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Original Research

Long-Term Changes in Nutrient Status of River Water

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Abstract

Our paper presents changes in the quality of water in the Bytowa River (in 1975-2003) against the background of changes which occurred in the river basin. The basis for an evaluation of those changes consisted of some physicochemical and bacteriological assays completed as part of a surface water monitoring program run by the Inspectorate for Environmental Protection.

Based on the collected information, the evolution of the quality of water in the River Bytowa can be divided into two stages. The first, lasting until the late 1980s, was characterized by steadily increasing river pollution. The second stage was a time of gradual improvement of river water quality, which was a result of several overlapping factors related to the political and economic transformation in Poland. Construction of a municipal wastewater treatment plant as well as much lower quantities of fertilizers applied to decreased areas of farmland meant that loads of contaminants both from urban sources and from agriculture were reduced.

The comparison of nutrient concentrations at different control points on the Bytowa suggest that from the mid 1970s to the late 1980s the contribution of municipal loads was increasing, and in the peak period such waste prevailed over non-point pollution along a considerable section of the river. From the late 1980s to 2003 both municipal and non-point pollution loads were decreasing, with the former declining to a much greater extent than the latter. In recent years non-point pollution has been dominant in total pollution load. Bacterial contamination was the only remaining evidence of the unsatisfactory condition of the river.

Keywords: eutrophication, nitrogen, phosphorus, point and non-point pollution sources, river monitoring

Introduction

Degradation of our environment is a major problem, if not the most serious one, in the modern world. Deteriorated quality of surface waters, which inevitably means that large quantities of water are of limited use, is becoming a grave issue in many parts of the globe [1]. Fresh water is essential in many spheres of human life, making it one of the factors that determine social and economic growth. Agriculture, industry, transportation, recreation and many other spheres of man's life depend on available freshwater supplies and water quality [2-3].

The area of Central Pomerania, consisting of the eastern part of West Pomeranian Province and the western part of the Province of Pomerania is one of the few regions in Poland where the natural environment is relatively well preserved. The region is characterized by many diverse lakes and extensive areas of forests (over 40% of total area). Owing to a low level of industrialization and small density of population (58 persons/km^2), the degree of natural environment devastation is much lower here than in other parts of Poland [4]. Despite such favourable natural conditions, many lakes and rivers in Central Pomerania hold waters of poor quality. Particularly bad water quality was observed in the late 1980s. Waters were polluted primarily with excessive amounts of nutrients originating from municipal sewage and runoff from farmland.

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In recent years, quality of waters, and especially running water, in all of Poland has been improving [4]. This is the result of two factors:

1. increased investment in conservation, especially in wastewater and sewage treatment from about 150 million euro in 1992 to about 870 million euro in 2000, and
2. drastically diminished (by nearly 2/3) use of mineral fertilizers in agriculture, which took place in Poland in the early 1990s as a result of economic collapse.

Until today, despite modernization and development of the country's economy, the use of fertilizers has not gone up to the levels recorded in the 1980s. The importance of either of the factors alone in terms of water quality improvement is difficult to assess as they occurred simultaneously during the economic transformation of Poland. Some light on this issue can be cast via an analysis carried out on a local scale (a selected basin or a section of a river), where it would be easier to separate both factors and follow their influence on changes in water quality.

The objective of this study was to present long-term changes in the nutrient status of the water in the Bytowa (a tributary of the Słupia River) in central Pomerania against the background of the changes in wastewater and sewage management and in the intensity of fertilization in this region of Poland. Our aim was to undertake an evaluation of the importance of both above-mentioned factors on the nutrient levels of the water in the Bytowa, by referring to the specific character of land management in the river basin.

Material and Methods

The Bytowa River (Fig. 1) is a left-hand, third biggest tributary of the Słupia River. The total length of the river is 25 km, and its width ranges from 1 to 8 meters while the depth does not exceed 1 meter. Average flow amounts to about 1.44 m^3/s [5]. The Bytowa is characterised by low range of flow variability [6], and differences between winter and summer half-years not exceeding 25% [5]. The river flows in the western part of the Province of Pomerania to the north, and its sources are found near Lake Gromadzkie in the commune of Studzienice. It is supplied with water by a number of drainage ditches and several streams, of which the longest one – the Boruja – is 12 km long and flows into the Bytowa in the town of Bytów. The surface area of the river's basin is 198.1 km^2, of which over half the land is covered by arable fields (54.9%), 33.5% by forests and 6.7% by meadows and pastures. The surface waters cover 3% of the river's basin [7].

In the upper course of the River Bytowa, the basin is agricultural in character, with prevailing acid brown soils, poor in nutrients and severely threatened by erosive processes. There is Madrzechowskie Lake (52 ha surface area) on the course of the river. The middle part of the river basin is mixed urban, forested and agricultural in character. Bytów (17,000 inhabitants) is the largest town in the area. In the lower course the basin is predominantly forested, with a much smaller percentage of farmland. The soil cover is formed from light sandy loams and boulder sands. The whole river basin is characterized by postglacial, highly diversified landscape relief and relatively severe weather conditions [5].

The River Bytowa receives pollutants derived from both point and non-point sources of pollution. This is due to the agricultural and forested character of the river's basin and the location of the town of Bytów on the river. The primary sources of pollution are:

- the mechanical and biological wastewater treatment plant in Przyborzyce, which is licensed to discharge 3,400 m^3/d of treated wastewater; the plant receives wastewater and sewage from Bytów and nearby villages;
- some outlets in Bytów, which discharge storm waters and untreated municipal waste from several houses unconnected to a sewage system;
- the mechanical and biological wastewater treatment plant in Ugoszcz (in 2002 the plant discharged 115 m^3/d of treated wastewater to the Bytowa) [8];
- small streams and drainage ditches empty into the Bytowa, and one major tributary to the Boruja, which carries waters affected by agriculture and near its mouth receives waste from the fish farm and some amounts of municipal waste;
- villages lying in the river's basin, which do not have proper wastewater and sewage management;
- runoff from fields and fish-farms.

The basis for the evaluation of the changes of water quality in the Bytowa consisted of periodic assessment conducted over the past 30 years by a laboratory affiliated with the Office of the Province in Koszalin (1975), in Słupsk (1987-89), the Provincial Inspectorate of Environmental Protection in Słupsk (1993), the Provincial Inspectorate of Environmental Protection in Gdańsk, branch office in Słupsk (1998-2003), all under the framework of the surface water monitoring programme [7-9]. Access to data was kindly provided by the authorities of the Provincial Inspectorate of Environmental Protection in Gdańsk, branch office in Słupsk. For this study, the moni-

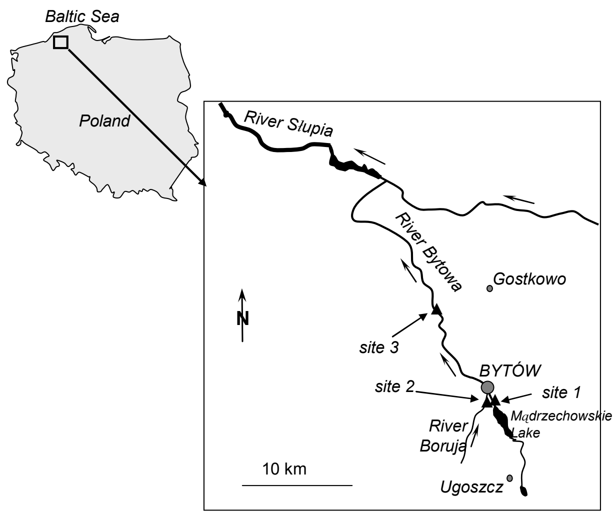

Fig. 1. The Bytowa River and location of measurement sites (black triangles).

Table 1. Characteristics of measurement sites situated along the Bytowa.

Name	Distance from Mądrzechowskie Lake	Characteristics	Pollutions
Site 1 Bytów	2.5 km	Upstream of Bytów, downstream of Lake Mądrzechowskie	-runoff from fields -wastewater treatment plant in Ugoszcz
Site 2 Bytów	3.5 km	In the suburb of Bytów, at the outlet of Boruja River to Bytowa River	-pollution from southern part of Bytów town -the Boruja River (runoff from fields and fish-farm)
Site 3 Gostkowo	12.1 km	Near Gostkowo village, 10 km downstream of Bytów	-wastewater treatment plant in Przyborzyce -runoff from fields and fish-farm -villages that do not have proper wastewater and sewage management

toring assays were performed by the above organizations at 3 sites. Two of these sites were situated on the Bytowa (sites 1 and 3) while the third one (site 2) – at the mouth of the Boruja. Site 1 was located upstream of Bytów, downstream of Lake Mądrzechowskie; site 2 was situated in a suburb of Bytów, upstream of the town's center; and site 3 was located 10 km downstream of the town, in the vicinity of the village of Gostkowo (Fig. 1, Table 1). The range of measurements and analytical procedures were established according to the then binding executive regulations of the Water Law (Resolutions of Main Inspector of Environmental Protection). The chemical analyses of nitrogen and phosphorus determinations have been performed according to respective photometric methods [10, 11]. Total phosphorus was determined after their oxidation to phosphates by autoclaving and digestion in perichloric acid.

The measurement programmes were performed in 2-5 year intervals, with the frequency once a month (12 measurements per year).

An attempt to compare the loads of nutrients originating from non-point sources versus municipal ones was made for site 3, lying about 10 km below Bytów. The load derived from multiplication of mean concentrations at sites 1 and 2 (C_1 and C_2) by the flow of water at site 3 (Q_3) was assumed as a load generated only by non-point sources (L_{np}). The difference between the load actually observed at site 3 (L_3) and the non-point pollution load computed as explained above was treated as the municipal load (L_m):

$$L_3 = Q_3 \cdot C_3$$
$$L_{np} = Q_3 \cdot (C_1 + C_2)/2$$
$$L_m = L_3 - L_{np}$$

In order to take account of the seasonal variation of the water flow and concentrations of nutrients, the annual loads were calculated as sums of the summer half-year and winter half-year loads, using mean, long-term summer (May-October) and winter (November-April) half-year waterflows [5] and averaged concentrations for each half of the year.

Results

Long-Term Fluctuations in the Concentrations of Some Water Quality Parameters

Apart from interannual changes, there were well-marked seasonal fluctuations, which involved a decrease in the concentrations of dissolved oxygen accompanied by an increase in the ammonia and phosphate concentrations in the summer (Fig. 2). As regards oxygen conditions, at site 1 no significant changes occurred during the analyzed time period except higher seasonal variation in years 1993-2003 (mean concentration 10.3 mg/dm^3, saturation 92%). At site 2 from the onset of the analyzed time period a gradual improvement was observed. In 1998 the mean annual oxygen concentration reached 10.9 mg/dm^3, whereas 23 years before it was only 8.6 mg/dm^3 (average oxygen saturation 72.3%). In contrast, oxygen conditions at site 3 deteriorated (Fig. 2a) until 1989, but have improved drastically since then. In 2003 average oxygen saturation was 91%.

Changes in nutrient concentrations during the 28 years studied are illustrated in Figs. 2b and 2c. Regarding the ammonium form of nitrogen at sites 1 and 2, its level was rather stable from 1975 to 1989. At site 1, however, the concentration of ammonium nitrogen was the lowest, with the multi-annual mean value on the level of 0.7 mgN/dm^3. The mean annual concentrations at site 2 ranged from 1.6 to 2.3 mgN/dm^3. After 1989 a rapid and considerable decline in the concentration of ammonium nitrogen appeared, down to less than 0.35 mg/dm^3. At site 3 concentrations of ammonium nitrogen increased until 1989, reaching the maximum of 9 mgN/dm^3 in August (annual mean of 3.2 mgN/dm^3). Afterwards the values fell considerably to 0.03-0.45 mgN/dm^3 in 2003. Unfortunately, measurements of nitrate and total nitrogen concentrations started as late as in 1990s. The concentration of nitrates at site 2 was analyzed only in two measurement cycles (1993 and 1998), and at site 3 the measurements were performed in 1998 and 2003. In those years small quantities of N-NO_3 were observed (concentrations within 0.2 to ca. 2 mgN/dm^3). The concentration of total nitrogen assessed only in 1998 and 2003 was from 1.31 to 4.29 mg N/dm^3.

Until 1993 the concentrations of phosphate phosphorus were increasing. The level of P-PO_4 (Fig. 2c) increased up to 0.77 mg/dm^3 at site 1 in August 1993 (annual mean 0.22 mg/dm^3), up to 1.30 mg/dm^3 at site 2 in May 1993 (annual mean 0.25 mg/dm^3) and up to 1.16 mg/dm^3 at site 3 in July 1989 (annual mean 0.46 mg/dm^3). From 1982 to 1989 large differences in the content of P-PO_4 between those three sites were recorded. In 1989 the mean annual P-PO_4 concentration at site 3 was nearly two-fold higher than at site 2, and three-fold higher than at site 1. The analyses completed in the following years showed that the quality of the river water improved considerably in terms of the content of inorganic phosphorus. The mean concentration of P-PO_4 in 1998 dropped to the level of 0.12 mg/dm^3 at sites 2 and 3, and 0.06 mg/dm^3 at control site 1. Total phosphorus concentration, as for total nitrogen, was measured only from 1998 and was from 0.11 to 0.33 mgP/dm^3.

Considering the parameters that represent pollution of water with organic compounds, i.e. BOD_5 and COD_{Mn}, the worst conditions appeared at site 2 located in the suburb of Bytów, at the mouth of the Boruja River. There, until 1993 inclusive, large fluctuations in BOD_5 during each year could be observed, up to 55 mgO_2/dm^3 at maximum in July 1993. Also, the values of the chemical oxygen demand

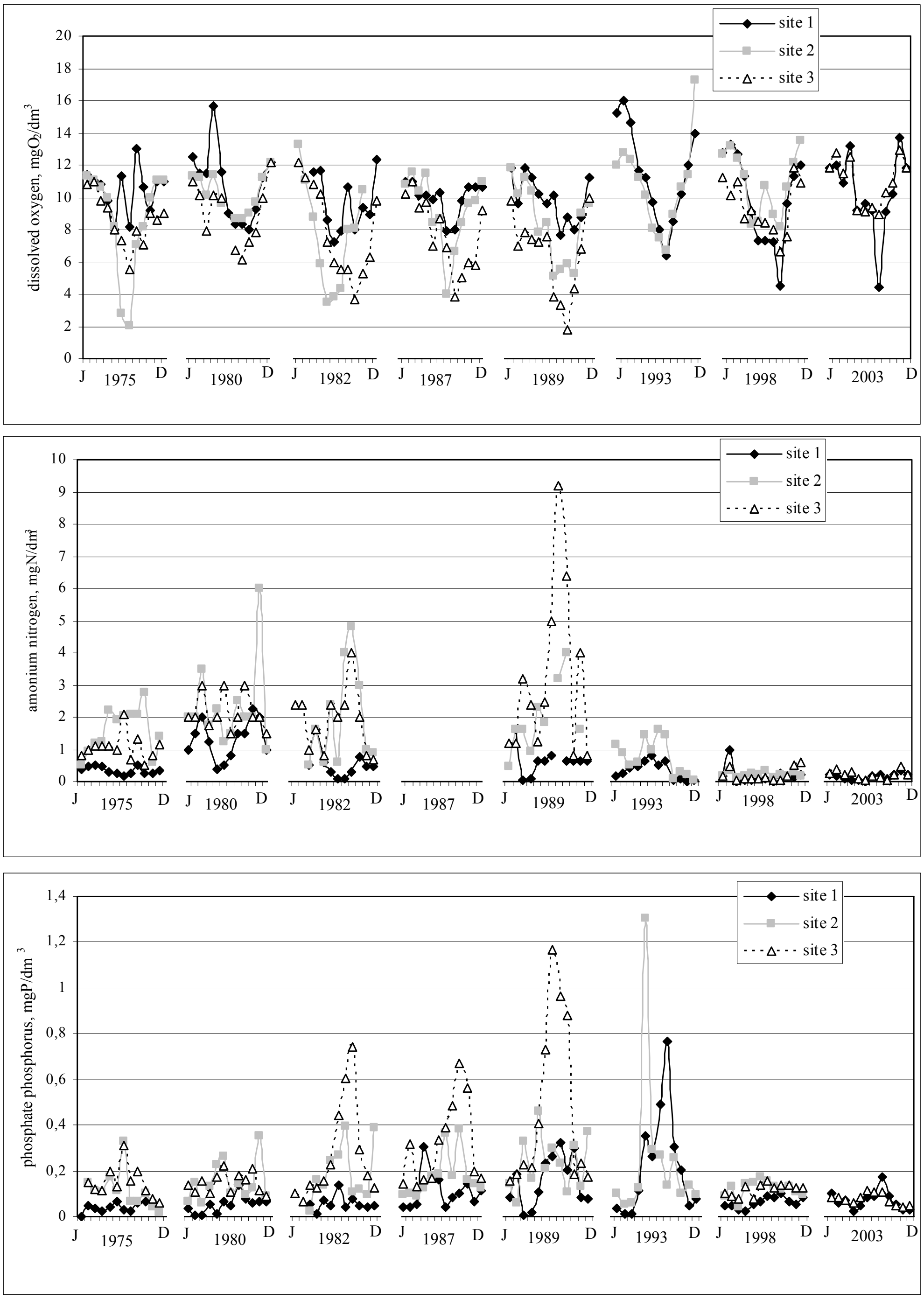

Fig. 2. Changes of dissolved oxygen (a), phosphate phosphorus (b) and ammonium nitrogen (c) concentration in the Bytowa, 1975-2003.

Table 2. Urban and non-point nutrient loads (tons/year) at site 3 in the Bytowa, 1975-2003.

Year	Parameter									
	NH_4-N tonsN/year		PO_4-P tonsP/year		NO_3-N tonsN/year		N-total tonsN/year		P-total tonsP/year	
	non-p	urban	non-p	urban	non-p	urban	non-p	urban	non-p	urban
1975	41.66	5.44	3.35	2.88	-	-	-	-	-	-
1980	83.51	12.89	4.47	1.96	-	-	-	-	-	-
1982	50.96	31.36	5.45	5.64	-	-	-	-	-	-
1987	-	-	6.28	7.02	-	-	-	-	-	-
1989	57.62	78.63	8.45	10.66	-	-	-	-	-	-
1998	9.20	0.84	4.01	1.18	32.95	6.35	106.54	13.34	9.15	6.25
2003	6.95	3.11	2.99	0.41	29.05	2,1	86.76	5.00	6.76	1.10

(COD) at that site were characterized by high annual variability (maximum value 91 mgO_2/dm^3 in July 1993), but most of the results were around 10 mgO_2/dm^3 (the mean value 13.7 mgO_2/dm^3). Probably the fish farm located at the mouth of the Boruja was the source of high organic contamination of this section of the river. At sites 1 and 3, the values of BOD_5 typically did not exceed 8 mgO_2/dm^3 and did not vary much during the analyzed time period. The mean COD values for both sites were about 9.5 mgO_2/dm^3. COD value was elevated only in 1998 compared to the remaining years.

Non-Point and Urban Loads of Ammonium Nitrogen and Phosphate Phosphorus

Taking advantage of the specific character of the Bytowa River basin, which in its upper area is agricultural and in the centre has only one non-agricultural source of pollution (the town of Bytów) an attempt has been undertaken to distinguish the part of the load of nutrients derived from agricultural areas from that generated by municipal sources, and to follow the dynamics of changes in both of those components during the years 1975 to 2003. It was assumed that the two sampling sites located at the highest points on the river – sites 1 and 2 (above Bytów) represented agricultural areas. Nutrient concentrations recorded at those sites can be treated as levels characteristic for the waters affected by non-point sources in the whole area, including the central part of the Bytowa's basin, downstream of Bytów. Due to the proximity of site 2 to the town, the concentrations at this location might have been elevated above the actual non-point background level. On the other hand, this might have been counterbalanced by some depression in the concentration of nutrients at site 1, which is attributable to the presence of Lake Madrzechowskie, through which the Bytowa flows (before site 1). Thus, the lake serves as a buffer reservoir in which some of the load carried by the river can be detained.

It is obvious that the contribution of point source pollution to total pollution at a given section of a river depends not only on the quantities of the pollutants derived from point sources but also on distance to the source of those pollutants. Because of biogeochemical processes in a river, the further from the source, the weaker the signal generated by point sources of pollution, which means that such pollution becomes more difficult to distinguish from the background of non-point contamination. Thus, relative proportions of pollution from different sources can be discussed only in reference to a specific point in the river course, and in the present case, to site 3, which lies midway between the town of Bytów and the outflow of the River Bytowa to the River Słupia.

Changes in the contribution of the two types of pollution at site 3 are presented in Table 2. As regards ammonium nitrogen, from 1975 to 1989 non-point source pollution was highly varied, but did not show any specific trend. On the other hand, the load of ammonium nitrogen derived from municipal sources of pollution increased 15-fold during those 14 years, from 8-fold lower than the non-point load in 1975 to 36% higher in 1989. From 1989 to 2003 the load of ammonium nitrogen from both sources of pollution decreased, with a particularly large decline in the load from urban sources of pollution (25-fold).

As regards phosphate phosphorus (Table 2), from the first year of observations (1975) to 1989, the amounts from non-point and point sources steadily increased. The contribution of phosphate phosphorus derived from municipal sources, at first lower than the load from non-point sources, increased faster and in the 1980s began to predominate. In the first 14 years under study, the amounts of phosphate phosphorus generated by municipal sources of pollution which reached site 3 increased 4-fold; during the same time period, the quantities of phosphate phosphorus from non-point sources rose 2.5-fold. After 1989 the loads of phosphate phosphorus from both sources of pollution decreased, and the decrease was faster in the case of municipal waste (by about 26-fold during the 14 years until 2003) as compared to non-point components (3-fold).

In 2003 pollution by phosphate phosphorus and ammonium nitrogen derived from point sources went down below the levels recorded in 1975; an analogous situation occurred in the case of NH_4 generated by non-point sources. The load of phosphate phosphorus from non-point sources was nearly the same as that observed in the early years of the monitoring programme.

The reduction of a large part of the load of ammonium nitrogen and phosphate phosphorus, which has occurred in the last ten or twenty years, does not necessarily mean that an equally large reduction in total nitrogen and total phosphorus has taken place. Some of the ammonium nitrogen may have been converted into oxygenated forms (nitrates, nitrites) or into an organic form; likewise, some of the phosphate phosphorus may have changed into an organic form or become bound into Fe-complexes. Measurements of the concentrations of total nitrogen and total phosphorus in the waters of the Bytowa were introduced in recent years and do not enable us to follow the changes that have occurred in the past thirty years. The studies from 1998 and 2003 showed, however, that the loads of N_t and P_t in those years were lower than the loads of ammonium nitrogen or phosphate phosphorus alone at the end of the 1980s. In 2003 the contribution of N_t and P_t derived from municipal sources to the overall loads of N_t and P_t was several-fold lower than that originating from non-point sources of pollution (Table 2).

Discussion

The comparative analysis presented in this paper demonstrated that the parameters which described the quality of the water in the River Bytowa underwent considerable changes during the long-term analysis period. Two stages can be distinguished during those 28 years:

- from 1975 to 1989,
- from 1993 to 2003.

The first stage was a time of heavy pollution of the river. During that time, an increase in the concentration of phosphate phosphorus in summer was observed, sometimes reaching up to 1.16 mg $P\text{-}PO_4/dm^3$ in July 1989 (an analogous concentration in January the same year was 0.15 mg $P\text{-}PO_4/dm^3$) (Fig. 2b). During the same time period, a considerable decrease in the concentration of oxygen in water was noticed (Fig. 2a). Later on, after 1993, summer maxima disappeared.

Lack of proper control over industrial wastewater and sewage management as well as the absence of municipal wastewater treatment plants (Fig. 3) were the first reasons why the quality of the water in the River Bytowa was so bad. At the turn of the 1970s and 1980s, a large increase in the pollutants derived from municipal sources of pollution was noticed (four-fold in terms of the load of $P\text{-}PO_4$ and 16-fold in $N\text{-}NH_3$). A 25% increase in the human population at that time was too small to explain such large changes. They were more likely to have been caused by the new sewage system being built in the 1980s while there was no professional wastewater treatment plant yet available. The river then was polluted by the waste collected by a system of sewers and having passed through not very efficient Imhoff sediment basins [7]. Prior to that, when fewer sewers were at work, some of the wastewater and sewage was discharged to the ground, and the part that reached the river had been previously treated naturally (passing through soil and vegetation). Another reason why the load of urban wastewater and sewage increased so much was that the lifestyle of the local population had changed (e.g. the amounts of household detergents used).

High nutrient levels in Bytowa water during the first stage resulted from intensive agricultural use of farmland (Fig. 4), inappropriately chosen doses of mineral fertilizers and inadequate application methods may have added to an increase in the amount of biogenic substances in the river water [12-14].

The second stage was a time of improvement in many of the parameters, especially a decrease in the concentrations of ammonium nitrogen, phosphate phosphorus and an increase in the amount of dissolved oxygen. Improved quality of the water in the river, which was noticed during the second stage, was a consequence of several overlapping factors associated with the political and economic situation in Poland. Gradual liquidation of state farms diminished the total area of farmland. Quite a large percentage of

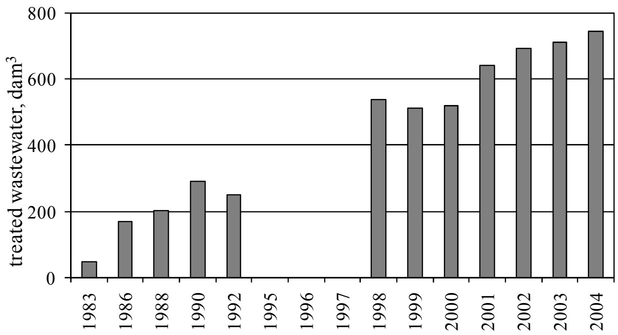

Fig. 3. The quantities of treated wastewater discharged to the River Bytowa (Statistical yearbook 1984-93, www.stat.gov.pl).

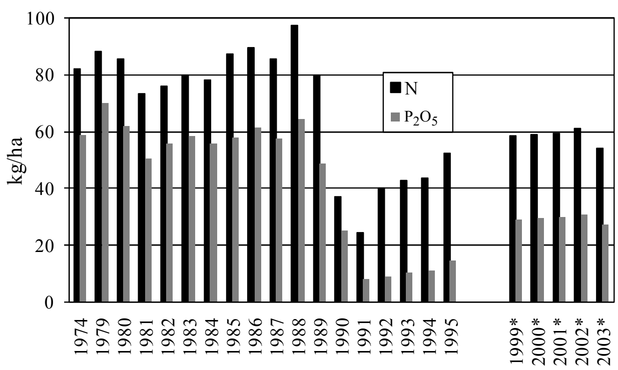

Fig. 4. Use of mineral fertilizers in Central Pomerania Region (kg/hectare). Period 1974-95 – data for the former Słupsk Province (Statistical yearbook 1976-97); period 1999*-2003* - data for the Pomeranian Province (note the difference in the administrative division of the country) (www.stat.gov.pl).

fields which had been cultivated by state farms was left fallow, and that meant that the share of uncultivated farmland increased. Also, some of the arable land was forested. Such changes, although small (over 11 years the area of farmland in the western part of the Pomeranian Province decreased by 5% to the advantage of forested land), could have had some positive influence on the quality of waters, by decreasing loads of non-point pollutants reaching the river.

After 1989 a market economy was introduced, so prices of mineral fertilizers were liberated, state subsidies were cancelled and costs of raw materials for production of fertilizers increased due to the transfer to dollar prices. This meant that mineral fertilizers on the market became expensive, and their consumption readily declined (Fig. 4) (by up to 70% in 1991). In addition, domestic demand diminished as agricultural production profitability quickly decreased, which was due to low market prices for farm crops. It can be also noticed that the rapid decline in the amounts of fertilizers applied (from 245.4 kgNPK/ha in 1988 to 97.6 kgNPK/ha in 1990 and 45.5 kgNPK/ha in 1991) did not cause an equally rapid reduction in the load of nutrients derived from non-point sources of pollution in the Bytowa. A similar situation has been described by many authors [14-20]. The waters in the rivers studied in Lithuania, Latvia and Estonia [15] in 1987-94 did not show any statistically significant changes in the concentration of nitrogen compounds and phosphates, even though the level of fertilization declined drastically after 1990. In the Czech Republic [14], the downward trend of fertilizer consumption, observed after 1989 (about 60% decrease) did not markedly affect water quality. Also, studies carried out in Denmark showed a delayed response, demonstrated as improved quality of surface waters, to a considerable decrease in the quantities of fertilizers (2-fold decrease in the amount of nitrogen and 3-fold decrease in phosphorus applied as fertilizers). The response was more pronounced when a given river basin comprised more farmland [16]. This means that the lack of immediate improvement in the quality of surface waters resulting from limited amounts of fertilizers in response to the reduction of fertilizer consumption could be due to the long-term accumulation of nutrients in soil (as sorptive complexes) and bottom sediments. The current level of the concentration of nutrients in the River Bytowa can depend on both surface pollution and the load of contaminants reaching the river with groundwater. The level of nutrient concentrations in groundwater can thus be the original background of the river water, which slowly reacts to changes in the agriculture practices in the river basin.

The decrease in the amounts of pollutants from urban sources first of all can be attributed to the construction and opening (in 1993-97) of a mechanical and biological municipal wastewater treatment plant (Bytów-Przyborzyce) that can treat up to 3,400 m^3 wastewater/day. The launching of the treatment plant meant that the quantities of treated wastewater discharged to the river increased dynamically (Fig. 3.) while the amounts of untreated wastewater decreased. In 2003, there was 13-fold more treated wastewater as compared to 1983. After the treatment plant was refurbished, the total phosphorus concentration in treated wastewater was 0.277 mg/dm^3, and total nitrogen – 19 mg/dm^3, which corresponds to the load of 0.22 tons of phosphorus and 15 tons of nitrogen annually, at the total amount of treated wastewater discharged equal to 2,163 m^3/day [8].

Unfortunately, not all problems have been solved since 1989. The sanitary condition of the River Bytowa is still worrisome. The coli titre determined during the monitoring programme is far from satisfactory [7-9]. This is a grave problem, as *Escherichia coli* is used as an indicator bacterium. The presence of *E. coli* in water suggests faecal pollution, and consequently a possible occurrence of pathogenic microorganisms. The wastewater treatment plant opened in the 1990s produced little improvement in the sanitary state of the river water, which is a contradiction to numerous references that suggest that during the biological treatment of wastewater (activated sludge) about 90-99% of all bacteria is removed [21-22]. The fact that the sanitary state of the Bytowa has not improved means that, in general, classification of its waters, although satisfactorily meeting physical and chemical requirements, are classless, and that is due to the excessive microbiological indices.

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