Scientific Review Engineering and Environmental Sciences (2022), 31 (4), 283–293

Sci. Rev. Eng. Env. Sci. (2022), 31 (4) https://srees.sggw.edu.pl

ISSN 1732-9353 (suspended) eISSN 2543-7496 DOI 10.22630/srees.4482

Received: 03.10.2022
Accepted: 29.11.2022

Wojciech CIĘŻKOWSKI[1]✉
Magdalena FRĄK[1]
Ignacy KARDEL[1]
Marcin KOŚCIELNY[2]
Jarosław CHORMAŃSKI[1]

[1] Warsaw University of Life Sciences – SGGW, Institute of Environmental Engineering, Poland
[2] Air-Concept Ltd Co., Poland

LONG-TERM WATER QUALITY MONITORING USING SENTINEL-2 DATA, GŁUSZYŃSKIE LAKE CASE STUDY

Key words: Sentinel-2, inland water, biological oxygen demand (*BOD*), dissolved organic carbon (*DOC*), electrical conductivity (*EC*), chlorophyll concentration (*CHL*)

Introduction

Water quality can be indicated by its physical, chemical and biological properties. Traditional water monitoring requires collecting samples in the field and analysing them in the laboratory. Although this in-situ measurement system offers high accuracy, it is a labour intensive and time-consuming process, and hence it is not feasible for providing a simultaneous water quality database on a regional scale (Duan et al., 2013a; Duan et al., 2013b). Traditional monitoring methods are not easily able to identify the spatial or temporal variations in water quality, which is crucial for the comprehensive assessment of inland reservoirs (Gholizadeh, Melesse & Reddi, 2016). Traditional data collection systems are only able to represent point estimates of the quality of water conditions in time and space, and obtaining the spatial and temporal variations of quality indices in large waterbodies is almost impossible (Ritchie, Zimba & Everitt, 2003). Other disadvantages of in-situ monitoring include: (i) cost and time of field and laboratory work; (ii) monitoring, forecasting, and management of the entire waterbody may be impossible due to its

✉wojciech_ciezkowski@sggw.edu.pl

inaccessibility, such as due to the topography; and (iii) accuracy and precision of the collected in-situ data may be questionable due to both field-sampling errors and laboratory errors (Gholizadeh et al., 2016).

In recent decades, due to advances in space science and computer development, remote sensing techniques have begun to be used in wide environmental applications, such as in water quality monitoring. Remote sensing techniques make it possible to monitor water reservoirs on spatial and temporal scales unattainable by traditional monitoring. Since the 1970's, remote sensing techniques have been used for water quality assessment (Morel & Prieur, 1977; Brando & Dekker, 2003; Ritchie et al., 2003; Hadjimitsis & Clayton, 2009).

For the past four decades, remote sensing techniques have shown their strong capabilities in monitoring the quality of inland waters. Visible and near infrared regions of the spectrum are typically using by researchers to obtain robust correlations between reflectance and the physical, chemical and biological properties of water. Parameters like transparency (Kloiber, Brezonik, Olmanson & Bauer, 2002), chlorophyll concentration, i.e., phytoplankton (Gitelson et al., 2008), organic matter and mineral suspended sediments have been estimated by researchers in different waterbodies (Mancino, Nolè, Urbano, Amato & Ferrara, 2009; Giardino et al., 2014). Although the capabilities of remote sensing in assessing water quality are undeniable, this technique alone is not sufficiently precise and must be used in conjunction with traditional sampling methods and field surveying. With this in mind, the main advantages of water monitoring using remote sensing techniques are: (i) comprehensive views of entire waterbodies; (ii) higher spatial and temporal scale of observations; (iii) possibility of synchronized monitoring of lake groups over a vast region; and (iv) comprehensive historical recording of water quality in an area and the possibility of trend analyses.

This paper focuses on applying existing empiric formulas to water quality estimation of Głuszyńskie Lake, located in the central Poland. Data from Sentinel-2 has been recorded since its launch in 2015, and has been used for estimating spatial and temporal changes in selected water quality parameters. The results were validated based on two field measurement campaigns (in 2021 and 2022). The aim of this work was to analyse whether existing empiric formulas could be applied for long-term quasi-continuous monitoring of inland waters in Poland, based on remote sensing data.

Material and methods

Study site

The study was conducted in Głuszyńskie Lake, central Poland. Głuszyńskie Lake is located near Radziejów, in the Kujawskie Lake District, part of the Kujawsko-Pomorskie Voivodship (Fig. 1), and it the largest reservoir in this region. It is a typical gutter lake, stretching along a north-south line, with two bays on the east and west sides. The lake is the deepest in the central part of the western bay. The lake is located in the upper part of the river basin of the Zgłowiączka river, where intensive farming is carried out. The lake is situated in one of the most intensively used agricultural areas in Poland and,

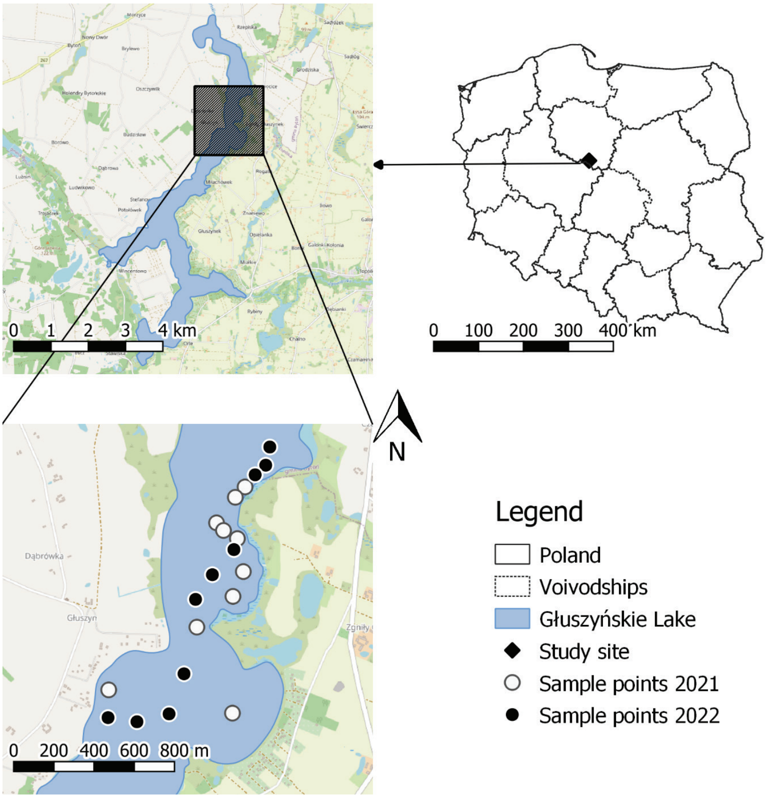

FIGURE 1. Study site location in Poland and water sample point locations in 2021 and 2022

Source: own studies (background map © OpenStreetMap).

consequently, the lake undergoes pollution from agriculture sources, especially in the northern part of the lake catchment area. Głuszyńskie Lake is part of in the State Environmental Monitoring of Surface Water process. Based on the monitoring results, high nitrate concentrations were identified during the spring and after intensive rains in the northern part of the lake. Currently, over 50% of the shoreline is occupied by recreational areas, including holiday cottages. This creates a threat to the water quality of the lake, as these develop without any legal or formal regulations for water and sewage management.

Water quality parameter calculations

For long-term spatial monitoring of the Głuszyńskie Lake the following water quality parameters were involved: biological oxygen demand (*BOD*), dissolved organic carbon (*DOC*), chlorophyll concentration (*CHL*) and electrical conductivity (*EC*). All values were estimated based on Sentinel-2 multispectral satellite images. Sentinel-2 L1C products with a relatively low cloud cover (less than 20%) were directly downloaded from Open Access Hub (https://scihub.copernicus.eu/dhus/#/home), dating back to its launch date on 23 June 2015 to 5 August 2022. Only the images acquired during the growing season (from May to early October) were used. A total of 70 images were used for further analyses. The lake coastline was acquired from Map of the Hydrographic Division of Poland (downloadable by QGIS "Wody Polskie – Baza WMS" plugin by Ścisłowski, Państwowe Gospodarstwo Wodne Wody Polskie – KZGW & Wydział SIGW, 2022), and a 10 m inner buffer was created to exclude mixed pixels.

Typically, the formulas used for water quality parameters required bottom-of--atmosphere (BOA) reflectance. Hence, Sentinel-2 L1C were pre-processed to BOA reflectance using the sen2r R package (Ranghetti, Boschetti, Nutini & Busetto, 2020) using the R programming language (R Core Team, 2021).

In the scope of the analyses, a number of different formulas found in the literature were tested (results not shown). Selection of the calculation formulas used in the study was based on geographical rules. We selected equations which had been validated in Poland, the Baltic sea basin and central Europe, or tested in the world at a similar geographical latitude. We also limited the selection of formulas to those used only for inland lakes, excluding many formulas calibrated for oceans and seas. We finally selected the following formulas which gave the most promising results:

Field and laboratory measurements

The validation of satellite-based water quality parameters were performed based on water samples (stored in two polypropylene containers: 60 ml and 1,500 ml) acquired from the top layer of the water on 8 October 2021 and 10 August 2022 in a total of 20 locations in the northern part of the lake (Fig. 1). The containers were transported to the laboratory by refrigerator and analysed on the same day. Point coordinates were recorded using a hand-held GPS unit with a measurement accuracy of 5 m.

In the field, *EC* was measured using a YSI Professional Plus probe (YSI Inc., USA), and the *CHL* was determined according the PN-ISO 10260 standard (Polski Komitet Normalizacyjny [PKN], 2002).

The biochemical oxygen demand (*BOD*) was determined using a volumetric method with a OxiTop® Control (WTW Ltd, Poland).

The analysis of dissolved organic carbon (*DOC*) concentration used a Formacs$^{HT/TN}$ (Skalar Analytical B.V., Netherlands) – in compliance with the ISO 8245 standard (International Organization for Standardization [ISO], 1999) and EPA Method 415.1 (U.S. Environmental Protection Agency [EPA], 1983) – fitted with a platinum/ /cobalt column.

$$BOD = -141.51 \cdot \frac{(B4 - B5)}{(B4 + B5)} + 39.62 \quad \text{(Słapińska, Berezowski, Frąk \& Chormański, 2016),} \tag{1}$$

$$DOC = 432 \cdot e^{-2.24 \cdot \frac{B3}{B4}} \quad \text{(Potes et al., 2018),} \tag{2}$$

$$CHL = 75.821 \cdot \frac{B5}{B4} - 42.644 \quad \text{(Osińska-Skotak, 2010),} \tag{3}$$

$$EC = 0.1252 \cdot \left[\left(\frac{B11}{B8} \cdot B12 \right)^2 + 4.1531 \cdot \left(\frac{B11}{B8} \cdot B12 \right) \right] + 10.527 \quad \text{(Abdelmalik, 2018),} \tag{4}$$

where BN is BOA reflectance in the Sentinel-2 N band.

Before the analysis of these water samples they were filtered using 0.45 μm filters. The *DOC* determination was conducted with a high temperature catalytic oxidation method at 850°C (samples were acidified with HCl, mixed and aerated for 1 min immediately before the determination), according to the method recommended by the manufacturer.

Results and discussion

The highest mean values (higher than 50 mg $O_2 \cdot l^{-1}$) of *BOD* were observed on 20 August 2015, 22 July 2016, 11 August 2018, 22 June 2019, and 1 July 2020 (Fig. 2). On 1 July 2020 a higher spatial variability (from 9.5 to 123.6 mg $O_2 \cdot l^{-1}$) of *BOD* was observed. The highest yearly mean value (41.7 mg $O_2 \cdot l^{-1}$) was observed in 2015 and the lowest (31.4 mg $O_2 \cdot l^{-1}$) in 2017 (Table 1). These results show low variability in the mean values of *BOD* (both yearly and between all images) simultaneously with high spatial variability indicated by the bars in Figure 2.

The highest mean values (higher than 25 mg$\cdot l^{-1}$) of *DOC* were observed for nearly all images in 2022 (besides the last one acquired on 5 August 2022), and in this year the lowest spatial variability of *DOC* was observed. In the other years, only three times (16 July 2017, 10 September 2018 and 20 May 2020) were the mean *DOC* values higher than 25 mg$\cdot l^{-1}$ (Fig. 3). The highest yearly mean value (28.9 mg$\cdot l^{-1}$) was observed in 2022 and the lowest (11.5 mg$\cdot l^{-1}$) in 2016 (Table 1).

Mean *CHL* values varied between 50 and 75 mg$\cdot m^{-3}$ for the majority of the images. Only once (10 July 2017) was the mean *CHL* value higher than 75 mg$\cdot m^{-3}$ and reached 80 mg$\cdot m^{-3}$ (Fig. 4). In 2022 the mean *CHL* values was lower than 50 mg$\cdot m^{-3}$ (Fig. 4), and the yearly value in this year was also the lowest (36.2 mg$\cdot m^{-3}$). The highest yearly value of *CHL* (62 mg$\cdot m^{-3}$) was observed in 2017 (Table 1).

TABLE 1. Yearly mean values based on all cloud-free pixels within Głuszyńskie Lake of estimated water quality parameters

Year	*BOD* [mg $O_2 \cdot l^{-1}$]	*DOC* [mg$\cdot l^{-1}$]	*CHL* [mg$\cdot m^{-3}$]	*EC* [μS$\cdot cm^{-1}$]
2015	41.7	13.0	49.3	1 074
2016	37.7	11.5	58.0	1 062
2017	31.4	16.2	62.0	1 069
2018	36.9	12.6	59.9	1 068
2019	38.1	12.2	58.5	1 060
2020	37.3	13.7	60.1	1 064
2021	36.4	13.2	57.6	1 059
2022	37.6	28.9	36.2	1 108

Source: own studies.

Mean *EC* values varied from 1,050 to 1,100 μS$\cdot cm^{-1}$ except in 2022 when the mean *EC* values were higher than 1,100 μS$\cdot cm^{-1}$ as well as four times in other years (9 August 2017, 10 September 2018, 22 June 2019 and 1 July 2020). For dates with high *EC* mean values, high spatial variability was also observed, except in 2022 (Fig. 5). The highest yearly values of *EC* (1,108 μS$\cdot cm^{-1}$) was observed in 2022 and the lowest (1,059 μS$\cdot cm^{-1}$) in 2021. This result shows low variability in the mean values of *EC* (both yearly and between all images) simultaneously with the high spatial variability indicated by the bars in Figure 2.

Satellite based water quality parameters were validated against 20 ground truth samples measured in 2021 and 2022. Water

Ciężkowski, W., Frąk, M., Kardel, I., Kościelny, M., Chormański, J. (2022). Long-term water quality monitoring using Sentinel-2 data, Głuszyńskie Lake case study. *Sci. Rev. Eng. Env. Sci.*, *31* (4), 283–293. DOI 10.22630/srees.4482

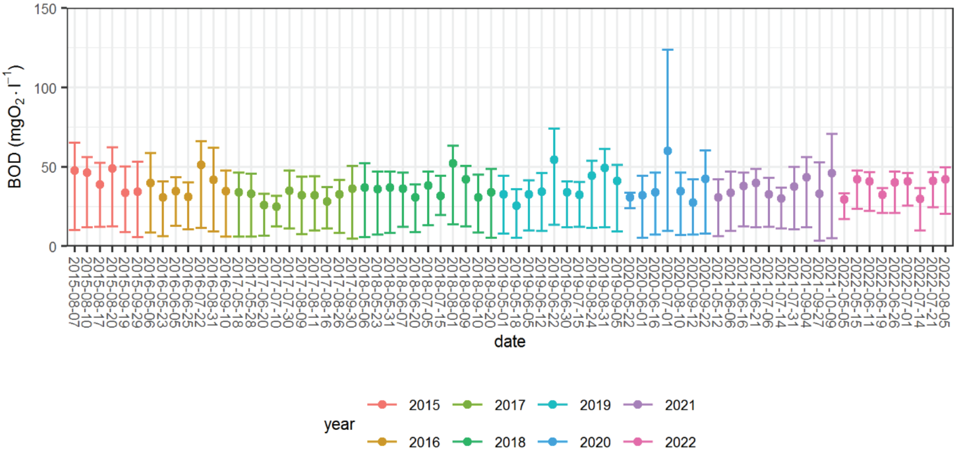

FIGURE 2. Temporal changes in biological oxygen demand (*BOD*) based on all cloud-free pixels within Głuszyńskie Lake for 70 Sentinel-2 images. The dots show mean values, the bars show 5% and 95% quantiles

Source: own studies.

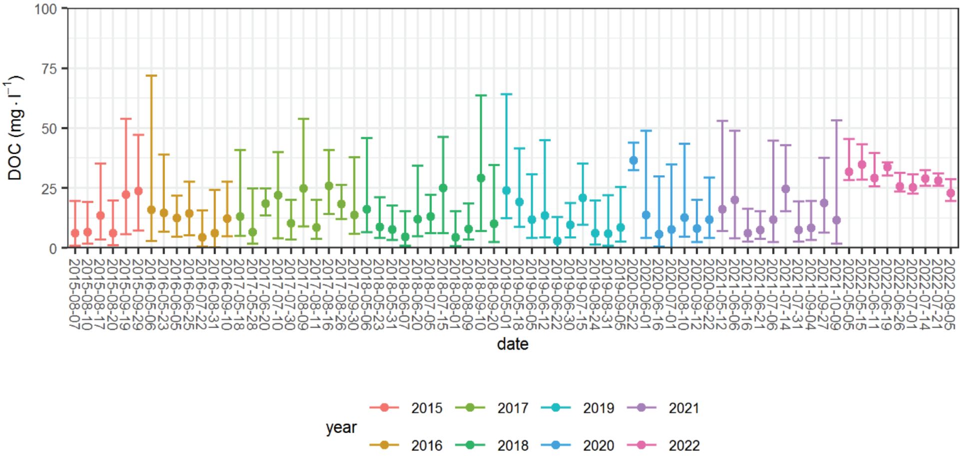

FIGURE 3. Temporal changes in dissolved organic carbon (*DOC*) based on all cloud-free pixels within Głuszyńskie Lake for 70 Sentinel-2 images. The dots show mean values, the bars show 5% and 95% quantiles

Source: own studies.

quality parameters calculated based on satellite images were averaged for neighbouring pixels (3 × 3 px) before further comparison. Satellite based water quality parameters would not correspond quantitatively to ground truth data (Fig. 6). However,

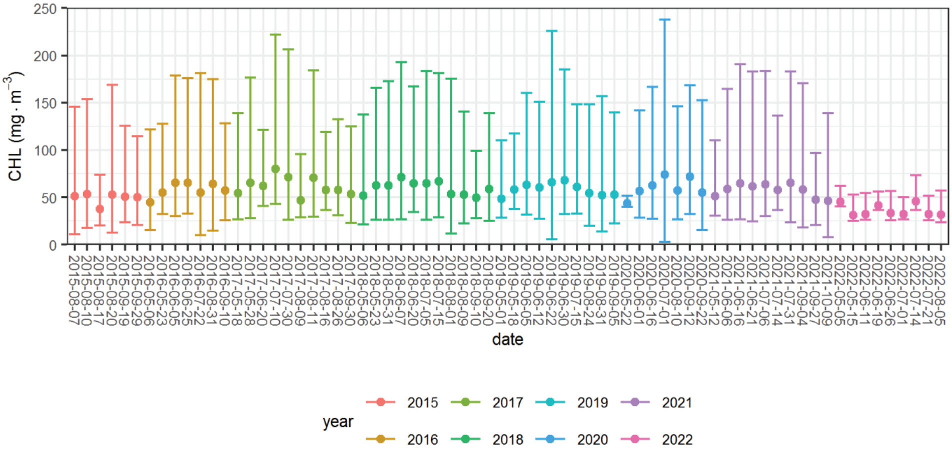

FIGURE 4. Temporal changes of chlorophyll concentration (*CHL*) based on all cloud-free pixels within Głuszyńskie Lake for 70 Sentinel-2 images. The dots show mean values, the bars show 5% and 95% quantiles

Source: own studies.

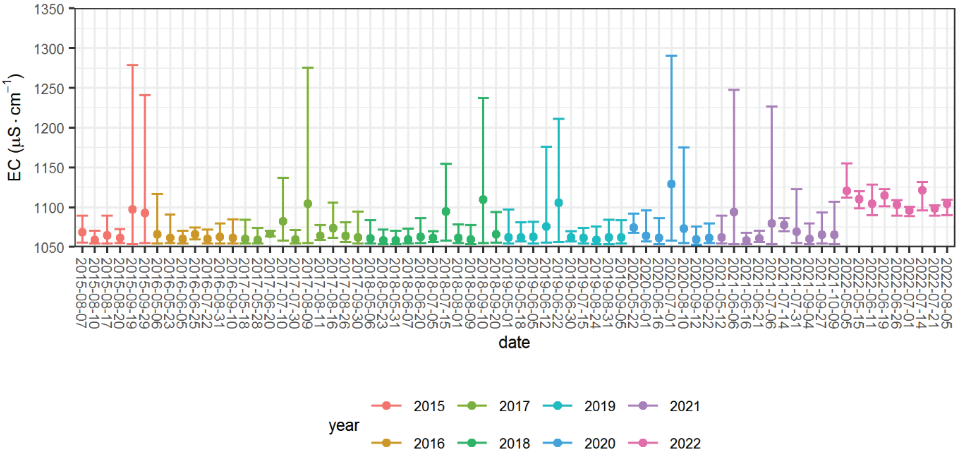

FIGURE 5. Temporal changes in electrical conductivity (*EC*) based on all cloud-free pixels within Głuszyńskie Lake for 70 Sentinel-2 images. The dots show mean values, the bars show 5% and 95% quantiles

Source: own studies.

for *BOD*, *CHL* and *DOC*, a statistically significant ($p < 0.01$) relationship was observed (for *BOD* and *DOC* linear and power for *CHL*) with an R^2 of 0.77 (for *CHL* and *DOC*) and 0.79 (for *BOD*). For *EC* the relationship was quadratic, but the R^2 of 0.45 shows that

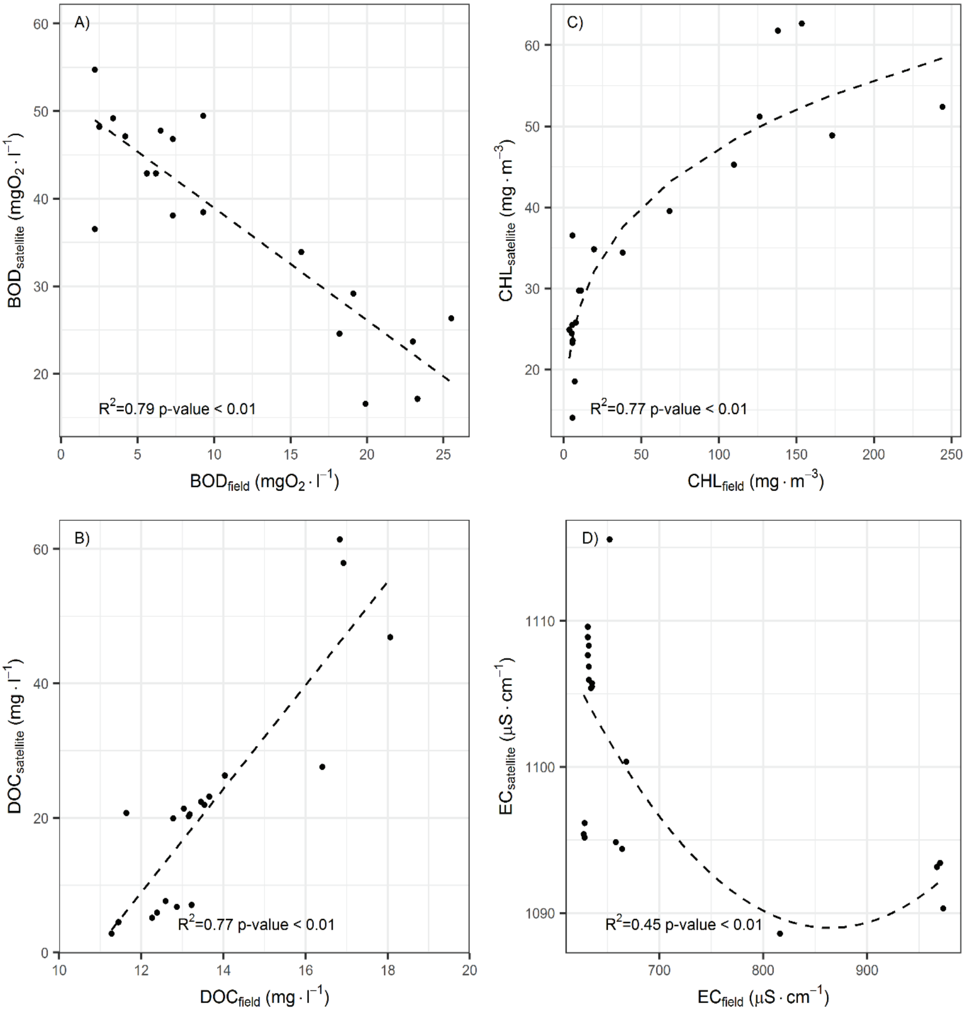

FIGURE 6. Relationships between the models based on satellite images and measurements based on filled measurements for: *BOD* – linear relationship (A); *DOC* – linear relationship (B); *CHL* – power relationship (C) and *EC* – quadratic relationship (D)

Source: own studies.

relationship for this parameter was weaker than for the other.

Additionally, based on data from the nearest meteorological station (Koło-Radoszewice, operated by the Institute of Meteorology and Water Management – National Research Institute – IMGW-PIB), we analysed the influence of meteorological elements (temperature, perception and insolation) on water quality parameters on a monthly scale (Table 2). Only for *BOD* and *DOC* did we observe a significant ($p < 0.05$)

TABLE 2. Relationship (and its *p* value) between the average monthly values of water quality parameters and meteorological elements for Głuszyńskie Lake

	Temperature		Precipitation		Insolation	
	relation	*p*	relation	*p*	relation	*p*
BOD	positive	< 0.05	negative	0.11	positive	0.33
CHL	positive	0.11	positive	0.48	positive	0.61
DOC	negative	< 0.05	positive	0.48	negative	0.11
EC	negative	0.98	negative	0.34	negative	0.66

Source: own studies.

relation with temperature, positive for *BOD* and negative for *DOC*.

Conclusions

This paper shows the results of long-term (since 2015) water quality monitoring of Głuszyńskie Lake using freely available Sentinel-2 data. The strong relationship ($R^2 > 0.75$) between the estimated parameters (*BOD*, *DOC*, *CHL*) and the ground truth data shows its potential qualitative temporal and spatial distribution monitoring to these parameters. Yearly mean values of the parameters show low variation, but the application of remotely sensed data allows the detection of peak values (if they occur close to a satellite overpass without cloud cover) and the spatial distribution of those parameters, which is practically impossible with the use of traditional monitoring methods.

Funding

The study was co-financed by the research and development project, RPKP.01.03.01-04-0001/19, co-financed by the European Regional Development Fund, under submeasure RPKP.01.03.01. Support for research and development processes in academic enterprises, the Regional Operational Program of the Kujawsko-Pomorskie Voivodeship for 2014–2020, "*Działania o charakterze badawczo-rozwojowym nad stworzeniem innowacji produktowej i procesowej w skali światowej związanej z wykorzystaniem bezzałogowego statku powietrznego, z zestawem dedykowanych urządzeń optyczno-analitycznych, do monitorowania szeregu elementów przyrody ożywionej i nieożywionej* [Research and development activities on the creation of a product and process innovation on a global scale related to the use of an unmanned aerial vehicle, with a set of dedicated optical-analytical devices for monitoring a number of elements of animate and inanimate nature]", led by Air-Concept Ltd Co.

Acknowledgements

The meteorological data were made available by the Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB) in Poland.

References

Abdelmalik, K. W. (2018). Role of statistical remote sensing for inland water quality parameters prediction. *The Egyptian Journal of Remote Sensing and Space Science*, *21* (2), 193–200.

Brando, V. E. & Dekker, A. G. (2003). Satellite hyperspectral remote sensing for estimating estuarine and coastal water quality. *IEEE Transactions on Geoscience and Remote Sensing*, *41* (6), 1378–1387.

Duan, W., He, B., Takara, K., Luo, P., Nover, D., Sahu, N. & Yamashiki, Y. (2013a).

Spatiotemporal evaluation of water quality incidents in Japan between 1996 and 2007. *Chemosphere*, *93* (6), 946–953.

Duan, W., Takara, K., He, B., Luo, P., Nover, D. & Yamashiki, Y. (2013b). Spatial and temporal trends in estimates of nutrient and suspended sediment loads in the Ishikari River, Japan, 1985 to 2010. *Science of the Total Environment*, *461*, 499–508.

Gholizadeh, M. H., Melesse, A. M. & Reddi, L. (2016). A comprehensive review on water quality parameters estimation using remote sensing techniques. *Sensors*, *16* (8), 1298.

Giardino, C., Bresciani, M., Cazzaniga, I., Schenk, K., Rieger, P., Braga, F., Matta, E. & Brando, V. E. (2014). Evaluation of multi-resolution satellite sensors for assessing water quality and bottom depth of Lake Garda. *Sensors*, *14* (12), 24116–24131.

Gitelson, A. A., Dall'Olmo, G., Moses, W., Rundquist, D. C., Barrow, T., Fisher, T. R., Gurlin, D. & Holz, J. (2008). A simple semi-analytical model for remote estimation of chlorophyll-a in turbid waters: Validation. *Remote Sensing of Environment*, *112* (9), 3582–3593.

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), 281–292.

International Organization for Standardization [ISO] (1999). *Water quality. Guidelines for the determination of total organic carbon (TOC) and dissolved organic carbon (DOC)* (ISO 8245). Geneva.

Kloiber, S. M., Brezonik, P. L., Olmanson, L. G. & Bauer, M. E. (2002). A procedure for regional lake water clarity assessment using Landsat multispectral data. *Remote Sensing of Environment*, *82* (1), 38–47.

Mancino, G., Nolè, A., Urbano, V., Amato, M. & Ferrara, A. (2009). Assessing water quality by remote sensing in small lakes: the case study of Monticchio lakes in southern Italy. *iForest-Biogeosciences and Forestry*, *2* (4), 154.

Morel, A. & Prieur, L. (1977). Analysis of variations in ocean color 1. *Limnology and Oceanography*, *22* (4), 709–722.

Osińska-Skotak, K. (2010). Metodyka wykorzystania super- i hiperspektralnych danych satelitarnych w analizie jakości wód śródlądowych [Methodology of using super- and hyperspectral satellite data for inland water quality analysis]. *Prace Naukowe Politechniki Warszawskiej. Geodezja*, *47*, 3–153.

Polski Komitet Normalizacyjny [PKN] (2002). *Jakość wody. Pomiar parametrów biochemicznych. Spektrometryczne oznaczanie stężenia chlorofilu a* (PN-ISO 10260). Warszawa.

Potes, M., Rodrigues, G., Penha, A. M., Novais, M. H., Costa, M. J., Salgado, R. & Morais, M. M. (2018). Use of Sentinel 2 – MSI for water quality monitoring at Alqueva reservoir, Portugal. *Proceedings of the International Association of Hydrological Sciences*, *380*, 73–79.

R Core Team (2020). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna. Retrieved from: http://www.r-project.org/index.html [accessed: 28.11.2022].

Ranghetti, L., Boschetti, M., Nutini, F. & Busetto, L. (2020). "sen2r": an R toolbox for automatically downloading and preprocessing Sentinel-2 satellite data. *Computers & Geosciences*, *139*, 104473.

Ritchie, J. C., Zimba, P. V. & Everitt, J. H. (2003). Remote sensing techniques to assess water quality. *Photogrammetric Engineering & Remote Sensing*, *69* (6), 695–704.

Słapińska, M., Berezowski, T., Frąk, M. & Chormański, J. (2016). Retrieval of water quality algorithms from airborne HySpex camera for oxbow lakes in north-eastern Poland. In *EGU General Assembly 2016*, 17-22 April 2016 Vienna. Book of abstracts. Vol. 18, EPSC2016-14167.

Ścisłowski, Ł., Państwowe Gospodarstwo Wodne Wody Polskie – KZGW, Wydział SIGW (10.03.2022). Wody Polskie – Baza WMS. ver. 1.0.1. QGIS Python Plugins Repository. Retrieved from: https://github.com/LScislowski/Wody_Polskie_Baza_WMS [accessed: 28.11.2022].

U.S. Environmental Protection Agency [EPA] (1983). Total Organic Carbon. Method 415.1. (Combustion or Oxidation). In *Methods* *for the Chemical Analysis of Water and Wastes* (EPA/600/4-79/020). Cincinnati, OH. Retrieved from: https://www.wbdg.org/FFC/EPA/EPACRIT/epa600_4_79_020.pdf [accessed: 28.11.2022].

Summary

Long-term water quality monitoring using Sentinel-2 data, Głuszyńskie Lake case study. This study shows the results of long-term inland water monitoring using Sentinel-2 data for Głuszyńskie Lake in the years 2015–2022. Four water quality parameters: biological oxygen demand (*BOD*), dissolved organic carbon (*DOC*), chlorophyll concentration (*CHL*) and electrical conductivity (*EC*) were calculated according to formulas found in the literature. The results were validated based on measurements conducted in 2021 and 2022, where for *BOD*, *DOC* and *CHL* high determination coefficients (0.77 and 0.79) were observed, and the *EC* determination coefficient was equal to 0.45. The results show that empirical formulas can be used for qualitative analyses of inland water quality, while for quantitative analyses more extensive field work needs to be performed.