FROM ACOUSTICS TO UNDERWATER ARCHAEOLOGY: DEEP INVESTIGATION OF A SHALLOW LAKE USING HIGH-RESOLUTION HYDROACOUSTICS—THE CASE OF LAKE LEDNICA, POLAND*

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One of the main challenges of underwater archaeology is to develop non-invasive research of heritage sites in order to enable their further protection for future societies. This study explores, identifies and classifies archaeological objects in a shallow lake using underwater acoustics. We solved the aforementioned challenges by developing an innovative, object-based, fuzzy-logic classification of nine archaeological object categories based on multibeam echosounder bathymetry, 13 secondary features of bathymetry and 106 underwater diving prospections. We achieved an 86% correlation with ground-truth samples, and 49% overall accuracy. The unique and repeatable workflow developed in this study can be applied to other case studies of underwater archaeology around the world.

KEYWORDS: UNDERWATER ARCHAEOLOGY, LAKE ARCHAEOLOGY, MULTIBEAM ECHOSOUNDER, UNDERWATER REMOTE SENSING, OBJECT-BASED IMAGE ANALYSIS, MIDDLE AGES, EARLY SLAVONIC STATE

INTRODUCTION

Context and already known aspects of underwater archaeology

Although 71% of the Earth is covered by water, less than 20% of the seafloor has been precisely mapped (Mayer et al. 2018). Seabed exploration is therefore one of the main challenges being undertaken by national and international initiatives such as GEBCO Seabed 2030, Norway’s MAREANO, Australia’s AusSeabed, Ireland’s INFOMAR or the UK’s MAREANO (Thorsnes et al. 2018). Precise maps of the seabed are crucial for the assessment of healthy oceans, seas and coastal waters, which constitute one of the five most significant challenges in the world, according to Horizon Europe, the main European research and innovation framework programme for the period 2021–27. While only 2.5% of worldwide water resources are freshwater, only

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0.4% of that freshwater is found in lakes, rivers, swamps and shallow groundwater. Compared with seafloor exploration, archaeological prospective of lakes is much less prevalent.

One of the biggest problems for underwater archaeology is to provide a data-acquisition methodology that allows for the precise and non-invasive exploration of heritage sites in order to enable their further maintenance for future societies (Ford et al. 2020). Hydroacoustic methods of seabed exploration allow accurate three-dimensional (3D) models of the seabed to be created using underwater acoustic technology that does not affect archaeological objects, thus providing one of the best responses to this problem.

One of the first works considering the use of high-resolution multibeam echosounder (MBES) for underwater archaeology was an investigation of shipwrecks located in Scarpa Flow in the Orkney Islands, north-east of Scotland, UK (Calder et al. 2007). Another study presented the recognition of the Stirling Castle shipwreck located in Plymouth Sound, also in the UK (Bates et al. 2011). These first studies demonstrated that MBES is relevant for the successful mapping and monitoring of shipwrecks, which allow integrated site management plans to be established. Whereas a later study used MBES to explore shipwreck sites in the Irish Sea (Plets et al. 2011), another used the same device to assess an archaeological site near Naples, Italy (Passaro et al. 2013).

Recent technological advancements in deep-sea exploration benefit from using autonomous underwater vehicle (AUV) systems, which allow close inspections of spot sites—even those in the deepest parts of the oceans (Zwolak et al. 2020). A narrow issue of great importance is how to detect changes that may affect an archaeological site, such as the ancient town Chunan at the bottom of Qinandao Lake in China. Recent results have demonstrated the usefulness of the terrain attributes of MBES bathymetry data sets, collected over 13 years in assessing effectively how the ancient town is being deformed (Yang et al. 2020).

Gaps in the existing knowledge that this study wants to cover

Hydroacoustic data sets from MBES have so far been used for initial investigations of underwater archaeological sites before further identification by remotely operated vehicles (ROVs) or divers (Plets et al. 2011). The recent development of MBES devices and positioning systems allows the discovery of underwater environments at high resolution and in unprecedented detail (Madricardo et al. 2019). While this new approach allows the precise identification of small seabed features that may belong to archaeological sites, hydroacoustic devices have only very rarely been applied as efficient tools for exploring lakes (e.g., Winfield et al. 2007).

Geomorphometric features have seldom been used as identifiers of underwater archaeological objects. For example, Stieglitz (2013) used local slope variations to identify numerous shallow holes that were related to the presence of shipwrecks and probable bioturbation. Slope and profile curvature have been used as predictive features to outline archaeological features at a site located near Naples (Passaro et al. 2013). Madricardo et al. (2019) used three secondary features of MBES bathymetry: slope, bathymetric position index (BPI) and roughness, to assess residues of human activity in Venice Lagoon, Italy. None of these works used object-based image analysis (OBIA) for efficient identification of underwater archaeological objects.

Recently, OBIA became a subdiscipline in the remote-sensing literature (Blaschke 2010). It has also influenced the development of other disciplines, including archaeology (Davis 2018). Because underwater exploration is much more challenging to perform than terrestrial research, the development of the OBIA methodology for underwater archaeology based on hydroacoustic measurements is still in its infancy.
Although methods for the automatic classification of MBES data sets are increasingly being used (Janowski et al. 2018a; Prampolini et al. 2018), they focus on its application for mapping benthic habitats and for sediment composition. Automatic remote-sensing methods often provide quick analysis. Because they are independent of human perception, they provide objective and repeatable results that cannot be achieved using traditional, manual analysis (Diesing et al. 2016). Automatic classification of MBES data sets for different time steps is the foundation of change-detection analysis, which has recently been a significant research topic in the discipline of benthic habitat mapping (Montereale-Gavazzi et al. 2019; Gaida et al. 2020; Janowski et al. 2020). The accuracy assessment based on ground-truth samples allows for the possible verification of classifier performance, which is highly desirable from a scientific perspective. Unfortunately, until now there has been a lack of automatic methods for the identification and classification of underwater archaeological objects.

Problems that this research aims to solve

This research aims to solve the following research problems: (1) the identification of underwater archaeological objects in a shallow lake using an MBES; (2) the characterization of the geomorphometric features of bathymetry that help to distinguish underwater archaeological objects; and (3) the development of an OBIA workflow to automatically classify archaeological objects based on prior knowledge.

MATERIALS AND METHODS

Study site

Lake Lednica is located in central-western Poland (Fig. 1). The length of the basin is 7.30 km and the total surface area is 3.48 km². In general, the depth of the lake does not exceed 10–12 m, and the maximum recorded value was 14 m. There are five islands on the lake, the largest of which is Ostrów Lednicki, with an area of 0.075 km².

Archaeological traces of settlement have been found on two of the aforementioned islands: Ostrów Lednicki and Ledniczka. The oldest of these traces date to the Stone Age, but the richest comes from the Middle Ages (Wyrwa 2016). From the end of the ninth century CE, and certainly in the tenth, a stronghold was developed in Ostrów Lednicki. In the initial stage of its existence, this stronghold was probably still associated with local tribal communities. In the latter tenth century, on the initiative of Mieszko I, the first historical ruler of Poland, the settlement layouts in Ostrów Lednicki were completely and comprehensively rebuilt. This centre became one of the most important in a network of fortified settlements securing the development of the early Piast state. The reconstruction involved the erecting of a much larger fortress protected by huge embankments. The settlement immediately adjacent to the fortress was extended, two sturdy bridge crossings were erected (Kurnatowska 2000; Kola and Wilke 2014), and on either shore of the lake open settlements were developed that constituted the economic base of the centre located on the island (Górecki 2016b). Within the adjacent settlement and open settlements there was a place for gathering and slaughtering animals. Furthermore, smelting, blacksmith, horn-working and goldsmith workshops were determined to have existed (Banaszak and Tabaka 2016).

The most important building on the island was a stone palace, which served residential and religious functions. Such buildings were built in several centres of the developing state of the early Piasts and were an expression of developing contacts with both Western and Southern Europe.
The origins of these buildings are still a matter of discussion, but their Latin name *Palatium* suggest their roots in Late Antiquity. The palaces in Ostrów Lednicki is the best-preserved building of its kind in Poland. In a chapel of the palace, two baptismal pools were found (Rodzińska-Chorąży 2016). Some researchers suggest this was where Prince Mieszko I was symbolically baptized. The inhabitants of Ostrów Lednicki certainly witnessed many important historical events, such as the birth of Bolesław I the Brave, the first king of Poland. They hosted Emperor
Otto III during his pilgrimage to the tomb of St Adalbert of Prague (Wyrwa 2016). The role of Ostrów Lednicki declined towards the end of the 1030s, that is, as the early Piast state was destabilized and after the invasion of Bretislav I, the Czech prince. After this period, Ostrów lost its role as the main centre, but it remained the seat of local power.

Data acquisition and processing

MBES survey  In the early spring (10–12 March) of 2017, a bathymetric survey using an IMOS 2 motorboat was carried out around the island of Ostrów Lednicki and the nearby island of Ledniczka. The survey covered a designated area of 0.53 km². A SeaBat 7125 MBES (Teledyne Reason) was used for the investigation. The device operated at 400 kHz, which guaranteed the detection of vertical differences in depth of > 6 mm. Very precise data on current position, heading, tilts and speed were provided by a HYDRINS compact unit (iXsea), which is an inertial system of navigation that is highly effective and optimized for hydrographic surveys. The transects were designed to obtain full coverage of the bottom area. The survey was carried out parallel to the long axis of the lake in a north–south direction.

QINSy v.8.14 software was used to collect and record the data from the MBES in the differential Global Positioning System and Real-Time Kinematic (DGPS RTK) altitude measurement system in real time, and these data were then corrected for the current water level reading from a nearby gauge and for sound velocity propagation in the water as measured using a CTD SD204 probe (SAIV). The sound velocity profile (SVP) measurements were conducted from a winch while the motorboat engine was stopped, and at least once every 6 h of MBES operation, or more often if the conditions of sound propagation in water required. In total, four profiles were carried out.

The data were processed in compliance with good practices using QINSy 8.14 and Qloud 2.2 software in order to remove acoustic noise, validate for changes in water level during the survey and to perform quality control. Data processing was performed in two stages. The first included checking and correcting positioning and water reference level; the water level was referenced to the average level of the lake. The data were then calibrated and checked in the QINSy 8.14 software. Each MBES swath was analysed to apply an appropriate sound velocity profile in the system. In the second stage, the bathymetric data were processed in Qloud 2.2 by cleaning all acoustic spikes using a qualitative filter. Next, additional manual data cleaning was performed to remove any remaining acoustic spikes. Finally, the processed data were exported to appropriate raster or ASCII data format (x, y, z).

Ground-truth survey  Locations of ground-truth archaeological objects were designated after careful manual exploration of bathymetric anomalies (concave and convex objects clearly distinguished from the surrounding lake bottom). Fieldworks were performed based on diving surveys. The locations of bathymetric anomalies were entered into a GPS-RTK Leica 1200 device and marked by buoys. A diver-archaeologist explored the area around the marked point in a pattern of circles of radii ranging from 0.5 to 5 m of the designated point, in increments of 0.5 m radius. Once the object was located, it was recovered, or left and described in the event that it was too large to extract.

Extraction of bathymetry features

The hydroacoustic surveys provided MBES bathymetry, which was the main feature—and the sole primary feature—used for classification in this study. To increase the predictive power of
classification, we calculated 13 additional secondary geospatial features, including geomorphometric and geometric types of features. They were extracted using two approaches: pixel based and object based (see Table S1 in the additional supporting information).

**Pixel-based features** The following pixel-based secondary features were extracted from the Lednica Lake digital elevation model (DEM): (1) slope, (2) aspect, (3) vertical ruggedness measure (VRM), (4) surface area to planar area (sapa), (5) curvature, (6) profile curvature, (7) planar curvature, (8) standard deviation of bathymetry (sd) and (9) variance. All extracted features were calculated in a Benthic Terrain Modeler (BTM) 3.0 Toolbox in ArcGIS 10.5 software using a $3 \times 3$ pixel window size (Wright et al. 2012). Additional secondary features were extracted using an object-based approach providing the geometric attributes of the lake-bed objects.

**Image segmentation and image-object features** Multi-resolution segmentation was performed using Trimble eCognition software. It allows the separation of image objects (or segments) that have homogeneous spectral properties, as expressed by parameters such as scale, shape and compactness, as described in detail by Benz et al. (2004). We determined the scale of multi-resolution segmentation using the Estimation of Scale Parameter 2 (ESP2) tool proposed by Dragut et al. (2014). Unlike other studies in the literature (i.e., Challis et al. 2011; Bennett et al. 2012; Kokalj and Hesse 2017; Kokalj and Somrak 2019), the initial segmentation based on bathymetry DEM did not appropriately differentiate archaeological objects. Because various settings of the segmentation algorithm did not bring significant improvement, we looked at how objects were made based on different layers. We concluded that it is worth determining image objects based on the slope layer. It seems that the majority of investigated archaeological objects were characterized by a steeper slope than the surrounding area. Shape and compactness parameters were both set to 0.1.

Image segmentation allowed us to extract the following image-object features: area, elliptical fit, length/width and compactness. A detailed description of the used image-object features is included in eCognition documentation (Trimble 2014).

**Feature selection** We used the locations of ground-truth samples to assign locations to the specific segments. Image-object statistics, including the means of all extracted features, were then used to select the most significant features in R software. We used a two-step approach consisting of cross-correlation and Boruta feature selection. The R libraries used included ‘Boruta’, ‘rgdal’, ‘mlbench’, ‘caret’, ‘reshape2’ and ‘ggplot2’.

The aim of the first step was to reduce the dimensionality of the data set by removing the most strongly correlated features (Diesing et al. 2016). We removed the features with a Pearson correlation $> 0.75$. Boruta feature selection allows the minimal optimal subset of features to be found by measuring their importance. The algorithm was invented by Kursa and Rudnicki (2016) based on a Random Forest-supervised classifier. The importance of features is measured by introducing other, random, irrelevant features that are used to evaluate the original ones. After a certain number of iterations, the algorithm selected the features with the highest importance. We determined their basic statistics and their value distribution for classification.
Object-based image classification

The results of feature selection allowed a rule-based classification to be developed in eCognition software (Blaschke et al. 2014). Based on our previous research using MBES, we expected that distributions of features’ values might overlap for different ground-truth categories (Janowski et al. 2018a, 2018b). Because our assumption was confirmed (see the results section), we classified image objects using unsupervised fuzzy-logic classification. The aim of this approach is that a certain object might belong to several classes with different rules (fuzzy rules) for each feature. This overall approach allowed us to manage multidimensional dependencies in the feature space. The detailed workflow presented in Figure 2 shows the object-based image-analysis workflow developed for this study.

Accuracy assessment

The performance of our classification was evaluated based on an error matrix and accuracy-assessment statistics (Foody 2002). The error matrix was calculated based on the whole ground-truth samples data set. It provided classification relationships between ground-truth categories. Accuracy-assessment statistics included user, producer (Story and Congalton 1986) and overall accuracy.

RESULTS

High-resolution MBES bathymetry and pixel-based secondary features

Data processing of MBES measurements allowed a DEM and secondary features of bathymetry to be created. All rasters were generated in high spatial resolution (0.1 × 0.1 m).

Identification of ground-truth samples

The ground-truth samples data set included 106 samples. After investigation, we separated them into nine categories that may be discriminated from MBES bathymetry and its features. They were determined as follows: boat, barrel, boulder(s), log, wooden object, other anthropogenic object, pile, scour hole and tyre. Summary descriptions of ground-truth samples are provided in Table 1.

Image segmentation and feature selection

The result of the use of the ESP2 tool suggested that image objects should be created with a multi-resolution segmentation scale of 15, which was applied in this study. According to the ‘Image segmentation and image-object features’ section, image segmentation was the basis for extracting image-object features. Cross-correlation of all 14 features allowed five highly correlated features to be removed, namely: sapa, sd, VRM, compactness and planar curvature. A cross-correlation matrix with a Pearson correlation coefficient is provided in Figure 3 (a). The result of the Boruta algorithm indicated that two additional features were not important (aspect and elliptic fit). It confirmed the importance of the seven following features: bathymetry, length/width, variance, slope, profile curvature, curvature and area. A box plot showing the result of the Boruta feature selection algorithm is provided in Figure 3 (b).
Knowledge-based classification

Image-object statistics for eight categories of objects and selected features formed the basis for developing fuzzy membership functions for the unsupervised classification of image objects.

Figure 2  Object-based image analysis (OBIA) workflow developed for this study. VRM, vertical ruggedness measure; sapa, surface area to planar area; and Pxl, pixel.

Knowledge-based classification

Image-object statistics for eight categories of objects and selected features formed the basis for developing fuzzy membership functions for the unsupervised classification of image objects.
| Multibeam echosounder (MBES) bathymetry | Classification result | Object class | Bathymetry description | Diving survey |
|----------------------------------------|-----------------------|--------------|------------------------|---------------|
|                                       |                       | Barrel       | Cylindrical object of approximately 2 m length, appearing 1 m above the bottom | Barrel        |
|                                       |                       | Scour hole   | Usually a round hole at the bottom | Scour hole: location of enhanced erosive activity |
|                                       |                       | Boulder(s)   | Round object(s) appearing a few dozen centimetres above the bottom | Boulder or a cluster of boulders of various sizes |
|                                       |                       | Wooden object| Long object appearing up to several centimetres from the bottom | Modern wooden object, such as a tree branch, etc. |
|                                       |                       | Anthropogenic object | Large, irregular object appearing several dozen centimetres from the bottom | Modern anthropogenic object, such as an anchor, a chair, fishing nets, etc. |
|                                       |                       | Log          | Oblong object of a few metres long | Probable horizontal construction element of a bridge |

(Continues)
Because the boat category was detected in only one place, we could not extract its relevant statistics. Therefore, this class was excluded from unsupervised knowledge-based classification. Related box plots of object statistics for all relevant features are provided in Figure 3 (c–i).

Classification results assigned numerous objects to most categories. Some classified image objects formed large clusters that did not visually match any of the investigated objects on the lakebed. We therefore decided to merge all regions and reclassify the whole scene again with the same fuzzy rules as before. This allowed us to remove excessively large clusters of classified objects (see Figure S1 in the additional supporting information).

From the total of 205,274 image objects, one was classified as a boat, seven were classified as barrels, 121 as anthropogenic objects, 647 as logs, 2602 as scour holes, 2681 as boulder(s), 2800 as wooden objects and 3890 as piles. The ratio of classified segments to all other segments was 6.5%. The overall result of the classification is provided in Figure 4.

**Accuracy assessment**

The error matrix of classification results is provided in Table 2. The ratio of classified to unclassified objects was 85.85% showing that the majority of ground-truth samples were confirmed using the developed fuzzy-logic rules. Because some categories were mixed up with others,
Figure 3  (a) Cross-correlation matrix with a Pearson correlation coefficient for all features created in this study; and (b) result of Boruta feature selection algorithm: y-axis = relative importance of features. Box plots of object statistics for all relevant features: (c) bathymetry, (d) slope, (e) curvature, (f) profile curvature, (g) variance, (h) area and (i) length/width; anthr, anthropogenic object; wooden, wooden object; VRM, vertical ruggedness measure; plan_curv, planar curvature; prof_curv, profile curvature; sapa, surface area to planar area; sd, bathymetry standard deviation; Elliptic, elliptic fit; Comp, compactness; and L_W, length/width.
the overall accuracy score reached a moderate 49.06%. A closer look at the per class accuracy results showed that the barrel and pile classes were classified with very good accuracy. By contrast, despite classifying 121 objects, none of the relevant ground-truth sample locations matched the tyre class. User and producer statistics of the other categories showed results that were fair (<0.4), moderate (<0.6) and good (<0.8).
Table 2  *Error matrix and accuracy assessment statistics of classification results*

|                | Barrel | Scour hole | Boulder(s) | Wooden object | Anthropogenic object | Log | Boat | Tyre | Pile | Sum |
|----------------|--------|------------|------------|---------------|----------------------|-----|------|------|------|-----|
| **User**       |        |            |            |               |                      |     |      |      |      |     |
| Barrel         | 2      | 0          | 0          | 0             | 0                    | 0   | 0    | 0    | 0    | 2   |
| Scour hole     | 0      | 4          | 1          | 7             | 0                    | 1   | 0    | 0    | 0    | 13  |
| Boulder(s)     | 0      | 0          | 17         | 4             | 1                    | 1   | 0    | 0    | 0    | 23  |
| Wooden object  | 0      | 2          | 3          | 15            | 1                    | 0   | 0    | 0    | 0    | 21  |
| Anthropogenic object | 0    | 1          | 3          | 0             | 4                    | 0   | 0    | 2    | 0    | 10  |
| Log            | 0      | 0          | 0          | 0             | 0                    | 1   | 1    | 0    | 0    | 1   |
| Boat           | 0      | 0          | 0          | 0             | 0                    | 0   | 0    | 0    | 0    | 1   |
| Tyre           | 0      | 0          | 2          | 0             | 0                    | 0   | 0    | 0    | 0    | 2   |
| Pile           | 0      | 3          | 1          | 3             | 2                    | 0   | 0    | 1    | 8    | 18  |
| Unclassified   | 0      | 3          | 5          | 4             | 2                    | 1   | 0    | 0    | 0    | 15  |
| **Sum**        | 2      | 13         | 32         | 33            | 10                   | 4   | 1    | 3    | 8    | 106 |
| **Producer**   | 1      | 0.31       | 0.53       | 0.45          | 0.40                 | 0.25| 1    | 0    | 1    |     |
| **User**       | 1      | 0.31       | 0.74       | 0.71          | 0.40                 | 1   | 1    | 0    | 0.44 |     |

Overall accuracy 0.49
DISCUSSION

Reference to the main objective and research tasks

The main objective of this research was the in-depth investigation of a shallow lake using high-resolution hydroacoustics with special attention to underwater archaeology. The objective was met by implementing the three research tasks provided in the introduction to this study: (1) the identification of underwater archaeological objects in a shallow lake using an MBES; (2) the characterization of the geomorphometric features of bathymetry that help to distinguish underwater archaeological objects; and (3) the development of OBIA workflow to automatically classify archaeological objects based on prior knowledge.

Summary of the main findings

The results demonstrate that underwater archaeological objects in a shallow lake are detectable using an MBES. The high-resolution bathymetry allowed geomorphometric and image-object features to be created that were successfully used to distinguish known underwater archaeological objects. This knowledge allowed an OBIA workflow to be developed for the entire region that allowed for the automatic classification of the lake bottom. The results demonstrate that segmentation and knowledge-based classification using fuzzy logic are useful for the recognition of archaeological objects with reasonable accuracy.

In comparison with hyperspectral data sets from satellite sensors, MBES usually provides the equivalent of only the two following bands (or channels): bathymetry and backscatter of the returned acoustic signal. The extraction of secondary features enlarges the dimensionality of the feature space, allowing in-depth analysis and increased classification performance. Therefore, any contribution of MBES secondary features is of great interest to the seafloor mapping community (Diesing et al. 2016; Trzcinska et al. 2020). Although the geomorphometric features of bathymetry are increasingly used in benthic habitat mapping (i.e., Janowski et al. 2018b; Fakiris et al. 2019), to the best of our knowledge this study is the first to have used numerous (eight) geomorphometric features as predictors for the identification and classification of underwater archaeological sites. Moreover, to the best of our knowledge, image-object features have not previously been used in underwater archaeological research based on MBES data sets.

Image segmentation and knowledge-based classification have lately been one of the most powerful methods for the automatic identification of specific features in the remote-sensing literature. They are also increasingly used in remote-sensing terrain archaeology (e.g., Verhagen and Drăguț 2012; Davis 2018; Magnini and Bettineschi 2019). However, to the best of our knowledge, this study is the first to have used OBIA for underwater archaeology based on MBES measurements.

Image classification based on fuzzy logic has rarely been adopted in sea- or lake-bottom mapping based on underwater acoustic measurements (e.g., Tęgowski et al. 2018). However, this approach is auspicious in remote-sensing exploration of underwater seabeds or lake bottoms (Fiorentino et al. 2018). Fuzzy logic was successfully adopted in our study for the classification of a multidimensional data set of secondary features. The results of classification are fundamental to the ability to determine those archaeological prospection areas that have the greatest chance of successful exploration in further diving surveys.
Interpretation of the main findings

The knowledge-based fuzzy-logic classification used in the area indicates the presence of objects such as logs, scour holes, piles and wooden objects. Most of the objects thus classified were detected in the locations of the bridges that used to connect the islands with the mainland (Fig. 4, a–c).

Archaeological descriptions of surveyed zones The first information about Ostrów Lednicki comes from 19th-century enthusiasts of antiquity, and since then researchers’ interest in this place has been, to all intents and purposes, constant (Górecki 2016a). The first underwater discoveries were made at the beginning of the 1960s when two bridge crossings connecting Ostrów Lednicki with the lake’s western and eastern shores were first discovered (Kurnatowska 2000; Kola and Wilke 2014). Since 1982, underwater archaeological research in the waters of Lake Lednica has been systematically conducted by the Nicolaus Copernicus University in Toruń (Kola 2000; Kola et al. 2016), currently represented by the Centre for Underwater Archaeology. For many years, these studies focused mainly on the remains of the aforementioned bridge crossings. Nevertheless, prospections were also carried out across the entire coastal zone of Ostrów Lednicki and in many other places of high archaeological potential. Unfortunately, this research was not accompanied by any hydroacoustic scans, and the areas for prospection were selected based on the experience and intuition of the archaeologists.

Despite this simple methodology for selecting study locations and methods, the results have been spectacular. The research conducted over the course of almost 40 years has resulted in an in-depth analysis of two medieval bridges (Kurnatowska 2000; Kola and Wilke 2014; Kola et al. 2016), seven logboats (Ossowski 2014), Europe’s largest collection of military items from the 10th and 11th centuries (Kurnatowska 2000; Kola and Wilke 2014), including 141 axes, 48 spearheads, seven swords, a conical helmet and chain mail, and a large collection of other archaeological items. This might, on the one hand, testify to the extraordinary intuition of the researchers, or it is perhaps confirmation of the site’s unique potential.

The approach to extensive underwater prospections in the lake changed significantly in 2017 when support from the Ministry of Culture and National Heritage made it possible to scan a large area with a multibeam sonar, a bottom-sediment profiler and a magnetometer (Pydyn et al. 2019). Apart from collecting a huge amount of data and creating an extremely precise mapping of the bottom, these works resulted in the discovery of another bridge from the Middle Ages: one that connected Ledniczka island with the lake’s western shore (Pydyn et al. 2018). The analysis of hydroacoustic data presented herein emphasizes four areas in particular. The first two are the relics of the bridges to Ostrów Lednicki, which have been studied intensively for several decades. It is in these bridge locations that many of the discussed objects were distinguished: piles, beams, barrels left by previous generations of archaeologists, negatives of objects and traces of exploration. The third area is located between Ledniczka island and the western shore of the lake. Here archaeologists located another bridge based on a very preliminary analysis of data from multibeam sonar. The fourth area was selected after a detailed data analysis: it covered the area between the south-western shore of Ostrów Lednicki and the island of Ledniczka. In this area, anomalies similar to those in the third area were found.

Characteristics of the designated areas The Gniezno (gnieźnieński) bridge (Fig. 4, b) led from the central part of the island to the lake’s eastern shore; it was 187 m long, with a reconstructed width of about 5 m. Based on dendrochronological analyses, it was determined this bridge was
built in the 960s, and then repaired in 976–978, 979–981, 982–1006, 1007–1017 and 1032 (Wilke 2000; Kola et al. 2016). The discovery of many structural parts of the bridge allowed for a reconstruction of its appearance. After piles had been driven into the lake bottom, they were combined into bundles. Two bundles—one on each side of the bridge axis—were then joined together by a yoke beam. One such joined assembly constituted one pillar of the crossing (Wilke 2000).

The Poznań (poznański) bridge (Fig. 4, a) on the other side of the island was about 440 m long and 5 m wide. This crossing was built in 961–963, and then rebuilt in 965–969, 980–981, 995–1004, 1007–1009, 1015–1018, 1020–1026 and 1033 (Wilke 2014; Kola et al. 2016). In general principles, this bridge was similar in structure to the eastern bridge, while the piles at greater depths consisted of more elements than those at the shore. This was necessitated by the considerable depth of the water here, which reached as much as 11 m (Wilke 2014; Kola et al. 2016).

Sessile oak (*Quercus patraea*) was used to construct both bridges, with trunks of up to 14–15 m long and 12–22 cm in diameter being selected. Mainly trees aged 21–60 years were used, accounting for 71.51% of all analysed piles (Kola et al. 2016).

The bridge to Ledniczka from the western shore of the lake (Fig. 4, c) was about 100 m long. The first works located horizontal beams, and then vertical piles in the central part of this bridge (Pydyn et al. 2018). The acquired artefacts, as well as dendrochronological and radiocarbon dates, suggest that there were two bridges in this place, the first in the 10th century and the second at the turn of the 14th century. The sediments in the area are very variable in character: in the immediate vicinity of Ledniczka there are none of the typical layers that ensure the anaerobic conditions that protect the organic material of cultural layers and wooden construction elements. On the other hand, on the opposite western shore, the thickness of such layers is > 2 m, which makes the structural elements in them inaccessible to archaeological prospecting and hydroacoustic scanning.

The fourth selected area was located between the south-west bank of Ostrów Lednicki and the island of Ledniczka (Fig. 4, d). The distance between the shores at this point is about 180 m, which is more than the length of the bridge from the west bank to Ledniczka, but not more than the length of the Gniezno bridge. The detailed hydroacoustic analyses carried out suggest the presence of anomalies similar to those known from other bridges discovered in the lake. Furthermore, the south-west area of Ostrów Lednicki is exceptionally interesting. It was here that the oldest phase of the fortified settlement was located; the palace was also erected here, and the coastal zone was protected by complex shoreline fortifications (Górecki 2011). The underwater research carried out in this area in 2020 located the shoreline fortifications that protruded furthest into the lake. A number of anomalies identified during detailed hydroacoustic analyses were also investigated. A significant proportion of them turned out to be small wooden elements of up to 0.5 m in size or medium-sized elements of up to 2 m. Larger elements were also found, the most characteristic of which was a yoke-like beam with many incisions. It may have been a structural element of the bridge, but for now it should be assumed that it is an element of bank fortifications that flowed down to the greater depth (4.5 m) at which it was found. A similar interpretation currently applies to other elements found.

*Study limitations*

Underwater environments are much more difficult to survey than are terrestrial ones. This is especially evident in sampling positioning accuracy, which is far less precise than in land research. Even ultra-short baseline (USBL) does not provide precise positioning in the marine realm. The design of fieldworks developed in this study allowed a ground-truth positioning accuracy of between 1 and 5 m to be achieved, assuming that a buoy was fixed to the bottom in the location
designated on the designed map. Because our error matrix was performed based on point locations of ground-truth samples, some deviations in accuracy may exist, especially immediately around the borders between classes.

Whereas different hydroacoustic devices allow the water column to be penetrated over various ranges, the MBES we used was designed to perform surveys in shallow waters. It can perform measurements at very high spatial resolution—greater than in traditional terrestrial remote-sensing research. However, compared with other hydroacoustic devices operating at much lower frequencies, MBES does not penetrate layers below the bottom of the lake. In general, the frequency we used (400 kHz) allows precise DEMs of the lake bottom to be generated. Because the environment of Lednica Lake is characterized by the occurrence of mud and suspended mud (Pydyn et al. 2019), most potential objects may be buried in the muddy sediments.

It should be emphasized that the nature of bottom sediments in the area in question significantly hampers both underwater prospecting and hydroacoustic scanning. The coastal zones are covered with vegetation; on the Ledniczka island side there is no soft bottom sediment that guarantees the preservation of organic material; at a depth of 5–6 m there are dense layers of shell deposits that inhibit underwater prospects and strongly reflect hydroacoustic signals. However, on the Ostrów Lednicki side and in the central part of the discussed area, the thickness of the bottom sediments is so significant that it limits any underwater prospections. It should be noted that sub-bottom profilers (SBP) may be the only way to investigate cultural heritage features embedded in the lake or the seafloor. MBES only allows the examination of the features that are exposed on the seabed. This study intended to develop an innovative methodology focused on getting as much information as possible from an MBES data set. The investigation of the cultural heritage underlying the seabed was beyond the scope of this research.

In the underwater remote-sensing literature, MBES measurements often allow a few classes (three to six) of sediments or benthic habitats to be precisely separate (e.g., Fogarin et al. 2019). Benthic habitat mapping studies almost always use MBES backscatter as the main feature corresponding to the seabed type. Therefore, they benefit from an additional primary feature that greatly improves the accuracy of classification. To compare, in this research we were able to perform an analysis only based on MBES bathymetry, as this was the only primary feature registered in the survey. To increase classification potential, we extracted multiple secondary features. However, as provided in the results section, distributions of feature values overlapped for various categories. To overcome this challenging problem, we developed a fuzzy unsupervised classification algorithm that allowed us to separate nine categories of objects. Despite this, in the error matrix and accuracy assessment, misclassifications were visible between classes that deviated from the mentioned similarity. For example, usually piles occurred in concave areas of the DEM that very likely would be classified as scour holes class, and vice versa; the class of log had very similar geometric characteristics to wooden object, etc. While it is true that reducing the number of classes may potentially increase classification accuracy (e.g., Montereale Gavazzi et al. 2016), we decided to settle on a detailed separation of nine classes. Therefore, the results suggest potential locations of the mentioned underwater archaeological objects with some probability of misclassification.

Summary and recommendations for future research

It is worth recalling that OBIA fuzzy classification in this research was performed for nine categories based on a single primary feature. Having an additional MBES primary feature (acoustic backscatter) would greatly improve the geospatial knowledge of the area, even allowing an additional set of secondary features to be extracted (i.e., grey-level co-occurrence matrices (GLCM)
As mentioned in the previous section, most archaeological objects may be buried in muddy sediments of the Lednica lake. Although MBES does not penetrate sedimentary layers below the lakebed, the research may be supplemented with the application of an SBP. These devices allow two-dimensional (2D) seismic profiles to be generated for even up to several metres below the lake bottom in shallow water basins. Such profiles may help to identify and preliminarily describe buried objects. Other studies described extensive utilization of SBP for the exploration of shipwrecks (Plets et al. 2009; Grøn et al. 2015), as well as whole cultural heritage sites (Wunderlich et al. 2005). Moreover, recent advancements in SBP technology that use multiple transducers allow 3D models of sediment layers to be created that may provide the detailed identification and description of buried objects (Missiaen et al. 2018). However, it should be noted that the 3D seismic data sets are much more difficult to interpret than MBES data sets, especially as a basis for automated classification.

Any of the aforementioned forms of research would require additional hydroacoustic surveys that would provide high-quality data sets for better investigation of archaeological sites. Depending on funding possibilities, such surveys are considered for future research. Integration with multiple sources will extend the existing automatic classification methodology and will precisely recognize more heritage sites.

Non-invasive methods of underwater bottom investigation are arguably the most convenient for recognizing archaeological sites without affecting their integrity. The developments presented in this study perfectly fit into current trends in underwater archaeological studies. We have demonstrated a step forward in using high-resolution MBES measurements. The proposed innovative methodology is logical and repeatable. It may be applied to other case studies of underwater archaeological prospection all over the world.

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CONFLICT OF INTEREST
The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS
All authors listed participated in the research presented in this manuscript. Conceptualization, L. J.; methodology, L. J.; data acquisition, A. P. and M. P.; data processing: L. J. and L. G.; writing: original draft preparation, L. J., M. K., A. P. and M. P.; writing: review and editing of the manuscript, L. J. and A. P.; visualization, L. J., M. P. and M.K; supervision, L. J., M. K. and A. P;
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PEER REVIEW

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DATA AVAILABILITY STATEMENTS

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

**Table S1.** List of all 14 features with their description and extraction method.

**Figure S1.** Results of segmentation before and after application of merge region algorithm. A1-A3 – close-ups of three characteristic areas of the study site (A).