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Analysis of Selected Physicochemical Parameters and Degradation Process Assessment in a Two-Stage Reservoir Jezioro Kowalskie Using Field and Remote Sensing Data

Joanna Jaskuła, Mariusz Sojka, Joanna Wicher-Dysarz[*]
Poznań University of Life Sciences, Poland
[*]*corresponding author's e-mail: joanna.wicher@up.poznan.pl*

1. Introduction

Reservoirs play an important role in water management worldwide. The predicted climatic changes will lead to constantly growing importance of retention reservoirs. Water stored in the reservoirs is used for agricultural, industrial and municipal purposes. The main factor limiting the possibility of using water is its quality (Pérez-Gutiérrez et al. 2017, Sojka et al. 2017, Xu et al. 2019). However, water stored in reservoirs is very sensitive to the inflow of pollution from natural and anthropogenic sources (Nicula et al. 2017, Simeonov et al. 2003). The dynamics of the pollutants inflow also depends on natural factors, such as hydrological and meteorological conditions, landform and soil permeability (Álvarez-Cabria et al., 2016, Yu et al. 2016). Currently, studies are being carried out to assess anthropogenic impacts and their effects on water quality (Gao et al., 2016, Hillel et al., 2015, Policht-Latawiec et al. 2016). The growing population, consequent increase of human settlements, and development of agriculture and industry have changed the landscape and raised the pressures on water resources (Dąbrowska et al. 2017, Zhou et al. 2016). Particularly dangerous is the inflow of trace elements, which occurs both in water and reservoir bottom sediments (Frankowski et al. 2009, Siepak & Sojka 2017, Sojka et al. 2019, Sojka et al. 2013, Sojka et al. 2018). However, on agricultural land the inflow of nitrogen and phosphorus is the main factor influencing the eutrophication and overgrowth process (Borek 2018, Huang et al., 2015, Najar et al. 2017, Noori et al. 2018, Sojka 2009, Sojka 2012, Sojka & Murat-Błażejewska 2009, Sojka et al. 2008, Sojka et al. 2019).

Protecting the European water resources is a high priority for the European Union (EU). In 2000 the EU adopted the Water Framework Directive (WFD) (Directive 2000/60/EC). The main purposes of this directive is to establish a framework which prevents further deterioration and protects and enhances the status of aquatic ecosystems, Progressive reduction of pollution of priority substances and phase-out of priority hazardous substances in surface waters and prevention and limitation of input of pollutants in groundwaters, reversal of any significant, upward trend of pollutants in groundwaters and promoting sustainable water uses, based on a long-term protection of the water resources, compliant with other European water Directives. The WFD establishes an innovative approach for water management based on the river basin, the natural geographical and hydrological unit, and sets specific deadlines for Member States to achieve ambitious environmental objectives at water body level.

Traditional monitoring of water physicochemical status and vegetation processes (overgrowing and eutrophication) is based on collecting data from in situ measurements. Recently, remote sensing techniques became one of the most valuable in water resources monitoring. Environmental monitoring is provided on the basis of satellite data from Landsat-7, Landsat-8, MERIS/OLCI, MODIS and Sentinel-2 satellites (Dörnhöfer et al. 2018, El Saadi et al. 2014, González-Márquez et al. 2018). Remote sensing data is defined by spatial, spectral, temporal and radiometric resolution. Due to multi-spectral resolution of satellite data, imagery is used in for agricultural, forestry, natural hazards – droughts and floods (Agutu et al. 2017, Brown 2015, Chen et al. 2017). Additionally, remote sensing techniques are widely used in monitoring dynamics of degradation processes in reservoirs from space (Klein et al. 2017, Matthews et al. 2012, Martins et al. 2019, Murray et al. 2018, Pekel et al. 2016). Identification and mapping of vegetation dynamics is based on vegetation indices (VIs), which are a combination of several bands formulae, mainly representing red and infrared wavelengths (Bohn et al. 2017, Villa et al. 2014). Several indices have been proposed for vegetation dynamics monitoring, but the most often used is the Normalized Vegetation Index (NDVI), originally proposed by Rouse et al. (1974).

Over the years in Poland, single-stage reservoirs were built, then two-stage with a separate initial zone and lateral reservoirs (Sojka et al. 2017). One of the most interesting and promising approaches related to protection of water resources quality is construction of two-stage reservoirs with two separate zones – main and pre-reservoir, also called the upper zone (Bendorf & Pütz 1987a, Bendorf & Pütz 1987b, Bus & Mosiej 2013, Czamara et al. 2008, Dysarz & Wicher-Dysarz 2013, Paul 2003, Paul & Pütz 2008). The results indicated the efficacy of this solution based on two-stage construction in the aspect of water quality protection in the main part of the reservoir and sediment collection

(Dysarz & Wicher-Dysarz 2011, Jaskuła et al. 2018, Pikul & Mokwa 2008). However, there are still not many papers concerning the spatiotemporal changes of the pollution cycle and eutrophication process in two-stage reservoirs using remote sensing data.

The primary objective of the study was to analyse the spatial changes of the physicochemical parameters in the two-stage reservoir Jezioro Kowalskie. The second purpose was to assess the dynamics of the vegetation process on the basis of Sentinel-2 satellite data. The study evaluates the following research hypothesis: (1) the pre-reservoir limits the inflow of the biogenic compounds to the main reservoir and (2) the vegetation process in the pre-dam reservoir is greater than in the main reservoir.

2. Materials and methods

2.1. Sample collection and laboratory analyses

The water quality in the Jezioro Kowalskie reservoir was evaluated on the basis of 13 physichochemical parameters: electrical conductivity (EC), chlorides (Cl^-), calcium (Ca^{2+}), magnesium (Mg^{2+}), iron (Fe^{3+}), hardness (Hard), Reaction (Reac), total alkalinity (TAl), total acidity (TAc), ammonium nitrogen ($N\text{-}NH_4$), nitrate nitrogen ($N\text{-}NO_3$), nitrite nitrogen ($N\text{-}NO_2$), phosphate (PO_4^{3-}). The physicochemical parameters were selected on the basis of the Directive of the Minister of Environment of 21sd July, 2016, on the way of classification of surface water bodies and environmental norms of the contents of priority substances. The samples were collected (depth 0.20 m from surface) from 4 points, including two points in the pre-reservoir and two points in the main part (Fig. 1). The measurements were carried out once a month in the years 2015-2016. Laboratory analyses were carried out according to the Polish regulations, presented in Table 1.

On the basis of laboratory analysis results, the minimum, average and maximum values for the pre-dam and the main reservoir were calculated. The spatial variability of the biogenic compounds was presented on the basis of the Inverse Distance Weighting (IDW) interpolation method implemented in ArcGIS 10.6.1 software.

Table 1. Methods and regulations for determining water quality parameters

Parameter	Method	Regulations
EC	conductometric	PN-EN 27888:1999P
Cl^-	argentometric	PN-ISO 9297:1994
Ca^{2+}	titrimetric	PN-C-04554-4:1999
Mg^{2+}	calculation	PN-C-04554-4:1999
Fe^{3+}	absorption spectrometry	PN-ISO 8288:2002
Hard	titrimetric	PN-C-04554-4:1999
Reac	potentiometric	PN-C-04642-7:1999P
TAl	titrimetric	PN-EN ISO 9963-1:2001
TAc	titrimetric	PN-EN ISO 9963-1:2001
$N\text{-}NH_4$	spectrophotometric	PN-ISO 7150-1:2002
$N\text{-}NO_3$	spectrophotometric	PN-C-04576-08:1982
$N\text{-}NO_2$	spectrophotometric	PN-EN 26777:1999
PO_4^{3-}	spectrophotometric	PN-EN ISO 6878:2006

2.2. Satellite imagery

The Sentinel-2 satellite is part of the Copernicus Earth Observation mission. Technical supervision is carried out by the European Space Agency (ESA). It works as a constellation of two satellites; launch of the first satellite (Sentinel-2A) occurred on June 23, 2015, while the second (Sentinel-2B) was launched on March 7, 2017. The main instrument of the satellite, Multi-Spectral Imager (MSI), features 13 spectral bands from the visible and near-infrared (VNIR) to the short-wave infrared (SWIR) in 10, 20 and 60 m spatial resolution with a 5-day repeat cycle.

The Sentinel-2 imagery was acquired from the Sentinel Hub website (https://sentinel-hub.com/). Remote sensing data were selected for the years 2015-2016, which corresponded to the years where field measurements were undertaken. Additionally, satellite data from 2017 and 2018 were used to assess the recent state of the vegetation process. Finally, for the analysis four Sentinel-2, level 1C images acquired on 20th August 2015 (10:00:15 UTC), 3rd September 2016 (10:05:58 UTC), 29th August 2017 (10:00:26 UTC) and 29th August 2018 (10:00:17 UTC) in a tile of 100 km^2 were used. Level 1C products are radiometrically and geometrically corrected (Top of Atmosphere – TOA), including orthorectification and spatial assignment to a global reference system (WGS84, EPSG:4326). In the first step, the satellite composites were created and resampled to 10 m spatial resolution. To scale the Sentinel-2 composites to surface reflectance, the Dark Object Subtraction (DOS) method was carried out (Chavez, 1996) in the Semi-Automatic Classification Plugin. In the second step, vegetation processes in the reservoir were analysed on the basis of the NDVI spectral index. The NDVI is the most recognized and frequently used spectral index for regional and global vegetation assessments. It was first proposed by Rouse et al. (1974). In recent years many researchers have used the NDVI to detect vegetation for environmental purposes (Dlamini et al. 2016, Gao et al. 2012, Zhengjun et al. 2008). The NDVI is expressed as a combination of near-infrared NIR (ρ_{NIR}) and red (ρ_R) bands in the following equation:

$$\mathrm{NDVI}= \frac{\rho_{\mathrm{NIR}} - \rho_{\mathrm{R}}}{\rho_{\mathrm{NIR}} + \rho_{\mathrm{R}}} \qquad (1)$$

The values of the NDVI vary from -1 to +1, depending on land cover. Low values (minus or approaching zero) represent water and soil surfaces, while higher values represent vegetation – in an aquatic environment there are seasonal algal blooms and overgrowth areas. In the second step, to assess spatio-temporal changes of the vegetation process, values of the NDVI for each satellite image were extracted to point data for the area of the main and pre-dam reservoir.

The analysis of differences in the values of water quality parameters and NDVI in the pre-dam and the main reservoir was performed using the non-parametric Mann-Whitney U test. The analysis was performed at a confidence level of 0.05 and 0.10.

3. Study area

The Jezioro Kowalskie reservoir (52°28'39.781" N, 17°9'49.022" E) is located on the Główna river in the central part of the Warta river basin (Fig. 1). The Jezioro Kowalskie was built in 1984 as a two-stage reservoir. The pre- dam includes a small sluice and is splitting object into the main and pre-dam reservoir. The area of the reservoir in the normal condition is 203 ha, where the main and pre-reservoir parts are 162.9 ha and 40.4 ha, respectively. The total capacity is $6.58 \cdot 10^6$ m^3, where capacity of the main and pre-reservoir is $5.99 \cdot 10^6$ m^3 and $0.59 \cdot 10^6$ m^3, respectively. The total length of the Jezioro Kowalskie reservoir is 7.1 km, and mean width is 0.27 km. The depth varies from 1.5 m in the pre-reservoir to 6.5 m near the dam in the main part of the reservoir. The mean depth of the pre-reservoir is 1.3 m while for the main part it is 3.1 m. The Jezioro Kowalskie reservoir is multi-purpose and works in the annual cycle.

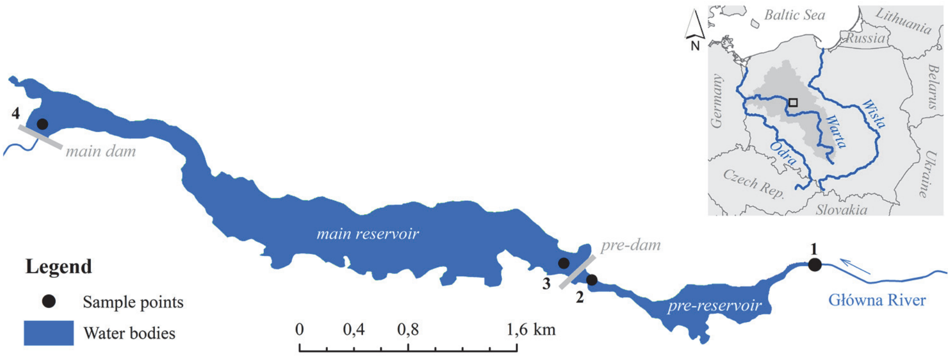

Fig. 1. Study site location

The total area of the Jezioro Kowalskie catchment is 189.35 km^2. Surface water bodies in the Główna River basin were identified as PLRW600025185925. It has lowland character, the absolute altitudes of the terrain varying from 85.52 to 135.02 m a.s.l. with a mean value of 110.27 m a.s.l. The area is mainly covered by arable lands, occupying 67.74% of the total basin area. Other forms of land use are forests (21.46%), artificial surfaces (5.41%) water bodies (3.62%) and pastures (1.77%). In 2016 the percentage of inhabitants who have access to the water supply system varied from 93.8% to 99.9%. The percentage of inhabitants able to use the sanitary sewage system varied from 41.6% to 94.4%.

4. Results and discussion

The values of the water quality parameters in the years 2015-2016 are presented in Table 2.

In the case of the most analyzed parameters, the lowest values occur in the main part of the reservoir, while the highest occur in the pre-dam reservoir. Mean values of the parameters are higher in the pre-dam reservoir, excluding Mg^{2+} and pH. The inflow of biogenic compounds (nitrogen and phosphorus) is the major factor of eutrophication. Jezioro Kowalskie is located in the Pobiedziska commune, which is characterized by the lowest percentage of inhabitants able to use the sanitary and water supply system. Additionally, next to the shoreline there are located leisure areas, where pollutions might flow directly into the reservoir. In Jezioro Kowalskie reservoir the concentration of nitrate nitrogen varies from 0.010 mg·dm^{-3} in the pre-dam reservoir to 5.20 mg·dm^{-3} in the main reservoir. The mean value in the main reservoir is 2.05, while in the upper zone it is 1.45 mg·dm^{-3}.

Table 2. Values of the water quality parameters in the Jezioro Kowalskie reservoir in the years 2015-2016

Parameter	Overall (n=76)	Main part (n=38)	Pre-dam part (n=38)	Statistically significant differences
EC uS·cm^{-1}	421 - 1170 647.94	436 – 840 597.22	421 – 1170 698.66	*
Cl^- mg·dm^{-3}	15 – 105 41.40	15 – 80 40.27	20 – 105 42.53	
Ca^{2+} mg·dm^{-3}	52 – 140 97.36	60 – 132 85.45	52 – 140 109.26	*
Mg^{2+} mg·dm^{-3}	4.86 – 24.32 15.29	4.86 – 24.32 15.48	4.86 – 24.32 15.10	
Fe^{3+} mg·dm^{-3}	0.025 – 0.54 0.120	0.025 – 0.18 0.09	0.025 – 0.54 0.15	*
Hard mVal·dm^{-3}	4.20 – 8.00 6.15	4.20 – 7.40 5.54	5.00 – 8.00 6.76	*
Reac pH	8.02 – 9.98 8.83	8.02 – 9.98 8.88	8.07 – 9.51 8.79	*
TAl mVal·dm^{-3}	2.00 – 6.40 4.32	2.00 – 5.20 3.75	2.60 – 6.40 4.89	*
TAc mVal·dm^{-3}	0.02 – 0.40 0.14	0.02 – 0.40 0.13	0.02 – 0.40 0.15	
$N\text{-}NH_4$ mg·dm^{-3}	0.005 – 3.77 0.51	0.005 – 1.19 0.27	0.005 – 3.77 0.76	
$N\text{-}NO_3$ mg·dm^{-3}	0.01 – 5.20 1.75	0.01 – 3.90 1.45	0.10 – 5.20 2.05	
$N\text{-}NO_2$ mg·dm^{-3}	0.01 – 0.44 0.06	0.01 – 0.35 0.05	0.01 – 0.44 0.07	
PO_4^{3-} mg·dm^{-3}	0.025 – 3.37 0.34	0.025 – 0.74 0.23	0.025 – 3.37 0.44	+

Upper values: minimum-maximum.
Lower values: mean.
Statistically significant differences at the level of 0.05 - * and 0.10 - +

Concentration of nitrite nitrogen is in range 0.01-0.44 mg·dm^{-3} while the average values were similar and were 0.05 and 0.07 mg·dm^{-3} respectively. Average ammonium nitrogen concentrations in the pre-dam reservoir were 0.76 mg·dm^{-3} and in the main reservoir 0.27 mg·dm^{-3}. Concentrations of phosphate are in the range 0.025-3.37 mg·dm^{-3}. Mean concentration in the main part is 0.23 mg·dm^{-3}, while in the upper zone it is 0.44 mg·dm^{-3}. The average value of the NO_3^- to PO_4^{3-} ratio in the initial tank was about 87 mg·dm^{-3} and in the main tank about 61 mg·dm^{-3}. Such values suggest the dominant role of green algae and to a more limited extent blue-green algae.

The statistical analysis performed by means of the Mann-Whitney U test shows the statistically significant differences at the level of 0.05 between concentration of EC, Ca^{2+}, Fe^{3+}, Reac, Hard and TAl in the pre- and main reservoir (Table 2). Moreover, the differences between concentrations of PO_4^{3-} in the reservoirs were statistically significant at the level of 0.10.

Spatial changes of the biogenic compounds' mean concentrations are presented in Figure 2. The highest values occur in the inflow of Główna river to Jezioro Kowalskie reservoir, except nitrite nitrogen. For this parameter, the highest concentration occurs near the dam in the pre-reservoir. High concentrations were also observed in main part of the reservoir, especially near the pre-dam. Spatial analysis of the parameters shows that the main reservoir is characterized by lower concentrations compared to the pre-reservoir. The lowest values of all biogenic compounds were observed near the outflow of the Jezioro Kowalskie reservoir.

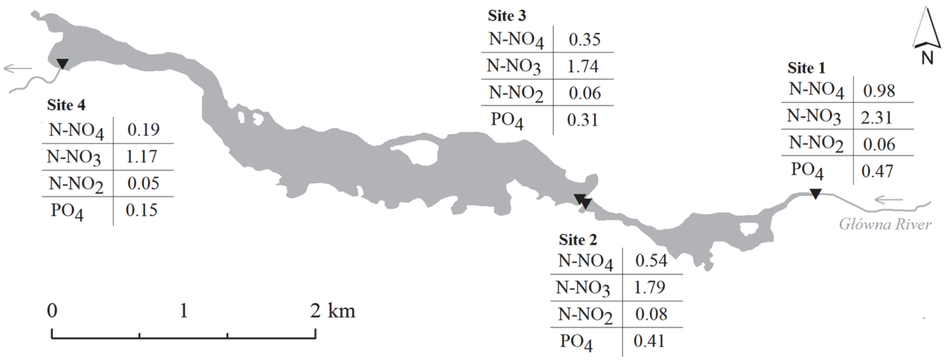

Fig. 2. Spatial changes of biogenic compounds in the Jezioro Kowalskie reservoir (mg·dm^{-3})

The main problem in the Jezioro Kowalskie reservoir is connected with the high inflow of nitrogen and phosphorus compounds, which limits the vegetation processes (Sojka et al. 2016). Figure 3 presents spatiotemporal changes of the NDVI index in August in the years 2015, 2017 and 2018 and September 2016.

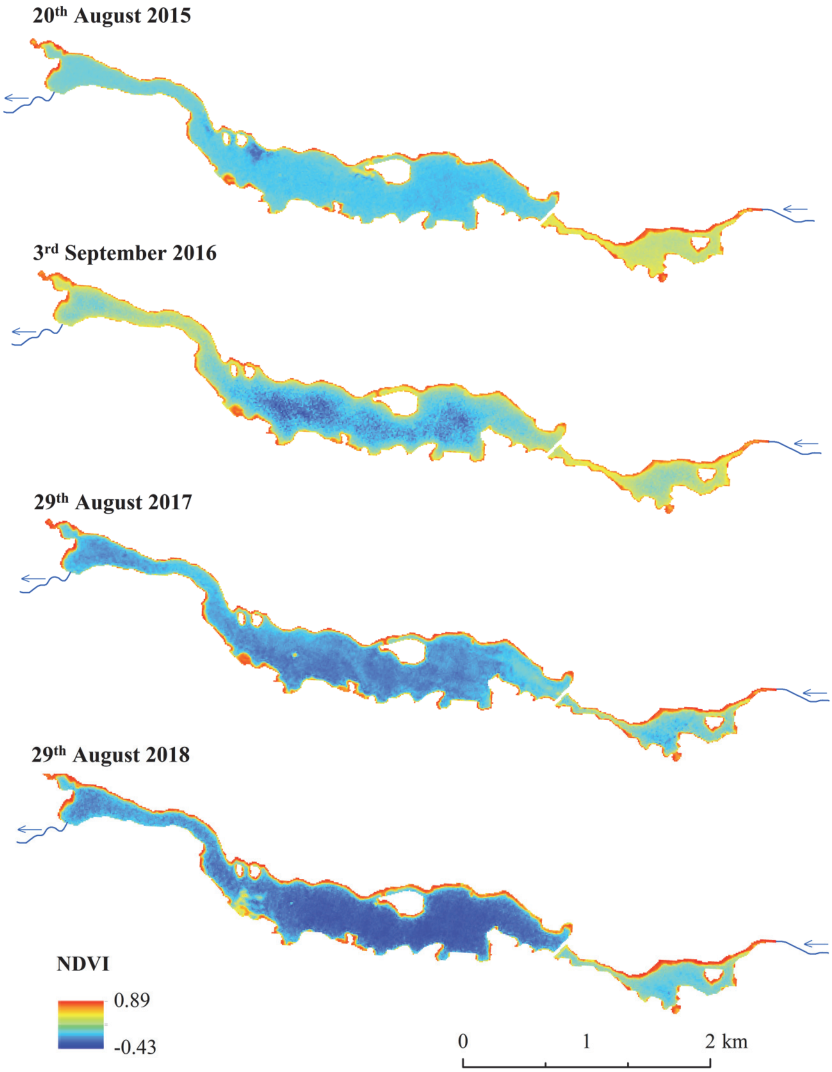

Fig. 3. Spatiotemporal changes of NDVI in the Jezioro Kowalskie reservoir

For the analysed period, the highest values of the NDVI were observed near the banks of the Jezioro Kowalskie reservoir, which is connected with overgrowth areas. In 2015 and 2016 the NDVI values were higher in the whole reservoir area compared to 2017 and 2018. Regardless of the analyzed years, the pre-reservoir was characterized by higher NDVI than the main part.

The NDVI in the Jezioro Kowalskie reservoir in August 2015 varies from -0.28 to 0.86 with the median value of 0.35 (Fig. 4). The lowest NDVI was observed in the main part, while the highest values were comparable between parts of the Radzyny reservoir. The difference between median values in the main and pre-dam reservoir is 0.37. During the first days of September 2016 the values of the NDVI were in range of -0.41 to 0.85. The limit values of the NDVI were observed in the main reservoir. The median value in the pre-reservoir was 0.30, while in the main part it was 0.05. In August 2017, the values of NDVI varied from -0.23 to 0.88. The difference between median values in pre-dam and main reservoir was 0.34. The lowest NDVI was observed in the main part, while the highest values were comparable between parts of the Jezioro Kowalskie reservoir. In 2018, the values of the NDVI were in the range -0.43 to 0.89. The median value in the pre-reservoir was 0.15, while in the main part it was -0.20. The Mann-Whitney U test shows that the NDVI value in the pre-dam reservoir was greater than in the main reservoir in all years. The differences were statistically significant at the level of 0.05.

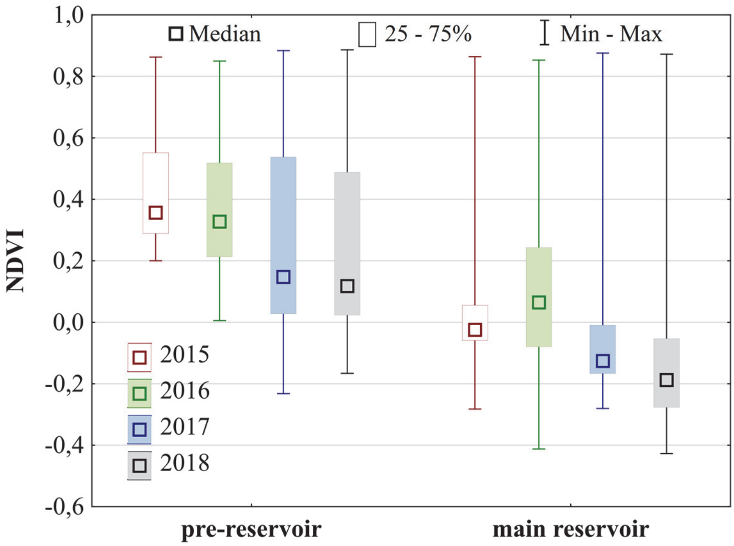

Fig. 4. Values of NDVI in the Jezioro Kowalskie reservoir in the years 2015-2018

The highest biogenic concentrations and NDVI values occurring in the pre-reservoir indicate that the two-stage construction of the reservoir is an effective solution in protection of water quality. The results presented in this paper confirmed the results obtained in the previous studies which indicated that the pre-reservoir protects water resources in the main part of the reservoir, including degradation processes – algae blooms, eutrophication and sedimenta-tion (Dąbrowska et al. 2016, Dysarz & Wicher-Dysarz 2011, Jaskuła et al. 2018, Jaskuła et al. 2019, Mazur 2013, Pikul & Mokwa 2008). The vegetation process may result from supply of biogenic compounds, hydrometeorological conditions as well as water management in reservoir (Dysarz et al. 2006, Nicula et al. 2017). The combination of these factors determines the spatio-temporal changes of the eutrophication process in the reservoir.

5. Conclusion

On the basis of the obtained results, the following conclusions can be made:

1. The results of this study confirm the efficacy of the solution based on two-stage construction in protection of quality of water stored in the main reservoir.
2. The pre-dam reservoir mainly reduces the inflow to the main reservoir of Ca^{2+}, Fe^{3+} and PO_4^{3-}. Also in the main reservoir there were lower values of EC, reaction, hardness and total alkalinity.
3. Higher values of the NDVI were observed in the pre-dam reservoir, which indicates greater degradation in relation to the main reservoir.
4. The highest values of the NDVI observed near the reservoir shoreline are related to overgrowth process of emergent plants.
5. Sentinel-2 satellite imagery allow to assess the spatial variability of the reservoir degradation process. Due to its spatial resolution, the Sentinel-2 satellite should not be used to assess vegetation areas whose width is less than 10 m.
6. Open-access satellite data are more effective source to water monitoring in terms of time and space than traditional in situ measurements.

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Abstract

The paper presents the results of changes of water quality parameters in a two-stage reservoir, observed in the period 2015-2016. The primary objective of the study was to analyse the spatial changes of the water quality parameters in the two-stage reservoir Jezioro Kowalskie. The second purpose was to assess the dynamics of the vegetation process on the basis of Sentinel-2 satellite data. The study adopts the following research hypotheses: 1) the pre-reservoir limits the inflow of the biogenic compounds to the main reservoir, 2) the vegetation process in the pre-dam reservoir is greater than in the main reservoir.

The Jezioro Kowalskie reservoir has two-stage construction – the main and the pre-dam zone. The main role of the pre-dam reservoir is to store sediments and water pollutants.

In this study, 13 water quality parameters were analyzed: electrical conductivity (EC), chlorides (Cl^-), calcium (Ca^{2+}), magnesium (Mg^{2+}), iron (Fe^{3+}), hardness (Hard), pH, total alkalinity (TAl), total acidity (TAc), ammonium nitrogen ($N\text{-}NH_4$), nitrate nitrogen ($N\text{-}NO_3$), nitrite nitrogen ($N\text{-}NO_2$), phosphate (PO_4^{3-}). The samples were collected from 4 points, including two points in the pre-reservoir and two points in the main part. In order to determine parts of the reservoir which are exposed to the degradation process, the spatio-temporal changes were analyzed on the basis of the Normalized Difference Vegetation Index (NDVI) spectral index. The analyses showed that the NDVI values in the period 2015-2018 in the pre-dam reservoir were higher than those recorded in the main reservoir. In the main reservoir, NDVI values were lower and characterized by similar variability.

The study confirms the research hypothesis: the pre-reservoir protects the main part, limiting inflow of biogenic compounds which have an impact on the degradation process (overgrowth, eutrophication). The obtained results confirm that Sentinel-2 satellite imagery allows analysis of the vegetation process in retention reservoirs in terms of time and space.

Keywords:
water quality, biogenic compounds, reservoir, NDVI, Sentinel-2

Analiza wybranych parametrów fizykochemicznych i procesu degradacji w dwustopniowym zbiorniku Jezioro Kowalskie na podstawie pomiarów in-situ i danych satelitarnych

Streszczenie

W pracy przedstawiono zmiany wartości parametrów jakości wody w dwustopniowym zbiorniku retencyjnym w latach 2015-2016. Podstawowym celem pracy była analiza przestrzennych zmian jakości wody zachodzących w zbiorniku Jezioro Kowalskie. Drugim celem była ocena dynamiki degradacji zbiornika (zarastania, eutrofizacji) na podstawie danych satelitarnych Sentinel-2. W pracy przedstawiono hipotezy badawcze: 1) zbiornik wstępny ogranicza dopływ zanieczyszczeń do głównej części, skupiając związki biogenne we wstępnej części, 2) procesy degradacji (zakwitów, eutrofizacji) występują w zbiorniku wstępnym.

Zbiornik Jezioro Kowalskie ma dwustopniową konstrukcję, wydzielono w nim część główną oraz wstępną. Do podstawowych zadań zbiornika wstępnego należy ograniczenie dopływu związków biogennych oraz sedymentacji do części głównej.

Przeanalizowano wartości 13 parametrów jakości wody: przewodność elektr. (EC), chlorki (Cl^-), wapń (Ca^{2+}), magnez (Mg^{2+}), żelazo (Fe^{3+}), twardość og. (Hard), pH,

zasadowość og. (TAl), kwasowość og. (TAc), azot amonowy ($N\text{-}NH_4$), azot azotanowy ($N\text{-}NO_3$), azot azotynowy ($N\text{-}NO_2$), fosforany (PO_4^{3-}). Próbki pobierane były łącznie z 4 punktów pomiarowo-kontrolnych, dwa z nich zlokalizowane były w części wstępnej oraz dwa w zbiorniku głównym. Woda dopływająca do zbiornika retencyjnego charakteryzowała się wysokimi stężeniami związków biogennych. W celu dokładnego określenia części zbiornika narażonych na proces degradacji, do analizy zachodzących zmian wykorzystano indeks NDVI obliczony na podstawie zdjęć satelitarnych Sentinel-2. Przeprowadzone analizy wykazały, że wartości wskaźnika NDVI w miesiącach wegetacyjnych 2015-2018 były wyższe w zbiorniku wstępnym. Część główna zbiornika charakteryzowała się niższymi wartościami i większą stabilnością wskaźnika NDVI.

Na podstawie uzyskanych wyników, potwierdzono, że część wstępna pełni funkcję ochronną zbiornika głównego, m.in. ogranicza dopływ związków biogennych, powodujących procesy degradacji (zarastania, eutrofizacji). Uzyskane wyniki potwierdzają możliwość zastosowania danych satelitarnych Sentinel-2 do analizy procesu wegetacji w zbiornikach retencyjnych w ujęciu czasowym i przestrzennym.

Słowa kluczowe:
jakość wody, związki biogenne, zbiornik retencyjny, NDVI, Sentinel-2