Seasonal fluctuations and long-term trends of nutrient concentrations in the Polish zone of the Baltic Sea

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Abstract

The article presents the state of productiveness of the Polish zone of the Baltic Sea assessed basing on the 5-year (1979–1983) investigations carried out within the frame of the Helsinki Convention according to the I stage of the Baltic Monitoring Programme. Seasonal fluctuations of phosphorus, nitrogen and silicon compound concentrations in the Polish zone of the Baltic Sea and long-term variations of phosphate and nitrate concentrations in the entire Baltic Sea area indicated the progressing eutrophication of this basin. The eutrophication affected also other chemical properties of the environment, such as oxygen conditions and water pH.

1. Introduction

Studies concerning the content of nutrients in the Baltic Sea water carried out for many years as a background in biological investigations have developed into an independent field from a certain moment, but all the same they remained the source of information on the quality of the marine environment.

Problems regarding the productiveness of sea branched out when the symptoms of eutrophication had appeared in the Baltic Sea and the origins of this eutrophication or the attempts to relate it to other phenomena of the marine environment had turned out to be more complex than the

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simple increase of the nutrient input and the effect of nutrient level on the primary production.

Determination of the origins, development and effects of eutrophication became one of the major tasks of the Baltic Monitoring Programme carried out in the Baltic Sea area within the frame of the Helsinki Convention since 1979. This Programme has been consequently realised by systematic control of environmental factors in the open sea regions by the Baltic countries and simultaneously conducted control of the national coastal zones, as well as the control of external sources of matter entering the Baltic Sea. Beside the scientific goals, the studies on eutrophication included the practical aspect determining the ways and the measures necessary for the protection of the Baltic Sea environment.

In the subsequent chapters two aspects of the productiveness condition of the Baltic Sea are presented. The first one concerns the draft assessement of the seasonal fluctuations of the average concentration of nutrients and of organic compounds of phosphorus and nitrogen in the Polish zone of the Baltic Sea; the assessement is based on the results of the I stage of the Baltic Monitoring Programme 1979–1983. The second – concerns the long-term variations of the concentration of the most important nutrients in the Baltic Sea – a recapitulation of the up-to-date knowledge in this field. The hydrochemical and biological characteristics of the Polish coastal zone of the Baltic Sea is presented in another article (Trzosińska *et al.*, 1988).

2. Materials and methods

The analyses of phosphorus, nitrogen and silicon compounds were carried out aboard the r/v HYDROMET and in the laboratories of the Institute of Meteorology and Water Management, Maritime Branch in Gdynia by methods accorded in the Guidelines for the I stage of the Baltic Monitoring Programme (Baltic Marine Environment, 1980). These methods had been in use for a long time, their precision and repeatability tested many times under variable conditions during intercalibration exercises before the monitoring programme started and during its course. The Guidelines set standards also in other methodic aspects of the monitoring, such as: the depths of water sampling (0, 5, 10, 15, 20, at every 10 m in deeper layers and 2–3 m above the bottom), the minimal frequency of cruises and the location of the international sampling stations. In the Polish zone of the Baltic Sea the international stations are: BY5 (P5 – BMP K2) at the Bornholm Deep (55°15'N, 15°59'E), BCS III 10 (P140 – BMP K1) at the southern edge of the Gotland Basin (55°33'N, 18°24'E) and P1 (BMP L1) at the Gdańsk Deep (54°50'N, 19°20'E). The I stage (1979–1983) of the monitoring required at least one research cruise in every season, in the II stage (1984–1988) the measurement frequency increased to minimum 6 expeditions a year.

Althought the extent of studies carried out in the Baltic Sea for many years by the Institute of Meteorology and Water Management, Maritime Branch, Gdynia, had varied, the applied methods of analyses had been usually intercalibrated, the sampling had taken place at the standard Baltic depths and the cruises had been scheduled according to the seasons. Thus, the results of these studies could have been used for the investigations on the long-term trends in nutrient levels. Besides the international stations the cruises included measurements at the coastal stations along the eastern, northern and the western borders of the Polish zone of the Baltic Sea (IMGW, 1987).

Table 1 presents the number of water samples analysed in the years 1979–1983. The results of these analyses set the basis for the determination of the seasonal fluctuations of nutrient concentrations; they were also included in the multi-year data series of the Institute of Meteorology that formed the background for trend calculations of nutrient concentrations in the Gdańsk Deep waters.

Table 1: The number of water samples collected in the Polish zone of the Baltic Sea and analysed in various seasons in the years 1979–1983

Parameter	Winter I–III	Spring IV–VI	Summer VII–IX	Autumn X–XII	5-years 1979–1983
Phosphates	537	518	651	463	2169
Total phosphorus	259	317	390	361	1327
Nitrates and nitrites	531	517	653	466	2167
Ammonia	503	515	600	433	2051
Total nitrogen	300	255	364	332	1251
Silicates	397	388	485	367	1637

Since the environmental conditions in the Gulf of Gdańsk change dramatically depending on the region, the article presents results according to the following partition of the Gulf: the internal part of the Gulf – from the coast line to the tip of the Hel Peninsula, and the external part – from the Hel to the geographic border of the Gulf.

3. Seasonal fluctuations

Due to a close connection with the primary production, the seasonal cycle of nutrient concentrations in the Baltic is well recognized and reffered to in literature. The state-of-the-art in this field before the beginning of the Baltic Monitoring Programme had been reviewed by Melvasalo *et al.* (1981).

The presented characteristics of seasonal fluctuations of phosphorus, nitrogen and silicone compounds in the Polish zone of the Baltic Sea (Tabls. 2–8) is based on the results of 5-year (1979–1983) systematic studies carried out in the open sea region (the southern part of the Bornholm Basin, Słupsk Furrow, the northern part of the Gdańsk Basin and the southern part of the Gotland Basin), in the Gulf of Gdańsk and in the Pomeranian Bay. As regards the coastal zone of the central Polish coast, following the isobath 20–30 m, the systematic analyses were carried out mostly in the years 1979–1980; however, the results obtained in 1986–1988 confirmed the representativeness of the earlier data.

Positive skewness, exedance, and bimodal distribution frequent at the bottom, are the specific features of regional frequency distributions of nutrient concentrations. The extent of deviation from the Gaussian distribution varies depending on the region, water layer and period, similary to the sources of these deviations.

In the case of the upper water layers the major causes of deviation are the irregular inputs of nutrients and organic matter from the land-based sources, while in the case of deep water layers they consist in antagonistic processes undergoing at the sea floor under variable oxygen conditions, *e.g.* nitrification and denitrification, precipitation and dissolution of phosphates. The fluctuations of standard deviations and coefficients of variation of mean nutrient concentrations well correspond to the intensity and duration of these processes.

The sinusoidal course of nutrient concentrations in the isohaline layer, with a well determined maximum in winter and a minimum in the vegetative seasons, generally spring or summer, is generally known; however, the seasonal amplitudes are particularly high at the moment, which is typical for the eutrophic environment. Still greater oscillations appeare in the euphotic layer; the mean differences between the euphotic and isohaline layers are of 10^{-2}, 10^{-1} and 1 $\mu mol \cdot dm^{-3}$ order of magnitude for phosphates, nitrates and silicates, respectively.

3.1. Phosphorus compounds

In the euphotic zone, the range of phosphate concentrations was very considerable: from below the detection limit to 3.7 $\mu mol \cdot dm^{-3}$. Values exceeding 1 $\mu mol \cdot dm^{-3}$ were recorded solely in the Pomeranian Bay, in the internal part of the Gulf of Gdańsk and locally along the central Polish coast which indicates their land origin. Complete utilization of

Table 2: Mean phosphate concentrations ($\mu mol \cdot dm^{-3}$) in the Polish zone of the Baltic Sea in 1979–1983. In brackets – standard deviations

Region, water layer	Winter	Spring	Summer	Autumn	1979–1983
OPEN SEA					
isohaline layer	**0.62**	**0.15**	**0.15**	**0.37**	**0.32**
	(0.10)	(0.09)	(0.20)	(0.19)	(0.23)
below isohaline layer	**1.35**	**1.30**	**1.57**	**2.28**	**1.55**
	(0.70)	(0.87)	(1.12)	(2.44)	(1.31)
COASTAL ZONE					
central Polish coast					
0–30 m depth	**0.56**	**0.17**	**0.30**	**0.51**	**0.38**
	(0.46)	(0.16)	(0.31)	(0.59)	(0.44)
POMERANIAN BAY					
entire water column	**1.01**	**0.12**	**0.56**	**0.78**	**0.61**
	(0.63)	(0.14)	(0.38)	(0.85)	(0.64)
GULF OF GDAŃSK					
internal part					
isohaline layer	**0.77**	**0.15**	**0.38**	**0.58**	**0.46**
	(0.42)	(0.35)	(0.48)	(0.39)	(0.46)
below isohaline layer	**1.25**	**1.10**	**1.16**	**1.04**	**1.13**
	(0.79)	(0.97)	(0.80)	(0.72)	(0.79)
GULF OF GDAŃSK					
external part					
isohaline layer	**0.62**	**0.10**	**0.14**	**0.28**	**0.28**
	(0.12)	(0.12)	(0.09)	(0.19)	(0.24)
below isohaline layer	**1.60**	**2.11**	**3.13**	**3.11**	**2.52**
	(0.75)	(1.75)	(3.66)	(3.15)	(2.27)

phosphates recurred in all the regions in spring, and sporadically was also observed in other seasons of the vegetative period.

The seasonal cycle of phosphate concentration (Tabl. 2) in the upper water layer was significantly marked in all the regions, but the highest mean amplitude between the winter maximum and the spring minimum (0.5–0.9 $\mu mol \cdot dm^{-3}$) occured in the bays and the lowest – in the open sea and the adjacent coastal zone (0.4–0.5 $\mu mol \cdot dm^{-3}$). Below the halocline the maximal phosphate concentrations were noticed in the second half of the year, when the resources of the dissolved oxygen diminished. In the Gdańsk Deep and the Bornholm Deep, together with hydrogen sulphide appearance in 1979–1982, the phosphate concentration started to exceed 8 $\mu mol \cdot dm^{-3}$.

Organic phosphorus compounds (Tabl. 3) constituted up to 58% on average of the total phosphorus content in the isohaline layer and about 20% in the deep water layers. In the euphotic zone the seasonal cycle

Table 3: Mean concentrations of organic phosphorus compounds ($\mu mol\ dm^{-3}$) in the Polish zone of the Baltic Sea in 1979–1983. In brackets – standard deviation

Region, water layer	Winter	Spring	Summer	Autumn	1979–1983
OPEN SEA					
isohaline layer	**0.41**	**0.52**	**0.40**	**0.33**	**0.42**
	(0.36)	(0.38)	(0.27)	(0.22)	(0.32)
below isohaline layer	**0.35**	**0.50**	**0.32**	**0.37**	**0.38**
	(0.35)	(0.41)	(0.31)	(0.35)	(0.36)
COASTAL ZONE					
central Polish coast					
0–30 m depth	**0.47**	**0.50**	**0.70**	**0.36**	**0.52**
	(0.25)	(0.44)	(0.48)	(0.28)	(0.40)
POMERANIAN BAY					
entire water column	**0.44**	**0.83**	**0.74**	**0.35**	**0.59**
	(0.34)	(0.53)	(0.30)	(0.25)	(0.42)
GULF OF GDAŃSK					
internal part					
isohaline layer	**0.75**	**0.89**	**0.77**	**0.44**	**0.66**
	(0.52)	(0.78)	(0.67)	(0.35)	(0.59)
below isohaline layer	**0.74**	**0.77**	**0.30**	**0.72**	**0.63**
	(0.79)	(1.02)	(0.25)	(0.83)	(0.76)
GULF OF GDAŃSK					
external part					
isohaline layer	**0.31**	**0.49**	**0.50**	**0.32**	**0.41**
	(0.26)	(0.40)	(0.29)	(0.28)	(0.32)
below isohaline layer	**0.44**	**0.56**	**0.64**	**0.38**	**0.51**
	(0.45)	(0.60)	(0.72)	(0.42)	(0.57)

manifested itself through maximal concentrations and a maximal share of the organic fraction in the periods of intensified primary production. The mean amplitudes between the spring–summer maximum and the autumn–winter minimum varied from 0.4 to 0.5 $\mu mol \cdot dm^{-3}$ in the bays and from 0.2 to 0.3 $\mu mol \cdot dm^{-3}$ in the open sea. Although in the deep water layers this cycle was additionally affected by hydrological factors and mineralization of organic matter of auto- and allochtonic origin, the mean seasonal amplitudes were of the same magnitude as in the upper water layers.

3.2. Nitrogen compounds

Nitrates form the main fraction of inorganic nitrogen compounds (Tabls. 4 and 5) in sea water. In the isohaline layer they made up, on average, 60% of the sum of nitrogen salts: the maximum – over 70% in winter, the minimum – about 30% in summer. Ammonium salts constituted about 40% of the inorganic nitrogen compounds dissolved in the isohaline water layer and 27% in deeper layers. The share of ammonium salts in water varied according to seasons from the greatest in summer to the smallest in winter. Nitrites formed only a minute fraction of nitrogen salts, with the average content of 4% in the isohaline layer and 2% in the deeper water layers.

The high phytoplankton demand for nitrates (Tabl. 4) was manifested in the differences between the winter maximum and the summer minimum that reached over 16 $\mu mol \cdot dm^{-3}$ (on average) in the Pomeranian Bay, over 6 $\mu mol \cdot dm^{-3}$ in the internal Gulf of Gdańsk and along the central Polish coast and 3.7 $\mu mol \cdot dm^{-3}$ in the open sea region. These amplitudes, as well as the absolute values of nitrate concentrations in winter, gave evidence of the considerable eutrophication of the Polish zone of the Baltic Sea and clearly indicated the land sources as the cause of eutrophication. Below the halocline the seasonal amplitudes were relatively small and aroused mainly from oxygen conditions and their impact on the processes of mineralization and denitrification.

The average concentration of nitrites was low in comparison with the other nitrogen salts, from 0.1 to 0.3 $\mu mol \cdot dm^{-3}$ in majority of regions, except for polluted areas of the Pomeranian Bay and the Gulf of Gdańsk. The respective seasonal amplitudes of nitrite concentrations were also small.

Table 4: Mean nitrate concentrations ($\mu mol \cdot dm^{-3}$) in the Polish zone of the Baltic Sea in 1979–1983. In brackets – standard deviation

Region, water layer	Winter	Spring	Summer	Autumn	1979–1983
OPEN SEA					
isohaline layer	**3.94**	**0.87**	**0.22**	**1.07**	**1.61**
	(1.50)	(1.38)	(0.16)	(1.16)	(1.69)
below isohaline layer	**5.39**	**4.47**	**5.52**	**5.16**	**5.15**
	(1.79)	(2.89)	(2.76)	(3.44)	(2.71)
COASTAL ZONE					
central Polish coast					
0–30 m depth	**5.95**	**2.63**	**0.73**	**2.59**	**2.64**
	(7.38)	(6.74)	(1.20)	(5.64)	(5.64)
POMERANIAN BAY					
entire water column	**15.46**	**8.07**	**1.19**	**4.45**	**6.50**
	(8.59)	(9.59)	(2.67)	(9.02)	(9.17)
GULF OF GDAŃSK					
internal part					
isohaline layer	**8.90**	**4.08**	**2.55**	**4.75**	**4.54**
	(6.84)	(9.12)	(4.57)	(8.59)	(7.66)
below isohaline layer	**4.81**	**3.57**	**3.96**	**4.12**	**4.76**
	(0.96)	(2.30)	(2.56)	(2.96)	(2.52)
GULF OF GDAŃSK					
external part					
isohaline layer	**5.93**	**0.64**	**0.32**	**1.27**	**1.96**
	(2.34)	(0.76)	(0.25)	(0.74)	(2.54)
below isohaline layer	**6.49**	**5.64**	**4.64**	**5.05**	**5.41**
	(2.18)	(3.58)	(3.94)	(3.58)	(3.46)

Ammonium salts, similarly to nitrates, are an important source of nitrogen for autotrophic organisms. The mean seasonal amplitudes of their concentration ranged from 0.8 $\mu mol \cdot dm^{-3}$ in the open sea region to over 3 $\mu mol \cdot dm^{-3}$ in the Pomeranian Bay and in the internal part of the Gulf of Gdańsk. Below the halocline the concentrations of ammonia depended on oxygen conditions, thus their seasonal cycle followed that of phosphates and opposed the nitrates one.

The amplitudes between the winter maximum and the summer minimum of the resultant seasonal fluctuations of the sum of nitrogen salts (Tabl. 5) ranged from 4 to 15 $\mu mol \cdot dm^{-3}$, depending on the region. The ratio of the seasonal amplitude of nitrogen salts to phosphates in the isohaline layer was 9 on average in the open sea area, while in the coastal regions it approached the Redfield ratio.

Table 5: Mean concentrations of the sum of nitrogen salts (NO_3^-, NO_2^-, NH_4^+) ($\mu mol\ dm^{-3}$) in the Polish zone of the Baltic Sea in 1979–1983. In brackets – standard deviation

Region, water layer	Winter	Spring	Summer	Autumn	1979–1983
OPEN SEA					
isohaline layer	**5.68**	**2.54**	**1.61**	**2.07**	**3.08**
	(2.13)	(3.05)	(1.10)	(1.44)	(2.51)
below isohaline layer	**6.90**	**6.56**	**7.08**	**6.76**	**6.84**
	(2.14)	(4.71)	(2.77)	(3.57)	(3.38)
COASTAL ZONE					
central Polish coast					
0–30 m depth	**8.16**	**3.31**	**2.58**	**4.10**	**4.25**
	(10.94)	(7.27)	(8.08)	(6.42)	(8.41)
POMERANIAN BAY					
entire water column	**20.69**	**10.43**	**5.96**	**6.47**	**10.12**
	(13.48)	(8.92)	(14.33)	(10.47)	(13.02)
GULF OF GDAŃSK					
internal part					
isohaline layer	**13.34**	**6.15**	**5.61**	**7.69**	**7.72**
	(9.47)	(9.71)	(4.96)	(11.34)	(9.66)
below isohaline layer	**8.74**	**8.46**	**8.77**	**6.64**	**8.01**
	(3.97)	(6.24)	(3.00)	(3.19)	(4.06)
GULF OF GDAŃSK					
external part					
isohaline layer	**7.48**	**1.31**	**2.36**	**2.12**	**3.24**
	(3.47)	(1.15)	(1.81)	(0.65)	(3.11)
below isohaline layer	**7.71**	**7.44**	**8.76**	**8.00**	**8.01**
	(2.30)	(3.57)	(4.73)	(3.46)	(3.71)

Organic compounds of nitrogen constituted about 80% of the total nitrogen dissolved in the isohaline layer (Tabl. 6); in the deep water layers this content amounted only to 60% . This percentage increased in the periods of intensive primary production. The seasonal cycle of organic nitrogen compounds was not so regular as those of other nitrogen compounds, possibly due to the imperfect analytical method of determination.

The N/P ratio, which comprised apart from phosphates either nitrates, or all the assimilable by phytoplankton nitrogen salts, gives a good indication of the productiveness condition of the marine environment. Earlier studies demonstrated (Melvasalo *et al.*, 1981) that this ratio was much lower in the Baltic Sea waters than in the ocean. None the less, assimilation of nitrogen and phosphorus by autotrophic organisms proceed in both cases probably in the same ratio (Baltic Marine Environment,

Table 6: Mean concentrations of organic nitrogen compounds ($\mu mol \cdot dm^{-3}$) in the Polish zone of the Baltic Sea in 1979–1983. In brackets – standard deviation

Region, water layer	Winter	Spring	Summer	Autumn	1979–1983
OPEN SEA					
isohaline layer	**21.0**	**12.7**	**15.1**	**11.7**	**15.4**
	(18.9)	(5.8)	(8.1)	(6.6)	(12.2)
below isohaline layer	**20.4**	**11.8**	**13.2**	**11.1**	**14.5**
	(19.4)	(5.5)	(8.0)	(6.6)	(12.6)
COASTAL ZONE					
central Polish coast					
0–30 m depth	**12.8**	**16.8**	**20.8**	**13.6**	**16.5**
	(7.0)	(9.8)	(12.0)	(7.7)	(10.1)
POMERANIAN BAY					
entire water column	**21.2**	**23.5**	**24.0**	**16.3**	**21.2**
	(23.4)	(14.3)	(19.0)	(9.4)	(17.1)
GULF OF GDAŃSK					
internal part					
isohaline layer	**26.2**	**20.6**	**16.5**	**9.8**	**16.2**
	(19.6)	(16.8)	(11.7)	(10.5)	(15.2)
below isohaline layer	**19.8**	**12.2**	**11.6**	**8.1**	**12.6**
	(11.7)	–	(9.9)	(6.6)	(9.6)
GULF OF GDAŃSK					
external part					
isohaline layer	**17.6**	**14.8**	**15.9**	**13.2**	**15.5**
	(17.5)	(8.0)	(11.4)	(7.9)	(12.0)
below isohaline layer	**15.8**	**9.7**	**14.5**	**13.3**	**13.4**
	(19.8)	(4.8)	(7.2)	(7.7)	(11.8)

1987). Seasonal oscillations of the N/P values in the Polish zone of the Baltic (Tabl. 7) supported this finding. In the isohaline water layer the ratio $NO_3 : PO_4$ reached the minimum already in summer, while the ratio $N_n : PO_4$ decreased gradually from spring to autumn. An increase of the N/P ratio in the upper water layer of the Polish zone of the Baltic Sea, as compared with the values recorded in the 1970s (Majewski *et al.*, 1976; Trzosińska, 1978) is remarkable, since it creates potential possibilities for the more and more intensive phytoplankton blooms. Below the halocline the N/P ratio still showed low values and its seasonal oscillations were small and depended mainly on seasonal changes of oxygen conditions.

Table 7: Mean values of the molar ratio of nitrates to phosphates ($NO_3 : PO_4$) and of the sum of nitrogen salts (NO_3^-, NO_2^-, NH_4^+) to phosphates ($N_n : PO_4$) in the Polish zone of the Baltic Sea in 1979–1983

Region	Ratio	Isohaline layer					Below isohaline layer				
		Wint.	Spr.	Sum.	Aut.	1979–1983	Wint.	Spr.	Sum.	Aut.	1979–1983
OPEN SEA	$NO_3 : PO_4$	6.4	5.8	1.5	2.9	5.0	4.0	3.4	3.5	2.3	3.3
	$N_n : PO_4$	9.2	16.9	10.7	5.6	9.6	5.1	5.0	4.5	3.0	4.4
COASTAL ZONE	$NO_3 : PO_4$	10.6	15.5	2.4	5.1	7.0					
central Polish coast	$N_n : PO_4$	14.6	19.5	8.6	8.0	11.2					
POMERANIAN BAY	$NO_3 : PO_4$	15.3	67.3	2.1	5.7	10.7					
	$N_n : PO_4$	20.5	86.9	10.6	8.3	16.6					
GULF OF GDAŃSK	$NO_3 : PO_4$	11.6	27.2	6.7	8.2	9.9	3.9	3.3	3.4	4.0	4.2
internal part	$N_n : PO_4$	17.3	41.0	14.8	13.3	16.8	7.0	7.7	7.6	6.4	7.1
GULF OF GDAŃSK	$NO_3 : PO_4$	9.6	6.4	2.3	4.5	7.0	4.1	2.7	1.5	1.6	2.2
external part	$N_n : PO_4$	12.1	13.1	16.9	7.6	11.6	4.8	3.5	2.8	2.6	3.2

3.3. Silicates

Silicates do not belong to the factors limiting primary production in the Southern Baltic because of the considerable river run-off. In the years 1979–1983, in spite of the immense phytoplankton blooms, the complete utilization of silicates was an exception. However, the significant number of diatoms in the Baltic phytoplankton population produced the clearly marked seasonal concentration cycle in the isohaline layer, from the winter maximum to the spring–summer minimum (Tabl. 8). The mean amplitudes of concentration ranged from 8 to 10 $\mu mol \cdot dm^{-3}$ in the open sea zone and the adjacent coastal area, and increased to 12–21 $\mu mol \cdot dm^{-3}$ in the bays. Silicate concentrations in the deep water layers were rather uniform and increased rapidly only under anoxic conditions.

Table 8: Mean concentrations of silicates ($\mu mol \cdot dm^{-3}$) in the Polish zone of the Baltic Sea in 1979–1983

Region, water layer	Winter	Spring	Summer	Autumn	1979–1983
OPEN SEA					
isohaline layer	**16.0**	**6.8**	**6.4**	**8.4**	**9.6**
	(2.9)	(3.3)	(2.2)	(4.2)	(4.5)
below isohaline layer	**32.4**	**32.7**	**33.0**	**31.9**	**32.6**
	(14.0)	(14.3)	(14.3)	(21.6)	(15.5)
COASTAL ZONE					
central Polish coast					
0–30 m depth	**11.6**	**3.3**	**9.0**	**8.8**	**8.3**
	(14.8)	(3.4)	(6.8)	(12.9)	(10.5)
POMERANIAN BAY					
entire water column	**27.6**	**6.4**	**15.4**	**13.6**	**15.1**
	(18.1)	(8.3)	(7.8)	(20.2	(16.0)
GULF OF GDAŃSK					
internal part					
isohaline layer	**23.5**	**6.0**	**11.7**	**14.0**	**13.1**
	(14.4)	(7.1)	(9.1)	(12.0)	(11.8)
below isohaline	**29.9**	**31.6**	**26.5**	**22.0**	**26.8**
	(13.4)	(14.7)	(13.0)	(18.7)	(15.1)
GULF OF GDAŃSK					
external part					
isohaline layer	**16.6**	**4.9**	**6.2**	**8.6**	**9.0**
	(7.4)	(4.4)	(3.5)	(2.3)	(6.5)
below isohaline layer	**36.7**	**40.6**	**38.7**	**41.7**	**39.4**
	(17.5)	(23.6)	(24.9)	(23.2)	(22.4)

4. Long-term variations

Long-term variations of nutrient concentrations in the Baltic Sea have been brought into view in literature around the end of 1960s (Fonselius, 1969, 1972, 1976, 1980; Majewski *et al.*, 1974, 1976; Trzosińska and Andrulewicz, 1977; Trzosińska, 1978; Nehring, 1979, 1982, 1984; Jurkovskis, 1980; Milewska and Andrulewicz, 1982; Cyberska and Trzosińska, 1984). Due to progressing eutrophication, the determination of the trend and the rate of the observed long-term changes became the main task in the assessment of the state of the Baltic Sea environment prepared by the group of the Helsinki Commission experts (Baltic Marine Environment, 1987). The analysis comprised the variations of nitrate and phosphate concentrations, being the most important nutrients for primary production in the Baltic Sea on one hand, and on the other hand constituting the final and chemically stable products of the organic matter biodegradation. The analysed material was deprived of data reflecting the effects of temporary factors. In the upper water layers these included seasonal oscillations of nutrient concentrations; in the deep water layers the data verification was based on the occurrence of anoxic conditions, when the nitrates undergo denitrification and considerable amounts of phosphates from the bottom sediments dissolve at the same time.

It has been established that phosphorus and nitrogen compounds accumulate in the quasi-homogeneous surface layer of the Baltic Sea in winter, and the nutrient pool renders possible the more and more intensive development of the spring phytoplankton species. The ratio of the mean annual increase of nitrate concentrations to the increase of phosphate concentrations was 7 to 8 in the open sea zone, while in the regions exposed to a significant land run-off of phosphorus and nitrogen, *e.g.* in the Gulf of Finland and in the Gdańsk Deep it was considerably higher, 14 and 22 respectively.

The winter surface water of the open sea region of the Baltic proper showed the mean annual phosphate accumulation of about 0.025 $\mu mol \cdot dm^{-3}$ (Tabl. 9) during the recent 20–25 years. A slower phosphate accumulation was noticed in the Gdańsk Deep, yet in comparison with the 1940s (Glowińska, 1963) the increase of phosphate concentrations in the euphotic zone in winter was still fourfold. The greatest increase of phosphate concentrations was recorded in the Gulf of Finland, the smallest and diminishing in the northern direction – in the Gulf of Bothnia. The

Table 9: Mean annual accumulation rate of phosphates and nitrates in the winter surface waters of the Baltic Sea (Baltic Marine Environment, 1987)

Region	Period	Phosphate	Nitrate
		($\mu mol \cdot dm^{-3} \cdot year^{-1}$)	
Central Arkona Sea	1964–1983	0.026[c)]	
	1965–1983		0.185[c)]
Central Bornholm Sea	1958–1983	0.026[c)]	
	1965–1983		0.174[c)]
Gdańsk Deep	1961–1983	0.015[c)]	
	1969–1983		0.338[c)]
South-eastern Gotland Sea	1958–1983	0.024[c)]	
	1969–1983		0.196[c)]
Gulf of Finland	1975–1983	0.05[a)]	0.73[b)]
central part	1973–1983	0.05[c)]	0.68[c)]

Probability of error according to Student's t-test:
$a < 5\%$, $b < 1\%$, $c < 0.1\%$

rate of phosphate accumulation in the winter surface water of the Baltic proper was slow in the 1960s (from 0.01 to 0.02 $\mu mol \cdot dm^{-3}$, depending on the region), and then significantly intensified in the subsequent years.

The highly statistically significant accumulation of phosphates was observed in the deep water layers of the Baltic proper, with the mean annual concentration progression 2–4 times higher than in the surface waters (Tabl. 10). The rate of accumulation in this water layer depended on the oxygen conditions below the halocline, diminishing visibly in the periods of oceanic water inflows, and increasing in the periods of stagnation. Due to the same reasons the average increase of phosphate concentrations in the Gdańsk Deep was two times smaller at the depth of 80 m than in the near bottom water layer.

Owing to the imperfect analytical methods applied earlier, the trends in the nitrate concentrations could be evaluated only from the fall of the 1960s. Nevertheless, this several years' span of analyses sufficed to point out that nitrates accumulated in the winter surface waters of the Baltic Sea much faster than phosphates (Tabl. 9). In the Gdańsk Deep the conspicuous increase of nitrate concentrations began in 1973 (Cyberska and Trzosińska, 1984; Cyberska *et al.*, 1987), and its rate was twice as that found by Nehring (1984) for the Baltic proper.

Table 10: Mean annual variations of phosphate and nitrate concentrations in the deep waters of the Baltic Sea (Baltic Marine Environment, 1987)

Region	Period	Depth [m]	Phosphate ($\mu mol \cdot dm^{-3} \cdot year^{-1}$)	Nitrate ($\mu mol \cdot dm^{-3} \cdot year^{-1}$)
Gdańsk Deep	1961–1983	80	0.028[a)]	
		100	0.055[b)]	
	1969–1983	80		0.239[b)]
	1969–1973	80		0.288
	1974–1978	80		0.496
	1979–1983	80		−0.108
	1969–1983	100		0.086
Gotland Deep	1958–1982	100	0.075[c)]	
	1968–1973	100		0.289[b)]
	1974–1978	100		0.716[c)]
	1979–1982	100		−0.754[b)]
Landsort Deep	1958–1982	100	0.041[c)]	
	1968–1973	100		0.073
	1974–1978	100		1.095[c)]
	1979–1982	100		−1.068[c)]
Bothnian Sea	1967–1984	100	0.015[c)]	
	1968–1984	100		0.27[c)]
Gulf of Finland central part	1967–1983	70	−0.05	0.15[a)]

Probability of error according to Student's t-test:
$a < 5\%$, $b < 1\%$, $c < 0.1\%$

Due to the alternating oxygen conditions below the halocline, the long-term variations of nitrate concentrations in the Baltic Sea are quite complicated (Tabl. 10). Similarly to phosphates, in the areas close to the Straits, *e.g.* the Arkona Sea or the Bornholm Deep, the long-term fluctuations of nitrate concentrations were completely masked by the oceanic inflows (Nehring, 1982, 1984). Only in the deeps of the Central and Northern Baltic Sea it was possible to distinguish that the period of moderate nitrate accumulation in 1968–1973 was followed by an intensive accumulation term in 1974–1978, with another subsequent decrease of nitrate concentrations in 1979–1983 due to the prolonged stagnation. Shaffer and Ronner (cit. after Larsson *et al.*, 1985) estimated that denitrification deprived the Baltic water of 470 thousand tons of nitrate-nitrogen per year. Considering the Gdańsk Deep example it becomes clear that this mechanism of nitrogen balance regulation was most effective in the near bottom water layers (Tabl. 10). Nevertheless, as regards the long scale trend, accumulation prevailed in the deep water layers of the Gulf of Bothnia, Gulf of Finland and the Gdańsk Deep.

The described long-term variations of phosphate and nitrate concentrations indicated the progressing eutrophication of the Baltic Sea. However, the eutrophication did not run regularly. In the surface waters, as well as below the halocline, there were observed alternating periods of intensified and reduced rate of nutrient variations and periods of stable concentration levels. It has been demonstrated that even in the case of the Gdańsk Deep, the region exposed to the influence of the Vistula River, these oscillations could not be directly attributed to the temporal increase or decrease of phosphorus and nitrogen land run-off (Cyberska *et al.*, 1987).

The attempt to define the oscillations of nitrate and phosphate concentrations in the Gdańsk Deep was undertaken basing on the annual mean concentrations amended with the mean annual trend coefficients for the respective long-terms: 24 years (1961–1984) and 16 years (1969–1984). The applied method of analysis was spectral-correlation analysis of Blackman-Tukey. Since the multi-year periods of observations were relatively short, the results could not be intepreted as real oscillations, yet they rendered possible to discern the characteristic terms in the periodic fluctuations of phosphates and nitrates content, independent of the eutrophication. The analysis of the power spectrum indicated that phosphate concentrations in the homogenous surface water layer in winter oscillated in 3-years, 6 to 7-years and 10–12-years cycles; phosphate fluctuations at the depth of 80 m and 100 m (Fig. 1) were of similar rhythmicity. The level of nitrate concentrations changed also every 3–4-years and 5–7-years (Fig. 2). However, the longer cycles could not be shown because the data series were too short. In both the figures the cycles which were poorly marked or uncertain due to a relatively short measurement period are given in brackets. The crosscorrelation analysis between the oscillations of the mean phosphate and nitrate concentrations in the surface winter water and at various depths below the halocline throughout the year supported the 3, 6–7 and 9–12-years periodicity of phosphates level fluctuations and 3 and 6-years cycles of nitrates level.

The results of the spectral analysis does not allow a complete explanation of the reasons for the periodic changes of nutrient concentrations

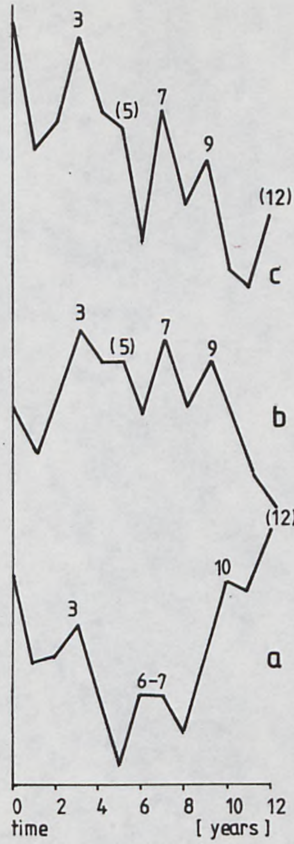

Figure 1: The relative course of the spectral power function in the analysis of the periodicity of phosphate concentration in the homogeneous layer of the surface water in winter (a), at the depth of 80 m (b) and 100 m (c) in the Gdańsk Deep, 1969–1984

in the Gdańsk Deep, but taking into account the information concerning the other phenomena at the Baltic Sea it is supposed that the cycle of 3–4-years results from the anomalies of the atmospheric circulation system, their effect on the salinity of the European shelf seas and on the oceanic inflows into the Baltic, as well as on the fluctuations of the river outflows (Kullenberg, 1981). The 3–4-year period fluctuations were easily distinguishable when analysing the amount of river water flowing into the Baltic Sea in 1950–1975 (Baltic Marine Environment, 1986). In the Polish zone of the Baltic Sea they were discernible in the long-term course of the hydrologic and meteorologic parameters, like water temperature and air temperature (Jednorał *et al.*, 1987). The interfering fluctuations

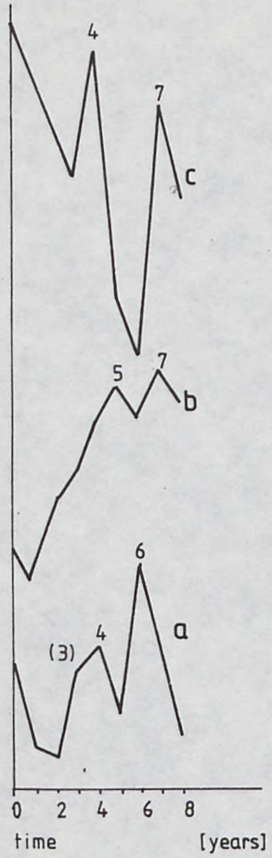

Figure 2: The relative course of the spectral power function in the analysis of the periodicity of nitrate concentration in the homogeneous layer of the surface water in winter (a), at the depth of 80 m and 100 m (c) in the Gdańsk Deep, 1969–1984

of the amounts of oceanic and fresh water entering the Baltic Sea manifested itself in the resultant oscillations of salinity. In winter the salinity and phosphate and nitrate concentrations in the surface water layer of the Gdańsk Deep were related by the following regression equations (Cyberska *et al.*, 1987):

$$PO_4(\mu mol \cdot dm^{-3}) = 1.68S - 12.47$$

$$NO_3(\mu mol \cdot dm^{-3}) = 3.88S - 27.58$$

The correlation coefficients and the probability of error, calculated according to the Student's t-test, were 0.54 and 0.41 and 1% and 5% respectively.

The phosphate and nitrate oscillations of the intermediate period, 6–7-years, were probably also the result of salinity fluctuations though of a different period, while the 9–12-years cycle seemed to correspond to the periodicity of the sunspots activity; similar oscillations, characteristic for several hydrometeorological parameters, had been observed in the Southern Baltic (Jednorał *et al.*, 1987). However, to establish any quantitative relations as regards the nutrient fluctuations would require much longer data series than the ones at hand.

The eutrophication of the Baltic Sea, seen as the long-term increase of phosphate and nitrate concentrations, is accompanied by changes of various chemical parameters of the marine environment. Some regions show the accumulation of the total phosphorus and nitrogen (Baltic Marine Environment, 1987). The surface water layer of the Gdańsk Deep demonstrates a considerable increase of the oxygen concentration in the warm seasons (Cyberska and Trzosińska, 1984; Cyberska *et al.*, 1987). It has been recently found that the pH of the Baltic Sea water also undergoes the long-term variations, which in the upper water layers can be due to various reasons, but first of all to enhanced primary production. Fonselius (1988) informed earlier of a weak, positive trend of pH measured during summer in the surface water of the Gotland Deep. The calculations based on pH measurements conducted by the Institute of Meterology and Water Management, Maritime Branch, Gdynia, in 1968–1986 and by various Baltic countries during the International Baltic Year

Table 11: Mean annual variations of pH in water of the Southern Baltic

Region and station	Period	Season	Water layer [m]	pH
Bornholm Deep	1969–1986	warm	0–20	0.011[a)]
BY5	1969–1986	cold	0–50	−0.006
South-eastern	1969–1986	warm	0–20	0.012[a)]
Gotland Basin	1969–1986	cold	0–60	0.000
BCS III 10				
Gdańsk Deep	1969–1986	warm	0–20	0.027[b)]
P1	1979–1986	cold	0–70	0.001

Probability of error according to Student's t-test:
$a < 10\%$, $b < 1\%$

1969/1970 (Tabl. 11), *i.e.* measurements carried out using the present method (Baltic Marine Environment, 1980), indicated the statistically significant trend of the weak increase of pH values in the upper water layers in the south-eastern part of the Gotland Basin and in the Bornholm Deep. At the same time the rate of increase of pH in the Gdańsk Deep was 2–3 times greater.

5. Recapitulation and conclusions

- The research carried out in the Polish zone of the Baltic Sea within the I stage of the Baltic Monitoring Programme, in the years 1979–1983, indicated the progressing eutrophication of the marine environment. As regards the nutrients, the eutrophication manifested itself in significant seasonal fluctuations of concentrations and in the long-term accumulation of phosphate and nitrate.
- The productiveness of the marine environment varies depending on the region. The greatest accumulation of phosphates, nitrogen salts and silicates (Tabls. 2, 4, 5, 8) was recorded in winter in the Pomeranian Bay and in the internal part of the Gulf of Gdańsk, pointing the land-based nutrient sources. Lower nutrient concentrations, though increased as compared with the previous years, were observed in the winter surface water layers of the Bornholm Deep, the Słupsk Furrow, the Gdańsk Deep and the south-eastern part of the Gotland Deep in winter.
- The differences between the winter maximum and the spring–summer minimum of the concentrations of the essential nutrients prove the high intensity of primary production. The ratio of the seasonal amplitudes of nitrogen salts and phosphates, calculated as a mean for the entire isohaline layer in the years 1979–1983, reached 9 in the open sea and exceeded 16 in the bays.
- The nutrient concentrations as well as the concentrations of organic phosphorus and nitrogen compounds in the deep water layers were influenced by the prolonged stagnation period in the Baltic Sea, which caused, on one hand, the accumulation of phosphates and silicates due to oxygen deficiency, and on the other – disappearance of nitrates and inhibition of the mineralization of organic matter (Tabls. 2–6, 8).

- The process of long-term accumulation of phospates in the surface water layer of the Central Baltic in winter was characterized by the mean coefficients of increase from 0.015 $\mu mol \cdot dm^{-3}$ per year in the Gdańsk Deep to 0.026 $\mu mol \cdot dm^{-3}$ per year in the Bornholm Basin (Tabl. 9). As regards the nitrates, the greatest rate of accumulation was recorded in the Gdańsk Deep (0.34 $\mu mol \cdot dm^{-3} \cdot year^{-1}$) and the smallest in the Bornholm Basin (0.17 $\mu mol \cdot dm^{-3} \cdot year^{-1}$).

- The highly significant accumulation of phosphates was observed in the deep water layers of the Central Baltic, with the mean annual concentration progression exceeding 2–4 times that of the surface water (Tabl. 10). Due to the alternating oxygen conditions the long-term variations of nitrate concentrations in these water layers revealed a complex character. However, considering the long-term trends, the accumulation of nitrates prevailed in the deep waters of the Gulf of Bothnia, the Gulf of Finland and the Gdańsk Deep.

- The long-term accumulation of phosphates and nitrates in the Gdańsk Deep oscillates periodically. 3, 6–7 and 9–12-years periods of oscillations had been found for the entire water column (Figs. 1 and 2).

- The eutrophication of the Baltic Sea is accompanied by changes in other parametrs of the marine environment, such as the increase of oxygen concentration in the surface water layer in the vegetative seasons and the increase of the water pH (Tabl. 11).

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