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Original Research

Nitrogen and Phosphorus in Bottom Sediments of Two Small Dam Reservoirs

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Abstract

Bottom sediments of two small shallow dam reservoirs, the Zalew Zemborzycki (ZZ) on the Bystrzyca River near Lublin and Brody Iłżeckie (BI) on the Kamienna River, were investigated. The sediment samples from both water reservoirs were collected at 17 sampling sites in the transects perpendicular to the shoreline, at the river inflow and at the frontal dam. The contents of total nitrogen (TN) and total phosphorus (TP) were measured and the research results analyzed statistically. A relationship between TP concentration in sediments and TN, Fe, and Al levels was determined. The maps of spatial distribution of TN and TP were drawn.

Sediments of the BI showed greater differentiation of TN and TP contents than sediments in the ZZ, which resulted from a sediment dredging operation performed in most of its area. The dredged part of the BI reservoir had many times lower levels of both TN and TP as compared to sediments in the undredged part. In the ZZ reservoir sediments, longitudinal zonation of TN spatial distribution was observed: the lowest content in the sediments in left-bank part of the reservoir, medium along the middle part, the highest in the right-bank area. In this water reservoir, the zone of the highest TP accumulation occurred in sediments of the upper part and at the frontal dam. It is likely to be caused by the high external loads of P from the Bystrzyca River and by its sedimentation process along with silt and clay particles, respectively. The TN and TP distribution in sediments in the BI was similar and displayed transverse zonation (parallel to the dam). Our research established a strong linear relationship between TP content and Fe and Al concentrations in BI sediments. It implies that a high level of Fe and Al in sediments of this reservoir contributed to the TP accumulation there.

Keywords: nitrogen, phosphorus, bottom sediments, dam reservoirs, eutrophication

Introduction

Dam reservoirs are susceptible to the eutrophication process caused by biogenic substance loads (among others, nitrogen and phosphorus compounds) delivered to the water reservoir from various catchment sources. The nutrients can be deposited in sediments and then released to enter the biogeochemical cycles of the reservoir again. Beside phosphorus, nitrogen has proven to be the primary nutrient responsible for water quality and a body of water`s trophic state [1-3].

Nitrogen and phosphorus contents and their forms in sediments depends on the allochthonous – point and diffuse sources, geological structure of catchment (type of rock and their mineral composition), and soils as well as hydrometeorological conditions [4-6]. The autochthonous sources are also of great importance, especially in the case of nitrogen – organic matter (phytoplankton, macrophytes) [2].

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Phosphorus transformation in the aquatic environment relies on numerous factors, including water quality (pH, redox potential, content of Fe, Al, Ca) [6-9]. It is known that sediments are the major reservoir of P and the part of its internal load in water ecosystems [8, 10, 11]. They act as a sink or a source of this element depending on sediment composition and limnological conditions. Sorptive capacity of sediments for P is related to the content of organic matter, Fe-Al-oxides/hydroxides, clay, and $CaCO_3$ [7, 12]. Inorganic P is strongly bound by $Fe(OH)_3$ in oxic and released in anoxic sediments. Generally, P has a higher binding affinity to $Fe(OH)_3$ surface sites than $Al(OH)_3$ [7].

Differentiation in nutrient accumulation in sediments of various parts of a water basin is affected by environmental conditions, morphology, and reservoir hydrology, (flow and level of water, resistance time). Generally, the highest amounts of biogenic components deposit in sediments of deep parts in slow-flowing waters, in stagnation zones, areas adjacent to arable land, and the sites where fine-size fractions prevail in the deposited material.

The research aim was to analyze nitrogen and phosphorus content in bottom sediments of the Zalew Zemborzycki reservoir (ZZ) on the Bystrzyca River near Lublin and the Brody Iłżeckie reservoir (BI) on the Kamienna, as well as their spatial distribution. In addition, a relationship between these elements and iron and aluminum levels in the sediments was studied.

Study Area and Methods

Dam Reservoir Characteristics

The reservoirs under investigation have comparable surface areas and similar functions (Table 1). They are both designed to control water flow, provide recreational opportunities, and are used by industry only to a small degree. The Brody Iłżeckie reservoir supplies water to the industrial plants in Starachowice, while the Zalew Zemborzycki reservoir feeds water into the Wrotków Thermal Power Plant in Lublin. However, these water basins are characterized by a different water outflow system, i.e. top in the ZZ and lower in the BI. Importantly, from the time the ZZ reservoir became operational, no work has been performed that could disturb the mass of sediment, whereas the Brody Iłżeckie one was rebuilt in the second half of the 1980s. The redevelopment efforts included the dam reservoir rebuild together with complete sediment load removal from most of the water part of the reservoir. Dredging was performed in the IV and V sector areas (Fig. 2b). The dredged sediments were disposed of for the reservoir bank superelevation and embankment on the southern (right) side, as well as for building a small island in the central part of the reservoir.

Table 1. Reservoir characteristics.

Feature	Brody Iłżeckie (BI)	Zalew Zemborzycki (ZZ)
Year of construction	1964, 1986 dam rebuilding	1974
Location	N51º00'13", E21º10'01"	N51º10'43", E22º31'25"
Surface area*	204 ha	282 ha
Volume*	7.6 mln m^3	6.34 mln m^3
Maximal depth	6 m	4 m
Maximal level of damming	195.0 m above sea level	178.5 m above sea level

* At the maximal level of damming

Sediment Sampling

The bottom sediment samples were collected from 17 sites in two objects in July 2010 using the Kajak sediment core sampler [13]. In the ZZ, sediments were taken in the following sampling locations – 4 samples in each of three perpendicular transects, i.e. in the upper (B), middle (C), and lower (D) parts of the reservoir, one sediment sample at the place of the Bystrzyca inflow (A), and one at the frontal dam (E) (Fig. 2a). Additionally, single samples were collected from the bay parts of the reservoir, between the B and C transects (15), C and D (16, 17). As for the BI, 13 samples were taken in four transverse transects (IV, V, VI, VII) – 2-4 samples each depending on transect length, then 3

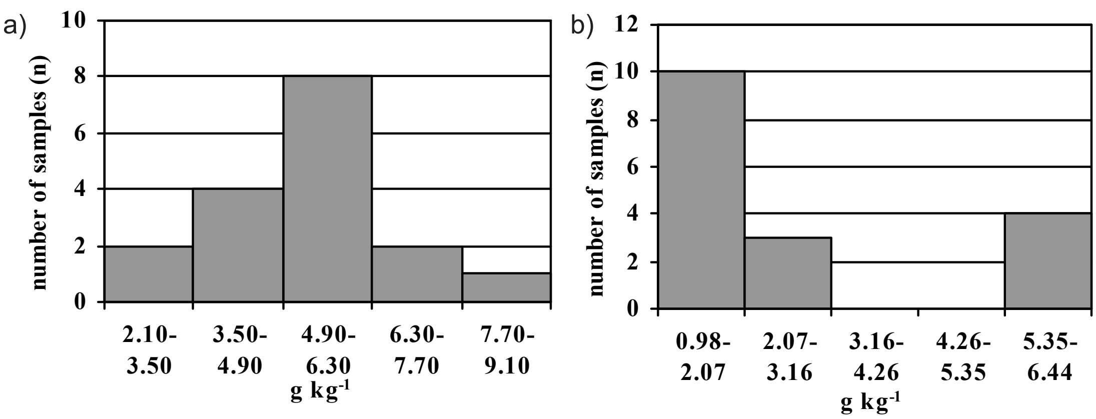

Fig. 1. Histogram of TN distribution in bottom sediments of the reservoirs: (a) Zalew Zemborzycki, (b) Brody Iłżeckie.

Table 2. Content of total nitrogen (TN), total phosphorus (TP), and C:N and C:P ratios in sediments of Zalew Zemborzycki reservoir.

Transect/site	TN	C:N	TP	C:P	Fe	Al
	g·kg-1		g·kg-1		g·kg-1	
A1	3.92	10.41	0.52	78.3	7.06	9.48
B2	3.64	8.81	0.42	76.5	6.67	8.96
B3	4.34	9.33	0.49	82.7	8.07	11.10
B4	9.10	9.56	0.62	140.8	8.98	12.60
B5	6.30	9.97	0.46	136.7	6.62	9.93
Mean B	5.85	9.42	0.50	109.2	7.59	10.65
C6	2.10	9.43	0.27	73.1	7.81	9.38
C7	2.52	6.55	0.23	73.0	4.15	5.82
C8	4.76	6.93	0.39	85.3	7.76	11.30
C9	6.30	7.29	0.41	112.2	7.69	11.30
Mean C	3.92	7.55	33	85.9	6.85	9.45
D10	5.32	6.54	0.44	79.1	7.60	11.80
D11	5.04	8.10	0.49	82.9	7.72	11.20
D12	4.90	6.24	0.42	72.9	7.30	11.80
D13	5.04	7.80	0.42	98.5	7.37	11.50
Mean D	5.08	7.17	0.44	83.4	7.50	11.58
E14	5.60	5.36	0.54	55.2	8.37	13.20
15	6.58	8.66	0.37	154.1	6.34	9.04
16	5.60	8.04	0.40	111.7	7.57	11.30
17	6.02	7.82	0.40	118.9	7.99	12.50
LSD* (B,C,D)	3.59	1.90	0.15	46.1	2.44	3.46

*LSD-the least significant difference

samples in the part of the Kamienna River inflow (I1, II2, III3) and one sample at the frontal dam (VIII17) (Fig. 2b). At each selected sampling site, from 10 up to 15 cores of hydrated sediments were collected to form the composite sample (ca. 5 dm^3). The sediments were air dried to be afterwards homogenized in an agate mortar.

Methods

The sediment samples were examined to determine the total nitrogen content (TN) using Kjeldahl method with a TEKATOR microwave oven and the distillation unit KJELTEC. The total phosphorus (TP), total iron, and aluminum concentrations were measured by the ICP-EAS method (Lemans Inc. PS950 instrument) applied after the sample mineralization in the mixture of concentrated HNO_3 and $HClO_4$ acids (1:1, v/v).

The following statistical analyses were performed: value intervals (minimum and maximum) mean values, the median, kurtosis and skeweness of distribution computed. In order to evaluate the differences between the means for the transects, Tukey's test was applied with LSD (the least significant difference) determination. There was determined a relationship (linear regression) between TP content in sediments and N, Fe, and Al levels.

The maps of nitrogen and phosphorus spatial distribution were made and to interpolate the distributions, the kriging technique was applied to provide optimal unbiased interpolation estimation for points and blocks. As the variables under study did not satisfy the stationary condition, they underwent a trend analysis. The detected trends were removed from the data and then empirical semivariogram values calculated and fitted to the mathematical functions used to estimate the studied values in the space by means of an ordinary kriging procedure. The analyses were based on the ArcGIS program.

Results and Discussion

Total nitrogen content in sediments in the Zalew Zemborzycki reservoir varied within the broad range, i.e. from 2.10 at point C6 up to 9.10 $g \cdot kg^{-1}$ at B4, and showed substantial differentiation related to a reservoir part (Table 2).

Table 3. Statistics of TN and TP contents in sediments of Zalew Zemborzycki and Brody Iłżeckie reservoirs.

Statistic	Zalew Zemborzycki		Brody Iłżeckie	
	TN	TP	TN	TP
Mean ($g \cdot kg^{-1}$)	5.12	0.43	2.81	2.04
Minimum ($g \cdot kg^{-1}$)	2.10	0.23	0.98	0.11
Maximum ($g \cdot kg^{-1}$)	9.10	0.62	6.44	6.02
Median ($g \cdot kg^{-1}$)	5.04	0.42	1.82	1.48
Kurtosis	1.48	0.90	-0.49	-0.34
Skewness	0.32	-0.21	1.10	0.97

The highest mean value was determined in the sediments of transect B (5.85 $g \cdot kg^{-1}$), slightly lower in D (5.08 $g \cdot kg^{-1}$), and the lowest in sediments of transect C (3.92 $g \cdot kg^{-1}$). However, statistical analysis showed that the differences between the mean values of TN for transects were insignificant (Table 2).

Lower TN concentration in transect C as compared to the others may be attributed to the reservoir narrowing in that area, where the water flow is faster and, consequently, less fine particle sediments get deposited. It is also reflected in the grain size composition of sediments, that is a higher percentage of coarse fractions and a lower share of fine ones as reported in the earlier studies [14]. Such conditions do not favor organic matter accumulation in sediments deposited in this part of the ZZ.

Most samples (n=8) showed nitrogen content in the 4.90-6.30 $g \cdot kg^{-1}$ interval (Fig.1a). Four samples had TN levels below the aforementioned range, whereas only three samples were in the intervals above it. As a result, nitrogen concentration distribution in the sediments of the ZZ reservoir was slightly right skewed (As=0.32). The mean content of TN and the median value for this water reservoir did not differ and were 5.12 $g \cdot kg^{-1}$ and 5.04 $g \cdot kg^{-1}$, respectively (Table 3).

The obtained TN contents in the sediments of the ZZ corresponded to those recorded 30 and 10 years ago [15, 16] and that indicates a relatively stabilized nitrogen cycle in this water reservoir. Noteworthy are the N levels, which tend to be considerably higher than those reported by Jasiewicz and Baran [17] for two dam reservoirs on the Wisłoka River and slightly higher than data presented by Koszelnik et al. [18] for the Solina and Myczkowce reservoirs.

The analysis of the TN spatial distribution has shown a marked regularity of longitudinal zonation of this element content in the sediments of the ZZ (Fig. 2a). The lowest nitrogen content was found in the sediments in the left-bank part of the Zalew Zemborzycki Reservoir, while the highest was in the right-bank area. The medium nitrogen concentrations were found in the sediments along the middle part of the ZZ. Low concentrations of TN in the left-bank part may be ascribed to the lower depth and higher water dynamics as compared to other areas. This is due to the parent river current that runs closer to the western shoreline [19]. Another important reason for the observed relationship can be relatively strong water waving, as this area is unscreened from the prevailing western wind. Wind-driven turbulence moves suspension and resuspended sediments [20]. Unlike the western part, the eastern one and especially bay sites (4, 5, 15) are situated at the greatest distance from the river channel. This fact together with forest vegetation surrounding it and screening from the wind cause this area of the reservoir to show features of lacustrine environment, which promotes sedimentation [21]. Besides, it should be highlighted that a high TN content in sediments of this part of the reservoir is also likely to be attributed to the character of peat soils occurring there, and not removed before the construction of the reservoir [3].

The stated regularity of the TN longitudinal zonation is in concurrence with the earlier observed one, from the very beginning of the reservoir functioning [15, 16]. That dependence is not typical for dam reservoirs as the literature indicates that spatial distribution of element concentration in bottom sediments is usually parallel to the frontal dam [8, 22].

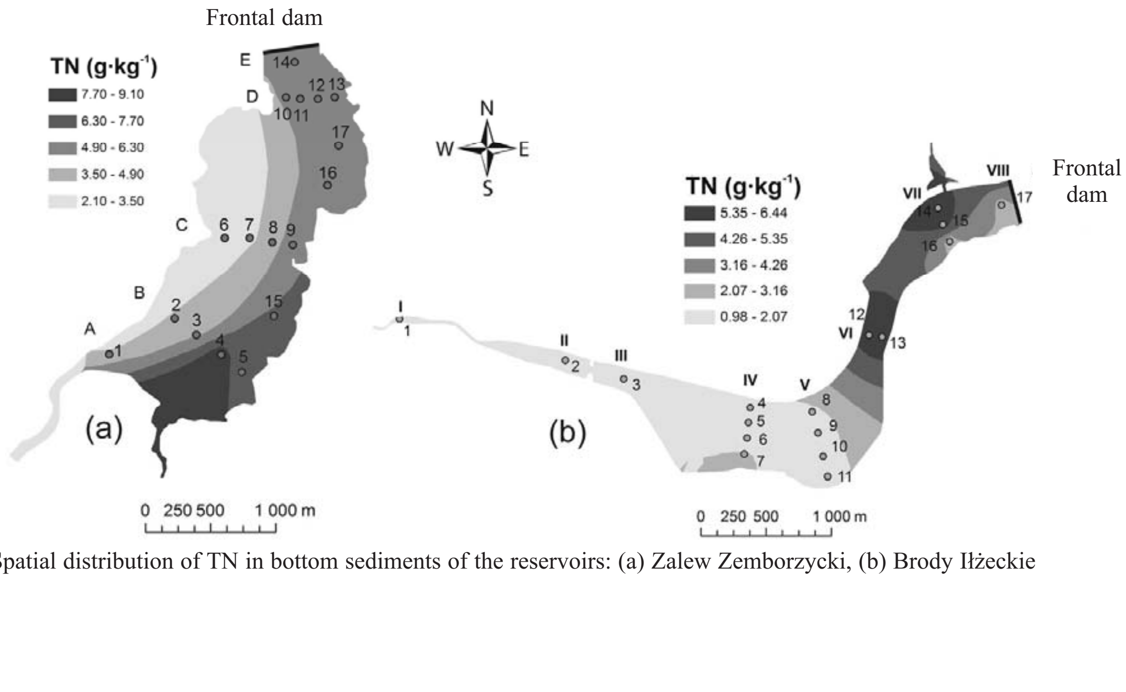

Fig. 2. Spatial distribution of TN in bottom sediments of the reservoirs: (a) Zalew Zemborzycki, (b) Brody Iłżeckie

Table 4. Content of total nitrogen (TN), total phosphorus (TP), C:N and C:P ratios in sediments of Brody Iłżeckie Reservoir.

Transect/site	TN	C:N	TP	C:P	Fe	Al
	g·kg^{-1}		g·kg^{-1}		g·kg^{-1}	
I1	1.54	0.39	0.13	4.7	1.76	1.63
II2	1.40	0.86	0.14	8.5	1.71	1.84
III3	1.40	8.79	1.63	7.5	8.07	5.43
Mean I-III	1.45	3.35	0.63	6.9	3.85	2.97
IV4	1.82	8.24	1.61	9.3	11.90	6.46
IV5	1.40	7.71	1.71	6.3	20.60	1.58
IV6	0.98	1.84	0.28	8.3	3.81	2.10
IV7	2.38	6.05	1.36	10.6	14.40	10.80
Mean IV	1.65	5.96	1.24	8.6	12.68	5.24
V8	1.82	2.06	0.11	35.0	2.50	1.71
V9	1.26	10.36	1.40	9.3	20.30	19.00
V10	2.06	11.21	1.48	15.9	20.50	18.20
V11	0.98	10.71	0.62	17.0	7.62	6.82
Mean V	1.54	8.59	0.90	19.3	12.73	11.43
Range I-V	0.98-2.38	0.39-11.21	0.11-1.71	4.7-35.0	1.71-20.60	1.58-19.00
Mean I-V	1.55	6.20	0.95	12.0	10.29	6.87
VI12	6.02	8.17	6.02	8.2	52.00	40.70
VI13	6.44	7.59	4.88	10.0	42.40	32.40
Mean VI	6.23	7.88	5.45	9.1	47.20	36.55
VII14	6.30	7.71	4.84	10.0	45.70	34.10
VII15	6.02	8.27	4.72	10.6	40.80	30.60
VII16	2.80	6.21	1.12	15.5	18.60	13.30
Mean VII	5.04	7.40	3.56	12.0	35.03	26.00
VIII17	3.08	8.67	2.78	9.6	24.50	19.70
Range VI-VIII	2.80-6.44	6.21-8.67	1.12-6.02	8.2-15.5	18.60-52.00	13.30-40.70
MeanVI-VIII	5.11	7.77	4.06	10.7	37.33	28.47
LSD* (IV,V,VI,VII)	2.27	6.79	2.58	15.4	21.56	17.38

* LSD- the least significant difference

The TN content in sediments of the Brody Iłżeckie Reservoir was more differentiated compared to the ZZ, and varied from 0.98 (point IV6 and V11) up to 6.44 g·kg^{-1} at point VI13 (Table 4). Parts I-III and the one where sediments were dredged (IV and V transect area), further called the first part, markedly differed from the rest (further called the second part) in terms of TN level in sediments. TN concentrations in the sediments in the first part oscillated between 0.98 and 2.38 g·kg^{-1}. The mean value in each transect was close and maintained at the ca. 1.5 g·kg^{-1} level. While in the sediments in the second part area it was more than three-fold higher (5.11 g·kg^{-1}). The differences between the mean values for IV and V transects of the first part and between VI and VII of the second part proved to be statistically significant (Table 4).

The results give evidence of high sediment nitrogen content in the not dredged part. It is worth mentioning that mean TN content in the sediments in this part approached this element mean concentration in the sediments of the ZZ Reservoir. This fact may suggest similar accumulation conditions and nitrogen compound transformations in both water reservoirs.

The histogram of the TN concentration in the BI reservoir sediments indicates that its content in most samples (n=10) was found within the lowest interval values (0.98-2.07 g·kg^{-1}), in three samples in the higher one (2.07-3.16 g·kg^{-1}) and, finally, four in the highest (5.35-6. 44 g·kg^{-1}) (Fig. 1b). It is clearly the right skewed distribution (As=1.1) (Table 3). Among the samples under investigation, no sediments of TN content in the medium intervals were recorded.

The analysis of TN spatial distribution in sediments in the BI shows the apparent division into two parts (Fig. 2b). In the first one, the area up to and including transect V, the TN content occurred in the lowest range. While in the other, there were zones of four and higher intervals of TN contents in the sediments. At first it was a distribution parallel to the frontal dam and then at the dam area slightly skewed. What attracts attention is the zone of relatively lower nitrogen concentration in the sediments deposited at the frontal dam – in the distant, southeastern part of the reservoir. The reason for that is undoubtedly the system of bottom water outflow from this reservoir. Such a system rises transport and outflow of sediments from the area of the frontal dam, especially fine size mineral and organic matter fractions. Along with organic matter, nitrogen is removed.

C:N Ratio

In the ZZ sediments, the C:N ratio, except for one case, was below 10.0 and varied from 5.36 at point E14 at the frontal dam up to 10.41 in A1 at the water inflow area (Table 2). The mean C:N value was equal to 8.1. There was observed an evident regularity of decreasing C:N ratio in the sediments advancing toward the frontal dam. The mean C:N value in the sediments in transect D tended to be lower (statistically significant) than that for sediments of transect B.

In the BI sediments, the C:N values were far more differentiated as compared to the ZZ bottom sediments, which proves greater variability of the organic carbon and total nitrogen contents. The lowest C:N ratios were less than 1.0 (min.=0.39), whereas the highest exceeded 10.0 (max.= 11.21) (Table 4). The highest C:N values were reported in the sediments in transect V, while the lowest were in the reservoir backflow (I-III). However, the differences between the means for the compared transects were statistically insignificant.

The carbon-to-nitrogen ratio indicates the sedimentary organic matter transformation, mineralization, and humification processes. Low values may provide evidence of a high degree of organic matter humification. According to

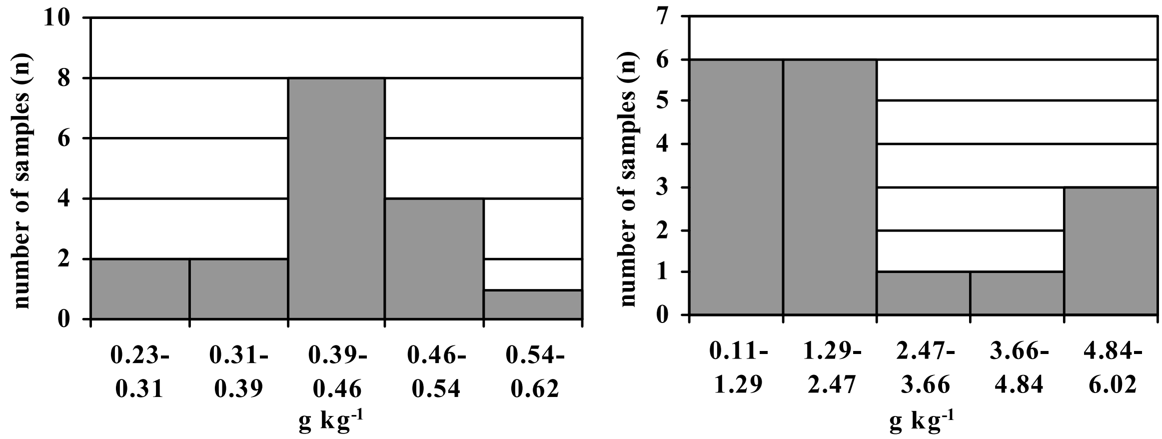

Fig. 3. Histogram of TP distribution in bottom sediments of the reservoirs: (a) Zalew Zemborzycki, (b) Brody Iłżeckie.

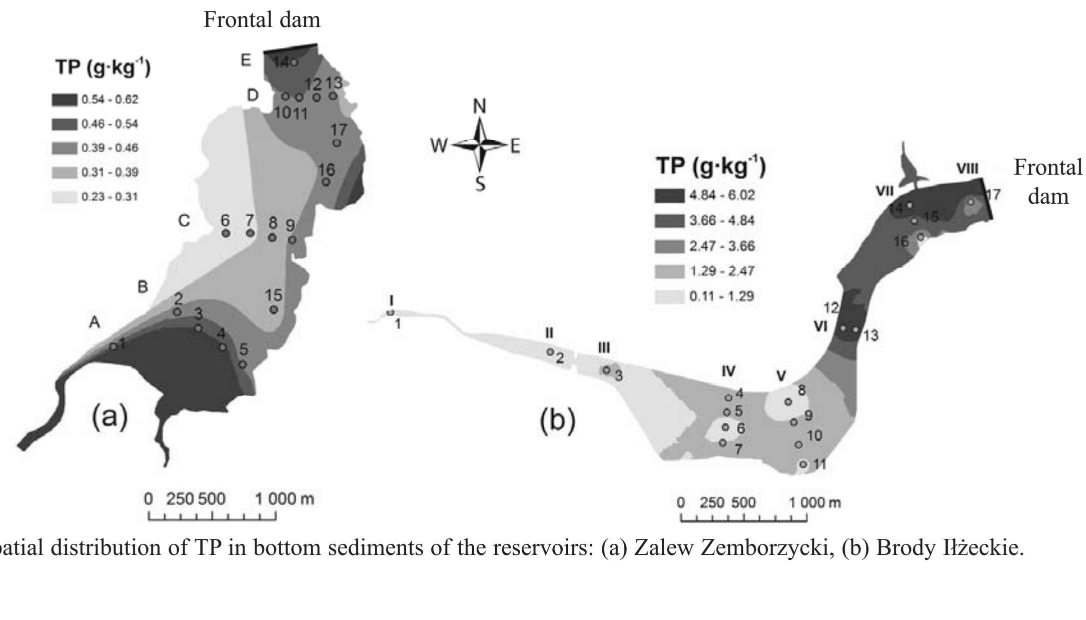

Fig. 4. Spatial distribution of TP in bottom sediments of the reservoirs: (a) Zalew Zemborzycki, (b) Brody Iłżeckie.

some authors, the C:N ratio may also indicate possible origin of the organic matter [23-25]. The C:N ratio is higher (greater than 20) in macrophytic and cellulose-rich terrestrial organic matter and lower (between 4 and 10) in algae and phytoplankton [26].

Phosphorus

In the sediments in the ZZ reservoir, phosphorus concentration varied subject to a sampling location and ranged from 0.23 at point C7 up to 0.62 $g \cdot kg^{-1}$ at B4 (Table 2). It should be noted that TP contents in the sediments in the upper and lower part of this water reservoir were the same. As for TN levels, the mean highest value of TP was recorded in the sediments of B transect (0.50 $g \cdot kg^{-1}$), the lowest in C (0.33 $g \cdot kg^{-1}$), and the medium in D (0.44 $g \cdot kg^{-1}$). Comparison of mean TP contents displayed statistically significant differences only between the sediments in transect B and C (Table 2). The mean total content and the median value did not differ and were 0.43 and 0.42 $g \cdot kg^{-1}$, respectively (Table 3).

In 8 out of 17 samples, the TP concentration was found within the medium interval (0.39-0.46 $g \cdot kg^{-1}$): in 5 samples it was higher and in 4 it was lower (Fig. 3a). It is a left-skewed distribution.

The TP contents in sediments of ZZ were slightly lower than sated 10 years earlier in this reservoir [27]. They were also lower than those presented by Trojanowska and Jezierski [28] concerning the Włocławski and Sulejowski water basins (the means 0.7 and 0.8 $mg \cdot g^{-1}$, respectively), and substantially lower than the mean content for the Turawa reservoir (1.8 $mg \cdot g^{-1}$). The mean TP level in the ZZ reservoir also was 2-fold lower than that in the eutrophic Siemianówka reservoir as the aforementioned authors determined (1.0 $mg \cdot g^{-1}$), and approximately 10 times lower (ca. 6 $mg \cdot g^{-1}$) than the value for this water reservoir studied earlier by Jekaterynczuk-Rudczyk [22].

The TP spatial distribution indicates two zones of the greatest element accumulation in the sediments in the ZZ. It is the upper and the lower – at the frontal dam part of the reservoir. A similar spatial distribution of TP concentration in the Włocławski dam reservoir (Poland) was observed by Trojanowska and Jezierski [28], as well as in the Krishnagiri reservoir (India) by Sudha nad Ambujam [8]. In the other water basins studied by Trojanowska and Jezierski [28] (Turawa, Sulejów, Siemianówka), there were not established clear regularities in the spatial distribution of P contents in sediments. The areas of the greatest TP accumulation in the sediments in ZZ for the most part covered the areas of high TN content in sediments. We found an explicit dependence (R^2=0.4151) between concentrations of these two elements in the sediments of the ZZ reservoir (Fig. 5a). The lowest TP content zone, just like the TN one, was determined in the left-bank ZZ, whereas the medium one was in the middle part.

High TP contents in the sediments of the inflow area result from the high external loads from the Bystrzyca River, while in the part at the frontal dam they are likely to be caused by its sedimentation process along with silt and clay particles [4, 29].

In the Brody Iłżeckie reservoir, concentration of total phosphorus in sediments, like TN content, was found to be more differentiated and overall many times higher than in the ZZ sediments (Table 4). The minimum level determined at point V8 (0.11 $g \cdot kg^{-1}$) was 2-fold lower than the minimum value, while maximum at point VI12 (6.02 $g \cdot kg^{-1}$) was nearly 10 times higher than the maximum in the ZZ. The overall mean of total phosphorus content (2.04 $g \cdot kg^{-1}$) (Table 3) was almost 5 times greater as compared to the mean established for the ZZ reservoir sediments.

The content of TP in sediments of the demarcated transects in the BI reservoir, especially in the first part (inflow and dredged area) of this water reservoir, also was more variable compared to the sediments in the ZZ transects.

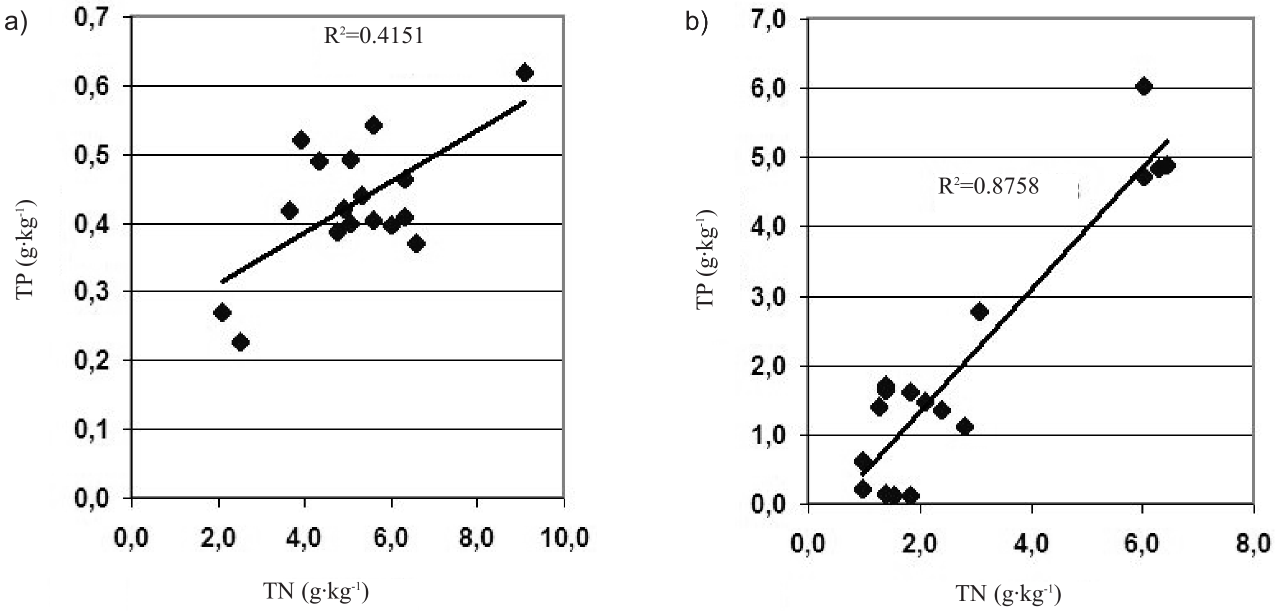

Fig. 5. Relationship between the content of TP and TN in bottom sediments of the reservoirs: (a) Zalew Zemborzycki, (b) Brody Iłżeckie

The mean concentration of TP was maintained at the 0.95 g·kg^{-1} level and it was the highest in the sediments of transect IV, whereas in the other part (not dredged) a total phosphorus level tended to be ca. 4-fold higher as opposed to the first part. The greatest contents were determined in the sediments of transect VI (average 5.45 g·kg^{-1}). The differences in mean phosphorus content in the sediments of transect IV, V, and VI, and between V and VII were statistically significant (Table 4).

The analysis of histogram of TP concentration distribution in the sediments of the BI indicated that most samples (n=12) were found within the two lowest intervals (6 samples each), 3 samples in the highest one, and 2 samples in two other intervals (1 sample each) (Fig. 3b). Evidently, the distribution is right-skewed (As=0.97), like the case of nitrogen (Table 3).

In the second part of the Brody object, the mapped spatial distribution of TP accumulation in sediments shows marked similarity to the nitrogen distribution in the sediments in this water reservoir, whereas in the first part it displays slightly more variability. There was stated a very strong relationship (R^2=0.8758) between the content of TP and TN in the sediments of the BI reservoir (Fig. 5b).

Figs. 6 and 7 present the dependencies between phosphorus concentration and Fe and Al contents in sediments of the investigated water reservoirs. As for BI, a very strong

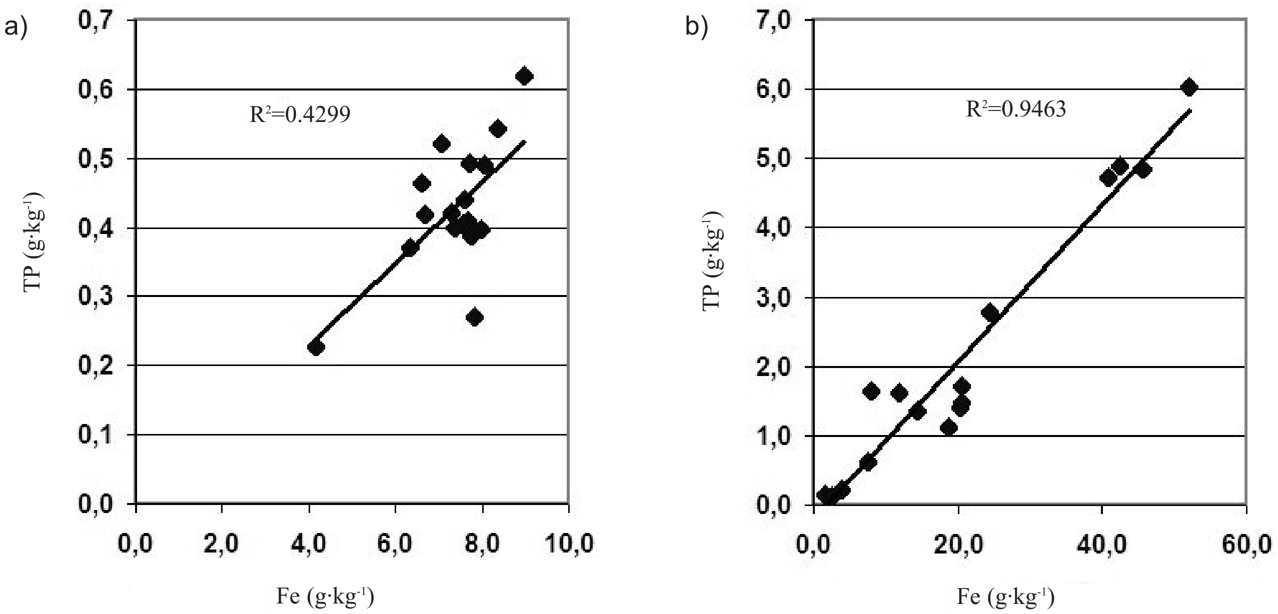

Fig. 6. Relationship between the content of TP and total Fe in bottom sediments of the reservoirs: (a) Zalew Zemborzycki, (b) Brody Iłżeckie.

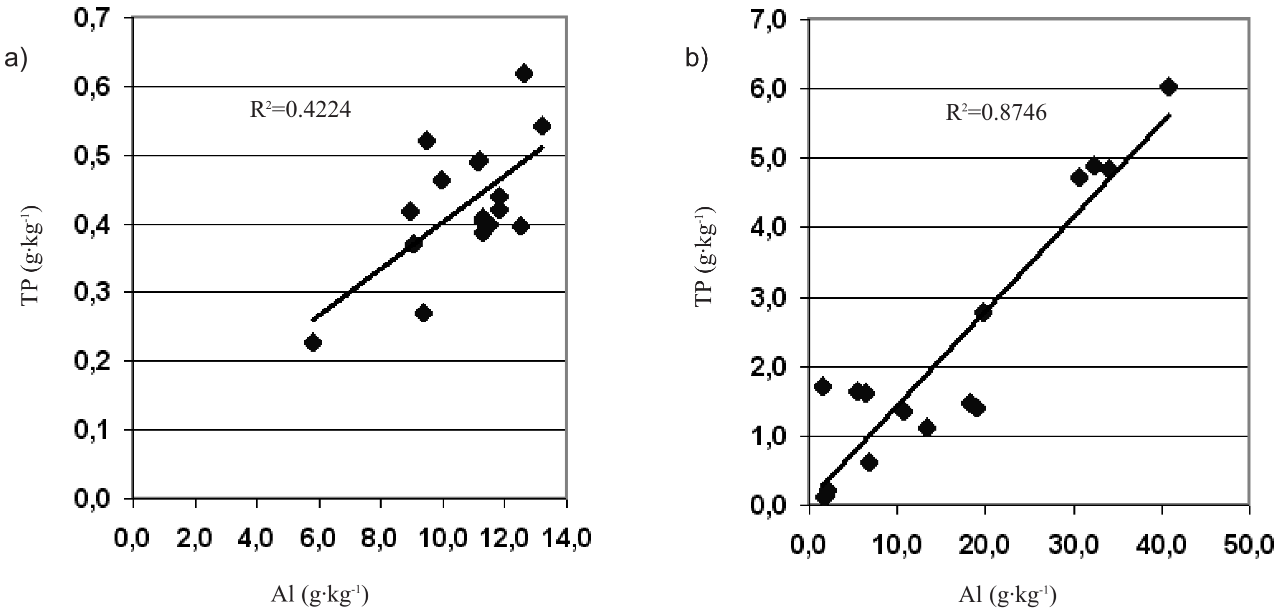

Fig. 7. Relationship between the content of TP and total Al in bottom sediments of the reservoirs: (a) Zalew Zemborzycki, (b) Brody Iłżeckie.

linear relationship was established between a level of P and Fe (R^2=0.9463), and Al (R^2=0.8746). In the ZZ sediments, a dependence between P and Fe and Al was far weaker (R^2=0.4299 and 0.4224, respectively). A high dependence between the contents of TP and Fe and Al concentrations in sediments of lakes and water reservoirs was reported by a number of authors [7, 8, 12, 30]. In sediments rich in Fe and Al, their compounds may be the most important factor affecting sorption of inorganic phosphorus [12, 31].

The dependencies presented above may explicate the observed substantially higher amounts of TP in the Brody reservoir sediments, especially in the undredged part, as compared to the ZZ sediments. They are likely to arise from multiple higher concentrations of Fe in BI (18.60-52.00 $g \cdot kg^{-1}$ in the not dredged part) and Al (13.30-40.70 $g \cdot kg^{-1}$) (Table 4) as compared to ZZ (4.15-8.98 and 5.82-13.20 $g \cdot kg^{-1}$, respectively) (Table 2). In turn, the varying Fe amounts emerge from different geological structures and soil covers of the studied catchments. The catchment of Brody Iłżeckie reservoir in a substantial part is built with rocks rich in iron (ferruginous sandstones), aluminum (claystones and clays, claystones, and variegated clays), or both (ferruginous sandstones with clay and claysands intercalations, claystones with clay ironstones, and claystones with siderite and ironstones) [32, 33]. Thus, soils of this area also are rich in Fe and Al compounds. In the catchment of BI reservoir also water-glacial sands, loesses, and loess-like rocks, valley fills, river valley sands, and silts occur. According to the soil-agricultural map (1:25,000) prepared by the Institute of Soil and Plant Cultivation in Puławy on the basis of the original map [34], in the Brody Iłżeckie direct catchment area, the agriculturally used soils consist primarily of Cambisol and Podzol with Luvisol soils. Luvisols and Cambisols are mainly of medium agricultural value, as they have a slightly acid and acid reaction. These soils are temporarily too dry or too wet [35].

In the catchment of the Zalew Zemborzycki loess-like formations on marls and gaizes, sandy silts and loesses prevail [33, 36]. Soils developed from these rocks dominate in the catchment area. Also, alluvial-periglacial sands with chalky gravels and eolian sands in dunes, sands, fluvial and fluvial-periglacial silts on the terrace above the floodplain occur there. In the agriculturally used soils the main soil types are Luvisols with Podzols and Cambisols [37]. In Lublin region, Luvisols and Cambisols formed from loess, in Ap horizon have on average: ca.10 $g \cdot kg^{-1}$ of C_{org}, pH_{KCl} 5.90, and cation exchange capacity (CEC) 15.0 $cmol(+) \cdot kg^{-1}$. They do not contain $CaCO_3$. Soils developed from loess-like formations have similar properties. Podzols formed from sands in Ap horizon show acid reaction (mean pH_{KCl} 4.8), C_{org} content below 10 $g \cdot kg^{-1}$, and CEC about 11.00 $cmol(+) \cdot kg^{-1}$ on average [38].

The C:P ratio in sediments of the ZZ proved to be very differentiated and ranged between 55.2 at point E14 and 154.1 at point 15. Notably, such values are frequently determined in water reservoirs [23]. As for C:N proportion, the C:P ratios decreased while approaching the dam. This indicates the dominant contribution of external land derived from organic matter, showing generally higher values of C:N [24] in sediments of the upper part of the studied reservoirs. Organic matter from the catchment is subject to decomposition during transport to the lower part and, in turn, participation of planctonic (autochtonous) carbon, of lower C:N and C:P ratio, in sediments increases [22]. The differences between the means for the sediments in the transects, though, were not statistically significant.

The C:P values in sediments in the BI appeared to be many times lower as compared to those established in the sediments of the ZZ and were within the interval from 4.7 at point I1 up to 35.0 in V8 (Table 4). This results from much higher TP content in sediments of BI than ZZ, which can be related to more effective P accumulation in sediments of BI than ZZ in the presence of much higher content of iron and aluminum compounds, as was shown earlier. The statistical analysis did not show significant differences between any of the compared pairs of the C:P ratios.

Conclusions

The sediments of the Brody Iłżeckie Reservoir showed more varied contents of TN and TP as compared to the Zalew Zemborzycki Reservoir sediments that result from the sediment dredging operation performed in most of its area. The concentration of TN and TP in the dredged part was many times lower than in the sediments of the undredged area. This indicates that during the past two decades following sediment dredging these elements' accumulation in the sediments was low.

The undredged part of the BI had TN contents close to those determined in the sediments of the ZZ may prove similar accumulation conditions and changes to the nitrogen cycle in both water reservoirs.

The reservoirs showed different spatial distribution of nitrogen and phosphorus. The ZZ reservoir was found to have clearly longitudinal (perpendicular to the dam) zonation of the TN distribution in sediments. The lowest nitrogen content was found in the sediments in the left-bank part of the reservoir, medium along the middle part, and the highest in the right-bank area. The zone of lowest contents may be related to the parent river current and strong water waving. In turn, the zone of the highest TN concentrations can be ascribed mainly to a lacustrine environment and features peat soils occurring there and not removed before reservoir construction. In ZZ the regularity stated for TN was not observed in the case of TP concentration. In this water basin, the zone of the highest TP accumulation occurred in the sediments of the upper part and at the frontal dam. In the first case it is likely to be caused by the high external loads of P from the Bystrzyca River, while in the second one by its sedimentation process along with silt and clay particles.

Contrary to the regularity in TN distribution in the ZZ sediments, the total nitrogen content in the BI sediments was distributed in transverse zonation (parallel to the dam).

The zone of the lowest TN content occurred in sediments in the upper (riverine) and in the dredged parts of the reservoir. In the remaining undredged lower part of BI the concentration of TN was much higher. The TP distribution in BI was similar to that of TN as well, which also is reflected in the strict linear relationship between these elements.

A dependence between TP content and Fe and Al concentrations in sediments of both reservoirs was found. In the BI, though, it was very strong and explicit while far weaker in the ZZ. This indicates that a high concentration of Fe and Al in sediments of the BI favored TP accumulation there. As a consequence, mean phosphorus concentration in both dredged and undredged parts of this object were substantially higher than in ZZ sediments.

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References

1. KAJAK Z. Hydrobiology and Limnology. Freshwater ecosystems. Wydawnictwo Naukowe PWN, W-wa, **1998** [In Polish].
2. MARTINOVA M.V. Nitrogen and phosphor compounds in bottom sediments: mechanisms of accumulation, transformation and release. Hydrobiologia, **252**, 1, **1993**.
3. RADWAN S. (Ed.). Zemborzycki Reservoir – ecological structure, anthropogenic dangers and protection. Wydawnictwo AR, Lublin, pp. 98, **2006** [In Polish].
4. BALLNTINE D.J., WALLING D.E., COLLINS A.L., LEEKS G.J.L. The phosphorus content of fluvial suspended sediment in three loweland groundwater-dominated catchments. J. Hydrol., **357**, 140, **2008**.
5. IGLESIAS M. L., DEVESA-REY R., PÉREZ-MOREIRA R., DIAZ-FIERROS F., BARRAL M.T. Phosphorus transfer across boundaries: from basin soils to river bed sediments. J. Soil Sediments, **11**, 1125, **2011**.
6. WALLING D.E., RUSSEL M.A., WEBB B.W. Controls on the nutrient content of suspended sediment transported by British rivers. Sci. Total Environ., **266**, 113, **2001**.
7. FONSECA R., CANÁRIO T., MORAIS M., BARRIGA F.J.A.S. Phosphorus sequestration in Fe-rich sediments from two Brazilian tropical reservoirs. Appl. Geochem., **26**, 1607, **2011**.
8. SUDHA V., AMBUJAM N.K. Longitudinal heterogeneity of sediment characteristics during southwest monsoon season in hyper-eutrophic Krishnagiri reservoir, India. Environ. Monit Assess. **184**, 1287, **2012**.
9. TOURNOUD M, PERRIN J., GIMBER F., PICOT B. Spatial evolution of nitrogen and phosphorus loads along a small Mediterranean river: implication of bed sediments. Hydrol. Process. **19**, 3581, **2005**.
10. MARTYNOVA M.V. Impact of the chemical composition of bottom sediments on internal phosphorus load. Water Resources, **35**, (3), 339, **2008**.
11. SØNDERGAARD M., JENSEN J.P., JEPPESEN E. Role of sediment and internal loading of phosphorus in shallow lakes. Hydrobiologia, **506-509**, 135, **2003**.
12. WANG Y., SHEN Z. NIU J., LIU R. Adsorption of phosphorus on sediments from the Three-Gorges Reservoir (China) and the relation with sediment compositions. J. Hazard. Mater., **162**, 92, **2009**.
13. KAJAK Z., KACPRZAK K., POLKOWSKI R. Tubular bottom sampler. Ekol. Pol., Ser. B, **11**, 159, **1965** [In Polish].
14. LIGĘZA S., SMAL H. Differentiation of pH and texture in bottom sediments of Zemborzycki dam reservoir. Acta Agrophysica, **70**, 235, **2002**.
15. LIGĘZA S., SMAL H., PIETRUCZYK D. Nitrogen forms in bottom sediments of the dam reservoir Zalew Zemborzycki. Teka Kom. Kszt. Środ. Przyr. **4**, 132, **2007**.
16. MISZTAL M., KRUPA D., SMAL H. The chemical composition of bottom sediments and phytoplancton in the manmade Lake Zemborzyce near Lublin. Acta Hydrobiol. **25/26**, 123, **1983/1984**.
17. JASIEWICZ C., BARAN A. Characterization of bottom sediments of two small water retention reservoirs. Journal of Elementology, **11**, (3), 307, **2006**.
18. KOSZELNIK P., TOMASZEK J.A., GRUCA-ROKOSZ R. Carbon and nitrogen and their elemental and isotopic ratios in the bottom sediment of the Solina-Myczkowce complex of reservoirs. Oceanological and Hydrobiological Studies, **XXXVII**, 3, 71, **2008**.
19. MISZTAL M., SMAL H. Some chemical, and physical properties submerged soils of the Zemborzyce dam reservoir. Roczn. Glebozn., **31**, (3/4), 253, **1980**.
20. SARA G. Variation of suspended and sedimentary organic matter with depth in shallow coastal waters. Wetlands, **29**, (4), 1234, **2009**.
21. SZAREK-GWIAZDA E., SADOWSKA I. Distribution of grain size and organic matter content in sediments of submontane dam reservoir. Environment Protection Engineering, **36**, (1), 113, **2010**.
22. JEKATERYNCZUK-RUDCZYK E. Characteristics of bottom sediments in Siemianówka reservoir [In:] GÓRNIAK A. (Ed.). Ecosystem of Siemianówka reservoir in years 1990-2004 and its reclamation. Department of Hydrobiology, University in Białystok. pp. 107, **2006** [In Polish].
23. CALVERT S.E. Beware intercepts: interpreting compositional ratios in multi-component sediments and sedimentary rocks. Org. Geochem., **35**, 981, **2004**.
24. GAO J., WANG Y., PAN S., ZHANG R., LI J., BAI F. Spatial distributions of organic carbon and nitrogen and their isotopic compositions in sediments of the Changjiang Estuery and its adjacent sea area. J. Geogr. Sci., **18**, 46, **2008**.
25. HEDGES J.I., OADES J.M. Comparative organic geochemistries of soils and marine sediments. Org. Geochem., **27**, 319, **1997**.
26. MEYERS P. A. Preservation of elemental and isotopic source identification of sedimentary organic matter. Chem. Geol. **114**, 289, **1994**.
27. SMAL H., LIGĘZA S. Total phosphorus content in bottom sediments of the eutrophic dam reservoir Zalew Zemborzycki near Lublin. Teka Kom. Ochr. Kszt. Środ. Przyr, **3**, 169, **2006**.
28. TROJANOWSKA A., JEZIERSKI P. Phosphorus in sediments and pore waters of selected Polish dam reservoirs. Oceanological and Hydrobiological Studies. **40**, (2), 72, **2011**.
29. KERR J.G., BURFORD M.A., VOLLEY J.M., BUNN S.E., UDY J. Examining the link between terrestrial and aquatic phosphorus speciation in a subtropical catchment: The role of selective erosion and transport of fine sediments during storm events. Water Research, **45**, 3331, **2011**.

30. HEIDENREICH M., KLEEBERG A. Phosphorus-binding in iron-rich sediments of shallow Reservoir: spatial characterization based on sonar data. Hydrobiologia, **506-509**, 147, **2003**.
31. CROWE S.A., O'NEILL A.H., KATSHEV S., HEHANUSSA P., HAFFNER G.D., SUNDBY B. MUCCI A., FOWLE D.A. The biogeochemistry of tropical lakes: a case study from Lake Matano, Indonesia. Limnol. Oceanogr. **53**, 319, **2008**.
32. STUDENCKI M. Explanations to the detailed geological map of Poland, 1:50000, Sheet Starachowice (780), Państwowy Instytut Geologiczny, Warszawa, pp. 87, **1993** [In Polish].
33. KONDRACKI J. Regional geography of Poland, Wydawnictwo Naukowe PWN Warszawa, pp. 441, **2000** [In Polish].
34. KOWALSKA W, MACHEJKO M. Original Soil-Agricultural map prepared by Provincial Biureau of Geodesy and Agricultural Areas in Kielce, Kielce, **1977**.
35. The Official Journal of Świętokrzyskie Voivodship No. 187, Item 2544, Resolution No. VI/89/2004 of the Brody Community Council on the adoption of the "Program of environmental protection for the Brody community" and the "Plan of waste management for the Brody community," Kielce, pp. 80, **2004** [In Polish].
36. HARASIMIUK M., HENKIEL A. Explanations to the detailed geological map of Poland, Sheet Lublin (749), 1:50000, Wydawnictwa Geologiczne, Warszawa, pp. 83, **1982** [In Polish].
37. GURBA W., MACIĄG D., WAWRYSZUK H. Original Soil-Agricultural map prepared by Provincial Biureau of Geodesy and Agricultural Areas in Lublin, Lublin, **1986**.
38. TURSKI R., UZIAK S., ZAWADZKI S. The natural environment of the Lublin District. Soils. Lubelskie Towarzystwo Naukowe, Lublin, pp. 107, **1993** [In Polish].