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Original Research

Applying Landsat Satellite Thermal Images in the Analysis of Polish Lake Temperatures

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Abstract

This paper presents a comparative analysis of thermal images from Landsat satellites with *in situ* measurements of water temperature based on the example of three analysed lakes in Poland (Łebsko, Gardno, and Jamno). The coefficient of determination R^2 in the first two lakes reached a value of 0.95, and in the third case 0.87. The obtained results suggest high coherence of both of the sources. Satellite data obtained with such coherence with *in situ* measurements can be considered to be of high quality. The fact opens a new chapter concerning continuous monitoring of surface temperature of lakes in Poland, which can be considerably expanded in comparison to the current state (the measurement network is currently constituted by several tens of relatively large lakes). The issue addressed in the paper refers to a dynamic development trend in research based on teledetection information. So far, however, such methodology has not been used for detailed research on lakes in Poland. The availability of information on thermal conditions in reference to a possibly high number of lakes is of key importance in the context of the observed climate changes and the resulting transformation of water ecosystems. Continuous monitoring offers a basis for the development of applicative solutions, potentially reducing the effects of global warming.

Keywords: lakes, water temperature, remote sensing, Landsat, Poland

Introduction

One of the basic parameters of water ecosystems is temperature. Its value and distribution are of key importance for the course of biotic and abiotic processes occurring in rivers and lakes. The issue of correlations of thermal conditions with the above elements is discussed by various scientific disciplines [1-4]. Proper interpretation of the occurring correlations requires possibly detailed data concerning water temperature. Such information is collected in various ways, and covers, among other things, surface measurements [5] and measurements performed in deeper parts of waters [6].

In the case of lakes in Poland, the history of measurements of water temperature dates back to the end of the 19th century [7]. Systematic observations of water temperature in lakes, however, commenced in the 1950s [8]. The measurements were coordinated by the State Hydrological-Meteorological Institute, which was later transformed into the Institute of Meteorology and Water Management (IMGW). Data concerning temperature refer to stationary (point) measurements of near-surface waters. The number of observation sites over the years has changed, partially due to frequent reorganisations

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performed by IMGW. According to Choiński [9], in 1998 the highest number of lakes was recorded for which measurements of surface waters was performed: 40 (out of more than 7,000 lakes in Poland). As emphasised by Hestir et al. [10], traditional methods of recording temperature have certain logistical limitations. They are also costly and time-consuming.

Information obtained by means of thermal imaging can turn out to be an important source of information concerning lake water temperatures. Research concerning thermal images has so far been conducted by plane or helicopter [11-13], or using earth-bound measurements [14]. Although according to Ciołkosz [15] the thermal method found broad application in oceanography and hydrology, detailed thermal analyses of Polish lakes based on satellite images remain unavailable (note that the method has been commonly applied around the world for several decades [16-18]). Many semi-empirical methods have been developed in which lake surface temperature is estimated based on the emitted radiation recorded in one channel of the sensor. Such methods are called “mono-window” methods. They are usually applied for data of MSS, TM, and ETM+ sensors from Landsat 1, 2, 3, 4, 5, and 7 satellites. “Split-window” methods use differences in the intensity of the recorded thermal radiation in two channels to determine the transmission capacity of the atmosphere, considerably improving the accuracy of estimation of surface temperature [19]. The development of models describing correlations between the temperature of surface waters in lakes and data obtained from satellite images requires *in situ* measurements. Satellites with low-resolution sensors such as MODIS, AVHRR, or AATSR can provide information on the temperature of the observed surfaces with daily frequency, but only if no cloudiness occurs during their passing [20].

The objective of this paper is to analyse thermal images performed by Landsat satellites and assess their usefulness for obtaining data concerning Polish lake temperatures. The adopted research objective was implemented in three analysed lakes: Łebsko, Gardno, and Jamno, located in the northern part of the country (Fig. 1). The basic parameters of the lakes are presented in Table 1.

Table 1. Basic morphometric parameters of the analysed lakes (after: 21).

No.	Lake	Area (ha)	Depth max (m)	Depth mean (m)	Volume (th. m^3)
1	Łebsko	7,020.0	6.3	1.6	117,521.0
2	Gardno	2,337.5	2.6	1.3	30,950.5
3	Jamno	2,231.5	3.9	1.4	31,528.0

Material and Methods

The paper uses two sources of data concerning surface temperature in the analysed lakes. The first data set constitutes thermal images performed by Landsat satellites, and the second one includes *in situ* measurements of water temperature.

Landsat Satellite Data

The launch of the first satellite in the scope of the Landsat program took place in 1972. Owing to the satellites of the series, successively placed on the orbits in the scope of other missions, entire series of systematic quantitative data are available, permitting the estimation of temperature, detection of its changes, and forecasting the resulting processes. Three sensors were subsequently placed on board the satellites, namely MSS (multispectral scanner) placed in satellites of series 1-5 with a terrestrial resolution of 80 m; TM (thematic mapper) for recording images in seven spectral channels, installed on board of satellites from series 4 and 5 (terrestrial resolution of 30 m, in thermal channel 120 m); ETM (enhanced

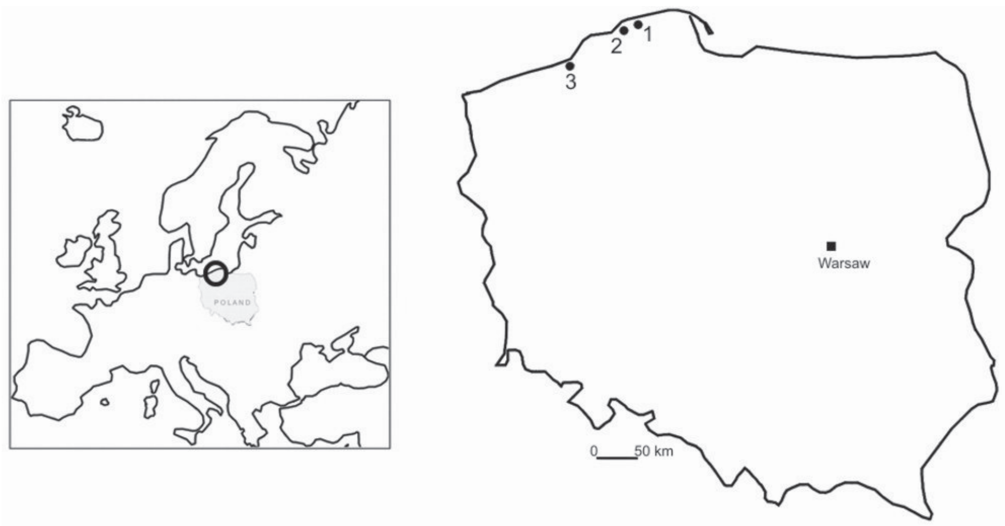

Fig. 1. Location of study objects: 1) Łebsko Lake, 2) Gardno Lake, 3) Jamno Lake.

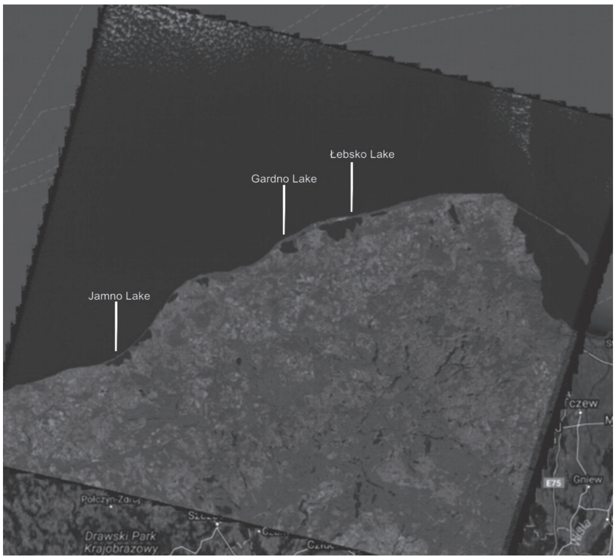

Fig. 2. Satellite image covering the analysed lakes (source: earthexplorer.usgs.gov).

thematic mapper) placed on board Landsat 7 (terrestrial resolution 15 m in the panchromatic channel, 30 m in spectral channels, and 60 m in the thermal channel, the satellite scene covers an area of 170 x 185 km). Two satellites of the series currently function on orbit, namely 7 and 8. The satellite of the sixth series was subject to a breakdown during launch in 1993. Landsat 7 failed in May 2003. The device compensating for the movement of the satellite in relation to the Earth's rotation, a scan line connector (SLC), was damaged. Since then, the recorded images involve errors deteriorating the quality of data. Satellites from the Landsat series have no possibility of deviation of the recording direction from the vertical. Therefore, repeated imaging of the same point on Earth is possible after 16 days. Interest in the application of Landsat images considerably grew with the disclosure, from 2 April 2009, of all images collected by the Geological Services of the United States, beginning from 1972. The paper uses satellite images from the period 1991-98 from missions Landsat 4 and 5, and data from the period 1999-2009 from mission Landsat 7. Due to the relatively small distance between the lakes, data referring to all three objects could be obtained in a single scene (Fig. 2).

Among several hundred satellite images constituting a data set from the multiannual 1991-2009, those where the analysed lakes were covered by clouds were removed. After this procedure, 93 scenes were obtained for Lake Łebsko, 86 for Lake Jamno, and 83 for Lake Gardno. The Landsat passes over Poland at around 09:30.

In Situ Measurements of Water Temperature

Field information concerning water temperature comes from stationary daily (point) observations conducted by the Institute of Meteorology and Water Management in the period 1991-2009. The measurements were performed at 07:00 at a depth of 40 cm. The information was recorded in the cycle of the hydrological year, beginning on 1 November and ending on 31 October.

Methods

The analysis of water temperature applied data from channel 6 of the Landsat satellite sensor. The channel records radiation in the range of thermal infrared (10,400-12,500 nm). Channel 6 provides an image with a spatial resolution of 120 m in the case of satellites Landsat 4 and 5, and 60 m in the case of Landsat 7. For each scene, a vector was developed composed of points corresponding to places of performance of field

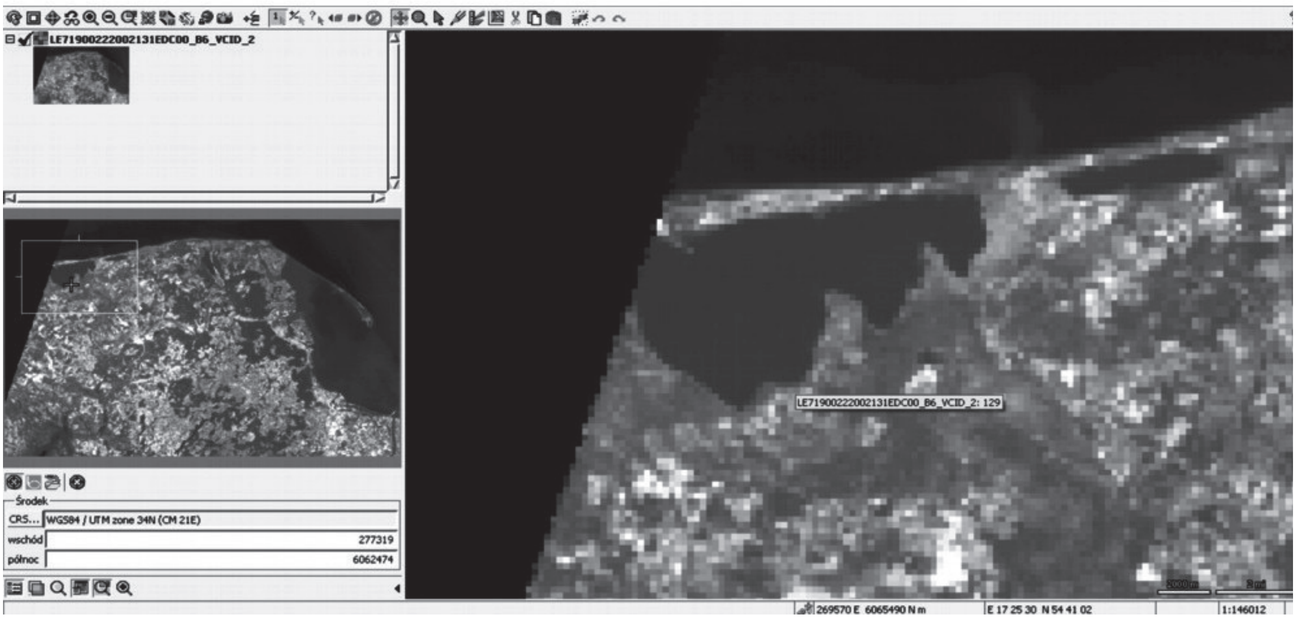

Fig. 3. Example pixel value (DN) on Lake Łebsko.

measurements. Such an approach permitted the calculation of the mean value of the pixel (DN – digital number) on the satellite image. Hovering the selected pixel over the corresponding place of measurement of water temperature permits determination of the value of the pixel, which in the example below (Fig. 3) amounts to 129. Data processing was performed using TNT MIPS 2015 software.

At the next stage of processing of image data, the obtained mean values of pixels from thermal channels were converted to radiation temperature by means of the following formula (after: 22):

$$CVR1 = gain * DN + bias \quad (1)$$

…where CVR1 is radiation temperature, gain (RADIANCE_MULT_BAND_6_VCID_2) is value of strengthening for a particular channel, DN is pixel brightness, and bias (RADIANCE_ADD_BAND_6_VCID_2) is bias value for a particular channel.

Gain and bias values were read from the metadata of satellite images. For Landsat 4 and 5, the values amount to 0.055 (gain) and 1.18243 (bias), and for Landsat 7 0.037 and 3.1628, respectively.

The obtained radiation values permit the calculation of temperature in Kelvin degrees. The calculations were performed based on the following formula (after: 22):

$$T = \frac{K_2}{\ln\left(\frac{K_1 * \varepsilon}{CV_{R1}} + 1\right)} \quad (2)$$

…where T is temperature in Kelvin degrees; K_1 and K_2 are calibration constants – for sensor TM placed on Landsat 4 and 5 amount to K_1 – 607.76 and K_2 – 1,260.56, and for sensor ETM+ on board Landsat 7, K_1 – 666.09 and K_2 – 1,282.71; and "ε" is emissivity, which usually amounts to 0.95.

Results obtained in Kelvin were then converted to Celsius and confronted with observations conducted in the field.

Results and Discussion

Correlations between temperature measured *in situ* and temperature obtained from satellite images (expressed

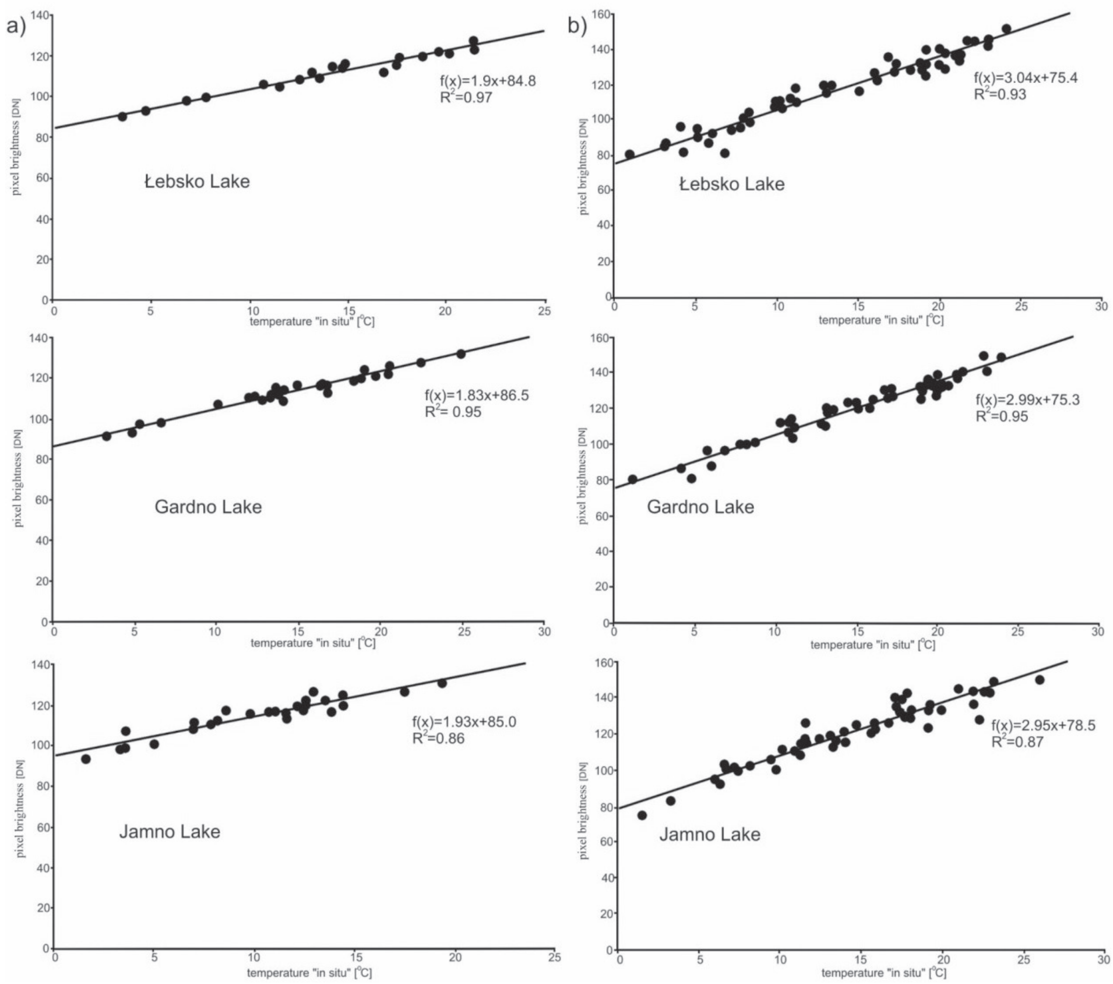

Fig. 4. Correlation between pixel brightness from channel 6 of MSS sensor a) and from channel 6 of ETM+ sensor b), and water temperature measured *in situ*.

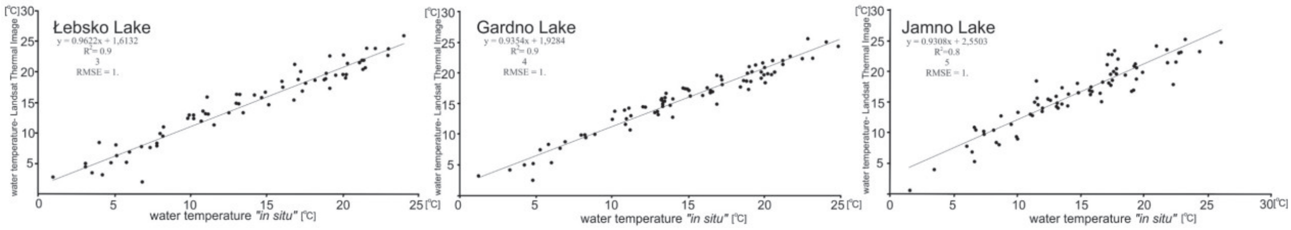

Fig. 5. Correlation between water temperature measured *in situ* and water temperature from satellite images.

in pixel brightness) are presented in Fig. 4a) correlation between water temperature measured *in situ* and water temperature from satellite images in Fig. 5.

According to the figure above, water temperatures obtained from field measurements and satellite images showed high correlation. In the case of all three lakes, differences between measurements from both of the sources were inconsiderable in the majority of cases. In the case of Lake Łebsko, for 40% of measurements the difference was lower than 1ºC, in 32% of measurements the difference was within a range from 1 to 2ºC, and in 28% of cases the difference was higher than 2ºC. In the case of Lake Gardno, in 45% of measurements the recorded differences of temperatures were at a level lower than 1ºC, in 32% of cases the differences varied from 1 to 2ºC, and in 23% of cases such differences were higher than 2ºC. In reference to Lake Jamno, 26% of performed measurements showed a difference in temperature not exceeding 1ºC, 34% showed a difference from 1 to 2ºC, and 40% showed a difference higher than 2ºC. The analysis of scenes with the greatest recorded differences showed that the above results are largely determined by two types of factors: technical and environmental. The former include the spatial resolution of the obtained images (pixel 120 m for Landsat 4 and 5, and 60 m for Landsat 7), and failure of the SLC device. One of the methods of retrieving missing data is the application of geostatistical tools, and performance of interpolation of the terrain. The second group of factors that can affect differences in both of the measurements should be associated with cloudiness and the terms of data collection. The temporal difference between standard water temperature observations (performed by IMGW) and performance of satellite images amounts to approximately 2.5 hours. In the context of high thermal stability of water, the interval is inconsiderable, but in the summer period, where over a short period of time rapid heating of the surface water layer occurs, the fact can cause certain divergences.

The paper refers to the global, dynamically developing trend of research on lakes with the application of modern satellite techniques. In this field, numerous papers concern studies on lake temperature [23-27]. Analyses conducted in the scope generally suggest considerable usefulness of satellite data for the knowledge of thermal conditions of lakes. In their review of teledetection studies on lakes, Dörnhöfer and Oppelt [28] point out that the authors of different papers using satellite data will consider them as being of high quality if the coefficient of determination R^2 was higher than 0.9. Such values, between temperature measured *in situ* and low-resolution satellite image data, were obtained by Politi et al. [29], analysing four large lakes located in different parts of Europe. Similar results were obtained with the application of data from Landsat satellites with higher spatial resolution, although with lower temporal resolution. Chao Rodríguez et al. [30] used data from the TM sensor on Landsat 5 from the period 2001-11 for the development of a model describing periodic changes in water temperatures in a small lake in northern Spain. The estimation of water temperature in lakes also applied other sensors of satellites of the Landsat series. Simon et al. [31] applied data from the ETM+ sensor in the estimation of temperature of two French lakes with an error RMSE = 1-2º and $R^2 = 0.93$.

In such a context, the obtained results for three analysed lakes in Poland correspond with the above situation. In the case of two of the analysed lakes (Łebsko and Gardno), value R^2 averages 0.95, and in the third case (Jamno) the value was inconsiderably lower than the specified threshold ($R^2 = 0.87$). It should be emphasised that the first two lakes are located in a protected area (Słowiński National Park, global biosphere reserve, MAB), and Lake Jamno is located near a large city (Koszalin, with more than 100,000 residents), and the lower coherence of field measurements and satellite observations can possibly be related to the impact of anthropopressure. The issue requires more detailed research.

Due to the rapid development of space technologies and their increasing availability, environmental data obtained this way find new applications in many domains. This is important in the context of the observed and confirmed with numerous climate warming studies [32-34]. The transformation of the current thermal conditions has and will have evident consequences, among others for lake ecosystems [35-36]. Undertaking measures potentially mitigating the effect of climate change on lake ecosystems requires the availability of possibly detailed data concerning their thermal regime. Schneider and Hook [37] point out that temperatures of large inland lakes are good indicators of climate change. Such research, however, is relatively scarce, and limited by the time of regular *in situ* measurements. Furthermore, the same authors emphasise that satellite data have the potential to provide a continuous record of surface temperature in inland water bodies. Importantly, satellite images permit the expansion of the data set on thermal conditions in lakes in reference to smaller objects, and the only limitation is image resolution (pixel size). The need for expansion of such monitoring by smaller lakes is mentioned by, among others, Tonooka and Hirayama [38], and Tonooka [39].

In Poland, the postulate can be implemented owing to satellite images. As emphasised in the introduction, such a methodology has not been applied so far, although detailed records of field temperature measurements exist, constituting a potential credible source of verification of satellite measurements. This fact opens a new chapter concerning continuous monitoring of surface temperatures in Polish lakes. This can be considerably expanded in comparison to the current state (the measurement network currently includes several tens of relatively large lakes). Obtaining information on the thermal conditions of a given lake (not covered by stationary measurements so far) would require the performance of a series of such observations, and then confrontation of such data with satellite thermal images. It is important that field measurements would constitute only a reference point for the continuation of satellite observations. Due to this, *in situ* measurements would not have to last for a dozen or several tens of years. In favourable climatic conditions (no cloudiness), and therefore an appropriate number of images, the completion of the activity of the measurement site could be within an annual cycle. The resulting scale of colours of particular pixels (expressing water temperature in accordance with temperature measured by traditional methods) could be interpolated in the future without the necessity of their constant verification with simultaneously conducted field measurements. Moreover, in order to minimise the risk of error, the conducted field measurements should be shifted from 07:00 to 09:30 to be in accordance with the time of the presence of the satellite above Polish territory.

Conclusions

The issue discussed in this paper refers to a dynamic trend developing in the research world based on teledetection information. Such a methodology, however, has not been used for detailed research on lakes in Poland so far. The performed analysis of Landsat thermal images on three analysed lakes showed high coherence of such data with the conducted field observations. The obtained results provide an encouraging basis for further works based on teledetection sources. In Poland, continuous (terrestrial) monitoring of water temperature is currently conducted on several tens of lakes. Based on satellite data, the group of lakes can be considerably expanded. The availability of information on thermal conditions in reference to the highest possible number of lakes is of key importance in the context of the observed climate changes and the resulting transformation of water ecosystems. Continuous monitoring provides a theoretical basis for the development of applicative solutions, potentially reducing the effects of global warming.

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