Reports on Geodesy and Geoinformatics, 2024, Vol. 117, pp. 30–37

DOI: 10.2478/rgg-2024-0004
Received: 17 December 2023 / Accepted: 12 February 2024
Published online: 1 March 2024

ORIGINAL ARTICLE

Selected methods for determining inconclusively identifiable shorelines of watercourses and lakes

Grzegorz Borkowski [1*], Adam Młynarczyk [1], Artur Plichta [2] and Remigiusz Tritt [1]

[1]Faculty of Geographical and Geological Sciences, Adam Mickiewicz University in Poznań, B. Krygowskiego 10, 61-680 Poznań, Poland
[2]Faculty of Civil and Transport Engineering, Poznan University of Technology, Piotrowo 3, 60-965 Poznań, Poland

[*]grzegorz.borkowski@amu.edu.pl

Abstract

The determination of a lake or natural watercourse shoreline is the subject of various administrative proceedings relating to, among others, the engineering of riverbeds, construction of hydro-technical facilities, remediation work, land division, or delimitation of parcels. The provisions of law, while laying out the rules for determining shorelines, do not explicitly specify the measurement method to follow. All the more so, as many shores of lakes and watercourses are among terrain details that are difficult to measure due to their varied accessibility, which depends on the terrain, vegetation, and water conditions. The purpose of this paper is to compare selected methods for determining the shoreline of watercourses and lakes in terms of their applicability under different environmental conditions under current legislation. This study comprises an assessment of the suitability of the applied methods of shoreline measurement under varying field conditions and their applicability in surveying work on shoreline determination. Surveys were conducted on 3 reservoirs and one watercourse using geodetic, photogrammetric, and remote sensing techniques, and the suitability of the various methods was evaluated with respect to the field conditions of the measurements.

Key words: shoreline, watercourse, lake, measurement methods

1 Introduction

Shorelines are becoming increasingly important in citizens' legal awareness, which is reflected by the fact that they are more frequently established in formal and administrative processes (Kucharzak and Kowalski, 2009). Capturing and understanding the shoreline change trends in a coastal management context is critical for a range of scientific, engineering, and management questions (Astsatryan et al., 2022). The stability of shorelines is ceaselessly beneath threat due to changes to the natural environment caused by the wind, waves, tides, and currents, and also because of human intervention that results in changes in the dynamic equilibrium prevalent at a given coastal stretch (Kaamin et al., 2020).

Determination of a shoreline is a complex issue which requires specialist knowledge of geodesy, hydrology, and administration issues, and the proceedings are based on the provisions of the Water Law, Geodetic and Cartographic Law, Code of Administrative Procedure, and Civil Code (Dąbrowska et al., 2012). When establishing a shoreline, it is also important to follow the sequence of procedures prescribed by law (Marszelewski and Marszelewski, 2014). In scientific literature, the concept of shoreline determination appears mainly in the context of changes in the boundaries of parcels due to erosion and accumulation effects of rivers (Bieda, 2012; Dąbrowska et al., 2012; Bieda and Parzych, 2012; Mika et al., 2016). This study complements these considerations by comparing shoreline measurement methods, particularly in conditions where its clear identification is challenging.

Geodetic services are largely focused on the correct definition of parcel boundaries, and as a result – the determination of ownership. In this respect, apart from traditional geodetic techniques

Publisher: De Gruyter

that allow for acquisitions of geometric data, we should consider photogrammetric methods and technologies which, due to their rapid development, are becoming increasingly important among measurement methods in a broad sense that enable the identification, control, and verification of parcel boundaries (Wyczałek and Plichta, 2020).

At present, the existing legislation offers new space for collecting and verifying the information contained in existing databases, including the land and buildings register database. It contains information about the legal status of land, and buildings, with their full spatial and feature specifications, including their ownership structure. In the case of the land and buildings register database of the Geodetic and Cartographic Documentation Centre containing data that conclusively identify land boundaries, it can be restored at any time by re-designating it on site and, if necessary, adding the ground sign. However, if there is no documentation in the geodetic resources that clearly indicates the boundary, and its line on site is not conclusive, a delimitation procedure should be used to ensure that the common sections of the boundary are correct. Therefore, it seems appropriate to develop measurement methods to enable efficient updates of the above-mentioned attributes of cadastre items, with a particular focus on information concerning parcel boundaries. A shoreline usually features a difficult, variable, and often inconclusively identifiable span. In this case, the determination of the boundary line of the adjacent parcel is a complex process with a high risk of error. The choice of methods, techniques, and technologies to be used to meet the conditions for taking measurements, and to ensure the required precision in determining the location of the object, is often with a responsibility of the geodetic work supervisor, as, for example, is stated in the Polish law, in line with the provisions of the "Ordinance on technical standards (…)" (Ordinance, 2020). The implementation of appropriate measurement methods allowing to verify data that specify the shoreline and take a correct geodetic measurement remains an outstanding issue. In this respect, two classic measurement methods can be identified. These are: tacheometry and GNSS. Both comply with the conditions for taking measurements and obtaining specified precision as provided for in the regulations for landmarks in the precision groups I, II, and III. The shoreline belongs to the precision group III of landmarks, so the on-site measurement to determine its line should be made with ± 0.50 m precision in relation to the horizontal geodetic control network used for measurement. The shape of linear objects or boundaries is determined using polygons based on these points, and their position is established through reference points (network) and observations, defined as angle and distance in the tacheometric method, and through measurement of X, Y and Z coordinates in the GNSS method (Doskocz, 2008; Kowalczyk, 2011; Wyczałek et al., 2018). However, both these methods show significant limitations in the absence of adequate lines of sight and inability to access the object, as the measurement takes place exactly at the point whose position is to be determined. In the case of a shoreline which is difficult to access, and whose span is difficult to identify, the use of the methods indicated here is not justified, either economically or in terms of the reliability of the measurement. The solution to this problem may lie in using measurement methods applied in photogrammetry, such as the analysis of multispectral photographs taken from a low aviation ceiling, as these can be used to develop an orthophoto map of the measured area with a resolution of several centimetres, and then performing the necessary analysis (Borkowski and Młynarczyk, 2019). Objective methods of shoreline detection are offered by the latest techniques in photogrammetry, topographic data collection, and digital image processing (Boak and Turner, 2005).

In recent years, an increase in employment of Unmanned Aerial Vehicles (UAVs) in environmental research has been observed (Xiang et al., 2019; Xing et al., 2019). Relevant examples include: hydrological research (Vélez-Nicolás et al., 2021) and transport of aeolian sediments (Shumack et al., 2022). UAVs and remote sensing techniques allow for the collection of more data in less time than in-situ techniques (Luo et al., 2020). Environmental studies use different UAVs and different sensors in terms of spectral and spatial resolution, depending on the relevant requirements and expectations (Carrivick and Smith, 2018). Airborne, satellite, and UAV platforms are commonly used to study shoreline delineation for different applications and study areas using various approaches (Gonçalves et al., 2020; Merlino et al., 2020; Astsatryan et al., 2022). Surveys carried out with UAVs are an intermediate element between in-situ measurements and satellite remote sensing for integrated, environmental measurements of coastal areas (Warren et al., 2015; Xing et al., 2019). A common use of UAVs is in the creation of accurate orthophotos, one of its most common methods being the Structure from Motion algorithm, which requires a large number of images (Westoby et al., 2012; Jiang et al., 2020). Spectral reflectance effect differentiation with aerial capture using specialist photo-aerial materials allows to use the information obtained from aerial photographs for limnology studies (Choiński and Kijowski, 2015). Orthophotos obtained using UAVs can be used to determine the course of a shoreline especially for inland bodies of water, where the shoreline may not be accessible to satellite positioning or other, non-geodetic methods (Makar, 2018). Nowak (2016) proposes a methodology for shoreline delineation for different types of natural water bodies, using topographic, hydrological, geomorphological and botanical analyses, while pointing out that statutory regulations are not always clear or sufficient to prevent ambiguity of measurement results. In the context of dynamics, shoreline variability can be determined by analysing multi-temporal satellite imagery (Dereli and Tercan, 2020; Specht et al., 2020; Ayalke and Sesli, 2022; Ayalke et al., 2023) and aerial orthophotos and multi-temporal Normalised Difference Vegetation Index (NDVI) (Michałowska and Hejmanowska, 2008). The shoreline can also be determined using laser scanning (Burdziakowski et al., 2020; Specht and Specht, 2020; Dąbrowski et al., 2021). Remote sensing is a useful tool for land cover mapping along a coastline region, however, using a new sensor always represents a challenge for scientists (Rupasinghe et al., 2018).

The determination of shorelines of lakes and natural watercourses has legal grounds. The main regulations of the method to determine shorelines are laid out in the Polish Act of 20 July 2017 — Water Law (Act, 2017). A very important provision is contained in Article 220(1) of said Act, stipulating that *the shoreline of natural watercourses, lakes and other natural water bodies shall be the edge of the shore, or a permanent grass growth line, or a line determined by the average water level over a period of at least the last 10 years*. Further in Article 220, the legislator provides guidelines regarding establishing the shoreline pattern considering whether the shore is distinct, not distinct, or engineered:

i. if the shore edge is distinct, the shoreline must be considered as running along that edge (paragraph 2);
ii. if the shore edge is not distinct, the shoreline must be considered as running along the permanent grass growth line, and if the permanent grass growth line lies above the water level referred to in paragraph 1 – along the line of intersection of the water surface at that level with the adjacent land (paragraph 3);
iii. if the water shores are engineered, the shoreline must be considered as running along the line linking the outer edges of the engineered structures, and in the case of wicker plantations on land acquired through engineering – along the land-side plantation boundary (paragraph 4).

Shorelines are determined, by way of a formal decision issued by local authorities, at the request of a properly interested party, by a competent local authority of the maritime administration – for internal sea waters and territorial sea waters or a minister responsible for water management – for natural watercourses, lakes, and other natural bodies of water with continuous or periodic natural surface water outflow (Article 220(5)). The shoreline is established based

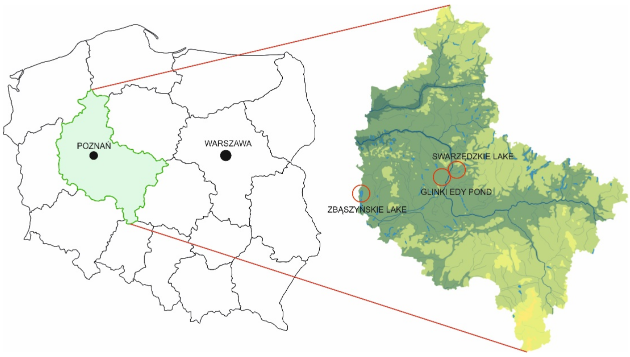

Figure 1. Location of studied water reservoirs in Greater Poland province, Poland (source: own elaboration based on data from www.geoportal.pl)

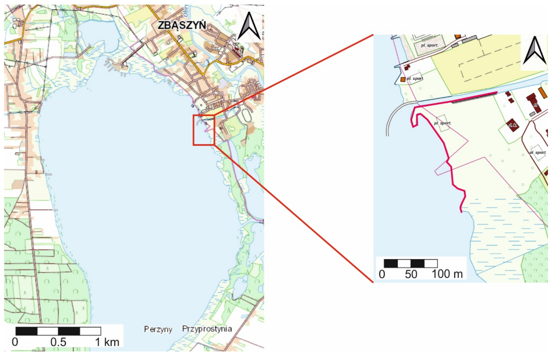

Figure 2. Location of measured shoreline section by east shore of Zbąszyńskie Lake (source: own elaboration based on www.geoportal.pl)

on a project provided by the applicant for the delineation between the land covered by water and the adjacent land, which considers the elements relevant to the adopted method of determining that line (Article 220(6)).

The purpose of this paper is to compare selected methods for determining shorelines of watercourses and lakes in terms of their applicability to varied environmental conditions under current legislation. The paper identifies the advantages, but also the disadvantages of different methods under different conditions when shorelines is covered with vegetation or difficult to access.

2 Research area

Field studies using all methods discussed above were conducted on a section of the shoreline of Zbąszyńskie Lake, including a small watercourse. Subsequent surveys, using remote sensing methods, covered the entire shoreline of Swarzędzkie Lake and the Glinki Edy Pond. All these water reservoirs are located in the Greater Poland Province in Poland (Figure 1).

Zbąszyńskie Lake is located in the commune of Zbąszyń, Nowy Tomyśl county, near the western border of the Greater Poland province in Poland. Zbąszyńskie Lake lies along a meridian, measuring more than 7 km north to south (Borkowski, 2014). Its surface area is 697.5 ha and its shoreline is 16120 m long (Borkowski, 2014). The representative 400 m-long section of the lake shoreline selected for measurements is located in the eastern part of the lake near the town of Zbąszyń (Figure 2). A section of the shore, which is the experimental area for this research, was selected to allow for a comparison of different research methods. One part of the area under consideration is free from trees and easily accessible from land, while the other part is a marshland overgrown with dense reeds and trees. In addition, the measurements covered a section of watercourse flowing out of the lake.

Swarzędzkie Lake is located in the municipality of Swarzędz, Poznan county, Greater Poland. From the east and south, it is almost directly adjacent to the residential areas of Swarzędz, while the western shore of the lake borders a small forest complex. It has an elongated shape, stretching from north-east to south-west. The area of Swarzędzkie Lake is 93.7 ha Rosińska (2017) and the length of the shoreline is 7800 m (Jańczak, 1996).

Glinki Edy Pond is located in Poznań. It is an anthropogenic reservoir surrounded primarily by reed vegetation, and on its south-eastern shore there are cultivated fields. Its northern shore is bounded by a small mixed forest, while a narrow strip of riparian vegetation runs along the western shore. The area of the Glinki Edy Pond is 7.22 ha, and the length of its shoreline is 1957 m (Tritt et al., 2022).

3 Materials and methods

The surveys were conducted between 2017 and 2022. The first attempts to determine the shoreline of Zbąszyńskie Lake were made during the 2017 growing season, then the measurements were repeated under different conditions in subsequent years. Also in 2017, the Swarzędzkie Lake shoreline survey was started, while the final survey of the Glinki Edy Pond took place in 2022.

The first method used to determine the shoreline of Zbąszyńskie Lake was tacheometry, which involves observation using a horizontal angle β, vertical angle α, and an oblique distance d, from a position with known coordinates X, Y and H. The measurement was taken with GTS 255 Topcon electronic tacheometer with an angular precision of 5"/15cc and a distance precision (at prism) of $\pm$ (2 mm + 2 mm/km). The photos of the shoreline of Zbąszyńskie Lake in 2017 were taken from a flying platform with a Sony Alpha A6000 camera with a matrix resolution of 6000x4000 pixels and a lens with a focal length of 19mm. A total of 195 photos were taken. Since the camera did not have a GNSS/RTK module, a ground control point (GCP) was designated: four ground points for calibration and four points for verifying the correctness of the model. The points were determined in the field using GPS-RTK (the device used: Trimble R4). The base was established through the VRSNet network and stabilised. Due to the range of the geo-referenced stations exceeding 40 km (Ławniczak and Kubiak, 2016), the reference corrections were taken from the local base. The obtained measurement accuracy was approx. 3 cm horizontally and 5cm vertically. In order to consider the possibility of adapting other photogrammetric methods for the purpose of acquiring shoreline information, an airplane flight with a multispectral camera and an infrared camera (Thermo GEAR G120EX) was made over a representative section of Lake Zbąszynskie's shoreline. The Thermo GEAR G120EX thermal imaging camera captured 8–14 μm images, with a thermal resolution of 0.1°C and an optical resolution of 320x240 pixels. A multispectral camera was used to take images for the following wavelengths: 440 nm, 560 nm, 660 nm, 700 nm, 780 nm, 842 nm, and 865 nm. The flight consisted of two laps over the water body to superimpose the captured area on the shoreline area. In addition, images of the investigated area were taken in the visible range with a digital camera attached to unmanned aircraft. The flight was made in seven strips at heights of 100 m and 200 m, and images were taken at a resolution of 3 cm. As noticed by Młynarczyk et al. (2019), compared to satellite and aerial methods, the use of BSP technology makes it considerably easier to adapt to the time, location, and resolution requirements of the acquired image data in order to solve a specific environmental problem. Templin et al. (2018) point out that even a low-cost fixed-wing UAV can provide an excellent tool for accurately surveying a shallow lake shoreline and create reliable geoinformation data collected faster than with traditional geodetic.

Through photogrammetric processing of the photos of Zbąszyńskie Lake, a model of land cover surface and an orthophoto map with a spatial resolution of 3.48 cm/pix were calculated. The average error of the location of control points on the orthophoto map was RMSE = 2.58 cm, which was lower than its resolution. The land cover model was used to determine the course of the shoreline so that the line was drawn at the water-shore junction in places not covered with vegetation, while in other places an orthophoto map was used. The photos and points taken in this way were uploaded into Agisoft Metashape 1.7.1 and the terrain surface model and orthophoto map were calculated.

Aerial photographs of Swarzędzkie Lake, taken in 2017 by Michał Wyczałek, were used to determine the shoreline in the visible range with a resolution of 15 cm and photos taken with a spectral camera in the range of 700 nm, 780 nm, and 842 nm with a resolution of 40 cm. Over Glinki Edy Pond, aerial photos were taken in the visible range with a resolution of 2.3 cm, as well as photos taken with a Parrot Sequoia spectral camera (wavelength range of 550 nm, 660 nm, 735 nm, and 790 nm, with a resolution of 5 cm). Based on the images taken from a DJI Phantom 3 unmanned aerial vehicle from a height of 50 m AGL, orthophotos were developed in Agisoft Metashape Pro 1.7.2 software, covering the study area.

4 Results

In order to compare the applicability of geodetic and non-geodetic measurement methods to determine the shoreline of a lake and watercourse, its shape was established through the tacheometric method, GNSS, and remote sensing technologies. The data so obtained were compared in both geometric and graphic terms. The results of the analysis are shown in Figures 4–7, together with the results of selecting the parameters of the shoreline measurement methods that allow its determination under different field conditions.

The method used to determine the part of the investigated shoreline of Zbąszyńskie Lake accessible from land was tacheometry. The line was determined with the polar method, directing the reflector prism to the boundary between land and shore. As it was not possible to reach overgrown areas and marshy shores, the necessary measurements were not taken at those points, while the method proved successful in determining the clearly visible shoreline.

The southern part of the measured shore of Zbąszyńskie Lake, marshy and overgrown, required a different measurement method, so an attempt was made to determine the shoreline using a differential GNSS satellite measurement technique with the accuracy level of the RTK. This method was used to take measurements both from land and water. The difficult-to-access, overgrown and marshy shore fragment of the investigated lake was measured from a boat with an electric outboard motor and a rover. Measurements of the parts of the shore inaccessible by land were taken during water line examination in optimum conditions: no wind, clear sky, without waves. The measurement allowed to determine the area covered by reed, which does not necessarily indicate the boundary between the land and water. A disadvantage of this method, in addition to the limited distance from the base station and the visible horizon required, is that the rover had to be stationary during the measurement, which was not always possible on the boat due to the waves.

In the absence of satisfactory results of measurements made using the above methods, the remote sensing method was used, taking photographs of the area under examination with a digital camera attached to an unmanned aerial vehicle. The obtained images enabled the orthophoto map to be developed in the orthorectification process. The orthophoto map was developed from 195 digital images. The resolution of the orthophoto map thus obtained is 3 cm. Based on the developed, current and geo-referenced orthophoto map of the examined area, Q-GIS was used to determine

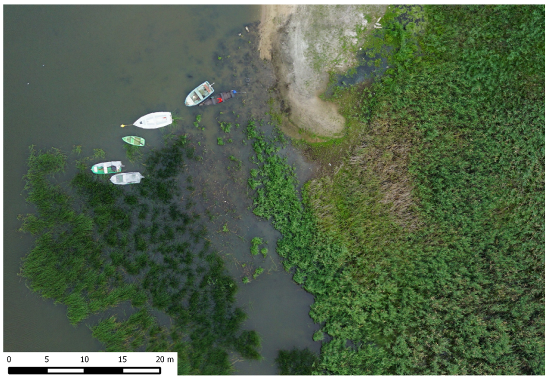

Figure 3. A section of the overgrown part of the shore in the investigated area on the orthophoto map (Borkowski and Młynarczyk, 2019)

the shoreline, and rectangular two-dimensional coordinates were obtained in the PUWG system of 1992 points on the shoreline. Despite the high accuracy and resolution of the map (Figure 3), the determination of the shoreline by this method in an area overgrown with reeds is not conclusive. Nevertheless, this method can be used as an valuable source of information on the current state and development of the shoreline.

To identify the shoreline of Zbąszyńskie Lake in the area overgrown with reed, aerial images were used, taken with a multispectral and an infrared camera. The aerial photographs captured near ultraviolet (0.3–0.4 μm), the entire visible range (0.4–0.7 μm), and near infrared (0.7–1.3 μm). These photographs, in the form of grayscale images (Figure 4), show water in dark tones, vegetation in brighter tones, and sand is the brightest.

Images taken at 865 nm are most useful in the interpretation of the course of the surveyed section of the shoreline of Zbąszyńskie Lake at the boundary between land and water, since, in this range, infrared radiation is most absorbed by water, so it presents as black in the image. In this wavelength range, vegetation reflects most of the radiation, which gives a high contrast at the boundary between water and vegetation, allowing the shoreline to be identified.

The comparative analysis of the shoreline shown in Figure 5, fitted to the EPSG:2180 coordinate system, illustrates the effect of using different methods to determine the studied section of the shoreline of Zbąszyńskie Lake.

The apparent differences in the shoreline are related to the accuracy of the methods used and the field capabilities of their application. The shoreline of the watercourse is characterized by the smallest differences in its course, which is due to its location in easily accessible terrain and its unambiguous course. For this part of the study area, the most accurate measurement method was tacheometry, so it was adopted as the reference. The distribution of measurement points in this part of the study area indicates a uniform shoreline course, and their scatter does not exceed 0.5 m. The differences in the accuracy of the shoreline delineation measured in section 1 (Figure 5) indicate that the distances between the shoreline plotted based on tacheometric measurements and the lines plotted based on the other measurement methods are: orthophoto map – 0.098 m; RTK – 0.122 m; 865 nm – 0.125 m, 780 nm – 0.23 m. A similar result is found in the northern part of the studied part of the lake (section 2), where the scatter of points is as follows: orthophoto – 0.384 m; RTK – 0.053 m; 865nm – 0.362 m; 780nm – 0.286 m. The scatter of points increases with the degree of coverage of the lake shore zone with vegetation and assumes maximum values in the part of the shore overgrown with reeds. For such measurement conditions, photogrammetry using images taken at 865 nm was adopted as the reference method. The differences in the shoreline in this area are significant and, compared to the reference

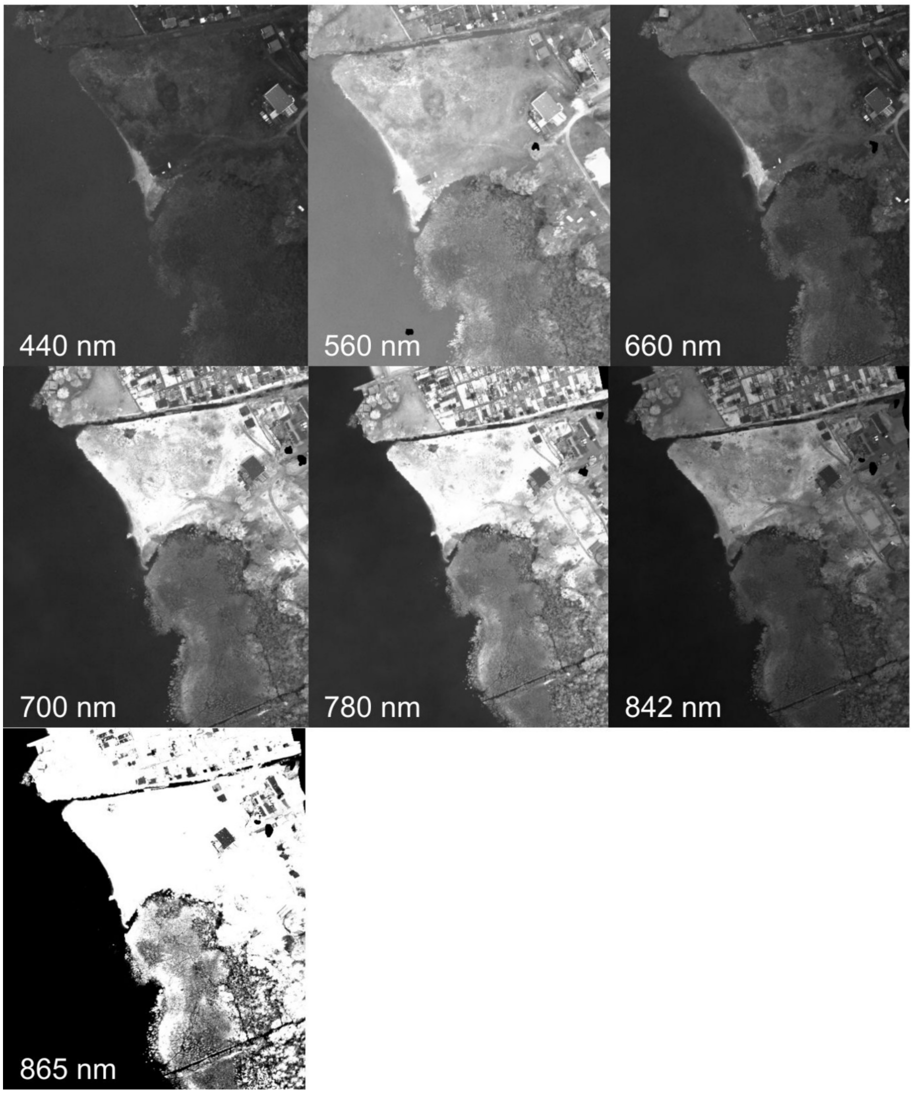

Figure 4. Photographs of the investigated area of Zbąszyńskie Lake shoreline in different spectral ranges (source: own elaboration)

method, are as follows in section 3: 780 nm – 2.255m; orthophotos – 5.001 m, and RTK – 7.213 m. However, the maximum scatter of points measured using RTK in the most reed-infested section is more than 30 m and depends on the width of the reed belt. In this zone for determining the course of the shoreline, photogrammetry is the optimal method, and direct measurement methods such as tacheometry or RTK are inapplicable since the calculated scatter of points exceeds the legally permissible values.

Studies of the Swarzędzkie Lake shoreline have confirmed the effectiveness of photogrammetric measurements for determining the shoreline at the interface between water and land covered with vegetation. A large part of Swarzędzkie Lake shoreline zone is overgrown with rush vegetation, making it impossible to measure the course of the 0 m isobath either from land or from the water, so to precisely determine the course of the shoreline aerial photos were used in the visible range with a resolution of 15 cm as well as photos taken with a spectral camera in the range of 700 nm, 780 nm, and 842 nm with a resolution of 40 cm (Figure 6).

In addition, a part of Swarzędzkie Lake shoreline is overgrown with trees, which cover the actual course of the shoreline during the growing season. This can make it difficult or impossible to accurately determine the shoreline using the method discussed above, making only measurements in winter, when the trees have no leaves, possible.

As in the case of Swarzędzkie Lake, images in both the visible and near-infrared ranges were taken for Glinki Edy Pond. The study confirmed that images taken with the spectral camera are useful for determining the shoreline of areas overgrown with rushes, floating and submerged vegetation, but less accurate for tree-lined shores during the growing season (Figure 7).

5 Summary

From a legal perspective, all methods described in the study are viable as they meet the required precision of 0.5 m specified for precision group III of landmarks. However, shores of lakes and watercourses are so diverse and particular that difficult site conditions often cause dilemmas as to the choice of the right measurement technique. The application of a variety of measurement methods makes it possible to compare the ability to determine the shoreline, depending on the accessibility and development of the area. The comparative analysis of the shoreline shows the advantages and limitations of the methods used. Tacheometric and levelling measurements allow the survey to be performed with the highest accuracy and offer a wide range of applications, but are not useful in areas which are marshy or overgrown with dense reedbed vegetation.

The shoreline measurements based on the orthophoto map give satisfactory results, but only in an open area with a clear shore-

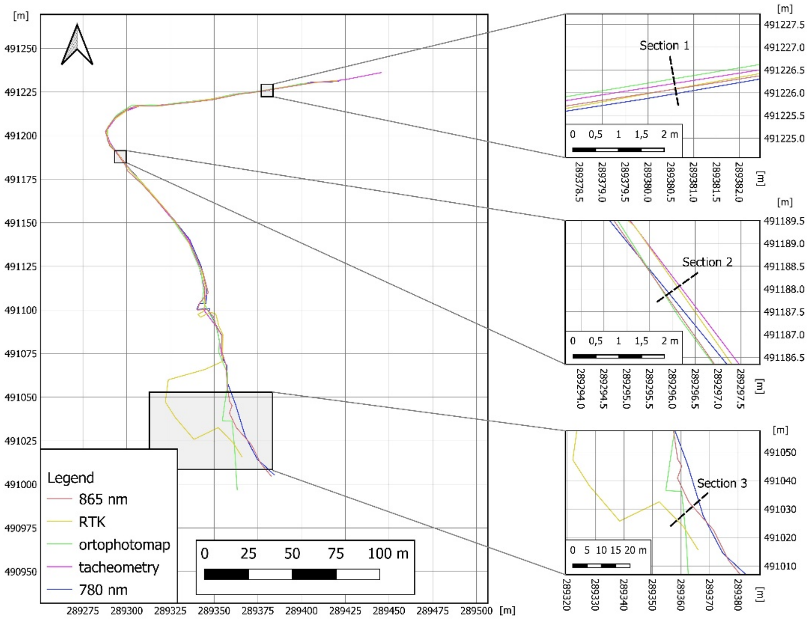

Figure 5. Chart of the shoreline determined using 865 nm and 780 nm spectral images, GNSS RTK, tacheometry, and the developed orthophoto map (source: own elaboration)

line, and cannot identify the boundary between land and water in a reedbed area. To determine the shoreline in the area overgrown with dense reeds, the analysis of spectral images taken in near-infrared seems most suitable. Data obtained from aerial photographs taken at a wavelength of 865 nm and 780 nm enable the identification of the shoreline as a boundary between dark water photo-tones and bright photo-tones of the shore, which is confirmed by measurements taken on all the studied reservoirs and watercourse. Therefore, the choice of the method for determining the shoreline of a lake or watercourse depends on the specific terrain conditions and is mainly conditional on the ability to reach the area under a geodetic survey.

Acknowledgments

The authors wish to thank anonymous reviewers for their valuable suggestions and corrections.

Author's contribution

GB: Conceptualisation, methodology, field research, formal analysis, writing – original draft, writing – review and editing, visualisation; AM: Formal analysis; AP: Methodology, formal analysis, writing – original draft, writing – review and editing, visualisation; RT: Formal analysis, field research, writing – review and editing, visualisation.

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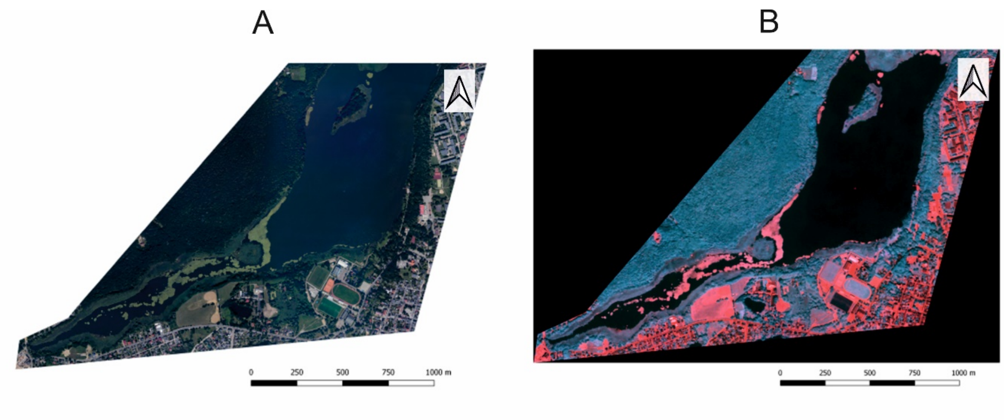

Figure 6. Shoreline of Swarzędzkie Lake determined with photograph in the visible range (A) and photographs taken with a spectral range (B) (source: own elaboration)

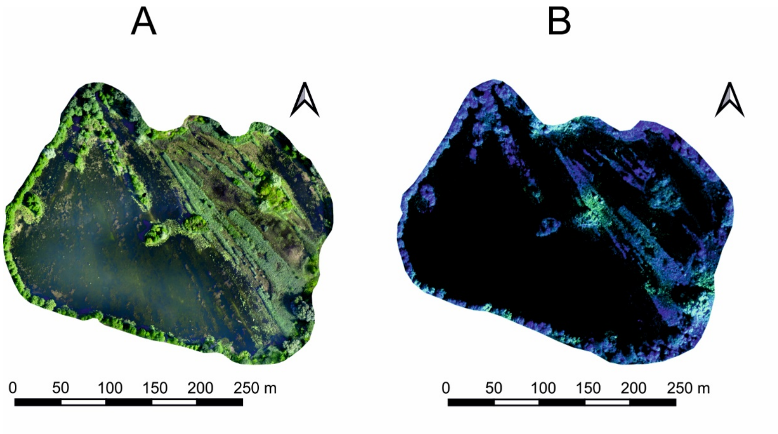

Figure 7. Shoreline of Glinki Edy Pond determined with photograph in the visible range (A) and photographs taken with a near-infrared range (B) (Tritt et al., 2022)

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