Transport of biogenes in the Szeszupa fluvial-limnic system in the Suwalski Landscape Park

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Abstract: Transport of biogenic matter along the course of the Szeszupa River in the Suwalski Landscape Park (SLP) occurs in accordance with the river continuum concept. Only TP concentration decreases along the river's course. TP and TOC concentrations classify the Szeszupa River to the moderate ecological state. The ecological state of three lakes (Linówek, Pogorzałek, and Perty) in the Szeszupa River catchment was estimated as very good. The remaining lakes, due to high TP concentrations, belong to the moderate state. The management of the catchment affects the amount of biogenic matter supplied to the Szeszupa River. The highest proportion of forests in the Jaczniówka River catchment clearly results in a decrease in the amount of biogenes in the river. The remaining partial catchments, with a higher proportion of arable land, meadows, and pastures, provide higher amounts of bioelements. The loads of bioelements stored in lakes in the summer period are determined by the size of the lakes (surface area of a lake and volume of water accumulated in the lake basin). This directly suggests a lack of anthropogenic activity in the catchments or the very slight effect of it on the lakes' ecological and trophic state.

Key words: water quality, biophilic elements, ecological state, trophic index

Introduction

Biophilic elements (nutrients, bioelements, biogenes) are necessary for life, and their content in the environment can limit the biological activity of ecosystems. In surface waters, bioelements affect processes such as primary production, microbiological decomposition of organic matter, and stimulation of growth of autotrophic organisms. Transport of biogenes in fluvial-limnic systems is a very complex process. A number of authors evidenced the accumulative role of lakes in relation to biogenes (Hillbricht-Ilkowska 1999, 2005; Lossow et al. 2006; Bogdanowicz and Cysewski 2008; Maślanka and Jańczak 2010). In the hydrometeorological conditions of the temperate zone, the role is variable throughout the year. In the summer period, when the shoreline of lakes is overgrown with macrophytes, the load of biogenes can be accumulated in plants and bottom sediments of the littoral zone. The objective of the hydrological-hydrochemical study on the Szeszupa River catchment in the Suwalski Landscape Park (SLP) was as follows:

- to analyse the concentrations and loads of biogenes in the Szeszupa fluvial-limnic system,
- to evidence the effect of the catchment management on the concentration and loads of biogenes in waters of the Szeszupa River and its tributaries,
- to determine the role of lakes in the accumulation of biogene elements.

Methods

The hydrological and hydrochemical study in the catchment of the Upper Szeszupa River in the Suwalski Landscape Park was conducted in July and August 2009-2010. Changes in the transport of biogenes along the course of the Szeszupa River were estimated based on 9 sites distributed along the course of the river (Fig. 1). In July 2009, the hydrochemical assessment of lakes in the Szeszupa River catchment was conducted (Fig. 1). Lake water for analyses was sampled from the epi-, meta-, and hypolimnion by means of the Bernatowicz's apparatus. In the field, the Secchi visibility, water reaction (pH), water temperature, electrolytic conductivity

Fig. 1. Study area: 1-9 – sampling points (rivers), I-XVII – sampling points (lakes)

(EC), and saturation of water with oxygen were measured with the application of the Hach Lange sonde. The discharge rate of the Szeszupa River and its tributaries was measured by means of an electromagnetic sensor by OTT. Measurements of the discharge rate of the Szeszupa River were conducted at the sites of sampling water for chemical analyses. The discharge rate of the Szurpiłówka River was determined below Lake Udziejek, and that of the Jacznówka River below Lake Kamendul (Fig. 1, Table 1).

At the laboratory of the Department of Hydrobiology of the University of Białystok, the following concentrations were determined: Kiejdahl nitrogen – by means of an analyser by Tecator; ammonia nitrogen (N-NH_4^+) – by means of the indophenol method;

nitrate nitrogen (N-NO_3^-) – by means of the reduction method with α -naphthylethylenediamine; nitrite nitrogen (N-NO_2^-) – by the reduction method with naphthylethylenediamine; soluble reactive phosphorus (SRP) – by means of the molybdate method; dissolved phosphorus (DP) and total phosphorus (TP) by means of the molybdate method after previous mineralisation with UV radiation; total organic carbon (TOC) and dissolved organic carbon (DOC) – by means of a Schimadzu TOC – 5050 apparatus, following methods proposed by Hermanowicz et al. 1999. The concentrations of the remaining forms of biogene elements were calculated based on the previous analyses: mineral nitrogen (TMN) = (N-NH_4^+) + (N-NO_3^-) + (N-NO_2^-), organic nitrogen (TON) = (Kiejdahl nitrogen – N-NH_4^+), total

Table 1. Morphometric parameters of the rivers in the Szeszupa catchment in SLP

River	Length of the river	Average rate of flow	Tortuosity	Slope of the river
	[km]	[$\text{dm}^3 \text{ s}^{-1}$]		
Szeszupa River (below Lake Postawełek)	13.95	208	1.4	3.7
Szurpiłówka River (below Lake Udziejek)	6.00	78	3.0	5.1
Jacznówka River (below Lake Kamendul)	5.00	55	3.1	1.6

nitrogen (TN) = (TMN+TON), and particle organic carbon (POC) = TOC-DOC.

Mean concentration of biogenes in lakes was calculated based on samples from the epi-, meta-, and hypolimnion. If more than one study site was located within a lake, the mean was calculated from all the sites. Mean concentration of biogenes in rivers was calculated based on measurements conducted in July and August 2009-2010. The Trophic Status Index (TSI) was calculated for the lakes studied following Carlson (Carlson 1977).

The analysis of transport of biogenes in the Szeszuapa fluvial-limnic system was conducted based on distinguishing four partial catchments: the source catchment of the Szeszuapa River with an area of 15.9 km² closed at the mouth of the Szurpiłówka River, the Jaczniówka River catchment with an area of 16.6 km², the Szurpiłówka River catchment of 16.1 km², and the direct catchment of the Szeszuapa River below the mouth of the Szurpiłówka River. The surface area of the partial catchments was calculated based on the watersheds marked on topographic maps at the scale 1:25 000.

The statistical analysis was conducted with the application of Statgraphics 5.0 software.

Study area

The Szeszuapa River is a left-bank tributary of the Neman River. It flows through territories of three countries: Poland, Russia, and Lithuania. Its length amounts to 298 km, whereas the "Polish" section has a length of 27 km. The length of the fragment subject to the study, flowing through the Suwalski Landscape Park, amounts to 13.95 km. The springs of the Szeszuapa River are located in riparian forests near Turtul. From there, the river flows in the NE direction in an extensive depression called the Szeszuapa River Depression (Bajkiewicz-Grabowska 1994). In the SLP, tributaries of the Szeszuapa River are the Jaczniówka and Szurpiłówka Rivers (Table 1). In physical-geographical terms, the Szeszuapa River catchment belongs to the Lithuanian Lakeland Macroregion, East Suwałki Lakeland Mesoregion (Kondracki 1998).

In the SLP, the Szeszuapa River flows through five shallow lakes: Gulbin, Okragłe, Krajwelek, Przechodnie, and Postawełek. The Szurpiłówka River, a right-bank tributary of the Szeszuapa River with a length of 6 km, drains an area of 16.36 km². Flowing in the northern direction, it drains Lakes Kopane, Udziejek,

Szurpiły, Jeglówek, and Jeglóweczek. The Jaczniówka River, a left-bank tributary of the Szeszuapa River with a length of 5 km, drains an area of 19.64 km² (Table 1) and flows through Lakes Jaczno and Kamendul (Bajkiewicz-Grabowska 1994).

The discharge rate during the study period along the course of the Szeszuapa River varied from 18.6 l s⁻¹ in the source section to 402.8 l s⁻¹ along the 14 km course of the river. The Szurpiłówka River was distinguished by a higher mean discharge rate (78 l s⁻¹) and higher inclination (5.1‰) than the Jaczniówka River (Table 1). The river development indices in the Szurpiłówka and Jaczniówka Rivers are similar, and exceed the development index of the Szeszuapa River more than twice (Table 1).

The largest lake in the Szeszuapa River catchment in the SLP is Lake Szurpiły with an area of 80.9 ha (Table 2). Almost half of the lakes in the area discussed are small lakes of less than 10 ha. The highest located lake is Lake Linówek – 199.7 m a.s.l.; the lowest lake is Lake Postawełek – 145.7 m a.s.l. The lowest volume of water is accumulated in Lakes Jeglóweczek and Linówek: 0.061 hm³ and 0.070 hm³, respectively. Lakes Szurpiły (8.2 hm³) and Jaczno (4.8 hm³) have the highest volume. According to the fishery classification, only Lake Linówek is a very shallow lake. The group of shallow lakes includes 8 lakes. The remaining lakes are deep and very deep (Table 2). The lowest proportion of forests (<20%) occurs in the catchments of Lakes Gulbin, Okragłe, Krajwelek, Postawełek, Kopane, Udziejek, and Szurpiły. In the catchments of Lakes Pogorzałek, Jaczno, Kamendul, and Jeglóweczek, the forest cover exceeds 50%, and reaches 74% in the direct catchment of Lake Pogorzałek. The source part of the Szeszuapa River catchment is dominated by cultivated land. Forests occupy only 30% of the area (Fig. 2). In the Szurpiłówka River catchment, forests constitute approximately 20% of the area. The Jaczniówka River catchment drains an agricultural-forest area dominated by forests (approximately 65% of the area). The direct catchment of the Szeszuapa River below the mouth of the Szurpiłówka River is agricultural-forest in character. It is dominated by cultivated land (approximately 60%). Forests occupy approximately 20% of the area. The land management and geological structure influence the degree of threat to groundwaters. Based on the Hydrogeological Map of Poland (PIG 2009), a moderate, low, and very low degree of threat to groundwaters was determined in the source part of the Szeszuapa River catchment. The moderate

Table 2. Morphometrical and hydrological characteristics of the lakes and Trophic Status Index in the Szeszupa catchment (roman numbers compatible with numbers in Figure 1; hydrological type of the lake: c – closed lake, f – flow lake, o – lake without outflow) (Bajkiewicz-Grabowska 1994; Jańczak 1999)

No.	Lake	Surface of the lake [ha]	Average depth (maximum depth) [m]	Volume of water [hm ³]	Hydrological type of lake	TSI
Szeszupa direct catchment						
I.	Linówek	2.6*	3 (5.6)	0.070	c	51
II.	Gulbin	8.5	5.6 (9.4)	0.266	f	57
III.	Okrągłe	16.5	4.6 (8.0)	0.716	f	61
IV.	Krajwelek	10	3.3 (6.0)	0.474	f	62
V.	Przechodnie	26.8	3.3 (6.3)	0.849	f	60
VI.	Postawelek	4.2	2.6 (5.4)	0.092	f	58
VII.	Kojle	19.3	10.9 (27.5)	1.755	d	54
VIII.	Perty	21.6	6 (31.0)	1.019	o	40
Jacznówka catchment						
IX.	Pogorzałek	6.5	3.5 (8)	0.111	c	66
X.	Jaczno	41.8	11.7 (29.6)	4.797	f	53
XI.	Kameduł	27.2	6.8 (24.5)	1.731	f	56
Szurpiłówka catchment						
XII.	Szurpiły	80.9	10.0 (46.2)	8.168	f	54
XIII.	Kluczysko	3.6	3.5 (13.6)	0.212	o	55
XIV.	Jegłowieczek	1.7	2.9 (6)	0.061	o	56
XV.	Jegłówek	20.6	7.5 (18.1)	1.444	f	44
XVI.	Kopane	17	7.3 (17.4)	1.059	f	64
XVII.	Udziejek	7.4	3.8 (7.2)	0.229	f	63

* – without peat

Fig. 2. Land use in the catchment of the Upper Szeszupa River (own study)

degree of threat to groundwaters refers to the entire Szeszupa River Valley in the SLP and the direct catchment of Lakes Jaczno and Kamendul. In the remaining area, a low and very low degree of threat to groundwaters was determined.

Inflow of groundwaters plays a considerable role in water circulation of the area. In the Suwalski Landscape Park, numerous natural outflows of groundwaters occur. Earlier studies reveal the existence of more than 100 springs, most of which are located in the Szeszupa River catchment (Nowakowski 1976; Bajkiewicz-Grabowska 1994). Studies conducted in the years 2008-2010 in SLP suggest a considerably lower number of natural outflows of groundwaters functioning in the summer period in the area discussed.

Results

In the summer period, water temperature in the Szeszupa River in the source section did not exceed 20°C, and in the lake section, it varied from 25 to 26°C. The multiple comparison test confirmed the statistical significance of the difference in temperature in both sections of the river. Apart from water temperature in the river, statistical significance of differences was determined for water reaction, water conductivity, concentrations of calcium and magnesium, nitrite and nitrate nitrogen, dissolved phosphorus, and silicon compounds. Much higher water conductivity occurring in the source section (530 $\mu\text{S cm}^{-1}$) than the lake section (443 $\mu\text{S cm}^{-1}$) entailed the variability of Ca (81 and 106 mg dm^{-3} on average) and Mg concentrations (8.4 and 14.5 mg dm^{-3}). In the summer period, waters of the Szeszupa River and its tributaries were well oxygenated (84-105%). Mean N-NH_4 concentration in the water of the Szeszupa River in summer 2009-2010 amounted to 353 $\mu\text{g dm}^{-3}$. The variability of this parameter along the river course reached 30% (Fig.

3A). Nitrate nitrogen constituted almost 40% of total nitrogen in the cross-section closing the catchment studied. Somewhat higher variability along the river course distinguished the remaining forms of mineral nitrogen N-NO_2 – CV=58% and N-NO_3 – CV=59%. In the source section, the concentration of those forms of nitrogen was considerably higher than in the lake section (Fig. 3A), and the calculated mean concentration in both sections differed significantly (multiple comparison test). The dominant form of nitrogen in the water of the Szeszupa River was TON. In the lake section, its content exceeded 2 mg dm^{-3} , which constituted almost 90% TN (Fig. 3B). High concentration variation occurred in the case of SRP (CV=97%). In the lake section, it grew to 180 $\mu\text{g dm}^{-3}$. In the lake section, the proportion of PP in the phosphorus structure was higher, and the percentage content of this form of phosphorus reached 50%. The content of the forms of organic carbon analysed decreased along the river course. In the lake section, POC content increased considerably (Fig. 3C).

The highest amounts of N-NO_2 and N-NO_3 inflow to the waters of the Szeszupa River from the source catchment (0.07 $\text{mg s}^{-1} \text{ km}^{-2}$ and 1.7 $\text{mg s}^{-1} \text{ km}^{-2}$, respectively), and the lowest amounts from the Jaczniówka River catchment (0.01 $\text{mg s}^{-1} \text{ km}^{-2}$ and 0.1 $\text{mg s}^{-1} \text{ km}^{-2}$, respectively) (Table 3). The most N-NH_4 is supplied from the direct catchment of the Szeszupa River (3.8 $\text{mg s}^{-1} \text{ km}^{-2}$), and the least from the Jaczniówka River catchment (0.8 $\text{mg s}^{-1} \text{ km}^{-2}$). The most intensive transport of TN occurs in the direct catchment of the Szeszupa River, and amounts to almost 21 $\text{mg s}^{-1} \text{ km}^{-2}$. In the Szurpiłówka River catchment, the amount of TN from each km^2 of the catchment is almost 5 times lower (Table 3). The highest contribution in the transport of phosphorus from the catchment to the waters of the Szeszupa River occurs in the catchment of the source section and the Szeszupa River catchment below the mouth of the Szurpiłówka Riv-

Table 3. Transport of nutrients ($\text{mg s}^{-1} \text{ km}^{-2}$) of the partitive Szeszupa catchment in the summer of 2009-2010

Catchment	Nitrogen compounds					Phosphorus compounds					Organic carbon compounds		
	N-NO_2	N-NO_3	N-NH_4	TON	TN	SRP	ORP	DP	PP	TP	DOC	POC	TOC
Headwaters of Szeszupa catchment	0.07	1.7	2.4	8.9	13.0	0.3	2.8	3.1	2.3	5.4	88.7	13.6	102.2
Jaczniówka catchment	0.01	0.1	0.8	5.0	6.0	0.2	0.05	0.2	0.2	0.4	24.9	3.3	28.3
Szurpiłówka catchment	0.02	0.2	1.7	1.7	3.6	0.2	0.5	0.7	0.1	0.8	70.6	4.5	75
Szeszupa direct catchment	0.04	0.8	3.8	16.1	20.9	1.2	2	3.2	3.1	6.4	161.2	59.6	220.8

Fig. 3. Changes in nutrient concentrations along the course of the Szeszupa River: A – nitrogen, B – phosphorus, C – organic carbon compounds

er (Table 3). The Szurpiłówka and Jaczniówka River catchment plays an insignificant role in the transport of TP, and particularly of the organic fraction (Table 3). In the source section, SRP plays an insignificant role in the structure of total phosphorus, constituting only 5% of TP content. In the remaining partial catchments, the content of SRP is much higher, and amounts from 20 to 45%. The highest amounts of DOC are supplied to the waters of the Szyszupa River from its direct catchment in the lake section ($161 \text{ mg s}^{-1} \text{ km}^{-2}$) (Table 3), and the lowest from the Jaczniówka River catchment ($25 \text{ mg s}^{-1} \text{ km}^{-2}$) (Table 3). The remaining catchments supply approximately half as much DOC. The main form of TOC in the fluvial water of the Szyszupa River catchment is DOC constituting more than 85% of TOC. Only in the lake section of the Szyszupa River does the content of DOC decrease to approximately 70%.

Mesotrophic lakes include Lakes Perty and Jeglówiek. Carlson's trophic state index of lakes through which the Szyszupa River flows oscillates around 60 (Table 2). The concentration and structure of biogenes in lakes of the SLP are varied. The highest amounts

of biogene matter among all of the lakes studied are stored in large and deep lakes (Szurpiły, Kopane, Jaczno, Kameduń, and Jeglówiek). Lake Szurpiły collects the highest loads of all the bioelements analysed except for the PP fraction, the highest amounts of which are accumulated in Lake Kopane (961 kg). The lowest amounts of biogene matter are accumulated in the small Lakes Postawełek and Kluczysko (Table 4).

Discussion

The water quality of rivers and lakes is determined by their geographical location, catchment management, quality of the inflowing waters, retention, land inclination, and mean depth of the water bodies. Human activity has a large impact on water quality (Bajkiewicz-Grabowska 2002; Ptak and Ławniczak 2012). In the SLP, anthropogenic transformations of the environment are still insignificant (Hillbrich-Ilkowska 1994, 2005). It is favoured by low population density in the area (population density of the Suwałki powiat is 28 people per km^2) and the manner of its management. The basic direction of economic activity is ag-

Table 4. Loads (kg) biogenic material stored in the lakes located in the Upper Szyszupa catchment

Lake	Nitrogen compounds					Phosphorus compounds					Organic carbon compounds		
	N- NO_2^-	N- NO_3^-	N- NH_4	TON	TN	SRP	ODP	DP	PP	TP	DOC	POC	TOC
Szyszupa direct catchment													
Linówek	1	3	7	19	29	1	3	4	2	6	1304	219	1523
Gulbin	2	14	75	197	287	6	35	40	13	53	2644	1104	3748
Okragłe	3	41	335	453	831	37	53	89	28	117	10178	1543	11721
Krajwełek	3	26	251	484	763	9	48	56	26	83	6508	1977	8485
Przechodnie	1	30	69	700	800	20	42	62	28	90	14620	2768	17388
Postawełek	1	6	29	52	89	2	6	6	7	15	1235	41	1275
Kojle	6	99	728	351	1291	16	220	236	109	345	15690	2381	18071
Perty	7	77	133	796	1014	10	12	22	28	50	7232	812	8043
Jaczniówka catchment													
Pogorzałek	0,2	75	10	53	71	4	5	8	2	10	2224	194	2418
Jaczno	12	173	1343	864	2391	156	559	715	149	864	35738	16070	51808
Kameduń	5	70	850	1014	1938	68	91	159	118	277	18729	1846	20576
Szurpiłówka catchment													
Szurpiły	26	720	2238	1110	4095	485	515	1000	549	1549	83427	12121	95545
Kluczysko	1	12	73	24	110	5	15	20	16	36	3260	193	3453
Jeglóweczek	0	3	7	20	30	1	1	2	4	6	1051	178	1229
Jeglówiek	11	69	215	747	1043	22	36	58	43	100	21944	8755	30700
Kopane	6	107	87	1253	1452	12	28	40	961	1001	7784	434	8217
Udziejek	1	13	77	63	154	9	35	44	7	51	2951	318	3269

riculture, often ecological, and agrotourism. Increased agrotourism traffic is observed in summer, but it does not result in considerable environmental changes in the Szeszupa River catchment, including water eutrophication. The stability of certain water properties (e.g. Secchi visibility) of SLP lakes was mentioned by Hilbricht-Ilkowska and Wiśniewski (1994). A decrease in water transparency was only recorded in the lakes of the Szeszupa system. Current studies reveal relative stability of the feature, and the trophic state index calculated based on Secchi visibility in Lakes Gulbin, Okragłe, Krajwelek, Przechodnie, and Postawełek oscillates around 50. In accordance with the suggestions of Hilbricht-Ilkowska and Wiśniewski (1994) as well as Górniak et al. (2007), TSI values calculated based on total phosphorus concentration significantly vary from the values calculated based on chlorophyll *a* concentration and Secchi visibility. This suggests that the majority of limnic waters are currently mesotrophic or mesoeutrophic. In the lakes studied, high TP concentration does not significantly affect the development of phytoplankton, because the majority of TP is in an unavailable form. SRP in the waters of the lakes of the Szeszupa system often constitutes less than 20% of TP. Such a situation is probably related to the character of soils occurring in the catchments of lakes strongly sorbing phosphorus, making it unavailable for autotrophs (Hilbricht-Ilkowska 1994). The available phosphorus resources can also be restricted as a result of complexing by calcium, aluminium, and iron compounds which can be subject to sedimentation (Bigaj et al. 2012). Certain unfavourable symptoms of transformation of water quality in summer in the SLP were recorded in the Czarna Hańcza River catchment. Their manifestation is an increasing TSI value in Lake Hańcza (Jekatierynczuk et al. 2012).

The ecological state of waters of the Szeszupa River is estimated as moderate. Three of the lakes studied are classified to the very good ecological state. These are Lakes Linówek, Pogorzałek, and Perty. The remaining lakes are classified to the moderate ecological state due to high phosphorus concentrations.

The high quality of the aquatic environment is confirmed by the recorded concentrations of bioelements and their loads in lakes (Table 4). Loads of bioelements accumulated in lakes in the summer period are determined by the size of the lakes. The correlation coefficients calculated for water volume in a lake and accumulated load of biogenes usually exceed 0.90 ($p < 0.05$). A somewhat lower correlation was de-

termined between the volume of lakes and TON ($r = 0.63$; $p < 0.05$), and lack of correlation in the case of PP. Similar correlations were determined between the surface area of the lakes and the amount of accumulated loads of bioelements. This unequivocally suggests the lack of anthropogenic activity in the catchments or the very insignificant effect of it on the lakes' ecological and trophic state.

Transport of biogenic matter in waters is a very complex process. Bioelements are incorporated in the biological matter cycle, and are subject to various transformations along the river course, adopting both soluble and insoluble forms (Bajkiewicz-Grabowska 2002). In accordance with the river continuum concept (Vannote et al. 1990; Bretschko 1995), in the Szeszupa River, the following parameters change continuously from source to sink: channel width and depth, water velocity, water volume, and organic matter inflow. The river continuum concept assumes a decrease in biogene concentrations along the river course except for phosphorus, the concentrations of which should increase. In accordance with the above assumptions, in the Szeszupa River, a decrease in organic matter concentration occurs. Only TP concentration grows. The highest mean concentrations of this bioelement occur in the source section ($1.2 \pm 0.2 \text{ mg dm}^{-3}$). In the vegetation season 2009-2010, TP concentration in the water of sources of the Szeszupa River was still high – $0.78 \pm 0.43 \text{ mg dm}^{-3}$. Similar values were recorded in the interstitial waters in the Szeszupa River valley floor in the source section ($0.78 \pm 0.35 \text{ mg dm}^{-3}$). The reason for the high TP concentration was the draining character of the river, and total precipitation in summer 2009-2010 being 25% higher in relation to the multiannual level. Intensive precipitation increased surface runoff from the nearby cultivated land. This combined with a low discharge rate could reduce the amount of biogene compounds in the water of the Szeszupa sources. According to Miler (2002), the amount of phosphorus compounds depends on the oxygen content in water. In the Szeszupa River sources, one of the reasons for such a high amount of total phosphorus may be the low concentration of dissolved oxygen ($5.26 \pm 0.57 \text{ mg O}_2 \text{ dm}^{-3}$). In the interstitial waters in the source part of the Szeszupa River valley, the mean oxygen concentration was even lower ($3.23 \pm 1.33 \text{ mg O}_2 \text{ dm}^{-3}$). According to Bajkiewicz-Grabowska (2002), in fluvial-limnic systems with deviations from the river continuum, transport and transformations of mineral materials are affected by the character of chemical

compounds. In the source section of the river, macro-molecular allochthonic organic matter occurs. Abundant grassy vegetation occurring there accumulates high amounts of nutrients inflowing from the catchment. A low discharge rate does not favour the fast transport of bioelements. On the contrary, it facilitates their accumulation. The source section of the Szeszupa River is located in the agricultural-forest part of the catchment, where cultivated land, meadows, and pastures constitute approximately 75% of the area of the partial catchment. Cattle breeding developing in the area, as well as considerable shortcomings in the storage of manure are the basic reason for the substantial transformation of groundwaters and disturbance of the river continuum.

The most important function in the migration of local agricultural pollutants is ascribed to ground outflow (Haag and Kaupenjohann 2001). This was confirmed in the source part of the Szeszupa River catchment. A significant role in the transport of dissolved compounds in water is played by surface runoff and shallow subsurface runoff (Banaszuk 2007), as well as natural and anthropogenic "surface hydrochemical corridors", including linear erosional forms, furrows, ruts, and ditch network (Haag and Kaupenjohann 2001). The occurrence of migration corridors may influence increased direct contact of the catchment with the river. Due to this, the migrating solutions can omit potential buffer structures securing surface waters against pollution (Krasowska and Banszuk 2011). It seems that in areas with high land denivelations, this phenomenon may be significant.

In Poland, the highest amount of nitrogen compounds supplied to groundwaters and surface waters comes from agriculture (Sapek and Sapek 2005). Soluble forms of nitrogen are transported with surface runoff (Kirylik and Rauba 2009). In flowing waters of the Szeszupa River catchment, the predominating form of nitrogen was ammonia nitrogen, constituting 65% of TN. This suggests slow transformation of ammonia ions and continuous supply of pollutants from the catchment in the summer period. The predominance of N-NH_4 in the waters of the Szeszupa River may result from the application in fertilisation of high

amounts of manure by local farmers. The field observations suggest intensive fertilisation of cultivated land in a natural manner. Continuous inflow of ammonia ions to water bodies also results from breeding of cattle remaining on pastures throughout the summer period, and grasslands usually located in the vicinity of rivers and lakes. Along 9 km of the river course, where the Szeszupa River flows out of Lake Gulbin, a decrease by 3-4 times in the concentration of N-NO_3 occurs. In the section where the Szeszupa River flows through Lakes Gulbin, Okragle, Krajwelek, Przechodnie, and Postawełek, the river valley is very wide, which favours strong growth of macrophytes. Little transformed anthropogenic lakes and forests in the functional-spatial structure of the catchment fulfil the function of biofilters of pollutants, and stabilisers of ecological conditions (Hilbricht-Ilkowska 2005; Bogdanowicz and Cysewski 2008). Along the river banks and around lakes, numerous forest assemblages occur. The littoral and rush vegetation, as a transitional zone between land and water, developing the waterland ecotone, constitutes a buffer for biogene compounds. Biophilic elements can be accumulated here and transformed together with autochthonic matter. Increased nutritive requirements of plants in the vegetation period result in a decrease in concentrations of forms of N-NO_3 . The use of N-NO_3 in niches of lowland well-heads was experimentally evidenced by Jekatierynczuk-Rudczyk (2010).

Along with the growth of the catchment area, the Szeszupa River's channel expands and the discharge rate increases. Due to this, in spite of a decrease in the concentration of biogenes in water along the river course, the amount of transported biogenic matter increases. The effect of an increase in the discharge rate on the intensity of biogenic matter transport is confirmed by significant correlation coefficients (Table 5).

Water quality depends on processes occurring both in the catchment and in the river channel (Jekatierynczuk-Rudczyk et al. 2006; Jekatierynczuk-Rudczyk 2010). The lowest amounts of biogenic matter are supplied to the Szeszupa River from the most intensively forested Jacznówka River catchment. Sim-

Table 5. Statistically significant correlations ($p < 0.05$) between the load of transported nutrients and the flow rate along the course of the Szeszupa River

	N-NO_2^-	N-NO_3^-	SRP	DP	TP
Flow rate	0.75	0.69	0.53	0.69	0.59

ilar results were obtained in the Białystok region. The highest increase in the load of bioelements in the waters of the Szeszupa River was recorded in the vicinity of the Udziejek village, where the river flows into a regulated channel. Intensive inflow of biogenic matter from meliorated areas occurs here. Meliorated areas can transport particularly high amounts of biogenes. In the vicinity of Lake Okragłe, the largest source of pollutants is located, namely numerous outlets of melioration ditches draining water from cultivated land located in the direct vicinity of the lake, and forest complexes located at a somewhat larger distance. Here, the amount of transported biogenic compounds in the waters of the Szeszupa River reaches its maximum, and increases twofold in relation to the upper course of the river. In the Szurpiłówka River catchment, in spite of the prevalence of agricultural land, an insignificant load of nitrogen and phosphorus occurs. In the case of TON and TN, elementary runoff is lower than that in the more forested Jaczniówka River catchment. This results from the bioaccumulation of biogenes in flow-through lakes (Bajkiewicz-Grabowska 2002; Lossow et al. 2006; Maślanka and Jańczak 2010). In fluvial-limnic systems, lakes constitute an element disturbing the river continuum. They change the outflow conditions and load of matter transported by the river. In lakes, accumulation of matter both supplied from the catchment and produced in the catchment occurs. They fulfil the function of a kind of "collector" of matter and sediments, and their stability is determined by hydrological conditions (Wetzel 2001). The greater the depth of a lake, the higher their water retention capacity, and the more effect it has on the modification of the fluvial outflow (Bajkiewicz-Grabowska 2002).

The transformation of the original landscape into an agricultural landscape results in a change in water relations in the area. This affects the small water circulation, causing its shortening and simplification. This, in turn, reduces water retention in soils, worsens the infiltration conditions, and facilitates surface runoff of precipitation waters (Stachowicz 1995). Higher concentrations of dissolved organic carbon in the rivers of the Szeszupa River catchment may result from the fact that meadow ecosystems can annually produce the amount of biomass similar to that produced by forest ecosystems (Jekatierynczuk-Rudczyk et al. 2006). The mean DOC concentration in the waters of the Szeszupa River amounts to 13.9 mg dm^{-3} , and constitutes almost the entire total organic carbon. The

low proportion of POC (16.5% on average) in total organic carbon was observed in numerous studies (Wetzel 2001; Parks and Baker 1997; Suchowolec and Górniak 2006).

Conclusion

1. Transport of biogenes along the course of the Szeszupa River occurs in accordance with the river continuum concept with the exception of TP. TP concentrations increase along the river course.
2. The increased proportion of forests in the Jaczniówka River catchment clearly decreases the number of biogenes in the river. The remaining partial catchments with a higher proportion of cultivated land, meadows, and pastures supply higher amounts of bioelements to the main river.
3. The hydrochemical state of the Szeszupa River is moderate due to the increased concentrations of total phosphorus and total organic carbon. Lakes Linówek, Pogorzałek, and Perty have a very good ecological state. The remaining lakes, due to increased phosphorus concentration, belong to the group with a moderate ecological state.
4. Loads of bioelements accumulated in lakes in the summer period are determined by the size of the lakes.

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