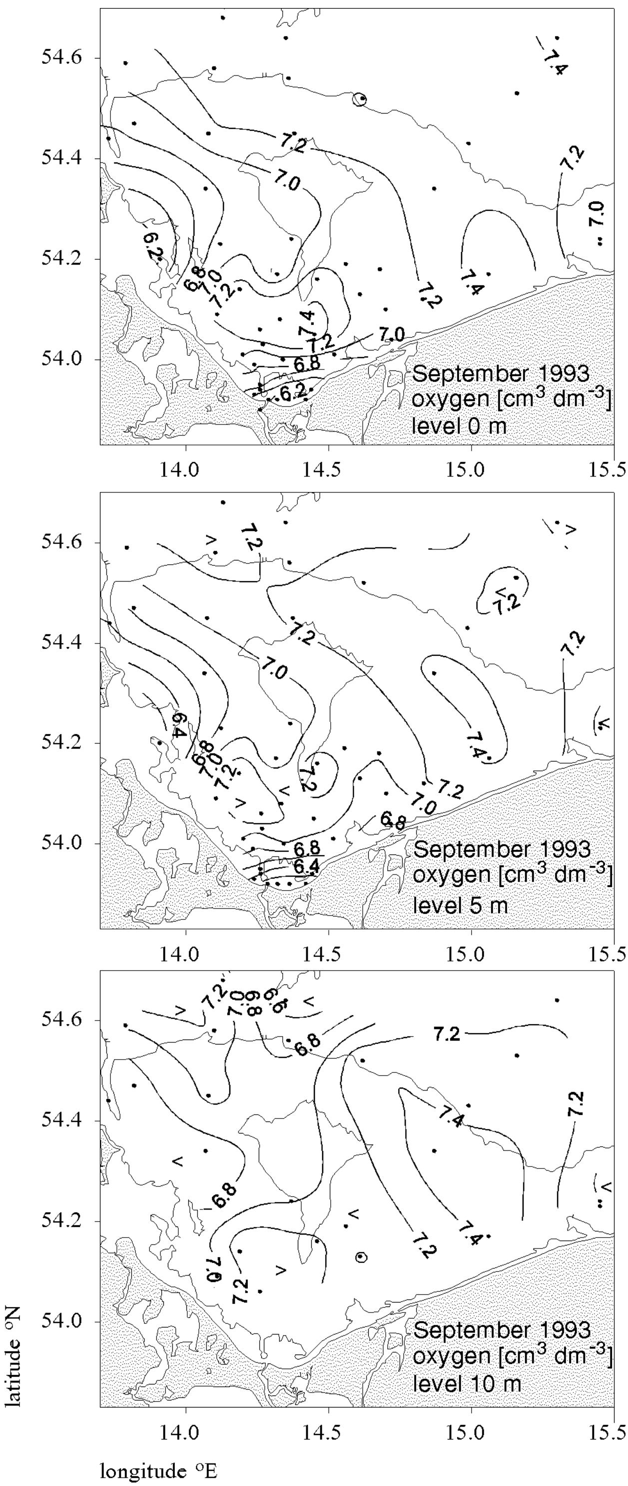


Fig. 4. Distribution of oxygen content at 0, 5 and 10 m depths on 22–30 September 1993

Nitrates

The nitrate distribution measured by r/v 'Baltica' and r/v 'A. v. Humboldt' (during the first run of the latter on 24–27 September 1993) showed a very similar horizontal pattern at 0, 5, and 10 m depths (Figs. 5, 6). The N–NO_3 concentrations measured by the two vessels in the waters surrounding the Odra Bank were in agreement: they were well below 0.5 μmol dm^{-3}. The waters of the coastal zone, namely north-east of the river Dziwna and to the east of the Greifswalder Bodden, were rich in nitrates, and their respective maximum concentrations, measured by r/v 'Baltica', were *ca* 3 and *ca* 2 μmol dm^{-3} (Fig. 5). Slightly higher values in these areas were recorded by r/v 'A. v. Humboldt', which could have been due to the closer location of the German sampling stations to the shore (Figs. 1, 5, 6).

The nutrient measurements done by r/v 'A. v. Humboldt' on 27–30 September 1993 revealed quite a different distribution pattern of nitrates in the coastal zone, three maxima being present there (Fig. 7). Two of them, the first north-east of the river Dziwna and the second east of the Greifswalder Bodden, coincided with those found three days earlier (24–27 September 1993), their values being *ca* 3 μmol dm^{-3} higher in the north-eastern area, and comparable with that in the vicinity of the Greifswalder Bodden. The third, well-pronounced maximum was observed in the Świna estuary at 0 and 5 m depth, where concentrations were in excess of 7 μmol dm^{-3}.

Ammonia

The horizontal distribution pattern of ammonia was similar, displaying maximum values of 2 μmol dm^{-3} in the Dziwna estuary and of *ca* 4 μmol dm^{-3} east of the Greifswalder Bodden, the latter horizontal gradient being more pronounced, particularly at 5 m depth. The highest values of ammonia corresponded with the low oxygen content and the elevated phosphate concentrations. The waters surrounding the Odra Bank had ammonia concentrations of < 0.5 μmol dm^{-3} (Fig. 8).

Phosphates

Phosphate concentrations in the waters around the Odra Bank varied from 0.3 to 0.5 μmol dm^{-3}. Elevated P–PO_4 concentrations were recorded in the Świna estuary (0.8–2.0 μmol dm^{-3}) and in the Dziwna estuary (*ca* 1 μmol dm^{-3}). The northern part of the region studied was marked at 10 m depth by a tongue of water with P–PO_4 concentrations 0.2–0.4 μmol dm^{-3} higher than those of the surrounding waters (Fig. 9).

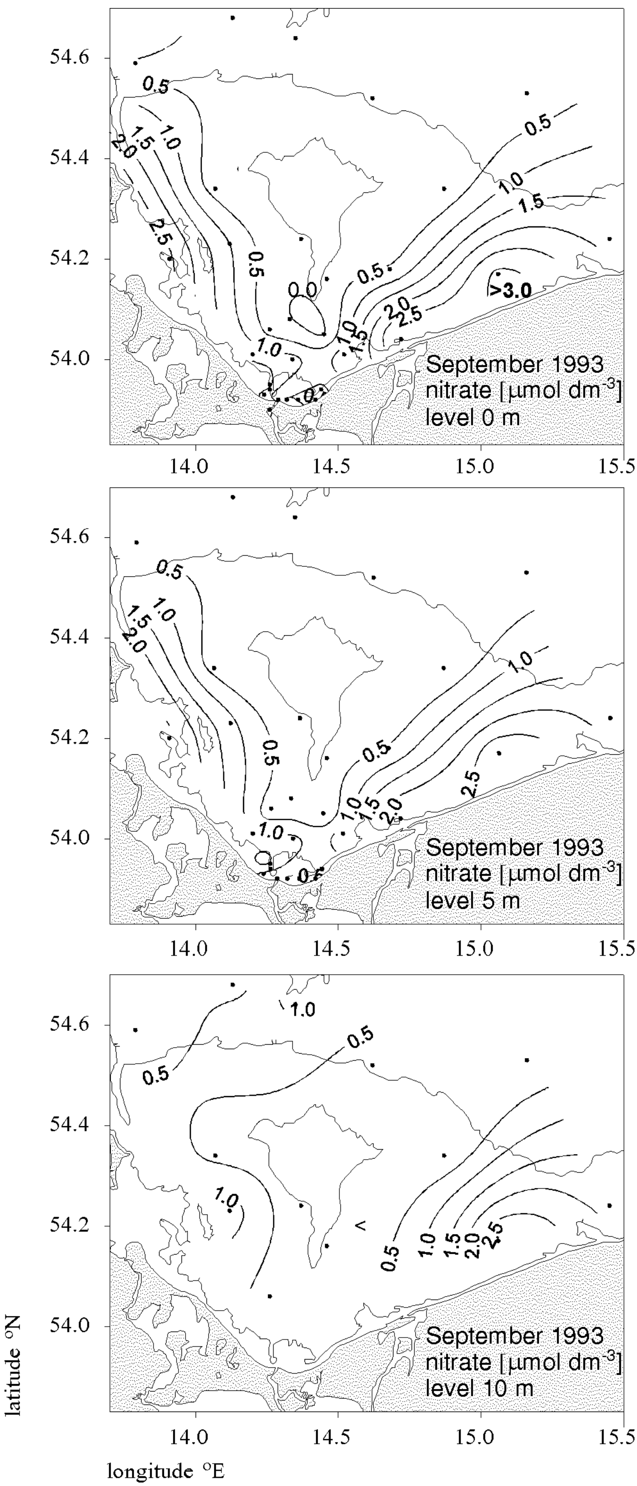


Fig. 5. Distribution of nitrates at 0, 5 and 10 m depths measured by r/v 'Baltica' and the motorboat 'Stynka' on 22–30 September 1993

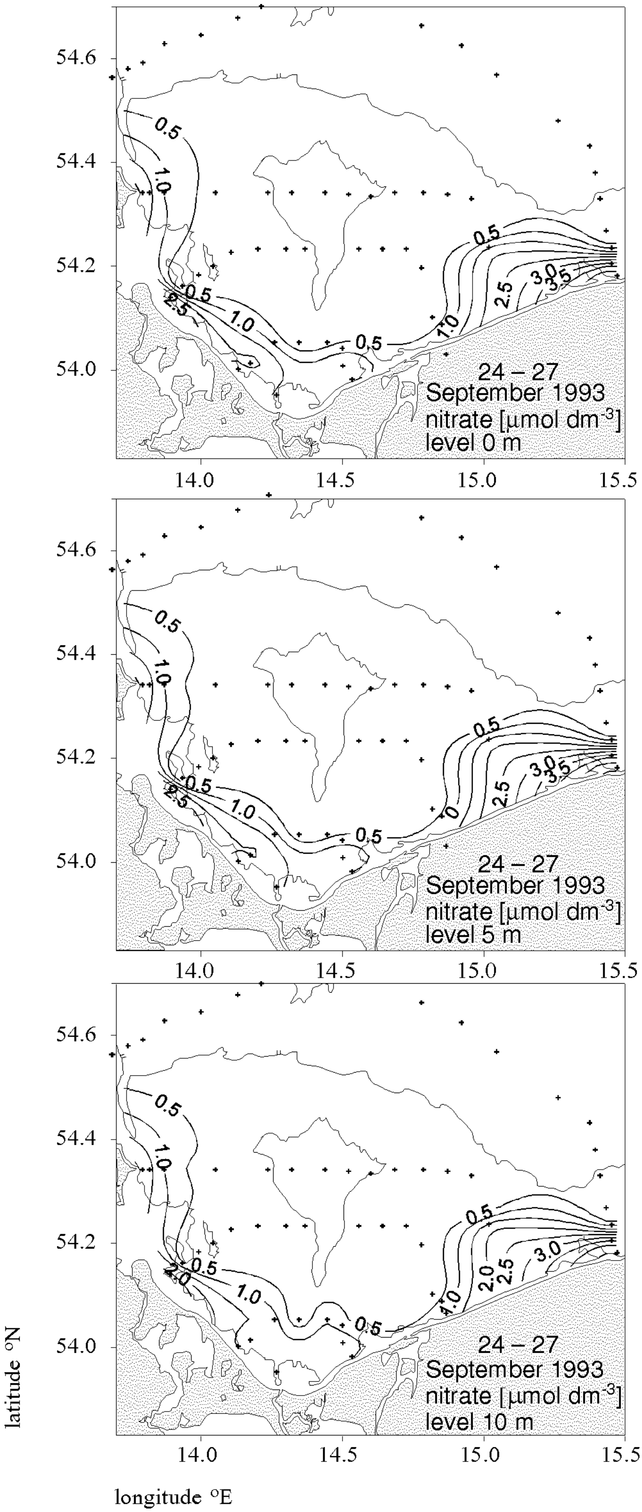


Fig. 6. Distribution of nitrates at 0, 5 and 10 m depths measured by r/v 'A. v. Humboldt' during her first run on 24–27 September 1993

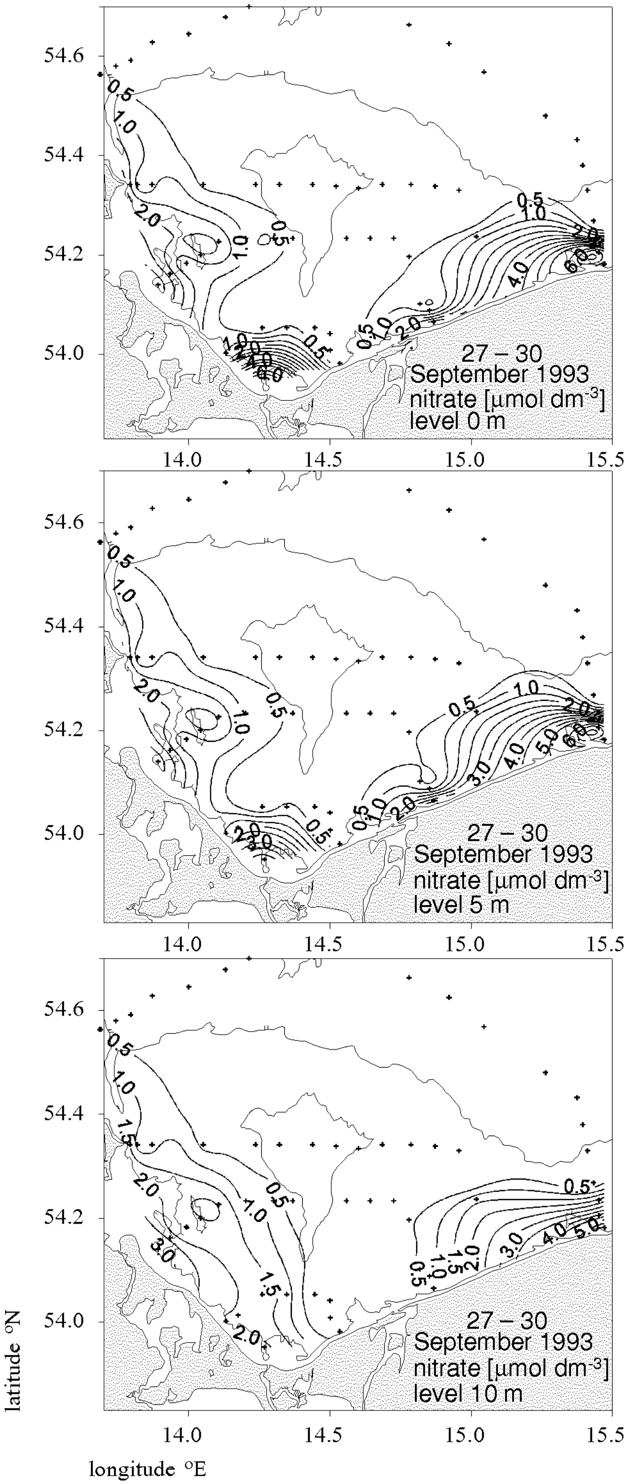


Fig. 7. Distribution of nitrates at 0, 5 and 10 m depths measured by r/v 'A. v. Humboldt' during her second run on 27–30 September 1993

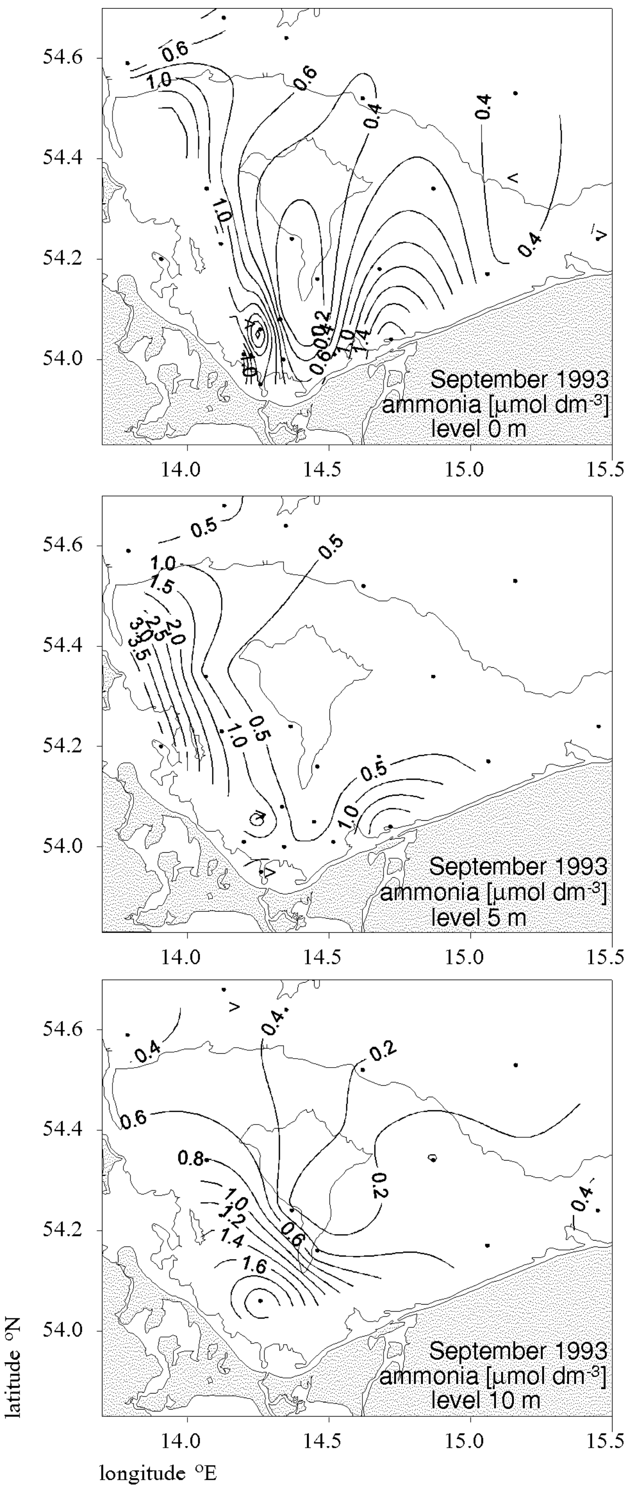


Fig. 8. Distribution of ammonia at 0, 5 and 10 m depths on 22–30 September 1993

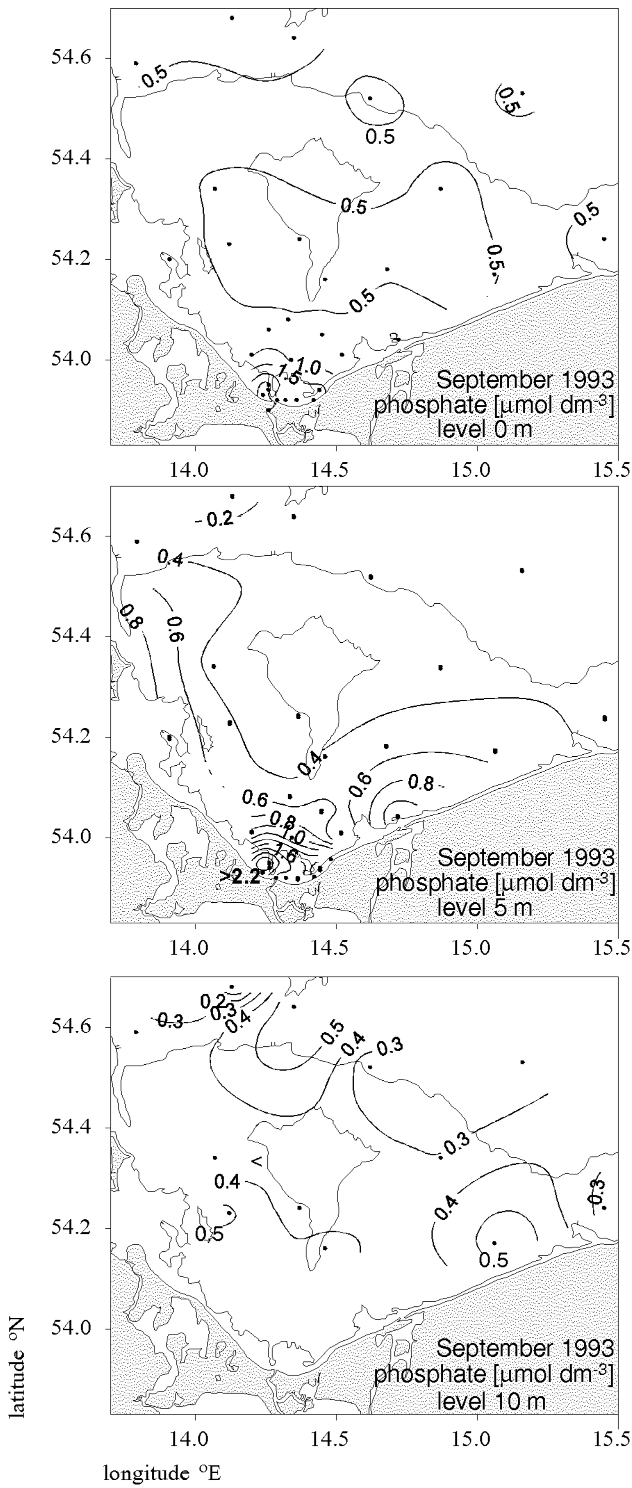


Fig. 9. Distribution of phosphates at 0, 5 and 10 m depths on 22–30 September 1993

Silicates

The central part of the area, around the Odra Bank, displayed low surface silicate concentrations, ranging from 10 to 12 μmol dm^{-3}. A pronounced horizontal silicate concentration gradient was recorded in the belt of waters spreading in a north-westerly direction from the Świna/Dziwna estuary. The highest silicate concentrations (30 μmol dm^{-3}) were found in the Dziwna estuary. Relatively high silicate concentrations were recorded in the entire water column (Fig. 10).

Total nitrogen and phosphorus

The total horizontal nitrogen and phosphorus distributions were variable at different levels, with some closed maxima/minima at 0 and 5 m depth. At 0 m, the influence of the land was in evidence, resulting in a belt of elevated concentrations of these species (22–28 μmolN dm^{-3} and 1.2–1.4 μmolP dm^{-3}) spreading eastwards from the Świna estuary. At 10 m depth the highest total N (22–32 μmol dm^{-3}) occurred north-east of the Lagoon outlets, whereas in the northern area a wedge of water with higher total nitrogen and phosphorus concentrations (22–26 μmolN dm^{-3} and 1–1.2 μmolP dm^{-3}) was recorded (Figs. 11, 12).

Studies in the river Świna

The data collected during 17 days of sampling from the motorboat 'Stynka', were indicative of the pulsating nature of the water outflow from the Szczecin Lagoon. The inflow/outflow of salt/fresh waters was reflected by an increase/decrease in salinity and decrease/increase in nutrient concentrations. The maximum salinity difference was 6 PSU, while in the case of nitrates and phosphates the greatest amplitude amounted to 5–6 μmol dm^{-3}. During the study period, salt water inflows occurred three times at the surface and four times near the bottom (Fig. 13). Maximum salinity values, accompanied by minimum nutrient concentrations, reflecting the inflow of Bay water up the river Świna, were observed on 23–26 September 1993, 3 and 6–7 October 1993. Low salinity and high nutrient concentrations, parameters typical of outflowing Lagoon waters, were found on 21–22 September, 27 September – 2 October, and 4–5 October 1993.

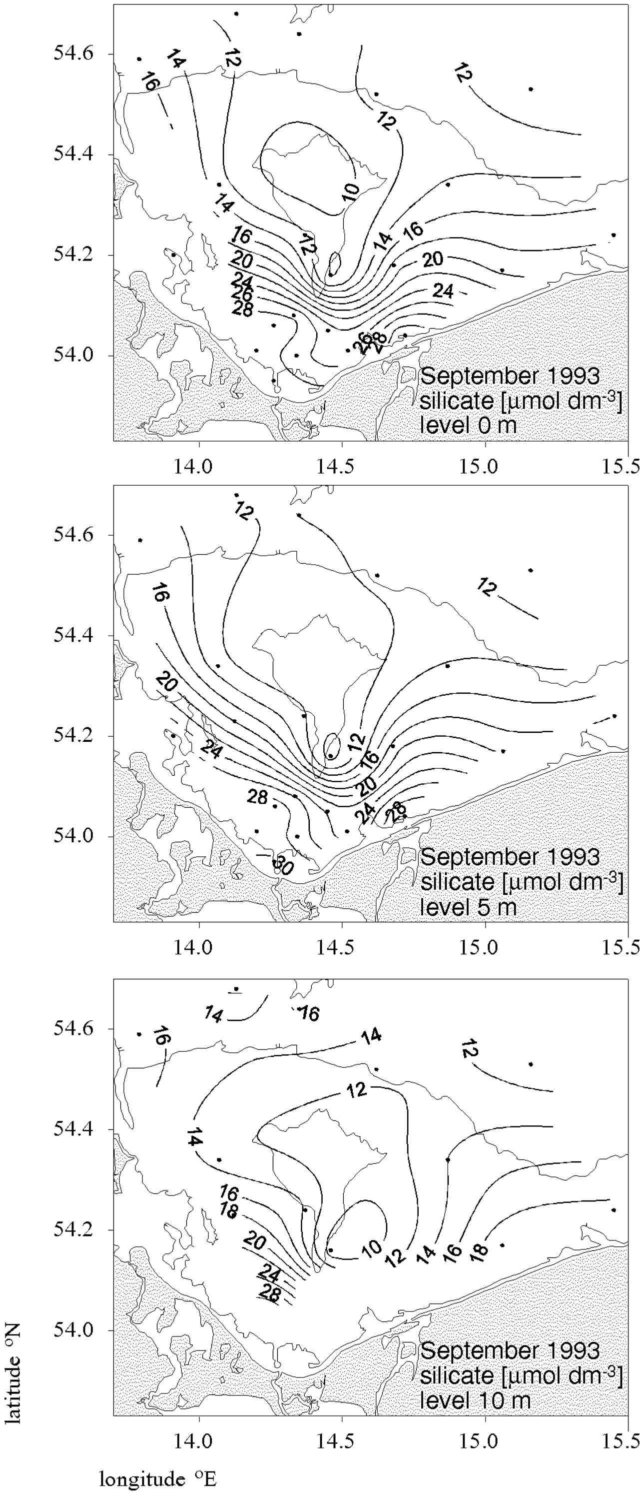


Fig. 10. Distribution of silicates at 0, 5 and 10 m depths on 22–30 September 1993

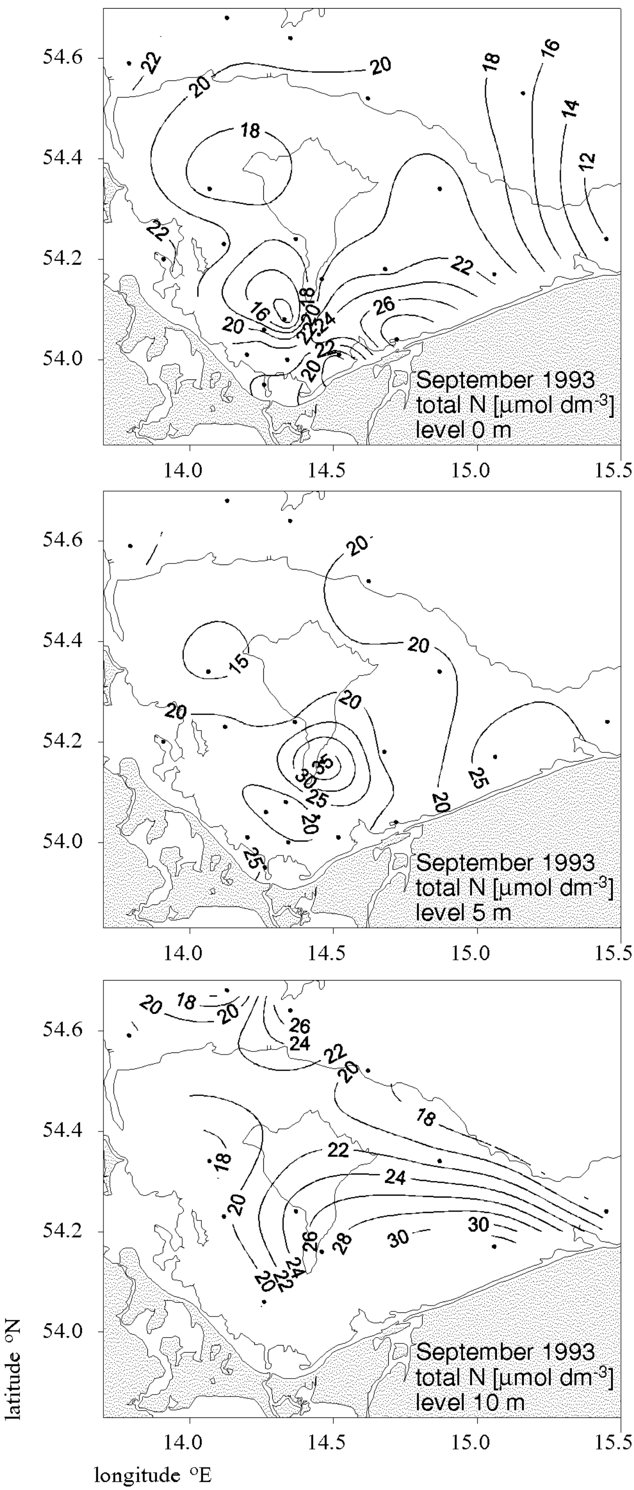


Fig. 11. Distribution of total nitrogen at 0, 5 and 10 m depths on 22–30 September 1993

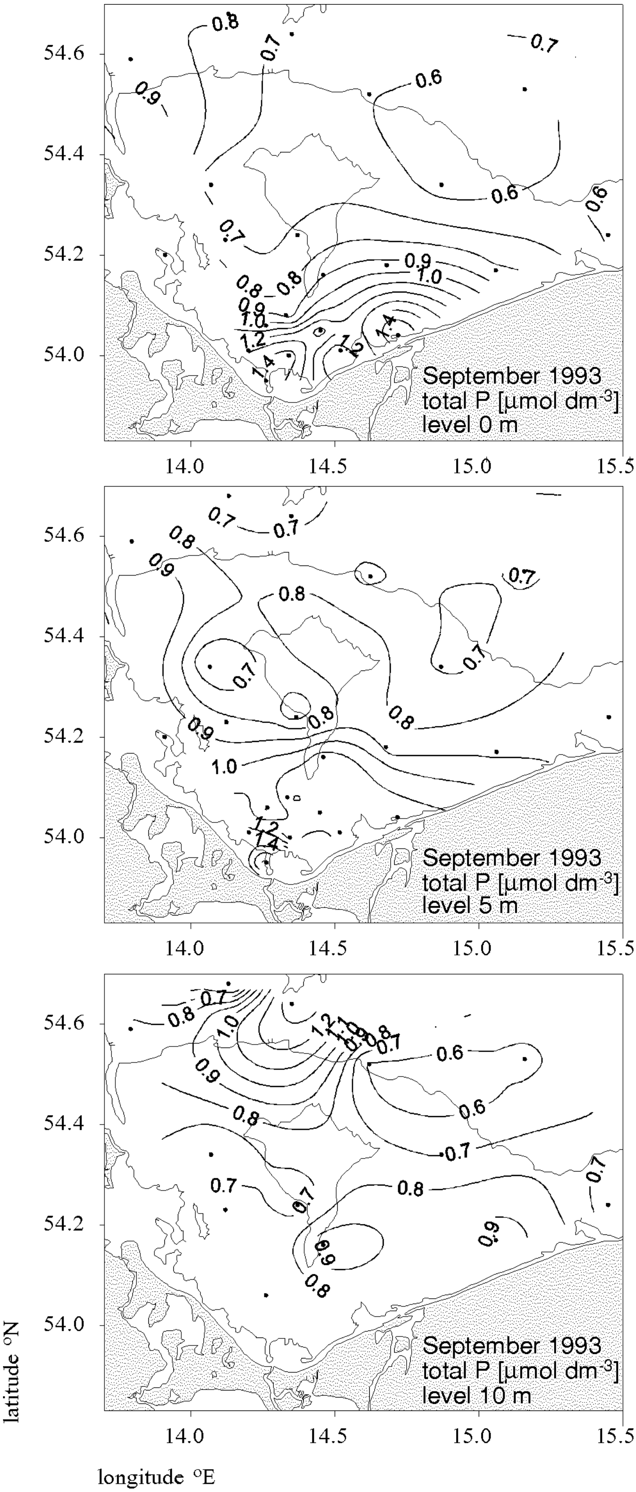


Fig. 12. Distribution of total phosphorus at 0, 5 and 10 m depths on 22–30 September 1993

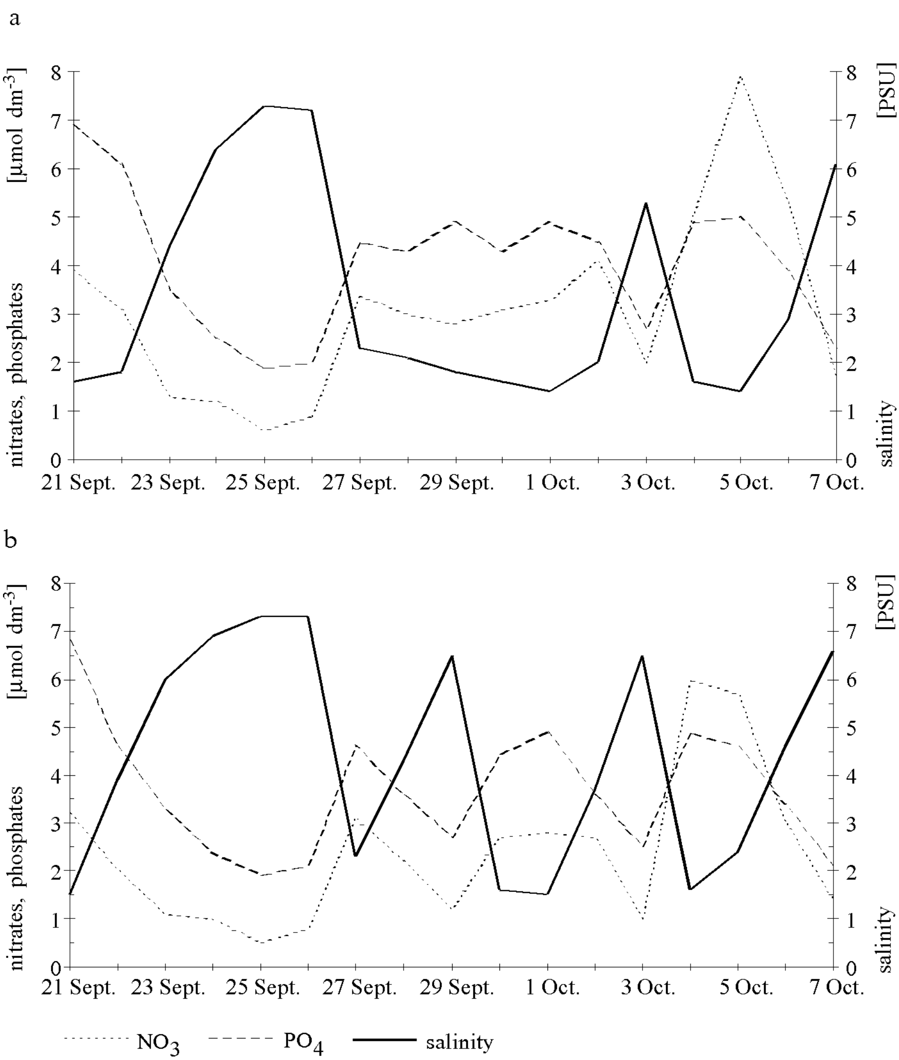


Fig. 13. Temporal variations in nitrates, phosphates and salinity at the surface (a) and near the bottom (b) at the station located in the mouth of the river Świna, 21 September – 7 October 1993

4. Discussion

Most of the drainage area of the Pomeranian Bay consists of the drainage area of the Szczecin Lagoon (89.5%); direct outflows of water into the Bay, however, are relatively insignificant, contributing as they do only a small percentage on either side of the frontier. The main supplier of water to the Bay is the river Odra, whose tributaries make up 86.3% of the entire drainage area. The only other rivers of importance flowing into the

Bay are the Parsęta and the Rega on the Polish side, and the Peene and the Uecker with its tributary the Randow, on the German side. Majewski (1974) calculated the total outflow of river water into the Bay for the years 1951–1960 at 560 m^3 s^{-1}, which gave a volume of 17.6 km^3 $year^{-1}$. Differences in the average monthly outflows in a given year are rather large, varying from 359 m^3 s^{-1} in September to nearly 900 m^3 s^{-1} in March, during the spring snowmelt. In the period between December and May as much as 2/3 of the entire annual volume of freshwater enters the sea, and the outflow into the Bay peaks between January and April (46%). The outflow of riverine water in summer and autumn (June–September) is relatively low. Being rather shallow, the Pomeranian Bay has a small volume (73 km^3), and this is fed by a relatively large volume of riverine water (15–20 km^3) (Robakiewicz, 1993). The freshwater supply plays an important role in shaping the hydrological and hydrochemical conditions in the annual cycle of the Bay (Majewski, 1974; Fig. 14).

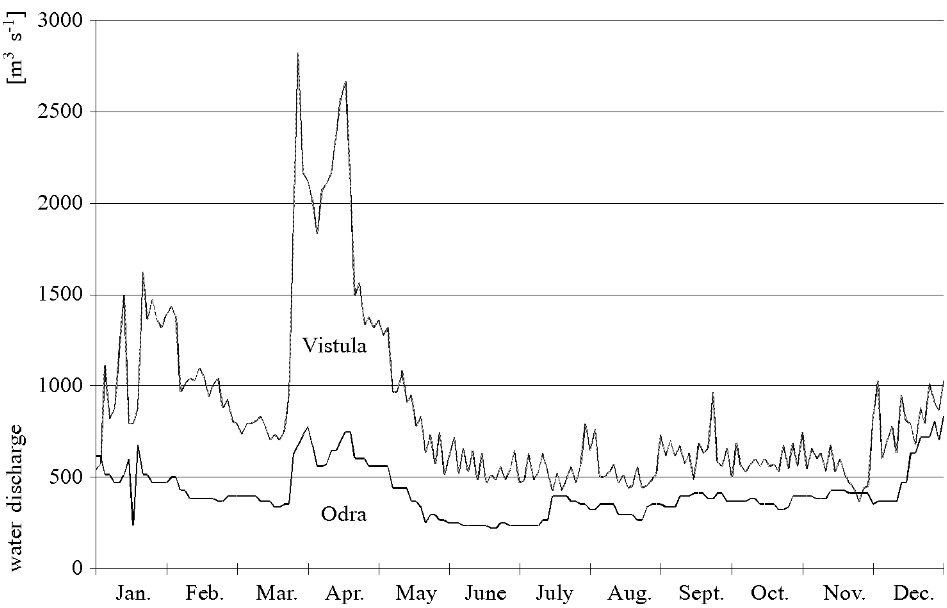


Fig. 14. Water discharge from the rivers Odra and Vistula during 1993 (after Niemirycz, 1994)

The horizontal distributions of salinity, temperature, oxygen content, and nutrients (Figs. 2–12), analysed on the basis of data collected on board r/v 'Baltica' and the motorboat 'Stynka', allow the following four subregions to be distinguished in the study area:

- a northern subregion with a much lower temperature and oxygen content, and slightly elevated concentrations of nitrates, phosphates and silicates (nutrients and oxygen at 10 m);
- a western subregion (east of the Greifswalder Bodden) with a distinctly lower oxygen content in the entire water column and elevated ammonia and phosphate concentrations;
- a subregion around stations 5A, 6 and 4PO (a separate water mass), characterised by a lower temperature and salinity, and a higher oxygen content; nitrates, however, are depleted;
- a belt of coastal waters, spreading north-east and north-west of the mouths of the Świna and Dziwna, characterised by a lower salinity and oxygen content but higher nitrate, silicate, ammonia, total N and total P concentrations.

The northern subregion, characterised by a lower temperature, an oxygen content lower by 0.6 cm^3 dm^{-3}, elevated nitrates, phosphates and silicates (nutrients and oxygen at 10 m), is considered to be a transition zone between the shallow Pomeranian Bay and the deep Arkona Basin (Figs. 2, 4, 5, 9 and 10). Pronounced differences in the surface water temperature are clearly visible in the infrared satellite images obtained by Siegel *et al.* (1994a). According to these workers the dynamic processes in the western Baltic Sea are caused by sea-level differences between the North and Baltic Seas, as well as by the local wind direction and the freshwater input. The response patterns are modified by the Earth's rotation, the bathymetric structure and the alignment of the coast. The cross – section done by r/v 'A. v. Humboldt' in the northern part of the Bay revealed the upwelling in the southern part of the Arkona Basin of cold and poorly oxygenated water (Lass, 1994). This water not only affected the northern flank of the Bay but also flowed in a southerly direction, in the intermediate layer, along the bottom of a flat trench east of the island of Rügen. That transport of water mass, having different characteristics, affected the distribution of the hydrochemical parameters in the western subregion. This area, adjacent to the Greifswalder Bodden, was characterised by a lower oxygen content in the entire water column and by elevated ammonia and phosphate concentrations, the latter two parameters having been measured at 5 m depth (Figs. 4, 8, 9). It seems, however, that the overall picture found in that part of the Bay was, and perhaps usually is, affected by the proximity of the eutrophic Greifswalder Bodden (Biester, 1991; Hantke and Oeberst, 1991).

The subregion around stations 5A, 6 and 4PO was distinguished by a separate water mass whose physical, chemical and biological parameters were different from those of the surrounding waters. It seems that this pocket of water, forming a 'mini-ecosystem' living its own life, had most probably undergone transformation before it was encountered in September 1993. A newly-separated portion of freshwater is characterised by the lower salinity but also the higher nutrient concentration typical of estuarine zones (Pastuszak, 1995). The elevated oxygen values observed at stations 5A, 6 and 4PO resulted from increased biological production, which in turn led to the depletion of nutrients (nitrates down to zero). According to measurements made by Ochocki *et al.* (1995a), primary production at station 6 peaked at 1930 mgC m^2 d^{-1}. This maximum was higher by about one order of magnitude than the lowest value found in the Pomeranian Bay in 1993, and over twice as high as the primary production measured at station 10 in the coastal zone. The above-mentioned authors found that the chlorophyll *a* concentration at station 6 was one of the highest recorded in the study area (8.66 mg m^{-3}) in the 0–10 m layer.

Although the chemical data obtained by r/v 'Baltica' and r/v 'A. v. Humboldt' show good agreement, there remain some differences in the spatial distribution of individual species, *e.g.* nitrates, which require explanation. The ship-to-ship differences in nitrates in the coastal region adjoining the Greifswalder Bodden and in the belt of waters spreading north-eastwards from the Dziwna estuary (Figs. 5, 6) should be attributed to 'A. v. Humboldt's' much denser grid of stations, covering waters very close inshore. The difference in nitrates measured by r/v 'A. v. Humboldt' in two consecutive runs (24–27 September and 27–30 September 1993) indicates that chemical parameters are highly time-variable. A striking feature of the 'A. v. Humboldt's' second run was the occurrence of both the large patch of nitrate-rich water in the Świna estuary and the higher concentrations found in the much greater area north-east of the Dziwna estuary, as compared with the results of the first run (24–27 September 1993). The elevated values north of the Świna mouth coincided with a large pulse of outflowing Lagoon water recorded on 'Stynka' (Figs. 7, 13).

There are two principal factors responsible for the formation of such an uneven spread of water, *i.e.* the pulsating nature of the water outflow from the river mouths (Majewski, 1974), and the wind-induced water mixing and water transport (Siegel *et al.*, 1994b).

The pulsating nature of the water flowing out of the Lagoon can be seen from the salinity and nutrient measurements made at the station located in the Świna mouth. It is evident from Fig. 13 that the number of salt water inflows is different at the surface and near the river bed. Near the bottom an additional inflow of salt waters was reported on 28–29 September 1993. The dates of this more intense riverine outflow are in very good agreement with German observations. The preliminary elaboration of the data collected by r/v 'A. v. Humboldt' confirmed the pulsating outflow of Szczecin Lagoon water (Lass, 1994). Such pulses were found to be of one day's duration, while the period between two pulses was *ca* 4 days. According to the above author, an intensive outflow of water from the Lagoon took place on 22 September 1993, *i.e.* immediately prior to the pilot study. That outflow was followed by a second one on 28 September 1993 which led to the formation of a separate pocket of water spreading along the island of Usedom/Uznam. It was located 8 km offshore and was *ca* 15 km in width. This outflow event could have given rise to the distribution of nitrates measured by 'A. v. Humboldt' on 27–30 September 1993 (Fig. 7). High concentrations were found in the surface layer (0–5 m) in the Świna estuary. Nutrient-rich Lagoon water was spreading across the top of a seawater mass which contained significantly lower concentrations of nitrate and had a much higher salinity. This spread was governed by south-easterly winds, which enhanced the northward transport of riverine water. The relation between the wind direction and the direction of riverine water transport in the Pomeranian Bay during 1993 is described by Siegel *et al.* (1994b).

According to Siegel *et al.* (1994b), local winds in the Pomeranian Bay are highly variable, with a time-scale from a few hours to a few days. These variations have a significant impact on the distribution pattern of a number of parameters, including chemical ones, in the shallow Bay. The sea surface temperature maps obtained from the Advanced Very High Resolution Radiometer (AVHRR) in 1991–1994 enabled the above authors to define distribution patterns for each wind direction. They are as follows:

- northerly (N) and north-westerly (NW) winds block the outflow of the river Świna and confine it to a narrow strip spreading close to the Polish coast,
- north-easterly (NE) winds favour transport of riverine plumes close to the coast of Usedom,
- easterly winds (E) give rise to upwelling along the Polish coast and cause the riverine water to spread along the shore of Usedom,
- south-easterly (SE) (recorded on 29 September 1993) and southerly winds enhance the northward spread of Świna waters,
- south-westerly (SW) winds transport Świna waters in a north-easterly direction, while westerly (W) winds result in the eastward movement of Świna water *i.e.* close to the Polish shore. The same authors found that wind speed and direction display great seasonal variability.

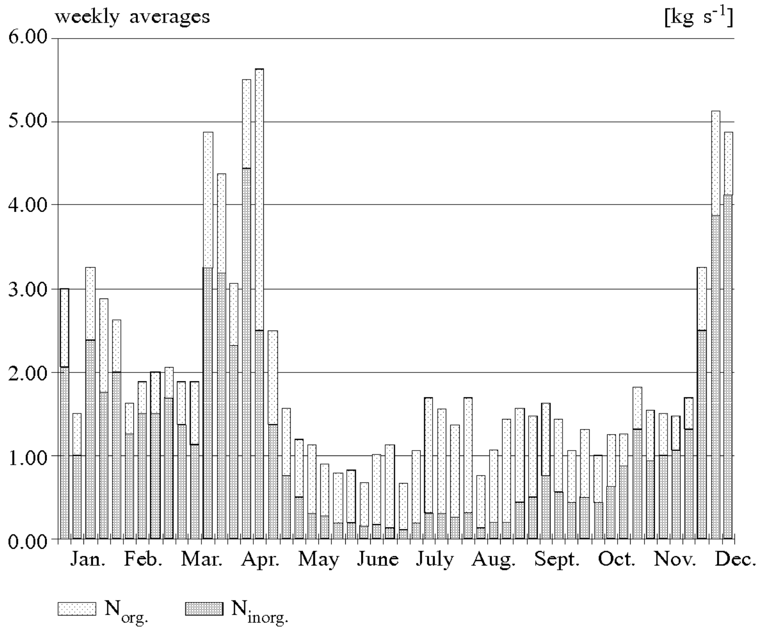
Wind-induced water transport affecting the distribution of chemical parameters was also reported in the Gulf of Gdańsk in 1994 (Pastuszak, 1995).

Majewski (1974) found a clear dependence between currents, and wind force and direction. He stated that particularly strong currents occur in the Świna estuary; moreover, the current velocity could reach 1 m s^{-1}, and during stormy periods it could vary from 1.3 m s^{-1} (when water was accumulating in the Lagoon) to no less than 1.75 m s^{-1} (when the water level in the Bay was falling). It arises from Majewski's findings that there is a periodicity, involving a decrease in the number of salt water inflows in spring and early summer due to intensified outflow from the land, and their increase in summer, autumn and winter owing to strong winds. The outflows of Lagoon water obviously follow the opposite pattern.

The belt of coastal waters adjoining the Świna and the Dziwna estuaries was characterised by lower oxygen but higher nutrient concentrations. It is interesting to note that the nitrate maximum was found east of the Dziwna estuary, but not in the river mouth itself (Fig. 5). This shifted N–NO_3 concentration was also observed by r/v 'A. v. Humboldt' (Figs. 6, 7). These elevated nutrient concentrations, mainly of nitrates and silicates, are apparent not only in the estuaries; they are also present in a broad offshore belt along the Polish and German coasts. Not all the mechanisms responsible for such a distribution pattern can be explained on the basis of the data collected in the pilot study, but they will be one of the objectives of the main studies planned for 1994–1996.

The pattern of nutrient distribution in the Pomeranian Bay is governed not only by the wind-induced water dynamics of the Bay and the Szczecin Lagoon, but also by the variable discharges of the river Odra, the second-largest Polish river. The volume of discharged riverine water and the weekly nutrient loads both display seasonal and interannual variations (Figs. 14, 15, 16), and there is some interdependence between these two parameters, particularly well-pronounced in the water/inorganic nitrogen relationship. There was a considerable predominance of inorganic nitrogen species in the nutrient discharges in outflowing water in 1993, a feature also typical of the years 1988–1993 (Fig. 15; Niemirycz, 1994; Niemirycz and Borkowski, 1993; Niemirycz and Makowski, 1992; Niemirycz and Markiewicz, 1993; Niemirycz and Żebrowska, 1992; Niemirycz *et al.*, 1991, 1994; Rybiński and Niemirycz, 1991; Rybiński and Makowski, 1991; Rybiński *et al.*, 1990). In the case of phosphates the relation between the water and the P–PO_4 discharge seems to be more variable during the year, with a poorly-defined peak even during the spring snowmelt (March, April), thus indicating sources of phosphorus other than penetration from the land. The organic fraction of phosphorus was considerably greater than P–PO_4 concentrations in 1993 (Figs. 15, 16).

a



b

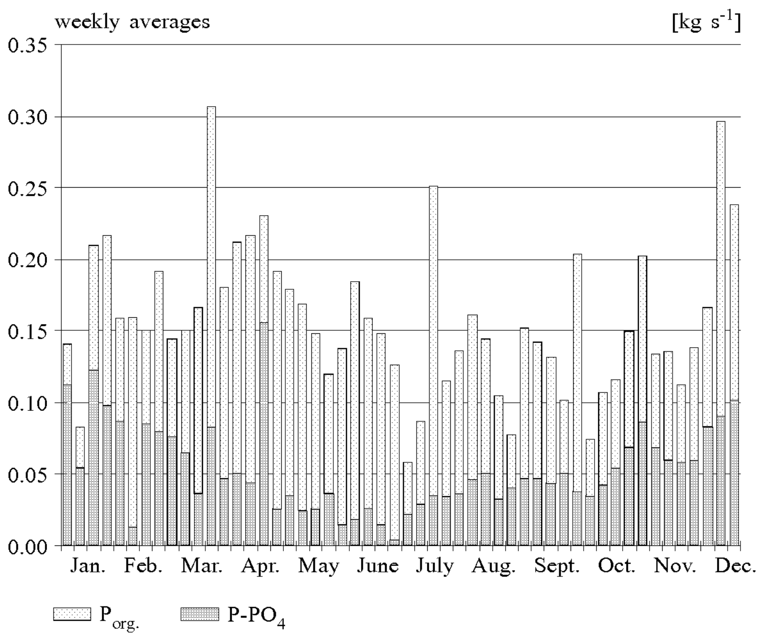
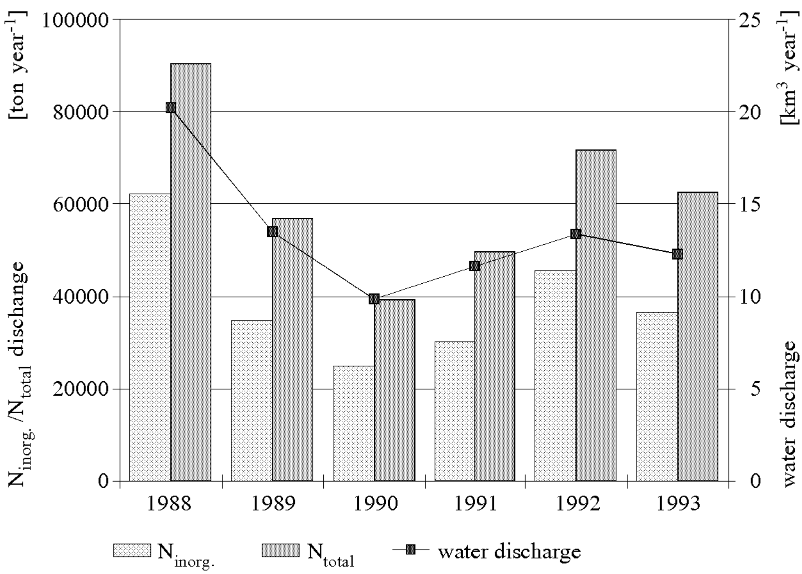


Fig. 15. Nitrogen (a) and phosphorus (b) discharged by the river Odra during 1993 (after Niemirycz *et al.*, 1994)

a



b

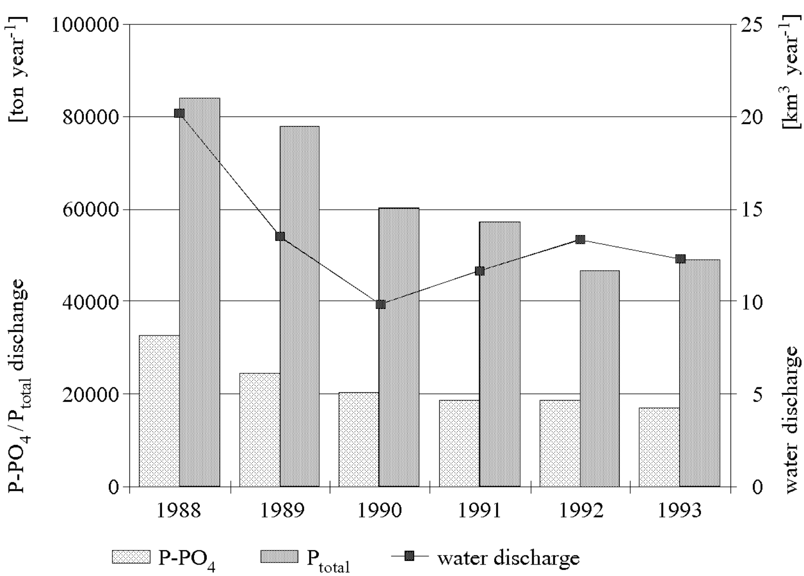


Fig. 16. Nitrogen (a), phosphorus (b) and water discharged by the river Odra in 1988–1993 (figure based on data published by Niemirycz, 1994; Niemirycz and Borkowski, 1993; Niemirycz and Makowski, 1992; Niemirycz and Markiewicz, 1993; Niemirycz and Żebrowska, 1992; Niemirycz *et al.*, 1991, 1994; Rybiński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

Both the discharge of water, as well as that of nitrogen and phosphorus fluctuate in the long-term (Fig. 16). The highest loads of N and P (*ca* 90 000 tons N year^{-1} and > 8000 tons P year^{-1}) entering the Pomeranian Bay during the past six years were recorded in 1988. A considerable decrease in nitrogen discharge, down to nearly 40 000 ton N year^{-1}, was noted in 1990; this was due not only to the reduced water discharge in that year, but also to the economic crisis in Poland at the beginning of the country's transformation period. The nitrogen discharges correlate well with the Odra outflow, but the corresponding relationship with phosphorus is not clear-cut.

In summary, the following factors exert a direct influence on the concentrations and the spatial distribution of chemical parameters serving as indicators of water masses in the Pomeranian Bay: the uneven seasonal and interannual discharge of nutrients and organic matter with the river Odra; the buffering capacity of the Szczecin Lagoon, which was not tackled in this study but should be accorded attention in the main studies; the pulsating nature of riverine water outflow to the Bay governed by the hydrological/meteorological situation in the Lagoon and in the Bay; the mainly wind-induced transport of outflowing river water, and the transformation of this water in the Bay; the impact of the eutrophic Greifswalder Bodden; local phenomena such as upwelling; the seasonal pattern in biological production; the factors stimulating the locally increased biological production which affects the chemistry; the mineralisation and regeneration of nutrients. Attention should be focused on at least some of these factors in the main investigation in order to achieve its objectives, and in order to ensure that the conclusions are not masked by the randomness of the physical phenomena, which are closely connected with the chemistry and biology of the marine environment.

5. Conclusions

- Temperature, salinity, oxygen content and nutrient concentrations seem to be good indicators of the transport of Lagoon water flowing out into the Pomeranian Bay and of its transformation there.

- On the basis of the horizontal distributions of temperature, salinity, dissolved oxygen and nutrients it was possible to distinguish four subregions in September 1993:

  – a northern subregion affected by upwelling in the southern part of the Arkona Basin (lower temperature and oxygen content; some nutrients elevated),

- a western subregion (in the vicinity of the Greifswalder Bodden) affected by upwelled waters, as well as eutrophic waters from the neighbouring Bay (low oxygen, high ammonia and phosphates),
- stations 5A, 6 and 4PO, characterised by lower temperature, salinity, and nitrate concentration, a higher oxygen content and a much higher primary production and higher chlorophyll *a* concentration; this pocket of water formed a separate 'mini-ecosystem',
- a belt of offshore waters with a lower oxygen content and higher nutrient concentrations along the Polish and German coasts resulting from the impact of the Greifswalder Bodden and the river Odra.

• The measurements made in the mouth of the river Świna demonstrated the pulsating nature of water outflow from the Szczecin Lagoon; however, the direction of flow can differ at the surface and near the river bed.

• A much wider belt of water with elevated nitrates as compared with phosphates, suggests the predominance of nitrogen compounds in the water flowing out of the Lagoon in September 1993. The discharge of nutrients by the river Odra varies both seasonally and interannually. Nitrogen discharge in the annual and interannual cycle is less dependent than phosphorus on the volume of discharged water.

• The observed time/space variability in the nutrient distribution is evidence not only of the pulsating nature of the riverine water outflow, but also of the great dynamics in this shallow coastal zone, the waters of which are subject to wind-induced transport.

Acknowledgements

The authors would like to thank the staff of the Institute of Meteorology and Water Management, Gdynia, for their assistance in determining the chemical parameters during the cruise. Our sincere gratitude is expressed to Alfred Grelowski and Mariusz Zalewski for their help in plotting the graphs. Special thanks are also due to Stanisław Sitek (from the Sea Fisheries Institute, Świnoujście Branch) for collecting water from the mouth of the river Świna and determining the physical and chemical parameters.

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