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VARIABILITY OF SELECTED HYDROCHEMICAL PARAMETERS OF THE 3RD ORDER RIVER ODRA ESTUARY IN RELATION TO HYDROLOGY OF THE AREA IN 1997-2000

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ABSTRACT

Hydrochemistry of River Odra (within the boundaries of Szczecin) and Lake Dąbie, which together fo-rm a 3rd order estuary, was studied over 1997-2000 from analyses of the following major parameters: water temperature, dissolved, oxygen content, BOD_5, and contents of inroganic nitrogen, reactive pho-sphorus, and chlorophyll *a*. Effects of environmental factors (temperature, primary production, flow rate) on the estuary's hydrochemistry were followed. The entire estuary was demonstrated to possess uniform hydrochemical conditions, the contents and seasonal variability of nutrients as well as the high primary production being typical of eutrophic water bodies. Primary production in the area was nitrogen- or nitrogen and phosphorus-limited. Hydrology (flow rate, sea water incursions) as well as anthropogenous pollution proved to be factors important for the hydrochemistry of the area.

Key words: southern Baltic, estuary, water temperature, oxygen, organic matter, nutrients, chlorophyll a.

INTRODUCTION

Inland waters are very susceptible to degradation and contribute substantially to pollution of the oceans. Particularly prevalent is organic and nutrient enrichment of inshore areas [18]. Estuaries, as regions of mixing of fresh and marine water, are characterised by intensified mass transfer and have a high potential for self-purification [13]. Although the literature concerning estuaries and coastal areas and processes affecting them is ample, references pertaining to the River Odra estuary (particularly with respect to the Odra and Lake Dąbie within the boundaries of Szczecin) are scarce [17].

Hydrography of the Odra estuary, far from a typical one with its specific water dynamics, as well as the hydrochemistry modified by human activities, creates dynamic environmental conditions, decisive for the high biodiversity of the area [2].

The present work is aimed at exploring interactions between water dynamics, thermal regime, and chemical variables (nutrient contents) that shape aquatic system productivity, as defined by the organic matter enrichment. The outcome of the study should contribute to a better understanding of phenomena taking place in water bodies subjected to excessive anthropogenous pressure.

Study area

The terminal section of River Odra forms a typical southern Baltic estuary [13] and – following Majewski [14] – can be divided into the following parts:

- the Pomeranian Bay, a 1st order estuary in which the effects of marine Baltic waters play the major role;
- the Szczecin Lagoon, a 2nd order estuary, characterised by mixed water of marine and riverine origin, the latter – supplied by River Odra – dominating the chemical regime;
- River Odra mouth opening to the Szczecin Lagoon along with Lake Dąbie and the stretch of the Odra, within the boundaries of Szczecin, that form two branches (western, called Odra Zachodnia, and eastern, called Odra Wschodnia), a 3rd order estuary with chemistry typical of inland waters, partly affected by sea water incursions and fed also by mixed water from the Szczecin Lagoon.

The Odra mouth area has a very specific, complex water dynamics, the complexity resulting from interplay between inflows from the catchment area, direct and indirect wind effects, ice cover, atmospheric pressure, and human activities [1].

The Odra mouth area is an intricate hydrographic system, formed by two branches of the river, numerous canals connecting them, water-logged islands, and the flow-through Lake Dąbie. This complexity makes it difficult to estimate the true magnitude of flow. As showed by Mikulski [16] and Majewski [14], Odra Wschodnia carries an annual average of 76% of the water, Odra Zachodnia transporting as little as 24%. Odra Wschodnia feeds Odra Zachodnia through Skośnica Canal, discharging about 20% of the water, while Odra Zachodnia feeds the Regalica via the Parnica; hence it is estimated that about 80-82% of the total Odra water is discharged into Lake Dąbie via the Regalica.

When estimating the magnitude of flow, reference is usually made to measurements taken at Gozdowice (kilometre 645.3) [1]. Table 1 shows average monthly flow rates during the period of study.

Average flow rates, as measured in 1997-2000, i.e., during the study reported on in this work, are shown in Table 2.

Table 1. Average monthly flow rates ($m^3 \cdot s^{-1}$) at Gozdowice on the Odra (km 645.3) in 1997-1999 [10]

	Month of the hydrological year											
	11	12	1	2	3	4	5	6	7	8	9	10
1997	643	533	362	494	632	541	510	411	1320	1510	588	464
1998	490	635	830	736	892	822	516	363	351	323	367	569
1999	787	691	738	823	1350	929	748	525	696	359	276	308

Table 2. Average diel flow rates ($m^3 \cdot s^{-1}$) at Gozdowice on the Odra (km 645.3) in 1997-2000 [10]

Date	Flow rate	Date	Flow rate	Date	Flow rate
9 June1997	484	12 May 1998	568	21 July 1999	753
16 September 1997	624	20 August 1998	310	12 October 1999	291
20 October 1997	500	27 October 1998	574	09 December 1999	344
15 January 1998	854	13 April 1999	894	16 March 2000	970
30 March 1998	854	16 June 1999	484	25 May 2000	318
1998		1999		2000	

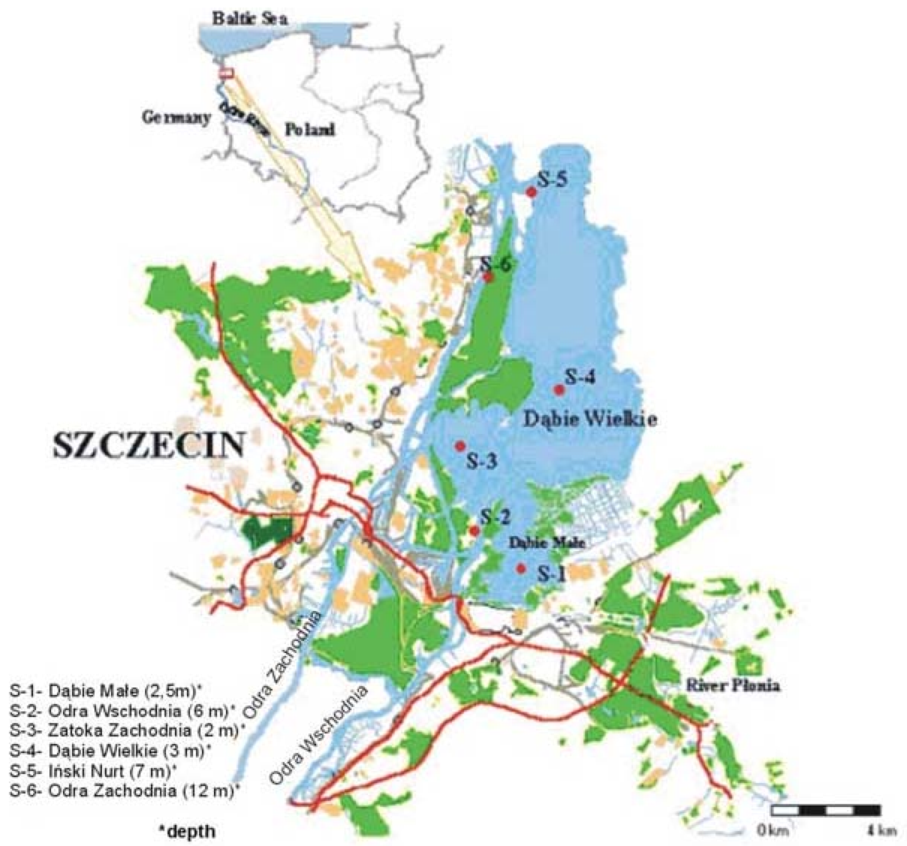
Lake Dąbie is the fourth largest Polish lake; its surface area and volume amount to 5600 ha and about 160 mln m^3, respectively. The 55 km long shoreline is well-developed (development index of 2.3) and forms a number of shallow coves. The lake is shallow (the maximum and average depths of 4.5 and 2.5 m, respectively), the isobaths being arranged fairly regularly. The depth increases to 8.0 m where the Odra discharges into the Lake (in Iński Nurt) [4]. The seawater incursion effect in the Dąbie is manifested as typically sea-like, periodic variations in the lake level and in salinity changes; the lake is clearly a flow-through reservoir, its water being exchanged 55 times within a year [14].

The 3rd order Odra estuary is particularly exposed to pollution. Odra Zachodnia receives about 70% of the amount of Szczecin's sewage and wastewater discharge, largely untreated; the pollution load is increased due to ship's traffic and as a result of operation of the harbour and shipyard. Odra Wchodnia receives the Dolna Odra Power Station cooling water as well as municipal sewage from the right-bank Szczecin [14, 24].

MATERIALS AND METHODS

Water chemistry in the area was studied from June 1997 to May 2000; sampling dates are given in Table 2. Water samples were collected, with a Ruttner sampler, at 6 sites (Fig. 1), from the near-surface and near-bottom layers. At the time of sampling, water temperature, pH, and Secchi disc visibility were measured. Chemical assays in the laboratory were run according to the methodology recommended by Hermanowicz *et al*. [6] and Standard Methods [22]. Dissolved oxygen content was determined iodometrically (the Winkler method), while the per cent oxygen saturation was calculated from the Fox tables. Biochemical oxygen demand (BOD_5) was determined directly, following a 5-d incubation without air at 20°C. Nutrient and chlorophyll *a* contents were determined colorimetrically on a Perkin Elmer Lambda 10 spectrophotometer at the recommended wavelengths. The inorganic nitrogen content was a sum of nitrate, nitrite, and ammonia nitrogen contents. Nitrite nitrogen was assayed with sulphanylamide at λ=543 nm; nitrate nitrogen was determined, following reduction to nitrates in a Cu-Cd column, with sulphanylamide at λ=543; ammonia nitrogen was determined with indophenol blue at λ=630 nm. Reactive phosphorus was determined with the molybdenate technique, with ascorbic acid as a reducer, at λ=882 nm. Chlorophyll *a* was 90% acetone-extracted and measured at λ =665 nm.

Fig. 1. Location of water sampling sites in the Odra estuary in 1997-2000



The data were subjected to statististical treatment involving linear regression analysis and the Pearson correlation coefficients (r_{xy}), with n = 15. The significance tests were run at the $\alpha_{0.05}$ confidence level. Following Stanisz [23], the following correlation scale was used:

$r_{xy} = 0$	variables not correlated,
$0 \leq r_{xy} < 0.1$	negligible correlation,
$0.1 \leq r_{xy} < 0.3$	poor correlation,
$0.3 \leq r_{xy} < 0.5$	intermediate correlation,
$0.5 \leq r_{xy} < 0.7$	high correlation,
$0.7 \leq r_{xy} < 0.9$	very high correlation,
$0.9 \leq r_{xy} < 1$	almost full correlation.

The following variables were subjected to statistical treatment:

- oxygen regime (dissolved oxygen and per cent oxygenation) versus water temperature, chlorophyll *a* content, and biochemical oxygen demand (BOD_5) (Table 3);
- organic matter loading (BOD_5) versus flow rate and chlorophyll *a* content (Table 3);
- nutrients (inorganic nitrogen and reactive phosphorus) versus flow rate, per cent oxygenation, water temperature, and BOD_5 (Table 4);
- chlorophyll *a* versus flow rate, temperature, inorganic nitrogen, and reactive phosphorus (Tables 3 and 4).

Table 3. Coefficients of correlations (r) between oxygen and thermal conditions and biochemical oxygen demand (BOD_5), chlorophyll *a*, and flow rate, (n=15) (s = surface water; b = near-bottom water)

Site		O_2 vs Temp.	$\%O_2$ vs Temp.	$\%O_2$ vs Chl *a*	Chl *a* vs Temp.	Chl *a* vs Flow rate	BOD_5 vs $\%O_2$	BOD_5 vs Flow rate	BOD_5 vs Chl *a*
Dąbie Małe	s	-0.50	0.07	0.59	0.52	-0.31	0.61	-0.45	0.81
	b	-0.58	0.03	0.64	0.50	-0.22	0.60	-0.07	0.78
Dąbie Wielkie	s	-0.63	0.05	0.34	0.47	-0.25	0.59	-0.44	0.45
	b	-0.67	-0.05	-0.03	0.57	-0.36	0.65	-0.34	0.59
Zatoka Zachodnia	s	-0.42	0.18	0.47	0.55	-0.39	0.46	-0.12	0.52
	b	-0.52	0.11	0.46	0.61	-0.34	0.64	0.05	0.77
Iński Nurt	s	-0.49	0.16	0.31	0.56	-0.31	0.81	-0.27	0.68
	b	-0.58	0.09	0.48	0.51	-0.12	0.66	-0.27	0.61
Odra Wschodnia	s	-0.24	0.34	0.61	0.66	-0.08	0.48	-0.01	0.59
	b	-0.43	0.24	0.50	0.64	0.04	0.11	-0.18	0.82
Odra Zachodnia	s	-0.66	-0.27	0.22	0.47	-0.26	0.49	0.00	0.42
	b	-0.68	-0.26	0.21	0.52	-0.23	0.19	0.23	0.23

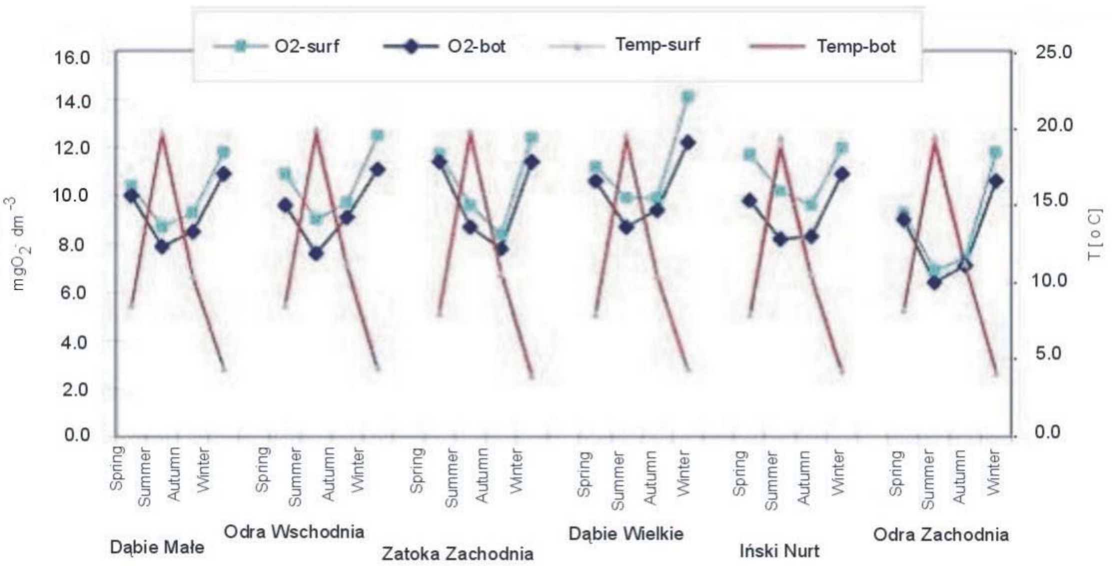
Table 4. Coefficients of correlations (r) between inorganic nitrogen and phosphorus compounds and per cent oxygenation, temperature, biochemical oxygen demand (BOD_5), chlorophyll *a*, and flow rate, (n=15) (s = surface water; b = near-bottom water)

Site		Inorg N vs $\%O_2$	Inorg N vs Temp.	Inorg N vs Flow rate	Inorg N vs BOD_5	Inorg N vs Chl a	React P vs $\%O_2$	React P vs Temp.	React P vs Flow rate	React P vs Chl a	React P vs BOD_5
Dąbie Małe	s	-0.69	0.19	-0.21	-0.33	-0.33	-0.51	0.32	-0.35	-0.03	-0.13
	b	-0.60	0.22	-0.17	-0.32	-0.37	-0.40	0.36	-0.43	-0.15	-0.27
Dąbie Wielkie	s	-0.39	-0.08	-0.60	-0.27	-0.61	-0.18	0.36	-0.20	-0.03	0.06
	b	-0.40	-0.08	-0.52	-0.39	-0.34	-0.31	0.37	-0.21	-0.34	-0.15
Zatoka Zachodnia	s	-0.65	-0.07	-0.29	-0.42	-0.47	-0.12	0.27	-0.22	0.06	0.29
	b	-0.52	0.15	-0.42	-0.30	-0.35	-0.16	0.30	-0.24	-0.02	0.01
Iński Nurt	s	-0.41	-0.09	-0.33	0.08	-0.47	-0.32	0.30	-0.30	0.01	-0.13
	b	-0.30	-0.06	-0.59	-0.45	-0.35	-0.04	0.35	-0.26	0.08	0.28
Odra Wschodnia	s	-0.37	-0.19	-0.30	-0.34	-0.21	-0.18	-0.18	-0.25	0.30	-0.15
	b	-0.30	-0.17	-0.57	-0.22	-0.45	-0.04	-0.38	0.39	-0.36	-0.35
Odra Zachodnia	s	-0.36	0.15	-0.35	-0.43	-0.47	-0.16	0.18	-0.17	-0.12	-0.20
	b	-0.49	0.16	-0.49	-0.33	-0.49	-0.35	0.24	-0.21	-0.21	-0.21

RESULTS

Thermal conditions of the area changed parallel to variations in meteorological parameters, typical of the temperate climate. The highest water temteratures (with a maximum of 23.4°C) were recorded in summer, the lowest temperatures (with the minimum of 3.8°C) being recorded in winter Water temperature did not vary extensively either down the water column or between sampling sites (Fig. 2).

Fig. 2. Seasonal variability of mean values of dissolved oxygen contents in relation to the variability of thermal conditions in the surface and near-bottom water of the 3rd order Odra estuary in 1997-2000



The Odra estuary **oxygen regime** was characterised by seasonal variability and variations between sampling sites and down the water column at individual stations (Fig. 2). The dissolved oxygen content and per cent oxygenation tended to increase during periods of the lowest temperature and in spring, a substantial reduction in oxygenation being recorded in summer months. Dissolved oxygen contents ranged from 2.2 mg $O_2 \cdot dm^{-3}$ (near-bottom water, Odra Zachodnia, 20 August 1998) to 16.3 mg $O_2 \cdot dm^{-3}$ (surface water, Lake Dąbie Wielkie, 15 January 1998). The per cent oxygenation was found to vary from 40.3% (near-bottom water, Odra Zachodnia, 20 August 1998) to 164.0% (surface water, Iński Nurt, 12 May 1998). Oxygenation values were higher in the surface than in the near-bottom water (Fig. 2).

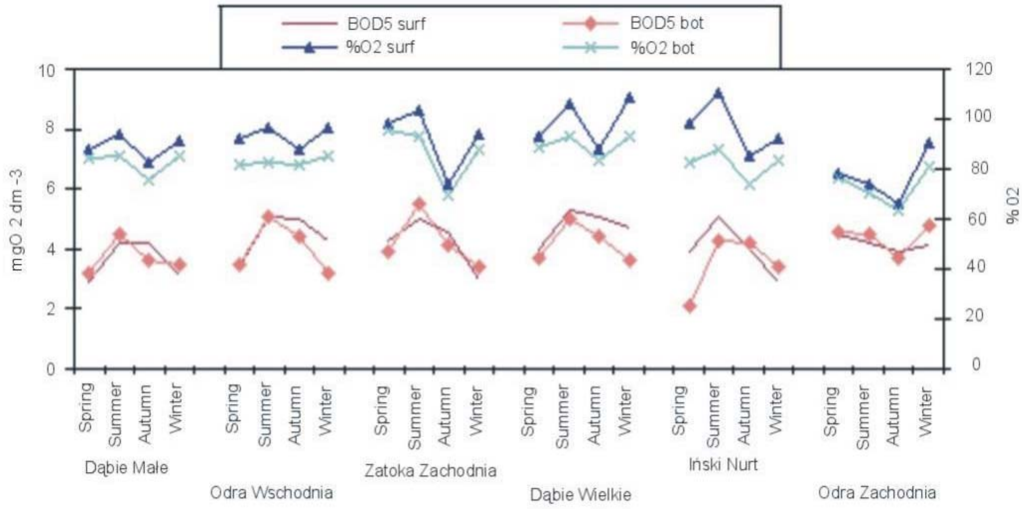
The poorest oxygen situation was typical of Odra Zachodnia, with average dissolved oxygen content and average per cent oxygenation of 8.1 mg $O_2 \cdot dm^{-3}$ and 75.4%, respectively, in the surface water, and 7.6 mg $O_2 \cdot dm^{-3}$ and 71.6%, respectively, in the near-bottom water. Average values in the remaining areas were found to range within 9.6-10.7 mg $O_2 \cdot dm^{-3}$ and 89.9 - 100.5% (surface water) and within 8.8 - 9.7 mg $O_2 \cdot dm^{-3}$ and 82.4 - 90.1% (near-bottom water).

Dissolved oxygen contents were found to correlate inversely with temperature (Table 3). Particularly high correlations were typical of riverine sites. Per cent oxygenation values correlated usually positively with temperatures, the correlations being intermediate at best. It was only in Odra Zachodnia that poor, negative correlations were obtained.

The maximum organic loading (evidenced by the highest **biochemical oxygen demand**) was usually typical of the height of the growth season. The trend was particularly pronounced in Lake Dąbie Małe and in Iński Nurt. Generally, the BOD_5 values varied, during the period of study, from 1.1 mg $O_2 \cdot dm^{-3}$ (near-bottom water, Iński Nurt, 30 March 1998) to 7.4 mg $O_2 \cdot dm^{-3}$ (near-bottom water, Odra Zachodnia, 15 January 1998).

The lowest overall mean BOD_5 (calculated for the surface and near-bottom water combined) was shown by samples collected from Lake Dąbie Małe (3.8 mg $O_2 \cdot dm^{-3}$), the highest overall value being calculated for samples from Lake Dąbie Wielkie (4.6 mg$O_2 \cdot dm^{-3}$) (Fig. 3). The Odra Wschodnia water showed a somewhat higher organic matter loading (4.5 mg $O_2 \cdot dm^{-3}$), compared to Odra Zachodnia (4.3 mg $O_2 \cdot dm^{-3}$).

Fig. 3. Seasonal variability of mean values of biochemical oxygen demand (BOD_5) in relation to the variability of oxygenation in the surface and near-bottom water of the 3rd order Odra estuary in 1997-2000



Biochemical oxygen demand was found to correlate highly and positively with the chlorophyll *a* contents. High positive correlations between BOD_5 and per cent oxygenation were typical of lake sites, intermediate correlations being recorded in the river water. BOD_5 formed both negative and positive correlation, of differing strength, with flow rate, positive correlations being shown only in the Odra Zachodnia samples (Table 3).

The **inorganic nitrogen** contents were found to vary from 0.055 mg $N{\cdot}dm^{-3}$ (surface water, Odra Wschodnia, 12 May 1998) to 0.592 mg $N{\cdot}dm^{-3}$ (near-bottom water, Odra Zachodnia, 12 October 1999). The lowest and the highest contents were being recorded in spring and winter months, respectively. The contents were higher in the near-bottom than in the surface water; the range of mean values in the first amounted to 0.221 mg $N{\cdot}dm^{-3}$ (Odra Wchodnia) – 0.354 mg $N{\cdot}dm^{-3}$ (Odra Zachodnia), the corresponding range in the latter being 0.211 mg $N{\cdot}dm^{-3}$ (Odra Wschodnia) – 0.322 mg $N{\cdot}dm^{-3}$ (Odra Zachodnia) (Fig. 5).

Fig. 4. Seasonal variability of mean values of biochemical oxygen demand (BOD_5) in relation to the variability of chlorophyll *a* contents in the surface and near-bottom water of the 3rd order Odra estuary in 1997-2000

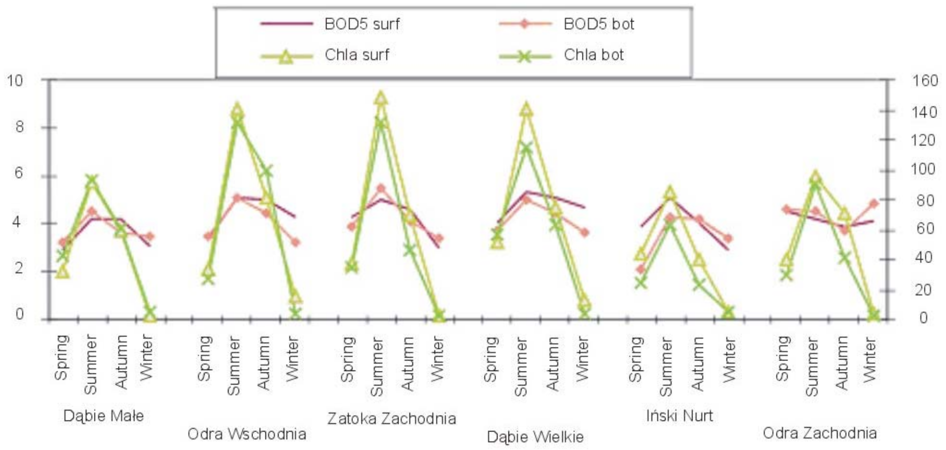


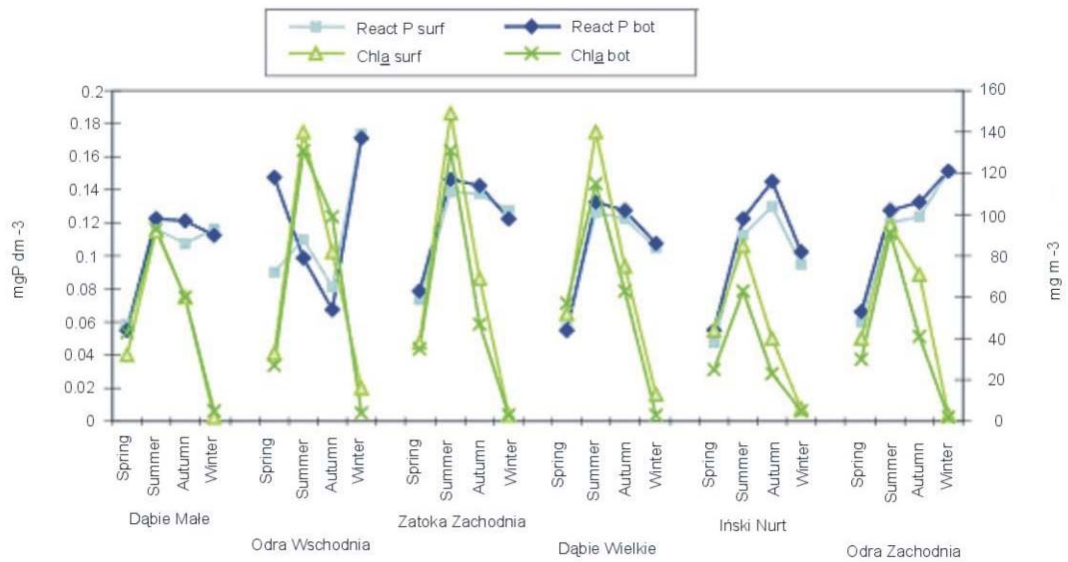
Fig. 5. Seasonal variability of mean values of inorganic nitrogen contents in relation to the variability of flow rate in the surface and near-bottom water of the 3rd order Odra estuary in 1997-2000

Inorganic nitrogen contents correlated highly negatively with per cent oxygenation in samples collected from Lake Dąbie Małe and Zatoka Zachodnia. The correlations were intermediate at the remaining sampling sites. A similar pattern of correlations was revealed for inorganic nitrogen versus chlorophyll *a* contents (Table 4).

Inorganic nitrogen contents correlated negatively with flow rate, the correlations being high in Lake Dąbie, Odra, Wschodnia and Iński Nurt, and intermediate to poor at the remaining sampling sites. Inorganic nitrogen showed usually negative, intermediate to negligible, correlations with temperature and with BOD_5 (Table 4).

Reactive phosphorus contents were found to range from 0.023 mg P·dm^{-3} (surface water, Iński Nurt, 12 May 1998) to 0.301 mg P·dm^{-3} (near-bottom water, Zatoka Zachodnia, 21 July 1999). On the average, the lowest reactive phosphorus contents were typical of Lake Dąbie Małe (0.104 mg P·dm^{-3}) and Iński Nurt (0.105 mg P·dm^{-3}), the highest average contents being found in Odra Zachodnia (0.115 mg P·dm^{-3}) and Zatoka Zachodnia (0.126 mg P·dm^{-3}). Mean contents in Odra Wschodnia and Lake Dąbie Wielkie were identical and amounted to 0.111 mg P·dm^{-3}. Average reactive phosphorus contents were higher (by about 0.007 mg P·dm^{-3}) in the near-bottom than in the surface water (Fig. 6).

Fig. 6. Seasonal variability of mean values of reactive phosphorus in relation to the variability of chlorophyll *a* contents in the surface and near-bottom water of the 3rd order Odra estuary in 1997-2000



Reactive phosphorus contents usually correlated poorly and negatively with flow rate. Correlations with per cent oxygenation were negative, poor or intermediate, as well. Correlations with chlorophyll *a* differed in terms of strength and direction, poor negative correlations dominating. Correlations with temperature and BOD_5 were mainly intermediate positive and predominantly poor, respectively (Table 4).

Chlorophyll *a* contents were found to vary from 2.2 $mg{\cdot}m^{-3}$ (surface water, Lake Dąbie Małe, 15 January 1998, and near-bottom water, Odra Zachodnia, 15 January 1998) to 327.9 $mg{\cdot}m^{-3}$ (surface water, Odra Wschodnia, 12 May 1998). Chlorophyll *a* contents were usually higher in the surface than in the near-bottom water (Figs 4, 5, 6). Odra Wschodnia, Zatoka Zachodnia, and Lake Dąbie Wielkie showed higher chlorophyll *a* contents than was the case at the remaining sampling sites. The respective average values for the first group of sites were 88.8, 84.5, and 85.3 $mg{\cdot}m^{-3}$. Average values for Lake Dąbie Małe and Odra Zachodnia were lower by about 20 $mg{\cdot}m^{-3}$, the Iński Nurt average being lower by more than 30 $mg{\cdot}m^{-3}$.

Typically, chlorophyll *a* contents correlated highly, or with intermediate strength, positively with per cent oxygenation and with temperature. Negative correlations, mostly intermediate or poor, were revealed for chlorophyll *a* content and flow rate (Table 3).

DISCUSSION

Estuarine ecosystems are characterised by specific environmental conditions, differing from those prevailing in lakes, rivers, or in the sea. Functioning of estuarine ecosystems depends on the estuary structure as well as on water transport and chemical composition [2, 13, 25].

Turbulent flow in rivers hardly allows the formation of thermal stratification, typical of summer stagnation in deep lakes. Vertical thermal homogeneity is found in polymictic lakes, too [9]; based on research carried out in 1997-2000, Lake Dąbie can be classified among such lakes. The slightly higher temperature in Odra Zachodnia than in Odra Wschodnia had already been recorded in upstream sections of both river branches by Tórz and Nędzarek [24] who ascribed it to the effect of the Dolna Odra power station cooling water discharge.

The oxygen regime in natural water bodies is a net result of processes during which oxygen is produced and consumed. Non-polluted water bodies show a strong reverse correlation between temperature and per cent oxygenation. The positive correlation between temperature and oxygen regime, revealed in the Odra estuary studied, is indicative of eutrophication. In such areas, the dissolved oxygen pool is primarily a result of intensive primary production [9, 27]. In 1997-2000, the maximum primary production in the Odra estuary was recorded in May-June.

Differences in oxygenation between the surface and near-bottom waters, observed during this study (Fig. 2) should be explained by the domination of oxygen-consuming processes in the near-bottom water, the processes being intensified by decomposition of organic matter that sinks in low-flow areas and is resuspended from bottom sediments. Those processes enhance the rather weak oxygen stratification in polymictic eutrophic areas [5, 18].

The poorer oxygen conditions in the riverine waters of the estuary, compared to those in the lake, are a result of organic loading differing between the sites. Generally, Odra Zachodnia showed a higher loading, as a result of being a recipient of raw sewage discharged from the left-bank Szczecin [24].

Organic matter flow in an ecosystem is a highly complex process the dynamics of which varies greatly, the variations running parallel to the variability induced by the growth season, hydrology, or a combination of both. Transboundary flow in rivers plays a major role both in the origin of organic matter and in the seasonal variability. As shown by the research conducted by Veyssy *et al.* [26] in the Garonne, as little as 8% of the organic matter in the river mouth resulted from *in situ* production, most of the loading being supplied by surface flow (54%) and by sewage discharged into the river (38%). It is estimated that 25% of carbon load in the rivers world wide is transformed within the ecosystem, 25% is accumulated in the sediment, the remaining 50% being discharged into the oceans [15].

A similar pattern was recorded in the estuary studied. Those sites located in Lake Dąbie showed a higher contribution of autochthonous organic matter in the water, compared to the riverine water of Odra Wschodnia and Odra Zachodnia. The autochthonous organic matter load is reflected in the BOD_5 values, as the parameter is primarily a measure of labile organic matter [6]. Primary production of the periphyton, macrophytes, and phytoplankton is an important source of organic matter; the magnitude of that primary production depends on light intensity, trophic status, temperature, and on area's morphometry. Primary production in shallow lakes is higher than that in deep ones; due to their extensive coverage by macrophytes, such lakes are considered macrophyte-dominated. The interaction between macrophytes and phytoplankton determines productivity and eutrophication rate in a lake. Chlorophyll *a*, a major indicator of the magnitude of primary production, is in such lakes highly positively correlated with organic loading indicators [5, 7, 20].

Contents of organic matter supplied by natural sources in rivers depend mainly on the flow rate and, to a lower extent, on biological processes in the river itself. Organic matter is also derived from dissolved organic carbon rinsed out from lagoonal areas. Interstitial water in the shore zone is saturated with organic matter, detrital particles, and bacterial flora and influences the magnitude of hydrochemical parameters, particularly in large rivers [7, 11, 26].

Inorganic nutrients (inorganic forms of nitrogen and phosphorus) play an important part in biological processes in natural waters; it is those nutrients that are taken up by autotrophs. Nutrient concentrations are reduced in lakes by the autotrophic uptake during the growth season, while in rivers the reduction is due to the dilution by water masses inflowing from the catchment. Polymictic eutrophic areas show a spatial homogenisation of nutrient concentrations, resulting from internal loading [5, 18, 27]. Those processes depend on the oxygen regime and were observed to proceed in 1997-2000 in the Odra estuary. An increase in mean nutrient concentrations in summer and winter was related to the increased per cent oxygenation, recorded in those seasons. Better oxygen conditions enhanced mineralisation of organic matter through ammonification and nitrification as well as resuspension from bottom sediments [21].

Autotroph growth is primarily dependent on availability of nitrogen and phosphorus, the inorganic salts of which are termed the limiting nutrients. Most frequently, primary production is limited by inorganic phosphorus salts, although, under certain conditions, also inorganic nitrogen salts, or salts of both elements, may be limiting [3, 21].

The atomic ration of inorganic nitrogen to reactive phosphorus indicates which of the elements is limiting. In marine algae, carbon, nitrogen, and phosphorus occur at a constant atomic weight ratio of 106:16:1 [12, 19]. Based on that ratio it may be assumed that at an N:P ratio lower than 16:1, there is less available nitrogen per unit phosphorus and thus primary production will be nitrogen-limited. A higher ratio is indicative of phosphorus limitation. At N:P ratios ranging from 10:1 to 20:1, the combined limitation by the two elements is most likely [8]. Sewage discharge leads to increased phosphorus loading, as the N:P ratio in raw sewage is as low as 4:1. Therefore, sewage discharge may lead to a switch from phosphorus to nitrogen limitation or both elements may become limiting at the same time. This type of limitation was prevalent in the 3^{rd} order Odra estuary studied, the mean N:P ratio being 6.3. It was only during the spring seasons that phosphorus became limiting. As demonstrated by Conley [3], phosphorus limitation in spring is quite common in numerous estuaries; they revert to nitrogen limitation in summer.

CONCLUSIONS

1. Seasonal variations in hydrology and seawater incursions were important factors affecting the Odra estuary hydrochemistry; they primarily influenced water level in Lake Dąbie, Odra Wschodnia, and Odra Zachodnia. Wide variations of the Odra flow rate as well as anthropogenous pollution from the catchment introduced additional complication to physical, chemical, and biological processes in the area and made it difficult to reveal unequivocal linear relationships between hydrochemical parameters.
2. Lake Dąbie and River Odra waters showed similar hydrochemical conditions; values and variability of hydrochemical parameters, particularly oxygen, organic matter loading, nutrient contents, and primary production, were indicativ of intensive biological processes, typical of eutrophic areas.
3. Biological productivity of the estuary studied within 1997-2000 was limited by nitrogen or by nitrogen and phosphorus combined, such limitation being typical of water bodies receiving excessive sewage loads.
4. The flow-through Lake Dąbie showed a higher primary production, compared to that in the riverine waters of Odra Wschodnia and Odra Zachodnia, in spite of a similar level of fertility of the areas studied; the difference is typical of that shown by lenitic and lotic waters. At the same time, a dilution effect, exerted by the Odra Wschodnia water entering Lake Dąbie, on the amount of organic matter produced by autotrophs was demonstrated. The Odra Zachodnia water showed the highest organic matter loading, which contributed to the presence of substantial oxygen deficiency, particularly during the peak growth periods.

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