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# Nutrients from beach recreation in the context of the limnological status of a mesotrophic lake

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**Abstract:** The study objective was to analyse the number of tourists present in the shore zone and bathing areas of lakes with regard to their tourist carrying capacity and the amount of biogenic substances potentially entering the ecosystem from the beach and bathing areas. The procedures from project between the EU and Poland, in the module "Development of the sanitary supervision of water quality" were used in three categories: physiological substances – sweat and urine; water-soluble and insoluble organic compounds; and biogenic elements – nitrogen and phosphorus. The research was conducted in two model mesotrophic lakes, Piaseczno and Zagłębocze, located in the Łęczna-Włodawa Lakeland (eastern Poland). The data were analysed in reference to biological trophic status indices defining the limnological status of lakes in the summer of 2014 and 2016. Analyses of gross primary production of phytoplankton using the light and dark bottles method and the analysis of chlorophyll *a* concentration were applied using the laboratory spectrophotometric method. The relatively small number of tourists recorded in the shore zone of both lakes did not exceed their tourist carrying capacity, and their potential contribution of biogenic substances to the lake ecosystems was small. Biological trophic indices for both lakes indicated that they had been continually late-mesotrophic for decades. The amount of biogenic substances directly linked to beach tourism usually has a minor effect on the limnological status of mesotrophic lakes. Due to the specific character of lake ecosystems, however, even small amounts of these substances can contribute to the destabilisation of the biocenotic system.

**Keywords:** beach tourism, eutrophication, lakes, nutrients, physical carrying capacity (*PCC*), trophic state indices (*TSI*)

## INTRODUCTION

The limnological status of lake ecosystems is determined by hydrological and morphometric parameters, physical geographic conditions, and mobilisation of biogenic compounds in the catchment area [Kalff 2002; Serafin *et al.* 2014a, b]. Increasing fluxes of allochthonous biogenic substances to lake water promote eutrophication and adversely affect physicochemical water parameters and the living conditions of many organisms, while reducing the social and economic potential of lakes. Limiting fluxes of these compounds to lakes, after correctly identifying their sources, is key to environmental protection and improvement of water quality [Kalff 2002; Ławniczak *et al.* 2010; Wetzel 2001].

One of the sources of biogenic substances in lake waters is stationary and independent (non-organised) beach tourism [Ginter-Kramarczyk *et al.* 2021]. Many hydrobiological studies underscore the effect of this type of human pressure on the productivity of lake ecosystems, while emphasising its relatively low contribution to the global nutrient balance [Vollenweider 1971; Wetzel 2001]. While these studies usually focus on the influx of biogenic substances from large areas subject to recreational development, a constant supply of even small amounts of biogenic substances affects water quality and may destabilise the primary components of the lake biocenosis, i.e. macrophytes or invertebrate macrofauna [Hadwen *et al.* 2007; Shortreed, Stockner 1990]. Moreover, short-term excessive amounts of nutrients can also facilitate the expansion of algal communities causing temporary water blooms [HADWEN *et al.* 2007; SMITH 1986].

Water blooms caused by cyanobacteria are particularly problematic. Their massive appearance disturbs the homeostasis of the lake ecosystem, conditioning the dominance of one or several phytoplankton species. This causes a loss of species biodiversity of the reservoir. The excess of organic matter in cyanobacteria determines the depletion of oxygen during its decomposition, which leads to the production of hydrogen sulphide under anaerobic conditions – a compound that is deadly for many organisms. The result is the extinction of benthic fauna and other aquatic organisms, e.g. fish die. The effect of blooms is also to reduce the transparency of the water, and thus reduce the depth to which the sun's rays reach, thus limiting the growth of aquatic plants (macrophytes). Mass occurrence of cyanobacteria adversely affects the functioning of aquatic environments and human health, also due to the production of many harmful metabolites. These are, among others, hepatotoxins (causing digestive system and liver disorders), neurotoxins (responsible for disturbances in the functioning of the neuromuscular system), cytotoxins (potential carcinogens) and dermatotoxins (acting on the skin surface). Symptoms and ailments appearing as a result of occasional or chronic contact with cyanobacteria result from the additive or synergistic action of their metabolites. Most often, these compounds penetrate the human body along with cyanobacteria cells, e.g. as a result of accidentally ingesting water or inhaling toxic aerosols while swimming or practicing other water sports. There are also cases of fatal poisoning of people undergoing dialysis with water containing cyanotic toxins. Water blooms therefore reduce the recreational value of bathing waters, lowering the quality of drinking water and posing a potential risk to human health and aquatic organisms [KOBOS *et al.* 2013; MAZUR-MARZEC, PLIŃSKI 2009].

Algae growth is stimulated not only by external factors (nutrient content, temperature, transparency and pH), but also by the hydrodynamic regime of the water body, including water disturbance, and the flow velocity and rate [CALLISTO *et al.* 2014; SENETRA *et al.* 2020]. Such issues are directly related to the effects of tourism in the immediate vicinity of lakes. The location of tourist facilities and activities such as fishing, sunbathing and sailing contribute to the degradation of the area. Among others, the effects are: trampling, littering, changing the shoreline of lakes, disrupting animal reproduction and other effects on the degradation of lake ecosystems [SENETRA *et al.* 2020].

The imbalance in the lake's ecosystem increases the values of biological trophic state indices, such as chlorophyll *a* concentration and gross primary production of phytoplankton [BLOMQVIST 2001; HADWEN *et al.* 2007], and negatively affects the organoleptic properties of lake water, thus reducing the lake's potential for tourism and recreation [GINTER-KRAMARCZYK *et al.* 2021].

The study objective was therefore to analyse tourist traffic at two model mesotrophic lakes in the Łęczna-Włodawa Lakeland (eastern Poland), Lakes Piaseczno and Zagłębocze, in the summer of 2014 and 2016, with regard to the amount of biogenic compounds and organic secretions potentially introduced to the ecosystem from beach recreation, as well as the tourist carrying capacity, based on the number of tourists in the shore zone of the lakes and in public bathing areas. An additional objective was to examine the relationships between these data and the productivity of lake ecosystems measured using biological trophic state indices.

## MATERIALS AND METHODS

Both research sites are model mesotrophic lakes subject to moderate agricultural impact, used in a similar manner for recreation, so their responses to beach and bathing recreation can be considered to objectively model the responses of this type of water body.

Lake Piaseczno is located in the south-western part of the Łęczna-Włodawa Lakeland, in the Ludwin Commune, approximately 13 km north-east of the region's major city, in close proximity to the villages of Rozpłucie, Kaniwola, and Piaseczno (Fig. 1).

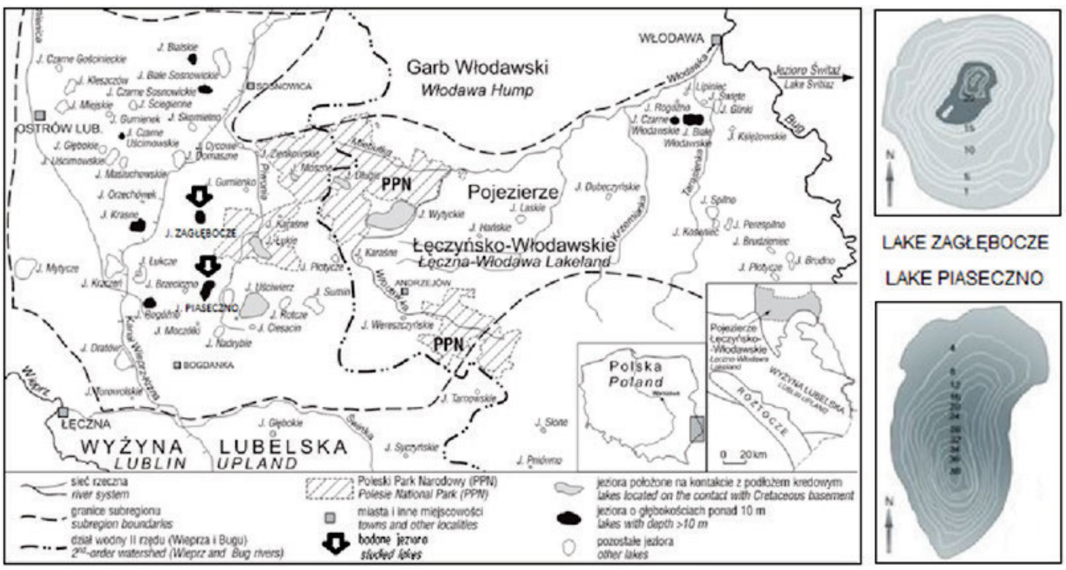


**Fig. 1.** Location of Lakes Piaseczno and Zagłębocze in the Łęczna-Włodawa Lakeland with their bathymetric charts; source: SERAFIN *et al.* [2019], modified

In limnological terms, it is a dimictic, late-mesotrophic lake with an irregular basin, maximum depth of 38.8 m, and a surface area of 85 ha, with a large water capacity (10.67 mln m$^3$) [WILGAT *et al.* 1991]. The water quality is usually good – class I or II, with low susceptibility to degradation – classes I and II (annual reports on the state of the environment of the Lublin Voivodeship (Voivodeship Inspectorate of Environmental Protection, Pol. Wojewódzki Inspektorat Ochrony Środowiska). The land use structure of its catchment area is dominated by natural forms, with a prevalence of forests, meadows and pastures (65%). Arable land accounts for a large share of the land use despite the low fertility of the sandy and permeable podzols, which are the main source of nutrient influx to the lake water [MISZTAL, SMAL 1995]. The lake is surrounded by a narrow belt of sandy beach, often overgrown with common reed (*Phragmites australis*). To the north-west and on the western shore, the lake neighbours on a transitional peatland, formerly active but currently degraded and subject to the pressure of stationary tourism and recreation [SERAFIN 2009]. In 1993, in order to preserve the unique environmental and landscape values of Lake Piaseczno and the adjacent areas, the Council of the Ludwin Commune (by resolution no. XX/114/93) established the "Lake Piaseczno and its vicinity" ecological site, with an area of 1534 ha, additionally increasing the area's appeal to tourists [KRUKOWSKA, KRUKOWSKI 2009].

The lake shore is intensively used for recreation, due to the progressive development of recreational areas, which constituted more than 13% of the catchment area at the end of the 1990s, and currently occupy more than 26% (SENDER and MAŚLANKO [2013], our own observations). In some cases the owners of vacation properties clear the lake shore of shrubbery, creating new sites for recreation.

Lake Zagłębocze is located in the south-western part of the Łęczna-Włodawa Lakeland, in Łęczna County, Ludwin Commune, between the villages of Jagodno and Lejno (Fig. 1). It is a relatively small water body (59 ha) with a capacity of approximately 4,300,000 m$^3$. Due to its maximum depth of 25 m, it is categorised as a deep lake of the Łęczna-Włodawa Lakeland. Zagłębocze is a dimictic lake with low trophic status (late-mesotrophic), and its shoreline shows little diversity [FURTAK, SOBOLEWSKI 1998; SERAFIN *et al.* 2014b]. It was originally an inland lake. As a result of hydrotechnical works associated with the construction of the Wieprz–Krzna Canal system (connecting the rivers of the region), the lake was partially surrounded by embankments and incorporated into the network of irrigation and drainage ditches by digging a drainage ditch functioning at high water stages on the north side. To the south-east, there is a periodically functioning artificial drainage channel directing water to the nearby forests and grasslands [SERAFIN *et al.* 2014b].

The catchment of Lake Zagłębocze consists of agricultural land and forests. Approximately 75% of the catchment area is occupied by meadows, pastures, arable fields, and fallow land, while forests cover more than 20% of the catchment area. Land designated for recreation borders on the lake shore to the east [FURTAK, SOBOLEWSKI 1998]. Apart from the southern shore and a small part of the marshy south-western shore, Lake Zagłębocze is surrounded by a belt of sandy beaches intensively used for recreational purposes (more than 27% of the shoreline is formed by natural beaches).

Due to the exceptional attractiveness of its natural features and landscape, Lake Zagłębocze and its vicinity are included in the Polesie Protected Landscape Area established in 1983 [KRUKOWSKA 2009], and together with Lakes Piaseczno, Białe Włodawskie, Krasne, Rogóźno, and Bialskie, it is a very popular tourist attraction [KRUKOWSKA 2009; KRUKOWSKA, KRUKOWSKI 2009].The potential impact of biogenic substances generated by tourism and beach recreation on Lakes Piaseczno and Zagłębocze was assessed in summer 2014 at the height of the recreational season (eight times from July 5 to 20) and summer 2016 (eight times from July 9 to 24) by analysing the number of tourists present on the shore zone of the lake, on all available beaches of both lakes, both with and without recreational infrastructure.

In accordance with the methodology adopted in earlier studies [SERAFIN *et al.* 2014a, b], tourists were counted at specified times, between 10 and 12 am and between 1 and 5 pm. The results were averaged for one day and for the entire study period.

Based on the number of tourists present at the lakes during the study period, estimated amounts of biogenic substances introduced to the lake were calculated in three categories: physiological substances – sweat and urine; water-soluble and insoluble organic compounds; and biogenic elements – nitrogen and phosphorus.

Materials from Twinning Project PL2005/IB/EN/03 between the EU and Poland, in the module "Development of the sanitary supervision of water quality", were used for the calculations. On this basis it was assumed that 100 bathing individuals potentially introduce to the water 0.1 kg of nitrogen, 5 dm$^3$ of urine, 30 dm$^3$ of sweat, 50 g of insoluble organic pollutants, and 400 g of insoluble organic pollutants, expressed as consumption of $KMnO_4$ [PRĘDOTA 2007].

For the amount of phosphorus potentially entering the lake water during bathing, Szyper and Zaniewska's index was adopted [SZYPER, ZANIEWSKA 1984], equal to 0.457 g P per person.

A descriptive statistical analysis of the results pertaining to the number of tourists was performed, taking into account means, medians, and quartiles, and presented in the form of box plots (descriptions under figures). The standard deviation and coefficient of variance were also calculated as measures of dispersion of the results.

The physical carrying capacity (*PCC*) was calculated for both lakes, determining the highest number of tourists that can occupy a given area in a specific time period with no negative effect on the natural environment [MEXA, COCCOSSIS (eds.) 2004]. The calculations were performed using the formula given by Cifuentes-Arias (CIFUENTES [1992], cited in KOWALCZYK and DEREK [2010]):

$$PCC = A \cdot V/a \cdot Rf \tag{1}$$

where: $A$ = area available to tourists (sandy beach); $V/a$ = number of tourists per m$^2$ that can comfortably stay on the beach [TRAN *et al.* 2007]; $Rf$ = ratio of the time during which the area is available to tourists to the average time spent there per tourist.

We also calculated the tourist carrying capacity of the open bathing areas, for which the threshold value is 20 m$^2$ per person, above which the tourist pressure on the lake ecosystem becomes excessive [OWSIAK *et al.* 2003].

The water surface available to bathers was calculated for each lake as a 30 m strip of coastal water along the entire shoreline (approximately 113,340 m$^2$ for Lake Piaseczno and 86,190 m$^2$ for Lake Zagłębocze). The average number of bathing tourists was calculated on the assumption that each person sunbathing at the beach also spent time in the water during their stay.

The biological trophic state indices of the lake water were tested three times during each summer study period (between 9 and 20 July 2014 and between 13 and 25 July 2016), on the same days that tourists were counted. The water was sampled each time in duplicate at the deepest part of each lake (see Fig. 1), at depths of 0.75 m and 2.5 m. This is the euphotic and trophogenic zone, which is the most susceptible to interactions with the catchment, where production of organic matter in photosynthesis exceeds its consumption in decomposition [Kalff 2002; Wetzel 2001].

Gross primary production of phytoplankton was measured in the laboratory by the oxygen method using light and dark bottles [Vollenweider (ed.) 1969]. Oxygen concentration was determined by Winkler's titration method [Hermanowicz *et al.* 1976], converting data to the amount of carbon assimilated per $m^3$ per hour (mg $C_{ass}$·$m^{-3}$·$h^{-1}$), based on the assumption of Strickland [1960] that 1 g of oxygen released corresponds to 0.312 g of carbon assimilated. Control samples were used to calculate the oxygen concentration at each depth (mg·$dm^{-3}$).

The biological analysis also included the trophic state index of the lake, measured as the chlorophyll *a* concentration, determined in laboratory conditions by spectrophotometry according to Nusch [1980] and expressed in µg·$dm^{-3}$. The data were averaged for the depth profile. In addition to the biological parameters, basic physicochemical water parameters were measured *in situ*: pH (CP 103, ELMETRON pH-meter, Poland), electrolytic conductivity (*EC*) (µS·$cm^{-1}$) (MultiLine P4 WTW, Poland), and water transparency as Secchi disk visibility (*SD*) (m). Air temperature was also measured (°C) with an alcohol thermometer (GERATHERM, Germany). The assimilation number (*AN*) of phytoplankton, as a reliable indicator of trophic state in the pelagic zone, was calculated as the ratio of gross primary production to chlorophyll *a* concentration expressed per unit area ($m^2$) [Ichimura 1968]. Chlorophyll *a* concentrations and Secchi disk visibility were used to determine Carlson's trophic state indices (*TSI* CHL*a* and *TSI SD*) [Carlson 1977].

Principal component analysis (PCA) was performed to analyse the data set and evaluate relationships between the data. The results are presented in diagrams using two scaling methods [Borcard *et al.* 2011]. All statistical analyses were performed in vegan (ver. 2.4-6), ggplot2 (ver. 3.0.0) and car (ver.3.0-2) in the R computing environment [R Core Team 2018].

## RESULTS AND DISCUSSION

An average of 374.38 people per day (in a range of 78–876) were present in the shore zone of Lake Piaseczno throughout the study period in summer 2014. The standard deviation (*SD*) was 322.38, which translated into a high coefficient of variation of nearly 86.13%. A total of 2995 people participated in beach recreation on Lake Piaseczno on the test days. In summer 2016 an average of 245.5 people per day were on the beaches and in the bathing areas of the lake. The range was similar to that noted in 2014 (75–807 people per day), but with a lower standard deviation (277.43) and thus considerable variation in the results ($V$ = 113.01%). The total number of tourists participating in recreation in the shore zone of the lake on the test days was 1964, which was lower than in 2014 (Fig. 2).

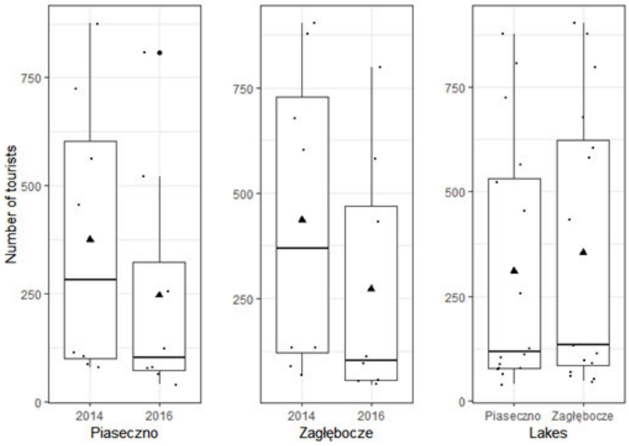


**Fig. 2.** Number of people participating in recreation in the shore zone of Lakes Piaseczno and Zagłębocze in 2014 and 2016 and in the entire study period; the box-and-whisker plots = the distribution of observations; the bottom and top of the box = the first and third quartiles, respectively; the horizontal line across the center of the box = the median; the mean is indicated with a solid triangle; whiskers are drawn to the most extreme observations located no more than 1.5 times the interquartile range from the box; any observation not included between the whiskers is plotted as an outlier, represented by a circle, where there are no outliers; the whiskers indicate the minimum and maximum values; the plot presents observed values of individual observations, indicated by dots; source: own study

In the case of Lake Zagłębocze, the average number of people on the beaches and in bathing areas was higher than for Lake Piaseczno (435.5 people per day in 2014 and 272.12 in 2016). The range of variability of the parameter was higher as well (69–902 people per day in 2014 and 46–798 in 2016). This translated into higher standard deviations (2014: *SD* = 365.65; 2016: *SD* = 292.49) and high coefficients of variation (2014: $V$ = 83.99%; 2016: $V$ = 107.48%). The total number of people participating in recreation on Lake Zagłębocze was also higher than at Lake Piaseczno (3483 in 2014 and 2177 in 2016 – Fig. 2). In accordance with initial expectations, in summer 2014 more tourists were recorded at both lakes on weekends (Piaseczno: 472.2 people per day on weekends vs. 211.3 on weekdays; Zagłębocze: 468.2 vs. 380.6), particularly at higher air temperatures (Fig. 3). This trend

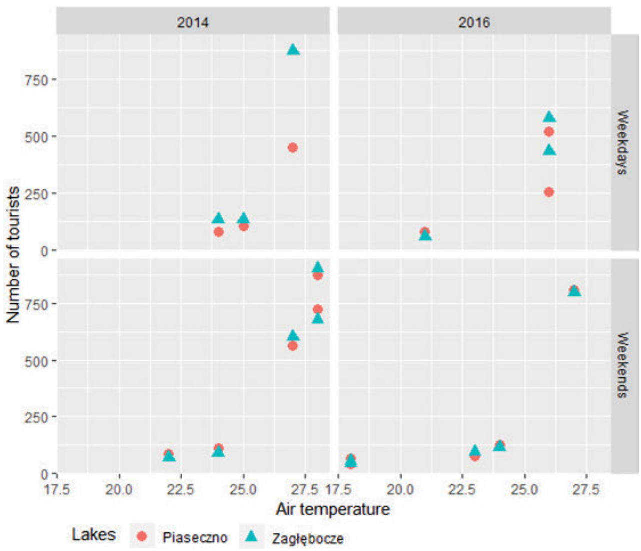


**Fig. 3.** Number of tourists participating in recreation in the shore zone of the lakes in relation to air temperature (°C) and part of the week (weekdays vs. weekends) in summer 2014 and 2016; source: own study

was broken in the 2016 season, when more tourists per day were recorded on the shore zone of both lakes on weekdays (Piaseczno: 221.8 people per day on weekends and 285 on weekdays; Zagłębocze: 221.2 on weekends and 357 on weekdays).

This appears to be explained by weather conditions, especially temperature distribution; higher numbers of tourists are noted at the beaches and in the bathing areas of the lakes at higher temperatures (Fig. 3).

The number of tourists on the beaches of the lakes determined the potential load of biogenic substances introduced to the lake ecosystems, in the following categories: biogenic elements (N and P), soluble and insoluble organic compounds, and physiological substances, i.e. urine and sweat (Figs. 4–6). Due to the linear relationship between the number of vacationers and the amount of substances potentially introduced to the lake, the trends in these values correspond to the trends in the number of tourists (Figs. 4–6). Accordingly, higher values for potentially introduced substances were noted for both lakes in 2014. In the case of Lake Piaseczno, assuming a similar number of tourists for the entire summer of 2014 (90 days), they would potentially

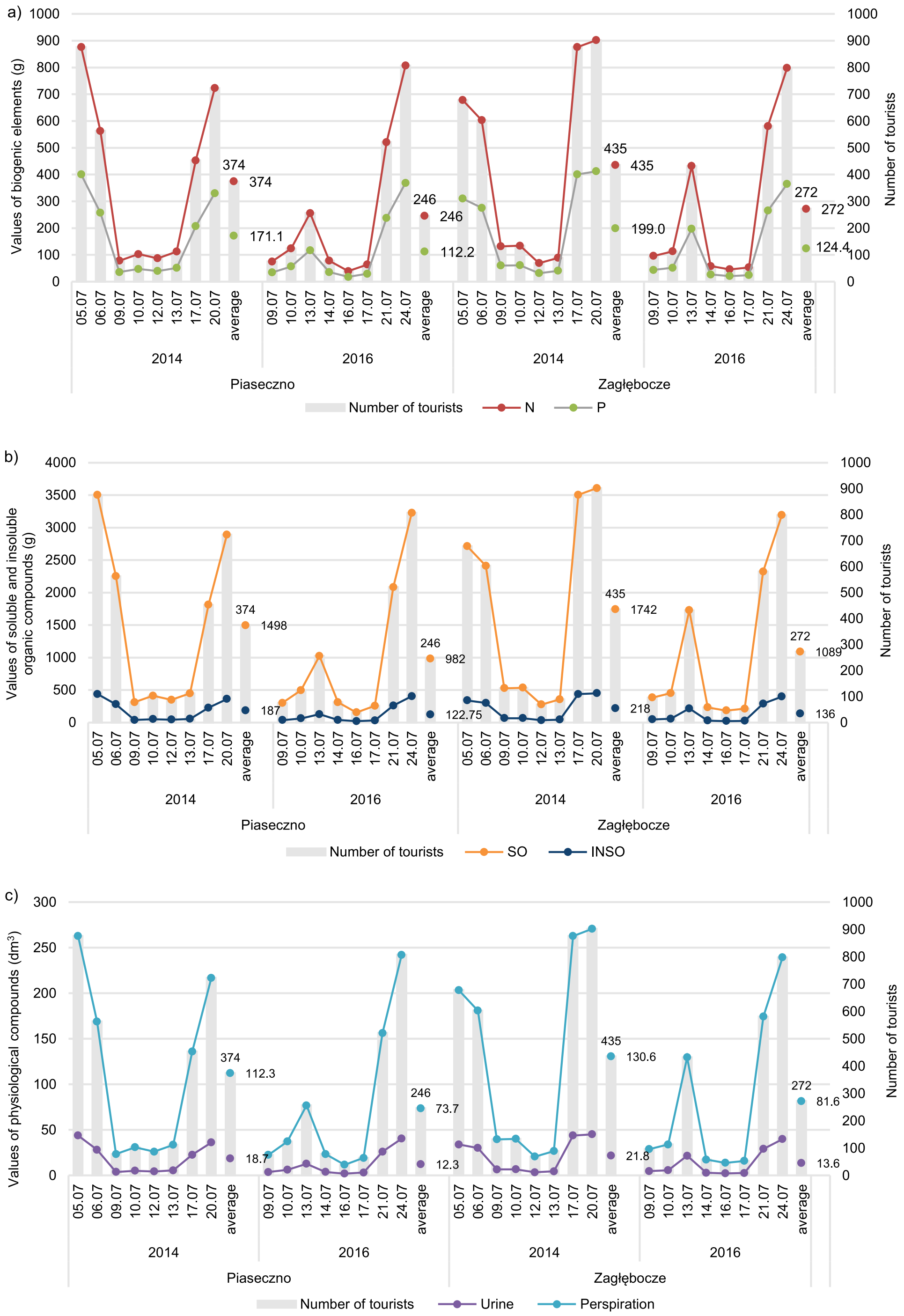


**Fig. 4.** Daily and average seasonal values of chosen parameters potentially introduced by beach tourists to the water of Lakes Piaseczno and Zagłębocze in the summer of 2014 and 2016 in relation to the number of tourists: a) biogenic elements: N = nitrogen, P = phosphorus (g), b) soluble (SO) and insoluble (INSO) organic compounds (g), c) physiological compounds – urine and sweat ($dm^3$); source: own study

introduce 33.69 kg N, 15.4 kg P, 1684.8 $dm^3$ of urine, 10,108 $dm^3$ of sweat, 134.8 kg of soluble organic compounds, and 16.85 kg of insoluble organic compounds to the lake water. In the case of Lake Zagłębocze, the potential load of biogenic substances from the beaches and bathing areas throughout the summer of 2014 was higher: 39.2 kg N, 17.9 kg P, 1959.3 $dm^3$ of urine, 11,754.9 $dm^3$ of sweat, 156.7 kg of soluble organic compounds, and 19.6 kg of insoluble organic compounds.

In 2016, the potential inflow of biogenic substances from beach tourism to the water of both lakes, based on the number of tourists, was about 35.5% lower than in 2014 in the case of Lake Piaseczno and 37.5% lower for Lake Zagłębocze (Fig. 4).

To calculate the physical carrying capacity (*PCC*), we determined the area available to tourists, i.e. the sandy beach (arbitrarily 8880 $m^2$ for Lake Piaseczno and 6780 $m^2$ for Lake Zagłębocze), and the number of tourists per square meter that can comfortably stay at the beach: the value of 9 $m^2$ per tourist (subjective value based on interviews with tourists) was adopted, and thus $V/a = 0.1$ person·$m^{-2}$. The beaches were assumed to be available for 16 h, and the average stay of one tourist was 5 h (survey data); therefore, $Rf = 3.2$. The *PCC* for the beaches of Lake Piaseczno was 2841.6 people per day able to participate in recreation in such conditions with no detrimental effect on the lake ecosystem. The corresponding value for the beaches of Lake Zagłębocze was 2169.6. In the case of both lakes in summer 2014 and 2016, neither the average number of tourists participating in recreation at the beaches and in the bathing areas nor the number of tourists on each test day exceeded the *PCC* value. This was also reflected in the physical carrying capacity of the open bathing areas: for Lake Piaseczno 0.06 person per 20 $m^2$ in 2014 and 0.04 person per 20 $m^2$ in 2016, and for Lake Zagłębocze 0.1 person per 20 $m^2$ in 2014 and 0.06 person per 20 $m^2$ in 2016, which did not exceed the threshold value of 1 person per 20 $m^2$. In the case of the biological trophic state indices, the average gross primary production of phytoplankton and the chlorophyll *a* concentration were higher in 2016. This was accompanied by a higher average number of tourists at the beaches and in the bathing areas of both lakes on the test days (Fig. 5). In 2014 the biological trophic state indices were lower for Lake Piaseczno than for Lake Zagłębocze, while in 2016 they were comparable for both lakes (Fig. 5).

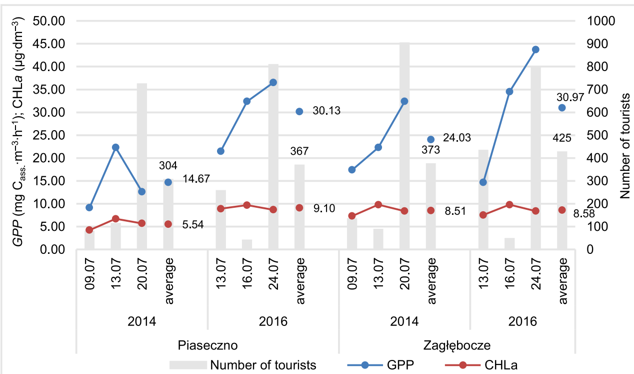


**Fig. 5.** Daily and average seasonal values of biological trophic state indices: gross primary production of phytoplankton (*GPP*, in mg $C_{ass}$·$m^{-3}$·$h^{-1}$) and chlorophyll *a* concentration (CHL*a*, in µg·$dm^{-3}$) for Lakes Piaseczno and Zagłębocze in the summer of 2014 and 2016 in relation to the number of tourists; source: own study

The physical and chemical water parameters of both lakes in both summers were typical for mesotrophic lakes (Fig. 6): average pH 6.17–6.60, electrolytic conductivity (*EC*) 84.33–111.57 µS·$cm^{-1}$, oxygen concentration ($O_2$) 8.28–9.70 mg·$dm^{-3}$, and water transparency measured as Secchi disk visibility (*SD*) 3.10–4.84 m (Fig. 6).

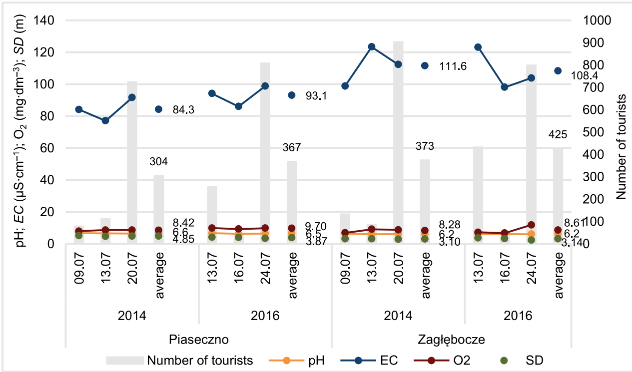


**Fig. 6.** Daily and average seasonal values of physical and chemical water parameters: reaction (pH), electrolytic conductivity (*EC*, in µS·$cm^{-1}$), oxygen concentration ($O_2$, in mg·$dm^{-3}$), and water transparency as Secchi disk visibility (*SD*, in m) for Lakes Piaseczno and Zagłębocze in the summer of 2014 and 2016 in relation to the number of tourists; source: own study

The average values of most of the physical and chemical water parameters (except *EC*) were higher in Lake Piaseczno in both years of the study. In that lake, high average *EC* and oxygen concentration were recorded in the summer of 2016. Low average values that summer were noted for pH and *SD*, corresponding to the number of tourists at the beaches and in the bathing areas. For Lake Zagłębocze in 2016, high average summer values were found for oxygen concentration and water transparency, with a high average number of tourists. The average pH was the same as in 2014, while *EC* was higher in 2014 (Fig. 6).

The biological trophic state indices of the water (*GPP* and CHL*a*) and the water transparency measured as Secchi disk visibility (*SD*) were used to calculate additional reliable indices of the trophic state of the lake water: Ichimura's assimilation number (*AN*) and Carlson's trophic state indices (*TSI* CHL*a* and *TSI SD*).

The ranges of means for both lakes and both seasons were as follows: *AN* = 2.183.02, *TSI* CHL*a* = 47.22–52.25, and *TSI SD* 37.26–43.8. In both study seasons, the average values of these indices were higher in most cases for Lake Zagłębocze, except for summer 2016, when *TSI* CHLa was higher for Lake Piaseczno (Fig. 7).

Principal Component Analysis (PCA) was used to analyse the physical and chemical properties of the water and its biological trophic state indices in relation to the number of tourists. The ordination analysis included a set of observations consisting of air temperature (*AT*), water acidity (pH), water transparency as Secchi disk visibility (*SD*), electrolytic conducivity (*EC*), oxygen concentration ($O_2$), gross primary production (*GPP*), chlorophyll *a* concentration (CHL*a*), and number of tourists (*NT*).

The first two PCA axes explained 71.28% of the total variance in the dataset (PCA1: 45.35%; PCA2: 25.93%). *EC* and *GPP* seem to be the major contributors to the positive part of first

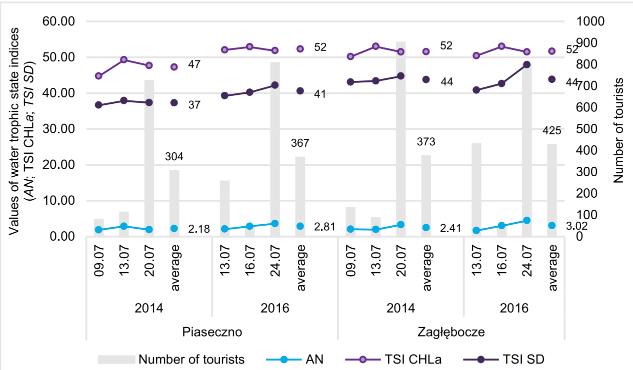


**Fig. 7.** Daily and average seasonal values of water trophic state indices: assimilation number (*AN*) and Carlson's trophic state indices (*TSI* CHL*a* and *TSI SD*) for Lakes Piaseczno and Zagłębocze in the summer of 2014 and 2016 in relation to the number of tourists; source: own study

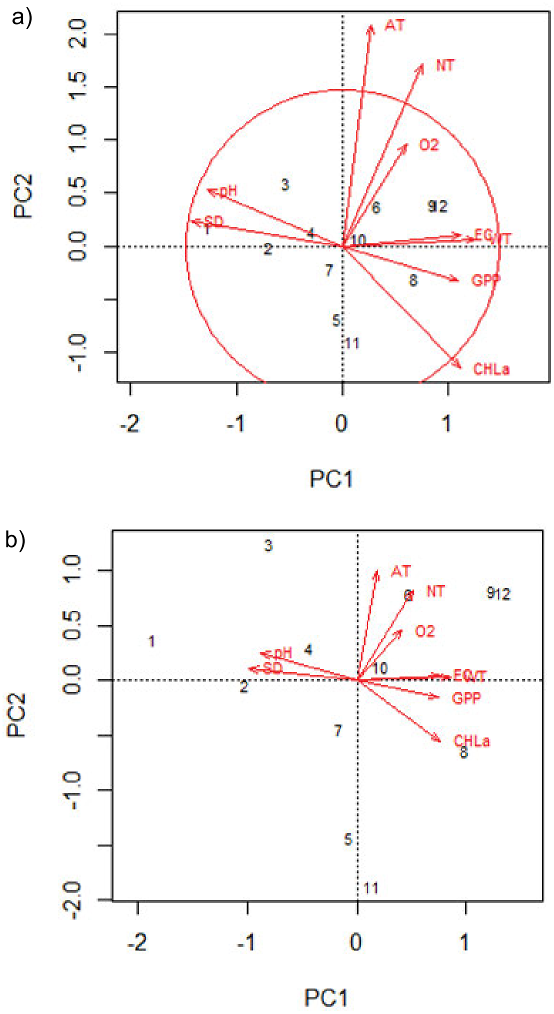


**Fig. 8.** Principal component analysis (PCA) biplot of the dataset: a) distance biplot (scaling 1) with circle of equilibrium contribution, b) correlation biplot (scaling 2); numbers indicate observations obtained for the lakes in the summer of 2014 and 2016: 1–3: Lake Piaseczno (2014), 4–6: Lake Piaseczno (2016), 7–9 Lake Zagłębocze (2014), 10–11: Lake Zagłębocze (2016); source: own study

component (PCA1), and *SD* and pH to the negative part (Fig. 8a). The second principle component PCA2 was strongly positively associated with *AT* (Fig. 8a). The biplot (Fig. 8b) indicates a strongly negative correlation between pH and *GPP* and between *SD* and *GPP*. Strong positive correlations were also observed between pH and *SD*; *EC* and *GPP*; and *NT* and $O_2$. We found near-zero correlations between *GPP* and *AT*; pH and *NT*; and *GPP* and *NT*. The biplot (Fig. 8a) shows a gradient from left to right, starting with a group formed by observations 1–4 (from Piaseczno), which display the highest *SD* and pH values and the lowest values for *EC*, *GPP*, and CHL*a*. On the other side, the group of observations (8, 9, 12 – all from Zagłębocze) has the highest values for *EC* and WT and the lowest for pH and *SD*. All observations (except for 7) from Lake Zagłębocze were grouped on the positive side of the first component, PCA1. This means that their values oscillated in varying degrees above average seasonal values.

MacCannell [2002] describes the phenomenon whereby areas with valuable natural and landscape features, often under protection, attract large numbers of tourists, and the maximisation of tourist traffic results in damage to the environmental features originally contributing to the site's appeal to tourists [Maślanko et al. 2011; Sun, Liu 2020].

Many regions in which tourism is the primary source of income have reached a level of environmental degradation that discourages tourists, leading to a decline in tourism and degradation of tourism infrastructure [Aktaz, Domnez 2019]. Only a sustainable tourism model provides a beneficial compromise between protecting the environment and enjoying its benefits. While meeting the fundamental objectives of recreational tourism, it does not exceed the compensatory capacity of the environment of the tourist area [Ouattara *et al.* 2019; Puczkó, Rátz 2000]. Tourism benefitting from the attractive natural features of surface water landscapes is unquestionably one of the oldest forms of tourist traffic [Potocka 2013]. Seaside, riverside, and lakeside areas are very popular with tourists, in Poland and around the globe [Koźmiński, Michalska 2016; Piasecki, Tomczykowska 2014].

Lake tourism is defined as tourism associated with lakes themselves and the surrounding areas, and includes all forms of tourism and recreational activity in the water, e.g. water sports and bathing, and on the surrounding land, such as walking, sunbathing, or cycling [Piasecki, Tomczykowska 2014]. Especially important in this context is analysis of types of lake tourism to determine what motivates tourists to choose a specific recreational site [Młynarczyk, Borkowski 2015]:

- tourism motivated exclusively by the lake itself (the lake *per se*), with tourist infrastructure and other forms of activity having no effect;
- tourism based on the existence of the lake (the lake as a resource), making use of the infrastructure developing around it;
- tourism developing in the vicinity of the lake (lake as a desirable backdrop, an added opportunity or scenery), where the recreation system is more important than the presence of the water body.

The Łęczna-Włodawa Lakeland, with its diverse forms of nature conservation owing to its valuable natural features and landscape, as well as its tourism and recreation infrastructure, is one of the most important tourist regions in eastern Poland, highly suitable for many types of tourism and recreation [Krukowska, Krukowski 2009; Krukowski, Krukowska 2013; Maślanko *et al.* 2011]. These primarily include various types of lake tourism. Due the increasing number of tourists on the beaches of many lakes in the Lakeland, in combination with the increase in the investment area and excessive pressure from various forms of tourism and recreation, the natural tourist carrying capacity of the sites is often exceeded [Krukowski, Krukowska 2013].

The lakes of the Łęczna-Włodawa Lakeland with exceptional recreational value, which are very popular among tourists, primarily include Lakes Piaseczno, Białe Włodawskie, Krasne, Rogóźno, and Zagłębocze [Krukowska, Krukowski 2009].

In the case of Lakes Piaseczno and Zagłębocze, intensive recreational use of the water body involves independent, non-organised tourism, dominated by beach recreation and bathing [Chmielewski 2001; Serafin *et al.* 2014a; b], which exerts physical, chemical, and biological effects on the lake ecosystem as well as the coastal areas [Hadwen *et al.* 2007].

In this respect, Lake Piaseczno was already one of the most crowded lakes of the Łęczna-Włodawa Lakeland in the mid-1990s, when there were more than 7000 tourists on the beaches on weekends [Chmielewski 2001]. At that time, despite the highly favourable topographic and hydrometric parameters making the lake resistant to environmental changes [Kudelska *et al.* 1997], numerous changes were observed that suggested increasing eutrophication of the water. These involved fluctuations in the productivity of the lake ecosystem [Serafin 2009; Wojciechowski *et al.* 1995], dominance of filamentous forms of algae, e.g. *Planktothrix rubescens*, causing periodic blooms indicative of eutrophication [Wojciechowski *et al.* 1995], and fluctuations in the retention of biogenic substances in communities of psammon algae [Czernaś 2001; Serafin, Czernaś 2003]. Moreover, there was an increase in the area inhabited by macrophytes, particularly emergent ones, and their homogenisation [Pieczyńska 1998; Sender *et al.* 2017]. All of these phenomena suggest limnological destabilisation of the lake, which may result in deterioration of its recreational value. It is worth emphasising that disturbances of environmental parameters can lead to catastrophic deregulation of systems associated with the current stable trophic state of the lake [Zeng *et al.* 2017].

In the case of Lake Zagłębocze, the numbers of tourists participating in beach recreation in the 1990s exceeded the natural tourist carrying capacity of the lake, sometimes threefold, resulting in numerous changes in the phytocenoses surrounding the lake [Chmielewski (ed.) 2000]. They did not, however, affect the lake itself [Grzywna 2002]. Like Lake Piaseczno, Lake Zagłębocze has a high compensatory capacity [Kornijów *et al.* 1993], supported by favourable morphological conditions in the catchment (considerable depth, complete thermal stratification, a low annual water exchange rate, the absence of point sources of pollutants, and a predominance of forests). Owing to these factors, the lake maintains high water quality (class I or II) and low susceptibility to degradation (class I or II) [Grzywna 2002].

In the summer of 2014 and 2016, the number of tourists at the beaches and in the bathing areas of Lakes Piaseczno and Zagłębocze reached a maximum of 12.5% of the numbers from the 1990s, and was just over half of the numbers noted in 2008 and 2010 [Serafin *et al.* 2014a; b]. Upward trends in summer recreation on weekdays relative to weekends were observed as early as the mid-1990s, when the level of weekend tourist traffic exceeded the number of tourists on weekdays by 35%, and at the end of the decade by only 26%, suggesting greater recreation pressure on the areas with summer houses and recreation centers [Chmielewski 2001]. Direct observations indicate that the number of tourists on the beaches of the lakes in 2014 and 2016 was linked more to weather conditions than to the day of the week, with higher air temperatures attracting more tourists to the lakes. Irrespective of the day of the week, at temperatures >25.5°C, about 75% more tourists were present at the lakes than at lower temperatures. According to interviews with beachgoers, owners and users of vacation property account for a small share of tourists in the shore zone of the lakes. Given the intensive development of this type in the catchments of both lakes, this suggests an increase in recreation pressure in the immediate vicinity of summer cottages.

Nevertheless, the relatively small number of tourists on the beaches and in the bathing areas of the lakes translated into a potential load of various biogenic substances introduced to the lake water. Data on the potential load of N and P originating in beach recreation and bathing can be compared to the amount of biogenic substances potentially generated from various types of catchment areas (the unit coefficients of the export of surface loads of biogenic substances in kg·ha$^{-1}$·year$^{-1}$) proposed by Soszka [2010].

In this context, the amounts of biogenic substances originating in beach recreation and bathing in 2014 and 2016 potentially account for only a small portion of the influx of substances to the lakes. The unit coefficients of the export of surface loads of biogenic substances from the catchment area of Lake Piaseczno (285 ha) showed that the annual load of biogenic substances entering the lake was 1151.1 kg N and 42.49 kg P [Serafin *et al.* 2019]. The maximum amount of biogenic substances from beach recreation could potentially reach approximately 170.49 kg N·year$^{-1}$ and 77.91 kg P·year$^{-1}$ (arbitrarily assuming 30 days a year with maximum pressure from beach recreation) [Serafin *et al.* 2019].

In the case of the considerably larger catchment of Lake Zagłębocze (463.6 ha), with substantial prevalence of grassland and forest and a slightly smaller area of arable fields, differences between the amount of potential biogenic substances originating in beach recreation/bathing and biogenic substances of other origins are substantially higher.

It should be emphasised, however, that tourists could also have introduced unspecified amounts of other organic pollutants, e.g. hair, skin, saliva, mucous, vomit, parasites, and microorganisms, as well as dust and residues of cosmetics, detergents, and textile fibers [Dokulil 2014; Prędota 2007], which can additionally affect the limnological status of lakes.

The number of tourists at the beaches of Lakes Piaseczno and Zagłębocze also did not exceed the physical carrying capacity (*PCC*) calculated for the lakes, which was well above 2000 people per day potentially able to enjoy recreation in comfortable conditions (subjectively determined as 1 person per 9 m$^2$, sufficient space for all present to take part in their chosen form of recreation undisturbed by others) without harming the lake ecosystem. The *PCC* depends in part on the subjective feelings of tourists (what they consider a comfortable space) and thus provides only subjective information regarding pressure on the water body from tourism. The small number of tourists was also reflected in the tourist carrying capacity of the open bathing areas, reaching a maximum of 0.1 person per 20 m$^2$ (Zagłębocze 2016), i.e. only a tenth of the threshold value representing a significant effect on the lake ecosystem according to Owsiak *et al.* [2003].

Because lakes are ecosystems whose functioning depends on the influx of allochthonous substances from the catchment, their amount, metabolism, and accumulation in the water determine the productivity of the ecosystem and thus the trophic state of the water [KALFF 2002; WETZEL 2001]. It is worth noting, however, that the inflow of biogenic substances from beach recreation to the lake ecosystem in the littoral zone (the primary bathing area) could be influenced by the presence of lake macrophytes, which can directly modify the habitat conditions in the water (light, temperature, and pH) and directly compete with algae through uptake of biogenic substances and allelopathy [SENDER, MAŚLANKO 2013; SERAFIN *et al.* 2019]. Lake macrophytes thus constitute a kind of biochemical barrier for recreational pressure on the lake. The presence of macrophytes could also stimulate the zooplankton concentration, which is a limiting factor for phytoplankton, thus reducing the potential for water bloom [SERAFIN *et al.* 2019].

At Lakes Zagłębocze and Piaseczno, the littoral vegetation is represented mainly by communities of *Nitelletum flexilis*, *Elodeetum canadiensis*, *Myriophylletum alterniflori*, *Ceratophylletum demersi*, *Eleocharitetum palustris*, *Phragmitetum*, and *Typhetum angustifoliae*, which are typical of the mesotrophic lakes of the Łęczna-Włodawa Lakeland [SENDER, MAŚLANKO 2013; SERAFIN *et al.* 2019].

Therefore measures of the productivity of the lake ecosystem, i.e. gross primary production of phytoplankton, chlorophyll *a* concentration, assimilation number [KALFF 2002; SERAFIN, CZERNAŚ 2003; WETZEL 2001], and Carlson's trophic state indices (*TSI* CHL*a* and *TSI SD*), can serve as indirect indicators of the intensification of water eutrophication associated with the inflow of biogenic substances from the catchment, determining the current limnological status of the lake. Gross primary production of phytoplankton (*GPP*) in the summer of 2014 and 2016 for the adopted depth profile of 0.75–2.50 m in Lakes Piaseczno and Zagłębocze, converted to mg $C_{ass}·m^{-2}·d^{-1}$ (assuming 14.5 h of daylight in the summer as per CZERNAŚ *et al.* [1991]), ranged from 327.26 to 973.24 mg $C_{ass}·m^{-2}·d^{-1}$, indicating that both lakes were mesotrophic (acc. to WEZEL [2001]).

For comparison, similar research in the pelagic zone of Lake Piaseczno in the years 1985–1989 showed gross primary production of phytoplankton ranging from 1087 to 5800 mg $C_{ass}·m^{-2}·d^{-1}$, indicative of hypertrophic phenomena in the lake [CZERNAŚ *et al.* 1991]. By 2001–2002, however, the maximum value was just 1044 mg $C_{ass}·m^{-2}·d^{-1}$, suggesting that there was no significant intensification of water eutrophication in Lake Piaseczno [SERAFIN, CZERNAŚ 2003].

The chlorophyll *a* concentrations in the summer of 2014 and 2016 in Lakes Piaseczno and Zagłębocze confirmed their mesotrophic limnological status. For Lake Piaseczno, the values were similar to those noted in the 1990s [WOJCIECHOWSKI *et al.* 1995].

However, the average seasonal values of all biological trophic state indices were found to increase as the number of tourists increased in 2014 and 2016. As there is a certain delay in the response of lake metabolism to changes in the nutrient balance [KALFF 2002; WETZEL 2001], this may reflect earlier fluctuations in the amount of inflowing allochthonous matter from the catchment from various sources.

Measurements of the basic physical and chemical water parameters (pH, *EC*, $O_2$, and *SD*) in both study seasons, which were more or less variable, revealed no negative phenomena associated with eutrophication of the lakes, as they were indicative of a low trophic state, and in the case of Lake Piaseczno did not deviate from the values obtained in 2000–2003 [SERAFIN 2004].

Additional indicators of the limnological status of the lakes, such as biological trophic state indices and Secchi visibility (*SD*), provided inconclusive information. The values were varied, suggesting that the trophic state of the water was varied. This was particularly evident in the case of the assimilation number (*AN*), which for both lakes and both study seasons ranged on average from 2.18 to 3.02, which according to ICHIMURA [1968] indicates a eutrophic state (although not advanced). The means for Carlson's trophic state indices (*TSI* CHLa and *TSI SD*) suggested a considerably lower degree of eutrophication in both lakes (mesotrophy). The latter index was shown to be less sensitive in the 1990s, when it indicated that the limnological status of Lake Piaseczno was oligotrophic (*TSI SD* = 38.3) [KORNIJÓW 1997] despite observations of biocenotic transformations in the lake suggesting an early-mesotrophic state as early as the mid-1970s [WOJCIECHOWSKI 1976], and a late-mesotrophic state by the 1990s [WOJCIECHOWSKI *et al.* 1995].

The information presented above suggests that the amount of biogenic substances directly linked to beach tourism generally had a minor impact on the limnological status of these two mesotrophic lakes during the study period. Determination of all recreational sources of influx of nutrients to lake water must take into account other forms of recreational use of lake catchments, e.g. land development for summer houses, which was particularly evident in the case of Lake Piaseczno. For this purpose, land in the vicinity of the eastern shore of Lake Piaseczno that had still been used for agriculture in the early 1990s was divided into plots on which over a thousand vacation homes were built. Due to the permeability of the sewage systems (septic tanks), these often leached substantial amounts of sewage into the soil [MISZTAL, SMAL 1995]. These trends are currently even more pronounced due to the fragmentation of recreational plots and the increase in construction of vacation homes.

On the other hand, due to the open character of the lake ecosystem, the introduction of even small amounts of pollutants to its metabolism may destabilise the biocenoses of lakes [AKTAS, DONMEZ 2019; DOKULIL 2014; SOSZKA 2010; WETZEL 2001] and thus alter their limnological status. It is crucial to determine all components of the balance of biogenic compounds and decrease their load supplied to the lake in order to improve water quality and counteract the degradation of lake ecosystems, thereby ensuring that they can be used for economic purposes, including recreation [HADWEN *et al.* 2007]. Moreover, owing to the specific hydromorphometric parameters of lakes in combination with the topographic conditions of their catchments, the internal metabolism may have an exceptionally high capacity to compensate for the effect of even substantial amounts of biogenic substances from various sources. This is exemplified by the lakes analysed in this study, which have maintained their low trophic status for many years.

## CONCLUSIONS

1. The number of tourists participating in beach recreation at the lakes was linked to weather conditions, particularly air temperature. It was less dependent on the part of the week (weekday or weekend).

2. The physical carrying capacity (*PCC*) and tourist carrying capacity of the open bathing areas were not exceeded during the study period, which suggests that the pressure of beach recreation on the lakes was most likely minor.
3. Values of biological trophic state indices recorded during the study period, as well as supplementary indices (assimilation number – AN and trophic state indices – *TSI*), in combination with basic physical and chemical water parameters, showed no fluctuations in the limnological status of the lakes.
4. There was a clear upward trend in the average values of biological trophic state indices when the average number of beach tourists was higher.
5. The amount of biogenic substances directly linked to beach tourism depends on the number of tourists in the shore zone and usually has little effect on the limnological status of mesotrophic lakes.
6. Determination of all components of the balance of biogenic compounds and a reduction in their load supplied to the lake is of fundamental importance for improvement of water quality and its economic use.

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