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Original Research

Influence of Spent Cooling Water on Primary Production

Arkadiusz Nędzarek, Agnieszka Tórz, Małgorzata Bonisławska, Arkadiusz Drost

Department of Water Sozology, West Pomeranian University of Technology in Szczecin,
K. Królewicza 4, 71-550 Szczecin, Poland

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Abstract

Our paper discusses research into primary production of water discharged from a power plant with 1,600 MW capacity in conjunction with select hydrochemical indicators. It was proven that, on average, the temperature of spent cooling water was higher by 6.3ºC than the temperature of natural waters. Oxygen conditions were favorable for water biocenoses, whereas concentrations and transformations of biogenic elements were characteristic for eutrophized waters. Average annual primary production of spent cooling water equaled 0.300 $mgC \cdot dm^{-3} \cdot h^{-1}$ and exceeded by 27% primary production of water that had not been subject to thermal pollution.

Keywords: primary production, nutrients, eutrophication, cooling water, power plant, Odra River

Introduction

Biological productivity in aquatic ecosystems depends on latitude, season, light intensity, temperature, rate of water flow, availability of biogenic elements, and geomorphology and management of a water catchment area [1]. Water temperature has an impact on viability, capacity for growth, and reproduction of aquatic organisms on all trophic levels [2-6]. Increasing water temperature implies a threat posed to biocenoses, but this unfavorable phenomenon can be utilized by technology of biomass production. One trend observed in recent years is studying the utilization of microalgae as, inter alia, a potential renewable energy source [7, 8].

An important factor modifying natural thermal conditions of aquatic ecosystems is spent cooling water, which affects aquatic organisms at the level of microalgae responsible for primary production in water [9-11]. This type of wastewater constitutes a considerable share of wastewater discharged by industry, especially in the industrialized countries of Europe, North America, Asia, and Australia. For example, in the United Kingdom it is estimated that one half of all river flow is used for cooling purposes and hence leads to some elevated discharge of higher temperature water. As early as the 1980s in the USA thermal discharges amounted to one sixth of the total national river flow. In Australia there are many instances of warm water discharge subsequent to cooling uses; however, cold water release downstream of reservoirs is at least as great a problem; for example, in New South Wales it is thought that up to 3,000 river kilometers may be adversely affected by such cold-water releases [12].

In Poland, spent cooling water amounts to 7,000 hm^3, which constitutes 87% of industrial wastewater and 75% of all wastewater discharged to the environment [13]. Similar proportions have been observed in West Pomerania Voivodeship, where one of the largest Polish power plants is located: Elektrownia Dolna Odra (EDO).

Research into the impact of wastewater discharged from EDO to aquatic biocenoses had been conducted sporadically and focused on chemical qualities of water discharged from the cooling water discharge canal in the context of its effect on fish populations [14, 15]. The aim of the present study was to evaluate primary production of

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*e-mail: arkadiusz.nedzarek@zut.edu.pl

warm water from the discharge canal in comparison to primary production of water taken in for cooling the power plant, in conjunction with selected hydrochemical indicators.

Study Area

The power plant Elektrownia Dolna Odra (EDO) in Nowe Czarnowo is situated in the northwestern part of West Pomerania Voivodeship, 35 kilometers south of Szczecin, and the main electric energy producer in the Voivodeship (Fig. 1). The plant has eight energy blocks with maximum power capacity of 1600 MW; gases emitted by the plant into the atmosphere remain within limits specified by Polish norms regarding air pollution [16]. Spent cooling water originates from water withdrawn from the East Odra River; the power plant also exploits deep groundwater. Industrial and rain wastewater, as well as domestic wastewater produced by EDO are treated in onsite sewage facilities. Water consumption by EDO for industrial and social purposes equals ca. 64 $m^3 \cdot s^{-1}$. Spent cooling water and other types of wastewater are discharged into the Odra River by a special canal characterized by an even depth (2 m on average) and 4 km length [17].

Methods

Our research was conducted in 2011-12 in two research sites. Research site No. 1: a canal used as a cooling water intake for the power plant; site No. 2: cooling water discharge canal (Fig. 1). Water samples necessary for analyses of hydrochemical parameters were collected once a month from the superficial layer, at a depth of 50 cm. The analyses of hydrochemical indicators were conducted according to methodology recommended by [18]. Inorganic forms of nitrogen (nitrite, nitrate, and ammonium), total nitrogen (TN), total reactive phosphorus (TRP), and total phosphorus (TP) were analyzed at the water samples without filtration. Total chlorophyll *a* was measured by filtrating 250 ml of water onto Whatman GF/C filters, which were stored at -20ºC until analysis. Chlorophyll was extracted by 90% acetone (λ=665 nm). Absorbances were measured at the recommended wavelengths in a Spectroquant Pharo 300 Merck spectrophotometer. Nitrite nitrogen was assayed with sulphanyl acid (λ=543 nm). Nitrate nitrogen was determined as nitrites after reduction on a Cu-Cd column. Ammonium nitrogen was assayed with indophenol blue (λ=630 nm). TN was determined, as nitrates, after mineralization with potassium hypersulphate. Total organic nitrogen (TON) content was calculated as the difference between TN and total inorganic nitrogen (TIN) (sum of nitrite, nitrate, and ammonium nitrogen contents). TRP was assayed using the molybdenate technique with ascorbic acid as a reducer (λ=882 nm). TP, after mineralization with potassium hypersulphate, was assayed as TRP. The difference between the two phosphorus fractions produced total organic phosphorus (TOP). Biological oxygen demand (BOD_5) was determined by a direct method after a five-day incubation of the samples with no access of the light at a constant 20ºC. Chemical oxygen demand (COD_{Cr}) [$mgO_2 \cdot dm^{-3}$] was determined by the dichromate method.

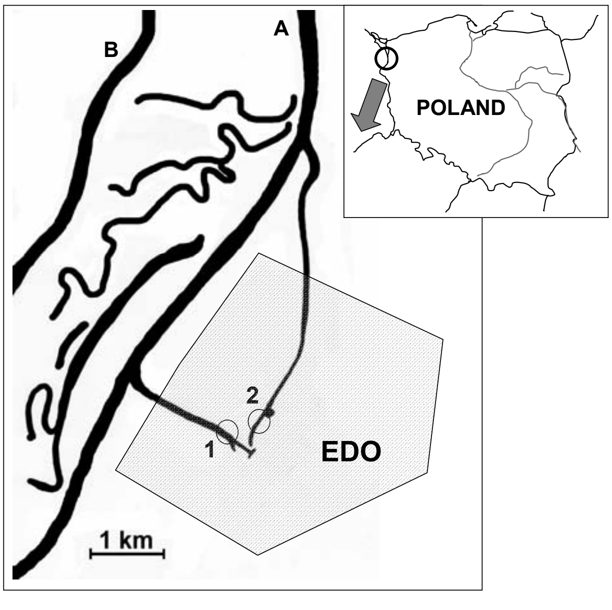

Fig. 1. Location of the power plant Elektrownia Dolna Odra (EDO), and sampling station (1 – a canal which was used as a cooling water intake for the power plant; 2 – cooling water discharge canal), A – East Odra River, B – West Odra River.

Such water parameters as water temperature, conductivity (Elmetron CC-101 conductivity mater), and pH (Elmetron CP-103 waterproof pH-meter) were measured directly at sampling.

Primary production was evaluated *in situ* in the superficial layer (at the depth of 50 cm), utilizing the light and dark bottle technique described by [19]. Concentrations of oxygen dissolved in water were determined by Winkler titration in three repetitions.

The data were subjected to statistical treatment involving one-way analysis of the Pearson's linear regression at α=0.05, using Statistica 10.1 software [20].

Results

Observed changes of thermal water condition in research sites were typical for seasons of temperate climate: minimum temperatures were noted in winter and maximum temperatures were noted in summer. At the same time, it was observed that the temperature of spent cooling water (research site No. 2) was always higher by an average of 6.3ºC from the temperature of water taken in by the power plant for cooling (research site No. 1). What is more, water in research site No. 2 also was characterized by higher conductivity (by 76.1 $\mu S \cdot cm^{-1}$ on average) and higher pH (by 0.19 on average) in comparison to research site No. 1 (Table 1). Seasonal changes of water pH were characterized by higher values at the peak of vegetation period (in both research sites: pH > 8.40).

Dissolved oxygen content in water was similar in both research sites: an average value for research site No. 1 equaled 9.38 $mgO_2 \cdot dm^{-3}$, whereas an average value for research site No. 2 equaled 10.06 $mgO_2 \cdot dm^{-3}$ (Table 1). However, dynamics of changes in dissolved oxygen concentrations differed between the two research sites. In research site No. 1, minimum values of oxygen dissolved in water were noted in September and October 2011. In research site No. 2, minimum dissolved oxygen concentrations in water were noted in June 2011 and May 2012, whereas the maximum ones were noted in the autumn-winter season. In spent cooling water there was observed a negative correlation between dissolved oxygen and temperature (r= -0.74), while in research site No. 1 such a correlation was not observed (Fig. 2).

Values of studied indicators characterizing organic matter content in water were similar in both research sites, but slightly higher concentrations of BOD_5, COD_{Cr}, and chlorophyll *a* were noted in samples collected from research site No. 1. Average concentrations of these indicators were higher by 0.24 $mgO_2 \cdot dm^{-3}$, 8.5 $mgO_2 \cdot dm^{-3}$, and 10.55 $mg \cdot m^{-3}$, respectively. Seasonal changes of the indicators were characterized by minimum values in winter and an increase during the period of intense vegetation. A statistical analysis showed significant correlations between chlorophyll *a* and water temperature (Fig. 2) as well as between chlorophyll *a* and BOD_5 on the one hand and primary production on the other (Fig. 3), which was statistically correlated with water temperature in both research sites (r=0.61 for research site No. 1 and r=0.85 for research site No. 2).

Concentrations of investigated forms of nitrogen and phosphorus displayed a wide range (Table 1) and were characteristic for waters with a high trophic status (eutrophy). As far as inorganic nitrogen forms were concerned, the lowest noted concentrations were those of nitrite nitrogen (average concentration equaled ca. 0.025 $mgN \cdot dm^{-3}$), whereas the concentrations of ammonia nitrogen were ca. three times higher, and the concentrations of nitrogen in nitric form were over twenty times higher than those of nitrite nitrogen. A comparison of the two research sites showed that organic nitrogen dominated in waters of research site No. 1 and constituted 56% of total nitrogen concentration, while inorganic nitrogen dominated in waters of research site No. 2, where it constituted 52% of total nitrogen concentration. As for total phosphorus concentration, reactive phosphorus was a dominant form and constituted ca. 60% of total phosphorus concentration.

Seasonal changes in concentrations of inorganic nitrogen and reactive phosphorus were characterized by a decrease coinciding with the vegetation peak and an increase in winter. Correlations between TIN and TRP on the one hand and temperature on the other were negative, and only in the case of TIN was the correlation statistically significant in both research sites: r=- 0.71 (research site No. 1) and r=-0.87 (research site No. 2). In the case of TRP, correlation with temperature in both sites equaled r=-0.10 and r=-0.15, respectively. Negative correlations also were discovered between TIN and TRP on one hand and primary production on the other (Fig. 4).

Table 1. Range and average values of indicators measured during the period of the study.

Indicator		Site No. 1	Site No. 2
$N\text{-}NO_2^-$	$mgN \cdot dm^{-3}$	0.014-0.040 0.026	0.015-0.039 0.025
$N\text{-}NO_3^-$		0.257-0.801 0.528	0.245-0.865 0.567
$N\text{-}NH_4^+$		0.019-0.182 0.070	0.020-0.233 0.082
TIN		0.303-1.005 0.623	0.292-1.045 0.674
TON		0.314-1.351 0.826	0.287-1.462 0.626
TN		1.188-1.838 1.462	0.892-1.754 1.300
TRP	$mgP \cdot dm^{-3}$	0.052-0.115 0.091	0.079-0.149 0.105
TOP		0.018-0.129 0.062	0.017-0.137 0.069
TP		0.082-0.235 0.148	0.127-0.235 0.174
Chlorophyll *a*	$mg \cdot m^{-3}$	8.54-194.36 74.85	10.00-170.88 64.30
COD_{Cr}	$mgO_2 \cdot dm^{-3}$	29.6-38.6 34.0	17.1-33.6 25.5
BOD_5		2.40-6.87 5.33	2.90-6.31 5.09
O_2		5.50-11.61 9.38	6.54-12.54 10.06
pH		7.23-8.52 7.96	7.65-8.48 8.15
Conductivity	$mS \cdot cm^{-1}$	550-735 648.1	684-748 724.2
Temperature	ºC	4.8-23.0 14.18	13.4-31.5 21.52
Primary production	$mgC \cdot dm^{-3} \cdot h^{-1}$	0.056-0.364 0.219	0.068-0.565 0.300

Discussion

Most of the studied indicators had similar values in water samples collected from both research sites, and at the same time these values were similar to those that had been given earlier by other authors [14, 15, 21, 22]. A crucial parameter differing environmental conditions of the two research sites was water temperature. As a rule, spent cooling water discharged by a power plant through the discharge canal is warmer in comparison to natural water. For instance, Domagała and Pilecka-Rapacz [15] noted that average annual temperature of the cooling water discharge canal amounted to 18.4ºC and was, on average, over 6.6ºC higher than in the canal withdrawing water for the power plant from the Odra. In the study discussed in this paper the difference equaled 6.3ºC. Furthermore, a considerable flow rate of spent cooling water was responsible for the fact that in the studied canal no diversification in water temperature was observed along the vertical gradient, and along the horizontal gradient a slight decrease in water temperature was observed as the water was flowing toward the mouth of the canal. According to Trzebiatowski [14], a difference in temperatures between research site No. 2 and the mouth of the cooling water discharge canal, discharging the spent water to the Oder River, amounted to 1.07ºC.

Oxygen conditions observed in the course of our research should not pose a threat to biocenoses. However, minimum oxygen concentrations noted in research site No. 1 in winter pointed out a danger to biocenoses in the case of formulation of an ice cover. As for research site No. 2, minimum oxygen content was noted at the vegetation peak, when water temperature exceeded 30ºC. Comparing correlation coefficients for the dependency between dissolved oxygen content and such parameters as water temperature and chlorophyll *a* (Fig. 2), it was stated that in waters of research site No. 1 the processes of diffusion and photosynthesis were equally important as sources of oxygen dissolved in water, whereas in waters of research site No. 2 diffusion of atmospheric oxygen was the main source of oxygen dissolved in water.

High dynamics of observed changes in concentrations of oxygen dissolved in water together with fluctuating concentrations of inorganic matter indicated that intense biochemical processes were taking place in connection with oxygen production and its consumption resulting from processes accompanying decomposition of organic matter. According to Domagała and Pilecka-Rapacz [15], oxygen conditions of the studied waters were affected by large amounts of organic matter of indigenous origin contained in river flora. This fact was confirmed by a study focusing on water in the Oder River conducted by Landsberg-Uczciwek et al. [16], who stated that the level of chlorophyll *a* content during vegetation season exceeded 150 $mg \cdot m^{-3}$. Intense assimilation taking place in waters of this river was accompanied by heightened pH levels and an increased amount of organic matter produced with the aid of COD_{Cr} and BOD_5 [23]. Such correlations are characteristic of water reservoirs with a high level of trophy.

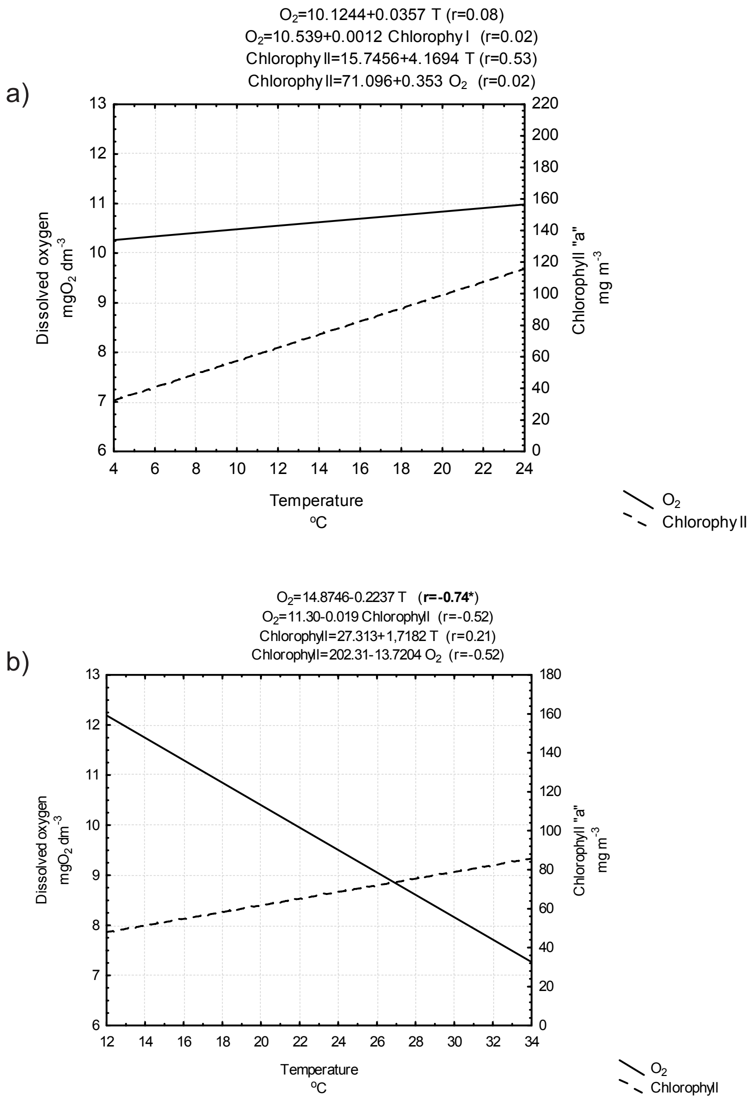

Fig. 2. Interdependencies between dissolved oxygen and chlorophyll *a* in the context of changes in water temperatures (a – research site No. 1; b – research site No. 2, * statistically significant correlations).

In surface waters practically unaffected by anthropogenic influences TIN concentration was low, and according to Meybeck [24] amounted to 0.120 $mgN\cdot dm^{-3}$. As for the studied reservoirs, values of TIN concentrations were five times higher on average and therefore they should be classified as subjected to strong anthropopressure. TRP and chlorophyll *a* concentrations were characteristic for reservoirs on the border between eutrophy and hypertrophy [25].

Primary production in studied research sites must be considered as high, similarly to that measured by Gouze et al. [10] in Barre Lagoon: for that reservoir primary production ranged from 0.150 to 4.350 $mgC\cdot dm^{-3}\cdot d^{-1}$. What is more, in Barre Lagoon primary production was not correlated with chlorophyll *a*, which was explained by significant seasonal changes in phytoplankton populations and their physiological state caused by considerable changes of environmental conditions, especially fluctuations in water salinity. In the present study the correlation between primary production and chlorophyll *a* was noted, which indicated that environmental conditions were stable for autotrophs. Negative correlations between TIN and TRP on the one hand and primary production on the other (Fig. 4) indicated consumption of biogenic elements by autotrophs. Intensity of the process was comparatively low, which confirmed high fertility of studied waters. In such waters, autotrophs are not able to use up the available amounts of nitrogen and phosphorus even under favourable environmental conditions, because the losses of N and P are made up for by means of the process of internal enrichment, for instance from bottom sediments or from excretions of living members of the biocenosis [25-27].

A higher primary production observed in research site No. 2 in comparison to research site No. 1 was characteristic of waters polluted with spent cooling water. For example, according to Wanders [28], discharging spent cooling water into Bergumermeer Lake resulted in an increase of chlorophyll *a* concentration by 5% in comparison to its concentration measured before a power plant started functioning.

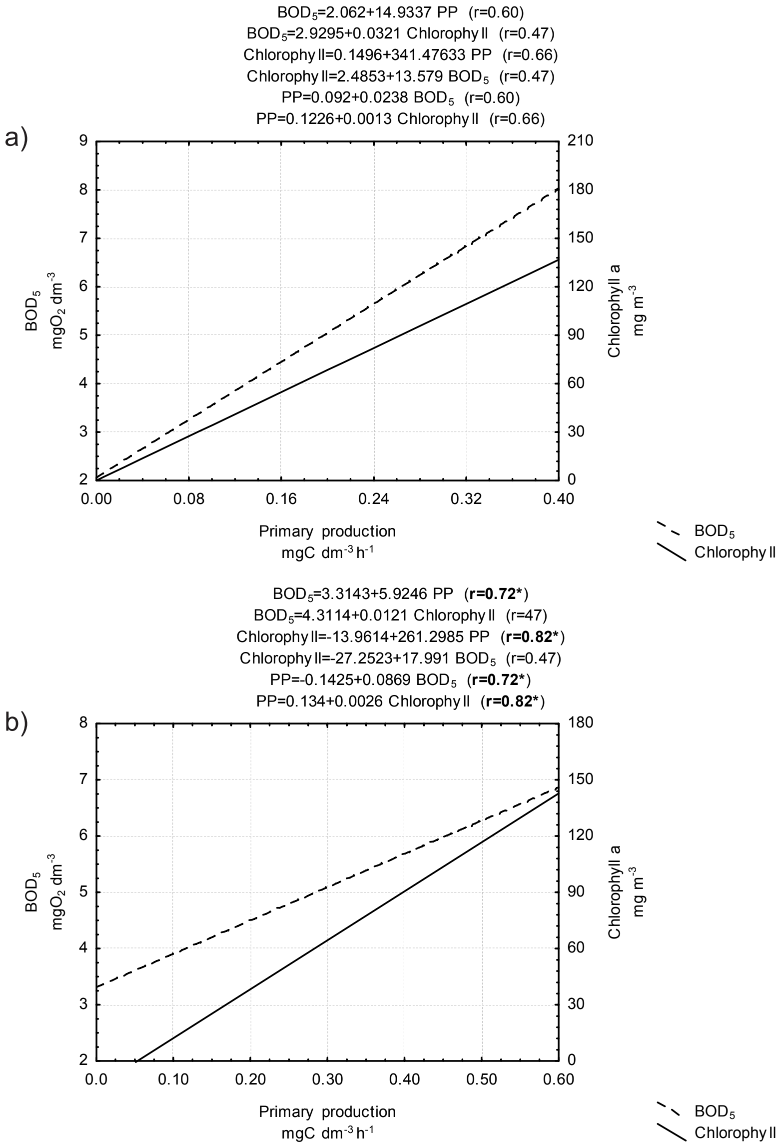

Fig. 3. Interdependencies between BOD_5, chlorophyll *a*, and primary production (a – research site No. 1; b – research site No. 2, * statistically significant correlations).

An increase of temperature in that lake (similarly to an increase observed in research site No. 2) maximally reached up to 30ºC. In the present research, a disparity of chlorophyll *a* concentrations between research site No. 1 and research site No. 2 equaled 4% on average. A considerably higher difference was noted with respect to primary production: it amounted to 27% on average. An increase of primary production observed as a result of an increase of water temperature was similar to data obtained by Benda et al. [29]. The authors observed an increase of primary production by ca. 36% as an effect of comparable increase of water temperature. Morgan and Stross [30] proved that an increase of water temperature by 8ºC stimulated photosynthesis when initial temperature equaled 16ºC or less, and hindered photosynthesis when initial temperature equaled 20ºC or more. In the present study an average increase of water temperature amounted to 6.3ºC and maximum temperatures of water withdrawn for cooling of the power plant ranged from 18.5ºC to 23.0ºC. It can be assumed, after [31, 32], that as far as temperature was concerned (lower than 34ºC) the studied spent cooling water provided favorable conditions both for diatoms (more sensitive to increased water temperature) and for green and blue-green – algae (less sensitive in this respect), for whom optimal temperatures for growth equaled 32-35ºC.

An increase of primary production in waters into which spent cooling water is discharged is conditioned by the availability of biogenic elements. For instance, discharging spent cooling water into Berre Lagoon increased primary production five times during vegetation peak in comparison to primary production noted before the power plant had been built in 1966 [10]. Before 1966 Berre Lagoon was a salt-water reservoir characterized by relatively low production, but functioning of the power plant triggered off signif-

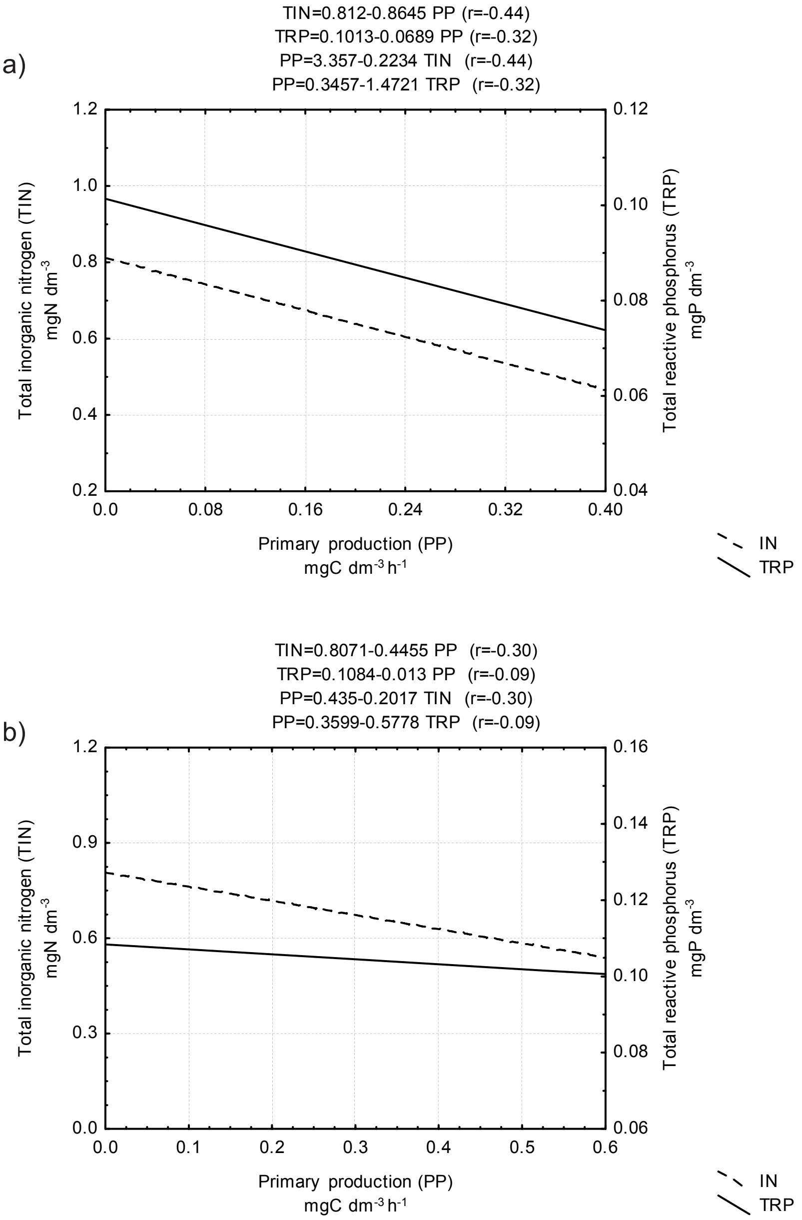

Fig. 4. Interdependencies between inorganic nitrogen, total reactive phosphorus, and primary production (a – research site No. 1; b – research site No. 2)

icant changes in its ecosystem. Discharge of spent cooling water together with domestic and industrial wastewater into the reservoir resulted in a considerable drop in water salinity and a simultaneous increase in suspension and organic matter, thus providing more favorable conditions for mass development of phytoplankton. Before 1966, phytoplankton in that reservoir produced 192 $gC\cdot m^{-2}\cdot yr^{-1}$ [33], and that value was from 2.5 to 4 times lower than values measured in 2006 [10]. Such a considerable increase of primary production was associated by the authors with temperature increase in the lagoon (photosynthetic rates – as assimilation number in grams of carbon/grams of chlorophyll *a* per time – increased with increasing temperature [34]) and availability of biogenic elements. Long-standing accumulation of organic matter as well as N and P in bottom sediments resulted in an increasing significance of internal enrichment of the reservoir with biogenes by means of their recirculation between water and sediments. For instance, nearly 95% of primary production in Berre Lagoon was conditioned by internal nitrogen sources: nitrogen regeneration in the process of its excretion by macrofauna and zooplankton, regeneration of nitrogen from dying biocenoses, and organic matter deposited in sediments [10]. Also, in the case of waters being the focus of this study, an important source of biogenic elements was internal enrichment of water with nitrogen and phosphorus in the course of metabolic processes and exchange between water and bottom sediments, similar to processes taking place in the Odra near Szczecin, and in Dąbie Lake, characterized by a comparably high trophic level [35-37].

Conclusions

Observed concentrations of select hydrochemical indicators and correlations between primary production, chlorophyll *a,* and water temperatures indicate favorable environmental conditions for autotrophs existing in spent cooling water discharged from EDO, both for diatoms and for green and blue-green algae. Further studies may provide the basis for utilizing these autotrophs as biomass.

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