An assessment of nutrient conditions in the southern Baltic Sea between 1994 and 1998

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Abstract

Temporal variations (1994–98) in nutrient distribution were analysed in the Polish sector of the Baltic Sea with reference to long-term (1979–98) fluctuations of hydrological and chemical factors. Between 1994 and 1998 the winter accumulation of phosphate declined noticeably in most of the regions with the exception of the Gulf of Gdańsk. The winter peaks of silicate were also reduced in the offshore region and in the waters along the central Polish coast, but continued to accumulate in the bays owing to riverine input. In the offshore region a decrease in the winter accumulation of nitrate was noted in the surface water layer whereas in the bays nitrate concentrations continued to increase. Large quantities of nitrate continue to accumulate in the Gulf of Gdańsk, although at a slower rate than in 1979–93.

1. Introduction

Eutrophication, defined as an increase in the rate of supply of organic matter to the ecosystem (Nixon 1995), is at present considered to be the major ecological problem of the Baltic Sea (HELCOM 1987, 1990, 1996). The characteristic feature of eutrophication is an enhancement of nutrient concentrations during the winter accumulation that forms the basis for the spring phytoplankton bloom. Studies of long-term changes in the Baltic Sea productivity (Nehring 1989, Trzosińska 1990, HELCOM 1993a, 1996) have indicated that nitrogen and phosphorus discharged from anthropogenic sources are the driving force behind eutrophication, especially in coastal areas. The negative effects of eutrophication are observed at all levels of the Baltic Sea ecosystem (Elmgren 1989, HELCOM 1996). Among them is oxygen deficiency, which leads to the formation of azoic areas on the sea floor of deep basins, and is potentially one of the most harmful effects of eutrophication (Matthäus 1995, Matthäus & Schinke 1999, Osowiecki 1999).

The aim of the monitoring programme of the Baltic Sea (BMP) environment, initiated by the Helsinki Commission in 1979, was to monitor and control the factors responsible for eutrophication on the one hand and the effects of eutrophication on the other. The steepest rates of increase in Baltic Sea productivity were noted in the nineteen-sixties and seventies. (HELCOM 1987, Nehring *et al.* 1995). The following decade witnessed a slowing down in the rate at which concentrations of assimilable phosphate and nitrogen compounds increased (Trzosińska & Łysiak-Pastuszak 1996). Despite the fact that by around 1990 the input of nitrogen and phosphorus salts into the Baltic Sea from land-based sources had fallen significantly (HELCOM 1993b), the amounts of nitrate and phosphate accumulated in the upper water layers of the sea were still sufficient to sustain primary productivity at a considerably elevated level.

The objective of the Helsinki Commission monitoring programme is pursued in five-year cyclic assessments of the state of the Baltic Sea environment (Melvasalo *et al.* 1981, HELCOM 1987, 1990, 1993b, 1996). This article presents the results of the Fourth Periodic Assessment (1994–98) related to nutrient conditions in the Polish sector of the Baltic Sea. The research was supported financially by the Polish State Committee for Scientific Research, which funds the statutory research activity of the Institute of Meteorology and Water Management.

2. Material and methods

The Fourth Periodic Assessment of the State of the Baltic Sea covers the period 1994–98 and compares the state of the environment then to that during earlier monitoring stages (1979–93). The data used in this assessment come from two sources:

(i) the data base of the Institute of Meteorology and Water Management (IMGW), which contains readings taken within the framework of the National Environmental Monitoring Programme – the surface water monitoring task, financed by the National Inspection Board for Environmental Protection and the IMGW statutory oceanographic service,

(ii) exchange of data with the Baltic Sea Research Institute (BSR) Warnemünde and the Oceanographical Laboratory of the Swedish Hydrological-Meteorological Institute, Göteborg (SMHI).

The number of data processed to display seasonal variability and long-term trends ranged between 200 and 500, depending on parameter and water layer; altogether 4000–8000 data were analysed.

The network of stations where the monitoring and oceanographic service measurements are conducted is shown in Fig. 1. The following representative stations were chosen to illustrate the ongoing changes in nutrient conditions: in the coastal region – B13 in the Pomeranian Bay, Ł7 along the central Polish coast, P116 and ZN2 in the Gulf of Gdańsk, and in the offshore area – P5 (BMP K2) in the Bornholm Deep, P140 (BMP K1) in the south-eastern Gotland Basin and P1 (BMP L1) in the Gdańsk Deep. The area delineated by stations ZN2, P1 and P140 is frequently referred to as the Gdańsk Basin.

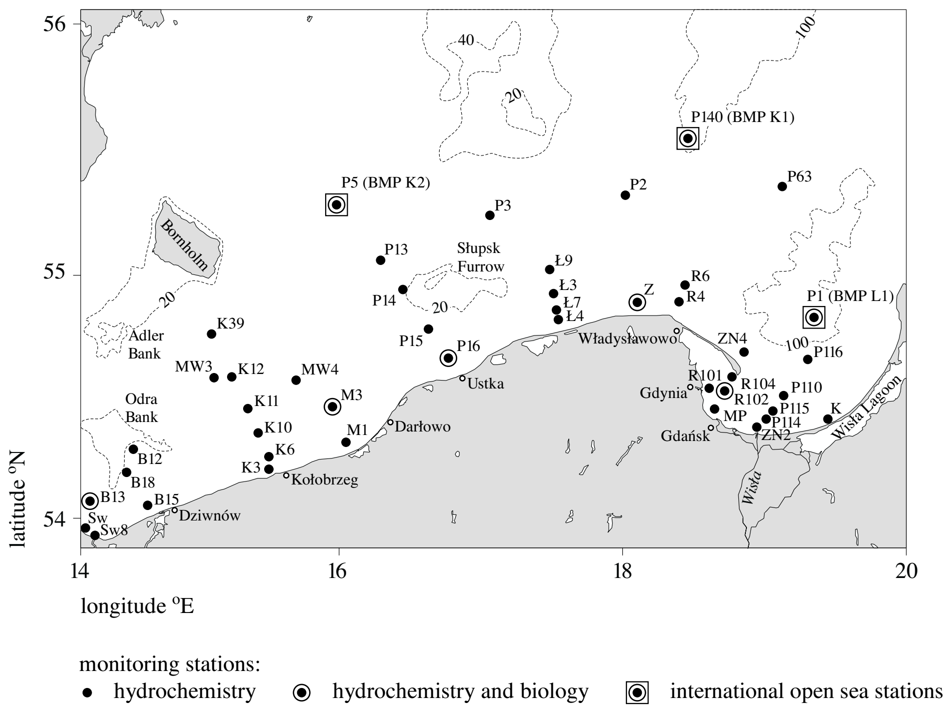


Fig. 1. The network of measurement stations of the Institute of Meteorology and Water Management

There is a considerable consistency in the measurement and analytical techniques agreed upon for the consecutive stages of the HELCOM Baltic Monitoring Programme (HELCOM 1988, 1997). The same analytical methods based on 'Methods of Seawater Analysis' by Grasshoff *et al.* (1974, 1983, 1999) were used for the determination of nutrient concentrations. Moreover, the methods have been subjected to regular intercomparison and intercalibration tests within the BMP framework, *e.g.* Kiel, Germany – 1977; Visby, Sweden – 1986; Arendal, Norway – 1990.

This assessment is presented in the same way as the outcomes of the earlier monitoring stages (Trzosińska 1990, 1992, Trzosińska & Łysiak-Pastuszak 1996), *i.e.* the same division of seasons was used (winter: January–March, spring: April–June, summer: July–September, autumn: October–December); the same analysis of multi-annual seasonal means (tables) as well as the seasonal development of nutrient concentrations (graphs) was conducted. With regard to seasonal changes, the SEASONAL program by Agger (1995) was applied and the long-term trends were studied using linear regression and the WHIRSCH.EXE non-parametric test (Sandén 1994) based on Hirsch *et al.* (1982) and Hirsch & Slack (1984). The calculations were performed for the surface water and deeper layers at 10 m intervals.

2.1. Seasonal variability of nutrients between 1994 and 1998

The seasonal pattern of phosphate in the surface layer of the Polish sector of the Baltic Sea displays a characteristic winter maximum, as well as a minimum, which occurs in spring in coastal waters but is delayed until the summer in the open sea (Figs. 2 and 3).

The highest seasonal variability of phosphate was found in the inner part of the Gulf of Gdańsk (Wisła (Vistula) Estuary – station ZN2) and in the Pomeranian Bay (Table 1). As in 1989–93 (Trzosińska & Łysiak-Pastuszak 1996), the respective mean seasonal amplitudes of phosphate in the Gulf of Gdańsk and the Pomeranian Bay, the basins most exposed to land-based discharges of phosphorus, were 0.5 and 0.8 mmol m^{-3} (IMGW 1995–98, 1999). Both bays still record the largest winter accumulation of phosphates in the surface water layer. However, the degree of winter accumulation was noticeably lower in 1994–98 than during the previous monitoring stage (1989–93) (Trzosińska & Łysiak-Pastuszak 1996). The declining winter accumulation of phosphate in the surface water was recorded in all regions of the Polish sector of the Baltic Sea.

The regular seasonal development of phosphate, and also that of nitrate and silicate, was distorted in the Gulf of Gdańsk and Pomeranian Bay in the summer of 1997, owing to the flood in the Odra (Oder) and Wisła catchment areas (Łysiak-Pastuszak *et al.* 1998, Matthäus *et al.* 1998, Trzosińska & Andrulewicz 1998), even though the impact of the flood waters was restricted to bay areas and was not detected either along the Polish central coast or in the open sea.

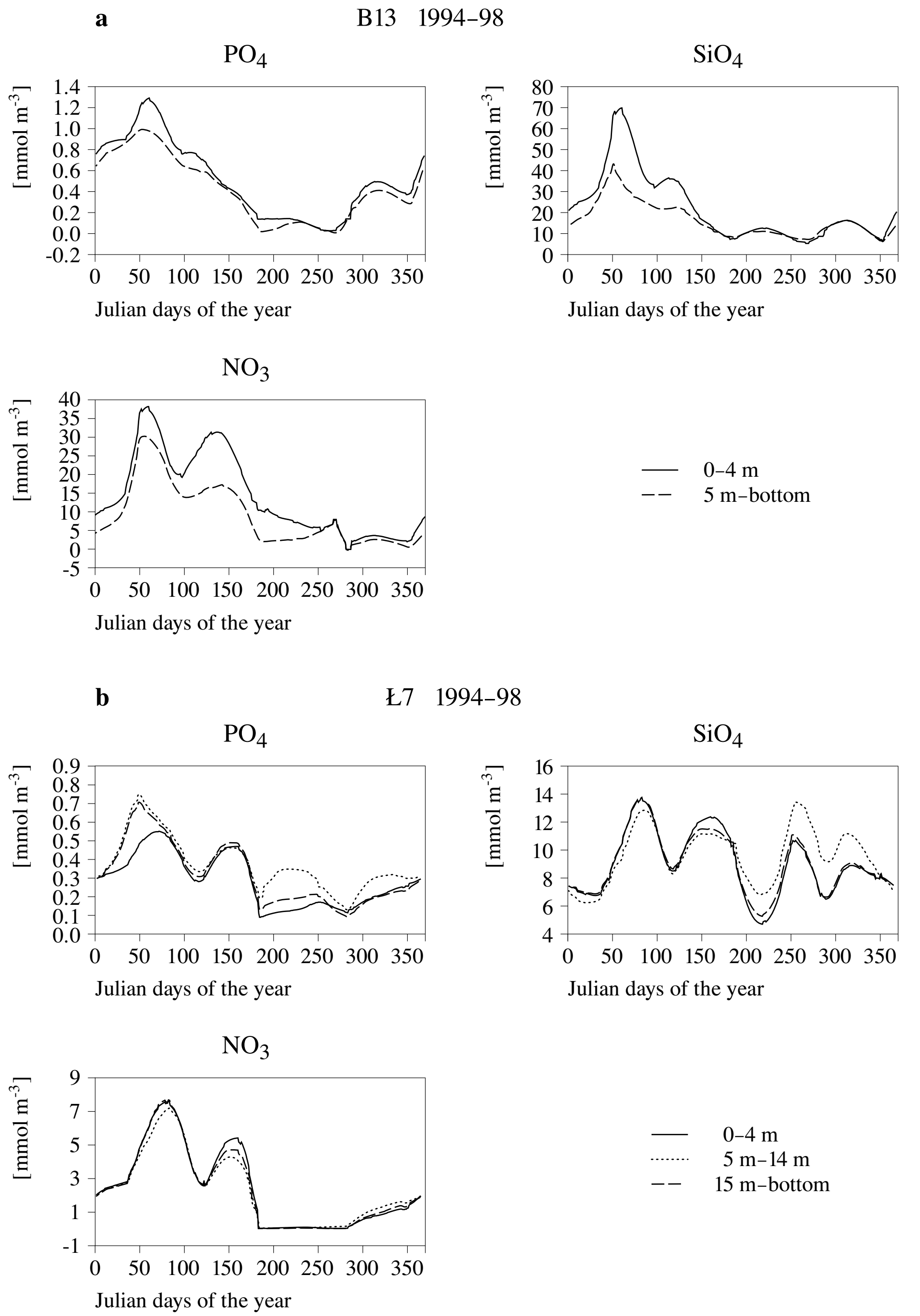


Fig. 2. The mean (1994–98) seasonal development of nutrient fluctuations in the coastal zone; Pomeranian Bay (B13) (a), central Polish coast (Ł7) (b), Gulf of Gdańsk (ZN2) (c)

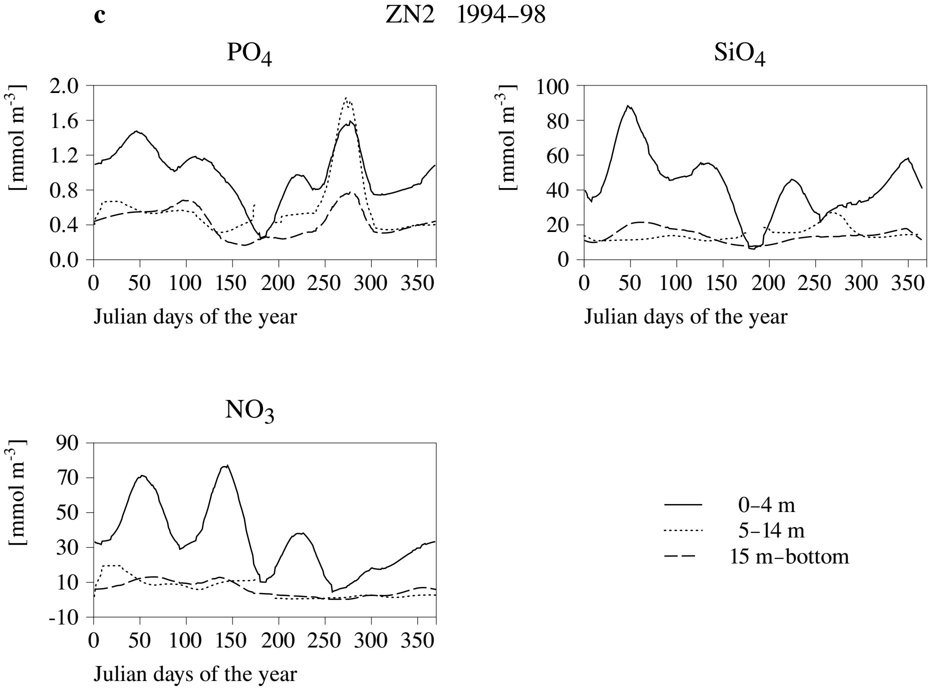


Fig. 2. (continued)

Generally, the increase in seasonal phosphate amplitudes between 1994–98 was clearly in evidence throughout the Polish Baltic (Table 1) and indicated an increased assimilation of this nutrient during the growing season.

Silicates are important in the growth of diatoms. Trzosińska & Łysiak-Pastuszak (1996) recorded a considerable decrease in winter silicate concentrations in the upper (0–10 m) water of the Gdańsk Basin between 1989 and 1993. This declining tendency continued in the subsequent period, but mainly in the offshore part of the Basin and along the central Polish coast (Table 2). In the Gulf of Gdańsk and the Pomeranian Bay, silicate concentrations remained at the same level as between 1989 and 1993 or increased only slightly, because of the continuous, high riverine supply. The mean annual concentrations of silicate decreased in the open-sea area, throughout the isohaline layer. An important divergence in the seasonal development of silicate concentrations in 1994–98, as compared to 1989–93, was the delayed stabilisation of the winter plateau in the Bornholm Deep and Gdańsk Deep regions (Fig. 3). The diminishing demand for silicates (HELCOM 1996) is continuing, this being manifested by the fact that the 1994–98 data record does not contain any incident of the complete

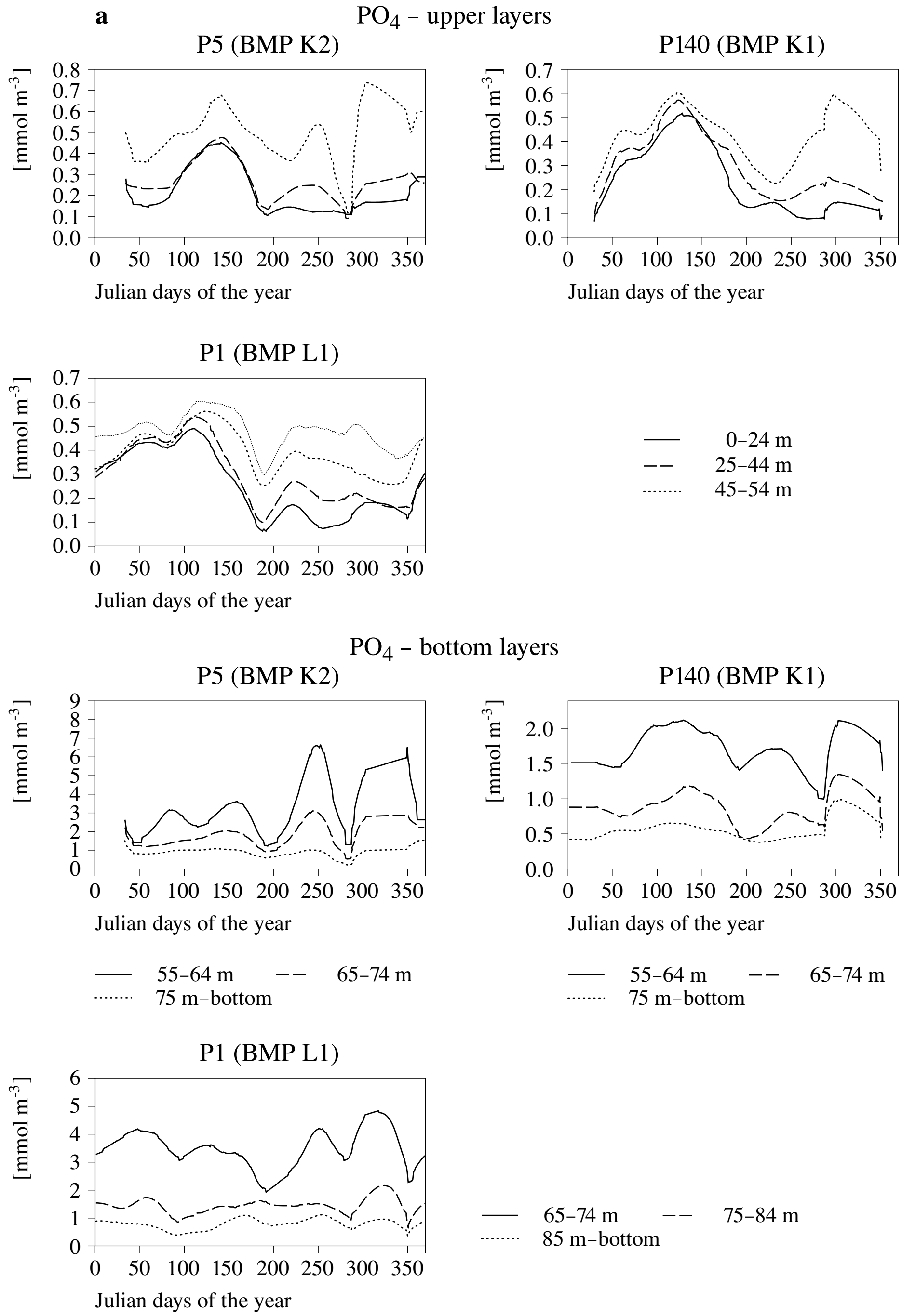
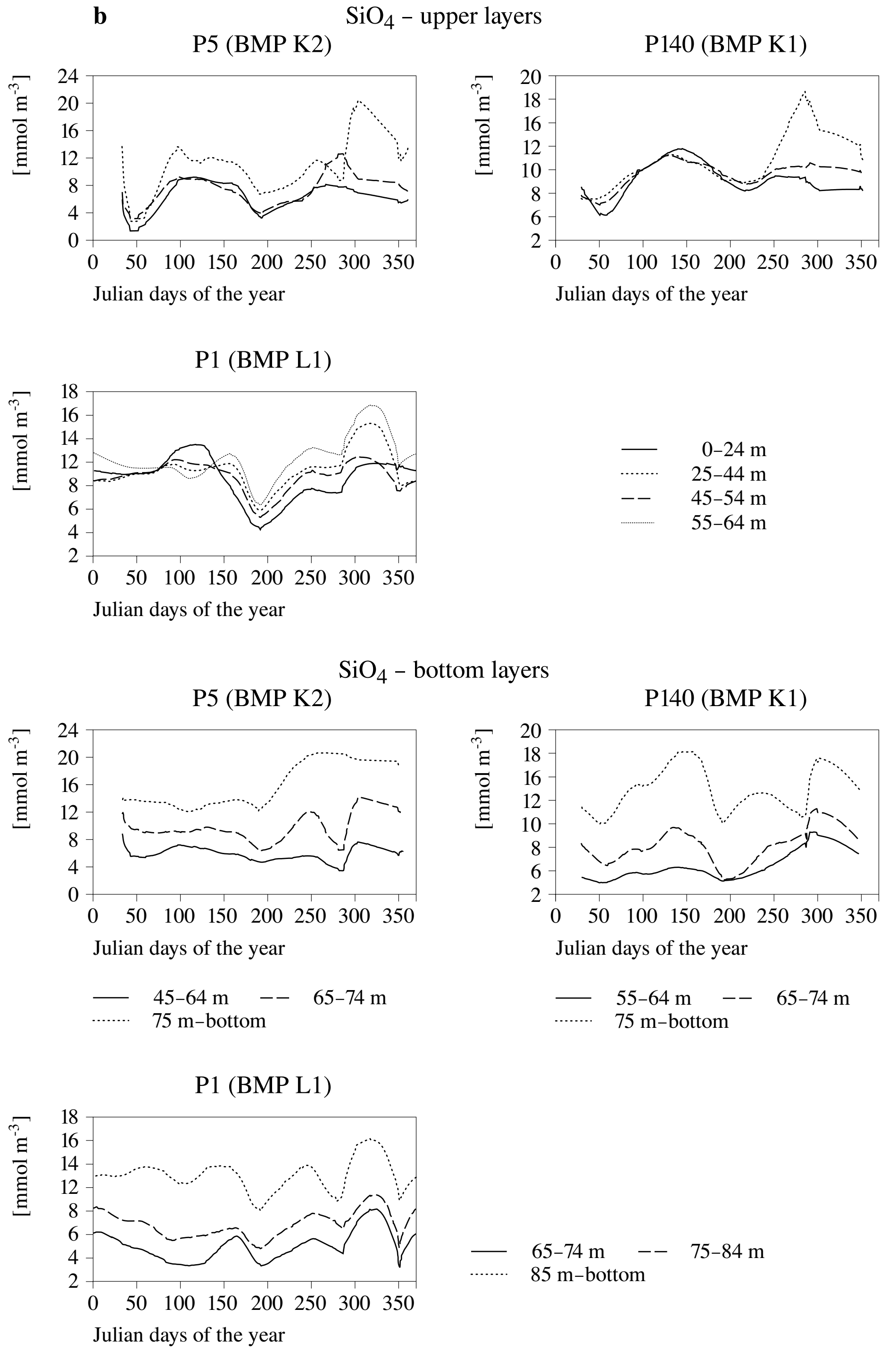


Fig. 3. The mean (1994–98) seasonal development of nutrient fluctuations in the offshore region; phosphate (a), silicate (b) and nitrate (c) in the upper and bottom layers



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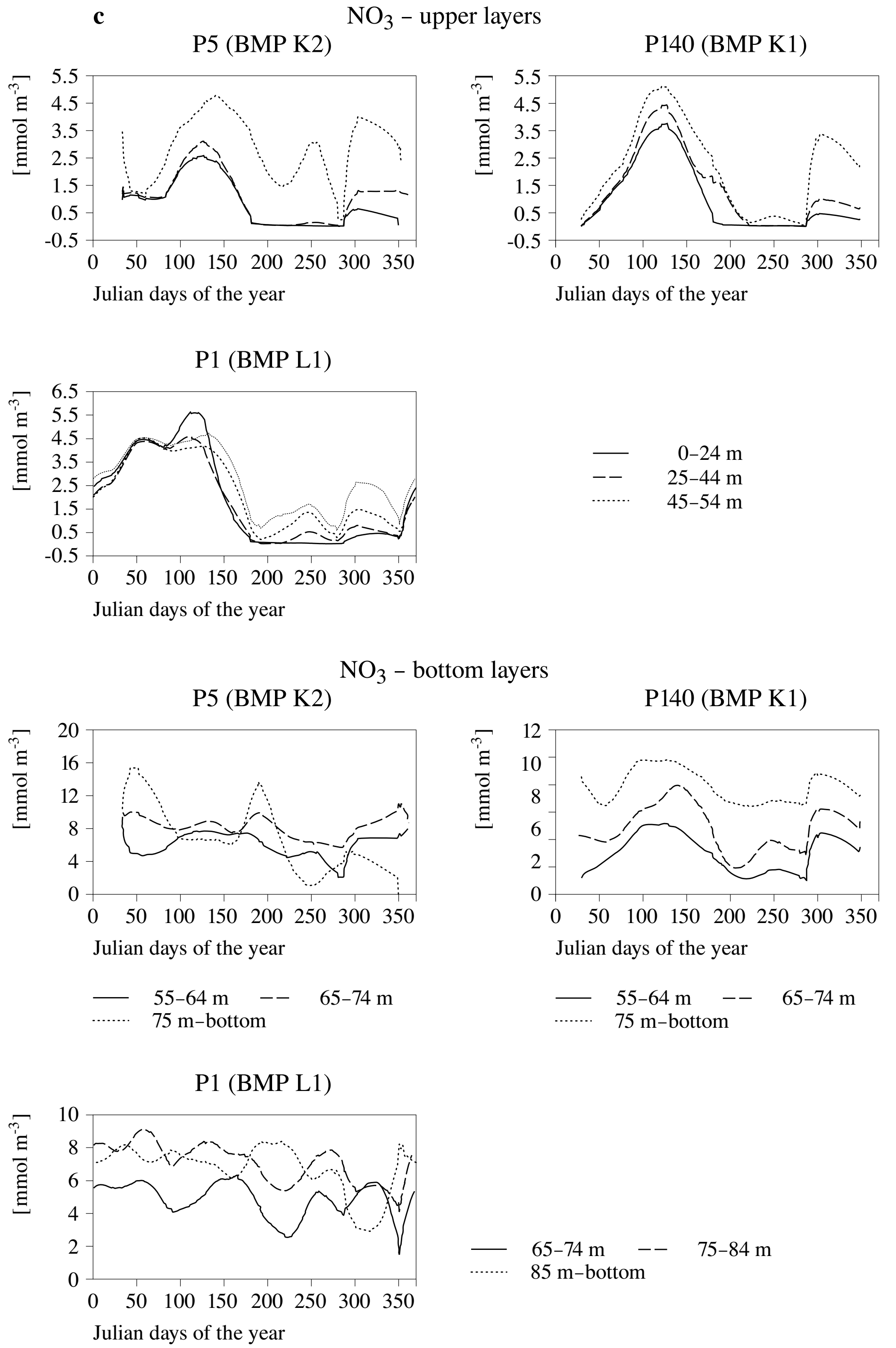

Fig. 3. (continued)

utilisation of silicate from the water along the central Polish coast or in the Gulf of Gdańsk (Fig. 2), whereas during the eighties and early nineties such incidents occurred quite frequently in spring (IMGW 1995–98, Trzosińska & Łysiak-Pastuszak 1996).

Table 1. Multi-annual (1994–98) mean concentrations of dissolved phosphate [mmol m^{-3}] in the Polish sector of the Baltic Sea (in brackets – standard deviation)

Region – water layer	Winter	Spring	Summer	Autumn	1994–98	1989–93
Gulf of Gdańsk						
inner						
0–10 m	0.66	0.17	0.31	0.49	0.44	0.51
	(0.43)	(0.27)	(0.42)	(0.36)	(0.43)	(0.51)
11 m–bottom	0.56	0.18	0.31	0.42	0.39	0.50
	(0.34)	(0.21)	(0.31)	(0.25)	(0.25)	(0.45)
Gulf of Gdańsk						
outer						
0–10 m	0.48	0.12	0.10	0.30	0.27	0.29
	(0.14)	(0.11)	(0.07)	(0.10)	(0.20)	(0.20)
isohaline	0.050	0.17	0.12	0.29	0.29	0.36
	(0.13)	(0.18)	(0.11)	(0.11)	(0.21)	(0.26)
heterohaline	1.75	1.63	1.58	1.90	1.70	1.53
	(1.50)	(1.57)	(1.38)	(1.47)	(1.47)	(1.69)
Open Sea						
0–10 m	0.49	0.18	0.08	0.28	0.24	0.29
	(0.12)	(0.08)	(0.10)	(0.07)	(0.19)	(0.24)
isohaline	0.54	0.26	0.18	0.37	0.31	0.40
	(0.13)	(0.17)	(0.19)	(0.29)	(0.23)	(0.30)
heterohaline	1.66	1.56	1.46	1.99	1.60	1.53
	(0.76)	(1.17)	(1.36)	(1.31)	(1.18)	(1.14)
Central Polish Coast						
0–10 m	0.50	0.18	0.15	0.38	0.31	0.37
	(0.18)	(0.12)	(0.11)	(0.13)	(20)	(0.28)
Pomeranian Bay						
0–10 m	0.98	0.17	0.60	0.85	0.60	0.65
	(0.62)	(0.16)	(0.65)	(0.77)	(0.65)	(0.72)

Table 2. Multi-annual (1994–98) mean concentrations of silicate [mmol m^{-3}] in the Polish sector of the Baltic Sea (in brackets – standard deviation)

Region – water layer	Winter	Spring	Summer	Autumn	1994–98	1989–93
Gulf of Gdańsk						
inner						
0–10 m	21.8	9.8	16.8	15.5	16.8	12.7
	(22.0)	(10.7)	(26.8)	(17.5)	(21.3)	(9.9)
11 m–bottom	12.9	9.9	12.0	10.8	11.6	12.4
	(3.9)	(7.1)	(4.2)	(5.7)	(5.2)	(8.0)
Gulf of Gdańsk						
outer						
0–10 m	13.0	7.4	10.0	9.4	10.3	10.4
	(4.5)	(4.2)	(7.4)	(5.3)	(5.9)	(4.4)
isohaline	11.8	7.9	9.8	8.7	9.9	11.2
	(3.5)	(0.18)	(5.0)	(4.0)	(4.4)	(4.4)
heterohaline	25.9	26.0	26.5	31.2	26.9	25.2
	(16.3)	(18.0)	(15.6)	(15.5)	(16.4)	(13.0)
Open Sea						
0–10 m	11.1	8.7	7.9	7.5	8.8	13.0
	(1.5)	(2.8)	(1.9)	(2.2)	(2.6)	(3.3)
isohaline	11.2	9.1	8.9	8.7	9.5	11.9
	(2.3)	(3.3)	(2.8)	(5.1)	(3.4)	(5.2)
heterohaline	28.7	28.9	26.3	30.7	28.0	28.8
	(12.1)	(14.7)	(16.1)	(17.8)	(14.4)	(11.8)
Central Polish Coast						
0–10 m	11.7	7.8	9.9	9.8	9.9	9.9
	(5.4)	(5.0)	(4.0)	(4.9)	(5.0)	(5.1)
Pomeranian Bay						
0–10 m	43.5	11.7	25.2	20.9	24.2	15.2
	(35.5)	(9.8)	(19.7)	(31.7)	(26.9)	(9.0)

Nitrogen is the principal nutrient limiting primary production in the Baltic Proper. Nitrates are the most important of the inorganic nitrogen compounds, as they form the basis of the 'new' biological production (Dugdale & Goering 1967). As regards winter concentrations of nitrate in the top water layer, a significant increase in the inner Gulf of Gdańsk (of *ca* 2 mmol m^{-3}) and in the Pomeranian Bay (*ca* 0.7 mmol m^{-3}) took

Table 3. Multi-annual (1994–98) mean concentrations of nitrate [mmol m^{-3}] in the Polish sector of the Baltic Sea (in brackets – standard deviation)

Region – water layer	Winter	Spring	Summer	Autumn	1994–98	1989–93
Gulf of Gdańsk inner						
0–10 m	14.04 (18.77)	12.39 (31.36)	3.48 (13.44)	6.75 (9.33)	9.50 (19.97)	5.43 (10.46)
11 m–bottom	6.31 (2.66)	2.57 (6.26)	0.73 (1.52)	2.78 (1.83)	3.37 (4.07)	5.83 (2.88)
Gulf of Gdańsk outer						
0–10 m	6.49 (3.88)	2.31 (12.35)	0.56 (2.92)	2.66 (2.78)	3.29 (6.56)	1.90 (2.50)
isohaline	5.56 (2.90)	1.48 (7.86)	0.33 (1.88)	2.14 (2.05)	2.68 (4.56)	2.24 (2.50)
heterohaline	6.68 (2.98)	6.12 (3.67)	4.51 (3.70)	6.14 (3.26)	5.84 (3.50)	7.48 (3.85)
Open Sea						
0–10 m	3.62 (1.30)	0.09 (0.18)	0.01 (0.03)	0.83 (0.50)	1.11 (1.70)	1.05 (1.00)
isohaline	4.01 (1.35)	0.64 (1.39)	0.22 (0.88)	1.40 (1.63)	1.44 (1.99)	1.62 (2.25)
heterohaline	8.41 (2.17)	7.10 (3.24)	4.77 (3.58)	6.58 (3.29)	6.53 (3.47)	7.55 (3.46)
Central Polish Coast						
0–10 m	5.81 (3.15)	0.97 (2.54)	0.25 (1.52)	2.21 (1.50)	2.48 (3.24)	1.79 (2.74)
Pomeranian Bay						
0–10 m	39.56 (51.01)	21.86 (43.42)	1.64 (3.85)	11.92 (24.96)	18.07 (38.00)	3.71 (7.13)

place in comparison to the preceding five-year period (Table 3). Since the annual loads of nitrate discharged with the Odra, Wisła and the Pomeranian rivers did not indicate any definite trend in 1994–98 (154 608 t year^{-1} in 1994 to 100 717 t year^{-1} in 1997 and 99 950 t year^{-1} in 1998) (IMGW 1995–98, 1999), this increase should be attributed to discharges from diffuse sources, situated below the riverine benchmark transects. A definitely positive observation is the stable level of winter nitrate concentrations along the central Polish coast and their decrease in open-sea water; however, the latter fact could be partly the result of mild winters in the period in question, when primary production did not diminish as usual.

The seasonal exhaustion of nitrate related to the growing season in the shallow water of the coastal zone, including the bays, extended from the end of May till late autumn (Figs. 2 and 3). A similar seasonal development took place in the euphotic layer in offshore areas, while in the deeper water layers discernible maxima and minima of nitrate concentrations occurred in accordance with the rhythm of organic matter input from primary production and its remineralisation (Fig. 3). This pattern also showed up in the seasonal development of phosphate, but with respect to silicate was less distinct. In the near-bottom layer of the southern Baltic deeps in summer, the maxima corresponding to the most intensive degradation processes are conspicuous for about 180–250 days of the year, depending on the region. The upward flux of regenerated nitrate was halted by the thermocline, and only the cooling of water and mixing, forced by wind-generated wave action during autumn and winter, allow further rebuilding of the winter pool of nutrients. Towards the end of the year, denitrification causes nitrate to disappear from near the sea floor of the deep basins. Because of the considerable deterioration of the oxygen situation in the heterohaline layer (Matthäus *et al.* 1996, Łysiak-Pastuszak & Drgas 2000), nitrate concentrations were depleted in the southern Baltic deeps between 1994 and 1998 (Fig. 3). Besides the changes from oxic to anoxic conditions, advective processes (inflows) carrying different nutrient concentrations and exchange with the sediment (phosphate and silicate) are also of significance in the central Baltic deep waters.

The N:P molar ratio in water is frequently applied as an indicator of the principal limiting nutrient (Wasmund *et al.* 2000). Trzosińska (1977) reported a significant increase of the N:P ratio in the upper water layers of the Gdańsk Basin in winter. The same conclusions were drawn in the 1989–93 assessment (Trzosińska & Łysiak-Pastuszak 1996). This trend, though slower paced, was also recorded in 1994–98 (Table 4).

The fastest increase in the N:P ratio was recorded in the inner part of the Gulf of Gdańsk and in the Pomeranian Bay. A very slight increase in N:P was found in the water along the Polish central coast but no changes were noted in offshore areas. In the bays, N:P displays great variability during the year: from 72.9 in spring to 8.7 in summer and 22.3 in winter in the Gulf of Gdańsk, and from 129.5 in spring through 2.3 in summer to 9.2 in autumn and 43.7 in winter in the Pomeranian Bay, which means there is a change in the limiting factor in these basins. Presumably, this factor

Table 4. Multi-annual (1994–98) mean values of the molar N:P ratio in the Polish sector of the Baltic Sea

Region – water layer	Winter	Spring	Summer	Autumn
Gulf of Gdańsk				
inner				
0–10 m	*22.3	72.9	8.7	15.9
	**27.8	87.7	14.5	22.7
11 m–bottom	13.7	19.2	2.1	10.3
	16.4	27.9	11.1	15.2
Gulf of Gdańsk				
outer				
0–10 m	14.3	31.7	6.6	14.1
	19.0	43.9	14.9	20.1
isohaline	11.7	16.6	3.3	7.4
	13.9	23.7	13.3	11.6
heterohaline	5.9	11.2	4.2	4.6
	7.1	14.2	8.9	6.2
Open Sea				
0–10 m	7.5	0.4	0.2	3.1
	8.5	3.4	9.4	5.8
isohaline	7.5	1.4	0.7	3.1
	8.7	3.8	8.7	5.5
heterohaline	5.6	5.8	5.5	4.0
	6.4	7.0	8.9	4.8
Central Polish Coast				
0–10 m	11.3	9.1	0.8	6.0
	13.8	15.4	4.8	10.0
Pomeranian Bay				
0–10 m	43.7	129.5	1.3	9.2
	51.2	145.1	5.4	12.6

*$(NO_3 + NO_2):PO_4$
** $N_{in}:PO_4$, $N_{in} = NO_3 + NO_2 + NH_4$

is subject even to local variation within the basins, *i.e.* some parts of the bays are limited by phosphorus, others by nitrogen (Pastuszak *et al.* 1996, Nowacki & Jarosz 1998).

2.2. Long-term changes in nutrient conditions in the southern Baltic Sea

The characteristic feature of eutrophication is the continuous rise in nutrient concentrations in the marine trophogenic sphere during the winter accumulation. Statistical trends in the long-term changes in nutrient concentrations were analysed by two methods: the non-parametric test (Hirsch *et al.* 1982, Hirsch & Slack 1984, Sandén & Rahm 1993, Sandén 1994) and linear regression. Because the results of both methods differed considerably as regards the magnitude of the trend coefficient and the direction of changes, and the non-parametric test proved more advantageous as it was robust to non-Gaussian distributions, missing measurements and seasonality, the evaluation of long-term trends was based on results from this test.

Phosphate accumulation in the surface water layer in winter shows a clear negative trend between 1979 and 1998 (Table 5), statistically significant in most regions of the southern Baltic, except for the SE Gotland Deep and the Wisła Estuary, and with the maximum rate in the Pomeranian Bay (Fig. 4). The latter observation is a highly positive sign, because it means that the pressure on the environment of the Szczecin Lagoon, and consequently on the Pomeranian Bay, due to the phosphate loads discharged by the Odra is beginning to wane. This is well in accordance with the long-term trends revealed in phosphate outflow with the River Odra (E. Niemirycz pers. comm.). Though winter phosphate concentrations fell less sharply than between 1979 and 1993, this decrease is now detectable throughout the water column. Released under anoxic conditions, phosphate is accumulating in the near-bottom water of sedimentation basins, the Bornholm and Gdańsk Deep (Fig. 5a); this is demonstrated by positive trend coefficients (Table 5).

The depletion of the silicate pool in Baltic waters is still detectable (Table 6); winter concentrations in the Bornholm Deep and SE Gotland Deep reveal negative trends with highly significant coefficients (Table 6). In the bays directly affected by riverine inflows the supply of silicate is continuously replenished, hence trend coefficients are positive although they are in good accordance with the spring and autumn peaks in the riverine outflow (Fig. 6). Statistically significant positive trends in silicate concentrations detected in coastal waters along the central Polish coast (station Ł7) in the warm season are a clear indication of the diminishing demand for this nutrient in summer (Table 7) (HELCOM 1993a, 1996).

Table 5. Statistically significant trends in phosphate concentrations in the southern Baltic Sea, 1979–98: calculated by non-parametric test

Region	Depth [m]	Year round p	Year round mean	Year round slope	Winter p	Winter mean	Winter slope
			Pomeranian Bay				
B13	0–4	HS	0.60	–0.02	HS	0.94	–0.08
	5–15				S	0.90	–0.04
			Bornholm Deep				
P5	0–24				S	0.59	–0.01
(BMP K2)	25–44	S	0.43	–0.01	S	0.61	–0.01
	45–54				S	0.73	–0.01
	65–74				HS	1.99	+0.05
			Gdańsk Basin				
ZN2*	5–15	HS	0.54	–0.02			
P116**	0–24				HS	0.53	–0.01
	25–44				HS	0.58	–0.01
	45–54				S	0.59	–0.02
P1	0–24				S	0.52	–0.01
(BMP L1)	25–44				HS	0.58	–0.02
	55–64				S	0.66	+0.02
	65–74	S	0.74	+0.02			
	85–109				S	2.37	+0.09
P140	25–44	HS	0.29	–0.01			
(BMP K1)	65–74	S	1.00	–0.02			

Explanations: * inner Gulf of Gdańsk, ** outer Gulf of Gdańsk, slope in [mmol m^{-3} y^{-1}], HS – highly significant $p < 0.05$, S – significant $0.05 \le p \le 0.1$.

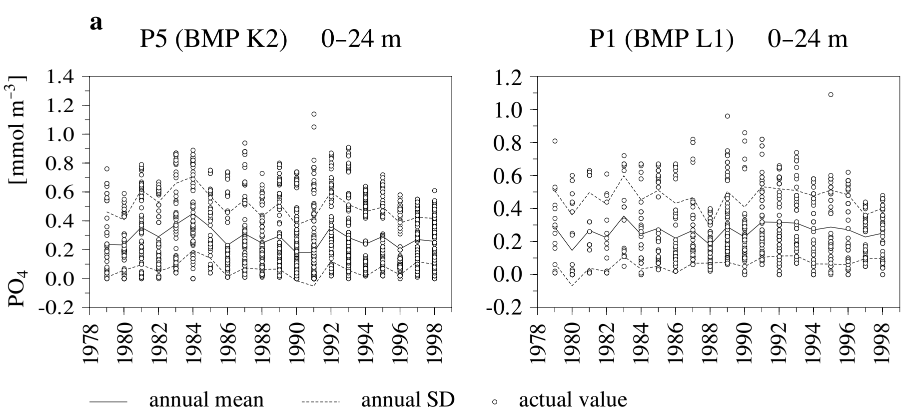

Fig. 4. Multi-annual (1979–98) changes in phosphate concentrations in the surface water layer of the open sea area (a) and in the Polish bays (b)

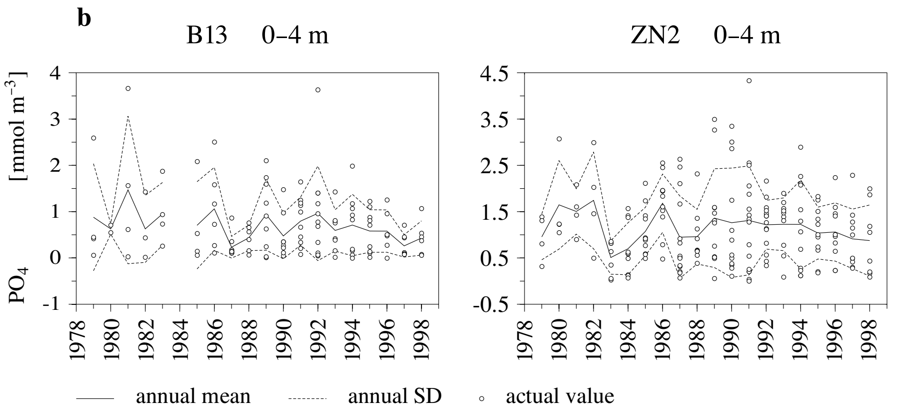

Fig. 4. (continued)

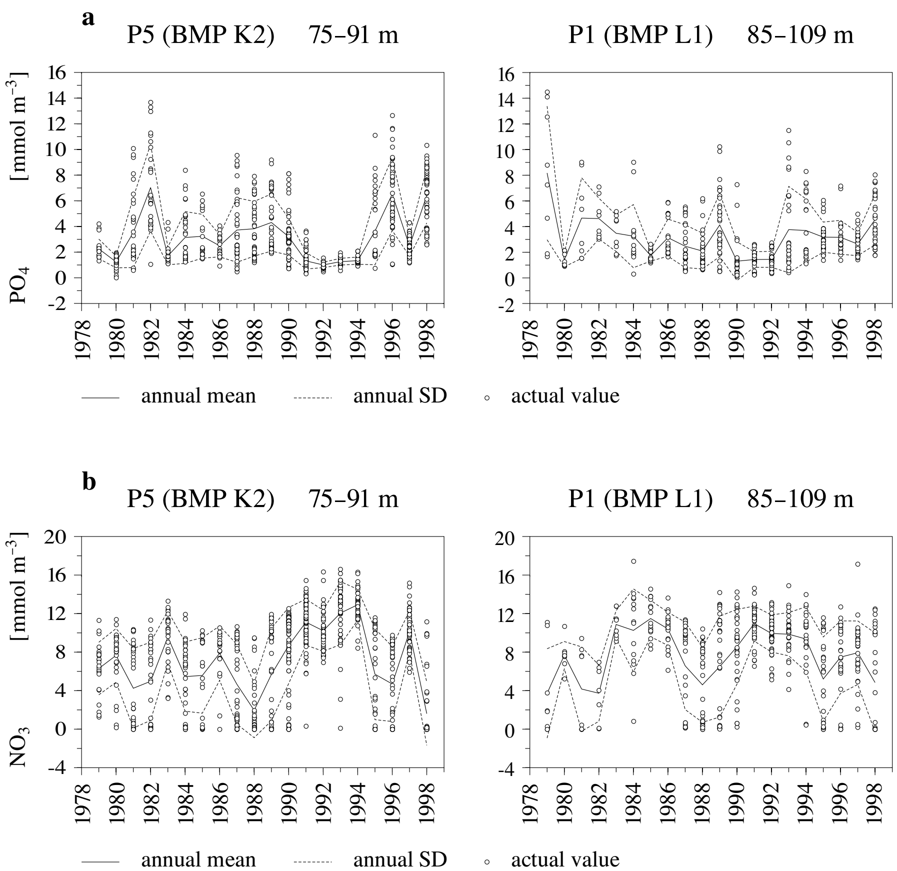

Fig. 5. Multi-annual (1979–98) changes in phosphate (a) and nitrate (b) concentrations in the near-bottom water of the Bornholm and Gdańsk Deeps

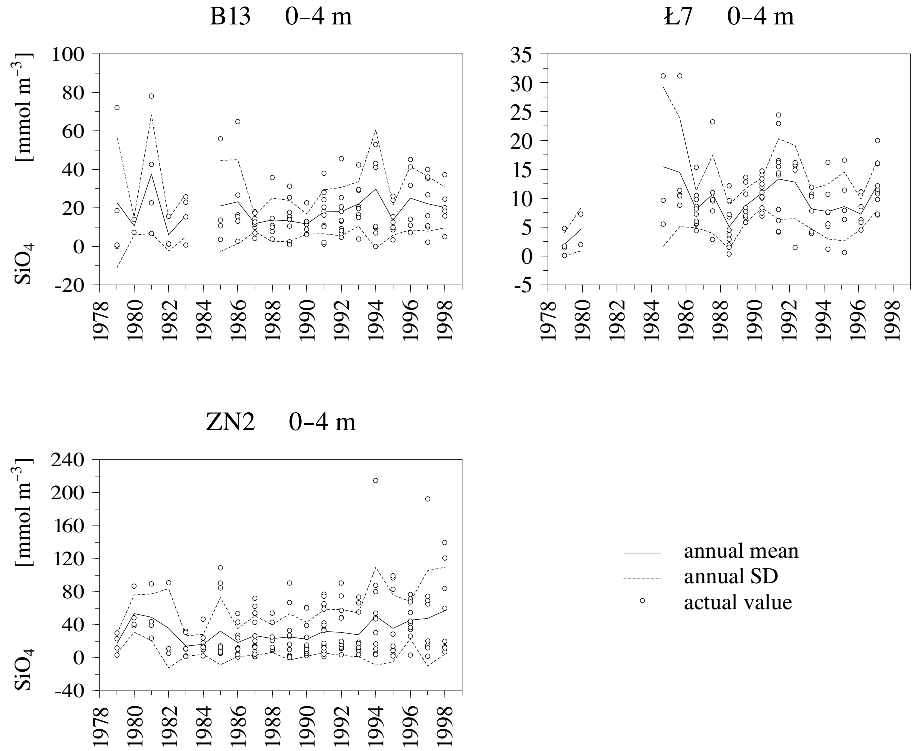

Fig. 6. Multi-annual (1979–98) changes in silicate concentrations in the water of the Polish coastal zone

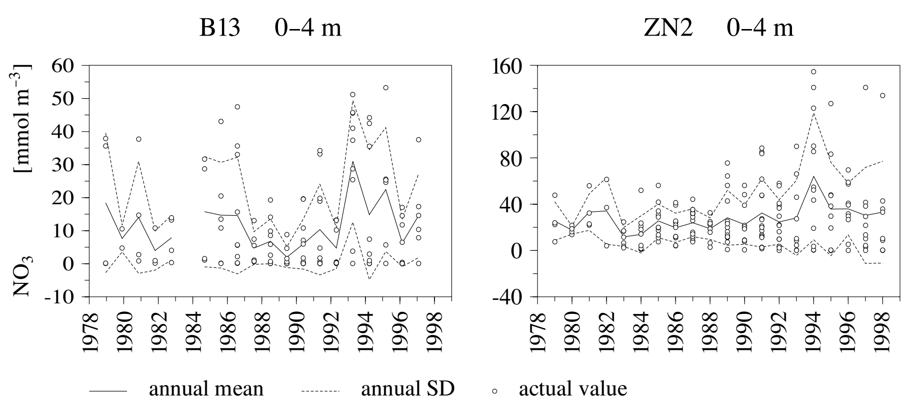

Fig. 7. Multi-annual (1979–98) changes in nitrate concentrations in the surface water of the Polish bays

Table 6. Statistically significant trends in silicate concentrations in the southern Baltic Sea, 1979–98: calculated by non-parametric test

Region	Depth [m]	Year round p	mean	slope	Winter p	mean	slope
			Bornholm Deep				
P5 (BMP K2)	0–24				S	13.58	–0.30
			Gdańsk Basin				
P116**	55–64				HS	11.08	–0.48
	75–92	S	36.26	–1.04			
P1 (BMP L1)	55–64				HS	14.15	–0.49
P140 (BMP K1)	0–24				HS	12.22	–0.14
	25–45				HS	12.18	–0.23
	45–54				HS	12.05	–0.33
	55–64				HS	12.00	–0.29
	75–90				HS	29.80	–0.81

Explanations as in Table 5.

Table 7. Statistically significant trends in silicate concentrations in the southern Baltic Sea, in warm seasons of the period 1979–98: calculated by non-parametric test

Region	Depth [m]	Spring/autumn p	mean	slope	Summer p	mean	slope
			Pomeranian Bay				
B13	0–4	HS	6.05	+0.631[2]	HS	7.40	+0.349
			Central Polish coast				
Ł7	0–4	HS	5.78	+0.338[2]	S	8.57	+0.334
	5–14	S	6.25	+0.431[2]	HS	8.77	+0.332
	15–21	HS	8.57	+0.239[4]	HS	9.93	+0.334
			Gdańsk Basin				
ZN2*	0–4	S	26.70	+0.740[4]			
	5–15	S	11.54	+0.300[4]			
P116**	0–24				HS	7.66	+0.205
	75–92	HS	17.36	–1.303[2]			
	75–92				HS	18.13	–1.160

[2] spring, [4] autumn. The other explanations as in Table 5.

Table 8. Statistically significant trends in nitrate concentrations in the southern Baltic Sea, 1979–98: calculated by non-parametric test

Region	Depth [m]	Year round p	mean	slope	Winter p	mean	slope
			Bornholm Deep				
P5	55–64	HS	6.05	+0.13	S	7.40	+0.06
(BMP K2)	65–74	HS	8.65	+0.12	HS	9.00	+0.11
			Gdańsk Basin				
ZN2*	0–4	HS	27.90	+0.92	HS	47.10	+2.39
	5–15	HS	3.76	+0.17			
P116**	55–64				HS	5.34	–0.48
	75–92	HS	7.71	–1.04			
P140 (BMP K1)	75–90	HS	7.79	+0.12	HS	8.02	+0.23

Explanations as in Table 5.

The trends as regards nitrate concentrations were statistically far less significant. These compounds are still accumulated at an unprecedented rate in the inner Gulf of Gdańsk (Table 8, Fig. 7), though no longer as rapidly as between 1979 and 1993 (Trzosińska & Łysiak-Pastuszak 1996). Nitrates are also accumulating in the intermediate water layers of the Bornholm Deep and SE Gotland Deep (Table 8) and near the bottom of the latter. Generally, however, it is denitrification, prevalent under unfavourable oxygen conditions, that is causing nitrate exhaustion from the near-bottom water in the deeper parts of the southern Baltic Sea (Fig. 5b). The loss in nitrate concentrations near the sea floor is shown up in the negative trend coefficients of the N:P ratio (Table 9). By contrast, the decrease in phosphate concentrations and concomitant increase in nitrate resulted in the exceptional rise of N:P in the Gulf of Gdańsk and Pomeranian Bay (Table 9). This is in good agreement with the long-term changes observed in the amount of nitrogen and phosphorus carried by the rivers Wisła and Odra (IMGW 1999).

Table 9. Statistically significant trends in molar ration ($NO_3 + NO_2/PO_4$) in the southern Baltic Sea, 1979–98: calculated by non-parametric test

Region	Depth [m]	Year round p	mean	slope	Winter p	mean	slope
		Pomeranian Bay					
B13	0–4	HS	54.5	+3.20			
	5–15	HS	68.5	+2.90			
		Central Polish coast					
Ł7	0–4	HS	42.3	+2.00			
	5–14	HS	42.7	+1.52			
		Bornholm Deep					
P5	55–64				S	24.2	–0.50
(BMP K2)	65–74				HS	23.5	–0.60
		Gdańsk Basin					
ZN2*	0–5	HS	37.9	+1.67			
	5–15	HS	36.5	+1.62			
P116**	0–24	S	59.1	+2.20			
	25–44	S	51.5	+1.47			
P1 (BMP L1)	0–24				S	25.4	+0.66
P140	0–24	HS	53.5	+1.80			
(BMP K1)	25–44	HS	36.3	+0.65			
	65–74	S	23.9	–0.42	S	24.6	–0.42
	75–90	HS	21.8	–0.38	HS	22.5	–0.40

Explanations as in Table 5.

3. Conclusions

- Between 1994 and 1998 a decline in the winter accumulation of phosphate was noted in the surface water of the entire Polish sector of the Baltic Sea, except in the Gulf of Gdańsk, where riverine input maintained previous levels. This was also demonstrated by long-term (1979–98) trend analysis.
- Seasonal amplitudes of phosphate (seasonal exhaustion) were extended in all regions; this indicates greater assimilation of this nutrient by phytoplankton.

- Winter accumulation of silicate also slackened between 1994 and 1998 and seasonal amplitudes diminished. Long-term trend analysis revealed statistically significant negative coefficients in the upper water layers of the open-sea region, though locally, in the bays, the riverine outflow is still a rich source of silicate supply.
- In sedimentation basins there was a steep increase in phosphate and silicate concentrations in the near-bottom water in 1994–98, owing to the fact that oxygen conditions had deteriorated considerably.
- In the offshore region a decrease in the winter accumulation of nitrate was noted in the surface water layer, while in the bays nitrate concentrations continued to increase. Nitrate accumulation in the Gulf of Gdańsk was still strong, though the rate was less steep than in the period 1979–93.
- Denitrification, triggered by an oxygen deficit during the new stagnation period, was responsible for nitrate vanishing from the deep-water layers of the Bornholm Deep and Gdańsk Deep.

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