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Analysis of the Vegetation Process in a Two-stage Reservoir on the Basis of Satellite Imagery – a Case Study: Radzyny Reservoir on the Sama River

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1. Introduction

One of the most serious problems related to the functioning of reservoirs is the vegetation process. Reservoirs are more sensitive to degradation than other water bodies (Oszczapińska & Szczykowska 2016). It is related to their morphometric parameters, especially smaller depth and volume and a larger elongation ratio (Dąbrowska et al. 2016, Staniszewski & Szoszkiewicz 2010). Additionally, reservoirs receive biogenic compounds from a larger basin area, including anthropogenic and natural factors (Borek 2017, Kowalik et al. 2014, Nicula et al. 2017, Sojka & Murat-Błażejewska 2009, Sojka et al. 2016). One of the most interesting and promising approaches related to protection of water resource quality is construction of two-stage reservoirs (Bartoszek & Koszelnik 2016, Dysarz & Wicher-Dysarz 2013, Paul & Pütz 2008, Sojka et al. 2017). In such construction, the reservoir is split into two parts – the main and the pre-dam zone. The pre-dam zone is a smaller reservoir located upstream of the main reservoir. The main role of the pre-dam reservoir is to store sediments and water pollutants. Over recent years, such constructions have been increasingly used in Poland (Stare Miasto on the Powa river, Jezioro Kowalskie on the Główna river and Mściwojów on the Wierzbak river). The effectiveness of the pre-dam zone has been confirmed in many studies (Dysarz & Wicher-Dysarz 2011, Dysarz & Wicher-Dysarz 2013, Pikul & Mokwa 2008).

Eutrophication of reservoirs significantly contributes to depletion of flora and restriction of available water resources. Degradation of global water resources forced EU Members to protect them by adopting the Water Framework Directive (WFD 2000). Monitoring of the aquatic environment is an integral part of the water management strategy to meet the objectives of the WFD. Recently, remote sensing and GIS techniques present the most effective solutions for mapping aquatic environments (Luo et al., 2017, Palmer et al., 2015, Walczak et al. 2013, Walczak et al. 2016, Wang et al., 2012). Satellite imagery data enable detection of temporal and spatial changes in water bodies by repeat coverage of satellite instruments and multispectral characteristics of provided data. Multispectral characteristic is defined as a number of wavelength intervals in the electromagnetic spectrum which a satellite records. Additionally, remote sensing techniques have an economic advantage – imagery is provided by non-cost access. In recent years, remote sensing data from environmental satellites such as Sentinel-2, Landsat-7, Landsat-8, MERIS/OLCI and MODIS have been widely used for agricultural, forestry and aquatic applications (Agutu et al. 2017, Brown 2015, Chormański et al. 2011, Gökkaya et al. 2017). Results obtained on the basis of satellite data have been validated by field and laboratory measurements in many studies (Dörnhöfer et al. 2018, Kiefer et al. 2015, Yadav et al. 2017). Remote sensing techniques in aquatic monitoring are mainly used to assess algal blooms (Clark et al. 2017, Nazeer et al. 2017) and water transparency (Lee et al. 2016).

Aquatic environment monitoring is based on spectral indices, which are a combination of selected bands, mainly representing red and blue wavelengths. One of the most popular and widely used vegetation indices is the normalized difference vegetation index (NDVI), first proposed by Rouse et al. (1974). 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 values of the NDVI vary from -1 to +1, depending on land cover. Low values (minus or approaching zero) represent water and soil areas, while higher values represent vegetation – in an aquatic environment there are seasonal algal blooms, and emergent and floating plants.

The main purpose of the study was to assess the dynamics of the vegetation process in a two-stage reservoir on the basis of satellite data. The analysis is based on Sentinel-2 satellite data from the period 2015-2017. The NDVI was selected to detect the vegetation process in the Radzyny reservoir located on the Sama river.

2. Materials and Methods

The Sentinel-2 is part of the Copernicus Earth Observation mission, previously known as Global Monitoring for Environment and Security (GMES) program. The Sentinel-2 is a constellation of two satellites. The launch of the first satellite (Sentinel-2A) occurred on June 23, 2015, while the second (Sentinel-2B) was on March 7, 2017. The main instrument of the satellite, Multi-Spectral Imager (MSI), provides systematic data with a 5-day repeat cycle (Xue & Su 2017). The MSI sensor features 13 spectral bands for visible, near-infrared (VNIR) and short-wave infrared (SWIR) radiation in 10, 20 and 60 m spatial resolution.

The remote sensing data were acquired from the Sentinel Hub website (*https://sentinel-hub.com/*). Satellite imagery was selected for the vegetation months (May, June, July, August and September) in the period 2015-2017. Finally, thirteen Sentinel-2 images were selected for the analysis, three for 2015, and five each for 2016 and 2017. Analysis was carried out for pixels more than 50% of whose area consisted of reservoir. In the first step of data processing the NDVI was calculated for each satellite image. According to Xue and Su (2017), NDVI is very sensitive to the effects of atmosphere, cloud, and cloud shadow, and requires remote sensing calibration. The equation of the NDVI for Sentinel-2 data is based on a combination of NIR (ρ_{NIR}) and red (ρ_R) bands:

$$\mathrm{NDVI} = \frac{\rho_{\mathrm{NIR}} - \rho_{\mathrm{R}}}{\rho_{\mathrm{NIR}} + \rho_{\mathrm{R}}}$$

Finally, to assess spatial and temporal dynamics of the vegetation process, values of NDVI for each satellite image were extract to point data. In this study, the degradation process was analyzed for the main and pre-dam reservoir. To specify areas mainly covered by vegetation, the reservoir was split into 10 parts, depending on the distance from the inflow of the Sama river (distance between profiles splitting polygons equals 500 m). All calculations were performed with Quantum GIS 2.18 and ArcGIS 10.5 software, and statistical analysis was conducted using Statistica 13 software. The statistical analysis was aimed at comparing the NDVI values in the pre-dam and main reservoir and additional between 10 parts of the reservoir designated for analysis. The assessment was based on the non-parametric Kruskal–Wallis (KW) test. One-way analysis of variance for Kruskal–Wallis ranks was employed for the verification of the hypothesis of significance of differences between medians value of NDVI (Ptak et al. 2018). Statistical analysis was made in Statistica 13 software.

3. Study area

The Radzyny reservoir was built in 2001 on the Sama river located in the Warta basin. The object has a two-stage construction. The main dam is located at 20.76 km, while the pre-dam is at 23.54 km of the Sama river. The total inundation area of the reservoir is 109.44 ha, while the capacity is 2.88 million m^3. The area of the main reservoir equals 80.31 ha and its capacity is 2.48 million m^3. The mean depth of the main reservoir is 3.10 m, while in the pre-dam reservoir it is 1.40 m. In the period from November to March, the water levels are 69 m a.s.l. and 71 m a.s.l. in the pre-dam and main dam reservoir respectively. However, in the period from March to November, the water levels in the reservoirs are set to 72 m a.s.l. and 72.5 m a.s.l. The Radzyny reservoir is a multipurpose reservoir. The main functioning purposes include water supply capacity, flood protection, stability of environmental flows for biological life in the Sama river, tourism and recreation. The total catchment area of the reservoir is 239.90 km^2, and it is mainly covered by agriculture lands. The mean flow from the years 1982-2012 in the main dam profile was 0.64 $m^3 \cdot s^{-1}$. However, extreme flows range from 0.016 to 12.38 $m^3 \cdot s^{-1}$.

The main problem related to the management of the Radzyny reservoir is water quality. According to the report "Water management and water quality assessment of the Radzyny reservoir with operational guidelines for water quality improvement" developed by the Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB), the vegetation process in the pre-dam reservoir may be caused by high concentrations especially of phosphorus compounds. The results of water quality monitoring are presented in Table 1.

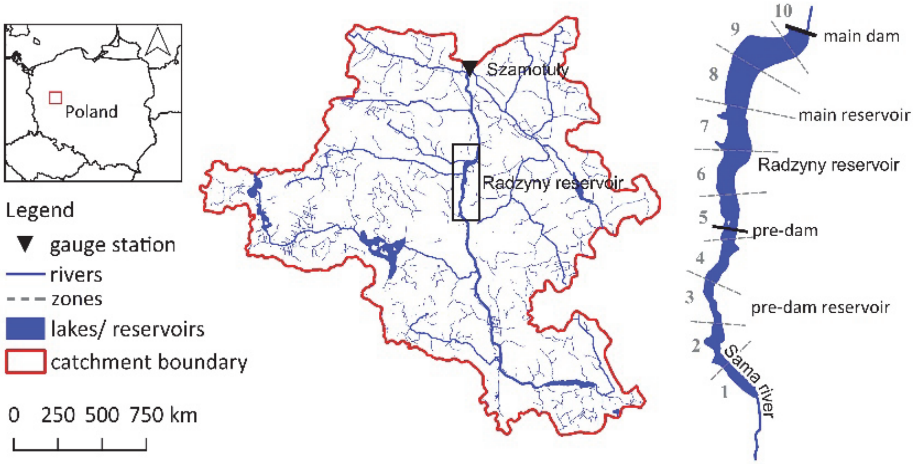

Fig. 1. Study site location
Rys. 1. Lokalizacja obszaru badań

Table 1. Mean values of water quality parameters in the Radzyny reservoir in the vegetation period in the years 2015-2017
Tabela 1. Średnie wartości parametrów jakości wody w zbiorniku Radzyny w miesiącach wegetacyjnych w latach 2015-2017

Parameters	Pre-dam reservoir	Main reservoir
Water temperature [°C]	22.90	23.15
Dissolved oxygen [mg O_2/dm^3]	9.85	8.15
Electrical conductivity [mS/cm]	936	973
Secchi depth [m]	0.48	0.68
Phosphates [mg P/dm^3]	0.65	0.24
Total phosphorus [mg P/dm^3]	0.85	0.43
Ammonia nitrogen [mg N/dm^3]	0.25	0.14
Total nitrogen [mg N/dm^3]	2.52	1.73

4. Results

Spatiotemporal changes of the NDVI value in the Radzyny reservoir are presented in Figure 2. During analyzed months in the period 2015-2017, the NDVI values varied from -0.528 to 0.917.

The NDVI in the Radzyny reservoir during July 2015 varied from -0.47 to 0.92. The difference between mean values in the main and pre-dam reservoir is 0.46 (Table 2). The highest value in August 2015 was 0.89 and was observed in the pre-dam reservoir. The difference between mean values depending on parts of the reservoir is 0.42. During September 2015, the difference between the two parts started to equalize, and was 0.22.

In May 2016, the difference between mean values in the pre-dam and main reservoir was 0.31. The lowest NDVI was observed in the main part. The highest values were comparable between parts of the Radzyny reservoir. During June 2016, the difference between NDVI mean values depending on parts of the reservoir was 0.21. The results obtained for July and August were in a similar range. Similarly to previous months, the mean values of the NDVI were higher in the pre-dam part, respectively 0.18 and 0.21.

During May 2017, the difference between NDVI mean values in the main and pre-dam reservoir was 0.23. The highest value in June 2017 was observed in the pre-dam reservoir, while the lowest value was observed in both parts. Similarly, to previous years, the mean values of the NDVI in July, August and September 2017 were higher in the pre-dam part. During September 2017 values of NDVI were in range of -0.53 to 0.88. The difference between parts was 0.47.

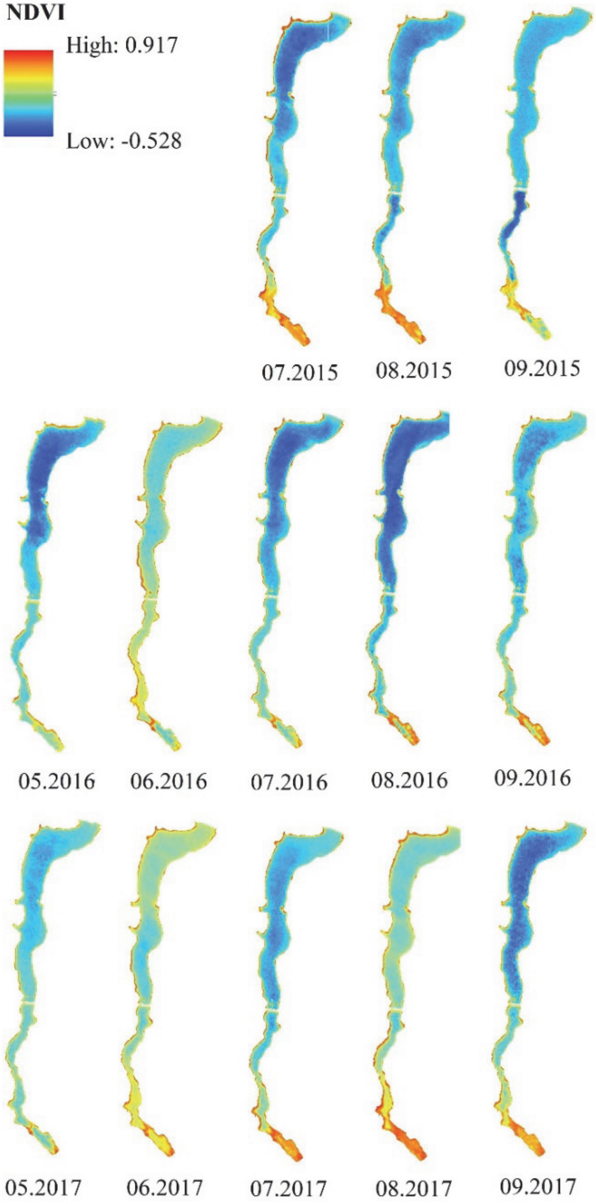

Fig. 2. Spatio-temporal changes of vegetation process for vegetation months in the period 2015-2017
Rys. 2. Przestrzenno-czasowa zmienność procesu wegetacji w miesiącach wegetacyjnych w latach 2015-2017

Table 2. Characteristics of NDVI in the Radzyny reservoir for vegetation months in the period 2015-2017 (minimum, maximum, mean and median)
Tabela 2. Wartości charakterystyczne NDVI w zbiorniku Radzyny w miesiącach wegetacyjnych w latach 2015-2017 (minimum, maksimum, średnia i mediana)

Date	Overall	The main part	The pre-dam part
07.2015	-0.47 / 0.92 0.01 / -0.13	-0.47 / 0.89 -0.10 / 0.20	-0.24 / 0.92 0.36 / 0.49
08.2015	-0.39 / 0.89 0.02 / -0.15	-0.39 / 0.84 -0.09 / 0.17	-0.38 / 0.89 0.33 / 0.51
09.2015	-0.52/ 0.83 -0.02 / -0.14	-0.27 / 0.81 -0.08 / 0.15	-0.52 / 0.83 0.14 / 0.18
05.2016	-0.47/ 0.86 -0.08 / -0.14	-0.47 / 0.86 -0.16 / 0.22	-0.21 / 0.86 0.15/ 0.08
06.2016	-0.17/ 0.91 0.18 / 0.11	-0.17 / 0.89 0.12 / -0.05	-0.11 / 0.91 0.33/ 0.29
07.2016	-0.47/ 0.85 -0.05 / -0.15	-0.47 / 0.84 -0.13 / 0.22	-0.17 / 0.85 0.18/ 0.07
08.2016	-0.48/ 0.88 -0.08 / -0.24	-0.48 / 0.84 -0.19 / 0.30	-0.35 / 0.88 0.21/ 0.07
09.2016	-0.39/ 0.87 0.01 / -0.09	-0.39 / 0.81 -0.05 / 0.14	-0.28 / 0.87 0.24/ 0.11
05.2017	-0.30/ 0.87 0.03 /- 0.04	-0.30 / 0.84 -0.03 / 0.08	-0.18 / 0.87 0.20/ 0.10
06.2017	-0.18/ 0.88 0.21 / 0.15	-0.18 / 0.86 0.15 / 0.12	-0.18 / 0.88 0.36/ 0.37
07.2017	-0.35/ 0.87 0.04 / -0.09	-0.35 / 0.85 -0.06 / 0.14	-0.29 / 0.87 0.32/ 0.23
08.2017	-0.18/ 0.91 0.21 / 0.09	-0.09/ 0.85 0.13 / -0.06	-0.18 / 0.91 0.46/ 0.48
09.2017	-0.53/ 0.88 -0.01 / -0.15	-0.53/ 0.80 -0.13 / 0.23	-0.27 / 0.88 0.34/ 0.33

The analysis showed that the NDVI values in the period from May to September in the pre-dam reservoir were higher than those recorded in the main reservoir (Fig. 3a). Also, in the pre-dam reservoir the variation of NDVI was over 2.5 higher than in the main reservoir. The highest variation of NDVI within the pre-dam reservoir was observed in August and the lowest in May. In the main reservoir, NDVI values were characterized by similar variability for all of the analyzed months.

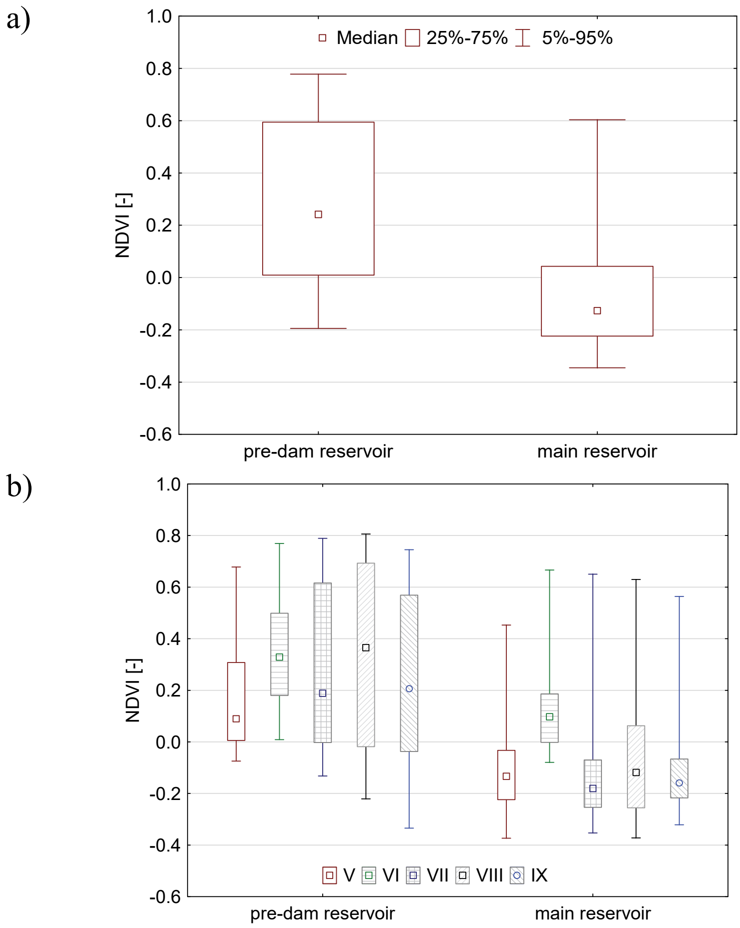

Fig. 3. Changes in NDVI values in pre-dam and main reservoir from July 2015 to September 2017 (a) and individual months (b)
Rys. 3. Zmienność wartości NDVI w części wstępnej i głównej zbiornika od lipca 2015 do września 2017 (a) i poszczególnych miesięcy (b)

NDVI median values in the main reservoir in May, July, August and September were at a similar level; the highest value was recorded in June (Fig. 3b). The NDVI values in the pre-dam reservoir were higher than in the main reservoir. These differences were statistically significant at the level of $\alpha = 0.05$.

The analysis of the vegetation process along the reservoirs showed that in the pre-dam reservoir in zones 1-4 there was a marked decrease in the NDVI value (Fig. 4a). The differences in NDVI values for zones 1 and 2, 2 and 3 and 3 and 4 were statistically significant at the level of $\alpha = 0.05$. The highest NDVI values occurred at the inlet to the pre-dam reservoir (zone 1) while the lowest occurred near the pre-dam (zone 4). In the inlet part of the pre-dam reservoir there are the lowest depths, which favors the development of vegetation. The highest variability of NDVI within the pre-dam reservoir occurred in the middle part (zones 2 and 3). In the main reservoir the NDVI values in each zone were at a similar level. Slightly higher values were recorded in the upper and lower parts of the main reservoir (zones 5 and 10) and the lowest in the middle part (zone 8). In the main reservoir, differences in NDVI values only for zones 5 and 6, and 9 and 10 were statistically significant at the level of $\alpha = 0.05$. The variation of NDVI values in zones from 5 to 10 was similar. The NDVI values within the pre-dam reservoir confirm the intensive process of overgrowth and degradation, which is particularly visible in zones 1 to 3. In the lower part of the pre-dam reservoir, the values are slightly higher than those recorded in the main reservoir. This confirms the effectiveness of this type of solution in the protection of the main reservoir against degradation. The analysis of changes in NDVI values along the pre-dam reservoir in the months from May to September showed that the greatest dynamics of changes in zone 1 occurred in May and June (Fig. 4b), whereas in zones 2 and 3 they occurred in July and August. In the main reservoir, the largest changes of NDVI were in August and the lowest in June. In June NDVI values in the main reservoir were the highest, and in July and September, generally at the lowest level.

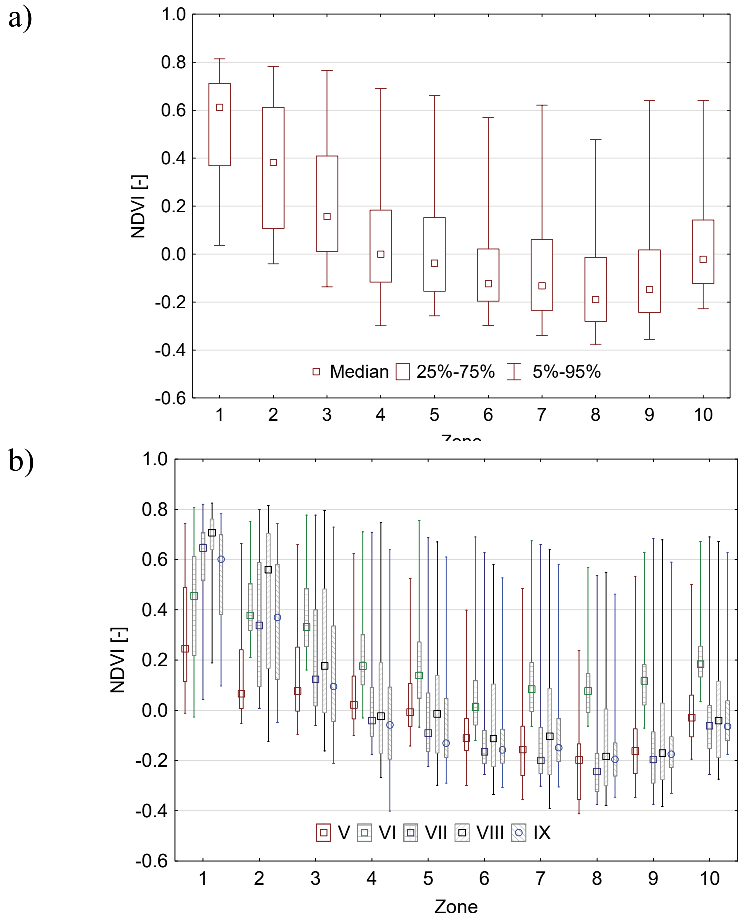

Fig. 4. Changes in NDVI values along pre-dam (zones 1 to 4) and main reservoir (zones 5 to 10) from July 2015 to September 2017 (a) and individual months (b)
Rys. 4. Zmiany wartości NDVI wzdłuż części wstępnej (strefy od 1 do 4) I głównego zbiornika (strefy od 5 do 10) od lipca 2015 do września 2017 (a) i poszczególnych miesięcy (b)

The analysis showed high variability of NDVI values in the corresponding months during the period 2015-2017. Also, the spatial changes of NDVI values were at a high level. The variability of the NDVI values show the dynamics of the vegetation process. This process in the analyzed period may result from thermal conditions and variability of inflows as well as the supply of biogenic compounds. These factors together determine the temporal and spatial direction of the vegetation process in the reservoir. The largest changes occurring in the preliminary reservoir indicate that the functions assumed at the design stage are implemented, i.e. protection of the main reservoir against sediment accumulation and water quality deterioration.

5. Discussion

Recently, open-access satellite data have enabled wider sources for aquatic monitoring than traditional in situ measurements, in which water bodies are represented by a single sampling point (Dlamini et al. 2016). Due to multispectral data, it is possible to detect areas of high vegetation abundance (Matthews et al. 2012). For aquatic monitoring there are in connection with the vegetation process seasonal algal blooms and the overgrowing process. The results obtained in this study confirm that remote sensing techniques have good potential for detecting the vegetation process in reservoirs in terms of spatial and temporal changes. Temporal changes could be detected especially by high temporal resolution of Sentinel-2, which provided data by a 5-day repeat cycle. In comparison to airborne imagery, satellite data have increasingly changed the possibility of using remote sensing data to monitoring of degradation phenomena of water bodies (Urquhart et al. 2017). Due to the spatial resolution of satellite imagery, the changes of the vegetation process are presented in resolution equal to 10 m. The analysis in this study was carried out on the basis of 10062 pixels, 7471 of them representing the main part and 2591 representing the pre-dam part of the reservoir. The obtained results show that spatial resolution of the Sentinel-2 allows detection of changes of the vegetation process in both parts of the reservoir.

6. Conclusion

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

1. SENTINEL-2 satellite imagery allows analysis of the vegetation process in retention reservoirs in terms of time and space.
2. Temporal changes of the vegetation process in the reservoirs are related to the thermal and hydrological conditions and the inflow of biogenic compounds.

3. The spatial changes of the vegetation process are the result of the reservoir morphometry and the dynamics of the water level in the reservoir.
4. In the Radzyny reservoir, large spatiotemporal changes in the NDVI value were observed.
5. Higher values and variability of NDVI in the pre-dam reservoir indicate its greater degradation in relation to the main reservoir.
6. The NDVI values in the pre-dam reservoir decrease from the inlet to the pre-dam, which indicates decreasing degradation of the reservoir along with the distance from the inlet.
7. The values of the NDVI index along the main reservoir were at a similar level and are characterized by similar variability, which indicates a similar course of the degradation process.
8. The lowest NDVI values in the pre-dam reservoir occur in May and the highest in August. In the main reservoir, the highest NDVI values occur in June and in the remaining months they are at a similar level.
9. The analyses carried out in this study confirm the effectiveness of the pre-dam part in protection of the main reservoir.

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Analiza procesu wegetacji w dwustopniowym zbiorniku retencyjnym na podstawie zdjęć satelitarnych – zbiornik Radzyny na rzece Sama

Streszczenie

Celem pracy była analiza procesu wegetacji w dwustopniowym zbiorniku retencyjnym na podstawie zdjęć satelitarnych. Do analizy wykorzystano zobrazowania z satelity Sentinel-2 z okresu 2015-2017. Ocenę procesu wegetacji w zbiorniku Radzyny na rzece Samie przeprowadzono na podstawie indeksu spektralnego - Normalized Vegetation Index (NDVI).

Analizowany zbiornik Radzyny ma dwustopniową konstrukcję. Wydzielono w nim część główną oraz wstępną. Do podstawowych zadań części wstępnej należy ochrona zbiornika głównego przed sedymentacją oraz dopływem związków biogennych. Jednym z podstawowych problemów związanych z funkcjonowaniem zbiornika Radzyny jest dopływ związków fosforu, który prowadzi do eutrofizacji wód gromadzonych w zbiorniku.

Proces wegetacji w zbiorniku Radzyny był analizowany dla części wstępnej oraz zbiornika głównego. W celu dokładnego określenia części zbiornika, które są najbardziej narażone na proces degradacji, podzielono zbiornik na 10 części, w zależności od odległości od wpływu rzeki Sama (dystans pomiędzy przekrojami ograniczającymi wydzielone strefy wynosił 500 m). Wszystkie analizy przestrzenne wykonane zostały w programie Quantum GIS 2.18 oraz ArcGIS 10.5. Analizy statystyczne zostały przeprowadzone w programie Statistica 13.

Przeprowadzone analizy wykazały, że wartości wskaźnika NDVI w okresie od maja do września były wyższe w zbiorniku wstępnym. Największą zmienność wskaźnika NDVI w części wstępnej zaobserwowano w sierpniu, natomiast najmniejszą w maju. Zbiornik główny w okresie 2015-2017 charakteryzował się niższymi wartościami i większą stabilnością wskaźnika NDVI. Analiza zmienności NDVI wykazała, że w części wstępnej (strefy 1-4) następuje spadek wartości na długości zbiornika. Najwyższe wartości wskaźnika występują w pobliżu wpływu rzeki do zbiornika (strefa 1), podczas gdy najniższe przy przegrodzie (strefa 4).

Na podstawie uzyskanych wyników, potwierdzono, że część wstępna pełni funkcję ochronną zbiornika głównego, m.in. ogranicza dopływ związków biogennych oraz skupia proces akumulacji osadów dennych. Uzyskane wyniki potwierdzają możliwość zastosowania danych satelitarnych Sentinel-2 do analizy procesu wegetacji w zbiornikach retencyjnych w ujęciu czasowym i przestrzennym. Stwierdzono, że analiza na podstawie zobrazowań satelitarnych charakteryzuje się większą efektywnością w monitoringu środowisk wodnych niż tradycyjne pomiary terenowe, w których wody powierzchniowe oceniane są na podstawie pojedynczych pomiarów.

Abstract

The main purpose of the study was to assess the dynamics of the vegetation process in a two-stage reservoir on the basis of satellite data. The analysis is based on Sentinel-2 satellite data from the period 2015-2017. The normalized difference vegetation index (NDVI) was selected to detect the vegetation process in the Radzyny reservoir located on the Sama river. The reservoir is split into two parts – the main and the pre-dam zone. The main role of the pre-dam reservoir is to store sediments and water pollutants. The main problem related to the management of the Radzyny reservoir is water quality. Particularly high concentrations of phosphorus compounds may lead to reservoir vegetation.

The vegetation process was analyzed for the main and pre-dam reservoir. To specify areas mainly affected by vegetation, the reservoir was split into 10 parts, depending on the distance from the inflow of the Sama river (distance between profiles splitting polygons is 500 m). All calculations were performed using Quantum GIS 2.18 and ArcGIS 10.5 software, and statistical analysis was conducted with Statistica 13 software. The analysis showed that the NDVI values in the period from May to September in the pre-dam reservoir were higher than those recorded in the main reservoir. The greatest variation of the NDVI within the pre-dam reservoir was observed in August while the lowest was observed in May. In the main reservoir, NDVI values were characterized by similar variability. The analysis of the vegetation process along the reservoirs showed that in the pre-dam reservoir in zones 1-4 there was a marked decrease in the NDVI. The highest NDVI values occurred at the inlet to the pre-dam reservoir (zone 1) while the lowest values occurred near the pre-dam (zone 4).

The results indicate that the functions assumed at the design stage for the preliminary reservoir have been implemented, i.e. protection of the main reservoir against sediment accumulation and water quality degradation. SENTINEL-2 satellite imagery allows analysis of the vegetation process in retention reservoirs in terms of time and space. The study suggests that open-access satellite data are a more effective source for aquatic monitoring than traditional in situ measurements, in which water bodies are represented by a single sampling point.

Słowa kluczowe:
proces wegetacji, zbiornik dwustopniowy, zobrazowania satelitarne, NDVI, Sentinel-2

Keywords:
vegetation process, two-stage reservoir, satellite imagery, NDVI, Sentinel-2