THE EFFECT OF DISSOLVED ORGANIC CARBON ON PELAGIAL AND NEAR-SEDIMENT WATER TRAITS IN LAKES

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ABSTRACT

The effect of dissolved organic carbon (DOC) on the environmental conditions of macrophytes has been studied in 35 lakes divided into soft- and hardwater: oligohumic (<4.0 mg C dm^{-3}), α-mesohumic (4.0-8.0 mg C dm^{-3}), β-mesohumic (8.1-16.0 mg C dm^{-3}) and polihumic (>16.0 mg C dm^{-3}).

The optimum environmental conditions for macrophytes have been found in oligohumic lakes, characterised by low water colour and its good transparency. In soft- and hardwater lakes increasing concentration of DOC is accompanied with an increase in the colour (r=0.95), while the visibility decreases. With increasing DOC in the near-sediment layer the pH values decrease while the concentration of nitrogen increases and the concentration of phosphorus slightly increases. In hardwater lakes with increasing DOC concentration, the redox potential, conductivity, total hardness and calcium concentration in the near-sediment water decrease, whereas the content of CO_2 remains at a very low level.

KEY WORDS: soft- and hardwater lakes, environmental conditions, pelagial, near-sediment water, DOC.

INTRODUCTION

Many lakes are connected into systems of drainage ditches and channels filled with waters rich in humus substances from the drained peat-bogs. Through them large amounts of dissolved organic carbon (DOC) enter the lakes (of different genesis, trophy and direction of development) and permanently change the environmental conditions in them. This influx of DOC leads, consequently, to significant changes in the lake ecosystem (Górniak 1996), including changes in the flora and vegetation (Bociąg 2000; Szmeja 2000).

With increasing content of allochtonous carbon compounds, especially humic acids, in the lakes, the pH values of water and bottom sediments decrease, the rate of organic matter decomposition decreases, the redox potential of the sediment increases and anaerobiosis becomes more enhanced (Lampert and Sommer 1996). These changes disturb the circulation of biogenic elements (Grahn 1985), causing the plants exchange according to their demand on inorganic carbon (DIC) including the species CO_2 and HCO_3^- (Sand-Jensen 1989), and the structure and species composition of phytocenoses change (Szmeja 1992). The acidic bottom sediments restrict the appearance of many aquatic plants, leading to changes in their population structure (Roelofs 1983; Grahn 1985; Arts 1987; Szmeja 1994a, b, c) and initiate the exchange of the basiphilous and neutrophilous species by acidophilous ones, mainly bryophytes (Szmeja 2000; Bociąg 2000).

The last two decades witnessed great progress in investigation of phenomena and physico-chemical processes involving organic carbon from humic substances (Stevenson 1982; Långvik et al. 1994; Morris and Hargreaves 1997; Hessen and Tranvik 1998; Keskitalok and Eloranta 1999; Artinger et al. 2000; Lehtonen et al. 2000). This recent accumulation of information makes a promising background to study the effect of DOC coming from the drainage of peat-bogs on the environmental conditions in the lakes. The excess of DOC in water and bottom sediments of the lakes leads to a decrease in the primary production, depauperisation of the diversity of flora and disappearance of the zonal arrangement of the vegetation (Bociąg 2000; Bociąg and Szmeja 2001; Szmeja 2000). However, it is still unknown which particular cause effected by DOC increase is the main reason for the plant withdrawal from humic lakes.

The following hypotheses have been accepted in the study:

1. The hard- and softwater lakes are equally susceptible to the effect of DOC.
2. The scale of transformations in the water environment is a function of DOC concentration.
3. The susceptibility of the environmental conditions to changes induced by increased concentration of DOC depends on the features of the limnic environment.

The subjects of the study were physical and chemical changes of the pelagial and near-sediment water in the lakes supplied with rich in organic compounds waters coming from fen and peat-bog.

MATERIAL AND METHODS

Sampling

The study was performed in the years 1997-2003, in soft- and hardwater lakes in NW Poland. On the basis of the DOC concentration in water the following division of the lakes was assumed:

1) oligohumic (<4.0 mg C_{DOC} dm^{-3}),
2) α-mesohumic (4.0-8,0 mg C_{DOC} dm^{-3}),
3) β-mesohumic (8,1-16,0 mg C_{DOC} dm^{-3}),
4) polihumic (>16,0 mg C_{DOC} dm^{-3}).

Analyses were performed for 35 lakes, including 15 oligohumic, 7 α-mesohumic, 7 β-mesohumic and 6 polihumic. In the oligohumic lakes DOC is of autochtonous origin, occurs in minimum concentrations and does not determine the specific character of the environmental conditions, while in the meso- and polihumic lakes these conditions are determined by allochtonous DOC.

The water samples were collected of pelagial at 0.5 m below the water surface and at 0.5 m above the bottom in the deepest site of the lake. The samples of near-sediment water were collected immediately above the sediment and from the levels at the depths of 1, 2, 3m etc., from the coat to the deepest limit of plants appearance in the lake. In each zone three subsamples of the near-sediment water of 1 dm^3 each were collected and then combined into one sample from a given zone. The environmental conditions were evaluated on the basis of 262 samples of near-sediment water, 35 samples of surface water and 35 ones of water from the deepest sites of the lakes.

Methods of water analysis

Evaluation of the environmental conditions in pelagial was performed on the basis of the following parameters: distribution of oxygen and temperature in the profile by an oxygen meter OXI 96 with EOT 196 electrode, visibility distance by the Secchi disk, pH value, conductivity, colour, total hardness, the contents of calcium, Kjeldahl nitrogen (N_{Kjel}), total phosphorus (TP) and dissolved organic carbon (DOC). The near-sediment water samples were characterised by pH value, conductivity, concentrations of calcium, $N_{Kjel.}$, TP and CO_2. The conduction was measured by a conductometer LF-95/SET with a four-electrode TetraCon 96 WTW system, pH and the redox potential were determined by a pH-meter SET-1, with a combined EPH-11 type electrode and a Mettier Toledo Pt 4805-57/120 electrode. Free CO_2 was determined by titration of 100 ml of water with carbonate free 0.05 N NaOH solution against phenolophtaleine as an indicator. The content of TP was found by a molybdate colorimetric method with ascorbic acid as a reductor (Hermanowicz et al. 1999). Total Kjeldahl nitrogen was determined after mineralisation by the method of nesslerization (Hermanowicz et al. 1999). The content of DOC was determined by spectrophotometric methods (Moore 1985, 1987; Collier 1987; Górniak 1995). The absorbency of the filtered off samples was measured on an UV-VIS spectrophotometer (Shimadzu UV-1202) at λ=330 nm. The concentration of DOC was read out from the calibration curve determined as the dependence of absorbency (A_{330}) on DOC concentration measured by a Multi C Analyser. The colour of water samples was assessed by comparison to a scale of chromium-cobalt standards according to Hermanowicz et al. (1999).

Statistical analysis methods

The arithmetic mean (x), standard deviation (s.d.), (min.-max.) range and median (Me) were calculated (Hays 1988). Statistical inference was carried out at a 5% error risk. The statistical significance of differences was tested by a single-factor variance analysis ANOVA with a Tukey test (Milliken and Johnson 1984; Hays 1988). The co-dependence in the pairs of the water parameters was determined for the lakes from oligo- to polihumic by the correlation analysis (Oktaba 1980; Łomnicki 1999).

RESULTS

Environmental conditions in softwater lakes

In oligohumic lakes the bulk water is colourless or weakly coloured (0-17 mg Pt dm^{-3}; Me=4.5) and transparent (visibility distance 5.6±2.1 m; Me=5.0; Table 1). The latter feature follows from a low concentration of dissolved organic carbon (2.9±1.2 mg C_{DOC} dm^{-3}; Me=2.5). The water is characterised by low total hardness (7.4±4.9 mg CaO dm^{-3}; Me=5.7) and low concentration of calcium (3.9±2.9 mg Ca dm^{-3}; Me=2.9; Table 1).

The near-sediment water has a pH from 4.0 to 7.5 (Me=5.3) and a very low electrolytic conductivity (48.1±

TABLE 1. Physical and chemical properties of near-sediment water and pelagial (bold) in softwater lakes.

Lake types:	Oligohumic			α-mesohumic			β-mesohumic			Polihumic		
Traits:	min-max	x±sd.	Me	min-max	x±sd.	Me	min-max	x±sd.	Me	min-max	x±sd.	Me
pH	4.0-7.5	5.5±1.0	5.3	4.2-7.6	5.5±1.2	5.1	4.3-7.0	5.6±0.9	5.4	3.9-6.6	4.8±0.8	4.6
Conductivity [µS cm^{-1}]	26-82	48.1±15.6	45.5	36.1-81	53.8±15.9	48.5	40.0-96.7	59.6±16.1	55.0	47.7-72.4	63.3±13.8	57.0
Eh [mV]	169-365	281±50	279	17-382	296±54	300	-210-383	219±146	220	31-466	232±133	290
TP [mg P dm^{-3}]	0.05-0.23	0.1±0.04	0.11	0.07-0.9	0.1±0.2	0.1	0.07-0.2	0.1±0.04	0.12	0.09-0.22	0.1±0.03	0.13
$N_{Kjel.}$ [mg N dm^{-3}]	0.5-3.0	1.3±0.5	1.1	0.9-3.1	2.1±0.7	2.2	1.4-6.0	3.4±1.2	3.5	1.3-7.2	4.2±1.6	4.5
CO_2 [mg dm^{-3}]	1.1-16.9	4.6±3.2	3.7	3.7-9.2	7.0±2.3	8.1	2.2-32.5	11.4±12.5	5.0	4.4	4.4	4.4
Colour [mg Pt dm^{-3}]	**0-17**	**5±5**	**4.5**	**13-43**	**25±13**	**22**	**44-150**	**83±43**	**68**	**150-600**	**348±189**	**320**
Visibility [m]	**4-11**	**5.6±2.1**	**5**	**1.5-3.5**	**2.5±0.9**	**2.6**	**1-2**	**1.4±0.4**	**1.4**	**0.5-1**	**0.6±0.2**	**0.5**
DOC [mg C dm^{-3}]	**1.8-5.6**	**2.9±1.2**	**2.5**	**4.7-5.5**	**4.9±0.4**	**4.8**	**8.0-14.3**	**9.6±2.4**	**8.8**	**18.8-44.0**	**32.4±10.5**	**33.3**
Ca [mg dm^{-3}]	**1.4-11.2**	**3.9±2.9**	**2.9**	**1.5-8.7**	**4.6±3.2**	**4.3**	**1.2-8.5**	**4.5±2.5**	**4.1**	**2.3-11.3**	**6.7±4.3**	**6.5**
Hardness [mg CaO dm^{-3}]	**2.7-17.9**	**7.4±4.9**	**5.7**	**3.4-15.5**	**8.5±5.3**	**7.5**	**2.5-13.2**	**7.7±3.5**	**7.5**	**3.8-15.9**	**10.3±5.1**	**10.7**

±15.6 µS cm^{-1}; Me=45.5). The contents of TP (0.1±0.04 mg P dm^{-3}; Me=0.11) and N$_{Kjel.}$ (1.3±0.5 mg N dm^{-3}; Me=1.1) are low. In this water the oxidation reactions prevail (Eh 281±50 mV; Me=279) it shows a high concentration of oxygen (6.8-10.2 mg O$_2$ dm^{-3}) but low of CO$_2$ (4.6±3.2 mg dm^{-3}; Me=3.7; Table 1).

In α-mesohumic lakes the bulk water has more colour (25±13 mg Pt dm^{-3}; Me=22) and is less transparent (visibility distance 2.5±0.9 m; Me=2.6). The differences are statistically significant for the colour p<0.001, for the visibility p=0.01. The yellow colour of the water and its considerable turbidity are a consequence of almost twice higher concentration of DOC (4.9±0.4 mg C$_{DOC}$ dm^{-3}; Me=4.8; p=0.006). The total hardness (8.5±5.3 mg CaO dm^{-3}; Me=7.5) and calcium concentration (4.6±3.2 mg Ca dm^{-3}; Me=4.3; Table 1) are still low.

The near-sediment water in the littoral has a similar pH as in oligohumic lakes (4.2-7.6; Me=5.1) and its electrolytic conductivity is only slightly higher (53.8±15.9 µS cm^{-1}; Me=48.5). The content of TP is similar (0.1±0.2 mg dm^{-3}; Me=0.1), while the content of N$_{Kjel.}$ is almost twice higher (2.1±0.7 mg N dm^{-3}; Me=2.2). In the near-sediment water the oxidation reactions dominate (Eh 296±54 mV; Me=300), the oxygen concentration is high (4.3-9.6 mg O$_2$ dm^{-3}), and that of CO$_2$ low (7.0±2.3 mg dm^{-3}; Me=8.1; Table 1).

The differences between the water parameters in oligo- and α-mesohumic lakes in N$_{Kjel.}$ concentration (p<0.001), DOC (p=0.001), visibility distance (p=0.01) and colour (p<0.001) are statistically significant.

In β-mesohumic lakes the bulk water has a more intense colour than that of α-mesohumic lakes (83±43 mg Pt dm^{-3}; Me=68) and is less transparent (visibility distance 1.4±0.4 m; Me=1.4). The brown colour of water is a consequence of a twice higher concentration of DOC (9.6±2.4 mg C dm^{-3}; Me=8.8). The total hardness (7.7±3.5 mg CaO dm^{-3}; Me=7.5) and calcium concentration (4.5±2.5 mg Ca dm^{-3}; Me=4.1; Table 1) assume similar values.

The near-sediment water has a pH 4.3-7.0 (Me=5.4), and the range of variation of this parameter is slightly smaller than in α-mesohumic lakes. Its conductivity (59.6±16.1 µS cm^{-1}; Me=55.0) and the content of TP (0.1±0.04 mg dm^{-3}; Me=0.12) are similar, while the content of N$_{Kjel.}$ is higher (3.4±1.2 mg dm^{-3}; Me=3.5; p<0.001). In the above-sediment water the oxidation reactions dominate (Eh 219±146 mV; Me=220), however, because of sometimes met anaerobic conditions (0.1-3.2 mg O$_2$ dm^{-3}), the redox potential takes also negative values (Eh -210-383 mV), which result in a significant increase in CO$_2$ concentration (11.4±12.5 mg dm^{-3}; Me=5.0; Table 1) in the above-sediment water.

Statistically significant differences between the conditions in β-mesohumic and α-mesohumic lakes occur in the content of N$_{Kjel.}$ (p<0.001), DOC (p=0.005), colour, visibility (p<0.03) and redox potential (p<0.02).

In polihumic lakes the bulk water is usually brown (348±189 mg Pt dm^{-3}; Me=320) and turbid (visibility distance 0.6±0.2 m; Me=0.5). This very intense colour is a consequence of a much higher concentration of DOC (32.4±10.5 mg C dm^{-3}; Me=33.3). The total hardness is higher than in β-mesohumic lakes (10.3±5.1 mg CaO dm^{-3}; Me=10.7), but statistically significant is the difference in the calcium concentration – much higher in polihumic lakes (p<0.001).

The near-sediment water has a pH ranging from highly acidic to almost neutral (3.9-6.6; Me=4.6). The range of pH variability is similar as in β-mesohumic lakes. The conductivity (63.3±13.8 µS cm^{-1}; Me=57) and the concentration of N$_{Kjel.}$ (p=0.02) are slightly higher. Because the maximum depths of polihumic lakes is relatively small the near-sediment water are well oxidised and the dominant reactions in it are those of oxidation (Eh 232±133 mV; Me=290), while the concentration of CO$_2$ is low (Table 1).

The differences between β-mesohumic and polihumic lakes are statistically significant in the concentration of calcium, N$_{Kjel.}$, DOC, CO$_2$, visibility and colour.

Environmental conditions in hardwater lakes

Pelagial of oligohumic lakes has a light colour (6-8 mg Pt dm^{-3}; Me=7), is transparent (visibility distance 6.2±1.6 m; Me=5.5) and has a low concentration of DOC (4.6±1.3 mg C$_{DOC}$ dm^{-3}; Me=4.4). It is characterised by a significant total hardness (51.6±19.3 mg CaO dm^{-3}; Me=58.3), and a high concentration of calcium (31.4±9.6 mg Ca dm^{-3}; Me=35.5).

The near-sediment water in littoral has pH varying from neutral to basic (7.1-8.4; Me=8.0), is characterised by high electrolytic conductivity (179±46.1 µS cm^{-1}; Me=191), low concentration of TP (0.1±0.05 mg dm^{-3}; Me=0.1) and N$_{Kjel.}$ (1.0±0.3 mg dm^{-3}; Me=1.0). Because of high concentration of oxygen in water (7.4-9.4 mg O$_2$ dm^{-3}), the oxidation reactions dominate (Eh 214±73 mV; Table 2).

Pelagial of α-mesohumic lakes has a stronger colour (36±15 mg Pt dm^{-3}; Me=37; p=0.03) than that of oligohumic ones and hence less transparent (visibility distance 1.8±0.8 m). The darker colour and its grater turbidity are

TABLE 2. Physical and chemical properties of near-sediment water and pelagial (bold) in hardwater lakes.

Lake types:	Oligohumic			α-mesohumic			β-mesohumic			Polihumic		
Traits:	min-max	x±sd.	Me	min-max	x±sd.	Me	min-max	x±sd.	Me	min-max	x±sd.	Me
pH	7.1-8.4	7.9±0.4	8.0	6.6-7.9	7.5±0.4	7.6	6.2-7.2	6.7±0.5	6.6	6.1-6.6	6.3±0.2	6.2
Conductivity [µS cm^{-1}]	121-262	179±46.1	191	156-403	250±102	202	157.7-174	164±7.2	162	59.9-112	77.0±18.2	74.4
Eh [mV]	125-331	214±73	189	13-352	187±112	149	25-76	59±23	68	44-242	129±101	52
TP [mg P dm^{-3}]	0.06-0.23	0.1±0.05	0.1	0.09-0.3	0.2±0.06	0.11	0.16-0.2	0.2±0.01	0.18	0.08-0.14	0.1±0.03	0.1
N$_{Kjel.}$ [mg N dm^{-3}]	0.3-1.7	1.0±0.3	1.0	0.6-2.8	1.4±0.7	1.4	1.4-1.9	1.7±0.2	1.8	3.0-4.5	3.8±0.6	3.6
CO$_2$ [mg dm^{-3}]	1.8-6.6	3.4±1.5	2.8	2.2-7.3	4.5±2.0	4.4	–	–	–	4.4	4.4	4.4
Colour [mg Pt dm^{-3}]	**6-8**	**7±1**	**7**	**20-50**	**36±15**	**37**	**96**	**96±0**	**96**	**240-360**	**300±85**	**300**
Visibility [m]	**5-8**	**6.2±1.6**	**5.5**	**1.0-2.5**	**1.8±0.8**	**2.0**	**1.5**	**1.5±0**	**1.5**	**0.5**	**0.5±0**	**0.5**
DOC [mg C dm^{-3}]	**3.4-6.0**	**4.6±1.3**	**4.4**	**5.6-7.2**	**6.2±0.9**	**5.8**	**15.7**	**15.7±0**	**15.7**	**23.5-46.1**	**34.8±16.0**	**34.8**
Ca [mg dm^{-3}]	**19.3-41.6**	**31.4±9.6**	**35.5**	**25.9-71**	**43.6±20.1**	**34.5**	**47.6**	**47.6±0**	**47.6**	**8.4-15.5**	**12.4±3.8**	**12.0**
Hardness [mg CaO dm^{-3}]	**29.8-66.7**	**51.6±19.3**	**58.3**	**39-105**	**66.9±34.2**	**56.4**	**59.4**	**59.4±0**	**59.4**	**17.6-24.3**	**21.0±4.7**	**21.0**

a consequence of the DOC concentration higher by almost 50% (6.2±0.9 mg dm^{-3}; Me=5.8). Its total hardness (66.9±34.2 mg CaO dm^{-3}; Me=56.4), the concentration of calcium (43.6±20.1 mg Ca dm^{-3}; Me=34.5; p=0.007) is very high (Table 2).

The near-sediment water has a pH lower than in oligohumic lakes (p=0.004), varying from slightly acidic to weakly basic (6.6-7.9; Me=7.6), higher electrolytic conductivity (250±102 µS cm^{-1}; Me=202; p=0.002), and Kjeldahl nitrogen concentration (p=0.006), while a similar TP concentration. It has slightly higher concentration of CO_2 (4.5±2.0 mg dm^{-3}; Me=4.4), a lower redox potential, however, the oxidation reactions are still dominant (Eh 187±112 mV; Me=149).

Pelagial of β-mesohumic lakes contains much more DOC than that of á-mesohumic ones (15.7 mg C_{DOC} dm^{-3}; p=0.01), so its colour is stronger (96 mg Pt dm^{-3}), tending to dark-brown and its visibility distance shorter (1.5 m). The concentration of calcium is the same.

The near-sediment water has a low pH (p=0.004) and much lower conductivity (164±7.2 µS cm^{-1}; Me=162). Because of the relatively high content of oxygen the oxidation processes dominate, but the redox potential is much lower (p=0.04).

Pelagial of polihumic lakes is dark brown (300±85 mg Pt dm^{-3}; Me=300), and the visibility distance is only 0.5 m. This strong colour is a consequence of the DOC concentration over twice greater than in β-mesohumic lakes (34.8±16.0 mg C dm^{-3}; Me=34.8; p<0.001). Its total hardness is lower than that in β-mesohumic lakes (21.0±4.7 mg CaO dm^{-3}; Me=21.0; Table 2).

The near-sediment water in littoral is characterised by slightly acidic pH (6.1-6.6; Me=6.2), lower conductivity (77.0±18.2 µS cm^{-1}; Me=74.4), lower concentrations of calcium (12.4±3.8 mg Ca dm^{-3}; Me=12.0; p=0.009) and TP (0.1±0.03 mg dm^{-3}; Me=0.1), while higher that of $N_{Kjel.}$ (3.8±0.6 mg dm^{-3}; Me=3.6; p<0.001). It is relatively well oxidised so the oxidation reactions are dominant (Eh 129±101 mV; Me=52), and the content of CO_2 is low (Table 2).

With increasing DOC concentration in lakes' pelagial its colour increases and the visibility distance decreases. The total hardness of softwater lakes does not change, whereas, the total hardness of hardwater lakes slightly increases in mesohumic lakes but in polihumic it decreases almost to the value typical of softwater lakes. With increasing DOC concentration in near-sediment water in soft- and hardwater lakes, the value of pH decreases, and the decrease is more pronounced in the hardwater ones. Increasing DOC concentration has been also found to be accompanied by increasing concentrations of nitrogen and phosphorus (slight), the changes are greater in softwater lakes. In hardwater lakes the redox potential of the near-sediment water, its conductivity, calcium concentration decrease with growing content of DOC, while the content of CO_2 remains at a very low level. The environmental conditions optimum for macrophytes have been found in oligohumic lakes characterised by low water colour and its good transparency. The main reason for the vegetation withdrawal from humic lakes is most probably restricted light accessibility caused by high colour and turbidity of their water rich in allochtonous DOC.

Correlation of environmental features of the lakes

Analysis of correlation of selected pairs of water characterising parameters has shown that only a few of them are strongly correlated (r>0.5). Namely, strong correlations have been found between pH and conductivity, redox potential, total hardness and calcium concentration (Fig. 1). Moreover, total hardness shows strong positive correlations with conductivity and calcium concentration and negative correlations with visibility distance and redox potential. A significant correlation has been found between the calcium concentration and conductivity.

With increasing DOC concentration the colour of the water gets stronger (r=0.95; p<0.001), and its visibility distance decreases (r=-0.6) (the decrease is abrupt even at a low concentration of DOC) as $y=5.3\ x^{-0.7}$. Above the DOC concentration of 14 mg C_{DOC} dm^{-3} the visibility distance does not decrease any further and remains equal 0.5 m (Fig. 2). A strong positive correlation has been found between the concentrations of $N_{Kjel.}$ and DOC (r=0.7), although the scatter of values in this correlation is significant, which most probably follows from different trophy and primary production of the lakes studied.

The correlations established for softwater lakes are stronger than those in hardwater ones, in the former strong correlations have been found between the DOC concentration and the water colour, visibility distance and $N_{Kjel.}$ concentration, while in the latter – only between DOC concentration and the water colour (r=0.7).

DISCUSSION

The environmental conditions in the lakes have been determined by the presence of allochtonous DOC coming from humic substances. In Pomerania there are many lakes with dark brown water (Banaś 1999, 2002; Banaś and Gos 2000; Gos et al. 1998), similarly as in many lakes of the northern hemisphere (Oliver et al. 1983; Laaksonen and Malin 1984; Rogalla 1986; Forsberg 1992; Jonsson A. and Jonsson M. 1997). The water colour is a result of accumulation of autochthonous and allochtonous humic substances. In the lakes the dominant are allochtonous carbon compounds (Tipping et al. 1988; Yan et al. 1991), originating from the catchment area (Schindler et al. 1992; Kaplan and Newbold 1993). Hence, there is a strong correlation between the DOC concentration and the water colour (Fig. 2). Low DOC concentration is characteristic of almost colourless water of oligohumic lakes, while high – of dark brown colour of polihumic lakes (Tables 1, 2). In some lakes the DOC concentration may reach up to 600 mg Pt dm^{-3}. With increasing DOC content the visibility distance strongly decreases. This decrease is rapid already at low DOC concentrations, and then above that of 14 mg C_{DOC} dm^{-3}, it remains constant and equals 0.5 m (Fig. 2). High concentration of DOC increases the water turbidity and restricts the accessibility of light in the lake, consequently the photic zone gets significantly narrower and in deep littoral zones the light conditions deteriorate. This is one of the reasons for the withdrawal of deep-water plants including stoneworts, bryophytes and elodeids from the lakes (Rørslett and Johansen 1995; Middelboe and Markager 1997; Bociąg 2000; Szmeja 2000, 2003; Banaś 2001).

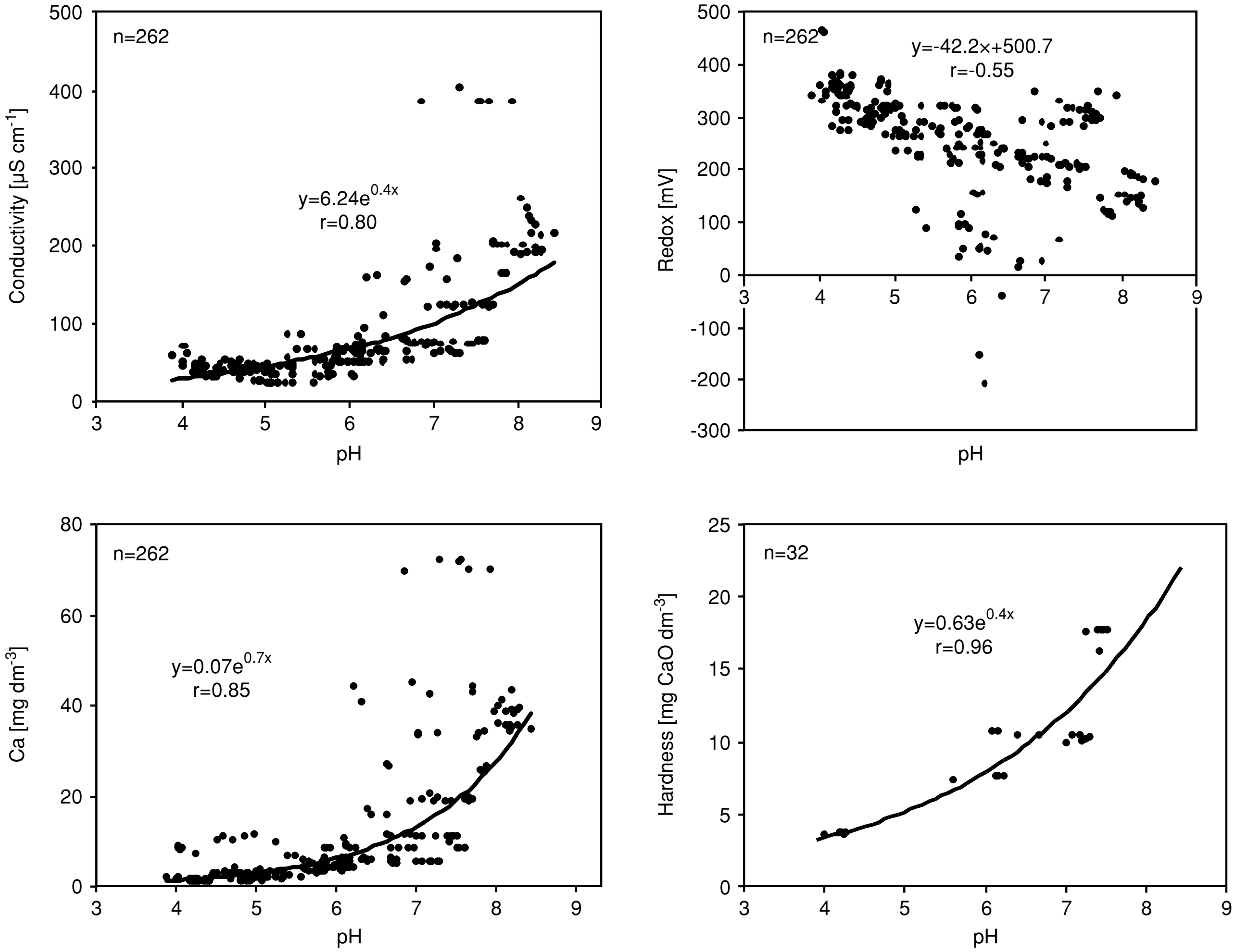

Fig. 1. Correlations between the lake water conductivity, redox potential, calcium concentration, hardness and the water pH.

The correlations established for softwater lakes are stronger than those in hardwater ones, in the former strong correlations have been found between the DOC concentration and the water colour, visibility distance and $N_{Kjel.}$ concentration, while in the latter – only between DOC concentration and the water colour. This is probably a consequence of a higher trophy of hard- than softwater lakes, and hence the higher concentrations of autochtonic DOC in the former.

The softwater lakes are usually small, without outflows, and localised in the surrounding of pine and mixed forests. This group includes e.g. lobelia lakes with vegetation composed mainly of isoetids and bryophytes (Szmeja 1996). Their bulk water is usually slightly acidic because of a low concentration of calcium (Szmeja et al. 1997). The environmental conditions in such water reservoirs have been mainly determined by external effects, including enrichment of

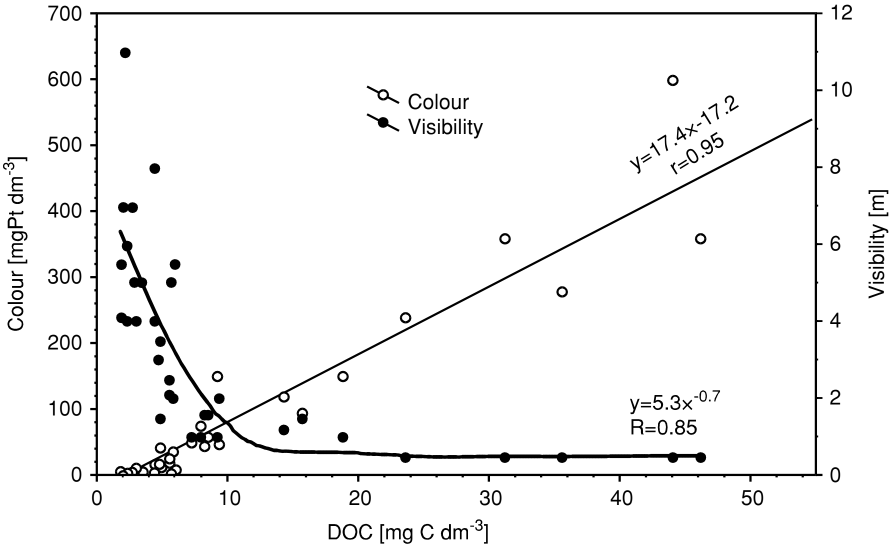

Fig. 2. The lake water colour or visibility distance as a function of DOC concentration.

lakes with allochthonous organic matter. Of course the processes taking place in the lakes like e.g. succession – in particular the exchange of vascular plants by bryophytes, are also of importance (Szmeja 1994a; Gos et al. 1998).

The hardwater lakes are usually large, deep, with outflows and inflows, localised in the land with more fertile soil than the softwater ones. The water vegetation in such lakes is often dominated by Charales and elodeids (Bociąg 2000), the bulk water pH is neutral or basic with high contents of calcium and hydrocarbons, which means it is less susceptible to pH changes. A significant DOC concentration in hardwater lakes does not have to lead to a decrease in pH of the surface water, but leads to acidification of the near-sediment water. Despite a considerable supply of DOC, the hardwater lakes are still able to preserve their primary character (hardwater) and high pH, on condition that the allochtonous hydrogen ions are neutralised by the carbonate complex. In the lakes without a constant supply of carbonates, the stock of mineral bases gets exhausted and the reservoir is more susceptible to changes. The pH value can decrease even to ≈5.5 and undergo strong seasonal fluctuations. At present many of the Pomeranian lakes are at this stage of transformation of the environmental conditions (Banaś and Gos 1998, 2000; Szmeja et al. 1997a, 1998). On continuous and considerable supply of DOC, the water pH can drop to highly acidic and stabilise at pH ≈4.5. Some lakes, especially those localised in the forests undergo further acidification, their pH values decrease below pH 4.5 that is typical of highmoor water (Banaś and Gos 2004). It should be emphasised that even a small drop of pH value leads to elimination of stoneworts being the main group of plants in hardwater lakes (Bociąg 2000; Szmeja 2000).

The stability of organic carbon compounds is different in hard- and softwater lakes. In the former they are quicker bound and quicker released, which follows from the presence of a larger number of components, especially mineral, which can bound them (Johnson et al. 1994; Ward et al. 1994). Thanks to these processes, organic carbon species enter into sediments and their concentration in the bulk water decreases. Nevertheless, on continuous supply of DOC, its concentration is still high. As a consequence, not only the physical and chemical properties of the lake water change, but also their bottom sediment layer gets richer in organic matter including humic and fulvic acids, nitrogen and phosphorus compounds (Banaś 2004).

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