Monitoring of Inland Surface Water Quality Using Remote Sensing on the Example of Wigry Lake

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Abstract. The study examines how LANDSAT images can be used to monitor inland surface water quality effectively by using correlations between various indicators. Wigry lake (area 21.7 km^2) was selected for the study as an example. The study uses images acquired in the years 1990–2016. Analysis was performed on data from 35 months and seven water condition indicators were analyzed: turbidity, Secchi disc depth, Dissolved Organic Material (DOM), chlorophyll-a, Modified Normalized Difference Water Index (MNDWI), Normalized Difference Water Index (NDWI) and Normalized Difference Vegetation Index (NDVI). The analysis of results also took into consideration the main relationships described by the water circulation cycle. Based on the analysis of all indicators, clear trends describing a systematic improvement of water quality in Lake Wigry were observed.

1 Introduction

Water resources should be specially protected as they play a significant role in human life. Over time, anthropogenic factors have caused many changes in water quality [1]. The term 'water quality' is hard to define [2], but throughout this research it refers to the quality of the aquatic environment, as described by measured indicators. Water quality monitoring refers to the actual collection of data at regular intervals [3]. This makes it possible to detect trends and relations between them [2]. In environmental monitoring, classic methods (direct monitoring) can be described as measuring the value of an indicator in the field. In this case the absolute value of the measured parameter is obtained [4]. Indirect methods refer to calculating the value of a parameter on the basis of specific functional dependencies by measuring the value of other parameters [5].

Since the first Landsat satellite was launched, the data it has collected has been widely used to monitor water quality, for example by [6-9] and many others in recent years. In general, satellite images are popular in many studies about water quality due to the fact that they have features that ground samplings do not offer, including the ability to sense large areas with good time resolution; moreover, satellite images provide access to historical datasets [10].

The purpose of this research was multi-temporal analysis of indicators that can help to define water quality. Two hypotheses were put forward: first, water quality in this lake changes over a period of years; second, remote sensing methods are an effective tool to monitor these changes. As a test area, Wigry Lake was chosen with the assumption that the main source of water contamination are waters from surface runoff and those transported by the Czarna Hańcza river.

2 Study area

Wigry Lake is located in Podlaskie Voivodeship in northeastern Poland. With an area of 21.2 km^2 and a maximum depth of 73 m, it is an important part of Wigierski National Park, being its biggest lake [11]. Wigry Lake is a kettle lake with a few smaller lakes nearby, including Pietry, Dowcień, and Żubrowo, all of which used to be part of Wigry until they were separated from the main reservoir by mire processes. The main river flowing through the lake is Czarna Hańcza, with 1.4 m^3 per second water discharge. Characteristic of this river is the huge amount of dark silt that is transported to Wigry Lake [12].

Due to the unique character of the lake, many attempts have been made to protect its waters. In 1975, Wigry Lake was listed as one of world's most valuable inland water reservoirs and became part of the "Aqua" project, run by the International Union for the Conservation of Nature. In 1989 Wigierski National Park was created to protect the lake and its surroundings at the national level [13].

3 Data

The study uses LANDSAT mission images obtained from the USGS Earth Explorer website, acquired in the years 1990–2016. The plan was to analyze one image from every month within the range April–October for the years 1990–2016. Rigorous criteria were applied due to the necessity of fulfilling specific conditions such as lack

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of precipitation on the day of sensing and the day prior to it and lack of clouds at the location. Theoretically, for one scene per month in perfect weather conditions, 189 images would be obtained. Data that did not fulfill the strict requirements of this research were excluded from analysis. Finally, 35 images were analyzed.

All images were pre-processed to re-calculate spectral bands to radiance and reflectance values. Then, a python script was implemented to automate the repetitive work such as clipping images to the smallest possible rectangle describing the boundaries of Wigry Lake, calculating indexes, and averaging results. All operations were carried out in ArcMap, provided by the ArcGIS platform.

4 Methods

For the purposes of this research the following indicators were calculated:

- Turbidity (1) [14]. Referring to [15] turbidity can be described as the amount of light scattered by particles suspended in water. The greater the number of suspended particles, the greater the scattering. To determine turbidity remote sensing methods, bands with spectrums of red, near infrared and blue regions are usually used due to the highest radiation scattering by particles in these spectral ranges [16].

$$\text{Turbidity} = 63.9 - 1401.7R_{TM2} + 1827.8R_{TM3} - 78.6(R_{TM3}/R_{TM2}) \quad (1)$$

$$R^2 = 0.92$$

- Secchi disk visibility (2) [17], also described as “Secci disk depth” [18]. The *SSD* method applied in-situ is used to measure the clarity of water. A white disk is lowered until it is no longer visible to observers [19]. In remote sensing methods, blue, green and red light are used for this indicator; this determines the utility of Landsat TM to calculate value of *SSD* [10].

$$SSD = 208 \cdot \exp(-9.82(\varrho_{TM3}/\varrho_{TM2})) \quad (2)$$

$$R^2 = 0.85$$

- Dissolved Organic Matter (DOM) (3) [20] (also referred to as colored dissolved organic matter, or yellow substance) has the ability to absorb light. Therefore, remote sensing can be used to estimate the amount present in water [16].

$$DOM = 42.33 - 28.48\,(\varrho_{617,5\text{-}626.6nm}/\varrho_{1002.7\text{-}1035.5nm}) \quad (3)$$

$$R^2 = 0.82$$

- Chlorophyll-a (4) can be defined as an indicator of the abundance of phytoplankton [21]. As Chlorophyll-a absorbs blue and red radiation, remote sensing methods are used to measure chlorophyll-a content [16].

$$\text{Chl-a} = TM4/(TM1+TM2+TM4) \quad (4)$$

$$R^2 = 0.69$$

- Normalized difference water index (*NDWI*) (5) proposed by McFeeters [22] uses the green and the near infrared band. This allows water features with positive values to be distinguished. Others, such as vegetation or soil, are expected to have negative values or zero [22].

$$NDWI = (TM2-TM4)/(TM2+TM4) \quad (5)$$

- The Modified Normalized Difference Water Index (*MNDWI*) (6) was proposed by Xu [23] as a modification due to imperfections in *NDWI*. The near infrared band was replaced with a middle infrared band that gives improved results, such as higher values for water bodies; moreover, unlike *NDWI*, *MNDWI* does not distinguish built-up areas [23].

$$MNDWI = (TM2-TM5)/(TM2+TM5) \quad (6)$$

- Normalized Difference Vegetation Index (*NDVI*) (7) uses the near infrared band and the red band due to fact that the greener vegetation is, the more NIR light it reflects and absorbs less visible light. This allows the *NDVI* ratio to highlight vegetation with positive values [24].

$$NDVI = (TM4-TM3)/(TM4+TM3) \quad (7)$$

5 Discussion

Analyzing the graphs that show the variability of indexes over time shows a series of dependencies between them. However, to fully understand the changes taking place in the lake, it is necessary to turn to the process of water circulation.

Water circulation is related to the thermal stratification that occurs due to temperature variations at different depths of a lake [15]. During the summer, the upper layers of water are heated intensively, thus their density is reduced. Therefore, the waters in these upper and lower layers do not mix and the level of oxygen in the lower layers decreases. As the level of insolation declines, the temperature falls, which intensifies the strength of the wind. This leads to fall turnover: the water in all layers mix and the temperature and oxygen level equalize between them. During winter, temperature circulation stops and the top layer of the lake freezes. The layering of waters in the lake is distinct. The temperature equalizes when spring arrives and circulation restarts [25].The effects of thermal stratification can be noticed in the results of this study. When circulation stops, suspended matter is deposited on the bottom of the lake. When turnover occurs, sediments are lifted closer to the surface and the Secchi Disk Depth

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and turbidity indexes values therefore fall (Fig. 1 and Fig. 2). As the next conclusion, the DOM value increases due to
increased vegetation growth in the surroundings of the lake (Fig. 3). This leads to a rise in humid acids, which causes the SSD index to start rising when Spring arrives. At the end of July, the Chl-a value starts to fall (Fig. 4). This is related to reduced production of algae.

All the indexes rise across the studied years. DOM and SSD increase systematically (Fig. 5 and Fig. 6), thus implying that water quality in Wigry lake is getting better. This suggests that actions taken to protect the lake, whose main goal is to limit the amount of dissolved substances deposited in the lake, are effective. This can be attributed to the efficiency of sewage treatment in the city of Suwałki, which was modernized in the late 1990s. Moreover, more responsible agriculture has reduced the use of pesticides, which reduces the amount of mineral and organic substances in the water. Due to this, water fertilization has decreased.

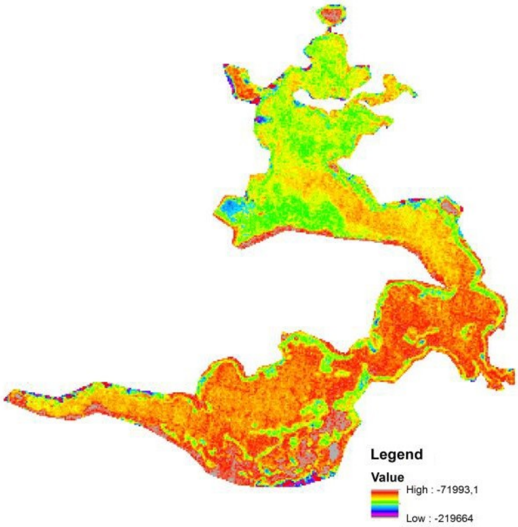

Fig. 1. Turbidity index in July 2010.

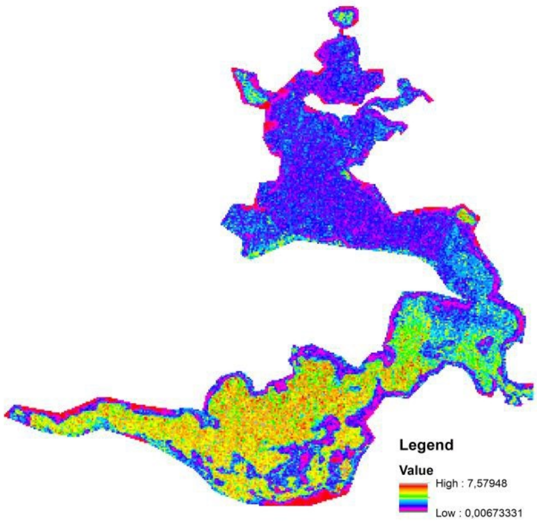

Fig. 2. SSD index in July 2010.

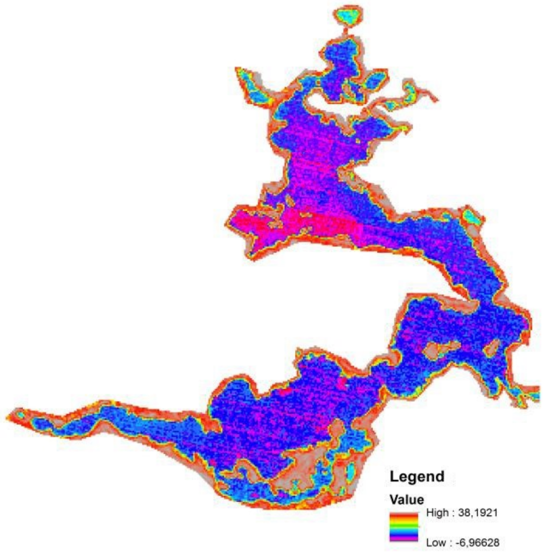

Fig. 3. DOM index in July 2010.

6 Conclusions

This research proves that multitemporal analysis with the use of remote sensing methods allows waters to be monitored indirectly. Water clarity together and other parameters describing water quality can be evaluated. The possible correlation of results obtained with remote sensing with in-situ testing would maximize the efficiency of future indirect monitoring. The research shows that remote sensing is a suitable tool to monitor the quality of Wigry Lake water. Moreover, the effectiveness of the actions taken to protect the lake has been confirmed.

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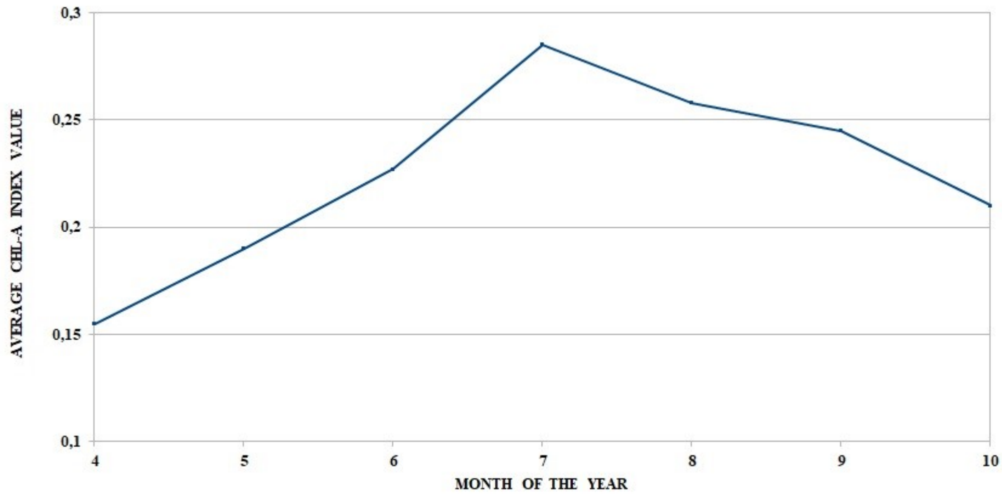


Fig. 4. Average Chl-a index value (y axis) for every analysed month (x axis).

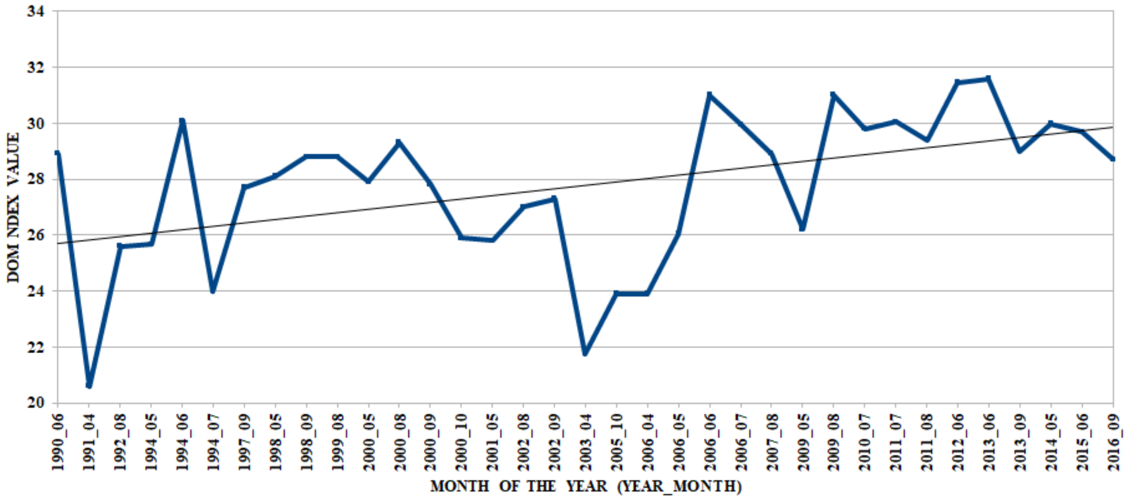
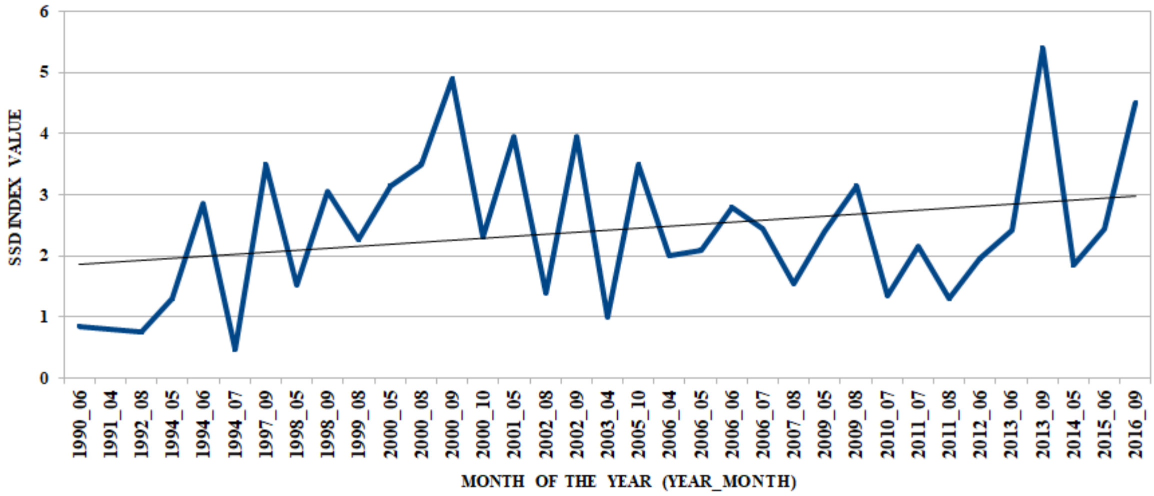


Fig. 5. DOM index value (y axis) for the whole period of research (x axis).



. **Fig. 6.** SSD index value (y axis) for the whole period of research (x axis).

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