An analysis of the restoration of Lake Durowskie: Physico-chemical properties

Authors: Caterina Migała[a], Rachel Brockamp[b], Hernán Abad[b], Patryk Kubiak[a]

Supervisors: Dr. Naicheng Wu[b], Dr. Uta Ulrich[b]

[a]Adam Mickiewicz University in Poznań, [b]Christian-Albrechts-Universität zu Kiel

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INTRODUCTION

Lake Durowskie is a polluted lake located in the city of Wągrowiec in central Poland. The lake is 143.7 hectares in area, with a volume of 11,322,900 m^3, a catchment area of 1,581 ha and an average depth of 7.9 m. Lake Durowskie is part of a network of lakes and rivers in Wągrowiec, all of which are important ecosystems that provide ecosystem services. Prior to restoration Lake Durowskie was hypereutrophic in 2008, meaning that the lake had excessive nutrients, depleted oxygen levels, and harmful algal blooms. Nutrients are the primary pollutants in Lake Durowskie, originating from point sources (e.g. households), and diffusing sources (fertilizers and pesticides used in agriculture). Since 2008, three restoration actions have been taken in Lake Durowskie: (1) chemical precipitation of excess phosphorus with ferrous sulfate, (2) biomanipulation by adding predator fish, and (3) aeration to help to provide oxygen, eliminate carbon dioxide & hydrogen sulfide, and reduce cyanobacteria. The water quality of Lake Durowskie is assessed annually based on chemical, physical, and biological factors, including physico-chemical properties, macroinvertebrates, algae, and macrophytes. The lake has shown steady recovery since 2008, but continuous monitoring remains necessary as the water quality fluctuates.

Physico-chemical properties are important for assessing lake quality and determining restoration measures. In this report, certain physico-chemical indicators were measured, including: nutrients, total dissolved solids (TDS), electrical conductivity, turbidity, pH, dissolved oxygen content and percentage, chlorophyll a content, and temperature. Nutrients are critical for biological activity of lake organisms, but too many nutrients can be responsible for excessive plant growth, which depletes oxygen and can be fatal to other lake organisms. This process of nutrient-oversaturation is known as eutrophication. The major nutrients responsible are different forms of Nitrogen (N) and Phosphorous (P).

Ammonium in ammonium chloride (NH_4Cl) can naturally occur in lakes. In abnormally high concentrations ammonium can cause overgrowth and imbalance in aquatic ecosystems, especially in the species composition of microbial communities living in the system (Wang, 2018). In high concentrations nitrogen in ammonium or highly mobile nitrate (NO_3^-), can contribute to the water-quality degradation by causing algae blooms, habitat and biodiversity loss, lack of oxygen, and the obstruction of normal ecosystem functions (Rabalais 2002).

Phosphorus in high concentrations cause disturbances that can increase primary production and macrophyte growth (De Anda et al, 2002). This will have considerable impacts in all trophic levels of the ecosystem.

Other physico-chemical parameters include electrical conductivity, which estimates the amount of TDS, or total dissolved ions in the water. Turbidity refers to how clear or transparent the water is, with higher turbidity (more suspended solids) meaning less light available for biological activity. pH influences biological activity, and solubility and precipitation of nutrients and toxic elements. Chlorophyll a is a pigment used in photosynthesis, and its presence indicates photosynthetic plant/algae biomass in the water. Chlorophyll a content is also used to determine the lake's trophic status, with more chlorophyll indicating more nutrients available for photosynthesis. Oxygen content indicates oxygen available for biological processes such as photosynthesis and respiration. Temperature influences biological activity, with certain organisms and events occurring at specific temperatures (Wu, 2019).

In this report we utilize one important classification system, Trophic State Index (TSI), that uses physico-chemical properties (indicators) to classify the lake status, i.e. oligotrophic (low nutrients, high oxygen, low TSI), mesotrophic (low-medium nutrients, intermediate oxygen), eutrophic (high nutrients, lower oxygen), and hypereutrophic (very high nutrients, very low oxygen, high TSI) (Wu, 2019). TSI uses three physico-chemical indicators: total phosphorus content, chlorophyll a, and transparency of the water. Higher values of total P and chlorophyll a indicate more nutrients for biological activity, and therefore a higher trophic state. A lower transparency or Sd--clarity of the water from the surface in meters, indicates less light availability and therefore a higher trophic state.

There are three main objectives with this physico-chemical report. In combination with the macrophyte, macroinvertebrate, and algae analyses, these physico-chemical data will indicate whether the Lake Durowskie restoration project is effective. The objectives are:

1. Determine the spatial distribution of the physico-chemical properties and the trophic states to map the water quality.
2. Analyze the nutrient load in Lake Durowskie, including the inflow and outflow streams.
3. Assess previous year's data to determine the temporal change in the water quality.

METHODS

1. Study Site

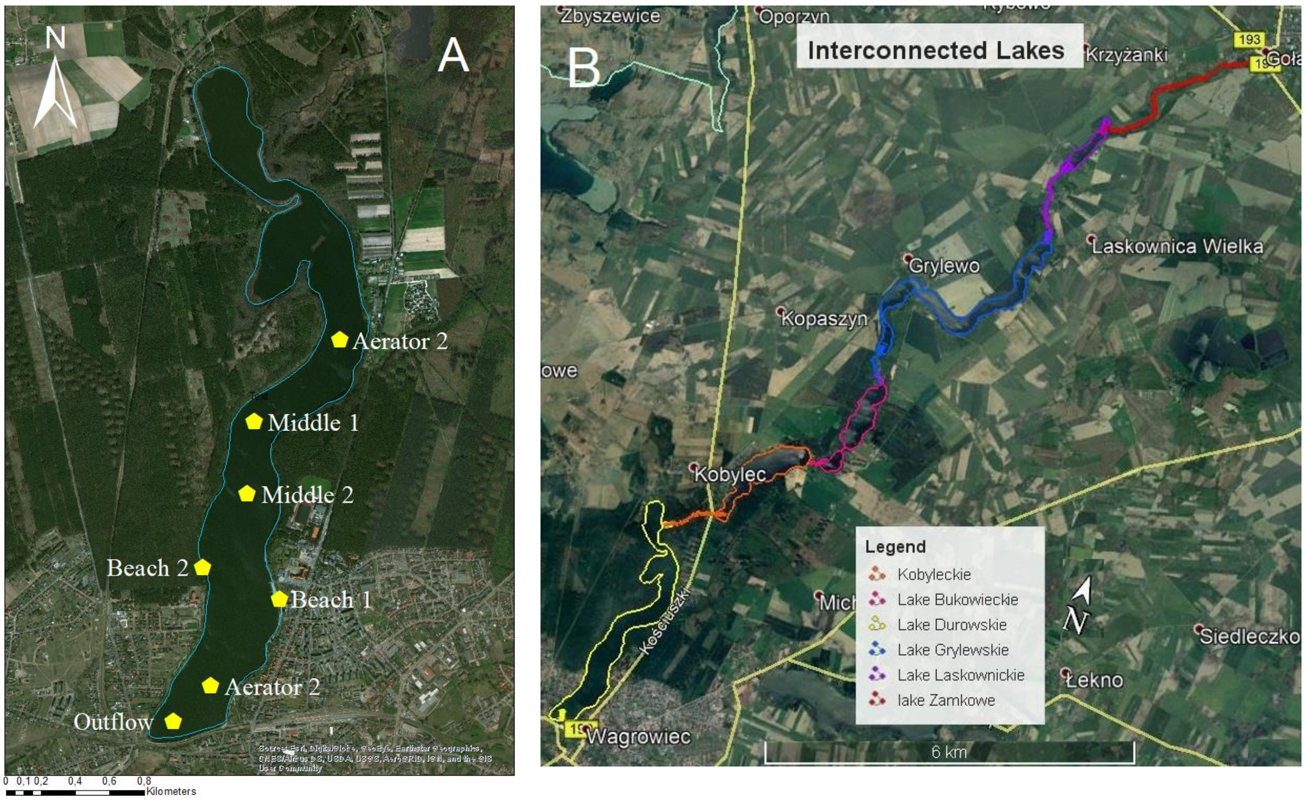


Figure 1. Seven sample sites on Lake Durowskie (A) and the lake system that includes Lake Durowskie (B). Source: Google maps.

The area of study includes six lakes (Figure 1B), all connected to each other by streams. The lakes are: Zamkowe, Laskowickie, Grylewskie, Bukowieckie, Kobyleckie and Durowskie. In order to collect water samples from Lake Durowskie, seven sites (Figure 1A) were determined: Aerator 1, Middle 1, Middle 2, Beach 2, Beach 1, Aerator 2, and Outflow. These sites have been chosen for their different environments, characterized by the presence of human activity and by water depth. The physico-chemical results from the surface water (0 meters) for these seven Lake Durowskie sites were averaged to create 'Lake Durowskie' data in lake system results, Trophic State Index (TSI_M) analysis, and time-series analysis results below. Physico-chemical parameters and chlorophyll a samples were collected from several lake inflow and outflow sites (Inflow Grylewskie, Inflow Bukowieckie, Inflow Kobyleckie, and Inflow & Outflow of

Durowskie) and in all lakes except Kobyleckie. Flow velocity was only measured in inflow and outflow sites.

2. Flow velocity

Flow velocity was measured in the field at inflow and outflow sites. First, the total width (x) of the inflow/outflow channel is measured in meters, to create a transect. Then, several depths (y) are measured along this transect at certain intervals (e.g. x_1, x_2...). In the following step the flow velocity is evaluated at each measured depth in 5-10 cm intervals with an electromagnetic velocity meter (FlowSens, SEBA, Hydrometric, Germany). Figure 2 represents an example of river cross-section. Using equation 1, the total discharge Q (m/s^2) was calculated by the sum of the cross-section area (m^2) multiplied by the sum of the average velocity of each interval (Wu, 2019).

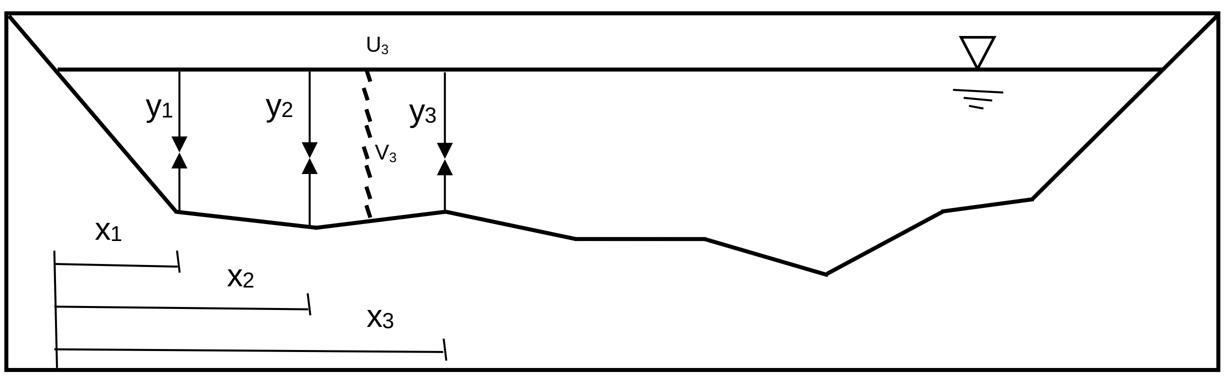


Figure 2. Subsection of river cross section. X_1 is distance from river bank, y_1 is water level, V_3 is the vertical on which flow velocity is measured in each subsection (source: www.hydroskript.de)

Equation 1.

$$\boldsymbol{Q} = \sum_{i=1}^{n} a_i v_i$$

Q = flow volume (m^3/s)
a - sum of sub-section area (m^2)
v – average water velocity (m/s)

3. Physico-chemical parameters

pH, Oxygen concentration (mg/L and %), electrical conductivity (µS/cm), and temperature (°C) were measured with a YSI probe (manufacturer) in the field. In inflow and outflow sites the parameters were measured in the central area of the water. In the lake sites, the parameters were measured at 1 m depth intervals, starting at the water surface. Transparency (Sd) was measured at lake sites with a secchi disk. Chlorophyll a was measured by collecting 1-liter samples of lake or stream water and filtering the water to concentrate the chlorophyll on a filter. In the laboratory, chlorophyll a was extracted from the filters with acetone. The absorbance of the extraction fluid was measured with a spectrophotometer, with and without acid, using a method from Lachert and Soszka, 1986. Equation 2 was used to calculate total chlorophyll a, with X as the amount of chlorophyll a, 26.73 as the conversion factor, V_E as volume of acetone, V_W as volume of filtered water sample, and A_b (absorbance when basic), Aa (absorbance when acidified) at 663 nm and 750 nm wavelength, and I as the thickness of the absorption in the cuvette in cm.

Equation 2. $X = 26.73[(A_{663b}-A_{750b}) – (A_{665a}-A_{750a})] * (V_E/V_W) * I$

In the laboratory nutrient analysis was performed from 1 L water samples for Nitrate N, Nitrite N with sulfanilic acid, Ammonium N with Nessler's reagent, Total Phosphorus, and Orthophosphates with ascorbic acid.

4. Nutrient Loads

It is important to know how many nutrients are entering and exiting Lake Durowskie on a daily and annual basis. The nutrient load of total phosphorus, nitrite-N, nitrate-N, and ammonium-N was calculated with the discharge (Q) of the inflow and outflow using the following equation 3 for kg/day (equation 3) and then multiplied by 365 to get kg/year, with N=nutrient in mg/L, Q for discharge in m^3/s.

Equation 3. Nutrient load (kg/day) =((NQ)*1000)/1000000)*(24 hours*60 minutes*60 seconds)

5. Trophic State Index (TSI)

To classify TSI of Lake Durowskie, the amount of chlorophyll a in μg/L, transparency/Sd in meters, and the total P in μg/L were first used in some calculations (equations 4-6). Then the TSI of each parameter was added together, to create the overall trophic state (equation 7), TSI_M. The trophic state class was then classified with Table 1 from Carlson and Simpson (1996):

Equation 4. $TSI_M(Chla) = 9.81 \ln(Chla) + 30.6$
Equation 5. $TSI_M(Total P) = 14.42 \ln(Total P) + 4.15$
Equation 6. $TSI_M(Sd) = 60 – 14.41 \ln(Sd)$
Equation 7. $TSI_M = 0.54 TSI_M(Chla) + 0.297 TSI_M(Sd) + 0.163 TSI_M(TP)$

Table 1. Trophic State Index (TSI) classification from Carlson and Simpson (1996).

Trophic Class	TSI_M	Chla (µg/L)	Total P (µg/L)	Sd (m)
Oligotrophic	<30-40	0-2.6	0-12	4 to 8
Mesotrophic	40-50	2.6-7.3	12 to 24	2 to 4
Eutrophic	50-70	7.3-56	24-96	0.5-2

RESULTS & DISCUSSION

1. Lake Durowskie Physico-Chemical parameters

According to figure 3, the nutrient content is relatively consistent going into the lake, out of the lake, and throughout the lake, with exceptions of high total nitrogen content at Aerator 2 and low total phosphorous at Middle 1. These exceptions deserve further exploration as potential sites of nutrient addition/depletion. The levels of total phosphorus at all sites (except Middle 1) are above the eutrophic standard of 0.0249 mg/L (Table 1). The highest total N level is 0.84 mg/L at Aerator 2, but to be considered eutrophic total N levels would have to exceed 1.875 mg/L (Vollenweider, 1979), so the Lake Durowskie values are not extreme, and instead are in the oligotrophic (< 0.661 mg/L) to mesotrophic range (0.661-1.875 mg/L) (Vollenweider, 1979).

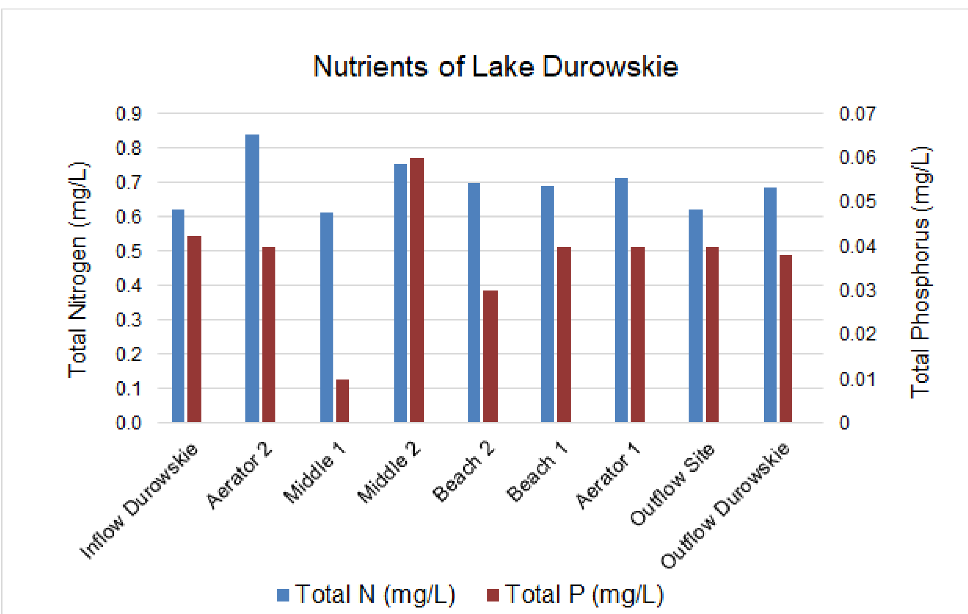


Figure 3. Distribution of major nutrients, Total N (sum of NO_3, NO_2, NH_4 in mg/L) and Total P (mg/L), in seven sampling sites in Lake Durowskie and the inflow and outflow streams of the lake (Figure 2).

The first map in Figure 4 shows eutrophic status (red) of transparency values throughout the lake. Greater transparency occurs near the aerators, which is likely because the aerators oxygenate the water, which may reduce the amount of suspended material (Siwek *et al.* 2018). In addition, the second map in Figure 4 shows there is also less chlorophyll a near the aerators, and therefore less photosynthetic biomass. Aerators have been shown to cause lower chlorophyll a (Siwek *et al.* 2018), possibly because the disturbance of the water limits photosynthesis. With less suspended photosynthetic organisms, the water may be more transparent. Low chlorophyll a content at Middle 1 may correspond to lower total phosphorous (Figure 3) at that site, since phosphorous limits photosynthesis (Siwek *et al.* 2018).

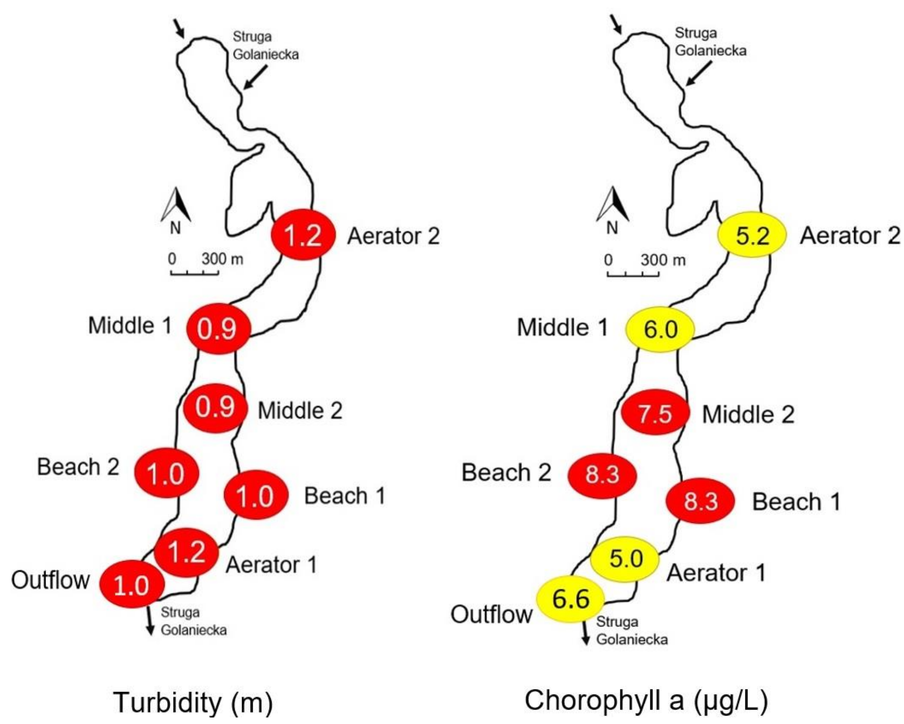


Figure 4. Maps of Lake Durowskie sampling sites with transparency values (meters) and chlorophyll a content (µg/L). *Values are yellow or red in correspondence with mesotrophic and eutrophic levels (Table 1).*

Figure 5 shows the estimated amount of nutrients entering and exiting Lake Durowskie in 2019, namely: phosphate, total phosphorus, and total nitrogen. There is a notable difference in the nutrient loads, with more nutrients exiting the lake than entering via Struga Gołaniecka river

(Inflow D) coming from lake Kobyleckie. Since there are more nutrients exiting, there may be a different source of phosphorus and nitrogen in the Lake Durowskie. These pollution sources could be wastewater from new urban infrastructures. These results are somewhat supported by nutrient contents in various sites on the lake (Figure 3), which show eutrophic levels of phosphorous.

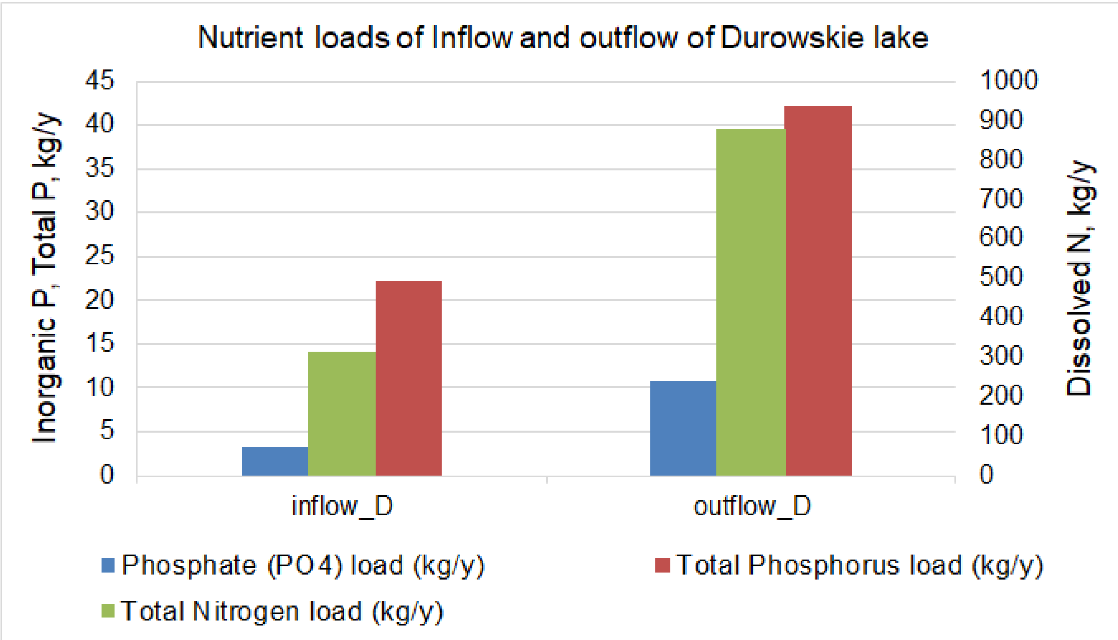


Figure 5. Nutrient load in kg/year of Inorganic P, Total P, and Dissolved N contributing to the inflow and outflow of Lake Durowskie.

3. Lake Durowskie Trophic State Index (TSI)

To understand the changes in time of the water quality status of the lake, it is important to look at the Trophic State Index (TSI). Figure 6 shows all seven Lake Durowskie sites as eutrophic based on TSI_M standards (Table 1). The average overall TSI_M of these seven sites of Lake Durowskie is 53.1. There are lower TSI_M values in site middle 1, and in the proximity of the aerators. The presence of the aerators is reducing the chlorophyll a, and may be improving the quality of the water, but not to mesotrophic or eutrophic status. At site middle 1, lower total P and chlorophyll a levels contribute to a lower TSI_M. The highest TSI_M values have been registered at sites middle 2, beach 1, and beach 2, where human activity is the most significant (entertainment, presence of boats, sports). The greatest disparity is between sites aerator 2 (50.1) and middle 2 (56..5) that, in less than a kilometer of distance, present two very different environments.

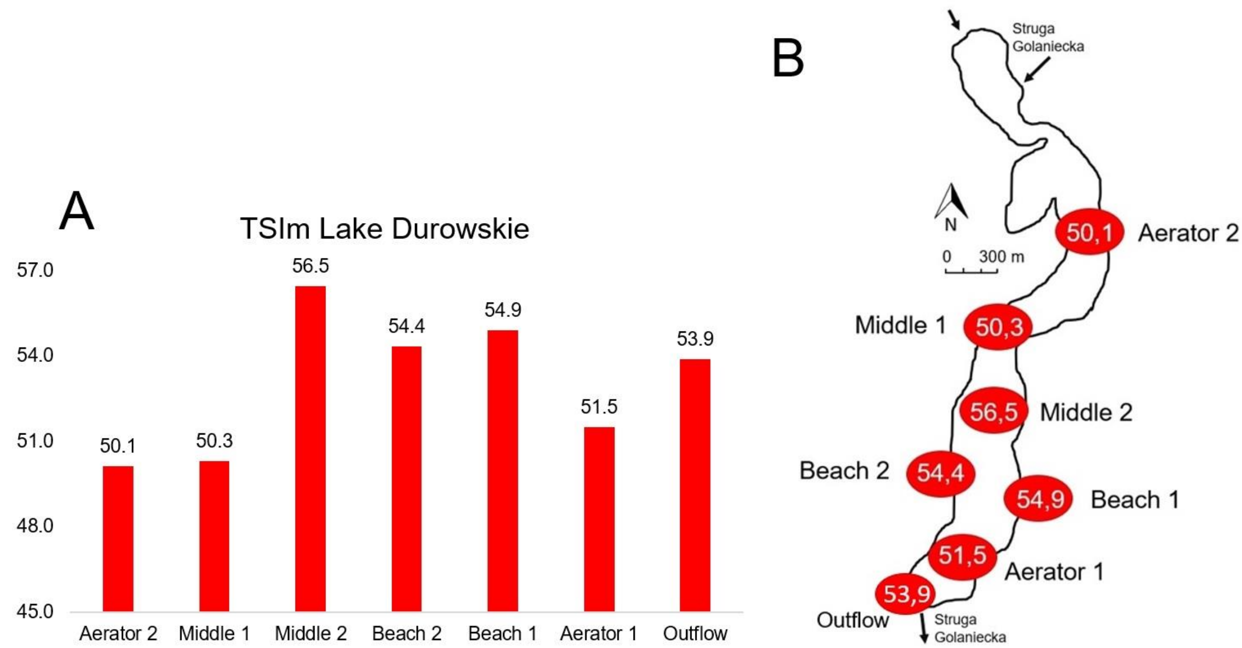


Figure 6. Current Trophic State Index status in values (A) and on a map (B) in different data collection sites on Lake Durowskie. Red bars and ovals signify the eutrophic status.

4. Lake Durowskie time-series analysis

Comparing 2018 and 2019 data, it is clear that total N values (Figure 7B) are much lower in 2019 than in 2018, with almost all 2018 values in the eutrophic range (>1.875 mg/L). Similarly, total P content (Figure 7A) is higher in 2018, especially at site Aerator 1. Therefore, the nutrient content of the lake seems to be improving this year compared to last year, leading to lower total N and P outflow from the lake. Despite less available nutrients in 2019, Figure 7C shows higher chlorophyll a in most lake sites in 2019 compared to 2018. However, this is less surprising when considering that the average June Wągrowiec temperature (Figure 9) was higher in 2019 than 2018, by ~3°C. Higher air temperature may enhance the photosynthetic activity of the algae and other photosynthetic organisms, leading to more chlorophyll a throughout the lake (Chen et al. 2012).

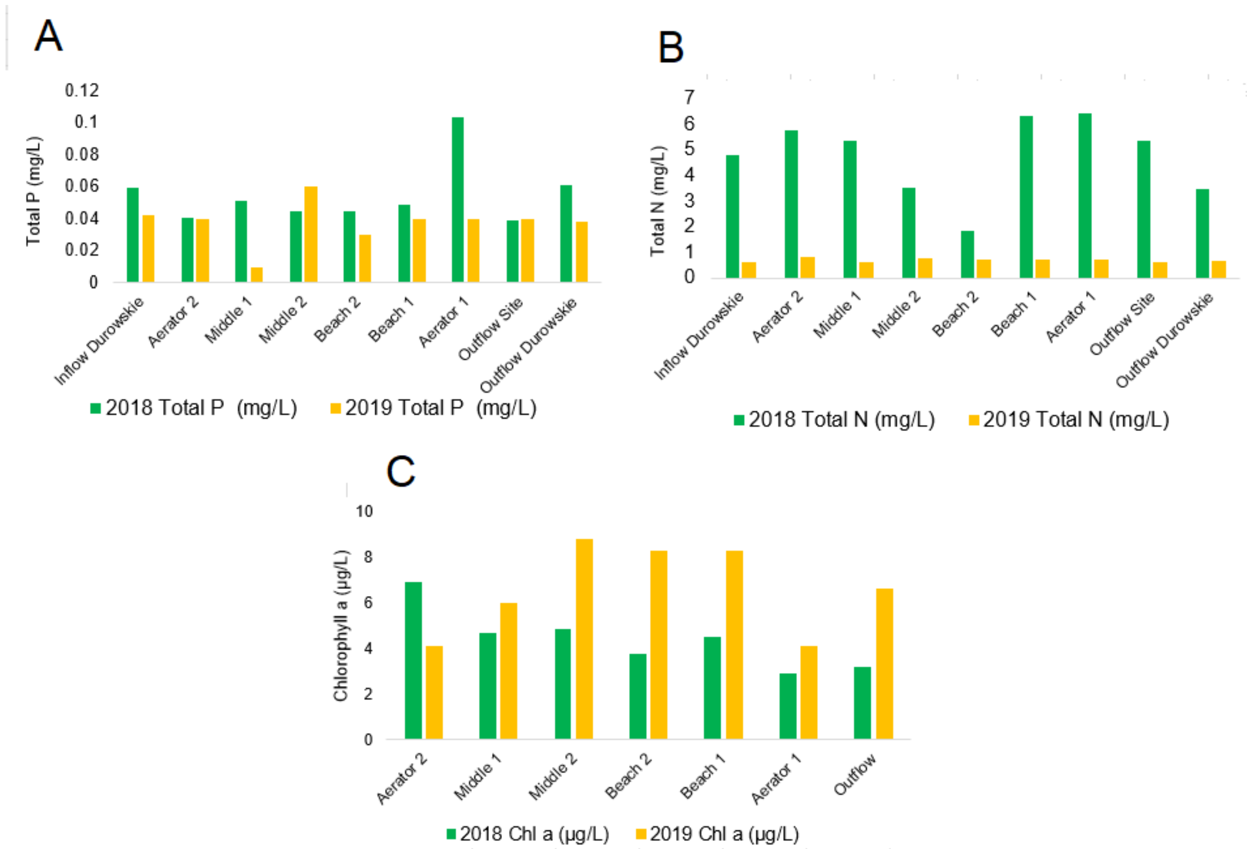


Figure 7. The total P (A), total N (B), and chlorophyll a (C) content at various sites and outflow and inflow sites of Lake Durowskie for 2018 and 2019.

Observing Figure 9, it is clear that after the start of the restoration process (2010-2012) the lake could be classified as mesotrophic or slightly eutrophic (Table 1). In 2019 the trophic status is the worst it has been since 2010, indicating that there may be a new source of contamination or failure of current restoration measures. The increase of the TSI_M's value may indicate a trend for further deterioration of water quality, which could lead to harmful algae blooms, known to be toxic for animals and humans.

On the other hand, our study group noticed abnormally high temperatures during our sampling sessions. There is literature indicating that high temperatures can affect the different metabolic processes occurring in different trophic levels of aquatic ecosystems (e.g. lakes) and the dynamic interactions occurring within the system may have a direct impact on its trophic state (Scharfenberger et al. 2018). Our group decided to average the data about the air temperature during June in Wągrowiec from 2011 to 2019. Then we compared these average temperatures to the trophic states of the respective years. Air temperature in the area has a correlation with the trophic state of the lake (Figure 9). This might mean that the eutrophic state of the lake might not be caused by new sources of nutrient inputs in the system, but might be caused by a mix of other factors like internal nutrient loading within the lake and high temperatures. These relationships are highly complex and further studies should be done concerning this topic to further analyze and corroborate these relationships.

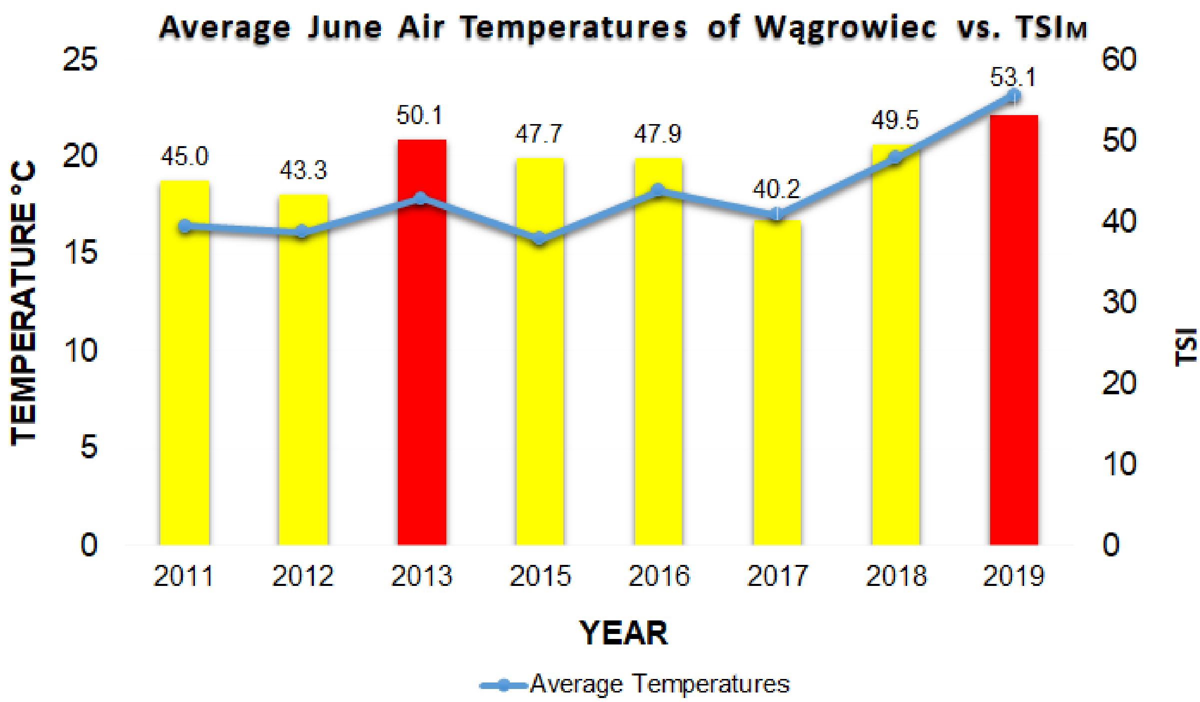
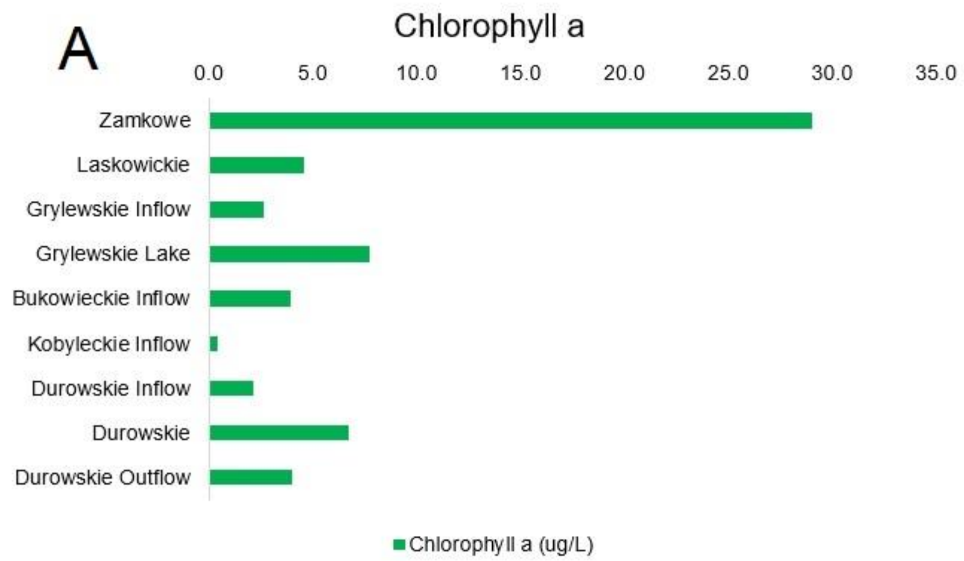


Figure 9. Comparison between average air temperature in Wągrowiec during June and the results obtained for the Trophic State Index in Lake Durowskie lake for the years 2011 to 2019. The numbers above the bars signify TSI_M, not temperature. Red bars signify eutrophic status, yellow bars signify mesotrophic status (Table 1).

2. Lake System Physico-chemical parameters

Once we obtained our results from the laboratory analysis, we decided to focus mainly on the data related to chlorophyll a, total phosphorus and total nitrogen. Some clear trends can be observed in the chlorophyll a (Chl a) data in figure 10A. Lakes Laskowickie, inflow of Grylewskie lake (Inflow G), lake Grylewskie, inflow of Lake Durowskie (Inflow D), Lake Durowskie and Lake Durowskie outflow (outflow D) have relatively similar Chl a concentrations of 4.6, 2.7, 7.7, 2.1 6.7 and 4.0 µg/L, respectively. On the other hand, lake Zamkowe is the site containing the highest chlorophyll a concentrations with 29.1µg/L. If the indexes of all the lakes were to be added together, lake Zamkowe would contain 60% of the total chlorophyll a. This high concentration could be explained by the urban land use of the lake surroundings versus its relatively small perimeter of 536 m (Lake Durowskie perimeter is 11 km). Being surrounded by densely populated urban areas, the nutrient load discharge coming from anthropogenic sources could be considerable. It is well documented that high concentrations of nutrients have high correlation with high chlorophyll a concentration.

Figure 10B shows a similar trend to chlorophyll a, with the total P and total N being higher in the upstream water bodies than the downstream ones. There may be additional nutrient loading/pollution in these northern areas than the contiguous streams and lakes further south. In addition, the same factors (e.g. lake surface area vs. urban or agricultural landuse) affecting chlorophyll a, also influence the accumulation of N and P. Although the occurrence of high concentrations of P and N may cause high concentrations of Chl a in lake systems (Filstrup & Downing 2017), some differences between the chlorophyll a results and the nutrients results can be found in figure B. For example, there is a very high chlorophyll a and total N in Lake Zamkowe, compared to much less chlorophyll a in the Grylewskie inflow which has the highest total N concentration. Another factor that may contribute to the high chlorophyll a, total P, and total N concentration is that the lake Zamkowe is not under proper management and hence pollutants may be accumulating without proper control schemes. However, it should be noted that lake Zamkowe is located in district Golancz which is independent from the district of Wągrowiec. Therefore, this group advises future collaboration between the managers of Lake Zamkowe and Lake Durowskie to investigate possible downstream contamination.



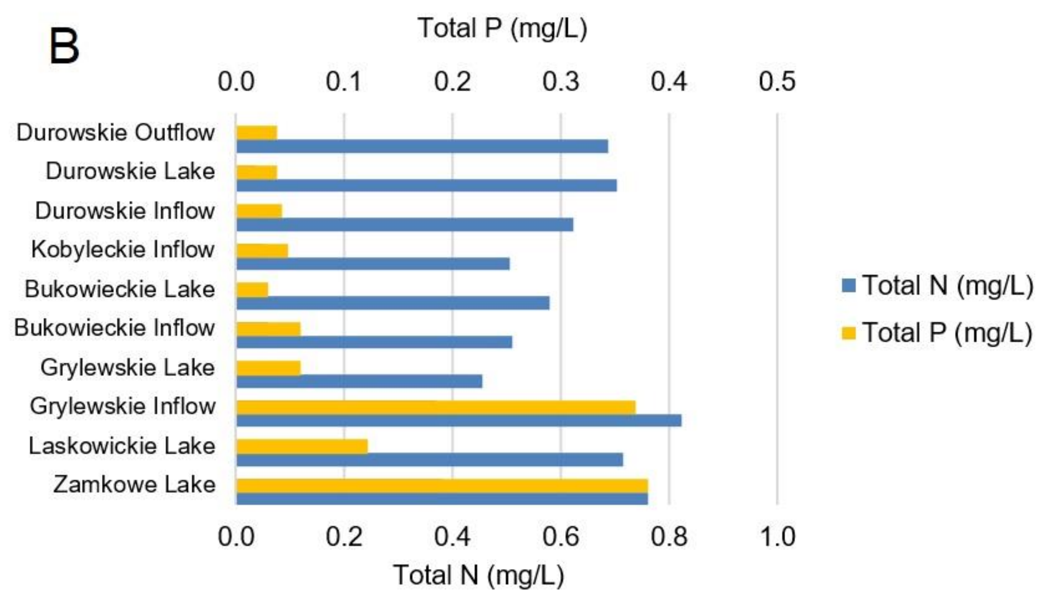


Figure 10. Chlorophyll a content (A), and nutrient content in mg/L of Total P and Total N (sum of NH_4, NO_3, and NO_2) (B) in lakes Durowskie, Grylowskie, Laskowickie and Zamkowe as well as some inflow and outflow sampling areas.

CONCLUSIONS

One of the points of future investigation include site Middle 1, where there is abnormally low phosphorus levels compared to the rest of the lake and Middle 1 results from previous years. There are a few major conclusions about Lake Durowskie. The lake has been classified as eutrophic, with the highest TSI_M since 2010. Currently we are unsure of why the water quality is decreasing. It is possible that there are environmental changes, such as temperature and internal nutrient loading that are affecting the lake quality. If climate change does play a role in the eutrophic status of the Lake Durowskie, then it is particularly important to consider these effects in future management plans. Otherwise, anthropogenic sources of contaminants may cause pollution as surrounding population and human activities such as tourism and agriculture are increasing. Related to this, there are more nutrients exiting Lake Durowskie than entering, which further supports the point that there might be a pollution source in the lake.

It is important that not only Lake Durowski and its nearby areas are managed to recover from a eutrophic state, but also the entire catchment area of the interconnected lake system to which Lake Durowskie belongs. For example, Lake Zamkowe may be an important source of nutrients upstream of Lake Durowskie. It is also recommended that all stakeholders in the area (e.g. citizens, farmers, tourists, decision makers, etc.) are involved in the management process and that they know the benefits that a restoration plan would signify for the entire community.

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