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THE DYNAMICS OF BACTERIOPLANKTON VERSUS RESOURCES OF ORGANIC CARBON IN THE HEATED KONIN LAKES

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ABSTRACT. This study demonstrates the significant effect of the thermal regime of the Konin lakes on the structure of bacterioplankton and the concentration of heteromorphic organic matter. Seasonal differentiation in the maximum concentrations of POC and DOC should be considered the most typical trait of the lakes examined. The dynamics of POC were characterized by the occurrence of maximum concentrations in the fall period of temperature decrease. Intensive lysis of dead hydrobionts was the main factor determining this phenomenon. The substantial decline in the DOC pool, occurring in the same period, was determined by the intensive course of microbiological processes of biotransformation. In contrast, the spring maximum of DOC was mainly linked with the occurrence of mass alga blooms and inflows of allochthonous matter. The response of bacterioplankton to changes in the thermal regime of waters was characterized by a high dependency between the number and temperature and the morphological structure and concentration of DOC. High correlation coefficients were obtained in both cases.

Key word: BACTERIOPLANKTON, DOC, HEATED WATER, LAKE

INTRODUCTION

The structure of organic matter occurring in various water ecosystems and processes of its transformation are relatively well known (Findlay and Sinsabaught 1999). Little is known, however, about the bioavailability of its individual components. Technological advances and the implementation of highly sensitive measuring methods have made it possible to undertake intense research in this area. It has been demonstrated that in water reservoirs, dissolved organic matter usually contains 90% of the total organic matter (Münster and Chróst 1990). Nevertheless, as little as ca. 20% of DOC occurring in water reservoirs readily undergoes microbiological degradation. This labile fraction is usually subject to biotransformation in a very short time span

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(Del Giorgio and Davis 2003). The intensity of secondary production of heterotrophic bacteria is determined, to a great extent, by the sustainability rate of the pool of the labile fraction of DOC. The allochthonous matter inflowing to water reservoirs is usually characterized by low biological lability. A high content of high-molecular aromatic compounds affects the high resistance of this fraction to microbiological degradation (McKnighti and Aiken 1998). Thus, this form of matter does not serve any significant function in the production of nutritional reserves for heterotrophic bacteria. A significant source of available organic compounds is autochthonous matter. Its presence in water results from a variety of processes leading to the release of DOC from POC produced by aquatic organisms. In large water reservoirs, the dissolved organic matter originates mainly from the primary production of phytoplankton (Norman et al. 1995). The active, intravital secretion of intermediate and end products of photosynthesis is the most important mechanism of lake water enrichment in DOC (Søndergaard et al. 2000, Rosenstock and Simon 2001). The intensity of this process is determined, to the highest degree, by the photosynthetic activity and species structure of phytoplankton. According to various authors, the amount of secreted DOC ranges from 10 to 70% of primary production (Simon and Tilzer 1987, Nagata 2000, Teira et al. 2001). The labile organic matter may also originate from other sources, including enzymatic solubilization of POM (Berman and Vinner-Mozzini 2001), secretion by protozoa and animal and feces solubilization (Rosenstock and Simon 2001), and autolysis and viral lysis of algae and bacteria cells (Augusti et al. 1998). A significant factor in increasing the pool of labile organic matter is also the inflow of municipal and industrial sewage. The metabolic activity of bacterioplankton depends on the concentration of dissolved organic compounds. In the regulation of the production bulk of bacterial biomass, apart from DOM concentration, an equally great significance is attributed to the biochemical composition of available organic compounds. The efficiency of the microbiological utilization of individual DOCs is mainly determined by their size and molecular mass (Carlson and Ducklow 1996). Biotransformation enables binding organic carbon in bacterial biomass that constitutes nutritional reserves for bacterivorous protozoa, mainly for nanoflagellates. This specific transfer and freeing of the primarily unavailable dissolved organic matter (DOC) for organisms of higher trophic levels is the basis of the microbiological loop. The intensity of microbiological processes of organic matter biotransformation and the yield of the microbiological loop are determined, to a great extent, by environmental factors. The elevated temperature and the short time of water retention in the heated Konin reservoirs are the main factors reducing the growth of phytoplankton (Socha 1994). The dynamics of this phenomenon affect the structure of the other trophic levels, including bacterioplankton. The aim of this study was to determine the dynamics of bacterioplankton, as well as particulate (POC) and dissolved (DOC) organic matter, in the Konin lakes characterized by different thermal regimes.

MATERIAL AND METHODS

Studies of lakes Ślesińskie and Licheńskie were carried out in 1999 in three periods: spring (May), summer (July), and fall (September). Twenty and twenty-four water sampling sites were located in lakes Ślesińskie and Licheńskie, respectively, which covered particular zones of the lakes (Fig. 1). For microbiological analyses, the samples were fixed with formalin (final concentration of 1%) immediately after collection. The total number of bacteria (BN) was determined by counting them directly on membrane filters (Hobbie et al. 1977). The size of bacterial cells and their morphological structures were estimated based on the computer analysis of microscopic images. Bacterial biomass (BB) was determined using the population number and the mean volume of bacterial cells (MCV) according to respective weight conversion factors (Norland 1993). The content of total organic carbon (TOC) was calculated in non-filtered samples, whereas that of dissolved organic carbon (DOC) was calculated in samples filtered

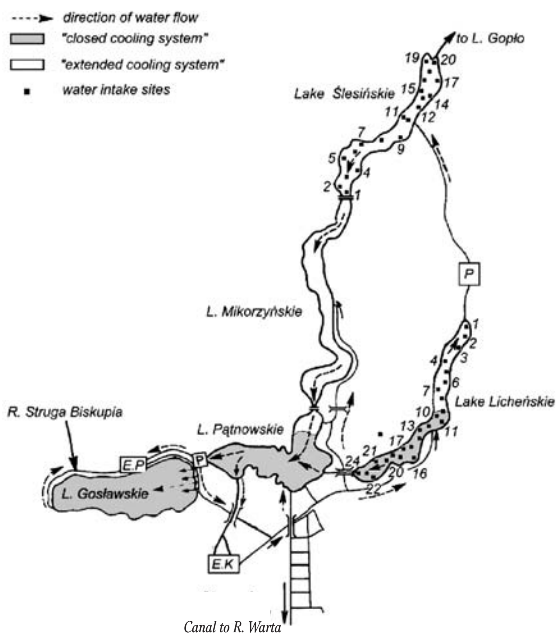

Fig. 1. Cooling system of Konin lakes.

through a 0.45 μm filter (Millpore). The content of particulate organic carbon (POC) was computed from concentrations of TOC and DOC. Determinations were carried out in a TOC-5000 organic carbon analyzer (Schimadzu, Japan) after previous acidification of the samples with 2 M HCl to pH of ca. 2 to remove CO_2. Measurements of the content of total phosphorus and BOD_5 were carried out following standard procedures (Zdanowski 1994). Water temperature and the concentration of dissolved oxygen were determined *in situ* with the use of a thermal-oxygen probe (Yellow Spring Instruments, USA).

RESULTS

BACTERIOPLANKTON

In Lake Licheńskie, permanently included in the cooling system, the number of bacterioplankton ranged from 3.7 to 10.6 × 10^6 ml^{-1}, i.e. 5.6 × 10^6 ml^{-1} on average. A typical trait of this lake appeared to be the similar values of BN in all the analyzed periods (Fig. 2). Considerable fluctuations in the numbers of bacterioplankton were, however, demonstrated in particular zones of the lake. Higher BN values were recorded at sampling sites located in the littoral zone of the lake (Fig. 3). The mean volume of bacterial cells ranged from 0.07 to 0.18 μm^3, i.e. 0.12 μm^3, on average. The highest values of this parameter were reported in the spring – 0.13 μm^3, on average. In the subsequent seasons, the size of bacterial cells was observed to decrease successively, with the lowest values recorded in the fall. Any significant difference was demonstrated in the structure of bacteria occurring in the pelagic and littoral zones of the lake. The content of BB ranged from 71.5 to 293.8 μg l^{-1}. In the spring and summer, the BB displayed similar dynamics and accounted for 161.5 μg l^{-1}, on average. The highest values of this parameter were recorded in the southern, runoff part of the lake. Substantially lower contents of BB were observed in the fall – 103.4 μg l^{-1}, on average. This period was characterized by a balanced level of that parameter in particular zones of the lake.

In Lake Ślesińskie, the recorded values of individual microbiological parameters were lower (Table 1). The number of planktonic bacteria ranged from 2.4 to 9.4 10^6 ml^{-1}, i.e., 4.7 10^6 ml^{-1}, on average. This lake was characterized by considerable seasonal differences (Fig. 2). Low BN values were observed in the spring and fall at 5.0 and 3.2 10^6 ml^{-1}, respectively. A very typical trait of these seasons were similar

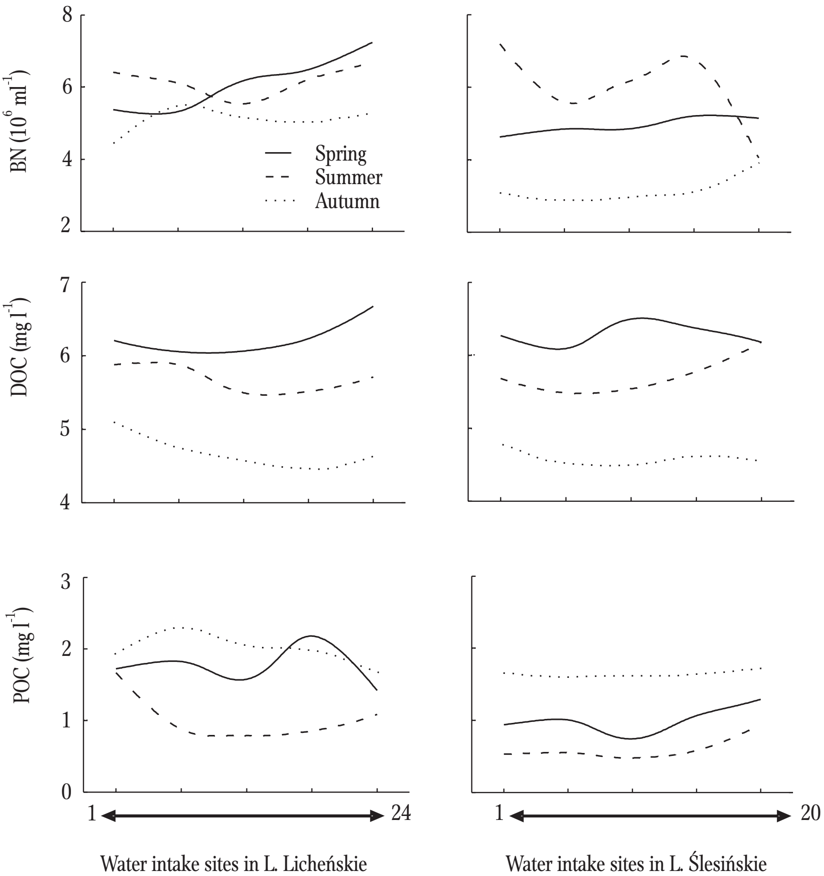

Fig. 2. Bacteria number (BN), concentration of DOC and concentration of POC in the studied lakes.

bacterial counts at all sampling sites examined. In the summer, when the lake was included in the cooling system, the number of bacteria appeared to increase significantly to 5.9 10^6 ml^{-1}, on average. In addition, great variability in the bacterial numbers was observed at particular sampling sites. The mean volume of bacterial cells was similar in the spring and summer and was 0.12 µm^3, on average. These seasons were characterized by the considerable diversification of this parameter in particular zones of the lake. In the fall season, the volume of the cells was substantially lower at an average of 0.08 µm^3. Simultaneously, a very balanced level of this parameter was reported throughout the lake. The biomass of planktonic bacteria ranged from 47.1 to 254.1 µg l^{-1}, i.e., 111.1 µg l^{-1}, on average. The dynamics of this parameter corresponded to changes in the number of bacteria. Lower values were recorded in the northern, cleaner part of the lake.

TABLE 1

Bacterioplankton parameters: bacteria number (BN), mean cell volume (MCV) and bacterial biomass (BB) of the studied lakes

	BN (10^6 ml^{-1})			MCV (μm^3)			BB (μg ml^{-1})		
Lake/ Month	avgerage	max	min	avgerage	max	min	avgerage	max	min
Licheńskie									
May	6.1	10.6	4.2	0.13	0.18	0.09	165.7	293.8	114.9
July	6.2	7.5	4.6	0.12	0.14	0.09	157.3	214.4	110.7
September	5.1	6.6	3.7	0.09	0.11	0.07	103.4	151.8	71.5
Ślesińskie									
May	4.9	6.8	2.9	0.12	0.15	0.09	123.4	168.0	61.5
July	5.9	9.4	3.6	0.11	0.14	0.07	147.2	254.1	86.9
September	3.2	5.9	2.4	0.08	0.1	0.07	62.7	135.8	47.5

ORGANIC CARBON

In both of the lakes studied the dynamics of organic carbon concentration were very similar (Table 2).

TABLE 2

Dissolved organic carbon (DOC), particular organic carbon (POC), biochemical oxygen demand (BOD_5) and total phosphorus ($_{Tot}$) of the studied lakes

	DOC (mg l^{-1})			POC (mg l^{-1})			BOD_5 (mg l^{-1})			Phosphorus$_{(Tot)}$ (mg l^{-1})		
Lake/ Month	avgerage	max	min	avgerage	max	min	avgerage	max	min	avgerage	max	min
Licheńskie												
May	6.2	7.5	5.7	1.8	3.2	0.7	2.03	3.78	1.18	0.1	0.14	0.08
July	5.7	7.0	5.0	1.1	2.1	0.5	1.76	4.20	0.61	0.13	0.15	0.06
September	4.7	5.6	4.3	2.0	3.4	1.4	1.81	3.14	0.80	0.08	0.09	0.06
Ślesińskie												
May	6.3	7.6	5.6	1.0	2.1	0.5	0.89	2.27	0.10	0.1	0.13	0.09
July	5.7	6.7	5.2	0.6	1.1	0.2	1.29	2.20	0.60	0.1	0.15	0.08
September	4.6	4.9	4.4	1.6	2.1	1.3	0.39	1.04	0.12	0.09	0.11	0.07

Significant seasonal differences were noted (Fig. 2). From May to September, the concentration of DOC was observed to decrease successively, reaching 6.2 mg l^{-1} in the spring, 5.7 mg l^{-1} in the summer, and 4.65 mg l^{-1} in the fall. Negligibly higher DOC values were recorded in the spring and summer in the littoral zones of both lakes (Fig. 3). In the lakes studied, the concentration of particulate organic matter (POC) was, on average, four times lower than that of DOC. In the permanently warmed Lake

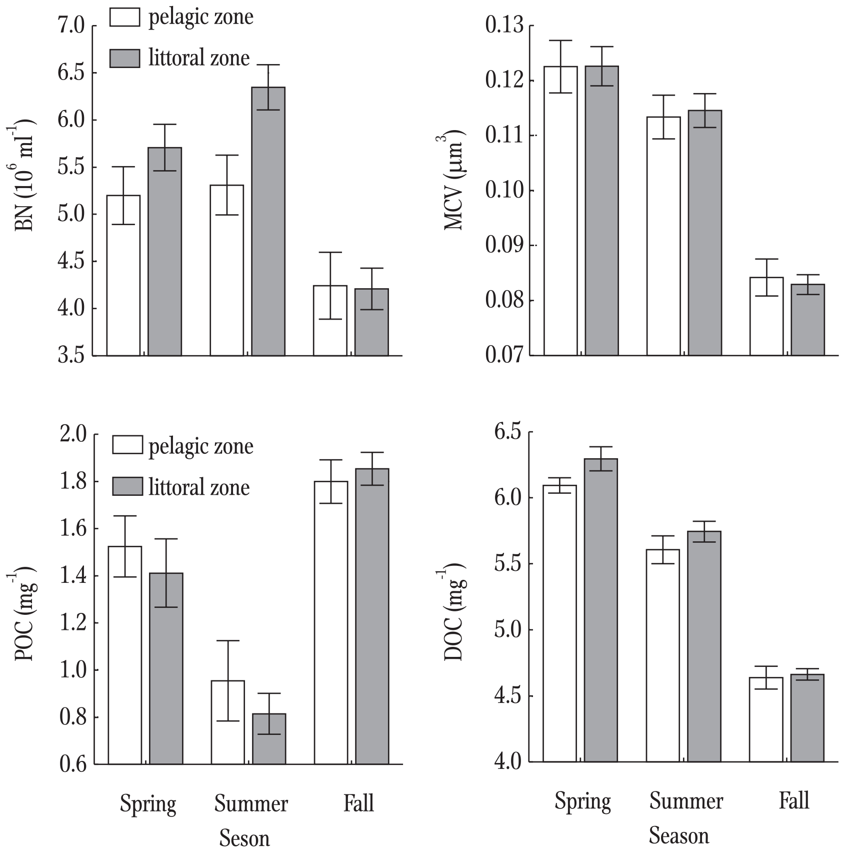

Fig. 3. Bacteria number (BN), mean cell volume (MCV), concentration of POC and DOC in pelagial an littoral zones of studied lakes.

Licheńskie, the lowest content of POC was noted in the summer at 1.05 mg l^{-1}, on average. In the spring and fall, the level of POC was nearly twice as high at 1.77 and 2.0 mg l^{-1}, respectively. In Lake Ślesińskie, POC concentration ranged from 0.24 to 2.12 mg l^{-1} and was lower by 1 mg l^{-1}, on average, than in Lake Licheńskie. The maximum values of particulate organic matter were recorded in fall at 1.64 mg l^{-1}, on average. The spring and summer seasons were characterized by substantially lower values of this parameter, i.e., 1.0 and 0.62 mg l^{-1}, respectively. A slightly higher level of POC was observed in the pelagic zone of the lakes studied.

The analysis of the dynamics of microbiological and physicochemical parameters demonstrated multiple correlations (Fig. 4). A statistically significant correlation was

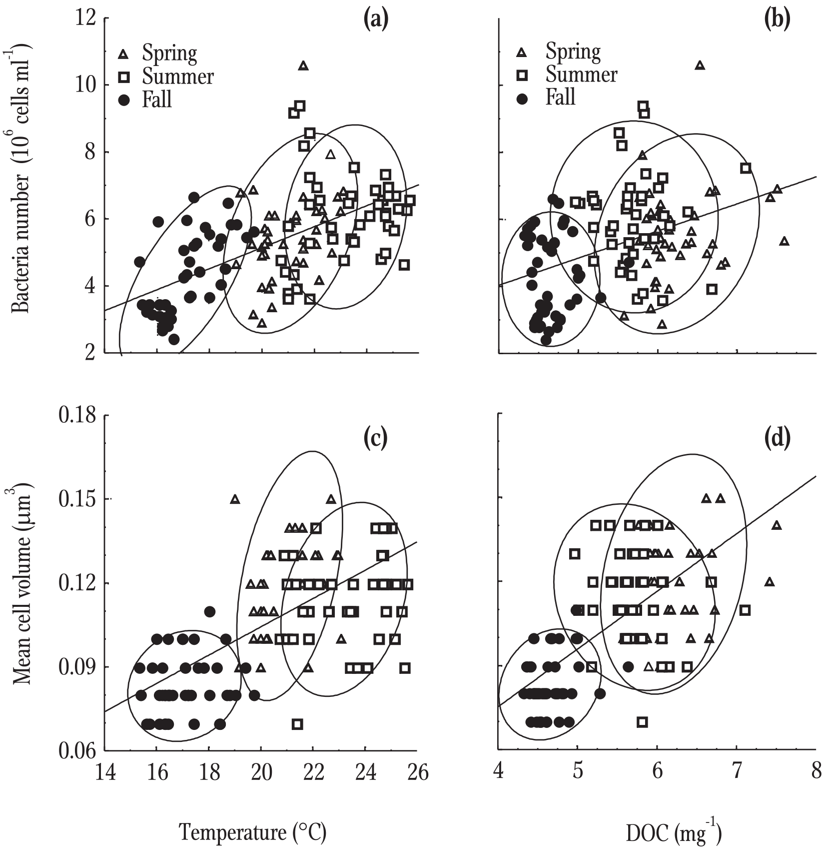

Fig. 4. Correlation between bacteria number (a, b), mean cell volume (c, d) and temperature and DOC concentration.

found between temperature and the number of bacterioplankton ($r = 0.53$, $P < 0.05$). Especially significant correlations occurred between these parameters in the spring and fall seasons, i.e., $r = 0.55$ and $r = 0.62$, respectively. A remarkably lower correlation was demonstrated between the number of bacteria and DOC concentration ($r = 0.42$, $P<0.05$). Opposite regularities were observed in the dynamics of bacterial cell volume. A high correlation was demonstrated between the volume of bacterial cells and the concentration of DOC ($r = 0.65$, $P < 0.01$). An especially high correlation was noted in May, in the period of the highest DOC concentrations ($r = 0.65$, $P < 0.05$). A lower regression level was observed with regard to temperature. In the spring during the period of maximum temperatures (25-28°C), a negative correlation was observed

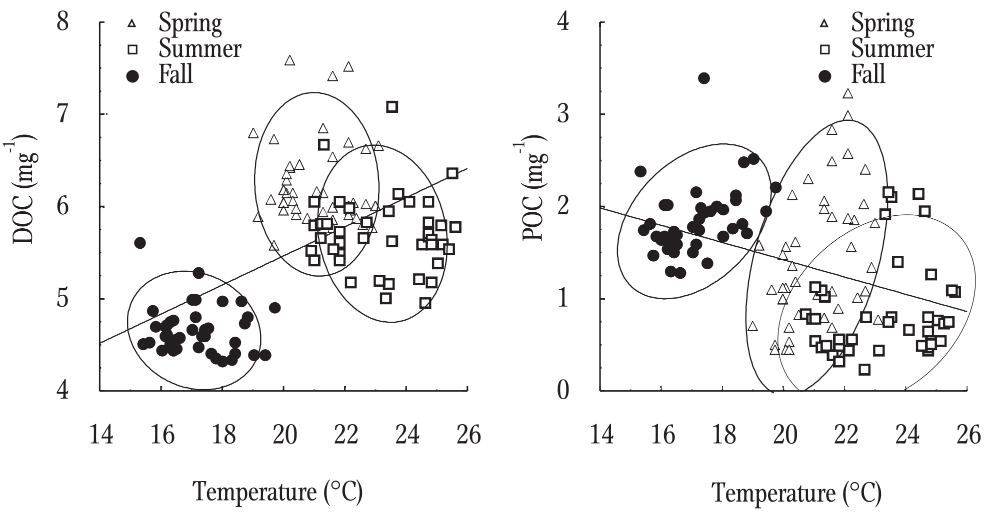

Fig. 5. Correlation between DOC and POC concentrations and temperature.

(r = -0.32, P < 0.05). The dynamics of the dissolved and particulate organic carbon demonstrated characteristic regularities. An opposite dependence was reported between concentrations of DOC and POC in the Konin lakes (Fig. 5). On average, the highest values of both forms of organic carbon were recorded in the spring at moderate water temperatures.

DISCUSSION

Thermal contamination, variable and usually low retention, as well as a variety of organic and mineral contaminations, should be considered as the main factors affecting the structure of the ecosystems of the Konin lakes (Zdanowski 1994). Numerous publications have provided in-depth analysis of issues of hydrochemistry, phyto- and zooplankton, periphyton, and fish (Protasov et al. 1994, Socha 1994, Świątecki 1994, 1997, Tunowski 1994). The most typical trait of the bacterioplankton of the Konin lakes appeared to be the increase in its number in the periods of intense water warming. Studies of heated reservoirs of Ukraine by Protasov (1991) demonstrated that a water temperature increase of 10°C led to a two-fold increase in bacterial count. In the current study, the phenomenon of bacterioplankton stimulation by temperature was especially distinct in the temporarily warmed Lake Ślesińskie and in the northern part of Lake

Licheńskie. It should be emphasized, however, that among the bacterioplankton parameters analyzed, changes in its number were well correlated with temperature. A surprisingly low correlation was demonstrated between the number of planktonic bacteria and the concentration of heteromorphic organic matter in the water. These two facts are indicative of the occurrence of highly complex biocenotic systems in communities of the pelagic zone of lakes. The change in the structure of bacterioplankton in warmed waters was mainly linked with a considerable fraction of large bacterial forms. This phenomenon determined the high increase in bacterioplankton biomass in "warm" periods. A significant factor affecting the structure of bacterioplankton was, undoubtedly, the concentration dynamics of the labile forms of DOC. This has been confirmed by the reported statistically significant correlation between these parameters. Unquestionably, easily-available organic matter stimulated the growth of enzymatically-active microorganisms whose number in the bacterioplankton was observed to increase considerably. Multiple studies have indicated that within bacteriocenoses, two basic populations of r- and K-strategists can occur (Weinabauer and Höfle 1998). The availability of labile DOC enhances the growth of large, metabolically-active and rapidly-proliferating r-strategists. The activity of these bacteria determines the rapid biotransformation of the dissolved matter and its transfer to the higher trophic levels. In periods of low DOC concentration, a predominating group of bacteria can be constituted by small, slowly-proliferating K-strategists with low metabolic activity. According to a number of authors, the most active bacterioplankton group are microorganisms with a volume exceeding 0.2 μm (Gasol et al. 1995). The distinct seasonal changes in temperature and organic matter concentration occurring in Lake Ślesińskie determined the high dynamics of bacterioplankton. A high bacterial number recorded in the summer season, with a simultaneous drop in DOC concentration and an increase in POC, may indicate the occurrence of intensive processes of microbiological biotransformation of organic matter. This phenomenon is likely to have been of decisive significance in the protection of Lake Ślesińskie against progressive eutrophication. In the permanently warmed Lake Licheńskie, the microbiological processes were characterized by a greater stability and a lack of distinct seasonal changes. In the spring and fall, i.e., in periods when the small cooling system was in operation, a typical phenomenon was the mosaic character of the microbiological parameters at particular sampling sites. Negligible differences in individual parameters in the summer season result from the intensified thermal regime of the lake. Intensive water flow in the lake eliminates the heterogeneity of the environment. Simultaneously, despite high loading of the lake with allochthonous matter carried with inflowing waters, most of the microbiological parameters were similar or slightly higher than those reported for Lake Ślesińskie. A typical trait of this period was the reduced concentration of DOC, which indicates highly intense processes of microbiological destruction. Previous studies have demonstrated, however, that exceeding the thermal regime and the occurrence of extreme temperatures in the period of intensive discharge of post-cooling waters were likely to decrease the rate of bacterial degradation processes. The results obtained indicate that intensified thermal regime is a factor that modifies, to a significant extent, the course of biocenotic processes in water bodies. It also has a modifying effect on the concentration dynamics of heterotrophic organic matter. Especially characteristic is the negative correlation occurring between concentrations of DOC and POC in particular seasons. The observed fall peak of POC may result from the atrophy of hydrobionts. In addition, reduced reserves of DOC are rapidly utilized in microbiological processes, which influences the very low level of this matter in water. The intensive, spring blooming of algae and the inflow of contaminated waters produced a considerable increase in the DOC concentration. In subsequent months, the pool of this matter successively decreased as a result of the microbiological processes of bioconversion. Short-term and usually insignificant warming of the waters of Lake Ślesińskie had no negative effects on the functioning of this ecosystem. The intensification of microbiological processes in the discharge zones of contaminated waters accelerated the rate of self-purification, which, in turn, facilitated the protection of the lake against contamination and progressive eutrophication. The overheating of Lake Licheńskie in the summer periods may further enhance degradation of the lake as a result of the reduced efficacy of the microbiological processes of self-purification. The reduction of contamination inflow and compliance with a thermal regime are the main conditions necessary to reduce the degradation of the Konin lakes.

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STRESZCZENIE

DYNAMIKA BAKTERIOPLANKTONU A ZASOBY WĘGLA ORGANICZNEGO W PODGRZEWANYCH JEZIORACH KONIŃSKICH

Badania dwóch podgrzewanych jezior Licheńskiego i Ślesińskiego wykazały, że temperatura była istotnym czynnikiem wpływającym na dynamikę liczebności i struktury bakterioplanktonu oraz koncentrację różnopostaciowej materii organicznej. Dynamika koncentracji POC i DOC w jeziorach charakteryzowała się określonymi prawidłowościami. Maksymalne stężenia partykularnej materii organicznej występowały jesienią, przy znacznie obniżonej temperaturze wody. Obumieranie i liza hydrobiontów były głównymi czynnikami determinującymi wzrost POC w tym okresie. Spadek ilości rozpuszczonej materii organicznej, rejestrowany w jesienią, uwarunkowany był wysoką intensywnością mikrobiologicznych procesów mineralizacji DOC. Zanotowany wiosną wzrost ilości rozpuszczonej materii organicznej był związany z występowaniem masowych zakwitów glonów oraz dopływem allochtonicznej materii. Reakcja bakterioplanktonu na zmiany reżimu termicznego podgrzewanych jezior konińskich charakteryzowała się wysoką dynamiką ilościową i strukturalną. Wykazano istotne statystycznie zależności pomiędzy parametrami mikrobiologicznymi a koncentracją rozpuszczonej materii organicznej.