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TRANSPORT OF BIOGENIC SUBSTANCES IN WATERCOURSES OF COASTAL LANDSCAPE PARK*

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Abstract

Eutrophication of the Baltic Sea is a serious problem, and as such it is frequently raised in relevant literature, where potamic supply of nutrients is implicated as one of the causes. Coastal waters like the Puck Lagoon, an area protected within the Natura 2000 network, as well as watercourses in adjacent Coastal Landscape Park, are particularly vulnerable to such degradation. Hence, the aim of our study, which was to determine the volume and fluctuations of transported total nitrogen and phosphorus. Another objective was to try and relate these changes to the transport of nutrients and runoff in streams flowing through Coastal Landscape Park into the Puck Lagoon (the Płutnica, Potok Błądzikowski, Gizdepka, Reda, Zagórska Struga) and into the Baltic Sea (the Piaśnica, Karwianka, Czarna Wda). This research drew on field investigations and laboratory assays performed in the hydrological year of 2009, and had been designed accordingly, including measurements of the flow rate in the selected watercourses and water sampling for further chemical analyses, including determinations of total nitrogen and total phosphorus. In brief, the highest average annual flow rate and load of total nitrogen and total phosphorus were found in the Reda and Piaśnica. The largest load variation, of both nitrogen and phosphorus, occurred in the Zagórska Struga. In most of the watercourses, the load of biogenic substances was strongly correlated with the flow, but the actual power of correlation depended on a stream and biogenes. The strongest statistical relationships for both tested substances ($r > 0.8$) occurred in the Potok Błądzikowski, Reda, Zagórska Struga and Czarna Wda. The Płutnica was an exception in that there were no statistically significant relationships between the water flow and the load of nutrients. However, the low value of the relationship determined suggests that we should view that series with some caution.

Keywords: total nitrogen, total phosphorus, water flow, load, flow.

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INTRODUCTION

The ongoing degradation of water resources has urged many scientists to undertake the problem of potamic transport of nitrogen and phosphorus, the substances which influence the eutrophication rate of waters in rivers and in water bodies fed by rivers (GRIMVAL et al. 2000, SMITH et al. 2003, BOYER et al. 2006, BILLEN, GARNIER 2007, HOWARTH 2008). The quantity and variability of the transport are indicated to depend on a number of factors, of which hydrological conditions are the most significant.

The Baltic Sea is an example of a marine water body whose trophic state depends, among other factors, on the supply of biogenes *via* rivers (ŁYSIAK-PASTUSZAK et al. 2004, VAGSTAD et al. 2004, HUMBORG et al. 2007, MÖRTH et al. 2007, KORTH et al. 2012). The dependence becomes particularly distinct in coastal areas, which receive river waters while acting as a buffer zone for open sea waters (WITEK et al. 2003, PASTUSZAK et al. 2003, 2005, HUMBORG et al. 2007, KORTH et al. 2013). The Bay of Puck, and especially its part called the Puck Lagoon (known also as the Inner Puck Bay), plays such a role. Research on the biogene supply to the Bay of Puck is extremely important for preservation of the area's unique natural assets. The Bay of Puck is legally protected as part of Coastal Landscape Park and the Natura 2000 network, where it is represented by a Special Bird Protection Area (PLB220005) and a Special Habitat Protection Area (PLH220032).

In Poland, the research on the transport of biogenes within the Baltic seashore zone, its fluctuations and the underlying hydrological conditions focuses on the Vistula and the Odra rivers as well as on coastal rivers in Pomerania (NIEMIRYCZ 1999, BOGDANOWICZ 2004). Abroad, similar investigations have been carried out, e.g. on the rivers of Sweden or the rivers flowing into the Gulf of Riga, e.g. the Daugava (LAZNIK et al. 1999, STÅLNACKE et al. 1999*a*,*b*, VAGSTAD et al. 2000).

The worrying degree of pollution and eutrophication of coastal waters justifies further research on the transport of biogenes *via* watercourses, including minor rivers and streams. The aim of our study has been to determine the volume and volumetric fluctuations of the main biogenes, i.e. total nitrogen and total phosphorus, transported by rivers. Another objective has been to make an attempt at mapping the findings onto the volumes and quality of water fed by the watercourses into the Bay of Puck and directly into the Baltic Sea.

MATERIAL AND METHODS

For the purpose of the research, the following watercourses draining Coastal Landscape Park (NPK) were selected: the Płutnica, Potok

Błądzikowski, Gizdepka, Reda and Zagórska Struga flowing into Puck Lagoon, and the Piaśnica, Karwianka and Czarna Wda feeding directly into the Baltic Sea. These watercourses drain over 60% of the area of the park (Figure 1). The largest are the catchments of the Reda (over 450 km²) and

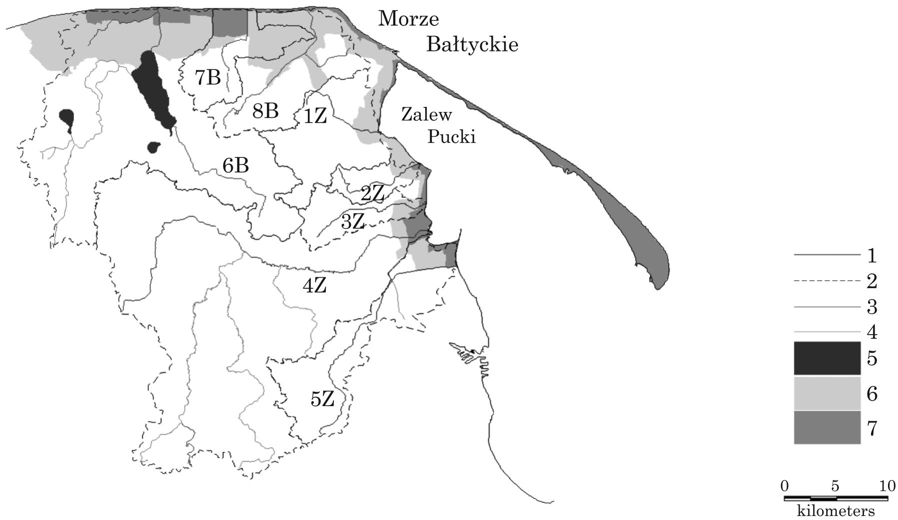

Fig. 1. Research area: 1Z – Płutnica, 2Z – Potok Błądzikowski, 3Z – Gizdepka, 4Z – Reda, 5Z – Zagórska Struga, 6B – Piaśnica, 7B – Czarna Wda, 8B – Karwianka, 1 – coastline, 2 – water divide, 3 – main rivers, 4 – tributaries, 5 – lakes, 6 – Coastal Landscape Park, 7 – lag of Coastal Landscape Park

Piaśnica (300 km²). The other river catchments are much smaller: 105.2 km² (the Zagórska Struga), 90.0 km² (the Czarna Wda) and 84.0 km² (the Płutnica) and less than 60 km² (the Karwianka). The smallest catchments are drained by the Gizdepka (37.2 km²) and Potok Błądzikowski (23.0 km²). These streams are supplied with water through atmospheric precipitation and groundwater, especially the Reda River, whose ice-marginal trough is essential for the drainage of groundwater in both the regional and local circulation systems. In addition to the Reda, Żarnowieckie Lake and two ice-marginal streams, the Płutnica and the Kaszubska with the Meander Kaszubski, make a substantial contribution to the groundwater drainage.

The drainage basins of the above watercourses represent diverse physiographic conditions. Apart from lakeland plateaus and isolated morainic plateaus, there are ice-marginal streams and coastal lowlands, within which streams flow into the receiving water bodies. The diversity of land relief carries broad implications, for example it manifests itself in the mosaic of various types of soils, thus entailing different types of land use in the catchments. The predominant forms of land use are farmland and forests, but they correspond to different shares in the structure of land cover within the analysed catchments. Most of the agricultural land is cultivated as arable land, mainly on the plateaus covered with brown soils; meadows and pastures occupy mostly river valleys and ice-marginal streamways, while the coastal lowlands are predominately covered with hydrogenic soils, including peat and bog soils and moorshed soils. Meanwhile, forests grow over some of the plateaus and theirs slopes, parts of the coastal lowlands in the northern part of the area, a shaft dune stretching from the Baltic Sea and Piaśnica Sandr (the southern part of the Piaśnica catchment) covered with spodic soils and rusty soils on sand. Farmlands, especially arable fields, dominate in the catchments of the Potok Błądzikowski (about 90%), Czarna Wda and Karwianka (over 65%) and Płutnica (almost 60%). In the catchments of the Reda and Piaśnica, agricultural use of land, corresponding to about 50% of the catchment's total area, slightly prevails over the afforested area. Conversely, forests slightly dominate over farmland in the catchments of the Gizdepka and Zagórska Struga. In addition, catchments of the ice-marginal streamways and coastal lowlands hold major towns in the area (e.g. Wejherowo, Reda, Puck) and popular holiday destinations (eg. Karwia, Dębki, Ostrowo, Białogóra), which entails some urban development. However, antropogenically transformed areas occupy a small share of the above catchments. This diversity of physiography is also responsible for the diverse hydrographic network in the catchments. In the area comprising the ice-marginal streamways, river valleys and coastal plains occupied by wetlands, the natural river system has been incorporated into an extensive and complex system of drainage ditches and canals that have been constructed for several centuries now. In the coastal lowlands, a network of polders has been created, which today stretches over the lower courses and estuaries of such rivers and streams as the Piaśnica, Karwianka, Czarna Wda and Płutnica, Reda and Zagórska Struga. The hydrographic network is also used for energy generation, e.g. Żarnowieckie Lake acts as a lower reservoir of a pumped storage power plant. The catchments of the Gizdepka and Potok Błądzikowski are two other examples of an antropogically transformed river network. Another specific feature of the hydrographic network in the investigated region is the presence of areas without outflow, which occupy nearly 20% of the whole surface area. The highest share can be found in the catchments of the Piaśnica and Reda and Zagórska Struga. Elsewhere, it corresponds to 5-10%, and such areas without outflow are dominated by evapotranspiration.

For the purpose of this study, research was conducted in the hydrological year 2009, with measurements taken at one-month frequency. The discharge intensity was measured using a Valeport model 801 electromagnetic current meter with a flat sensor and a StreamPro acoustic Doppler current profiler. In water samples, the concentrations of total nitrogen and total phosphorus were determined by the colorimetric method (Merck Spectoquant test, after prior digestion with a set CrackSet 20 Merck for total nitrogen and set CrackSet 10 Merck for total phosphorus). The results were used to calculate the value of instantaneous load according to the formulas given by Bogdanowicz (2004). Next, they were analysed statistically for chosen measures of central tendency and dispersion. Moreover, correlations between discharge and load of biogenes were calculated using Pearson R correlation coefficient. All the calculations were made using MS Exel and Statistica programmes.

RESULTS AND DISCUSSION

In the hydrological year 2009, the annual average air temperature recorded at the weather station in Lębork was 8.3°C. July was a warm month (18.3°C), while January was the coldest (-1.1°C). The annual sum of precipitations was 772 mm, with a distictly higher amount of rainfalls in the summer half year. The highest monthly precipitation sum was in July (166 mm) and in October (over 100 mm). April was the driest month (less than 3.0 mm).

The analysed watercourses contained different volumes of water. Their mean annual discharge ranged from over 6.0 $m^3 s^{-1}$ to less than 0.1 $m^3 s^{-1}$ (Table 1). The highest and most even discharge value was achieved for the

Table 1

Mean annual values of discharge intensity and total nitrogen and total phosphorus loads in the hydrological year 2009

Watercourse	A (km^2)	Q		N		P	
		($m^3 s^{-1}$)	Cv (%)	(g N s^{-1})	Cv (%)	(g P s^{-1})	Cv (%)
Płutnica	84.0	0.527	58.90	2.217	107.1	0.386	152.1
Potok Błądzikowski	23.0	0.052	117.4	0.402	144.4	0.015	104.6
Gizdepka	37.2	0.226	52.60	0.490	84.40	0.064	118.6
Reda	485.5	6.274	34.00	7.348	59.90	0.742	50.00
Zagórska Struga	105.2	0.185	43.50	1.360	52.40	0.094	42.10
Piaśnica	324.4	3.185	44.30	3.816	67.30	0.444	56.60
Karwianka	57.0	0.436	73.70	0.868	52.70	0.112	51.20
Czarna Wda	90.0	0.905	95.10	2.241	120.80	0.248	131.6

Reda. The Piaśnica had the second most abundant discharge (> 3.0 $m^3 s^{-1}$). In the remaining watercourses, the mean annual discharge was below 1.0 $m^3 s^{-1}$. Noteworthy, the discharge intensity on the Karwianka could not be measured in June, when the mouth of that watercourse was dammed with a shore embankment. Consequently it was impossible to calculate the load of biogenic substances transported by that stream.

The pattern of mean annual quantities of total nitrogen and total phosphorus loads was similar. The highest values were calculated for the Reda (> 7.0 g N s^{-1} and 0.6 g P s^{-1}) and the Piaśnica (almost 4.0 g N s^{-1} and 0.5 g P s^{-1}), while the lowest ones occurred for the Potok Błądzikowski. The above differences could be attributed mainly to the diversity of the surface of the examined drainage areas. The load variability was different. The total nitrogen load was the most stable in the Reda, Zagórska Struga and Czarna Wda, while being the least stable in the Karwianka. The total phosphorus load was the most stable in the Zagórska Struga and the least stable in the Płutnica (Table 1). The results obtained for the Reda, Zagórska Struga and Potok Błądzikowski could be associated with the presence or absence of the equalization of water flow. Another contributing factor is that most outflow sections of the analysed streams lie on polders, and therefore are active at different frequency. Moreover, the valleys of the Reda, Płutnica and Czarna Wda are drained though though the three watercourses are not fully submitted to forced water circulation.

The annual course of discharge fluctuations in all the watercourses, except the Płutnica, Reda and Zagórska Struga, demonstrated one main maximum and two time points with a discharge close to the maximum. The Płutnica, Reda and Zagórska Struga were observed to have three such maxima. The main maximum usually occurred in October (the Potok Błądzikowski, Reda, Zagórska Struga, Karwianka, Czarna Wda) or March (the Płutnica and Piaśnica), although for the Gizdepka the principal maximum discharge was noted in August. The months with the lowest measured discharge value were May (the Czarna Wda), June (the Reda and the Piaśnica), September (the Płutnica, Gizdepka, Zagórska Struga, Karwianka) and November (the Potok Błądzikowski) – Figure 2. In some watercourses, the discharge intensity in certain months was at a level close to the lowest value in the year. This was distinctly observable in the case of the Potok Błądzikowski, in which such minimal discharge levels occurred in November and June. Moreover, a relatively low discharge was measured in May (the Reda, Piaśnica) and September (the Reda, Piaśnica, Czarna Wda). The above changeability of the flow is attributable to several factors, such as meteorological conditions, land use on different fragments of the drainage area, specific response of individual drainage areas, including the ones with a forced water cycle, as well as the feeding with groundwater, especially flows of watercourses within ice-marginal valleys and deep indented valleys occupied by boggy areas.

Analysing the annual course of changes in loads of biogenic substances, we could notice that such loads were on a relatively low level. The total nitrogen load did not exceed 0.5 g N s^{-1} in the Potok Błądzikowski and Gizdepka, 8.0 g N s^{-1} in the Reda and Piaśnica and 2.0 g N s^{-1} in the remaining watercourses (Figures 3, 4).

Extremely high or low load values of both nitrogen and phosphorus often occurred at similar dates in different watercourses. For instance, the maximum values of both biogenic substances were detected in August (the Płutnica and Gizdepka) and October (the Potok Błądzikowski, Reda, Czarna Wda). The minimum values of nitrogen and phosphorus loads were recorded in September (the Gizdepka, Zagórska Struga). In the remaining streams, i.e. the Zagórska Struga, Piaśnica and Karwianka, the maximum and mini-

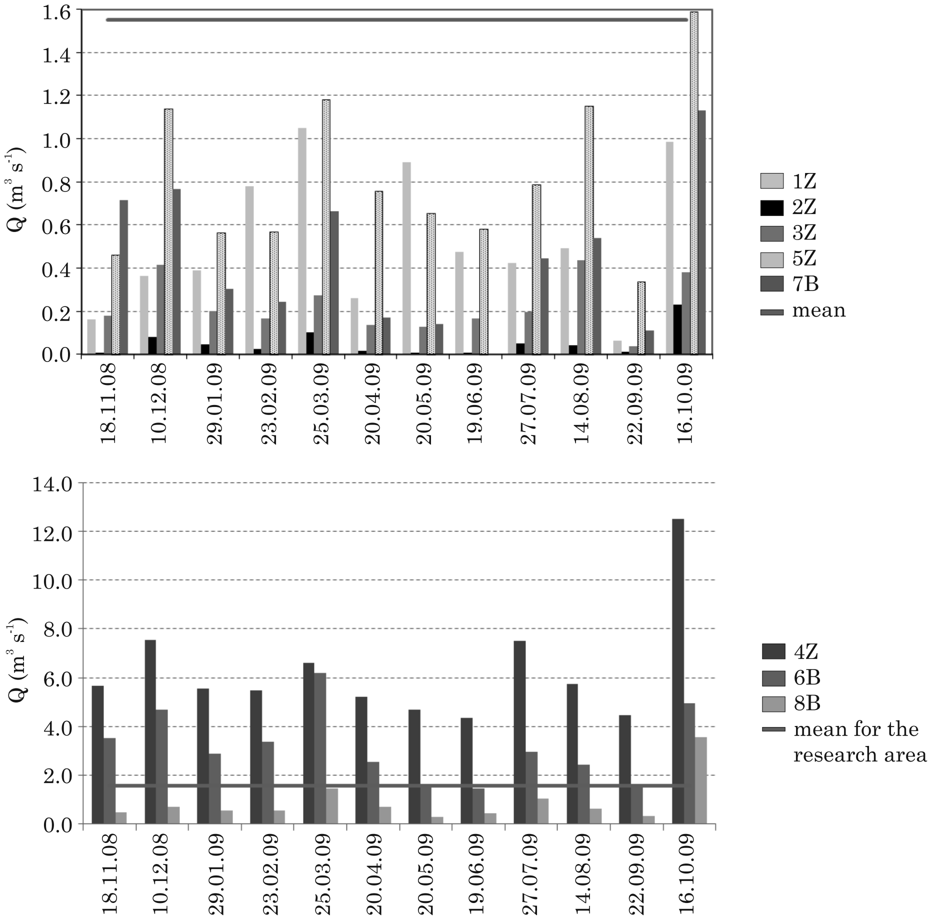

Fig. 2. Annual course of changes in flow in watercourses of Coastal Landscape Park: 1Z – Płutnica, 2Z – Potok Błądzikowski, 3Z – Gizdepka, 4Z – Reda, 5Z – Zagórska Struga, 6B – Piaśnica, 7B – Czarna Wda, 8B – Karwianka

mum values of loads did not occur at the same time. The maximum load of total nitrogen occurred in October (the Zagórska Struga), November (the Karwianka) or December (the Piaśnica), while the maximum load of total phosphorus was in March (the Zagórska Struga), July (the Piaśnica) or October (the Karwianka). It is noteworthy that the maximum loads of both analysed substances in the Gizdepka, Potok Błądzikowski, Reda and Czarna Wda coincided with the dates of the highest discharge in these streams. In the Zagórska Struga, such a relationship was verified only for total nitrogen load, and in the Karwianka – for total phosphorus load. In the Płutnica and Piaśnica, the highest loads occurred on different dates than the highest discharge. Analogously, some lowest values coincided with dates of the lowest discharge. This happened for both substances in May (the Potok

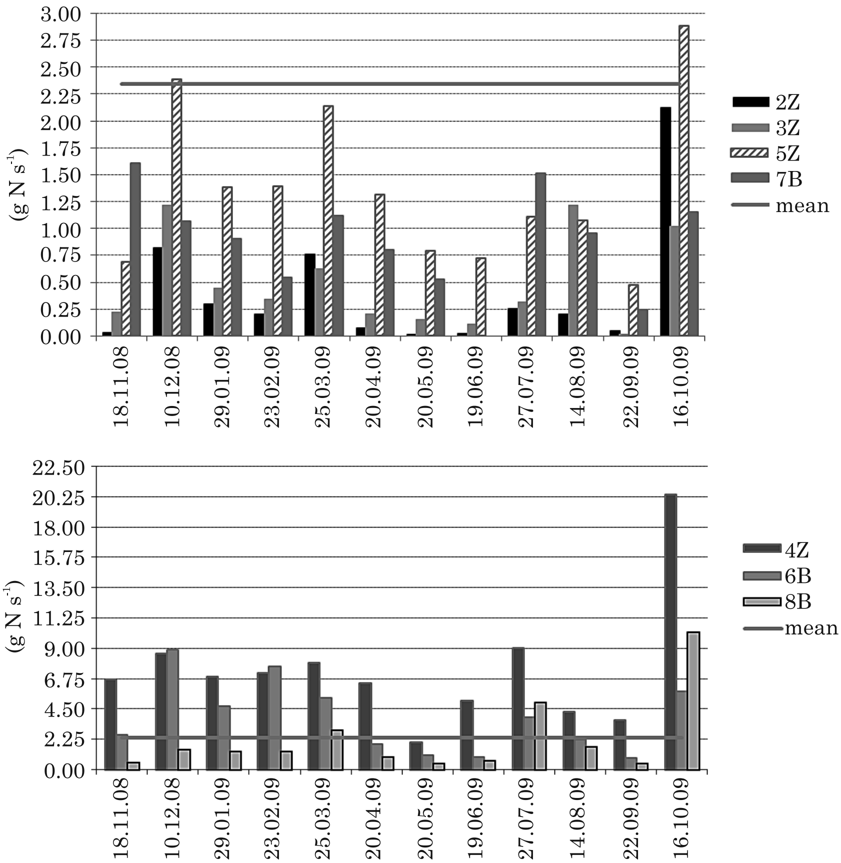

Fig. 3. Annual changes of total nitrogen load in watercourses of Coastal Landscape Park (explanation – Figure 2)

Błądzikowski), September (the Gizdepka, Zagórska Struga, Karwianka), and only for total phosphorus in June (the Piaśnica). In the remaining streams, i.e. the Płutnica, Reda, Piaśnica and Czarna Wda, the minimum values of discharge and load occurred on different days.

Our statistical analysis revealed a strong relationship between the load of biogenic substances and the discharge intensity in most watercourses, which was manifested by high correlation coefficients between the variables ($R > 0.7$, significance of correlation coefficient at a level of $\alpha = 0.05$ with $n = 12$). The Płutnica was an exception in that no significant relationship between discharge intensity and loads of total nitrogen and total phosphorus was found in the analysed year (Table 2). BOGDANOWICZ (2004) claims that anthropogenic activity can be one of the reasons why there is no interdependence between the rate of flow and the load of biogenic substances. The strength of the correlations for individual streams and biogenic substances varied. The strongest correlations were confirmed for total nitrogen ($R > 0.9$)

Table 2

Correlation coefficients for the: a) total nitrogen and flow b) total phosphorus and flow in the analysed catchments in 2009 (significance level of the correlation coefficient $a = 0.05$, $n = 12$)

	1 Z	2 Z	3 Z	4 Z	5 Z	6 B	7 B	8 B
a)	0.14	0.99	0.98	0.96	0.86	0.74	0.73	0.96
b)	0.00	0.83	0.72	0.89	0.81	0.71	0.81	0.95

Explanations: 1Z – Płutnica; 2Z – Potok Błądzikowski; 3Z – Gizdepka; 4Z – Reda; 5Z – Zagórska Struga; 6B – Piaśnica; 7B – Czarna Wda; 8B – Karwianka

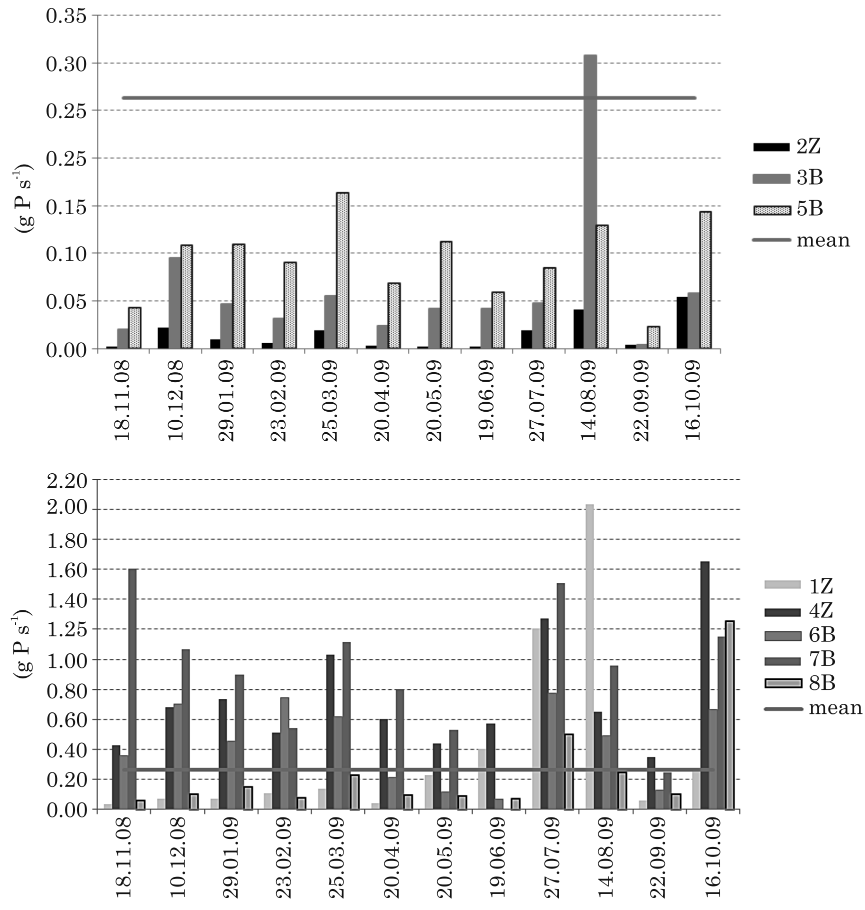

Fig. 4. Annual changes of total nitrogen load in watercourses of Coastal Landscape Park (explanation – Figure 2)

and total phosphorus ($R > 0.8$) in the Potok Błądzikowski, Reda and Czarna Wda. Moreover, equal strength was demonstrated by the relationship between discharge and total nitrogen load in the Gizdepka and between discharge and total phosphorus load in the Zagórska Struga and Karwianka. These findings, due to a small number of series, should be treated with caution.

CONCLUSIONS

1. The water resources expressed as an annual average flow of watercourses draining Coastal Landscape Park are mostly lower than those given for the region of Pomerania (*Pomorze*) in Poland. The Reda is an exception.

2. The Reda average flow rate over 1989 - 1998 was 3.9 $m^3 s^{-1}$, and this means that the influx into the Reda in 2009 was lower by 2.4 $m^3 s^{-1}$.

3. The largest contribution to the supply of nutrient loads in the hydrological year 2009 was made by the Reda River, a finding which does not deviate from the results of studies completed in 2006-2008.

4. The research revealed strong correlations between total nitrogen and phosphorus loads and discharge intensity, especially in the Potok Błądzikowski, Reda and Czarna Wda.

5. The above results support earlier findings produced by research in the same area, thus indicating that hydrological factors dominate in the shaping of loads of pollutants. Investigations performed elswhere in the Baltic coastal zone also support this conclusion.

6. Due to the short research period and the unique character of the water bodies which belong to the NATURA 2000 network, further research is required.

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