Trophic state and recreational value of Lake Mikołajskie

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Abstract: Lakes along with their surroundings are an attractive landscape component that play an important role in recreation and relaxation. In Poland, the Great Masurian Lakeland, visited by a million tourists every year, is considered to be the most attractive lake area. However, tourist pressure has several negative effects which cause degradation of the water environment. The aim of this study was to determine the trophic state of Lake Mikołajskie which is a hub for sailing and motorboating traffic. Values of the trophic status index were calculated from the content of total phosphorus, chlorophyll *a* and Secchi disc visibility, according to the data from the Voivodeship Inspectorate for Environmental Protection. In summer, the concentration of total phosphorus was 0.019–0.042 mg dm⁻³ in 2013 and 0.022–0.055 mg dm⁻³ in 2014. The concentration of chlorophyll *a* was in the range of 8.3–45.0 µg dm⁻³ in 2013 and 8.9–22.0 µg dm⁻³ in 2014. The maximum visibility of Secchi disc reached 2.0 m (2013) and 1.8 m (2014). Based on the calculated, Lake Mikołajskie can be classified as a eutrophic lake. In order to protect lakes from degradation tourists should be educated about the rational use of surface waters and the surrounding catchment. However, it is not only the massive influx of tourists, but also the activity of residents (dictated by economic reasons) that contribute to the pollution of lakes. Therefore, the development of tourism and the economy of the whole region should be harmonious and balanced so that the natural resources can serve us and future generations for as long as possible.

Key words: eutrophic lake, trophic status index, recreation, tourism

Introduction

The Great Masurian Lakeland is one of the most valuable aquatic ecosystems in the world. It covers an area of approximately 1730 km², stretching between the Mrągowo Lakeland in the west, the Ełk Lakeland in the east, the Węgorza Land in the north, and the Masurian Plain in the south. The Great Masurian Lakeland comprises Poland's largest complex of lakes connected by canals, with a total area of 302 km² (Kondracki 2002). The inter-connected water bodies are divided into three basic lake systems: the northern basin drained by the River Węgorza occupying an area of 615.167 km² and a lake cover percentage of 17%, an endorheic central basin with an area of 592.624 km² and lake cover percentage of 8%, including Lake Mikołajskie, and the largest, southern basin occupying an area of 1 961.163 km² (lake cover percentage just over 8%) drained by the River Pisa (Bajkiewicz-Grabowska 2008). The Great Masurian Lakeland contains large and medium lakes (size over 50 ha), endorheic ones or fluvial-lacustrine systems connecting with other water bodies (e.g. the system of the River Jorka). For landscape and biodiver-

sity protection, and biodiversity, small lakes (less than 50 ha), midfield and midforest ponds, wetlands and peatlands are important. All these elements perform natural, landscape and social functions.

The Great Masurian Lakes are the most popular and most beautiful navigable route in north-eastern Poland. This is an area of unique natural beauty, which is not only rich in historical monuments but also provides opportunities for practising all kinds of water tourism (Jastrzębiec and Kuczkowski 2009). The high appeal of this area attracts one million domestic and foreign tourists, e.g. from Germany, France, Russia.

In the centre of the endorheic middle basin lies the town of Mikołajki, said to be the summer and sailing capital of Mazury. The lake's waterfront is dotted with marinas, taverns and holiday homes. In the high season there are some annual events, such as sailing or shanty contests. Lakes and lake environments are attractive for the public and play an important role in recreation and relaxation (Hall and Härkonen 2006; Krukowska and Krukowski 2013). Tourism is associated with intensive use of lakes, for example sailing, power boating,

water and sunbathing as well as angling (Jastrzębiec and Kuczkowski 2009). Direct and/or indirect use of lakes often has several negative effects which can lead to their degradation. The abuse of lakes and their catchment basins causes changes in the physico-chemical and biological properties of water, which significantly decrease water quality.

The aim of the study was to determine the trophic status of Lake Mikołajskie, which is a hub for tourists sailing or riding motorboats on the Great Masurian Lakes route.

Study area and methods

Lake Mikołajskie (Fig. 1) is located in the municipality of Mikołajki, in the Mrągowo District (latitude 53°78.2'N, longitude 21°59.5'E, elevation 116.1 m a.s.l.). The lake lies midway in a chain of gutter lakes between the towns of Ryn and Ruciane-Nida. Lake Mikołajskie connects with Lake Tałty in the north and lakes Beldany and Śniardwy in the south (WIOŚ 2014).

The lake has a surface area of 497.9 ha and a maximum depth of 25.9 m. Its basin is elongated along the NW-SE axis. Its maximum length is 5750 m, and maximum width is 1600 m. The shoreline is moderately diversified, as evidenced by the shoreline development index (1.9). Detailed morphometric data are shown in Table 1 (Dunalska 2010).

The total catchment of Lake Mikołajskie covers an area of 1808.7 km² and its direct catchment an area of 2.3 km². Much of this area is covered by forests (43.2%), with smaller percentages of wasteland and developed land (Table 2). The lake is intensively used for

Fig. 1. Bathymetric map of Lake Mikołajskie (according to WIOŚ)

Table 1. Morphometric characteristics of Lake Mikołajskie (according to IRŚ in Olsztyn)

Parameter	Value
Surface area [ha]	497.9
Maximum depth [m]	25.9
Average depth [m]	11.2
Relative depth	0.0116
Depth index	0.43
Volume [dam ³]	55 739.7
Maximum length [m]	5 750
Maximum width [m]	1 600
Elongation [d.u.]	3.5
Average width [m]	865
Length of coastline [m]	15 100
Shoreline development [d.u.]	1.9

recreation because of the popular watercourse leading from Mikołajki to Ruciane-Nida and to Lake Śniardwy. The north-eastern part of the lake's shoreline is occupied by buildings which house hotels, resorts, taverns, a port and marinas with water equipment rentals. To the west, the lake is surrounded by the Pisz Forest, where there are campsites. The southern and central part of Lake Mikołajskie stretch into the Masurian Landscape Park.

The annual monitoring carried out by the Voivodeship Inspectorate for Environmental Protection (WIOŚ) revealed that treated wastewater was discharged to Lake Mikołajskie from the holiday resort "Leśna Polana" and from the Hydrobiological Station in Mikołajki. Until 1997 the lake had been receiving untreated wastewater from two small sewage treatments and raw wastewater from many town buildings. In 1997, an automatic-biological sewage treatment plant with a chemical system for removal of phosphorus was built. Now, treated wastewater flows into the southern part of Lake Tałty, and then to Lake Mikołajskie and further to Lake Śniardwy (Dunalska 2010). Despite the expansion and modernization of wastewater management installations, occasional failures of sewage treatment and uncontrolled wastewater discharge can pose a particularly dangerous threat to the purity of Lake Mikołajskie. In addition, approx. 2.5 km northwest of the lake there is a municipal waste landfill. Another threat to water quality could be posed by the petrol station opened (in

Table 2. Land use in the direct catchment of Lake Mikołajskie (according to WIOŚ)

Form of land use	Area (ha)	
	[ha]	[%]
Forest	100.5	43.2
Agricultural land	12.1	5.2
Wasteland	62.3	26.8
Built-up areas	57.7	24.8
Total	232.6	100.0

Table 3. Evaluation of susceptibility to degradation of Lake Mikołajskie (according to data WIOŚ)

Parameter	Value	Category	Score
Maximum depth [m]	11.2	I	1
Volume to shoreline length ratio [dam ³ m ⁻¹]	3.82	II	2
Water stratification [%]	17.0	III	3
Active bottom area to epilimnion volume ratio [m ² m ⁻³]	0.05	I	1
Schindler's ratio [m ² m ⁻³]	32.5	III	3
Flushing rate [%]	270	III	3
Land use in the direct catchment [%]	43.2 – forest 24.8 – built-up areas	II	2
		Total	15
		Average	2.14
		Category	II

2003) at the sailing port, which supplies fuel to watercrafts (WIOŚ 2005). However, the main threat to water quality of Lake Mikołajskie is the intense tourist traffic which introduces a large pollutant load in the holiday season.

Lake Mikołajskie belongs to lakes with an average susceptibility to degradation (Table 3). The most unfavourable features for lake condition are: per cent of water stratification, the Schindler coefficient (the ratio of the catchment area to lake volume) and the annual water replacement. While the most favourable features are the average depth and the ratio of the active bottom surface to epilimnion volume (Dunalska 2010).

Lake Mikołajskie is one of 22 benchmark lakes included in the diagnostics monitoring network in Poland. It represents a stratified lake classified as a heavily modified water body. Water analyses are carried out by the Voivodeship Inspectorate for Environmental Protection (WIOŚ) in Olsztyn, 6–8 times in the vegetation season each year. The monitoring makes it possible to track the changes in water quality that occur both naturally and under human impact.

The results of selected physicochemical and biological parameters of water quality measured in the years 2013 and 2014 by WIOŚ (2014) were analysed in this study. Afterwards, Carlson's trophic state indices

were calculated according to the following simplified equations (Carlson 1977):

$$TSI(TP) = 14.42 \ln(TP) + 4.15,$$

$$TSI(Chl) = 9.81 \ln(Chl) + 30.6,$$

$$TSI(SD) = 60 - 14.41 \ln(SD),$$

where: $TSI(TP)$, $TSI(Chl)$ and $TSI(SD)$ are Carlson Trophic State Indices, respectively, for total phosphorus (TP), chlorophyll-*a* (Chl), and Secchi disc transparency (SD) and is a natural logarithm. TP and chlorophyll-*a* are in micrograms per litre, and transparency in metres.

Results

The water temperature in Lake Mikołajskie changed in the analysed season (May–September) depending on the ambient temperature changes. From May, the water temperature gradually increased, peaked in August, and then decreased (Fig. 2). In summer 2013, it ranged from 10.8 to 22.0°C, whereas in the next year it varied from 15.3 to 21.1°C. The pH of water was comparable in the analysed period, between 8.2–8.5 (Fig. 2). In 2013 electrolytic conductivity changed from 251 to 292 $\mu\text{S cm}^{-1}$. In the following year, it was relatively lower: 230–277 $\mu\text{S cm}^{-1}$. In both years, the

Fig. 2. Physical properties of waters of Lake Mikołajskie in the summer season 2013–2014 (* no data July 2014)

Fig. 3. Concentrations of total phosphorus and total nitrogen in Lake Mikołajskie in the summer season 2013–2014

highest value was recorded in June and the lowest occurred in September (Fig. 2).

In the summer season the concentration of total phosphorus was $0.019\text{--}0.042\text{ mg dm}^{-3}$ in 2013 and $0.022\text{--}0.055\text{ mg dm}^{-3}$ in 2014 (Fig. 3). Maximum values were recorded in August and September. The dominant form of phosphorus was the organic fraction, which accounted for an average of 83% of total phosphorus. The content of mineral phosphorus remained the same and equalled 0.05 mg dm^{-3} throughout the study period.

The concentration of total nitrogen ranged within $0.650\text{--}1.190\text{ mg dm}^{-3}$ in 2013 and $0.770\text{--}1.760\text{ mg dm}^{-3}$ in 2014 (Fig. 3). The highest concentrations were recorded in May and June. The dominant form of nitrogen was the organic fraction, which accounted for an average of 96% of total nitrogen. The content of ammonium nitrogen in the analysed period was 0.01 mg dm^{-3} . Higher values were recorded in June 2013 and September 2014 (respectively 2- and 4-fold higher). Nitrate nitrogen III and V were observed only in May 2013 ($0.05\text{ mg NO}_2\text{ dm}^{-3}$; $0.19\text{ mg NO}_3\text{ dm}^{-3}$) and in August 2014 ($0.08\text{ mg NO}_2\text{ dm}^{-3}$).

In the analysed period, the TN to TP ratio ranged from 21 to 53 (Fig. 4). In the summer season 2013, the stoichiometric ratio of the nutrients gradually increased from May to July, after which it declined in

Fig. 4. The stoichiometric ratio for primary production occurring in Lake Mikołajskie (dark line – optimum weight ratio)

August and reached its maximum value in September. The following year, the highest ratio of TN/TP was observed in May, while it was lower in June–August and the lowest in September. Despite the fluctuations between months and years, the TN/TP ratio was higher than an optimum weight ratio by Redfield (16). This indicates that Lake Mikołajskie was significantly rich in nitrogen compounds, while phosphorus had a limiting role in the development of primary production.

The intensity of primary production is also indicated by the transparency of water and content of chlorophyll-*a*. The maximum Secchi disc visibility was 2 m (May 2013) and 1.8 m (May, June 2014) (Fig. 5). In the plant growing season of both years water transparency

Fig. 5. Water transparency and chlorophyll-*a* concentrations in Lake Mikołajskie in the summer season 2013–2014

Fig. 6. Diagram of trophic state indices for Lake Mikołajskie in 2013 and 2014

decreased until July/August (1.3/1.1 m), after which it slightly increased and stood at 1.5–1.7m. The concentration of chlorophyll *a* was in the range of 8.3–45.0 $\mu\text{g dm}^{-3}$ in 2013, and 8.9–22.0 $\mu\text{g dm}^{-3}$ in 2014 (Fig. 5). The highest concentrations were recorded in August in both years.

Based on the concentrations of total phosphorus, transparency and chlorophyll-*a*, the value of the trophic status index by Carlson was calculated. Mean values for Lake Mikołajskie in 2013 and 2014 were respectively: $TSI(TP)$ 58 and 51, $TSI(SD)$ 57 and 53, $TSI(Chl)$ 64 and 58. In both years, $TSI(Chl)$ dominated. In 2013, $TSI(TP)$ and $TSI(SD)$ were at a comparable level, while in the following year $TSI(SD)$ was slightly higher than $TSI(TP)$ (Fig. 6).

Discussion

Eutrophication occurs when large amounts of nitrogen and phosphorus from allo- and autochthonous sources are supplied to a lake. The highest amount of these elements reaches water bodies via inflows from drainage basins, surface flow and precipitation. Illegal sewage inflows may be an additional source. Nutrients are also released from bottom sediments in a lake (Hanson et al. 2008; Kajak 2001). The main source of nutrients in Lake Mikołajskie is wastewater discharged into the lake. The refurbished municipal sewage treatment plant discharged approx. 800 $\text{m}^3 \text{d}^{-1}$ of wastewater to Lake Tałty in 2013. The inlet of wastewater is only 1 km from the lake. According to calculations, Lake Mikołajskie could be receiving a load of pollutants consisting of approx. 4.0 tonnes of nitrogen and 0.1 ton of phosphorus per year. Furthermore, the lake was directly supplied with approx. 10 $\text{m}^3 \text{d}^{-1}$ of wastewater from

the “Leśna Polana” holiday centre and from the Hydrobiological Station in Mikołajki (WIOŚ 2014).

Both residents and tourists are responsible for the production of these amounts of wastewater. Most of the pollution is transported into sewers and then subjected to mechanical-biological sewage treatment with the chemical removal of phosphorus. However, a large part of the municipality is not connected to the sewage system and household wastewater is collected in septic tanks. If there is a leak in a septic tank, untreated wastewater can permeate into soil and surface waters. Furthermore, the largest source of pollution in the lake is considered to be sailing boats which directly introduce wastewater into Lake Mikołajskie. Although ecomarinas are equipped with modern infrastructure for wastewater collection from watercraft, they are not used very frequently. An additional source of nutrients delivered to Lake Mikołajskie can also be in the form of fish bait. Its intensive use by anglers supplies the lake with large amounts of nutrients and minerals.

The predominance of organic forms of nutrients and the depletion of mineral phosphorus and ammonium ions in the surface layers indicate intensive primary production occurring in the lake. The optimal stoichiometric ratio of N to P is 16:1. In the considered time this ratio was higher, which suggests that phosphorus was a nutrient that limited primary production in Lake Mikołajskie. Then, the abundance of water in nitrogen compounds primarily affects the growth and dominance of blue-green algae in the lake (Vrede et al. 2002). Both the increase in pH and water temperature may intensify cyanobacterial blooms. Excessive growth of cyanobacteria can lead to extinction of fish and displacement of indigenous species (plants and animals) by invasive species (Vrede et al. 2002). In the Great Masurian Lakes, and specifically in Lake Mikołajskie and Lake Kuc, the presence of invasive alien species namely *Elodea nuttalleni* and *Elodea canadensis* was detected. Nitrogen compounds in water are conducive to the growth of these species (Woźniak-Wilk et al. 2012).

Higher concentrations of organic nitrogen observed in the summer months indicate the enrichment of water in this form of nitrogen. It mainly had an autochthonous character, resulting from the intensively growing phytoplankton in the lake. The content of chlorophyll-*a* in phytoplankton, amount of organic and mineral suspended matter and colour all affect Secchi depth. In 2013 the process of primary production was higher than in the following year. In the summer (June–September) the concentration of chlorophyll-*a* in the water was almost twice as high, while water transparency was lower than 0.5m. The calculated from the content of total phosphorus, chlorophyll-*a* and transparency classifies the water in Lake Mikołajskie

as eutrophic. Further interpretation of the provides information about the functioning of the ecosystem and factors limiting primary production. was higher than , which may indicate the dominance of cyanobacteria in phytoplankton (Carlson 1977; Szymański et al. 2014). Intensification of this phenomenon would be very disadvantageous because cyanobacteria can produce toxic compounds.

Furthermore, the eutrophication of Lake Mikołajskie has been increased by natural environmental factors, including climate change. The increased frequency and intensity of natural disturbances recorded in recent years may cause the mixing of the entire volume of water. This is associated with huge amounts of nutrients from the bottom sediments being introduced to all trophic layers. Global warming increases water temperature, which can stimulate the growth of blue-green algae. A rapid response to changes is characteristic of blue-green algae, which are adaptable to habitats and able to compete effectively and dominate under unstable environmental conditions. Changes in the structure of phytocoenoses (increase in the proportion of invasive thermophilic and highly toxic blue-green algae) can lead to the exclusion of a lake from recreational use (Dunalska 2010).

An overall assessment of the water status in accordance with the guidelines contained in the Regulation of the Minister of Environment of 15 November 2011 indicates the poor state of Lake Mikołajskie (GIOŚ 2014). Based on the monitoring studies of WIOŚ in 2013–2014, the ecological potential changed from low to moderate, and the chemical status remained good (WIOŚ 2014). Physicochemical elements, such as electrolytic conductivity, concentration of total phosphorus and total nitrogen in the analysed summer seasons did not exceed threshold values for the good status of water ($600 \mu\text{S cm}^{-1}$; $0.075 \text{ mg TP dm}^{-3}$; $2.0 \text{ mg TN dm}^{-3}$). The main adverse impact on the condition of water in Lake Mikołajskie was produced by biological elements, which resulted in the ecological potential of the lake being less than good. In the analysed period, *Phytoplankton Metric for Polish Lakes* decreased from 3.45 to 2.92, changing the status of water to moderate. In addition, the third class of water purity is indicated by other parameters, i.e. *Ecological State Macrophyte Index* (ESMI = 0.34), *Multimetric Diatom Index for Lakes* (IOJ = 0.77) and *Lake Fish Index* (LFI = 0.44) (WIOŚ 2014). Among the water quality parameters analysed in Lake Mikołajskie in 2010–2013, the lowest variability (13–23%) was determined for the physicochemical parameters. The highest variation was detected for biological parameters (23–25%), while cyanobacteria biomass varied within the range of 65% (GIOŚ 2014). This

proves the ongoing intensive primary production and hence progressing eutrophication.

Both the natural processes occurring in lake and the increased input of pollutants in summer months affect the water quality in Lake Mikołajskie. The increasing eutrophication of the lake is a consequence of its attractiveness. Every year, the summer capital of Masuria attracts more and more tourists, which tempts local residents to derive material benefits from tourism. More and more land around the lake is developed for holiday resorts. The land development, especially in the surroundings of Lake Mikołajskie, has destroyed its buffer zone. This has limited the natural protection of the lake against the inflow of nutrients.

Conclusion

The water quality of Lake Mikołajskie depends primarily on the manner and intensity of the recreational use of the lake and its catchment. For recreational functions lakes should contain clean and clear water. In turn, lake surroundings should create opportunities for both land and water tourism. The attractiveness of Lake Mikołajskie and its surroundings has long been stimulating tourism, which has affected the trophic state of waters. The pollution produced by land tourists is directed to the sewage system, but in water tourism sanitary tanks are often emptied directly into the lake instead of using the facilities at ecomarinas. Not only the massive influx of tourists, but also activity of the residents dictated by economic reasons contribute to pollution of lake. The current state of water quality has been significantly influenced by the an uncontrolled discharge of untreated sewage and sporadic failures of municipal sewage treatment.

In order to protect the lake from degradation, tourists should be informed about the rational use of surface waters and the surrounding catchment. Recreational activity should be more carefully monitored by administrative authorities, one particularly important aspect being to ensure that sanitation tanks are emptied in ecomarinas. The development of tourism and economy of this region should be harmonious and balanced, so that the natural resources will be able to serve us and future generations for as long as possible. .

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