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Impact of morphometric and catchment variables on summer organic carbon richness in deep temperate lakes

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ABSTRACT

Key-words: *organic carbon, lakes, morphometry, catchment*

The study lakes are located in north-eastern Poland, in the same physiographic system. These lakes were formed during the last glacial period. The lakes differed in morphometry, catchment size and environmental conditions. The study included deep, clear water lakes that stratify in summer. The results from multiple linear regression equations indicate that the morphometric and catchment variables may influence mainly the particulate fraction of OC during summer stratification. No significant correlation was found between the examined parameters and the quantity (DOC) or the carbon-specific absorbance ($SUVA_{260}$) of the dissolved fraction. The most important factors which determine POC abundance in lakes are the maximum depth (z_{max}), length and development of shoreline (L, D_L), catchment area to lake volume (C_A/V), and stratification percentage ("% strat."), as well as epilimnion bottom area to epilimnion volume (A_E/V_E). Thus, in the summer the quantity of OC in lakes, especially of POC, will be determined by the in-lake production and consumption processes. Low productivity can be easily maintained in deep, strongly stratified lakes, and therefore should be protected and high water quality should be preserved.

RÉSUMÉ

Influence de la morphométrie et des caractéristiques du bassin versant sur le carbone organique estival dans des lacs tempérés profonds

Mots-clés : *carbone organique, lacs, morphométrie, bassin versant*

Les lacs étudiés sont localisés au Nord-Est de la Pologne, dans la même écorégion. Ces lacs se sont formés durant la dernière période glaciaire. Ils diffèrent par leur morphométrie, la taille du bassin versant, et les conditions environnementales. Cette étude inclut des lacs profonds aux eaux claires stratifiés en été. Les résultats des régressions linéaires multiples montrent que les variables morphométriques et du bassin versant peuvent influencer fortement la fraction particulaire du carbone organique pendant la stratification estivale. Aucune corrélation n'a été trouvée entre les paramètres mesurés et la quantité (DOC) de carbone organique dissous, et l'absorbance spécifique du carbone ($SUVA_{260}$) de la fraction dissoute. Les facteurs les plus importants déterminant l'abondance du carbone organique particulaire (POC) dans les lacs sont la profondeur maximum (z_{max}), la longueur et le développement des berges (L, D_L), la surface du bassin versant rapportée au volume du lac (C_A/V), le pourcentage de stratification (« % strat. »),

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en plus du rapport de la surface benthique dans l'épilimnion au volume de l'épilimnion (A_E/V_E). Ainsi, en été la quantité de carbone organique en lacs, et spécialement celle du POC est déterminée par la production interne et les processus de consommation. La faible productivité peut être facilement conservée dans les lacs profonds très stratifiés qui sont ainsi préservés et gardent une très bonne qualité des eaux.

INTRODUCTION

Organic carbon plays an important role in lake metabolism, determining the activity of plankton and bacteria. Through water color changes it also affects the depth of the euphotic zone and the extent of the littoral zone (Tranvik, 1992; Kankaala *et al.*, 1996; Klug, 2002; Kritzberg *et al.*, 2004; Tulonen, 2004). Moreover, it modifies water pH, controls availability of phosphorus, and binds metal cations, toxic substances and organic contaminants (Williamson *et al.*, 1999; Shaw *et al.*, 2000; Schwartz *et al.*, 2004).

Organic carbon in lakes comes from natural (autochthonous and allochthonous) and anthropogenic sources. Autochthonous organic carbon is mainly a sum of the primary production by peryphiton, macrophytes and phytoplankton *in situ* (Wetzel, 2001; Mei *et al.*, 2005). Its sources are also synthesis and polymerization processes or detritus decomposition by viruses and bacteria (Hygum *et al.*, 1997; Søndergaard *et al.*, 2000). The allochthonous fraction is the organic matter produced outside the lake and is imported via streams, surface runoff, groundwater and precipitation (Aitkenhead and McDowell, 2000; Pace and Cole, 2002; Tranvik and Jansson, 2002; Canham *et al.*, 2004).

In aquatic ecosystems organic carbon is transformed in numerous processes such as remineralization, utilization by consumers, accumulation in bottom sediments or export through surface outflows (Moran *et al.*, 2000; Pullin et al., 2004). The rate of these processes can depend on lake morphometric and catchment parameters. The literature clearly shows that there is a strong relationship between the DOC concentration and the catchment surface area, shoreline length (Gasith and Hasler, 1976; Hanson *et al.*, 2007), forest cover, wetland area and water residence time (Curtis, 1998; Gergel *et al.*, 1999; Xenopoulos *et al.*, 2003). Among the most frequently examined morphometric parameters in lakes are: lake area, volume, and mean and maximum depth (Rasmussen *et al.*, 1989; Houle *et al.*, 1995; Xenopoulos *et al.*, 2003; Håkanson, 2005). However, there is still very little information concerning these parameters that determine the natural predisposition of a lake for low or high productivity.

In this study new morphometric indexes describing the lake's potential for organic carbon richness were developed. Ultimately, the aim of this work is to examine the relationships between the lake morphometry, catchment properties and the amount of the summer organic carbon in stratifying lakes. On the one hand, the study helped to identify the factors responsible for organic matter abundance in lakes, stimulating their eventual degradation, but on the other hand, protecting lakes from organic matter decomposition and promoting the system's stability by eutrophication rate reduction. All these issues are important in water quality management and planning of the protection and restoration activities in lakes.

MATERIAL AND METHODS

The study lakes are located in north-eastern Poland, in the same physiographic system. These lakes were formed during the last glacial period. Under such conditions, differences in the aquatic conditions in the studied lakes may be looked upon as the outcome of a set of factors; *i.e.*; individual characteristics of the reservoirs and geographic environment and land development in the catchment. This comparative study included lakes varying in morphometry, water residence time, catchment size and environmental conditions. The selected

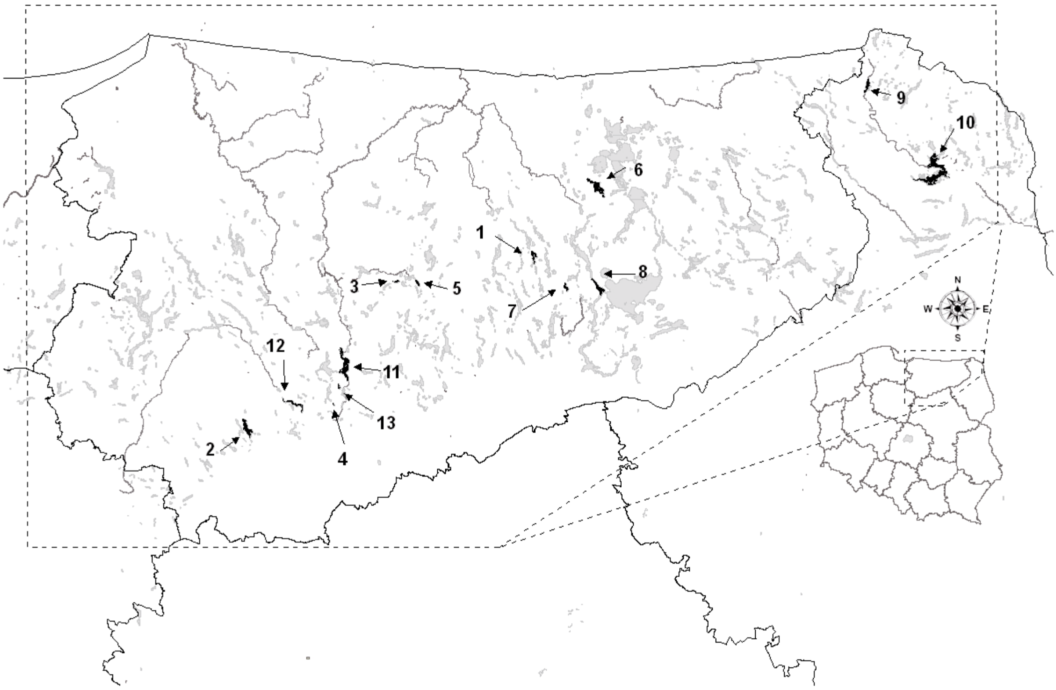

Figure 1
Localization of the surveyed lakes.

lakes characterized by biotic and abiotic diversity reflected different intensity of degradation processes. The study included 13 deep, clear water (not dystrophic) lakes that are stratified in summer (Figure 1).

Water samples from the lakes were taken at the deepest point, in the second half of the summer stratification (August) from the surface water layer, according to the lake monitoring system in Poland. Unfiltered water samples were analyzed for total organic carbon (TOC) content, and water filtered through a 0.45 μm Millipore filter was analyzed for DOC. Particulate organic carbon (POC) was calculated as the difference between TOC and DOC. Analyses were done by high-temperature combustion (HTC) using a Schimadzu TOC 5000 analyzer.

The carbon-specific absorbance was marked as $SUVA_{260}$ (Abs 260/DOC). A UV-1601PC spectrophotometer was used to measure the UV absorbance (at 260 nm) in the water samples.

In parallel to organic carbon (OC) determinations, the physical and chemical water parameters were measured and oxygen and temperature profiles prepared. Temperature and dissolved oxygen (DO) were measured in the water column at one-meter intervals using a YSI 58 oxygen probe. Water transparency was determined with a Secchi disk. Total phosphorus (TP) and total nitrogen (TN) were determined according to standard methods (1999). Colorimetric analyses were performed on a Shimadzu UV 1601 spectrophotometer. Chlorophyll a was analyzed spectrophotometrically with correction for pheopigments (PN-86/C-05560/02). pH was measured with an Orion pH meter of the Ross type.

Morphometric and catchment indices were calculated from bathymetric charts (Institute of Inland Fishery in Olsztyn) and data obtained from the Voivodeship Inspectorate of Environment Protection in Olsztyn. The A_E/V_E index – was calculated from the difference in the surface of zero isobath and isobath which the epilimnion reached. The range of the epilimnion was determined from the thermal stratification in the peak of summer stagnation – the temperature gradient at 1 meter depth must be lower than 1 °C.

Table I
Morphometric and catchment parameters of the surveyed lakes.

Number of lake	Name of lake	A km^2	V Thousand **m^3**	D_L	L m	z_{max} m	z_{ave} m	"% strat."	A_E/V_E	C_A/V	% F_C	C_A km^2
1	Czos	279.1	31 012.0	2.50	1496	42.6	11.1	45.5	0.05	3.44	23.1	103.80
2	Dąbrowa W.	615.1	50 610.9	2.10	18 125	34.7	8.2	25.2	0.11	1.87	25.9	88.70
3	Kiermas	69.2	2150.0	1.72	5050	9.3	3.1	1.0	0.30	194.41	20.0	417.30
4	Maróz	332.5	39 566.2	2.80	18 000	41.0	11.9	37.0	0.05	5.55	79.0	216.10
5	Tumiańskie	120.6	8110.9	1.43	5550	17.0	6.7	17.1	0.07	61.87	70.0	500.60
6	Dejguny	765.3	92 617.4	2.42	23 770	45.0	12.0	44.8	0.11	4.49	29.0	408.00
7	Majcz W.	163.5	9862.8	1.80	8200	16.4	6.0	6.5	0.11	2.22	83.0	20.30
8	Mikołajskie	497.9	55 739.7	1.90	15 100	25.9	11.2	28.9	0.02	32.34	33.0	1797.80
9	Hańcza	311.4	120 364.1	1.88	11 750	108.5	38.7	77.0	0.03	0.37	16.0	41.36
10	Wigry	2118.3	336 726.7	4.36	72 225	73.0	15.4	74.0	0.06	1.41	58.0	453.70
11	Łańskie	1042.3	168 047.3	2.99	34 250	53.0	16.0	51.0	0.05	2.60	91.0	426.98
12	Mielno	362.8	43 947.3	3.26	22 125	39.9	12.1	37.0	0.04	3.10	40.0	132.50
13	Święte	59.4	4291.5	1.60	4275	40.8	6.8	18.1	0.10	70.72	98.0	302.91

Legend: A - lake area, km^2; V – lake volume, thousand m^3; D_L – development of shoreline; L – shoreline length, m; z_{max} – maximum depth, m; z_{ave} – mean depth = V/A, m; ("% strat.") $V_H/V \times 100\%$; A_E/V_E – epilimnion bottom area to epilimnion volume index; C_A/V – catchment area to lake volume index; % F_C – % forest cover; C – catchment area, km^2

The results of the study were processed statistically using *Statistica 9* software and *Canoco for Windows* 4.5. The overall characteristics of the data set include:

- basic statistics; *i.e.*, minimum value, maximum value, standard deviation (SD);
- dendrograms of hierarchical agglomeration prepared in order to identify similarities between the lakes with regard to the parameters which describe OC quantity (the following correlation coefficients: measure of length – Manhattan distance of the Euclidean group and Ward's Method were applied);
- RDA, performed in order to indicate the relationships between morphometric and catchment parameters, and carbon parameters. The proper ordinance technique was selected on the grounds of the data structure using Detrended Correspondence Analysis (DTA) (Hill and Gauch, 1980). As a result of the analysis, it was found that the data were linear or represented part of the Gaussian spectrum, because the gradient length representing the first axis was 0.992SD < 2SD. The value obtained (0.992SD) allows application of unconstrained ordination PCA or constrained ordination RDA (Cajo *et al.*, 2002). RDA was selected as a canonical form of the analysis of main components (Jongman *et al.*, 1995). For analyses *Canoco for Windows* 4.5 was used (Cajo and ter Braak, 1997–2003; Cajo *et al.*, 2002).
- Multiple regression analysis, applied in order to find the relationships between the parameters describing quantity and quality of OM, and the morphometric and catchment parameters of the examined lakes.

RESULTS

The lakes vary widely in their sizes and shapes (Table I). Their surface areas range from 59.4 ha (Lake Święte) to 2 118.3 ha (Lake Wigry).The maximum and mean depths also vary significantly (9.3 and 3.1 m for lake Kiermas; 108.5 and 38.7 m for Lake Hańcza, respectively). Lake volumes ranged from 4 291.5 thousand m^3 (lake Święte) to 336 726 thousand m^3 (Lake Wigry). The shoreline development index (D_L) was highest for lake Wigry (4.36).
The factors that determine primary production are the stratification percentage, showing the share of hypolimnion in the total lake volume, and the index between the "active" bottom area

Table II
Summer values of individual parameters in surface water layers of the of the surveyed lakes.

Number of lake	Name of lake	Temp. °C	Oxygen $mg \cdot L^{-1}$	SD m	TP $mg \cdot L^{-1}$	TN $mg \cdot L^{-1}$	Chl a $\mu g \cdot L^{-1}$	TOC $mg \cdot L^{-1}$	DOC $mg \cdot L^{-1}$	POC $mg \cdot L^{-1}$	SUVA $cm^{-1} \cdot (g\ C)^{-1} \cdot L^{-1}$
1	Czos	21.8	8.6	4.0	0.06	0.70	5.3	6.0	5.2	0.8	16.5
2	Dąbrowa W.	20.3	9.7	3.0	0.08	0.91	10.7	6.4	5.6	0.8	14.9
3	Kiermas	19.0	9.7	0.8	0.34	2.41	197.0	18.2	10.8	7.4	15.5
4	Maróz	20.4	10.3	2.3	0.03	0.57	9.3	5.1	3.6	1.6	17.1
5	Tumiańskie	20.4	12.2	1.0	0.08	1.21	45.1	20.2	8.8	11.4	22.0
6	Dejguny	19.2	11.9	1.4	0.07	0.39	6.4	9.9	8.0	1.9	22.2
7	Majcz W.	18.2	7.8	3.5	0.05	1.39	14.0	8.6	6.9	1.6	24.6
8	Mikołajskie	18.2	8.1	1.5	0.06	1.01	31.6	10.8	8.6	2.3	24.6
9	Hańcza	22.7	9.4	4.0	0.05	0.40	1.6	5.9	5.0	0.9	28.2
10	Wigry	23.4	9.0	2.1	0.07	0.70	8.3	5.6	3.6	2.0	37.7
11	Łańskie	21.2	8.4	3.0	0.05	0.75	1.9	5.3	4.2	1.0	33.2
12	Mielno	20.5	8.3	2.6	0.05	1.33	3.1	6.8	4.3	2.5	34.4
13	Święte	20.2	9.4	1.6	0.06	0.99	5.1	6.5	4.6	2.0	32.5

(the bottom area underneath the epilimnion) and epilimnion volume (A_E/V_E), showing nutrients loading from the bottom deposits collected under the epilimnion and hence, the littoral's influence on the lake. The values of these two factors varied significantly, from 1.0 to 77.0 and from 0.02 to 0.30, respectively.

The relationships between the lakes and their catchments are highly variable (Table I). C_A/V ranges from 0.37 (Lake Hańcza) to 194.4 (Lake Kiermas). The share of forests (% F_C) in the catchments is from 16% (Lake Hańcza) to 98% (Lake Święte).

The examined lakes varied with respect to the intensity of degradation processes. The lowest concentrations of chlorophyll a (1.6 $\mu g \cdot L^{-1}$) and nutrients (TP – 0.05 $mg \cdot L^{-1}$; TN – 0.40 $mg \cdot L^{-1}$) were recorded in Lake Hańcza, where at the same time the visibility was high (4 m). The most polluted was Lake Kiermas. The chlorophyll a concentration in this lake was as high as 197.0 $\mu g \cdot L^{-1}$. The concentrations of total phosphorus and total nitrogen were 0.34 $mg \cdot L^{-1}$ and 2.41 $mg \cdot L^{-1}$, respectively, whereas visibility was less than 1 m (0.8 m) (Table II).

The examined lakes vary significantly with respect to the content of organic carbon forms in the water, including TOC, DOC and POC. The hierarchical agglomeration method helped distinguish two main groups of the lakes (Figure 2).

Group I was further divided into 2 sub-groups: A and B, notably varying in the range of concentrations. In group IA TOC concentrations varied from 5.1 to 6.8 mg $C \cdot L^{-1}$, 25% of that being POC. In group IB the TOC concentrations were higher: 8.6 to 10.8 mg $C \cdot L^{-1}$, 21% being POC. The highest TOC (18.2 to 20.2 mg $C \cdot L^{-1}$) and the corresponding highest share of POC (49%) were observed in group II (Table II).

The relationships between the parameters characterizing quantity (TOC, DOC, POC) and quality ($SUVA_{260}$) of OC, and the morphometric and catchment parameters are shown by RDA (Figure 3). The first two axes of RDA explain 62.9% and 84.5% of total variability, with the gradient lengths 1 = 0.629 and 2 = 0.216. The highest correlations were observed on the first axis: TOC (0.939), V (0.627), L (0.616), D_L (0.603), z_{max} (0.602), "% strat." (0.587), A (0.545), A_E/V_E (–0.542) and C_A/V (–0.516). Strong correlation with the second axis was found only for DOC (0.900). RDA revealed two general directions of differentiation of the surveyed lakes: deep ($z_{max} > 40$ m) and poor in TOC (< 7.0 mg $C \cdot L^{-1}$), and shallower ($z_{max} < 40$ m) and rich in TOC (> 7.0 mg $C \cdot L^{-1}$).

DISCUSSION

The results of multiple linear regression equations (significance level $\alpha = 0.05$) indicate that the morphometric and catchment variables may influence mainly the particulate fraction of

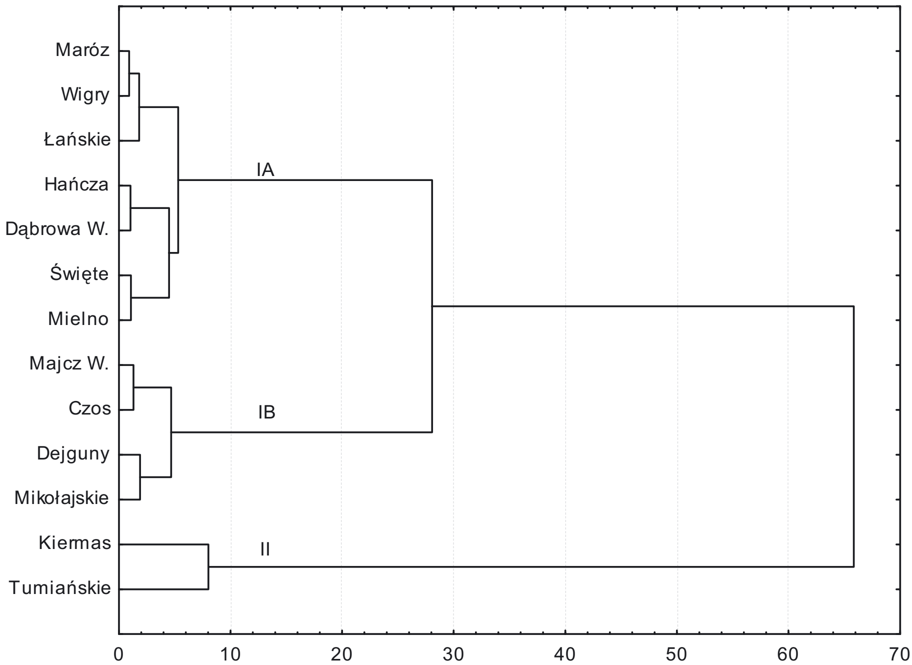

Figure 2
Dendrogram of the summer TOC, DOC and POC concentrations in surface water layers of the surveyed lakes.

OC during summer stratification. No significant correlation was found between the examined parameters and the quantity (DOC) and the carbon-specific absorbance ($SUVA_{260}$) of the dissolved fraction.

$$TOC = 44.28 - 2.7z_{max} - 1.8D_L \quad r^2 = 0.99 \quad p = 0.032$$

$$POC = 26.65 + 2.83\text{ “\% strat.” } + 2.78L + 1.41C_A/V - 3.0z_{max} - 1.3A_E/V_E - 1.0C_A - -2.0D_L$$
$$r^2 = 0.99 \quad p = 0.018$$

Lake Hańcza, with a depth of 108.5 m, has a high stratification percentage (“% strat.” 77) and has low productivity. The DO content of this lake in the second half of the summer stagnation (August) in the surface water layer was 9.4 mg $O_2 \cdot L^{-1}$, while near the bottom it was 7.5 mg $O_2 \cdot L^{-1}$, and therefore was characterized by the nearly orthograde oxygen curve typical of low-productivity waters. Meanwhile, Lake Kiermas has a maximum depth of 9.3 m and a low stratification percentage (“% strat.” 1.0). The trophogenic and tropholitic processes occur there in isolated layers and are characterized by less intensive matter circulation and lower productivity, as shown by the oxygen curves for both lakes. The situation observed in Lake Kiermas showed that the DO concentration in the surface water equaled 9.7 mg $O_2 \cdot L^{-1}$, decreasing rapidly from 7 m depth toward the bottom (9.5 m) where oxygen was deficient. The oxygen curve in Kiermas was of the clinograde type which characterizes heavily eutrophic lakes (Figure 4).

The main source of OC during summer was primary production, as confirmed by the statistically significant correlation between TOC and TP, chlorophyll and transparency (0.64; 0.73; –0.69; $p < 0.05$; $n = 13$, respectively). The natural predisposition of lakes towards high productivity (and the related POC abundance) was also determined by the A_E/V_E ratio. The larger the area of “active” bottom, the higher the possibility for nutrient exchange across the water–bottom interface. The study by Dunalska (2009) of natural and anthropopressured lakes, conducted in early spring turnover through late fall turnover, revealed a positive correlation between POC and A_E/V_E. The high A_E/V_E value indicates an exchange of nutrients between water and bottom deposits. The main mechanism of ammonium nitrogen transfer from the bottom deposits is the diffusion process, whose rate depends on oxygen conditions

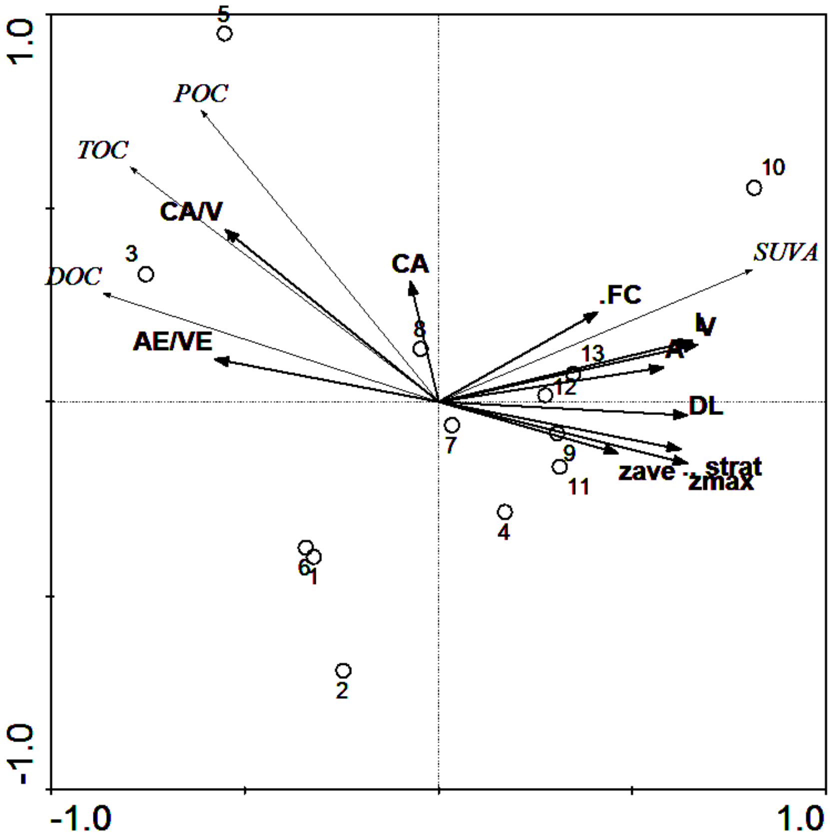

Figure 3
*RDA diagram of carbon content parameters (TOC, DOC, POC, $SUVA_{260}$), and lake morphometric and catchment variables (A, V, DL, L, z_{max}, z_{ave}, "% strat.", A_E/V_E, CA/V, %*Fc*, C_A. Names of lakes: 1-Czos, 2-Dąbrowa W., 3-Kiermas, 4-Maróz, 5-Tumiańskie, 6-Dejguny, 7-Majcz W., 8-Mikołajskie, 9-Hańcza, 10-Wigry, 11-Łańskie, 12-Mielno, 13-Święte).*

(Forsberg, 1989; Höhener and Gächter, 1994). As for phosphorus, there is a significant reduction of the redox potential (Nürnberg, 1994). The observed (statistically significant) correlation between phosphates ($r = -0.60$; $n = 11$; $p < 0.05$) and ammonium nitrogen ($r = -0.70$; $n = 11$; $p < 0.05$), and the oxygen content near the bottom confirms the above rule (Dunalska *et al.*, 2006). Nürnberg (1985) claims that phosphorus released in the initial phase of the fall turnover is transferred to the trophogenic layer where it remains as easily available phosphate. In conclusion, internal loading can be the main factor responsible for lake eutrophication. On the other hand, a high A_E/V_E ratio may indicate the conditions to accelerate nutrients to the bottom sediments of the littoral zone. In the present study this dependence was analyzed only for the summer period, and an inversely proportional, statistically significant correlation between POC and A_E/V_E was found. In summer, although primary production in lakes is high, the constantly high pH favors phosphorus precipitation from the water in the form of apatite, which in turn limits further production. This kind of organic matter transfer is indicated by the statistically significant correlation between DOC, calcium and hydrocarbons ($r = 0.33$; $r = 0.54$; $n = 354$; $p < 0.05$, respectively) (Dunalska, 2009). Such a process can inhibit much of the allochthonous and autochthonous OM in the bottom but simultaneously reduce the epilimnion phosphorus, easily available to phytoplankton. Such a natural protective mechanism is typical of clear mesotrophic lakes, river-lake ecotones, or lakes intensely grown with submerged plants (Avnimelech, 1983; Hillbricht-Ilkowska, 1993; Zdanowski 2003). Conservation of high water quality is therefore a durable inhibition of phosphorus in the bottom deposits. Positive or negative correlation between POC and A_E/V_E, depending on the studied period, indicates

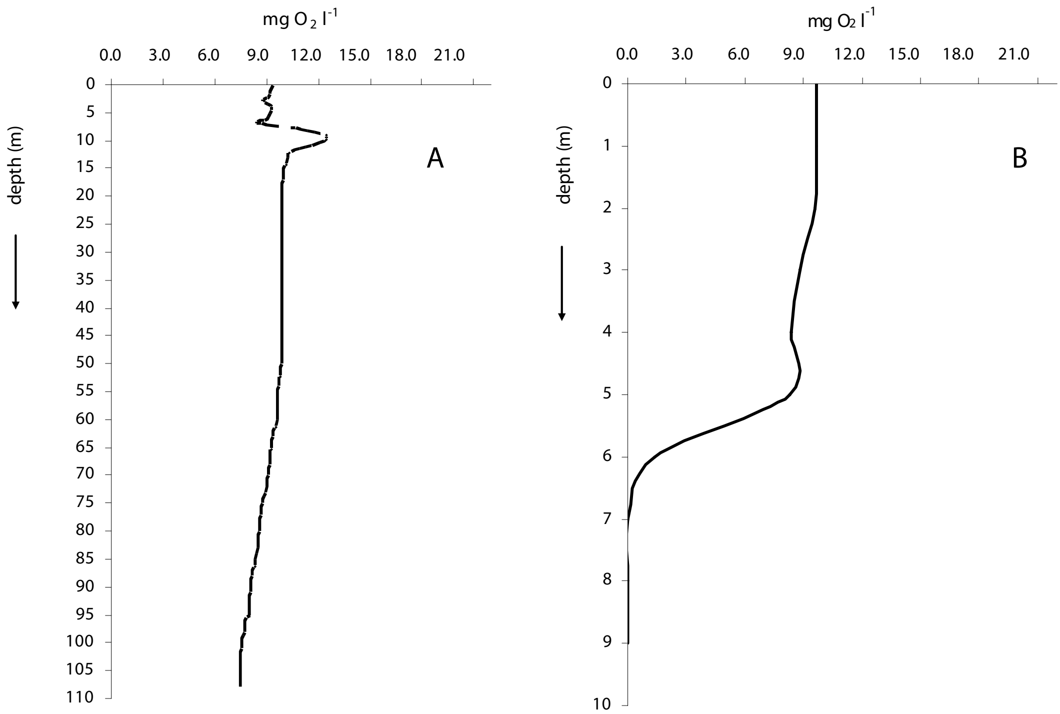

Figure 4
Summer oxygen profiles in Hańcza Lake (A) and Kiermas Lake (B).

that bottom deposits of the littoral zone may both limit and intensify primary production in the epilimnion.

Previous studies of OM input into lakes have revealed that the most important factors regulating import of allochthonous DOC are the areas of forest cover and the areas of wetlands in the catchment (Gergel *et al.*, 1999; Xenopoulos *et al.*, 2003; Brönmark and Hansson, 2005). Wetlands are the important source of the matter sustaining food chains in lakes (Hillbricht-Ilkowska, 1993), mainly due to land and marsh plant decomposition, as well as the detritus deposit found in wetlands. Wetzel (2001) pointed out that wetlands were very active with respect to metabolism and far more productive than the water body. Water flowing through wetlands can wash out high quantities of mobile DOC (Kortelain, 1993; del Giorgio and Peters, 1994; Dillon and Molot, 1997; Hanson *et al.*, 2004). In the studied lakes, no significant correlation was found between the summer DOC concentration and the catchment parameters. However, there was a negative correlation between POC, C_A and L. In the summer, low levels of allochthonous carbon enter the lakes via runoff; therefore, the quantity of OC in lakes, especially of POC, will be determined by the in-lake production and consumption processes.

CONCLUSIONS

The parameters discussed in this paper describe the conditions for lake ecosystem functioning associated with the individual lake morphometry and the potential catchment impact. It can be the starting point for the assessment of OC abundance and of the lake productivity. The assessment includes the common criteria, available without detailed knowledge of the lake and catchment conditions.

The quantity of OC (particularly of the POC) in similar lakes at the peak of the summer stagnation depends more on the individual morphometric parameters than on the catchment properties. Low productivity can be easily maintained in deep, strongly stratified lakes, and therefore should be protected and high water quality should also be preserved.

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