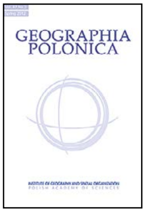

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DETERMINING WATER LEVEL FLUCTUATIONS IN SMALL-AREA LAKES USING SATELLITE RADAR DATA

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Abstract

The research objective was to determine whether and to what extent SAR data can be used to determine changes in the water level in small glacial lakes (with an area of ~1 km^2). The research object was Lake Biskupińskie – a small post-glacial lake in central Poland. As part of the research, a methodology for determining water level in small-area lakes based on radar data was developed, the potential for determining lake water levels using high- and medium-resolution SAR data was determined, and the results were verified against field measurements. The analyses employed data from two satellites, TerraSAR-X and Sentinel-1. The research confirmed the effectiveness of using SAR data to determine water-level fluctuations in small glacial lakes. The proposed methodology for working with data from the Sentinel-1 satellite allows for accurate estimation of WLF based on the results of interferometric analyses. Comparative analysis of the radar data results (lake surface) and field measurements (water level) were fully consistent with the data from TerraSAR-X and partially consistent with the data from Sentinel-1. The methodology of radar data analysis to determine WLF proposed in the paper has major research and applied potential, especially in the reconstruction of historical lake water levels.

Key words

lake • SAR • Poland • water level fluctuations

Introduction

In many places around the world, lakes constitute a major element of inland ecosystems. They perform many important natural functions related to, for example, the water cycle, the movement and deposition of sediments, and biochemical processes. They are also home to many species of flora and fauna. Lakes are an important reservoir of Earth's freshwater (Woolway et al., 2020), which humans use for social and economic purposes

(Palomino-Ángel et al., 2022). For this reason, they are treated in many parts of the world as objects of strategic importance for the functioning of local economies and communities (Nagabhatla et al., 2021).

Being natural objects, lakes are subject to various transformations. These are both qualitative changes (changes in the optical and chemical properties of the water) and quantitative changes (water level fluctuations [WLFs], fluctuations in the amount of water resources, and transformations in lake basin morphometry). In connection with the observed climate change (which is, for example, disturbing the water cycle in many inland ecosystems), the aforementioned WLFs deserve special attention. It should be noted that changes in lake water levels can also be short-term, temporary, or related to wind or pressure (seiches). The dynamics, trend and course of WLFs in lakes is an important element affecting the structure and function of the lake ecosystem, as it can determine the availability, complexity and quality of aquatic habitats (Gownaris et al., 2018). Furthermore, knowledge of WLF is necessary for the proper management of water resources for economic purposes (energy, fishing, etc.), tourist and recreational purposes, and societal purposes (as a source of drinking water). For these reasons, the issue of lake WLF is both important and timely – hence the abundance of related studies in the literature.

Currently, the dominant approach to the lake WLF in the literature is to use data collected from water-level observations and to extrapolate them using various mathematical and statistical models (Altunkaynak, 2007; Coulibaly, 2010; Piasecki et al., 2018; Piasecki & Witkowski, 2021; Demir & Yaseen, 2023). As a result, many articles in the literature share a similar methodology for forecasting the WLF of lakes. These works usually differ in mathematical and statistical method applied and variables selected (with those most relevant to the studied lake and region being selected). These articles often provide extremely valuable information about the studied lakes. Nevertheless, the methodology that those works share is limited, as it restricts analysis to those lakes subject to water-level monitoring. This is an extremely important problem, because there are very few lakes on Earth subject to constant monitoring, considering that there is a total of about 117 million lakes (Palomino-Ángel et al., 2022). The main reasons for the relatively small number of monitored lakes are the significant costs and logistical issues that prevent observation in poorly accessible regions (Hegerl et al., 2015). It should also be emphasised that monitoring of lake water levels is mainly conducted for large lakes (of >10 km^2) of significant societal and economic importance. Smaller lakes, which are significantly more numerous, are monitored far less often. Thus, knowledge about their past and current state is incomplete.

The continuous development of satellite technologies and tools for processing and analysing satellite data is constantly allowing progress in many research areas dealing with the natural environment. Particularly valuable are satellite data based on spectral imaging. Among them, special attention should be given to radar sensors (Synthetic Aperture Radar [SAR]), which allow terrain surfaces to be imaged regardless of weather conditions. The results of analyses using such data have been used in monitoring water levels on, for example, vegetated tropical wetlands (Brisco et al., 2015; Cao et al., 2018; Zhang et al., 2018) and extensive river floodplains (Wdowinski et al., 2008; Zhang et al., 2016; Yuan et al., 2017; Palomino-Ángel et al., 2019).

Previous studies on the monitoring of lake levels have focused on using the backscatter coefficient as a key quantity that is based on radar signal amplitudes. However, very little research has been done on using the phase portion of the SAR signal in analysing lake water levels (Palomino-Ángel et al., 2022). This method can provide better information about water level fluctuations in lakes where such observations are not carried out. This is particularly important for lakes of small surface area, which are the most numerous and, as mentioned, the least monitored.

The study objective was to determine whether and to what extent SAR data can be used to determine changes in the water level in small post-glacial lakes (with an area of ~1 km^2). The research object selected to meet the objective was Lake Biskupińskie – a small post-glacial lake in central Poland. The following specific objectives were also formulated in the work:

- to establish the possibility of determining the water level of lakes using high- and medium-resolution SAR data;
- implementation of SAR interferometry technique for observing land surface displacement to determine the water level in small-area lakes;
- to establish the relationship between water level values determined from radar data and from field measurements.

A novel aspect of the work is its indication and demonstration of the effectiveness of using radar data to determine water levels in small-area lakes

Study area

As already mentioned, the research object selected for the study was Lake Biskupińskie, located in the Wielkopolsko-Kujawskie Lake District (Poland). This is a young glacial area formed during the last glaciation. Climatically, it lies in a moderately warm zone. The annual average temperature in the study area is ~8.1°C (with an upward trend of 0.25°C per decade. The average temperature is lowest in January (-2°C) and highest in July (18.3°C). The annual average wind speed ranges from 3 to 4.5 $m{\cdot}s^{-1}$. There is a slight downward trend in relative humidity, whose average value falls in the range 74-84%. Annual sunshine duration ranges from 1500 to ~2000 $hr{\cdot}yr^{-1}$, with an upward trend of ~9.5 $hr{\cdot}yr^{-1}$. The area has low sums of precipitation (about 500 mm) and high evaporation, which in recent years has also shown an upward trend. As a result, evaporation from waters in this area have for several years exceeded 800 mm (Piasecki & Marszelewski, 2014), and the balance of vertical water exchange is among the least favourable in Poland.

The basic morphometric parameters of Lake Biskupińskie are:

- area: 1.16 km^2
- volume: 6.4 million m^3
- average depth: 5.5 m
- maximum depth: 13.7 m

In shape, it is approximately oval and of not very diversified shoreline. Because it is shallow, the shore zone is covered with aquatic vegetation, mostly concentrated in the north-eastern part of the lake.

The catchment area of Lake Biskupińskie covers the upper and middle part of the catchment area of the Gąsawka River and is characterised by a dense network of watercourses and drainage ditches (Fig. 1). Natural watercourses, including principally the Gąsawka River, have been deepened and their beds straightened. The main drainage works were carried out in the 19th century, and the drainage network was extended to be denser after the Second World War (in the 1950s–70s). The effect of these works was to lower the water table, to eliminate wetlands, to add formerly drained areas into the drainage network, to extend the duration of low water levels, and to cause the periodic drying of smaller watercourses (Kaniecki, 1997).

The current water level in the lake is about one metre below the level at the end of the 19th century, when it was 79.6 metres above see level (a.s.l). The cause of the drop in the water level was the aforementioned drainage works. In the 1930s, the lowering of the water level exposed archaeological relics in the lake related to a defensive settlement of the Lusatian culture (Zawol, 2020). The lowering of the lake's level (in combination with the large annual amplitude of water-level fluctuations) caused the exposed wooden archaeological objects to quickly deteriorate. This motivated the creation (in 1992) of a dam that raised the water level in the lake to keep it at a sufficiently high level.

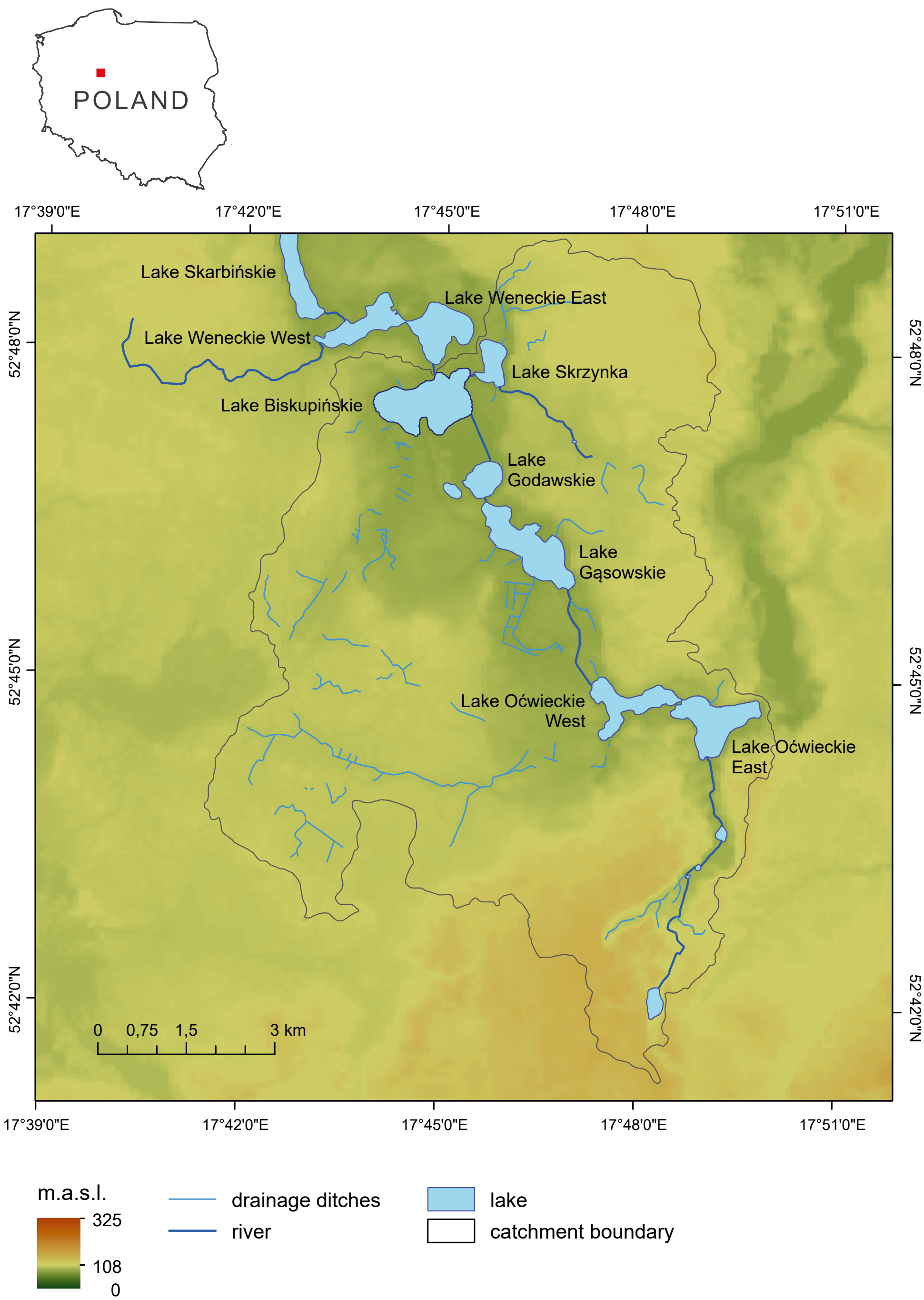

Figure 1. Location of study area and Lake Biskupińskie

Methods and materials

Selected meteorological and hydrological data from observations conducted by the Institute of Meteorology and Water Management-National Research Institute were used in the work. Daily values of the following meteorological parameters were analysed: air temperature, wind speed, humidity, total precipitation. These parameters were recorded at the meteorological station in Gniezno (the closest station to the lake). Data on daily changes in the water level of Lake Biskupińskie were also collected and analysed. It should be noted that daily observations of the water level of Lake Biskupińskie have been carried out continuously since 1951. Detailed analysis of meteorological and hydrological data was limited to the years 2015-16 – the period for which the satellite data included in the study originated.

Satellite radar images from the Sentinel-1 and TerraSAR-X missions were used in the research (Tab. 1). The former are public data made available under the Copernicus programme by the European Space Agency. The products used in the research are images recorded in Terrain Progressive Scan (TOPS) mode with a terrain resolution of ~4×14 m. The latter set of commercial data were high-resolution images of the TerraSAR-X satellite with a terrain pixel of ~1.5×2 m obtained in StripMap mode for a descending pass. A total of eight high-resolution images were accessed covering the period from July 12, 2015 to August 22, 2016. For the same observation period, 31 images of the Sentinel-1A satellite from July 5, 2015 to August 16, 2016 were also available for a descending pass.

For both sets of data, a radiometric calibration was performed to eliminate factors related to the imaging geometry and to allow results from different sensors to be compared against each other. The radar image expresses the ratio of signal sent by the sensor to reflected energy. This ratio is called the backscatter coefficient ($\sigma 0$) and allows water or wetlands to be identified (Wdowinski et al., 2008). This parameter was determined for both TerraSAR-X data and Sentinel-1 images. From the set of images from the Sentinel-1 mission, eight images whose dates were close to the date of acquisition of the TerraSAR-X images were selected. Subsequently, the range of $\sigma 0$ values for lakes in the study area was determined. The cut-off threshold allowed the study area to be classified and the extent of occurrence of water bodies to be determined. The resulting classification images for both Sentinel-1 and TerraSAR-X images were then geocoded. This made it possible to delimit the surface of Lake Biskupińskie. The results were compared against the field measurements of the water level in the lake at selected times.

The next stage in the research was to identify the displacement field of the area around the Lake Biskupińskie. Images taken on a descending pass were processed using SNAP Software by the European Space Agency to create interferograms, and the StaMPS/MTI algorithm (Hooper et al., 2012) was used to determine ground surface displacement. In total, 30 interferograms were generated in the analyses for the data from the Sentinel-1 mission related to the primary image from February 18, 2016. No such analysis was performed for the data from the TerrSAR-X mission, as we had access to only 8 acquisitions

Table 1. Radar data used in the research

Sensor	Geometry	Timespan	Perpendicular Baseline [m]	No. of acquisitions
TerraSAR-X	descending	12.07.2015 – 22.08.2016	-51.23 – +140.73	8
Sentinel-1A	descending	05.07.2015 – 16.08.2016	-71.97 – +115.25	31

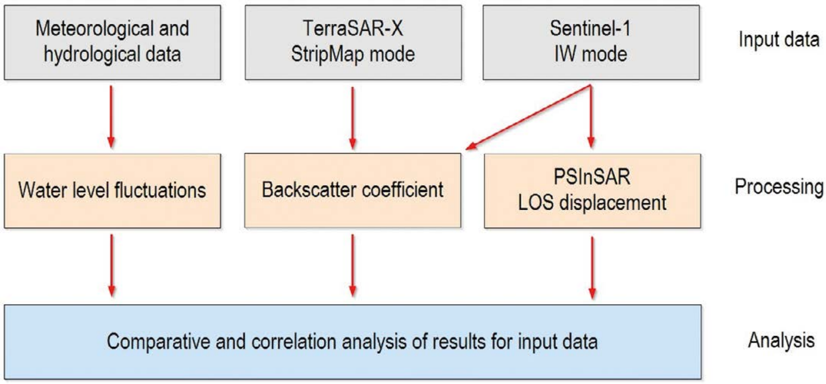

Figure 2. Flowchart of the methodology used in the study

of SAR data. In the interferometric analysis for the Sentinel-1 mission data, the amplitude dispersion threshold was taken to be 0.4. The obtained results were converted into metric values to determine the velocity of land displacement of ground surface. The final results were geocoded to identify Persistent Scatter (PS) points in the surrounding of the lake. Then, the PS point located in the immediate neighbour of water bodies with a high signal coherence value was selected. Time series of displacement values and water level changes were analyzed to determine the correlation between them. The lag in displacements between the plots was determined based on the correlation coefficient.

Analysis and results

Water level fluctuations

Before the construction of the dam in 1992, the water level in Lake Biskupińskie was highly annually variable. The amplitude of water level fluctuations was 40-80 cm over the course of a year. Since 1992, the annual amplitude of water level fluctuations has clearly decreased and now amounts to about 20-40 cm. In 2015-16, water level fluctuations in Lake Biskupińskie had the typical course for lakes of northern Poland. Water levels were highest in winter and spring and lowest in autumn (Fig. 3). In 2016, as compared to 2015, air temperatures were lower in the study area, whereas humidity and wind speeds were similar. This translated into a decrease in the evaporation value. In 2016, there were also slightly higher sums of precipitation (Fig. 4).

Backscatter coefficient

The radar data were used to determine backscatter coefficient ($\sigma 0$) values for the TerraSAR-X and Sentinel-1 data. For the Sentinel-1 sensor, $\sigma 0$ was determined for only the eight images acquired for periods similar to those of the TerraSAR-X images. Mean $\sigma 0$ values were calculated for the area identified as lakes (Fig. 5 – Lakes [I]) and for the entire area, which included both water and terrestrial areas (Fig. 5 – Entire area [II]). For the TerraSAR-X data, the histogram for the entire area (II) shows two zones of values. The histogram of the distribution of values for data from the Sentinel-1 satellite looks similar. Water and land areas are included across the distribution of $\sigma 0$ values on a histogram. In analysing the histograms for values from water regions only (I), it is possible to determine values on the histograms for such regions for both TerraSAR-X and Sentinel-1 data. Based on these, the cut-off threshold $\sigma 0$ of -15 dB was determined, which characterises water bodies. On this basis, the radar images were classified into water and land areas. For Lake Biskupińskie, the surface of the lake (in m^2) was determined using this

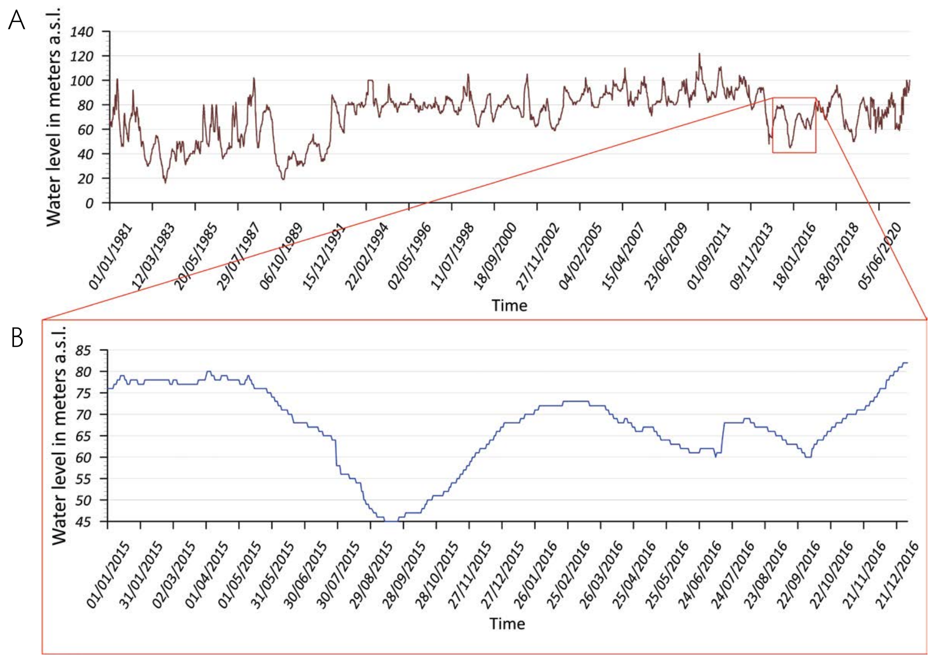

Figure 3. Change in water level in Lake Biskupińskie: (A) 1981-2022; (B) 2015-2016

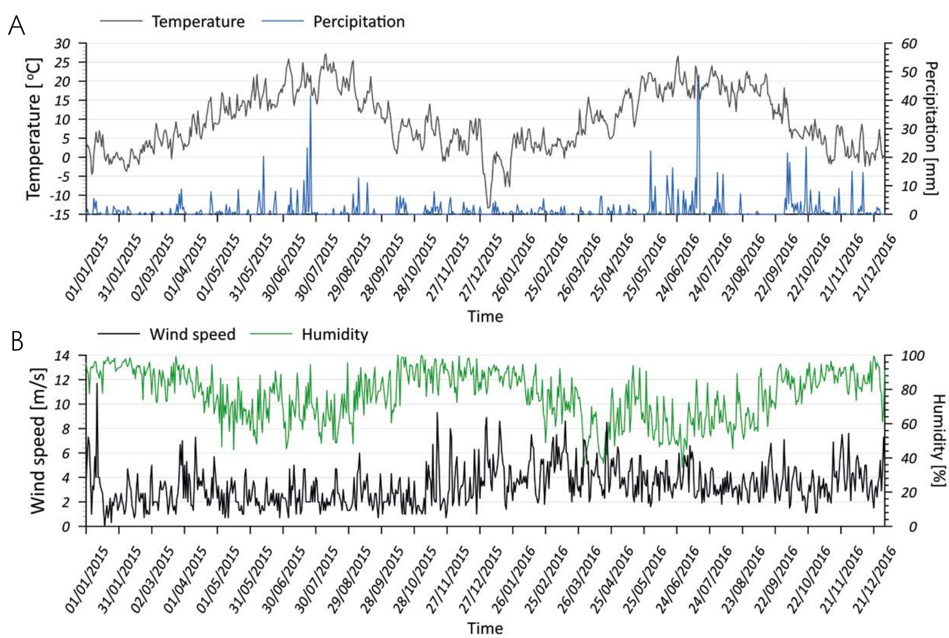

Figure 4. Selected meteorological parameter values, Kołuda Wielka station (Poland), 2015-2016

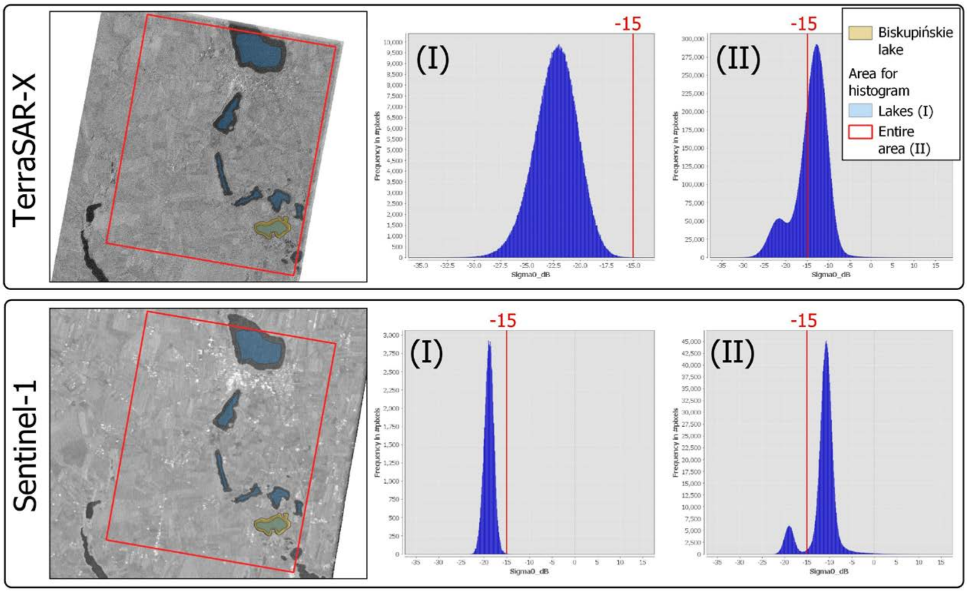

Figure 5. Histograms of distribution of backscatter coefficient (σ0) values for water areas (I) and the entire area around lakes (II) obtained for data from TerraSAR-X and Sentinel-1 satellites. Each histogram has a cut-off threshold of -15 dB

classification at selected times related to the acquisition of the image.

Changes in the water level recorded by in-field monitoring were compared with the surface of Lake Biskupińskie determined based on backscatter coefficient (σ0). The direction/trend of changes in the water level in the lake was fully consistent with its area determined based on data from TerraSAR-X (Fig. 6A). The data from Sentinel-1 were not fully consistent with the direct measurements of water level (Fig. 6B). The main reason for this is the difference in the spatial resolution of the Sentinel-1 data compared to TerraSAR-X. In one field pixel of the image from Sentinel-1 (pixel 4×14 m) there are about 19 pixels of the image from TerraSAR-X (pixel 1.5×2 m). This often results in misclassification for areas outside the lake. In addition, a detailed comparative analysis of the results against the collected meteorological data indicates a deterioration in the quality of results during heavy precipitation (one example is the measurement made on July 11, 2016).

Persistent Scatters Interferometry

In Persistent Scatters Interferometry (PSInSAR) analysis, first, differential interferograms are determined based on primary image (Fig. 7). Then, based on the amplitude dispersion, PS points are selected from the stack of interferograms. That is, by effectively "looking down" through the stack at each point, one can identify those points whose signal is stable (i.e. have high coherence). Such points are termed "time-coherent pixels" for their reliable behaviour. PS analysis can thus identify time-coherent pixels that are dominated by a strong single scatterer visible through the entire differential interferogram stack. This makes the PS method an ideal tool for analysing surface displacement caused by natural or antropogenic deformations. Contrary to traditional PS techniques, which assume the phenomenon to be linear over time, StaMPS/MTI uses a spatial correlation of the signal to identify non-linear phenomena. In other words, this algorithm allows time-varying deformation processes to be identified, and these are expected

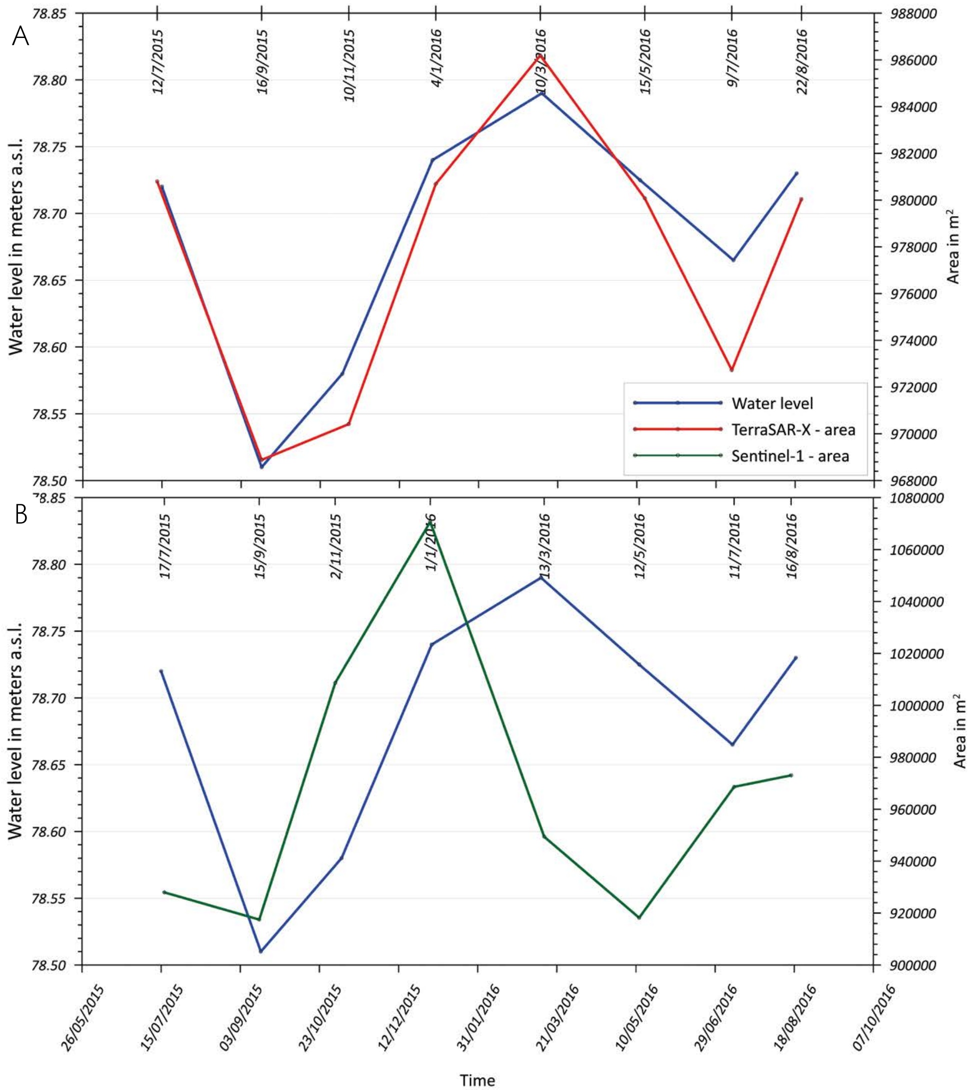

Figure 6. List of changes in water level and surface of Lake Biskupińskie determined using TerraSAR-X (A) and Sentinel-1 (B) data

close to a lake as the soil reacts to changes in water relations.

The displacement in the direction of the line of sight (LOS) obtained from the PS analysis does not show significant, clear deformation patterns (Fig. 8A). The values range from -24.1 mm·yr^{-1} to +19.9 mm·yr^{-1}, but 95% of them are between -10 mm·yr^{-1} and +10 mm·yr^{-1}. The region to the north of the lake shows a negative trend in LOS values, and the region to the west of the lake has a positive trend. The increased intensity of displacements near the lake is probably due to the area having been largely covered by wetlands in the 19th century. Thereafter, local drainage works resulted in a significant drying out of the land here. For the same reason, a significant proportion of the area is former

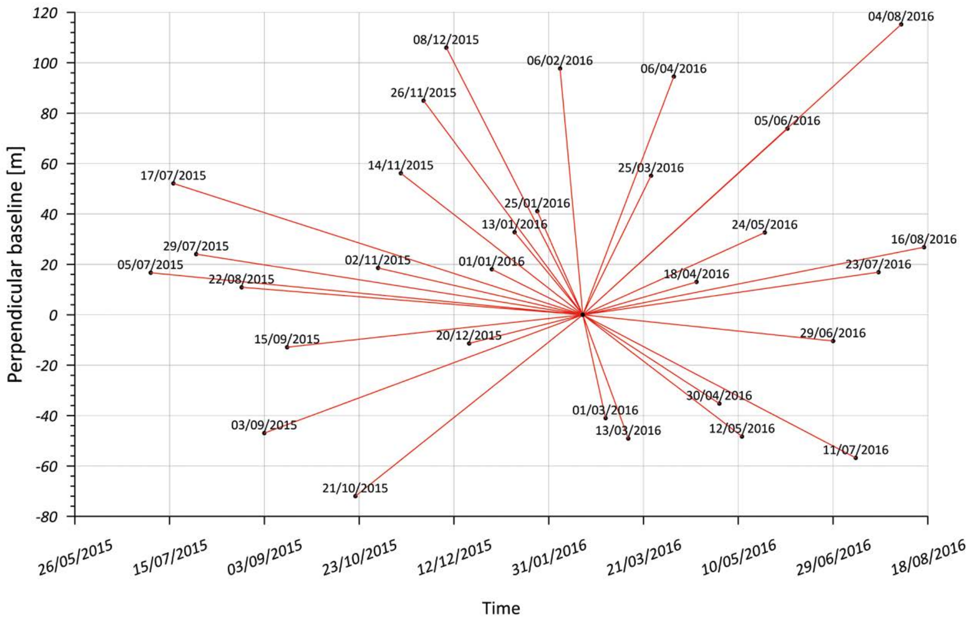

Figure 7. Interferograms used in the research on a time plot, with the perpendicular baseline for Sentinel-1 satellite acquisitions

peatlands, which are reacting strongly to the rising level of the nearby lake. However, these changes are non-significant and range within the method's own limits of accuracy. Therefore, the surface distribution lacks clear surface deformation patterns that can be correlated with surface level changes in Lake Biskupińskie.

The results for PS points in the immediate vicinity of the lake vary (Fig. 8B). The selected point PS No. 54985 has the highest time coherence value at 0.59, which is high value despite vegetated area surround the lake. For this selected point displacement value range from -8 mm to +5 mm with a linear trend of -2.3 mm·yr^{-1}. In the analysed period of 1 year, the time series exhibits a clear cyclicity, with more than one cycle in the year (Fig. 9). The fitted polynomial trend of degree 4 both averages and generalises these displacement values. Thus fitted, the chart can be treated as a theoretical model of changes in the surface of the land in the vicinity of the lake, whose values will depend on the soil properties and changes in water relations in the lake. This model of the phenomenon was compared against the observations of the water level in Lake Biskupińskie (Fig. 10). To compare the two curves, the displacement values and the observed water level fluctuation values on the chart were standardised. The changes in the height of the water surface cover a period of two years, with three clear cycles of increased and decreased values over a period of 2 years. The two curves (blue and red) correlated most highly (0.93) when a 63-day lag between them was assumed. This suggests that the soil's reaction time to changes in water relations is 63 days. This information can be used to determine the mechanical properties of the soil for hydrological modelling purposes.

Discussion

Water level changes in small-area lakes are rarely analysed, due to the lack of measurement data. Palomino-Ángel et al. (2022)

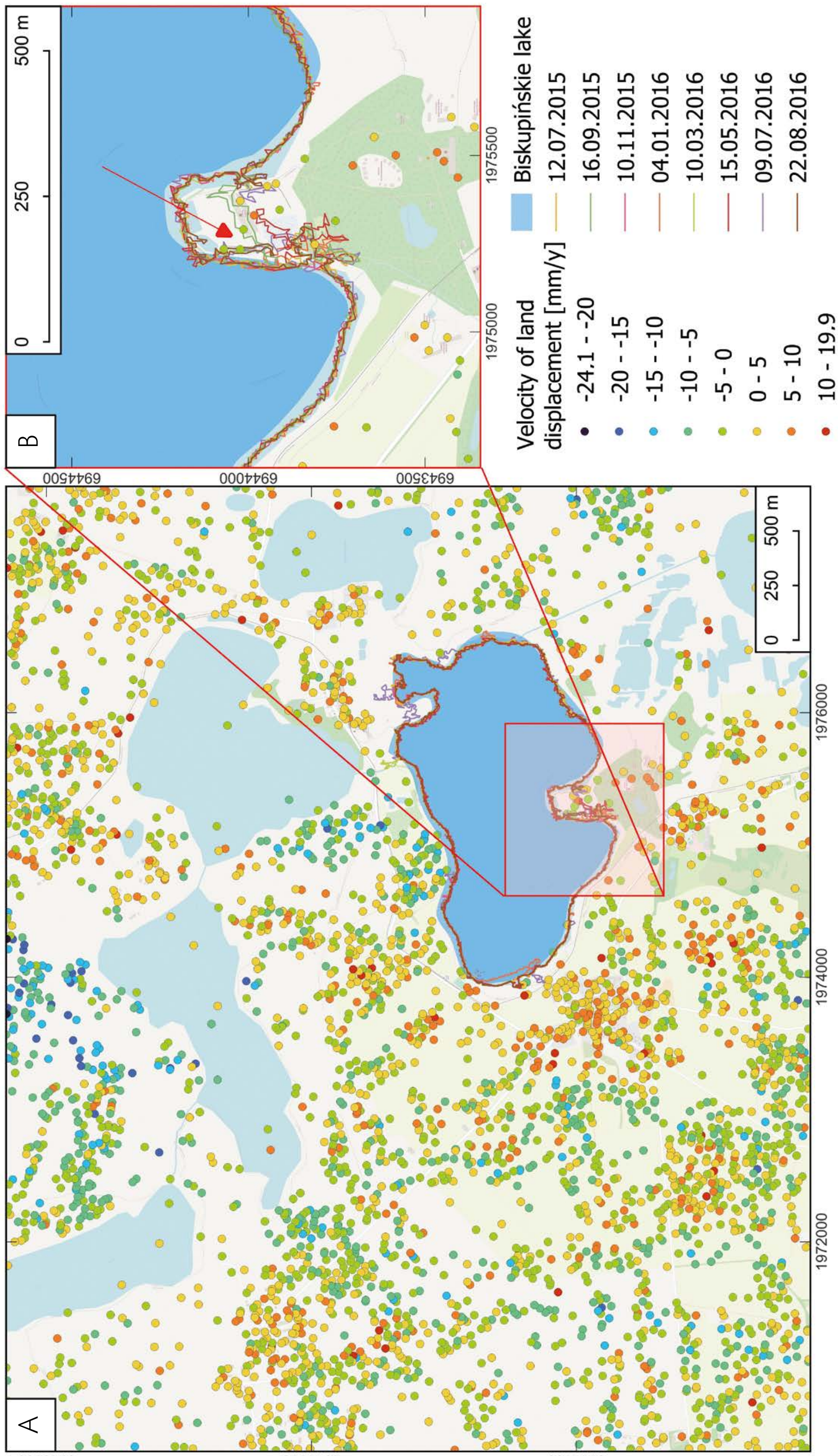

Figure 8. Velocity of land surface displacements in the Lake Biskupińskie area in the period 07.2015-08.2016 in the surroundings of the entire lake (A) and in its selected area (B). Red arrow indicates location of point PS No. 54985, which was selected for analysis of the time series

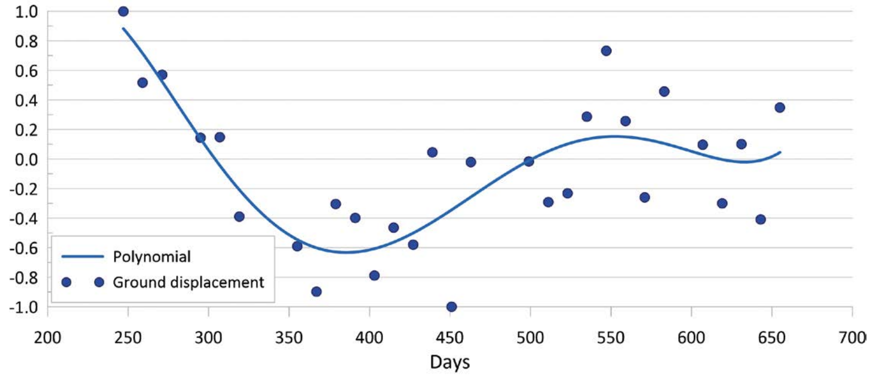

Figure 9. Displacements of ground surface for a selected PS point (see Fig. 7). Horizontal axis marks are determined with regard to the water level (see Fig. 3B)

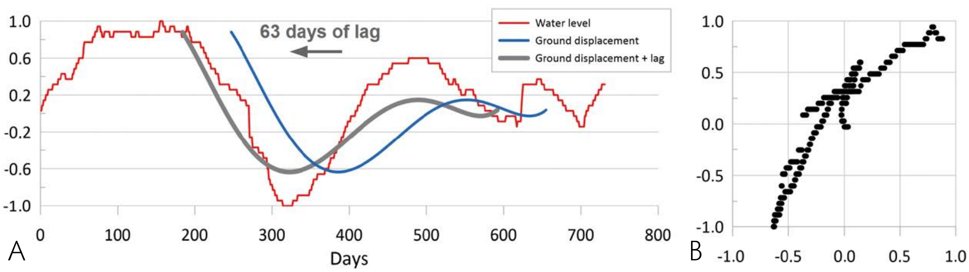

Figure 10. (A) Estimated land surface displacement values (blue) compared to the height of lake surface (red) and lag between curves as determined by correlation coefficient in standardized values. Horizontal axis marks are determined with regard to the water level (see Fig. 3B) (B) Correlation plot for lag-corrected model values and lake level values

attempted to determine relative changes in water level in small lakes in a mountainous area. They indicated that small, high-altitude lakes are the best aquatic environment for radar imaging and interferometric analyses. This is because of the increased coherence value, which is due to the near-unidirectional specular reflection from the water surface and the double reflection effect from the surrounding rocky topography. However, the natural conditions at Lake Biskupińskie differ significantly from the assumptions presented by Palomino-Ángel et al. The region is a lowland area of poorly diversified topography. In addition, the lake shores are covered with vegetation, which also makes WLF analysis difficult. Therefore, it should be noted that analyses of WLF in small glacial lakes at mid-latitudes are more difficult in many respects. For this reason, it is important to verify the model results against in-situ studies, as this may the results to be interpreted reliably.

Data from the two TerraSAR-X and Sentinel-1 satellites were used in the work. The analyses showed that, after appropriate processing, the data from Sentinel-1 allow for an accurate estimation of WLF based on interferometric analyses. This is extremely important considering that this data is fully public and free to access. The proposed methodology may allow WLF to be reconstructed for lakes not subject to in-situ monitoring, provided that satellite data results are fitted to the actual water level based on field measurements. This will improve our ability to analyse the impact of climate change on the aquatic ecosystems of small glacial lakes.

The presented results still need to be verified against results for lakes of similar surface area but differing in, for example, morphometry and hydrological type. Using the results of interferometric analyses also assumes that the soil in the vicinity of the lake reacts elastically to changes in water relations. Thus, it is an alternative to the results obtained using the backscatter coefficient analysis, which did not provide satisfactory results using data from the Sentinel-1 satellite.

However, data from the TerraSAR-X satellite allowed for an accurate assessment of relative changes in the surface of the lake using information about the backscatter coefficient. In this respect, their results were significantly better than the results for the Sentinel-1 data. This was due to the significantly higher spatial resolution of the TerraSAR-X data. The significant impact of local conditions (including topography, vegetation and weather conditions) on the accuracy of assessment of lake surfaces should be emphasised. During the analysis, it was found that these conditions significantly hinder the accurate identification of lake surface when such a large pixel is used. Therefore, it is advisable to use additional measurement data to eliminate the identified inaccuracies. The intention is to obtain more accurate results regarding the surface of the lakes, and thus to enable an absolute analysis of surface changes. Since this was not the aim of this paper, this topic will be developed and discussed in detail in subsequent studies.

Water levels in lakes also fluctuate on short-term time scales during wind-driven events (Wilcox et al., 2007), heavy precipitation, thaws, or short-term changes in lake hydrological types (Piasecki & Marszelewski, 2014). These factors are particularly important for small lakes, which, due to their size, have lower inertia and thus are more susceptible to external factors. For this reason, additional control is indicated when analysing the WLF of small lakes using meteorological data. As shown in the research, radar data, of high and medium resolution alike, can be effectively used to determine lake level. The presented methodology uses information on both the intensity and the phase of the radar wave to determine WLF. The methodology requires adaptation to local conditions for small lakes, but also allows WLF to be estimated retrospectively using historical radar observations; this may allow for a better understanding of the behaviour of water levels in changing environmental conditions.

Comprehensive WLF analysis in small glacial lakes is extremely important and urgent. Lakes are extremely delicate and sensitive parts of Earth's aquatic ecosystems. Therefore, any changes that affect them are extremely important and can irreversibly affect their functioning. A good example of this is the effect of water level fluctuations on the spread of the invasive species Phragmites australis in many coastal wetlands of the Great Lakes (Keddy & Reznicek, 1986; Wilcox et al., 2003; Bourgeau-Chavez et al., 2015). The spread of Phragmites australis has changed wildlife habitats that depend on wetlands and assemblages of native plant species. In the case of small glacial lakes, which are much less resistant to the impact of invasive species than the Great Lakes, this threat seems to be much greater. It is therefore important to conduct further research aimed at a comprehensive analysis of WLF in small glacial lakes. This is especially true for lakes at temperate latitudes, where the symptoms of climate change are more numerous and more frequent.

Summary

The WLF of lakes can be analysed in many scientific dimensions. Analyses have already been undertaken on the impact of WLF on lake flora and fauna (Coops et al., 2003), changes in the morphometric parameters of lakes (Hakanson, 1977) and water temperature (Nowlin et al., 2004). These works have always been limited to lakes subject to water-level monitoring. As already indicated, this is the main limiting factor accounting for why very little is still known about how WLF is shaped in small-area lakes. Therefore, research on the above-mentioned consequences of WLF

has to date focused mainly on large-area lakes. These lakes, due to their often significant socio-economic importance, are usually covered by water-level monitoring. The methodology of radar data analysis in the WLF survey proposed in the paper allows information on lakes not covered by traditional field measurements to be obtained. Comparative analysis of the results from radar data (lake surface) and field measurements (water level) turned out to be fully consistent for the data from TerraSAR-X and partially consistent with the data from Sentinel-1.

It is planned to continue works on the use of SAR data to determine the WLF of small glacial lakes. In the next stage, the research will be extended to a larger number of lakes of differing morphometries and hydrological types. Attempts will also be made to use data from other available satellites.

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Unless otherwise stated, the sources of tables and figures are the authors', on the basis of their own research.

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