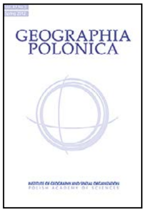

Geographia Polonica
2025, Volume 98, Issue 2, pp. 211-229
https://doi.org/10.7163/GPol.0300

INSTITUTE OF GEOGRAPHY AND SPATIAL ORGANIZATION
POLISH ACADEMY OF SCIENCES
www.igipz.pan.pl

www.geographiapolonica.pl

PHYTOPLANKTON BLOOMS LOCALIZED BY SENTINEL-2 IMAGES AND HYDRODYNAMIC MODELLING – SULEJÓW RESERVOIR ON THE PILICA RIVER, POLAND

Peshang Hama Karim[1] • Monika Kalinowska[2] • Aleksandra Ziemińska-Stolarska[3] • Artur Magnuszewski[4]

[1] Doctoral School of Exact and Natural Sciences
Discipline of Earth and Related Environmental Sciences, University of Warsaw
Stefana Banacha 2c, 02-097 Warsaw: Poland
e-mail: peshang.hamakarim@student.uw.edu.pl (corresponding author)

[2] Institute of Geophysics
Polish Academy of Sciences
Księcia Janusza 64, 01-452 Warsaw: Poland
e-mail: mkalinow@igf.edu.pl

[3] Faculty of Process and Environmental Engineering
Technical University of Lodz
Wólczańska 213, 93-005 Łódź: Poland
e-mail:aleksandra.zieminska-stolarska@p.lodz.pl

[4] Faculty of Geography and Regional Studies
University of Warsaw
Krakowskie Przedmieście 30, 00-927 Warsaw: Poland
e-mail: asmagnus@uw.edu.pl

Abstract

Reservoirs created by damming rivers significantly modify abiotic and biotic environmental components. A major consequence is the accumulation of sediments and nutrients, degrading water quality through eutrophication. This study focused on the Sulejów Reservoir in Central Poland, examining nutrient balance, phytoplankton blooms using Sentinel-2 satellite data, and wind-driven surface currents with the CCHE2D hydrodynamic model. Eight Sentinel-2 images from the 2020 vegetation season and the Normalized Difference Chlorophyll Index (NDCI) were used to assess phytoplankton distribution. Results indicate the reservoir mainly acts as a nutrient sink, but under low-flow and intense bloom conditions, it can become a nutrient source. Coupling remote sensing with hydrodynamic modeling effectively interpreted flow patterns and nutrient dynamics. For the first time, the influence of eddy structures and wind on phytoplankton distribution in the lacustrine zone was demonstrated.

Keywords

eutrophication • phytoplankton blooms • Sentinel-2 • hydrodynamic modelling • Pilica River • Sulejów Reservoir • NDCI • CCHE2D

Introduction

In modern water management and environmental protection, particular attention is paid to the nutrient loads transported by the rivers. High nutrient concentrations are responsible for eutrophication processes in natural lakes, artificial reservoirs, and coastal sea waters. This phenomenon, defined as the excessive enrichment of aquatic ecosystems with nutrients, leads to primary production surges and phytoplankton blooms. (Harper, 1992). One of the earliest studies on eutrophication related to massive cyanobacterial bloom on Lake Haruna (Japan) in 1933 (Yoshimura, 1933). The driving factor of lake eutrophication, as manifested in phytoplankton blooms, is phosphorus flux (Schindler, 2012). Two forms of phosphorus are measured at water quality monitoring stations – dissolved phosphate ions and total phosphorus (TP). Total phosphorus measures all phosphorus found in a sample, both dissolved and particulate (organic).

Phytoplankton blooms are composed of a mixture of cyanobacteria and algae. Cyanobacteria is a group of heterogeneous bacteria that have existed for 3.5 billion years and have the ability to colonise all environments, from thermal springs to arctic lakes. Cyanobacteria have undergone many adaptations, including the ability to conduct oxygenic photosynthesis, and have the potential for nitrogen fixation. One of their representatives is the genus *Microcystis*, which is commonly found around the world (Whitton & Potts, 2002).

The occurrence of cyanobacteria in artificial reservoirs is of global concern. The Sulejów Reservoir experiences cyanobacterial blooms every year, all having the ability to produce cyanotoxins (Szczukocki et al., 2014). Cyanotoxins, as secondary metabolites, affect aquatic organisms at all taxonomic levels, including different groups of algae, macrophytes, zooplankton, and fish (Zanchett & Oliveira-Filho, 2013; Godlewska et al., 2018). In the Sulejów Reservoir, the dominant species of bloom-forming cyanobacteria is usually *Microcystis aeruginosa* which forms large colonies ranging from 100 μm to even 2 cm in size (Komárek, & Anagnostidis, 1999; Mankiewicz-Boczek et al., 2016). Artificial reservoirs on lowland rivers, such as the Sulejów Reservoir in Poland, are especially prone to eutrophication due to nutrient-rich inflows from large catchments, extended water retention times, and sedimentation. Easily available nutrients are used in primary biological production, resulting in phytoplankton blooms dominated in summer by cyanobacteria (Tarczyńska et al., 1997). Ziemińska-Stolarska and Kempa (2021) concluded that nutrient loads from agricultural areas and septic tank discharges are the primary contributors to poor water quality and intensified eutrophication in the Sulejów Reservoir.

Blooms are formed when there is a high concentration of algae within a particular lake area, accompanied by some form of the physical mechanism that concentrates cells further (Glibert et al., 2005). Lakes with high retention times offer favourable conditions for cyanobacteria because cyanobacteria have slow growth rates relative to other algal groups (Paerl, 1988). Also, water column stability is important because cyanobacteria can regulate their buoyancy and depth of submergence, maintaining an optimal position in the water column for light harvesting. Another parameter that increases cyanobacterial concentration is a high-water temperature of 25-50°C. However, cyanobacteria are very sensitive to the rapid cooling of the water. A drop in the temperature by 5°C in a few days may destroy the blooms (Tarczyńska et al., 1997).

Phytoplankton blooms can be observed from satellite platforms equipped with multispectral scanners. Remote sensing offers several significant advantages: (1) it provides a synoptic view of the study site, which allows the user to obtain information on the entire aquatic system surface; (2) it can acquire data from remote, inaccessible locations; and (3) it can record data over time, providing a historical dataset for more comprehensive monitoring (Hadjimitsis & Clayton, 2009; Palmer et al., 2015).

The major techniques are based on optical sensing through the detection of coloured phytoplankton pigments, for example phycocyanin (Ryan et al., 2011). Examples of detection of phytoplankton using phycocyanin and Landsat satellite images are shown in (Vincent et al., 2004; Kumar et al., 2020; Zhao et al., 2020).

New satellite data are available from the European Space Agency (ESA) Sentinel-2 missions (European Space Agency (Sentinel-2), 2015). The Multispectral Imager (MSI) sensor of Sentinel-2 provides 13 spectral bands covering spectrum from visible and near-infrared (VNIR) to shortwave infrared (SWIR) wavelengths. It has good spatial resolution of 10 m in bands B2, B3, B4 and B8. A short revisit time (2-3 days at mid-latitudes) is important for monitoring water bodies showing high dynamics controlled by hydrological processes (European Space Agency, 2020).

Sentinel-2 data can be used to monitor small and highly dynamic water bodies like coastal lagoons (Matthews, 2011) or subalpine lakes (Bresciani et al., 2018). There is also an example of using Sentinel-2 data for lakes water quality monitoring for the purpose of reporting on inland waters ecological status according to the European Union Water Framework Directive (Ansper & Alikas, 2018).

Hydrological control of the phytoplankton bloom includes the nutrient loads and balance, and the timing of the fluxes. These data come from water quality monitoring stations and hydrological gauges and require long-term observations.

Large reservoirs are complex water bodies with flow conditions typical of lakes (the so-called lacustrine zone), transitional zones, and riverine zones. Hydrodynamic models can be used to differentiate these zones and understand the pattern of water circulation (Carrick et al., 1994; Kawara et al., 1998; Tufford & McKellar, 1999; Verkhozina et al., 2000). One-dimensional (1D) models, such as HEC-RAS, are commonly utilized to calculate key hydraulic parameters in cross-sections, such as water level, area, velocity, and shear stress. For instance (Hama Karim et al., 2024a) used HEC-RAS to delineate the riverine, transitional, and lacustrine zones in the Sulejów Reservoir, aiding in the understanding of the longitudinal gradients of water quality parameters from the backwater area to the dam.

The use of two-dimensional (2D) models, exemplified by the CCHE2D model, has been prominent in studying flow and sedimentation processes in large reservoirs in Poland (Magnuszewski et al., 2010, 2018). Unlike 1D models, which primarily calculate parameters in cross-sections, CCHE2D allows for a more comprehensive analysis by considering spatial variations in water flow, for example average velocities in verticals.

Furthermore, three-dimensional (3D) hydrodynamic models, such as one developed in a previous study (Ziemińska-Stolarska et al., 2015), offer even more detailed insights into velocity patterns, revealing the complex pattern of wind-driven water circulation in the lacustrine zone.

In this paper, we focus on the application of a 1D and 2D hydrodynamic models to analyze flow dynamics combined with satellite imagery in order to investigate a pattern of the phytoplankton bloom formation.

Materials and Methods

Study area

The Pilica River is the biggest tributary on the left bank of the Vistula River in Poland. It stretches for 342 km and has a catchment area of 9,258 km^2 (Fig. 1). The Sulejów Reservoir was built between 1969 and 1973 to supply drinking water to the fast-expanding metropolis of Łódź, situated about 50 km north-west of the reservoir. The reservoir has an earth dam located in Smardzewice village, measuring 15.4 m in height and spanning 1210 m in length. It is 15.5 km long, with a maximum width of 2.1 km, covering a surface area of 22 km^2. The reservoir serves multiple purposes, including flood management and hydropower generation. Agricultural land covers 60% of the Pilica River basin, while forests occupy 31%. The

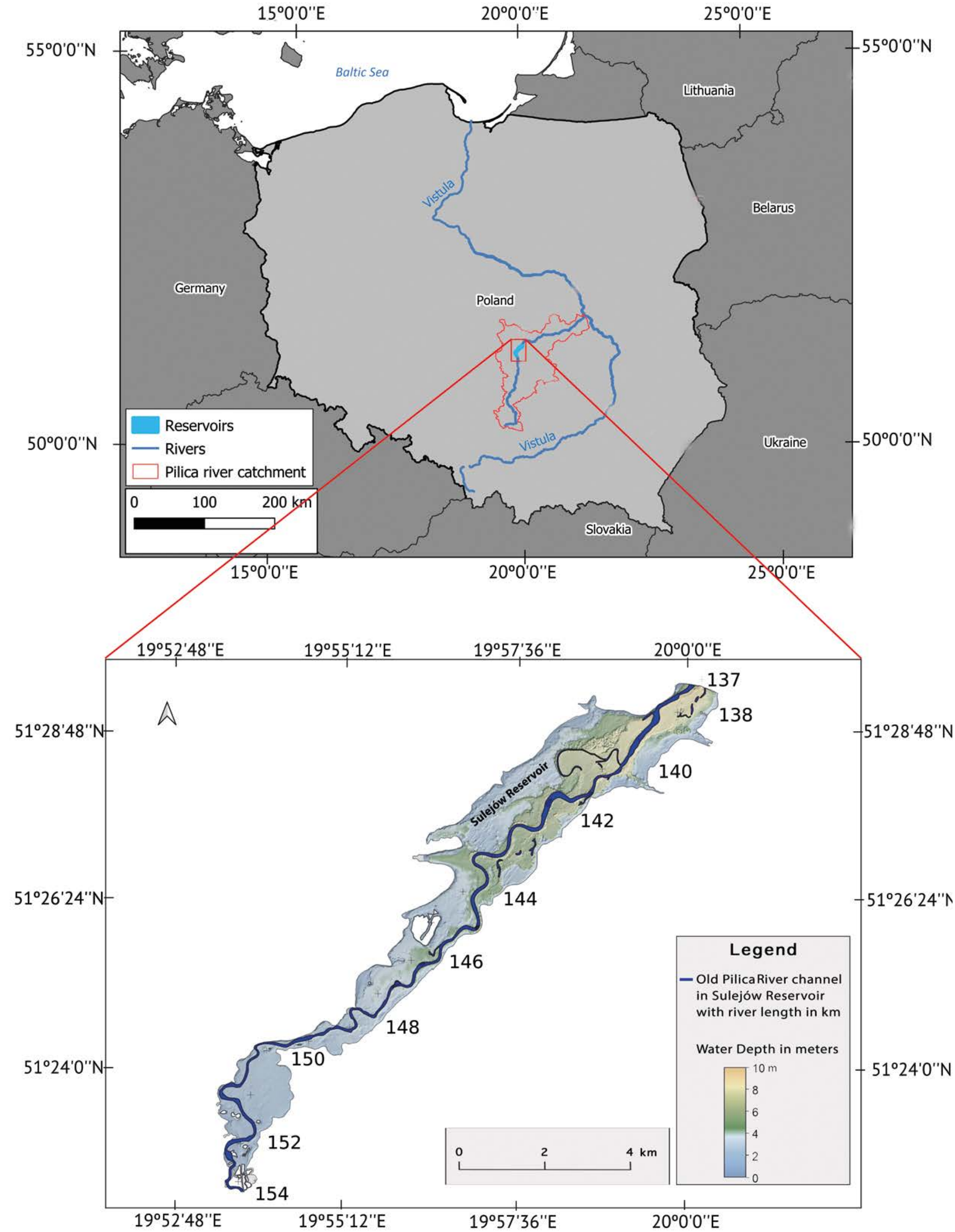

Figure 1. Location of the Sulejów Reservoir on the Pilica River

Pilica River catchment, particularly the Sulejów Reservoir's differential catchment, experiences significant anthropogenic pressure due to high population density and large volumes of municipal wastewater discharge (Magnuszewski et al., 2014).

The two main rivers supplying the Sulejów Reservoir are Pilica and its left tributary, the Luciąża River. The long-term average discharge of Pilica at Sulejów gauge is 22.8 $m^3 \cdot s^{-1}$, while that of Luciąża at Kłudzice is 3.03 $m^3 \cdot s^{-1}$. The water turnover in the Sulejów Reservoir is long, with an average discharge of more than 30 days. This feature enhances the sedimentation processes through stable hydrodynamic conditions in the reservoir (Hama Karim et al., 2024a). Although the reservoir has a large volume, sedimentation is not very intense. A previous study (Pieron et al., 2021) estimated that the reservoir lost approximately 46,000 m^3 of water annually over 50 years due to sedimentation.

The occurrence of cyanobacteria has been consistently observed every year since the reservoir began operating and was one of the reasons for closing the surface water intake for the Łódź city waterworks (Tarczyńska et al., 1997). The Sulejów Reservoir receives inflow from the Pilica and Luciąża rivers at its backwater area, monitored by hydrological gauges (Sulejów and Kłudzice). Water quality at the inflow to the reservoir is measured at water monitoring posts (Sulejów and Przygłów) (Fig. 2). Below the dam, there are hydrological posts in Spała and Zawada, while a water quality post is located in Smardzewice. Hydrological gauges operated by the Institute of Meteorology and Water Management (IMGW) provide information on daily discharges (IMGW-PIB, 2024). Water quality posts are operated by the Chief Inspectorate of Environmental Protection (GIOŚ) in a monthly sampling interval.

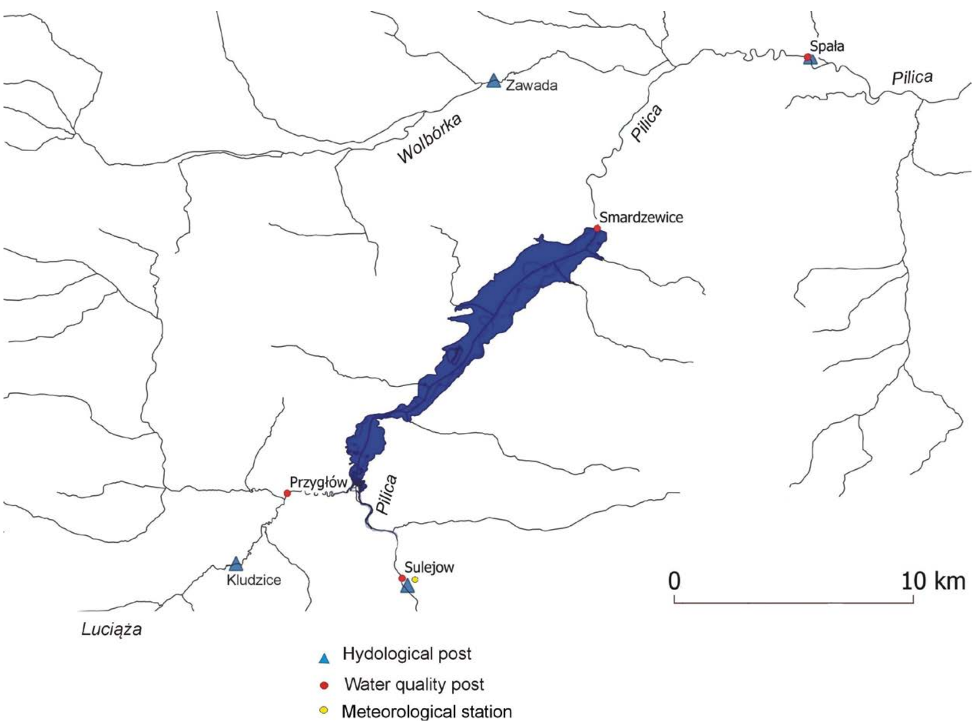

Figure 2. Location of the IMGW hydrological gauges and GIOŚ water quality monitoring stations of the Sulejów Reservoir

Hydrological control of the eutrophication

Urbaniak et al. (2012) has shown that the Sulejów Reservoir was a trap for suspended particulate matter (SPM). In 2006, the mean inflow concentration of SPM in the backwater area was 13.56 mg·dm^{-3}, and the mean outflow concentration was 7.48 mg·dm^{-3}. The research showed an annual significant reduction of nutrients and SPM concentrations and retention in the reservoir compared with 1992, which amounted to 28% of TP, and 45% of SPM.

From the long-term observation data, the period 2004-2009 was selected which has a complete list of hydrological (discharge Q m^3·s^{-1}) and water quality (Total Phosphorous TP concentration g·m^{-3}) parameters. This period is representative for the long-term river discharge of the Pilica and Luciąża rivers. TP loads are calculated at monthly intervals at the inlet and outlet of the reservoir.

We have used a methodology to calculate the TP load at the outlet of the reservoir from concentrations measured at the Smardzewice monitoring point below the dam and the average monthly discharge from the Spała gauge minus the discharge from the Wolbórka River tributary, controlled at the Zawada gauge.

Monthly values of TP load at the inlet to the reservoir (Sulejów and Przygłów monitoring points) and at the outlet of the reservoir (Smardzewice monitoring point), together with the average monthly discharge values of the Pilica and Luciąża rivers, are shown in Figure 3. Additionally, the average discharge of the Pilica and Luciąża rivers in July to September periods is marked. This graph shows that most of the time, as the load below the reservoir is smaller than the load at the backwater inlet, Sulejów Reservoir acts like a trap for a TP. In the period of summer, when discharge of Pilica and Luciąża rivers is low, and there is a vegetation period with phytoplankton bloom, the Sulejów Reservoir turns into source of TP.

Hydraulic control of the phytoplankton blooms

The geometry of the reservoir is represented as a 5 m resolution DTM (Digital Terrain Model), which was calculated from precise bathymetric measurements. Measurements

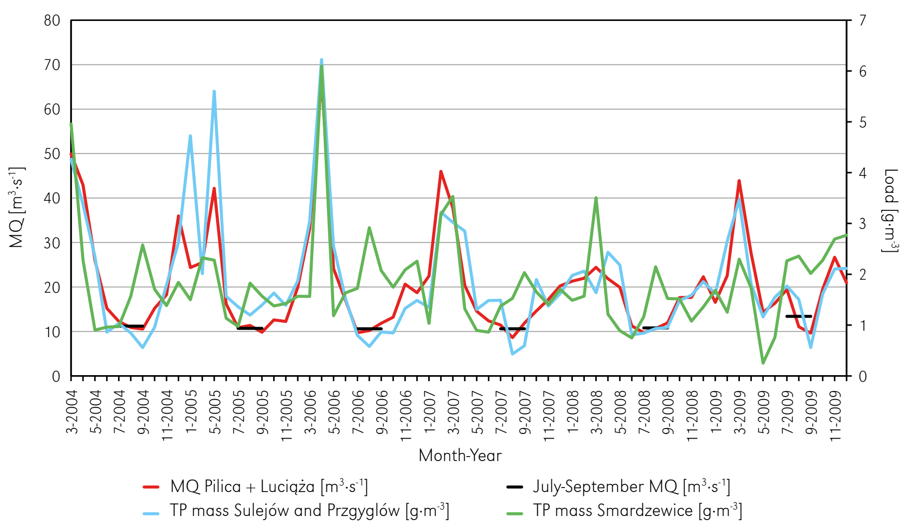

Figure 3. Monthly values of TP load years 2004-2009 at the inlet to the reservoir (Sulejów and Przygłów monitoring points) and at the outlet of the reservoir (Smardzewice), together with monthly discharge and average discharge in months July–September of Pilica and Luciąża rivers (July-September mean discharge – MQ)

performed in 2016 by Lowrance HDS-3 sonar include 440,000 echo sounding points (Jaskulski et al., 2018).

To understand the longitudinal distribution of velocities in the Sulejów Reservoir, the one-dimensional (1D) hydrodynamic model HEC-RAS, developed by the US Army Corps of Engineers, Hydrologic Engineering Center, was applied. Geometry of the reservoir as a set of cross-sections was obtained from 5 m resolution DTM. The number 73 cross-sections were set with an average spacing of 200 m. One Manning roughness coefficient n = 0.025 has been designed for all cross-sections. That value represents an earth, a fairly uniform channel without vegetation. The lower boundary condition was set as a water head elevation at the dam, while the upper boundary condition is the combined average discharge of Pilica and Luciąża rivers.

More detailed picture of velocities pattern at the Sulejów Reservoir was obtained using the CCHE2D hydrodynamic model developed at the National Center for Computational Hydro Science and Engineering (NCCHE) at the University of Mississippi, USA. This is a two-dimensional (2D) depth-averaged, unsteady, turbulent open-channel flow model based on the depth-averaged Navier-Stokes equations, incorporating the impact of wind on water surfaces, so the model may be used for cases in which water flow is affected by the wind field. Examples of CCHE2D use for rivers and reservoirs may be found in previous works (Altinakar et al., 2005; Kalinowska et al., 2012; Kalinowska & Rowiński, 2012; Magnuszewski et al., 2010, 2018), and also a detailed description of the model (Jia & Wang, 2001).

The two-dimensional computational grid and bed profile necessary for the velocity simulations were prepared using the CCHE_MESH generator developed by NCCHE. The final computing mesh had a dimension of I = 80 x J = 700 elements. The simulations were run for 60-second time steps. The upper boundary condition was the discharge of the Pilica River and Luciąża River, and the lower boundary condition was a water head at the dam profile. All boundary conditions for water flow and wind action simulations were obtained from the IMGW hydrological and meteorological stations.

For both models' verification, the results of water surface leveling in cross-sections located at 150.25, 151.05 and 151.65 km at the reservoir backwater, measured in the field on 2011-08-30, were used. Comparison of calculated by the model water levels and measured in the field by leveling is shown in Table 1. The maximum difference between the simulated and measures water surface elevation is 4 cm in case of CCHE2D model.

Instrumental measurements for the verification of velocities in the lacustrine zone are problematic because of the slow current and the problem of instrument anchorage. Literature (Ziemińska-Stolarska et al., 2015) shows an example of time averaged ADCP measurements in the Sulejów Reservoir for 3D hydrodynamic model verification. Velocities measured by this method in the lacustrine part of the reservoir are similar to our results from 2D modeling

The Sulejów Reservoir does not show thermal stratification, which allows nutrients circulate easily in the biosystem and intensify primary production. Surface water temperature

Table 1. Comparison of water surface elevation (m a.s.l.) calculated by HEC-RAS and CCHE2D models and measured in the field by leveling

Location of the cross-section [km]	HEC-RAS	CCHE2D	Field levelling
150.25	166.63	166.60	166.63
151.05	166.63	166.60	166.63
151.65	166.63	166.60	166.64

measured close to the dam in the lacustrine part of the reservoir in the May–October period in 2015 and 2016 showed that the temperature reached 25°C in mid-June of 2016 and at the beginning of August 2016. In 2015, high water temperatures in the lacustrine part of the Sulejów Reservoir were recorded at the beginning of July and lasted (except for weekly periods) until mid-August 2015 (Ziemińska-Stolarska et al., 2019).

Remote sensing data for phytoplankton detection

The distribution of phytoplankton blooms on the Sulejów Reservoir was documented using Sentinel-2 satellite imagery available from the archive Sat4Envi (https://sat4envi.imgw.pl). The availability of cloud-free images were taken into consideration for the reservoir during the vegetation period (May–October) in the years 2016-2024. The highest number of images used in the study was 8 images in the year 2020. The year 2023 was not included due to maintenance works in the reservoir, which required lowering water surface. For the other years, authors got cloud free images ranging from 1-6 images per year during the vegetation period (May-October).

Downloaded images were processed by SNAP (v8) which is a free open toolbox designed for processing data from the Sentinel missions. Processing included resampling original scene data to the subset representing reservoir.

In many water bodies, concentrations of phytoplankton are strongly influenced by the occurrence of dissolved organic material and suspended sediments (Magnuson et al., 2004). To overcome this limitation, numerous algorithms have been proposed to quantify chlorophyll-a (Chl-a) in turbid productive waters using remote sensing data and red and near-infrared (RED-NIR) bands. These algorithms use different numbers of bands: (1) two bands (Tzortziou et al., 2007; Moses et al., 2009), (2) three or four bands (Gons, 2002; Dall'Olmo & Gitelson, 2005; Gons et al., 2008; Le et al., 2009).

Phytoplankton pigment concentration (Chl-a) is the most commonly derived parameter in water-quality remote sensing mainly because it can be used as a proxy for phytoplankton concentration. Basic ratio of reflectance at about 700 nm to that near 670 nm is widely used for estimating Chl-a concentration in inland and coastal waters (Matthews, 2011).

In this study, we use the Normalized Difference Chlorophyll index (NDCI) formula based on two band ratios (Mishra & Mishra, 2012) showed in Equation (1):

$$NDCI = \frac{(B5 - B4)}{(B5 - B4)} \tag{1}$$

where:

B5 (705 nm) and B4 (665 nm) are Sentinel-2 spectral bands. The values of the NDCI index for a single scene (2020-08-02) with the highest contrast between water and phytoplankton range from 0.5 to -0.04. Negative values represent pure water without phytoplankton. This index highlights areas of increased phytoplankton biomass and is particularly useful for detecting and quantifying algal blooms. Sentinel-2 bands B5 and B4 were selected for their specific sensitivity to chlorophyll-a absorption and reflectance. We choose NDCI because the literature overview shows it as a reliable tool for assessing phytoplankton dynamics in eutrophic water bodies, it has a simple form and is easy to interpret.

A comparison of the eight NDCI images from the year 2020 is shown in Figure 4. As additional information, the wind direction and velocity at the moment of image sensing were obtained from synoptic meteorological station in Sulejów operated by the Institute of Meteorology and Water Management.

To show the places of most frequent and intensive phytoplankton bloom on the Sulejów Reservoir NDCI values from eight Sentinel-2 images have been summarized. The bloom intensity hotspots are located in the lacustrine zone of Sulejów Reservoir (upper part) (Fig. 5).

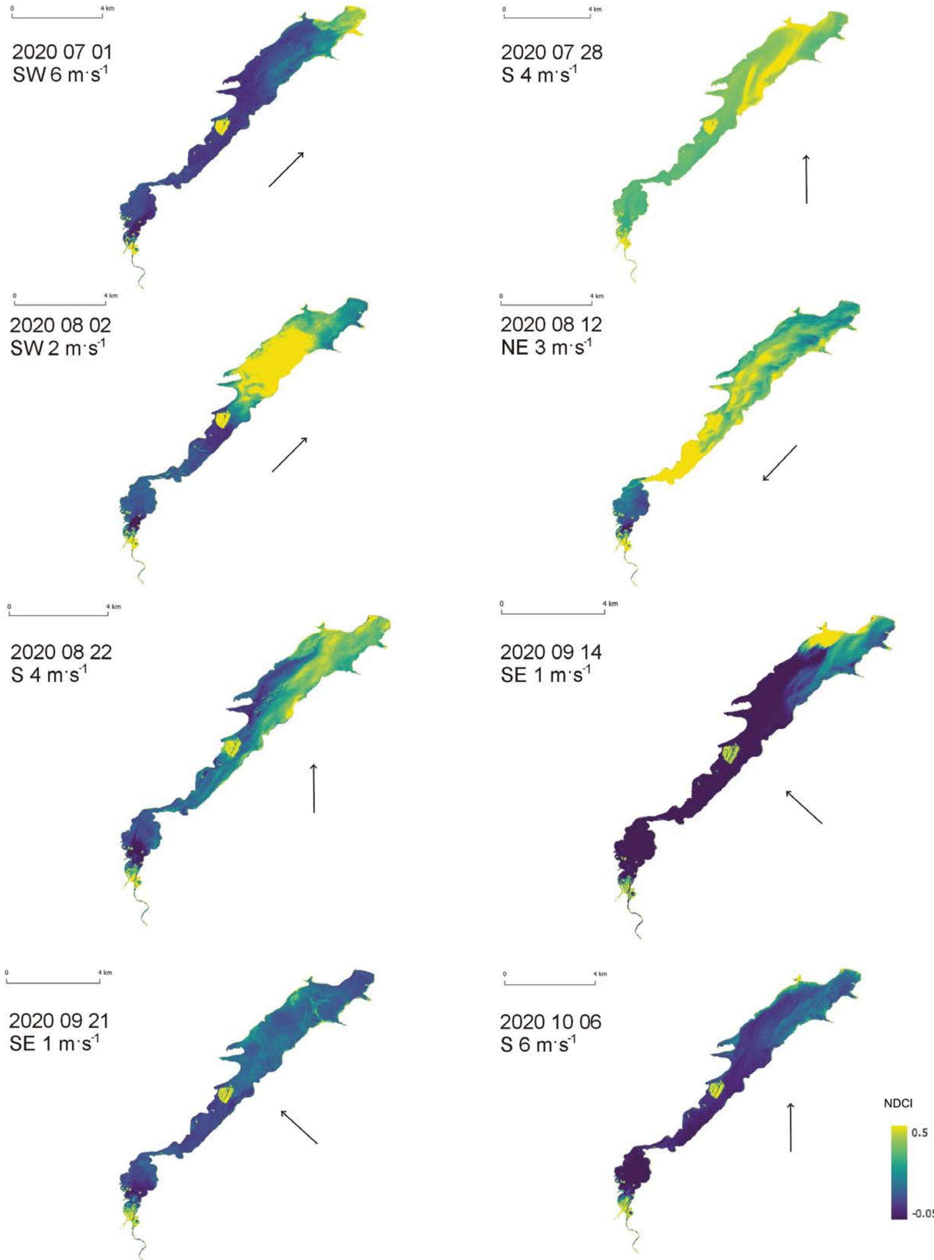

Figure 4. Distribution of phytoplankton blooms on the Sulejów Reservoir in 2020: documented using the NDCI index, calculated from bands B4 and B5 of Sentinel-2 satellite images. Below the date of image recording, wind direction and velocity are given, and arrows show wind direction

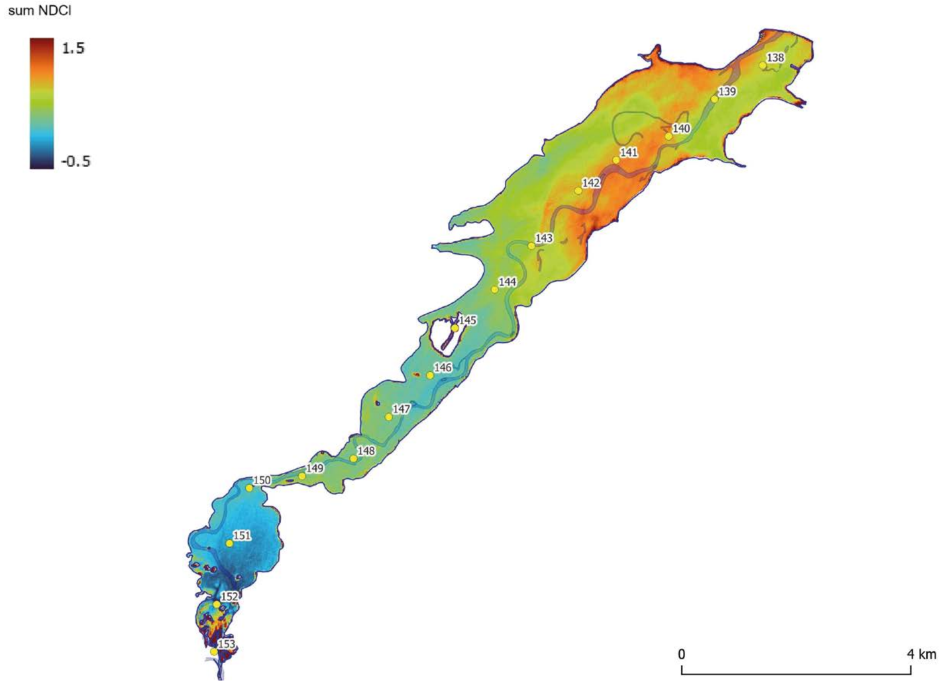

Figure 5. The sum of NDCI indexes, calculated from eight Sentinel-2 images recorded in the period 2020-07-01 till 2020-10-06, showing the most frequent and intensive occurrence of phytoplankton blooms on the Sulejów Reservoir, with km of river chainage

Results and Discussion

The results of the 1D HEC-RAS model show the longitudinal profile of the velocity in cross sections (Fig. 6). Upstream from the dam in the longitudinal profile of the reservoir, it can be a delineated zone with lacustrine conditions which stretch from the dam to 145 km. Riverine conditions are characteristic for the reach 148-152.6 km. Finally, a transition zone between the riverine and lacustrine parts of the reservoir stretches from 145-148 km. The average in the cross-sections velocity distribution in the reservoir shows that in the lacustrine zone, there is practically standing water with velocities in the order of 0.01-0.02 $m{\cdot}s^{-1}$.

This pattern of the velocity distribution is more visible from results of CCHE2D model calculations. Lacustrine zone between the dam and 148 km has very low velocities and covers the deepest part of the reservoir. There are two zones of accelerated velocities in the reservoir narrowing at reach 148-150 km (Fig. 7).

Low velocities of flow and large depth of the reservoir in the lacustrine zone enhance the sedimentation conditions. Field sampling of the bottom sediments and analysis of the total organic carbon, total phosphorous, and cadmium concentrations show that this area acts like deposition zone (Hama Karim et al., 2024b).

In this study, we use the NDCI index to determine the location and intensity of phytoplankton blooms on the Sulejów Reservoir. The sum of the values of the NDCI indexes, calculated from the eight images registered in 2020, shows where the phytoplankton occurs most frequently. It has been shown that the most intensive occurrence of phytoplankton blooms is found in a lacustrine zone of the Sulejów Reservoir between 137 km and

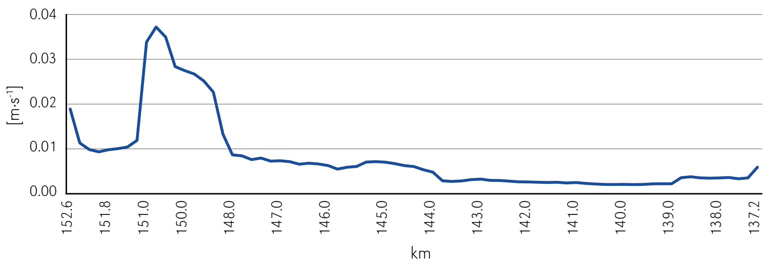

Figure 6. Longitudinal profile of Sulejów reservoir showing distribution of average velocity in the cross-sections calculated by HEC-RAS model for the conditions of long-term average discharge and normal water head at the dam

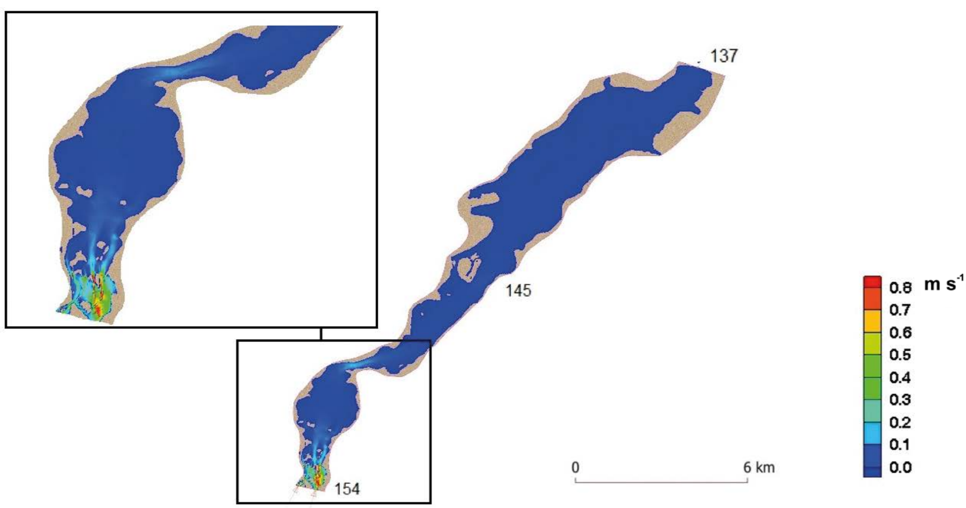

Figure 7. Distribution of depth average velocities (m·s^{-1}) in the Sulejów Reservoir calculated by CCHE2D model for the conditions of long-term average discharge and normal water head at the dam

145 km. This pattern confirms the hydraulic differentiation of the reservoir obtained from hydrodynamic models.

The distribution of phytoplankton bloom cover shows that it starts to develop in July near the dam and reaches maximum levels in August, then starts to diminish at the beginning of October (Fig. 4). That sequence is confirmed by the former studies on the reservoir by Ziemińska-Stolarska et al. (2019). Unfortunately cloud cover on Sentinel-2 images limits the number of images available during the vegetation period, so it is impossible to analyze the phytoplankton bloom in higher time resolution. It is possible to add the NDCI images from many years to get the long-term average picture of most common and intensive phytoplankton bloom.

The drawback for detecting the intensity and location of phytoplankton blooms on reservoirs in middle latitude regions is cloud cover, which makes the optical satellite images unsuitable. The maximum number of Sentinel-2 cloud-free images during the vegetation period in the years 2016-2024 was only 8 (in 2020). In unfavourable conditions, there may be only a few images available, which does not provide sufficient time resolution to study the dynamic development of phytoplankton blooms during the vegetation period.

Presented results explain mechanism of changing the balance of TP in the reservoir. The sum of the NDCI index, calculated from eight Sentinel-2 images (period July–October 2020), shows that the most intensive and frequent phytoplankton blooms can be found in the lacustrine part of the Sulejów Reservoir. The comparison of TP loads at the inflow and outflow of the reservoir shows that, during the summer months and under low-flow conditions, the reservoir acts as a source of nutrients. The TP load leaving the reservoir through the dam spill is higher than the inflow from the Pilica and Luciąża rivers (Fig. 3). This can be explained by the fact that in the lacustrine zone, intensive phytoplankton bloom, which contains an organic part of TP, is transported by the flow of water through the reservoir.

This pattern corresponds with the chemical properties of the bottom sediments. The highest concentrations of TP is found in the bottom sediments in the area of the former Pilica River thalweg at the lacustrine zone (Hama Karim et al., 2024b; Ziemińska-Stolarska et al., 2020) (Fig. 8). That part of the reservoir's bottom sediments may act as pool of TP responsible for an internal nutrient loading mechanism, supplying cyanobacteria with phosphorus during phytoplankton bloom.

Internal nutrient loading from bottom sediments significantly contributes to summer phytoplankton blooms. Studies (Kalinowska et al., 2012; Kalinowska & Rowiński, 2012) identified the lacustrine zone as a hotspot for TP accumulation in sediments, particularly in areas with fine-grained deposits. In these zones, wind action creates secondary circulation patterns, such as eddies, which influence bloom distribution (Altinakar et al., 2005).

In the lacustrine part of the reservoir, the flow velocities are very low, and the water circulation pattern is controlled not only by reservoir geometry but also by wind. Image form

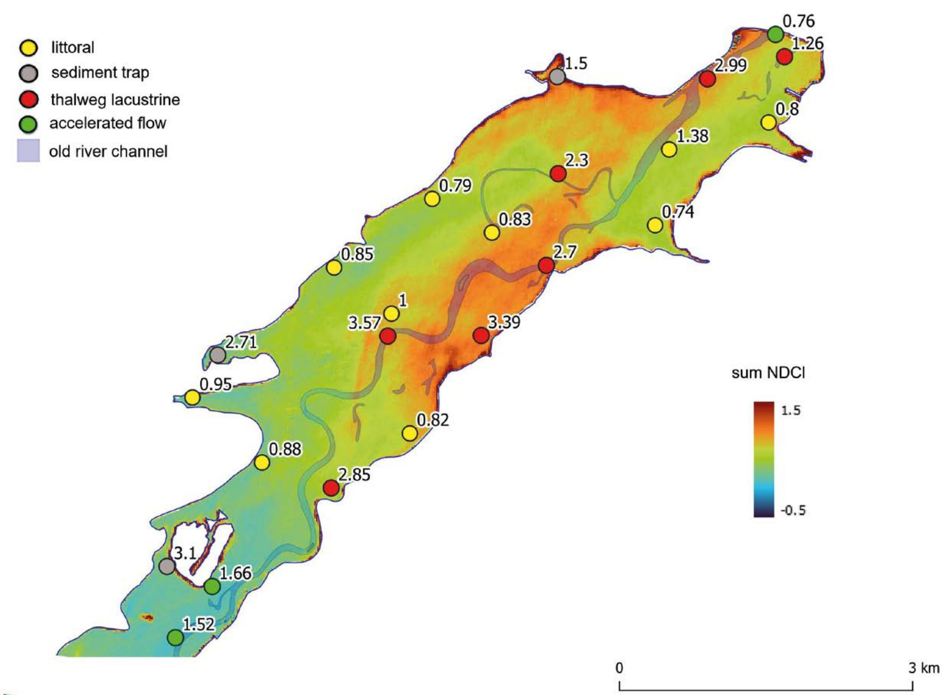

Figure 8. The Sulejów Reservoir lacustrine zone in 2020; summarized NDCI index, and concentration of TP in bottom sediments (mg·L^{-3}) with different sedimentation conditions

2020-08-12 shows that wind blowing from NE direction can relocate the phytoplankton bloom from lacustrine zone toward the transitional zone of the reservoir (see Fig. 4).

Wind can create also circulation patterns in the surface of the water in the lacustrine zone of the reservoir. Two cases of the effect of the wind on surface water velocities were studied using the CCHE2D model. These were following days: 2020-07-28 and 2020-08-02. The pattern of vectors showing surface water circulation was displayed on top of NDCI images.

The pattern of surface currents caused by S wind velocity 4 m·s^{-1} and NDCI index on 2020-07-28 at the lacustrine zone is shown in Figure 9. The inflow to the reservoir was 10.5 m^3·s^{-1} and the water head at the dam was 166.60 m a.s.l.

The pattern of surface currents is caused by wind direction SW and velocity 2 m·s^{-1} at the lacustrine part of the Sulejów Reservoir and NDCI index on 2020-08-02 (Fig. 10). The inflow to the reservoir was 9.9 m^3·s^{-1} and the water head at the dam was 166.57 m a.s.l.

Both cases show that wind affected flow in the lacustrine zone created circulation structures – eddy dipoles. Eddy dipoles are two coupled counter-rotating eddies separated by a central jet between them. Eddy dipoles located between 140 km and 143 km increase the concentration of phytoplankton. The study of Ziemińska-Stolarska et al. (2015) with the use of 3D hydrodynamic model ANSYS FLUENT 14.0 has shown a similar general pattern of eddies on the Sulejów Reservoir.

Eddies forming at the right bank of the reservoir near-shore expansion close to the dam (138 km) are located away from the former Pilica River thalweg and do not create convergence zones, which would increase the concentration of the phytoplankton.

A similar approach in larger-scale oceanographic studies was used by researchers (Mohn & White, 2007) who selected seven years (1998-2004) of remotely sensed data

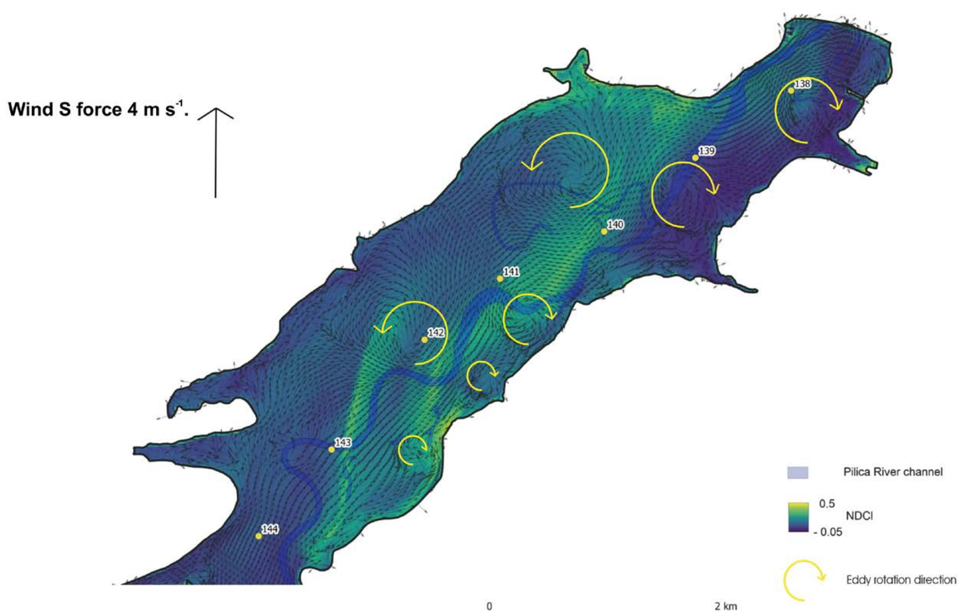

Figure 9. The Sulejów Reservoir lacustrine zone; summarized NDCI index; the result of a simulation shown as a pattern of surface currents caused by S wind velocity 4 m·s^{-1} and NDCI index on 2020-07-28

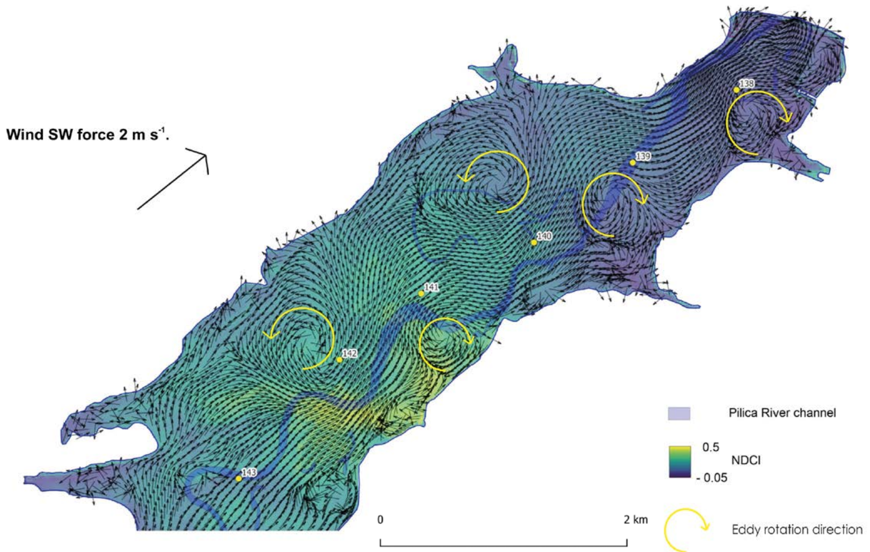

Figure 10. Lacustrine part of the Sulejów Reservoir – NDCI index, calculated from Sentinel-2 image from 2020-08-02; and velocity field of surface currents, calculated using the CCHE2D model at wind direction SW and velocity 2 $m \cdot s^{-1}$

to create monthly climatological fields, and numerically simulated the spatiotemporal characteristics of chlorophyll-a in the waters of Porcupine and Rockall Bank in the north--eastern Atlantic.

In another study (Soontiens et al., 2019), researchers applied combined hydrodynamic modelling with remote sensing data to develop a hydrodynamic model of algal bloom transport for Lake Erie, and remotely sensed chlorophyll-a data from the European Space Agency's Sentinel-3A OLCI sensor.

Hensen et al. (1989) tried to monitor SPM by comparing satellite remote sensing retrieval with numerical simulation. In their work, they modelled SPM distribution using a coupled hydrodynamic and dispersion model and analysis of Landsat TM data in Laguna de Terminos, Campeche, Mexico.

Another study (Kouts et al., 2006) combined MERIS satellite remote sensing data with numerical modelling to study Pakri Bay in the southern Gulf of Finland to improve the understanding of sediment dynamics. The results show good agreement with the in-situ measurements and simulated SPM dynamics in clear waters, with an SPM concentration of lower than 20 $mg \cdot dm^{-3}$.

Remote sensing data on chlorophyll-a and suspended sediment distribution can also be used to verify hydrodynamic models. The pattern of sediment flux from the river to the reservoir is visible on multispectral and hyperspectral images and may be compared to the field of suspended sediment concentration calculated by the 2D model (Sabat-Tomala et al., 2018).

The work of Ginzburg et al. (2024) on Lake Sevan has shown that eddies can form at inland water bodies and their patterns can be recorded by satellite images. Images showed that eddy circulation elements largely determine the spatiotemporal variability of phytoplankton distribution on the lake surface.

Attempts were made to find the relation between NDCI index values and chlorophyll-a concentrations. The problem encountered in many studies is that spectral channels in the blue-green part of the electromagnetic spectrum are heavily affected by the presence of constituents such as Colored

Dissolved Organic Matter (CDOM), detritus, tripton, and suspended sediment (Mishra & Mishra, 2012).

In this study, we use NDCI index as a method for visualization of phytoplankton bloom pattern and distribution. Obtained results are in accordance with field measurements of chlorophyll-a concentrations performed in years 2015-2016 using stationary measuring instruments mounted on a buoy. Maximum concentrations were measured in the lacustrine region of the reservoir from mid-June to mid-August (Ziemińska-Stolarska et al., 2019).

Conclusions

In this study, remote sensing and hydrodynamic modelling results were used for the first time to show the location of phytoplankton blooms along the Sulejów Reservoir. The Sulejów Reservoir is a large and complex water body and therefore, remote sensing data can provide a synoptic view on phytoplankton distribution.

The calculation of TP load has shown that under low-flow conditions during the summer months (July-September), the reservoir can act as a source, supplying the lower reach of the Pilica River with TP. This is caused due to the high concentration of the organic form of phosphorus enclosed in phytoplankton blooms in the lacustrine part of the reservoir.

In the lacustrine part of the reservoir, the flow velocities are very low, and the water circulation pattern is controlled not only by reservoir geometry but also by wind. Image form 2020-08-12 shows that wind blowing from NE direction can relocate the phytoplankton bloom from lacustrine zone toward the transitional zone of the reservoir

Coupling remote sensing data and hydrodynamic numerical modeling helps in understanding the pattern of phytoplankton bloom. Phytoplankton can be seen as a natural tracer that shows the pattern of circulation in the Sulejów Reservoir. This property is useful for hydrodynamic model verification. For the first time in the study of the Sulejów Reservoir, it was possible to show that the structure of eddies in the lacustrine zone of the reservoir affects phytoplankton distribution. Further studies can be made since eddies increase water residence time in the reservoir and can also create a vertical flux of nutrients from the deeper parts of the reservoir.

Acknowledgments

We thank Institute of Geophysics of Polish Academy of Science for providing access to CCHE2D model. This research received no external funding.

Authors' contribution

Conceptualization: **PHK**, **AZ-S** and **AM**; Methodology: **MK**; Software: **MK**; Formal analysis: **PHK** and **AM**; Investigation: **AM**; Data curation: **PHK**; Writing original draft: **PHK**, **MK**, **AZ-S** and **AM**; Writing – review & editing: **MK** and **AM**.

Editors' note:
Unless otherwise stated, the sources of tables and figures are the authors', on the basis of their own research.

References

Altinakar, M., Czernuszenko, W., Rowiński, P., & Wang, S. (2005). *Computational Modeling for the Development of Sustainable Water-Resources Systems in Poland*. Institute of Geophysics, Polish Academy of Sciences, E-5, 387.

Ansper, A., & Alikas, K. (2018). Retrieval of Chlorophyll a from Sentinel-2 MSI Data for the European Union Water Framework Directive Reporting Purposes. *Remote Sensing*, *11*(1), 64. https://doi.org/10.3390/rs11010064

Bresciani, M., Cazzaniga, I., Austoni, M., Sforzi, T., Buzzi, F., Morabito, G., & Giardino, C. (2018). Mapping phytoplankton blooms in deep subalpine lakes from Sentinel-2A and Landsat-8. *Hydrobiologia*, *824*(1), 197-214. https://doi.org/10.1007/s10750-017-3462-2

Carrick, H. J., Worth, D., & Marshall, M. L. (1994). The influence of water circulation on chlorophyll-turbidity relationships in Lake Okeechobee as determined by remote sensing. *Journal of Plankton Research*, *16*(9), 1117-1135. https://doi.org/10.1093/plankt/16.9.1117

Dall'Olmo, G., & Gitelson, A. A. (2005). Effect of bio-optical parameter variability on the remote estimation of chlorophyll-a concentration in turbid productive waters: Experimental results – erratum. *Applied Optics*, *44*(16), 3342. https://doi.org/10.1364/AO.44.003342

European Space Agency. (2020). *Sentinel-2: Multispectral Imager (MSI) Overview*. https://www.esa.int/Applications/Observing_the_Earth/Copernicus/Sentinel-2

European Space Agency (Sentinel-2). (2015). [Dataset]. https://www.esa.int/

Ginzburg, A. I., Kostianoy, A. G., Sheremet, N. A., & Lavrova, O. Yu. (2024). Water Dynamics and Morphometric Parameters of Lake Sevan (Armenia) in the Summer-–Autumn Period According to Satellite Data. *Remote Sensing*, *16*(13), 2285. https://doi.org/10.3390/rs16132285

Glibert, P. M., Anderson, D. A., Gentien, P., Graneli, E., & Sellner, K. G. (2005). The global, complex phenomena of harmful algal blooms. *Oceanography Society*, *182*(136-147). https://agris.fao.org/search/en/providers/122415/records/64736847e17b74d22254c85e

Godlewska, M., Balk, H., Kaczkowski, Z., Jurczak, T., Izydorczyk, K., Długoszewski, B., Jaskulska, A., Gągała-Borowska, I., & Mankiewicz-Boczek, J. (2018). Night fish avoidance of Microcystis bloom revealed by simultaneous hydroacoustic measurements of both organisms. *Fisheries Research*, *207*, 74-84. https://doi.org/10.1016/j.fishres.2018.05.025

Gons, H. J. (2002). A chlorophyll-retrieval algorithm for satellite imagery (Medium Resolution Imaging Spectrometer) of inland and coastal waters. *Journal of Plankton Research*, *24*(9), 947-951. https://doi.org/10.1093/plankt/24.9.947

Gons, H. J., Auer, M. T., & Effler, S. W. (2008). MERIS satellite chlorophyll mapping of oligotrophic and eutrophic waters in the Laurentian Great Lakes. *Remote Sensing of Environment*, *112*(11), 4098-4106. https://doi.org/10.1016/j.rse.2007.06.029

Hadjimitsis, D. G., & Clayton, C. (2009). Assessment of temporal variations of water quality in inland water bodies using atmospheric corrected satellite remotely sensed image data. *Environmental Monitoring and Assessment*, *159*(1-4), 281-292. https://doi.org/10.1007/s10661-008-0629-3

Hama Karim, P., Ziemińska-Stolarska, A., & Magnuszewski, A. (2024a). Hydraulic properties of Sulejów Reservoir in Poland as a driving factor of sedimentation processes. In M. B. Kalinowska, M. M. Mrokowska, P. M. Rowiński (Eds.), *Advances in Hydraulic Research. ISH 2023.* GeoPlanet: Earth and Planetary Sciences). Springer International Publishing. https://doi.org/10.1007/978-3-031-56093-4_17

Hama Karim, P., Ziemińska-Stolarska, A., & Magnuszewski, A. (2024b). Hydraulic control on sedimentation processes and bottom sediments chemistry of Sulejów Reservoir in Poland. *Miscellanea Geographica. Regional Studies on Development*, *28*(1), 39-46. https://doi.org/10.2478/mgrsd-2023-0029

Harper, D. M. (1992). *Eutrophication of freshwaters: Rinciples, problems, and restoration* (1st ed). Chapman & Hall.

IMGW-PIB. (2024). [Dataset]. https://hydro.imgw.pl/#/

Jaskulski, M., Szmidt, A., Zbiciński, I., Ziemińska-Stolarska, A., & Adamiec, J. (2018). Konstrukcja mapy batymetrycznej na podstawie badań sonarowych sztucznego zbiornika wodnego na przykładzie Zalewu Sulejowskiego. *Teledetekcja Środowiska*, *59*(2), 5-12.

Jensen, J. R., Kjerfve, B., Ramsey, E. W., Magill, K. E., Medeiros, C., & Sneed, J. E. (1989). Remote sensing and numerical modeling of suspended sediment in Laguna de terminos, Campeche, Mexico. *Remote Sensing of Environment*, *28*, 33-44. https://doi.org/10.1016/0034-4257(89)90103-X

Jia, Y & Wang, S. (2001). *CCHE2D : Two-dimensional Hydrodynamic and Sediment Transport Model for Unsteady Open Channel Flows over Loose Bed, Technical Report No. NCCHE-TR-2001-1*. School of Engineering The University of Mississippi.
http://www.ncche.olemiss. edu/sites/default/les/les/docs/cche2d/techmanual.pdf

Kalinowska, M. B., & Rowiński, P. M. (2012). Uncertainty in computations of the spread of warm water in a river – lessons from Environmental Impact Assessment case study. *Hydrology and Earth System Sciences*, *16*(11), 4177-4190. https://doi.org/10.5194/hess-16-4177-2012

Kalinowska, M. B., Rowiński, P. M., Kubrak, J., & Mirosław-Świątek, D. (2012). Scenarios of the spread of a waste heat discharge in a river – Vistula River case study. *Acta Geophysica*, *60*(1), 214-231. https://doi.org/10.2478/s11600-011-0045-x

Kawara, O., Yura, E., Fujii, S., & Matsumoto, T. (1998). A Study on the role of hydraulic retention time in eutrophication of the asahi river dam reservoir. *Water Science and Technology*, *37*(2). https://doi.org/10.1016/S0273-1223(98)00030-4

Komárek, J., & Anagnostidis, K. (1999). Süsswasserflora von Mitteleuropa. Cyanoprokaryota 1. Chroococcales. Jena: Gustav Fischer.

Kouts, T., Sipelgas, L., Savinits, N., & Raudsepp, U. (2006). Environmental monitoring of water quality in coastal sea area using remote sensing and modeling. In *2006 IEEE US/EU Baltic International Symposium* (pp. 1-8). https://doi.org/10.1109/BALTIC.2006.7266166

Kumar, A., Mishra, D. R., & Ilango, N. (2020). Landsat 8 Virtual Orange Band for Mapping Cyanobacterial Blooms. *Remote Sensing*, *12*(5). https://doi.org/10.3390/rs12050868

Le, C., Li, Y., Zha, Y., Sun, D., Huang, C., & Lu, H. (2009). A four-band semi-analytical model for estimating chlorophyll a in highly turbid lakes: The case of Taihu Lake, China. *Remote Sensing of Environment*, *113*(6), 1175-1182. https://doi.org/10.1016/j.rse.2009.02.005

Magnuson, A., Harding, L. W., Mallonee, M. E., & Adolf, J. E. (2004). Bio-optical model for Chesapeake Bay and the Middle Atlantic Bight. *Estuarine, Coastal and Shelf Science*, *61*(3), 403-424. https://doi.org/10.1016/j.ecss.2004.06.020

Magnuszewski, A., Kiedrzyńska, E., Kiedrzyński, M., & Moran, S. (2014). Gis approach to estimation of the total phosphorous transfer in the Pilica River lowland catchment. *Quaestiones Geographicae*, *33*(3), 101-110. https://doi.org/10.2478/quageo-2014-0033

Magnuszewski, A., Moran, S., & Yu, G. (2010). Modelling lowland reservoir sedimentation conditions and the potential environmental consequences of dam removal: Wloclawek Reservoir, Vistula River, Poland. *IAHS Publication*, *337*, 345-352.

Magnuszewski, A., Sabat, A., Jarocińska, A., & Sławik, Ł. (2018). Application of the AISA Hyperspectral Image for Verification of Sediment Transport Results Obtained from CCHE2D Hydrodynamic Model – Zegrze Reservoir Case Study, Poland. In M. B. Kalinowska, M. M. Mrokowska, & P. M. Rowiński (Eds.), *Free Surface Flows and Transport Processes* (pp. 103-112). Springer International Publishing. https://doi.org/10.1007/978-3-319-70914-7_4

Mankiewicz-Boczek, J., Jaskulska, A., Pawełczyk, J., Gągała, I., Serwecińska, L., & Dziadek, J. (2016). Cyanophages infection of Microcystis bloom in lowland dam reservoir of Sulejów, Poland. *Microbial Ecology*, *71*(2), 315-325. https://doi.org/10.1007/s00248-015-0677-5

Matthews, M. W. (2011). A current review of empirical procedures of remote sensing in inland and near-coastal transitional waters. *International Journal of Remote Sensing*, *32*(21), 6855-6899. https://doi.org/10.1080/01431161.2010.512947

Mishra, S., & Mishra, D. R. (2012). Normalized difference chlorophyll index: A novel model for remote estimation of chlorophyll-a concentration in turbid productive waters. *Remote Sensing of Environment*, *117*, 394-406. https://doi.org/10.1016/j.rse.2011.10.016

Mohn, C., & White, M. (2007). Remote sensing and modelling of bio-physical distribution patterns at Porcupine and Rockall Bank, Northeast Atlantic. *Continental Shelf Research*, *27*(14), 1875-1892. https://doi.org/10.1016/j.csr.2007.03.006

Moses, W. J., Gitelson, A. A., Berdnikov, S., & Povazhnyy, V. (2009). Satellite estimation of chlorophyll-α concentration using the red and NIR bands of MERIS – The Azov Sea case study. *IEEE Geoscience and Remote Sensing Letters*, *6*(4), 845-849. https://doi.org/10.1109/LGRS.2009.2026657

Paerl, H. W. (1988). Nuisance phytoplankton blooms in coastal, estuarine, and inland waters. *Limnology and Oceanography*, *33*(4part2), 823-843. https://doi.org/10.4319/lo.1988.33.4part2.0823

Palmer, S. C. J., Kutser, T., & Hunter, P. D. (2015). Remote sensing of inland waters: Challenges, progress and future directions. *Remote Sensing of Environment*, *157*, 1-8. https://doi.org/10.1016/j.rse.2014.09.021

Pieron, Ł., Absalon, D., Habel, M., & Matysik, M. (2021). Inventory of reservoirs of key significance for water management in Poland – Evaluation of changes in their capacity. *Energies*, *14*(23). https://doi.org/10.3390/en14237951

Ryan, J., Greenfield, D., Marin, R. I., Preston, C., Roman, B., Jensen, S., ... & Scholin, C. (2011). Harmful phytoplankton ecology studies using an autonomous molecular analytical and ocean observing network. *Limnology and Oceanography*, *56*(4), 1255-1272. https://doi.org/10.4319/lo.2011.56.4.1255

Sabat-Tomala, A., Jarocińska, A. M., Zagajewski, B., Magnuszewski, A. S., Sławik, Ł. M., Ochtyra, A., ... & Lechnio, J. R. (2018). Application of HySpex hyperspectral images for verification of a two-dimensional hydrodynamic model. *European Journal of Remote Sensing*, *51*(1), 637-649. https://doi.org/10.1080/22797254.2018.1470905

Schindler, D. W. (2012). The dilemma of controlling cultural eutrophication of lakes. *Proceedings of the Royal Society B: Biological Sciences*, *279*(1746), 4322-4333. https://doi.org/10.1098/rspb.2012.1032

Soontiens, N., Binding, C., Fortin, V., Mackay, M., & Rao, Y. R. (2019). Algal bloom transport in Lake Erie using remote sensing and hydrodynamic modelling: Sensitivity to buoyancy velocity and initial vertical distribution. *Journal of Great Lakes Research*, *45*(3), 556-572. https://doi.org/10.1016/j.jglr.2018.10.003

Szczukocki, D., Krawczyk, B., Dałkowski, R., Juszczak, R., Miekoś, E., Zieliński, M., ... & Jereczek-Korzeniewska, K. (2014). *Monitoring hydrochemiczny zbiorników zaporowych województw łódzkiego*. In *Problemy badań wody w XX I XXI wieku*. Wydawnictwo Uniwersytetu Gdańskiego.

Tarczyńska, M., Osiecka, R., Kątek, R., Błaszczyk, A., & Zalewski, M. (1997). *Przyczyny i konsekwencje powstawania toksycznych zakwitów sinicowych w zbiornikach*. In M. Zalewski, M., & R. J. Wiśniewski (Eds.), *Zastosowanie biotechnologii ekosystemalnych do poprawy jakości wód* (51-72). Instytut Ekologii PAN.

Tufford, D. L., & McKellar, H. N. (1999). Spatial and temporal hydrodynamic and water quality modeling analysis of a large reservoir on the South Carolina (USA) coastal plain. *Ecological Modelling*, *114*(2-3), 137-173. https://doi.org/10.1016/S0304-3800(98)00122-7

Tzortziou, M., Subramaniam, A., Herman, J. R., Gallegos, C. L., Neale, P. J., & Harding, L. W. (2007). Remote sensing reflectance and inherent optical properties in the mid Chesapeake Bay. *Estuarine, Coastal and Shelf Science*, *72*(1-2), 16-32. https://doi.org/10.1016/j.ecss.2006.09.018

Urbaniak, M., Kiedrzyńska, E., & Zalewski, M. (2012). The role of a lowland reservoir in the transport of micropollutants, nutrients and the suspended particulate matter along the river continuum. *Hydrology Research*, *43*(4), 400-411. https://doi.org/10.2166/nh.2012.108

Verkhozina, V. A., Kozhova, O. M., & Kusner, Yu. S. (2000). Hydrodynamics as a limiting factor in the Lake Baikal ecosystem. *Aquatic Ecosystem Health & Management*, *3*(2), 203-210. https://doi.org/10.1080/14634980008657015

Vincent, R. K., Qin, X., McKay, R. M. L., Miner, J., Czajkowski, K., Savino, J., & Bridgeman, T. (2004). Phycocyanin detection from LANDSAT TM data for mapping cyanobacterial blooms in Lake Erie. *Remote Sensing of Environment*, *89*(3), 381-392. https://doi.org/10.1016/j.rse.2003.10.014

Whitton, B. A., & Potts, M. (Eds.). (2002). *The Ecology of Cyanobacteria*. Kluwer Academic Publishers. https://doi.org/10.1007/0-306-46855-7

Yoshimura, S. (1933). Rapid entrophication within recent years of Lake Haruna, Gunma, Japan. *Japanese Journal of Geology and Geography*, *11*, 31-41.

Zanchett, G., & Oliveira-Filho, E. (2013). Cyanobacteria and cyanotoxins: From impacts on aquatic ecosystems and human health to anticarcinogenic effects. *Toxins*, *5*(10), 1896-1917. https://doi.org/10.3390/toxins5101896

Zhao, Y., Liu, D., & Wei, X. (2020). Monitoring cyanobacterial harmful algal blooms at high spatiotemporal resolution by fusing Landsat and MODIS imagery. *Environmental Advances*, *2*. https://doi.org/10.1016/j.envadv.2020.100008

Ziemińska-Stolarska, A., Imbierowicz, E., Jaskulski, M., & Szmidt, A. (2020). Assessment of the chemical state of bottom sediments in the eutrophied dam reservoir in Poland. *International Journal of Environmental Research and Public Health*, *17*(10), 3424. https://doi.org/10.3390/ijerph17103424

Ziemińska-Stolarska, A., Imbierowicz, M., Jaskulski, M., Szmidt, A., & Zbiciński, I. (2019). Continuous and periodic monitoring system of surface water quality of an impounding reservoir: Sulejow Reservoir, Poland. *International Journal of Environmental Research and Public Health*, *16*(3), 301. https://doi.org/10.3390/ijerph16030301

Ziemińska-Stolarska, A., & Kempa, M. (2021). Modeling and monitoring of hydrodynamics and surface water quality in the Sulejów Dam Reservoir, Poland. *Water*, *13*(3). https://doi.org/10.3390/w13030296

Ziemińska-Stolarska, A., Polańczyk, A., & Zbiciński, I. (2015). 3-D CFD simulations of hydrodynamics in the Sulejow dam reservoir. *Journal of Hydrology and Hydromechanics*, *63*(4), 334-341. https://doi.org/10.1515/johh-2015-0033

Article first received • 17 February 2025
Article accepted • 18 May 2025