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CARBON DYNAMICS IN A HEATED WATER SYSTEM (WIELKOPOLSKO-KUJAWSKIE LAKE DISTRICT, POLAND)

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ABSTRACT. The aim of the study was to examine the spatial and seasonal variability, and the dynamics of organic carbon compared to the hydrochemical parameters, and subsequently, to determine the productivity of the waters included in the cooling system of two power plants. The results of the study revealed obvious differences in the content of dissolved (DOC) and particulate (POC) fractions of organic carbon in the whole system of heated waters. The dominant form was DOC (mean 6.7 mg C l^{-1}) comprising 67% of TOC. Intensive primary production occurred as early as spring, which was shown by the high amount of easily available organic matter (high DOC concentrations and simultaneously low $SUVA_{260}$ values), and by the statistically significant relationship between POC and organic phosphorus, and BOD_5 and seston. In spring, the process was additionally favored by elevated water temperature and the enzymatic activity of the bacterioplankton, shown by the significant relationship between total bacterial count (TBC), DOC, and $SUVA_{260}$. In summer, the dynamics of organic carbon were lower compared to those in spring; the cooling system waters were abundant in organic matter unavailable to bacteria, as shown by the high value of $SUVA_{260}$. The amount and quality of organic matter in the cooling system waters were also determined by abiotic factors. The phenomenon of simultaneous precipitation of phosphate and iron on the humic complexes was observed in the near-bottom waters of Lake Licheńskie.

Key words: ORGANIC CARBON, HEATED WATERS, LAKE, EUTROPHICATION

INTRODUCTION

Lakes that fill land hollows collect material of terrestrial origin in the form of suspended solids and dissolved mineral salts. This phenomenon is accompanied by changes in reservoir morphometry and transformations in the physical and chemical conditions of the aquatic environment. The gradual shallowing of lake basins that is caused by the collection of deposits and its becoming overgrown with vegetation, result in their slow levelling and eventual transformation into bogs and peat lands. The

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natural process of lake ageing is accelerated by rapid eutrophication. The reasons for this should be sought in ongoing urban and industrial development, the development of tourism, and changes in land cultivation and animal husbandry techniques.

Thermal pollution constitutes a specific kind of anthropogenic impact. The effects of thermal pollution are very complex and result directly from increased temperature and water flow in reservoirs. An increase in the heat stock in lake waters prolongs the growing season, and eliminates ice cover, but, most of all, it accelerates the element turnover rate in systems. In effect, primary production increases.

In investigations of surface waters, organic carbon is used as an indicator to assess the degree of pollution and the trophic state in water bodies (Thurman 1985, Górniak 1996). In inland waters, DOC comprises the largest portion of organic carbon. DOC breaks up into bioavailable dissolved organic carbon (BDOC) and resistant dissolved organic carbon (RDOC) (Pempkowiak 1988, Tranvik 1992). The quantity of DOC changes seasonally and spatially. The lowest values of DOC occur in the Arctic and Alpine zones (up to 2 mg C l^{-1}), whereas the highest values are noted in wetlands and bogs (up to 25 mg C l^{-1}). In stagnant waters, DOC content is dependent mainly on their trophic state. DOC concentration in clean, humus-deficient inland waters varies between 2 and 25 mg C l^{-1}, while in humic reservoirs, DOC concentration is ten times higher, on the average (Lampert and Sommer 1996).

A growing trend has been observed regarding DOC content in surface waters. This refers to both Europe and North America. Lakes in northwestern Ontario are exceptions, as a study by Schindler et al. (1997) conducted from 1970 through 1990 revealed the opposite trend. Many authors share the opinion that such phenomena are a consequence of climatic changes and human activity (Carpenter et al. 1997, Wetzel 2001, Bade et al. 2007).The aim of the present study was to examine the spatial and seasonal variability and the dynamics of organic carbon, compared to hydrochemical parameters, and, subsequently, to determine the productivity of the waters included in the cooling system of two power plants.

METHODS

STUDY AREA

The Konin lakes (a conventional name referring to the complex of heated lakes in the area around the city of Konin, namely: Ślesińskie, Mikorzyńskie, Pątnowskie, Licheńskie, Gosławskie) are situated in the Wielkopolsko-Kujawskie Lakeland, 20 km north of Konin, in the drainage basin of Lake Gopło (Kondracki 1998). The Konin lake system is connected with the Warta River by the 32-km long Warta-Gopło sailing channel (Socha and Zdanowski 2001). The drainage basin surface area is 418 km^2; it is mostly urbanized and modified by the power industry and quarries.

This study focused on Lake Licheńskie, the initial cooling reservoir, and the water intake and effluent water channels of the Konin (KPP) and Pątnów power plants (PPP). The surface area of Lake Licheńskie is 147.6 ha, the maximum depth is 12.6 m, and the mean depth is 4.5 m. It is a ribbon-like reservoir with a well-developed shoreline. The effluent water channel runs along the southeast shore, and it is separated from the lake by an earth dike. The direct drainage basin has 20 km^2 of surface area. Lake Licheńskie is fed with cooling waters by a free inlet, which means that they are mixed with the lake waters in the surface layers, and that horizontal temperature gradients develop as a consequence. Lake Licheńskie is a mictic lake with a tendency for polymixis. The northern and southern parts receive cooler waters and, therefore, in cold winters the lake can develop thin ice cover. Lake Licheńskie comprises an element of the cooling system of the power plant throughout the year and receives the main flow of the discharged cooling waters. Thermal conditions in the reservoir vary from those in natural, non-heated lakes. The initial cooling reservoir of the KPP has a surface area of 75 ha and a maximum depth of 3 m. It lies east of the KPP and comprises a hydrotechnical element that receives waters of 7-10 $m^3 s^{-1}$ directly from the KPP. The total length of the water intake and discharge channels is 26 km. The channels make up a system that interconnects the individual reservoirs, and they comprise a closed system in which water discharge is controlled by pumping stations (Socha and Zdanowski 2001).

SAMPLING

Water sampling was done once a month: in spring (March until May), in summer (from June to September), and in fall (October and November), in 2002 and 2003. In Lake Licheńskie, water was sampled from the surface and bottom layers. In the intake and discharge channels, and in the initial cooling basin, water samples were taken only from the surface layer (Fig. 1).

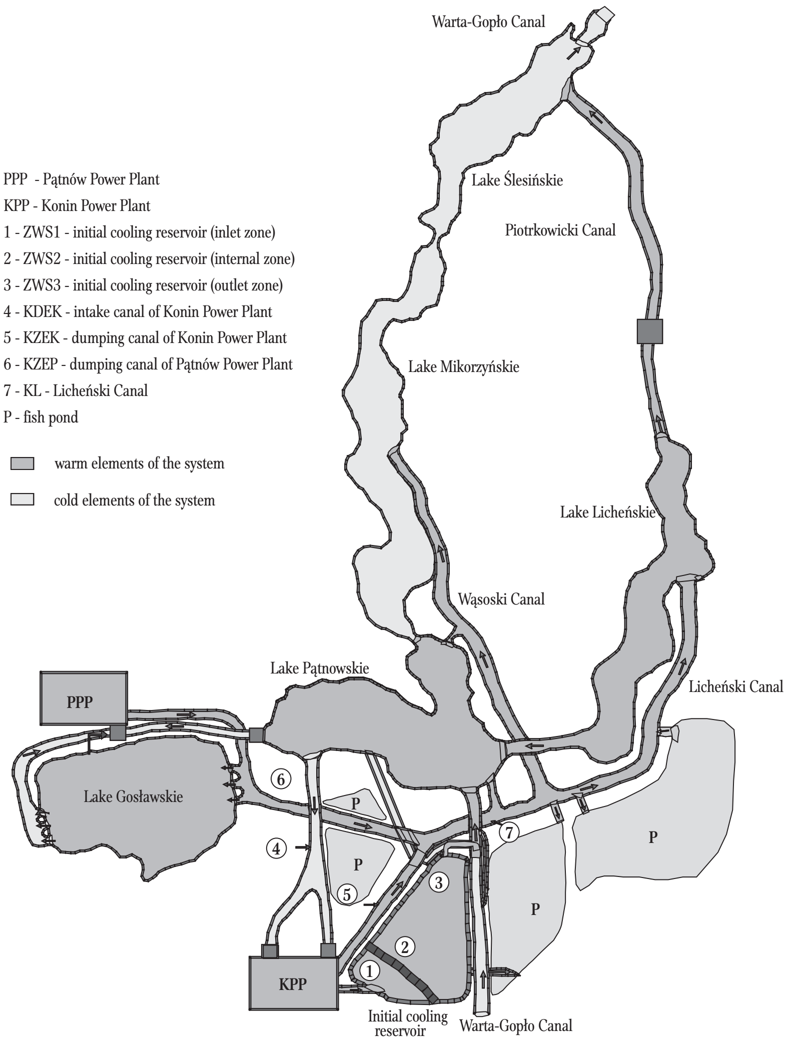

Fig. 1. Water sampling stations in the Konin lakes system in 2002-2003.

TOC content was marked in unfiltered samples, and DOC after filtration on a 0.45 μm Millipore filter. POC was calculated as the difference between TOC and DOC concentrations. Determinations were done on an organic carbon analyser TOC-5000 (Schimadzu, Japan) after prior acidification of the samples with 2M HCl to about 2 pH in order to remove CO_2 (Sugimura and Suzuki 1988). The quality of dissolved organic matter (DOM) was determined based on the properties of selected segments of the 200-400 nm absorption spectrum. The examinations were performed in filtered samples (0.45-µm Millipore filters). Spectra in the range 200-400 nm were obtained with a double-channel UV-1601PC spectrophotometer (Shimadzu, Japan) and 10-mm quartz cells, and with demineralized water as the reference (Kukkonen et al. 1990, Rostan and Callot 1995).

In parallel with the organic carbon examinations, microbiological analysis was performed along with the determination of the physicochemical parameters of the water. The total count of bacterial plankton (TBC) and its biomass (BB) were determined, using the direct analysis method of bacteria stained by acridine orange on polycarbonate black membrane filters (0.2 µm) (Hobbie et al. 1977). Bacteria were analyzed under an Axioskop epifluorescent microscope (OPTON) with automatic display analysis by MultiScan (Świątecki 1997).

Temperature and dissolved oxygen measurements were done in the vertical profile, at every meter of water depth using an YSI 58 oxygen probe (YSI Inc., USA). Total phosphorus and phosphates, as well as total nitrogen and ammonium nitrogen were marked by colorimetry with a UV 1601 spectrophotometer (Shimadzu, Japan). Calcium and hydrocarbonates were measured by titration and seston with the weighing method (Hermanowicz et al. 1999, APHA 1999). A Hanna Instruments pH-meter (HI 22, Romania) was used to determine the reaction of the water, while a Digitalmeter (DIGI 610, Germany) conductometer served to measure electrolytic conductivity.

The strength of linear relationships between the concentration of organic carbon and the hydro-chemical parameters and bacterial parameters were computed using Pearson´s correlation. Pearson´s correlation coefficient was calculated assuming a level of significance of $P < 0.05$.

RESULTS AND DISCUSSION

In the examined period (2002-2003) water temperature at the individual sampling sites ranged from 3.5°C to 32°C (Table 1). Minimal value was determined in the spring of 2003 in the intake channel of the KPP, and maximal value was measured in the summer of 2003 in the initial cooling reservoir.

The waters of the studied lakes were characterized by a salinity of the carbon-calcium type. The content of hydrogen carbonates ranged from 226.3 to 317.2 mg l^{-1}, the change in calcium content was 59.3-98.6 mg l^{-1} and

TABLE 1

Variability (mean ± SD) of the hydro-chemical parameters at the individual sampling stations in 2002-2003

Sampling site	Temp. (°C)	O_2 (mgO_2 l^{-1})	pH	Conductivity (µS cm^{-1})	HCO^{3-} (mg l^{-1})	Ca^{2+} (mg l^{-1})	Tot-P (mg l^{-1})	P-PO_4 (mg l^{-1})	Tot-N (mg l^{-1})	N-NH_4 (mg l^{-1})
Intake canal of KPP	16.1±7.0	11.0±2.6	8.4±0.1	533±32	259.9±19.1	67.9±4.9	0.121±0.023	0.045±0.032	1.125±0.525	0.081±0.019
Discharge canal of KPP	21.5±6.4	9.9±1.9	8.4±0.1	533±32	258.9±18.8	67.9±5.4	0.123±0.023	0.051±0.032	1.025±0.5	0.079±0.022
Discharge canal of PPP	23.5±5.9	8.7±1.7	8.3±0.1	548±34	268.3±18.4	70.8±5.7	0.129±0.029	0.057±0.034	1.072±0.515	0.085±0.023
Initial cooling reservoir – inlet zone	22.1±6.8	10.1±2.4	8.4±0.2	532±31	261.6±8.6	69.9±8.4	0.121±0.024	0.05±0.035	1.12±0.531	0.09±0.039
Initial cooling reservoir – internal zone	22.2±6.7	10.0±2.4	8.4±0.1	534±33	260.9±17.3	67.5±4.9	0.122±0.027	0.05±0.034	1.096±0.528	0.091±0.027
Initial cooling reservoir – outlet zone	17.7±6.9	10.4±2.0	8.4±0.1	532±33	257.3±17.0	66.6±4.0	0.111±0.025	0.042±0.033	1.032±0.377	0.081±0.034
Licheński Canal	21.3±6.5	8.0±1.7	8.3±0.1	542±31	268.8±17.5	69.0±5.3	0.145±0.044.0	0.062±0.038	1.319±0.591	0.092±0.043
Lake Licheńskie surface	17.5±7.6	9.8±2.7	8.4±0.1	541±33	263.4±11.4	69.1±5.5	0.126±0.029	0.053±0.035	1.032±0.452	0.08±0.021
Lake Licheńskie bottom	10.9±3.2	5.4±0.2	8.1±0.3	546±42	274±24.0	71.4±4.0	0.346±0.319	0.239±0.291	1.429±0.679	0.454±0.665

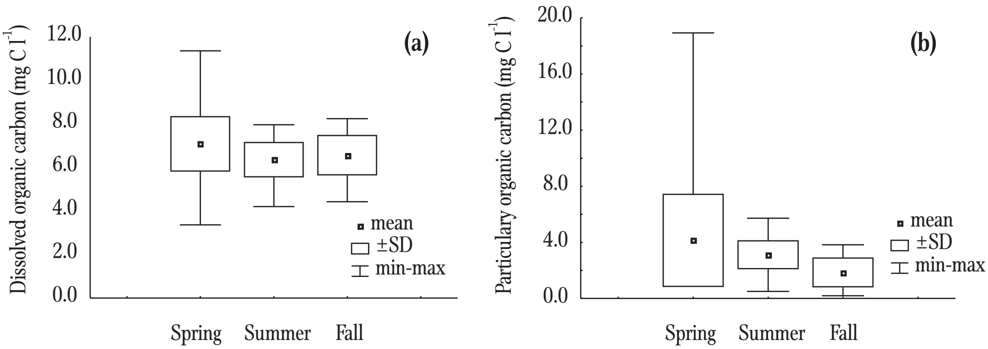

Fig. 2. DOC (a) and POC (b) seasonal variability in cooling waters of the power plants in 2002-2003.

469-619 µS cm^{-1} in conductivity. The mean pH of the examined waters was alkaline (pH = 8.3). Oxygen content in the surface water layers did not drop below 5.1 mg l^{-1}. In the 2002-2003 period, the mean contents of nutrients were as follows: total phosphorus 0.149 mg Tot-P l^{-1}, phosphates 0.072 mg P-PO_4 l^{-1}, total nitrogen 1.139 mg Tot-N l^{-1}, and ammonium nitrogen 0.126 mg N-NH_4 l^{-1} (Table 1).

The present study revealed an obvious difference in DOC and POC content in the cooling waters. The DOC form was dominant at 6.7 mg C l^{-1} on average, and comprised approximately 67% of the total organic carbon. The highest concentrations of dissolved and particulate organic carbon in the analyzed lakes were detected in spring (Fig. 2). High concentrations of DOC and low values of specific ultraviolet absorbance ($SUVA_{260}$) in spring in the cooling waters are contradictory phenomena to the processes occurring in natural reservoirs in the temperate zone. Dunalska et al. (2003, 2004) revealed that in spring organic matter originates mainly from the land.

Intensive primary production in the spring in Lake Licheńskie was confirmed by the significant correlation between POC content and organic phosphorus ($r = 0.65$, $P < 0.05$) and seston ($r = 0.75$, $P < 0.05$). Primary production was favored by the elevated temperature (the correlation between DOC and temperature was statistically significant only in this period; $r = 0.79$, $P < 0.05$). Another factor enhancing primary production is the intensive growth of water bacteria. Enzymatic activity of planktonic bacteria, especially of photo- and chemotrophic microorganisms, increases in higher temperatures and when there is a high content of humic substances (Górniak 1996).

Intensive production of hydrolytic enzymes allows the microorganisms to break down high molecular weight substrate. Organic matter transfer in the following reservoirs stimulates their development, which is confirmed by the high POC values in spring, compared to other examined periods (Table 2). The significant correlations observed in the channels, between TBC and DOC ($r = 0.86$, $P < 0.05$), and TBC and $SUVA_{260}$ ($r = -0.96$, $P < 0.05$), with a simultaneous lack of correlation between bacterial biomass (BB); ($r = -0.02$; $r = -0.16$, $P < 0.05$, respectively) are evidence of the presence of bioavailable organic matter, which stimulates rapid bacterial growth. Processes with planktonic bacteria participation confirm that, in the Konin waters, a so-called microbiological loop (ML) occurs. The ML controls the processes of decomposition and mineralization of organic matter. This organic matter is the base for large bacterial biomass development, which eventually makes a substrate for protozoans and microzooplankton (Moran and Hodson 1993, Chróst 1995, Hessen and Tranvik 1998).

TABLE 2

DOC and POC variability (mean ± SD) at the individual sampling stations from spring to fall 2002 and 2003

Sampling site	Spring		Summer		Fall	
	DOC (mg C l^{-1})	POC (mg C l^{-1})	DOC (mg C l^{-1})	POC (mg C l^{-1})	DOC (mg C $^{l-1}$)	POC (mg C l^{-1})
Intake canal of KPPt	7.2±1.4	4.7±3.2	6.5±0.7	3.2±0.6	7.3±1.1	1.9±1.2
Discharge canal of KPP	7.2±1.2	4.8±5.5	6.2±1.2	2.8±1.3	6.9±0.6	1.6±1.1
Discharge canal of PPP	6.4±1.7	6.2±6.3	6.1±0.4	3.0±3.0	6.2±1.4	2.1±2.1
Initial cooling reservoir – inlet zone	7.4±0.5	3.3±0.9	6.5±1.1	3.2±0.7	6.2±0.3	1.7±1.2
Initial cooling reservoir – internal zone	7.5±0.8	3.5±1.6	6.5±0.8	2.9±1.3	6.3±0.4	1.6±1.2
Initial cooling reservoir – outlet zone	7.7±1.8	3.6±2.0	6.4±1.1	3.5±0.7	6.7±0.6	1.7±1.0
Licheński Canal	6.5±1.1	4.2±1.7	6.0±0.8	3.3±1.4	6.4±1.5	2.4±0.8
Lake Licheńskie surface	6.7±1.2	2.9±1.3	6.5±0.7	3.1±1.4	6.4±0.9	1.8±1.0
Lake Licheńskie bottom	6.4±0.5	2.5±0.7	6.6±0.4	2.8±0.5	6.6±0.9	2.0±1.0

In addition to bacteria, the filtering organisms which feed on organic matter suspended in the water, and animals feeding on detritus in the bottom sediments play the main role in organic matter transformation in individual reservoirs (Tunowski 1994, Afanasjev et al. 1998). The main filtering species in the bottom of Lake Licheńskie is the *Dreissena polymorpha* Pall. (Sinicyna and Zdanowski 2007), while in the channels it is the stenothermal Chinese mussel *Sinanodonta woodiana* (Lea). According to Sinicyna et al. (1998), the water filtration rate achieved by these organisms in a day can be as high as 15 m^3 m^{-2} of bottom surface. The computed take up of suspended solids in the channels reaches up to 5 tonnes per day. Sedimentation of organic matter continuously provides the molluscs with food and thus they remove suspensions and planktonic algae from the water, improving its quality. Additionally, by the accumulation of nutrients and other compounds, they can actively participate in improving the trophic state of the whole Konin system.

The high dynamics of organic matter production in the spring decreases in the summer, as is shown by the value of $SUVA_{260}$, which is high compared to the whole study period (Table 3).

TABLE 3

$SUVA_{260}$ variability (mean ± SD) at the individual sampling stations from spring to fall 2002 and 2003

	Spring	Summer	Fall
Sampling site	$SUVA_{260}$ $cm^{-1}(g\ C)^{-1}\ l$	$SUVA_{260}$ $cm^{-1}(g\ C)^{-1}\ l$	$SUVA_{260}$ $cm^{-1}(g\ C)^{-1}\ l$
Intake canal of KPP	22.1±4.8	29.5±2.7	26.5±2.2
Discharge canal of KPP	23.1±5.2	31.3±4.6	27.2±2.6
Discharge canal of PPP	27.8±13.9	30.5±1.6	29.7±3.0
Initial cooling reservoir – inlet zone	21.8±3.6	28.7±2.3	28.9±1.5
Initial cooling reservoir – internal zone	22.0±3.8	29.3±2.9	28.2±1.0
Initial cooling reservoir – outlet zone	20.9±4.8	9.2±3.3	28.2±0.8
Licheński Canal	26.1±7.9	30.9±1.7	30.9±6.6
Lake Licheńskie surface	25.1±7.4	29.7±2.5	30.7±1.8
Lake Licheńskie bottom	25.1±4.8	31.42.3	29.4±2.1

Heterotrophic bacteria participating in the bioconversion of organic matter use up only the peripheral aliphatic organic compounds bound to biopolymers of humic acids or free fulvic acids (Moran and Hodson 1990, Wetzel 1990). Organic matter inert to bacterial degradation remains mainly in the cooling waters; thus the observed increase of the $SUVA_{260}$ value. Moreover, the high temperature (>30°C) and the increased flow rate, especially in the channels, may reduce the metabolic reactions in bacteria (Świątecki et al. 1998). Low DOC:POC ratios, in comparison to other study periods

(2:1 at all sampling sites), indicate reduced mineralization of organic matter. The latter can be additionally confirmed by the A_{260}:A_{330} ratios, indicating transformations of the substituents in aromatic rings in a molecule. The value of this absorbance ratio is often used as an empiric indicator of the origin or composition of the molecules of humic substances. Larger values are typical for organic compounds with a high contribution of carboxyl groups (Kukkonen et al. 1990). In the examined waters, the absorbance value was low, but the distinct decrease, in comparison to the spring (by 33%), may indicate different properties of the dissolved organic matter.

Primary production in the cooling system waters is dependent not only on biotic but also on abiotic processes. Humic substances, the main constituent of dissolved organic matter, play an important role in the limitation of primary production (Moore 1987, Górniak 1996). Humic acids occurring in water obstruct solar penetration in reservoirs, and, thus, reduce the range of the trophogenic layer (Górniak 1996, Williamson et al. 1996, Carpenter et al. 1997). In primary production, the co-precipitation of phosphates on humic substances, and the formation of phosphorus complexes on calcite, play an important role. Adsorption of phosphates to HS-Fe complexes (Francko 1986, Jones et al. 1993, Kulberg et al. 1993) reduces the availability of this element to algae (Jackson and Hecky 1980, Shaw 1994). According to Gerke and Herman (1992), the intensification of phosphorus complexes on calcite processes grows proportionally with the increase of Ca^{2+} concentration. In the lakes studied, this was displayed by the high concentrations of calcium ions (69.5 on average in Lake Licheńskie; 68.2 in the channels; 67.5 in the initial cooling reservoir). When Ca and DOC are present in water, Fe and P-PO_4 are subjected to complexing and suspended solids settle. This can be confirmed by the significant correlation between POC and Fe in the bottom waters of Lake Licheńskie ($r = 0.73$, $P < 0.05$).

Autolysis and decay of dead organisms after the growing season intensified considerably in fall, which was shown by the high DOC:POC ratios oscillating between 3:1 and 4:1. The increase of DOC:POC was accompanied by the growth of $SUVA_{260}$ values. The possible main source of organic matter resistant to degradation is decomposing macrophytes, especially the stenothermal *Vallisneria spiralis* L., which can be found even at 2 m above the bottom. *V. spiralis* has a high ability to grow over and dominates in Lake Licheńskie (85.6% in the total biomass of submerged plants in 1999) (Socha and Zdanowski 2001).

The parallel low POC values in fall (Table 2) indicate the high mineralization of organic matter. The participation of bacteria in the destruction processes is quite considerable, as is shown by the survey of 1995-1997. In the warm channels, bacteria were responsible for up to 80% of the total destruction. In the zone of warm and anaerobic water input, the mineralization processes in the bottom deposits comprised up to 50%, and in the outer zone, up to 30% (Świątecki et al. 1998). The high rate of decomposition and organic matter utilization by heterotrophic bacteria prevents the excessive accumulation of organic matter, which eventually reduces degradation in the examined waters.

An attempt to characterize organic matter leads to the conclusion that, in the analysed system, organic matter varies quantitatively and qualitatively. Matter turnover in lakes is based mainly on autochthonous reserves. Intensive mineralization processes of the organic matter by bacteria and the phenomenon of phosphorus precipitation on calcite diminish the lakes' richness in nutrients and in the same way limit their strong eutrophication.

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STRESZCZENIE

ZMIENNOŚĆ WĘGLA W SYSTEMIE PODGRZANYCH JEZIOR KONIŃSKICH (POJEZIERZE WIELKOPOLSKO-KUJAWSKIE, POLSKA)

Celem badań było prześledzenie przestrzennej i sezonowej zmienności oraz dynamiki form węgla organicznego na tle parametrów hydrochemicznych, a na tej podstawie określenie produktywności wód włączonych do systemu chłodzenia dwóch elektrowni.

Wyniki badań wykazały wyraźne zróżnicowanie zawartości rozpuszczonego (DOC) i cząsteczkowego (POC) węgla organicznego w całym systemie wód podgrzanych. Dominującą formą był DOC (średnio 6,7 mg C l^{-1}), co stanowiło 67% ogólnej puli całkowitego węgla organicznego. Głównym źródłem węgla organicznego była materia pochodzenia autochtonicznego. Intensywną produkcję pierwotną obserwowano już wiosną, o czym świadczyła duża ilość łatwo przyswajalnej materii organicznej (wysokie stężenia DOC przy jednocześnie niskich wartościach $SUVA_{260}$) oraz istotna statystycznie zależność pomiędzy POC a fosforem organicznym, BZT_5 i sestonem (odpowiednio: r = 0,65; r = 0,73; r = 0,75; P < 0,05). Wiosną procesowi temu sprzyjała podwyższona temperatura wody (tylko w tym okresie istotna statystycznie zależność pomiędzy DOC a temperaturą: r = 0,79; P < 0,05) oraz aktywność enzymatyczna bakterioplanktonu, o czym świadczyła istotna statystycznie zależność pomiędzy ogólną liczbą bakterii (OLB) a DOC i $SUVA_{260}$ (odpowiednio: r = 0,86; r = -0,96, P < 0, 05). Latem dynamika zmian form węgla organicznego była mniejsza niż wiosną. W wodzie systemu chłodzenia występowała głównie trudno przyswajalna dla bakterii materia organiczna, charakteryzująca się wysoką wartością parametru $SUVA_{260}$. O ilości i jakości materii organicznej w wodach systemu chłodzenia elektrowni decydowały również czynniki abiotyczne. Zjawisko współstrącania fosforanów na kompleksach substancji humusowych z żelazem obserwowano w przydennych warstwach wody Jeziora Licheńskiego.