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TROPHIC STATE OF A SHALLOW LAKE WITH REDUCED INFLOW OF SURFACE WATER

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Abstract: According to the general classification of shallow eutrophic lakes, two alternative types are distinguished: phytoplankton-dominated and macrophyte-dominated lakes. The latter type is rare and currently endangered by human activity. In order to determine the effect of reduced inflow of surface water by an earth dyke on the lake trophic state, certain biological and physico-chemical parameters were evaluated. This work focuses on two lakes of similar morphometric characteristics situated in the agricultural landscape. The effect of the earth dyke on the trophic state was positively verified. The lake situated in the catchment basin, in which the inflow of surface water was reduced, was defined as meso-eutrophic, with a small amount of phytoplankton and high water transparency. The reference lake was highly eutrophic, with low water transparency and a large amount of phytoplankton. The water body surrounded by the earth dyke was macrophytes dominated (65% of the lake area), whereas the reference lake was a phytoplankton-macrophyte type (42% of the lake area). The trophic evaluation of a lake can be underestimated because of a significant amount of biogenic compounds accumulated in plant tissues. Thus, the values of Carlson's indices in macrophyte-dominated lakes may not account for the total amount of nutrients in the water body.

INTRODUCTION

Small and shallow lakes are commonly affected by anthropogenic pressure. Nutrients originating from the catchment basin change the functioning of lakes, stimulate the phytoplankton development and negatively influence the submerged vegetation [17, 28].

There are two main groups of primary producers in lake ecosystems: phytoplankton and macrophytes. Both groups compete for resources limiting the plant development, such as light and nutrients. The more phytoplankton in the water, the less light is available to macrophytes. On the other hand, if the main primary producers are macrophytes, the phytoplankton contribution is highly limited and consequently the water is highly transparent and poor in biogenic compounds.

For that reason, two alternative states occur in shallow eutrophic lakes: the phytoplankton dominated state with mass appearance of algae called "water blooms" and the macrophyte dominated state with abundant development of aquatic vegetation [30].

The latter state is desirable due to a relatively high biological diversity, the opportunity of fishing, the recreational and agricultural use. In addition to natural factors, water bodies are commonly affected by anthropogenic eutrophication [9, 21]. Unfortunately, macrophyte dominated lakes are currently endangered by human activity, e.g. land use and agriculture. Therefore, restoration measures are needed to improve the water quality and functioning of lakes.

In some cases, changes in the area adjacent to a lake can positively influence the state of a lake ecosystem [13]. Restriction of drainage from a catchment basin can reduce the input of nutrients and contribute to lake re-eutrophication [35].

The objective of the present study was to estimate the effect of an earth construction situated in a catchment basin on the trophic state of a lake, based on two main groups of primary producers − phytoplankton and macrophytes, and physico-chemical parameters.

METHODS

The study was carried out in two lakes, Czarne (51°29’ 08” N, 22°56’ 34” E) and Głębokie (51°28’ 34” N, 22°55’ 23” E), located near the village of Uścimów, in the West Polesie region (Eastern Poland) [14]. The lakes are situated in the close proximity, ca. 1 km from each other, and have similar morphometric characteristics (Table 1). Both lakes are situated in the agricultural landscape, although Lake Czarne is located between fishery ponds and since the 1950s it is surrounded by the earth dyke, whereas Lake Głębokie (the reference lake) − by fields (Fig. 1) [7, 8]. The earth dyke was built in order to storage the water from the Wieprz-Krzna Canal, but Lake Czarne has never been used as the water reservoir. The fishery on these lakes is poorly-developed.

Table 1. Morphometric characteristics of studied lakes by Wilgat et al. [33]

Lake	Area (ha)	Length (m)	Mean width (m)	Depth (m)		Volume (10^3 m^3)	Mean slope inclination
				max	mean		
Czarne	24.8	596	416	10.3	3.7	915	2º 20’
Głębokie	20.5	585	350	7.1	3.4	689	2º 10’

In order to estimate the trophic level, as well as the importance of phytoplankton as a primary producer in the water, both lakes were sampled biweekly from May to August in 2010 and 2011. The sampling points were located in the sublittoral zone of the lakes. The water transparency was measured *in situ* with the Secchi disk (SD). All water samples for chemical and biological analysis were collected with the Ruttner type water sampler (2.0 dm^3 capacity), from the water surface to a depth of 3 m at 1 m intervals, and poured into one collective sample. Next, in the laboratory, the concentration of chlorophyll-*a* (Chl-*a*) was determined according to the standard method [22], and chemical analyses of total nitrogen (TN) and total phosphorus (TP) were performed according to colorimetric methods [10].

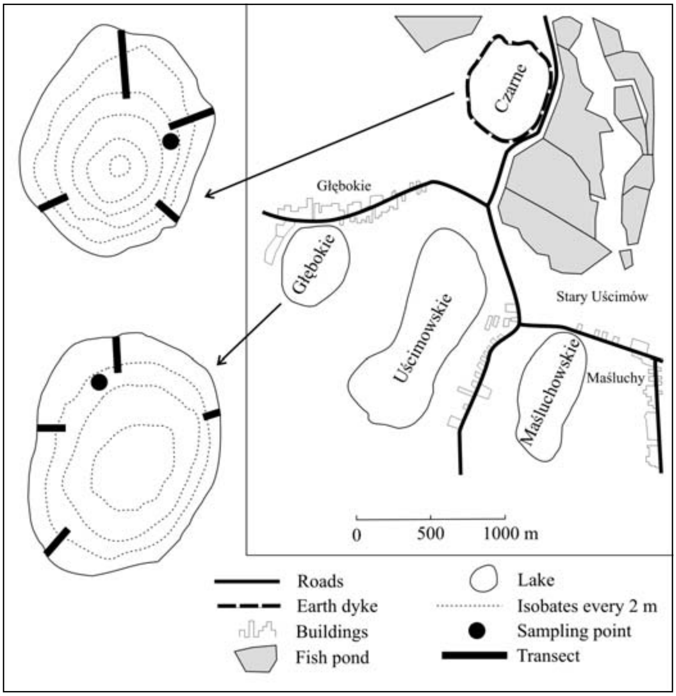

Fig. 1. Study area and localisation of sampling points

Based on the physico-chemical (TN, TP, SD) and biological (Chl-*a*) data, trophic state indices (TSI) were calculated using the equations described by Carlson [3] and Kratzer and Brezonik [16]:

$$TSI\ (CHL) = 30.6–9.81\ \ln(CHL),$$
$$TSI\ (SD) = 60–14.41\ \ln(SD),$$
$$TSI\ (TP) = 4.15–14.42\ \ln(TP),$$
$$TSI\ (TN) = 54.45–14.43\ \ln(TN).$$

Vegetation cover in both lakes was studied in June-July 2011 in four transects located evenly in the phytolittoral zone, each of them running from the lake shores to the maximum depth of macrophyte colonization (Fig. 1). Geographical coordinates were determined with a GPS receiver (Garmin 60Cx) and next, measurements of macrophyte distribution in the lakes were taken with the MapSource Trip & Waypoint Manager program. The area covered with aquatic macrophytes was calculated using bathymetric plans of the lakes [33].

Differences in the amount of phytoplankton (determined by chlorophyll-*a* concentration) and Secchi disk values in the lakes were evaluated with Wilcoxon's nonparametric test. The effect of chlorophyll-*a* concentration on water transparency was evaluated by Spearman's rank correlation test. Calculations were performed according to Sokal and Rohlf [31] with Statistica 9.

RESULTS

Water transparency and the amount of phytoplankton measured by chlorophyll-*a* concentration were different in the studied lakes (Wilcoxon's test in both cases Z = 3.52, p<0.001). Mean value of chlorophyll-*a* in Lake Czarne was much lower (9.5 µg dm^{-3}) and water transparency was much higher (2.95 m) than in Lake Głębokie (36.8 µg dm^{-3} and 1.2 m, respectively). The lowest chlorophyll-*a* concentrations (4.4–8.0 µg dm^{-3}) were observed in Lake Czarne, whereas the highest (often above 30 µg dm^{-3}) in Lake Głębokie (Fig. 2).

Vegetation covered approximately 65% of the bottom in Lake Czarne. In the lake surrounded by the earth dyke, the abundance of the main macrophyte groups: helophytes, nymphaeids and elodeids, was similar (Fig. 3). The submerged vegetation, which was the most abundant macrophyte group in the water body, covered 22% of the lake to the maximum depth of 4.5 m. Elodeids in Lake Czarne included *Ceratophyllum demersum* L., *Myriophyllum spicatum* L. and *Stratiotes aloides* L. Nymphaeids, such as *Nymphaea candida* C. Presl., *Nuphar lutea* (L.) Sibth. & Sm. and *Potamogeton natans* L., were also abundant; they accounted for 20% of the vegetation in the lake. The emerged vegetation covered 21% of the lake. *Phragmites australis* (Cav.) Trin. ex Steud. (14%) and *Typha angustifolia* L. (7%) were the most common emerged helophytes. The remaining vegetation comprised mainly of shrubs at the lake shores and accounted for ca. 2% of the total vegetation cover.

In Lake Głębokie, the vegetation covered 42% of the lake area. Helophytes were more abundant and elodeids were less abundant in the reference lake compared to Lake Czarne, whereas the area covered by nymphaeids was much smaller (Fig. 3). In Lake Głębokie, helophytes (mostly *P. communis*) covered 26% of the lake bottom and nymphaeids represented by *Nuphar lutea* covered only 1% of the lake. Submerged macrophytes (mainly *C. demersum*) accounted for 15% of the littoral zone and penetrated the lake bottom to the maximum depth of 2.5 m.

The small amount of phytoplankton (chlorophyll-*a* concentration ranged from 4.4 to 25.5 µg dm^{-3}) in Lake Czarne affected high water transparency (Fig. 2), which was confirmed by Spearman's rank correlation test (r=-0.65, p<0.01). Thus, the visibility of Secchi disk was relatively high and ranged from 1.75 to 4.5 m. In contrast, the amount

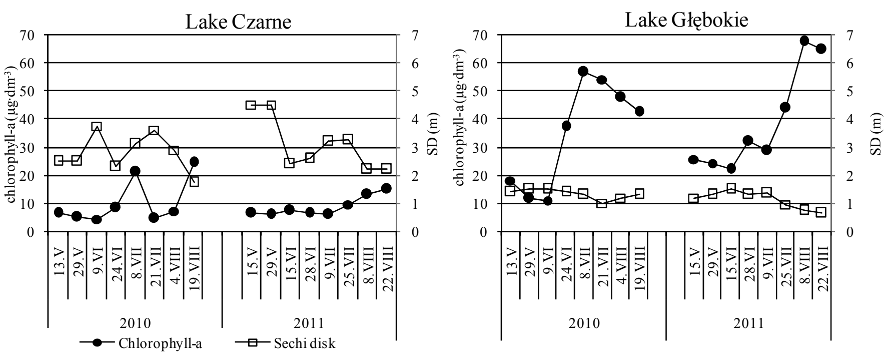

Fig. 2. Chlorophyll-*a* concentration and Secchi disk (SD) visibility in the lake with reduced inflow of surface water (Lake Czarne) and in reference Lake Głębokie

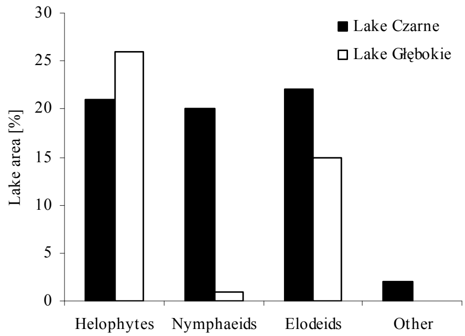

Fig. 3. Lake area occupied by particular macrophyte groups in the lake with reduced inflow of surface water (Lake Czarne) and in reference Lake Głębokie

of phytoplankton in Lake Głębokie was high (chlorophyll-*a* concentration ranged within 11.0–67.6 µg dm^{-3}) and water transparency was much lower (from 0.65 to 1.5 m) (Fig. 2). It was evident that the correlation was stronger in Lake Głębokie (r=-0.83, p<0.001).

According to OECD criteria [23], based on chlorophyll-*a* and Secchi disk values, Lake Czarne should be classified as a mesotrophic lake and Lake Głębokie as a hypertrophic one.

The trophic status of Lake Czarne, calculated on the basis of Carlson's indices, was different in both years of the study (Fig. 4). The TSI values generally ranged from mesotrophy to eutrophy, only TSI(TN) values ranged between eutrophy and hypertrophy. Mean values of TSI indices for TSI(SD), TSI(Chl), TSI(TP) and TSI(TN) were 45, 50, 52 and 72, respectively, and therefore Lake Czarne was classified as the meso-eutrophic water body.

Carlson's indices in Lake Głębokie varied between eutrophy and hypertrophy (Fig. 4). Mean TSI values for TSI(SD), TSI(Chl), TSI(TP) and TSI(TN) were 57, 65, 58 and 74, respectively, therefore Lake Głębokie was classified as the eutrophic water body. In both lakes, the highest trophic status was estimated on the basis of TSI(TN) values, which were very similar in both studied lakes.

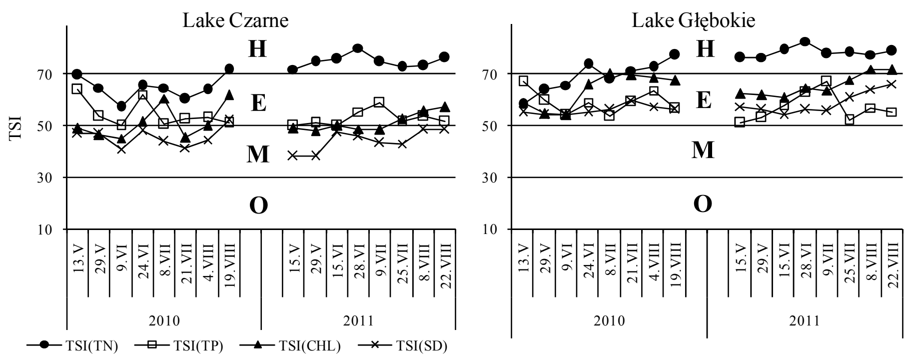

Fig. 4. The values of Carlson's indices in the lake with reduced inflow of surface water (Lake Czarne) and in reference Lake Głębokie. Explanations: H – hypertrophy, E – eutrophy, M – mesotrophy, O – oligotrophy

DISCUSSION

Water bodies in the West Polesie region are commonly disturbed by nutrient enrichment. The functioning of the lakes in this region is significantly affected by agricultural activity and hydrological transformations [33]. Rapid eutrophication of the water bodies, which are mostly small and shallow, was induced by nutrient enrichment. Some consequences of this process can be currently observed in the lakes, e.g. high water turbidity, high phytoplankton development and large blue-green algae biomass [34]. Poor light conditions in highly eutrophic lakes, which are unfavorable to submerged macrophytes, determine highly reduced colonisation of the lake bottom by vegetation [1, 28, 29].

Factors other than water quality could also affect the differences in the vegetation cover of the studied lakes. Despite of the fact that the particular morphometric characteristics in both lakes were similar (Table 1), local slope inclination of the bottom was more differentiated in Lake Czarne (Fig. 1). Higher development of nymphaeids in Lake Czarne, in comparison to Lake Głębokie, could be supported by the large share of shallows, especially in the northern part of the lake. Moreover, the earth dyke surrounding Lake Czarne was overgrown by large trees and shrubs that could provide favourable conditions for nymphaeids due to a limited wave action. The difference between the development of helophytes in both lakes seems to be negligible.

Both studied lakes are situated in the close proximity to each other, but they present different alternative states of shallow lakes [30]. Lake Czarne is macrophyte dominated and Lake Głębokie represents a phytoplankton-macrophyte dominated state [15]. Lake Głębokie is strongly affected by the agricultural catchment, which influences the water quality and functioning of primary producers. In contrast, Lake Czarne is one of the lakes in the West Polesie region which still maintain clear water state. Vegetation development, a large depth of macrophyte colonisation, a small amount of phytoplankton and TSI indices show that the trophic state of this lake can be evaluated positively [3, 28].

The results show that an earth construction situated in a catchment basin can stabilise a macrophyte dominated state and positively affect the lake water quality. An earth dyke surrounding a water body can limit the nutrient supply from a catchment basin and consequently, hinder the water eutrophication. A similar effect was observed in shallow Lake Bikcze located near Lake Czarne in the West Polesie region. Ditches surrounding this lake restrained the drainage from the catchment area, which caused the de-eutrophication process in the water body [35]. Artificial solutions can affect the reduction in external nutrient loading, such as natural wetlands [13].

Macrophyte dominance in a lake may be caused by different mechanisms. Submerged vegetation is enhanced by a small number of phytoplankton and favorable light conditions. Macrophytes compete for nutrients with algae and they can secrete allelopathic substances that hamper the development of phytoplankton [20, 30]. Moreover, they provide habitats for predatory fishes and zooplankton, which indirectly reduces the amount of phytoplankton in water [12]. This could explain a less significant relationship between the amount of phytoplankton and the water transparency in Lake Czarne with large macrophyte beds compared to Lake Głębokie, which is poor in

submerged vegetation. In the macrophyte lake, water transparency could be interfered by a large number of zooplankton, which was observed during the study together with the decreasing amount of phytoplankton.

According to the EU Water Framework Directive [4], both lakes are considered as shallow, however, they are classified as dimictic [27]. Water stratification has a positive effect on the lake functioning, because the bottom sediments are excluded from the mixing almost throughout the vegetation season, which could positively affect the water visibility [17].

Turbulence of the water column due to wave action was similar for both lakes (3.4 m) according to Patalas' formula [25]. The submerged vegetation reached the depth of 2.5 m in Lake Głębokie and 4.5 m in Lake Czarne. In consequence, a large part of the bottom in Lake Głębokie was exposed to resuspension, whereas the bottom exposed to turbulence in Lake Czarne was completely covered by macrophytes. A high sedimentation rate and low resuspension from the bottom within dense macrophyte beds additionally improve the water transparency [11, 18].

The macrophyte dominated state is maintained in Lake Czarne, surrounded by the earth dyke, despite the fact that this lake is situated in the agricultural area. In fact, the comparison of our data with the observations of Fijałkowski [7] indicates that the abundance of submerged macrophytes and nymphaeids considerably increased during the last decades. It may be caused by the improved water transparency and consequently by favourable light conditions for submerged vegetation [32]. Phytolittoral in Lake Głębokie, with the agricultural catchment, reached 2.5 m [7] and decreased to ca. 20% of the lake area before the year of 2000 due to a strong decline of *M. spicatum* [5]. Our data show, that nowadays phytolittoral recovered to ca. 40% of the lake bottom because of *C. demersum* spread. Vegetation changes in the lake indicate that the water transparency significantly varied between the particular years. In fact, the literature data show rapid eutrophication of the lake between the 1980s and the beginning of the 21st century [26], and after that period up to the present – increase in water transparency was observed [19, 24].

Functioning of the lakes is often reflected by the Trophic State Index [3]. Application of Carlson's method in the evaluation of the trophic state is reasonable for phytoplankton-dominated or phytoplankton-macrophyte types of lake, like Lake Głębokie. The trophic status of macrophyte Lake Czarne, classified on the basis of TSI indices as meso-eutrophic or on OECD [23] criteria – as mesotrophic, can be underestimated, because of the role played by vegetation, especially submerged macrophytes. Plants are able to accumulate a large portion of biogenic compounds in their biomass and thus they inhibit the phytoplankton development. In consequence, values of Carlson's indices associated with the phytoplankton biomass TSI (Chl) or TSI (SD) can be very low, even if the total amount of nutrients in a lake is considerably high. Therefore, the phosphorus and nitrogen content in the macrophyte biomass should also be included in the trophic state evaluation in the case of lakes dominated by macrophytes [2].

The eutrophic lake with the Potamion and Nymphaeion type of vegetation is included in Annex I of the Habitats Directive [6] as a habitat type in danger of disappearing and whose natural range has diminished within the area of the EU community. Because of the human impact exerted on the lakes, the protection of the macrophyte dominated lake is necessary.

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STAN TROFICZNY PŁYTKIEGO JEZIORA ZE ZREDUKOWANYM DOPŁYWEM WÓD POWIERZCHNIOWYCH

W ogólnej klasyfikacji płytkich jezior eutroficznych można wyróżnić dwa alternatywne typy zbiorników: zdominowane przez fitoplankton i zdominowane przez makrofity. Ten drugi typ jezior jest rzadki i obecnie zagrożony działalnością człowieka. W celu określenia wpływu zredukowanego dopływu wód powierzchniowych przez ziemną groblę na stan troficzny jeziora, poddano ocenie wybrane parametry biologiczne i fizyczno-chemiczne dwóch zbiorników o podobnej morfometrii, położonych w krajobrazie rolniczym. Efekt oddziaływania grobli na jakość ekosystemu jeziornego oceniono jako znaczący. Jezioro położone w zlewni, w której dopływ wód powierzchniowych był ograniczony, zostało zaklasyfikowane jako mezo-eutroficzne, z małą ilością fitoplanktonu i o dużej przezroczystości wody. Jezioro porównawcze było silnie eutroficzne, z dużą ilością fitoplanktonu i o niskiej przezroczystości wody. Zbiornik otoczony przez groblę reprezentował typ makrofitowy (65% powierzchni jeziora pokryta przez roślinność), a stan jeziora porównawczego, w którym roślinność zajmowała 42% misy jeziornej, mieścił się między typem fitoplanktonowym i makrofitowym. Ocena trofii jezior może być jednak niedoszacowana, ponieważ znaczna część nutrientów może być zakumulowana w tkankach roślin. Stąd, wartości wskaźników Carlsona w przypadku jezior makrofitowych mogą nie uwzględniać ogólnej ilości nutrientów w jeziorze.