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Between water and land: Connecting and comparing underwater, terrestrial and airborne remote-sensing techniques

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ABSTRACT

Ostrów Lednicki is one of the most important early medieval sites in Poland. Land and underwater archaeological excavations have been carried out there for many decades. This has allowed for a significant reconnaisance of the Lednica settlement complex. However, further research, especially that carried out underwater and in the shore-zone, has required the use of modern methods involving a multibeam echosounder (MBES), sub-bottom profiler (SBP), caesium magnetometer and LiDAR scans. The primary platform used for combining the underwater and aerial survey data was a Geographic Information System (GIS) environment. This software made it possible to compare and correlate acoustic, magnetic, seismic and laser data. As a result, new important archaeological features were discovered, including two previously unknown bridges and extensive shore-zone fortifications.

1. Introduction

The first surveys at Ostrów Lednicki began back in the 19th century and very quickly covered the entire extensive settlement complex. Underwater surveys have also been carried out in the lake for more than 40 years. In recent years, these have been supplemented by non-invasive prospections, including by multibeam echosounder (MBES), sub-bottom profiler (SBP), caesium magnetometer and LiDAR scans. The results of these surveys have allowed the following research questions to be formulated:

1. How might correlating different prospecting methods improve the perception of significant archaeological sites like Ostrów Lednicki?

2. How does the use of new research techniques increase our knowledge of the changes that took place in the Lednica settlement area?

1.1. Archaeological context

Lednica Lake is located in the central part of the Greater Poland Voivodeship. The surface area of the lake is approximately 3.48 km^2. It is a relatively shallow postglacial lake with a maximum depth of 14 m. There are five islands on the lake, and traces of human presence in the Middle Ages have been recorded on two. The largest and archaeologically most significant is the island of Ostrów Lednicki, with an area of 0.075 km^2 (Fig. 1). As well as on Ostrów, traces of settlement have been located on the island of Ledniczka (Wyrwa, 2016; Pydyn and Popek, 2020).

Medieval traces of the settlement of the largest islands date back to the late 9th century. At that time, it was probably one of the main strongholds of the local community. In the 50 s and 60 s of the 10th century, at the order of Mieszko I, the first historical ruler of Poland, the fortified system of Ostrów Lednicki was completely rebuilt. The island was incorporated into the system of central places of the state of the first Piasts. The changes included the construction of a new, larger hillfort with a *Palatium* in its interior. This was the part intended for the ruler's family and the elites of the new state. A production and commercial zone was arranged outside the hillfort. Meanwhile, the island was connected to the mainland by two bridges (Kurnatowska, 2000; Kola and Wilke, 2014).

The most important building on the island was the *Palatium*, located inside the hillfort. It had both a residential and a sacral function. Such buildings were erected in the most important centres of power of the state of the first Piasts. The monument on Ostrów Lednicki is the best-preserved *Palatium* in Poland, as the island was never urbanised. In

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addition to the residential part, the building included a chapel where two baptismal pools were located (Rodzińska-Chorąży, 2016).

Some researchers link this place with the symbolic baptism of Mieszko I. It was probably on this island that Bolesław I the Brave, the first king of Poland, was born. Here, King Bolesław also welcomed Emperor Otto III during the latter's pilgrimage to the tomb of St Adalbert of Prague. Ostrów Lednicki, as a centre of power, lost its importance in the 30 s of the 11th century during the crisis of the state of the first Piasts (Wyrwa, 2016).

Integral to the centre at Ostrów Lednicki were its two bridges (Fig. 2). Their relics were found at the end of the 1950 s and named the "Poznań" and "Gniezno" bridges by researchers. Their names are derived from the directions of the tracts that lead from them to other strongholds of the early Piast state (Kola et al., 2016: 107).

The Gniezno Bridge leading from the central part of the island to the lake's eastern shore was 187 m long and about 5 m wide. Based on numerous dendrochronological analyses, it has been determined that this bridge was built in the 60 s of the 10th century, after which it was rebuilt or repaired five times in the years 976–78, 979–81, 982–1006, 1007–17 and 1032 (Krąpiec, 2000; Wilke, 2000; Kola et al., 2016: 111–117). On the other side of the island was a bridge about 440 m long and 5 m wide. This crossing was built between 961 and 963, then rebuilt between 965 and 969, 980 and 981, 995 and 1004, 1007 and 1009, 1015 and 1018, and 1020 and 1026, and in 1033 (Radka, 2014; Wilke, 2014; Kola et al., 2016: 117–121).

A large collection of early medieval militaria was found during the excavation of the bridges themselves and surveys around the lake. Apart from the bridge's relics, these artefacts were concentrated on the island's western side (Wilke, 2006; Kola et al., 2016: 127). The items of weaponry include: 141 axes (Sankiewicz, 2013: 28); 48 spearheads, including three specimens preserved in their entirety (Sankiewicz, 2018: 28); seven swords (Sankiewicz, 2011: 13); a conical helmet; and a chainmail. However, besides the militaria, many other objects were also found around the island – especially sickles and items of equestrian tack. This gives rise to two interpretations that are somewhat distant from one another. The first suggests that these are traces of a battle on the bridges and the western shore of the island (Wilke, 2006), while the second, less likely, interpretation links these finds to the result of symbolic activity by the local community (Chudziak 2013: 63–66).

The site located on Ledniczka Island is very important from the point of view of non-invasive research on Lednica Lake. It contains a motte-type settlement that is 6 m high and 20 m in diameter at the top. In the north-west is a semi-circular earth embankment of 1.80 m high and 20 m wide. Between the embankment and the hillfort, there is a depression that may be the remains of a moat (Górecki et al., 1996: 200). The chronology of this site has been determined based on excavated archaeological materials and the form of the motte to the 14th century (Górecki et al., 1996: 234–235). The motte-type foundation on Ledniczka is linked to the functioning of the Ostrów castellany established on this island in the 13th century or transferred here from neighbouring Ostrów Lednicki at the end of that century (Wasilewski, 1967: 554; Leśny, 1976: 19; Górecki et al., 1996: 239).

During non-invasive research of Lednica Lake in 2017, two hitherto-unknown bridges leading to Ledniczka island were discovered. The current state of the research makes it possible to conclude that one bridge was erected in the first half of the 10th century (Pydyn et al., 2018; Pydyn and Popek, 2020). Another bridge to Ledniczka Island was erected at the turn of the 14th century. The general archaeological context of a recognised motte-type residence broadly dated to the 13th–15th centuries would justify the erection of a structure connecting the island to the mainland. The function of this fortified settlement has not been clearly explained (Górecki et al., 1996: 197); it was certainly no longer a centre of central authority but the seat of local government, perhaps of a castellan or a local magnate family (Pydyn et al., 2018; Pydyn and Popek, 2020).

1.2. Multibeam echosounder (MBES)

Several non-invasive prospecting methods have been used during the many years of underwater research on Lake Lednica to investigate the lake bottom as accurately as possible. Using a multibeam echosounder (MBES) allowed the creation of an accurate bathymetric map with a resolution that made it possible to identify archaeological objects, such as bridge relics. The survey system was based on a proven configuration of equipment: a multibeam echo sounder (SeaBat 7125), a tilt compensator (iXsea Hydrins), a dual satellite positioning system (RTK

Fig. 1. Airborne photography of Lednica Island (M. Popek).

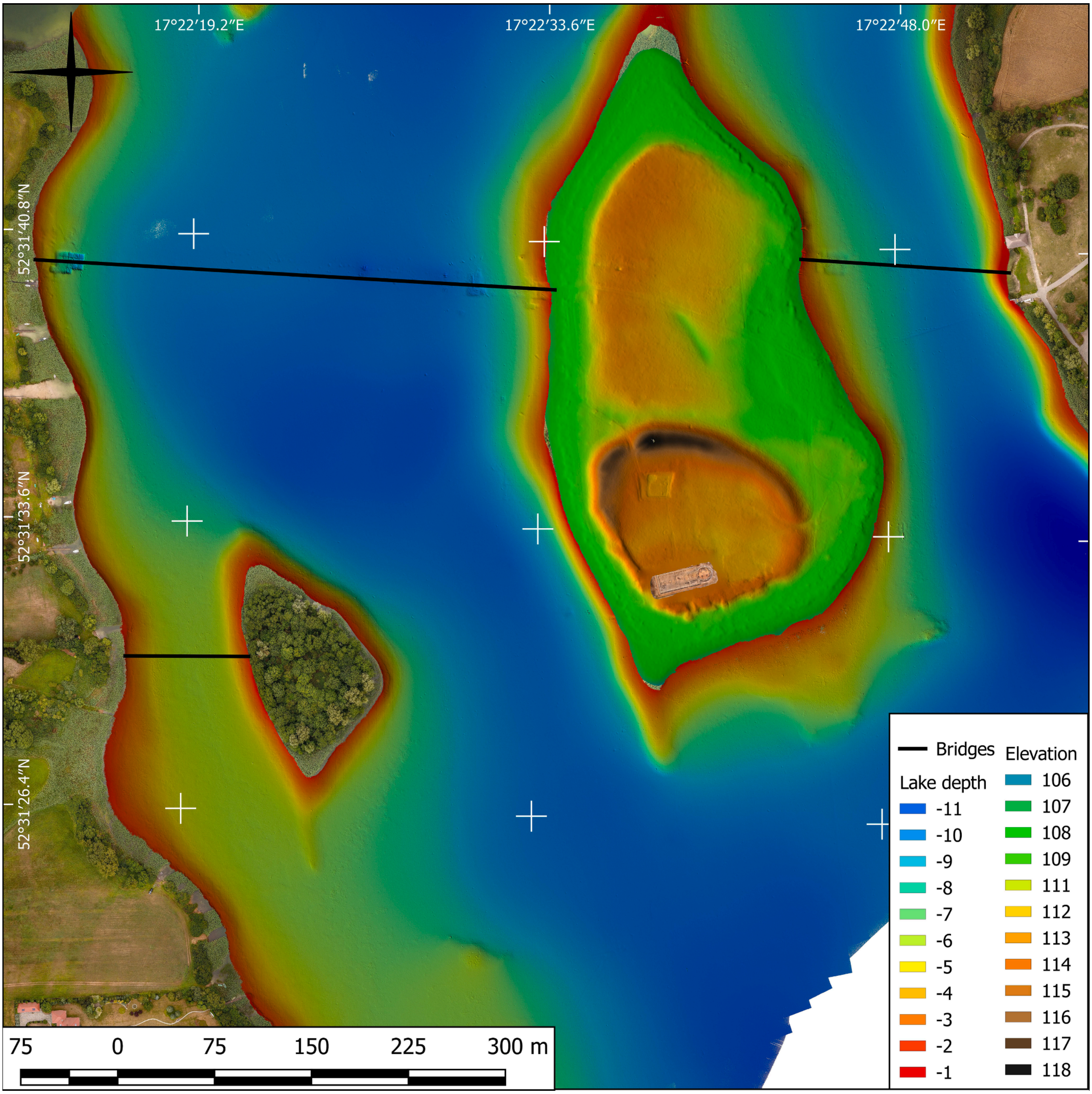

Fig. 2. Digital elevation model of the lake and islands showing location of bridges (M. Popek).

GPS - BX 982), together with an RTCM RTK satellite corrections reception system (EUPOS/SAPOS transmitted via internet link). All devices operating within the Qinsy (Quality Integrated Navigation System) 8.5 measurement system (Hac, 2017: 34; Pydyn et al., 2019; Janowski et al., 2021; Pydyn and Popek, 2022).

Acoustic measurements were conducted around the islands of Ostrów Lednicki and Ledniczka, where anthropogenic objects were most likely to be located. Measurement profiles were conducted along the range limit of the SeaBat 7125 multibeam echosounder operating at 400 kHz, which guaranteed the detection of local differences in depths of more than 6 cm. The survey lines were run to ensure complete coverage of the entire area selected for the survey. In addition, measurements were supplemented where necessary. All scans were made at high resolution (50 to 100 pts/m^2). The acquired data were used to select potential archaeological artefacts lying on the surface of the lake bed (Pydyn and Popek, 2022).

The measurements resulted in an accurate bathymetric map of the lake bottom with a 10 × 10-cm pixel size (Fig. 3). Analysis of the data obtained made it possible to determine 204 bathymetric anomalies that could be traces of human activity in the past. These were objects protruding by more than 10 cm from the lake bottom, as allowed by the accuracy of the obtained map. Objects with a natural appearance, such as submerged trees or branches, were discarded, and no prospection was carried out there in further stages. The rest of the selected bathymetric anomalies were visually inspected. This resulted in an inventory of sites with descriptions (Pydyn et al., 2019; Janowski et al., 2021; Pydyn and Popek, 2022).

Most objects protruding from Lake Lednica turned out to be

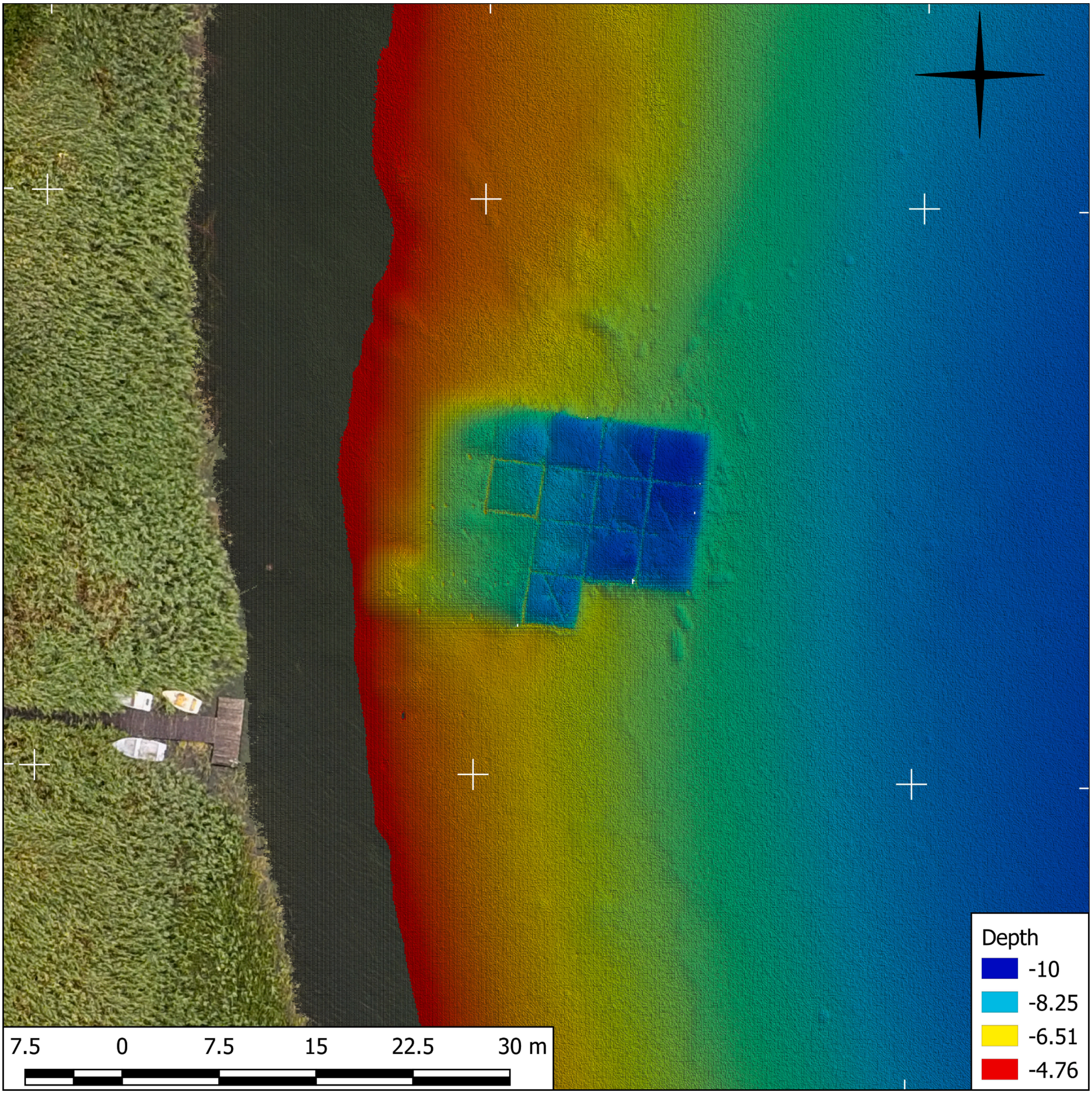

Fig. 3. Archeological trench on MBES scan (J. Koszałka, M. Popek).

contemporary remains of human activity. A large group consisted of points relating to objects already known to archaeologists: relics of early-medieval bridges and medieval and modern dugout boats known from previous research seasons (Kurnatowska, 2000; Kola and Wilke, 2014). These already-known objects served as a reference base to identify other objects with archaeological potential (Pydyn et al., 2019; Janowski et al., 2021; Pydyn and Popek, 2022).

While examining structures on the lake bed, relics of wooden structures were encountered between Ledniczka Island and the lake's western shore. A preliminary inventory, followed by regular excavations, identified the site as the remains of bridges. Relics of two bridge crossings were inventoried – one from the 10th century and the other from the turn of the 14th (Pydyn et al., 2018; Pydyn et al., 2019; Pydyn and Popek, 2020; Janowski et al., 2021).

Of all the non-invasive methods used during the survey of Lake Lednica, the multibeam echosounder has probably been the most effective. Its application in shallow and very shallow waters is difficult and requires dense coverage by the surveying boat. Nevertheless, the results achieved are extremely interesting. On the one hand, the method (MBES) made it possible to find the aforementioned bridges to Ledniczka Island. These bridges had been sought by underwater archaeologists for more than 30 years. This method makes it possible to find even single beams, as was the case with the western shore of Ostrów Lednicki Island. On the other hand, MBES provides the possibility to examine previous archaeological work, even in places with zero visibility. An additional benefit of using multibeam sonar on Lake Lednica was the possibility to establish the exact course of the bridges, whose lengths were 187 and 438 m, and which were excavated only within limited areas.

The use of MBES, which allows for highly accurate imaging of the bottom offers underwater archaeological research tremendous learning opportunities. It is currently the only method to produce such accurate bottom maps. The device produces point clouds and high-resolution bathymetric models of the bottom with pixel sizes as small as 5 × 5 cm. This makes it possible to locate and even identify very small objects protruding from the bottom. In addition, specialists from the Maritime Institute in Gdańsk have developed an algorithm for automatically identifying objects located on the scan, improving archaeologists' fieldwork (Janowski et al., 2021).

The ability to obtain a reliable high-resolution spatial image of the bottom allows for a detailed overview of the surface of the surveyed area and potential archaeological objects. Regardless of the size of the surveyed area, it is possible to maintain adequate detail in the data (Le Deunf et al., 2020; Madricardo et al., 2017). The ease with which sectioned images of the bottom can be created allows specific features to be searched for, which facilitates identifying and classifying different types of objects (Passaro et al., 2013). On the other hand, the disadvantages are its inability or very limited ability to penetrate bottom sediments, the narrow width (swath) of the measured strip in shallow water (typically 4 × the bottom depth) and the results' high susceptibility to distortion, which may be caused by the presence of dense vegetation covering the bottom (Pydyn et al., 2019). Generally, when MBES is used, any vegetation, anthropogenic elements and even floating suspended matter (Suspended Particulate Matter) above the bottom are also recorded (Fromant et al., 2021; Held and von Deimling, 2019; Kruss et al., 2017), which can cause difficulties in delineating the bed in such areas.

1.3. Sediment profiler system (SBP)

The aim of using seismoacoustic equipment to survey the bottom of Lake Lednica was to locate potential archaeological objects buried in the bottom sediments. The sediment profiler system - Innomar SES 2000 Medium, combined with a laser tilt corrector (iXsea Hydrins) and a dual satellite positioning system (RTK GPS - BX 982), together with the RTCM RTK satellite corrections reception system (EUPOS/SAPOS transmitted via internet link), was the basic set-up for the scan. All equipment operated within the framework of the Qinsy (Quality Integrated Navigation System) 8.5 measurement system. Recording of geological features of surface soils was carried out to a depth of several metres below the bottom surface. Potential anomalies originating from human activity were searched for in the 4–10-kHz band. CHIRP (Compressed High-Intensity Radiated Pulse) technology achieved 1–5-cm layer differentiation (Gutowski et al., 2002). This made it easier to search for anomalies caused by archaeological artefacts or other natural objects such as stones (Hac, 2017: 37; Pydyn et al., 2019).

During the survey, 161 profiles were made. This number included primary profiles – made every 5 m, on north–south axes, and control profiles perpendicular to them – at 25-metre intervals. Based on the archaeological knowledge already available and the results of the hydroacoustic scans, additional areas were selected, over which further thickened profiles were made every 2 m (Hac, 2017: 37; Pydyn et al., 2019). The detected anomalies were subjected to visual inspection by underwater archaeologists (Fig. 4). However, due to the non-invasive nature of the project, the bottom layers were not probed, which significantly limited the possibility of identifying the detected objects (Pydyn et al., 2019; Pydyn and Popek, 2020). Despite this, several objects of

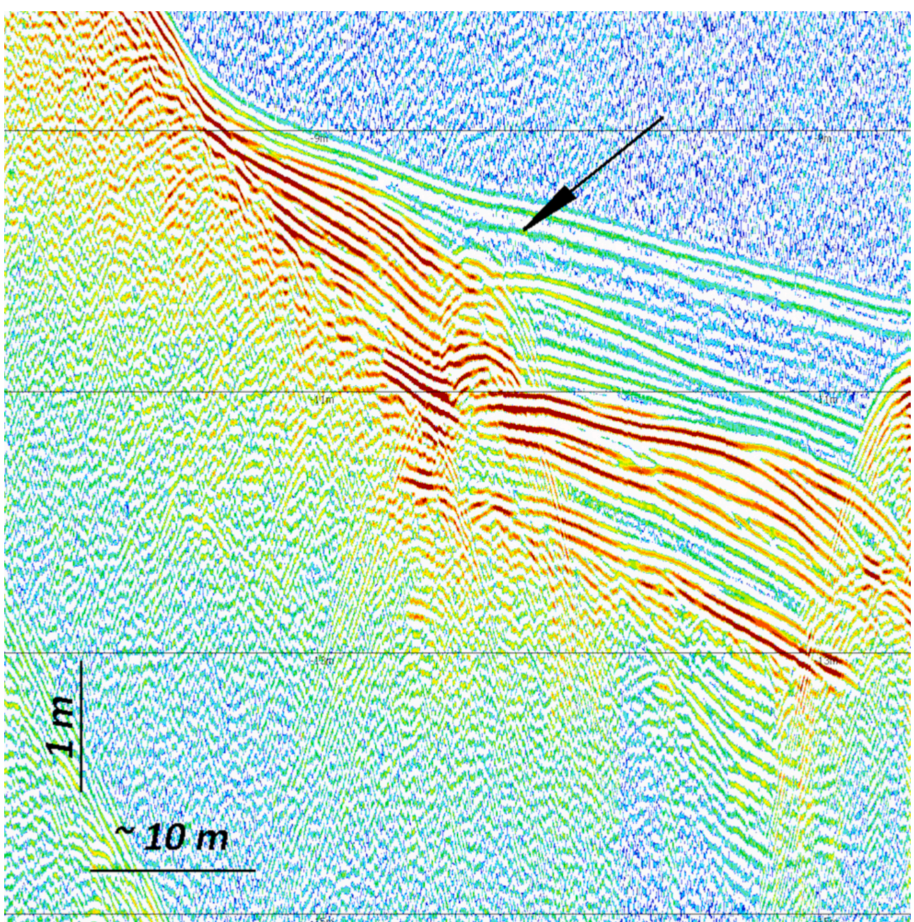

Fig. 4. Example of SBP scan, with potential archaeological object (J. Koszałka).

archaeological interest were recognised among the anomalies. These were relics of known bridges in locations not previously investigated (Pydyn et al., 2019). It is noteworthy that this method of archaeological prospection allows the non-invasive identification of objects, especially on sites subject to strict protection.

SBP has made it possible to detect objects embedded in the bottom sediments that could not be sensed by other non-invasive methods (Wunderlich et al., 2005). The instrument and the measurement methodology do not allow the detected anomalies to be accurately described or their parameters to be precisely determined. As a result, natural objects (e.g., a stone) may give the same image as anthropogenic objects (e.g., a wooden pile or beam from a medieval bridge). In order to get more detailed data, it would be necessary to use multi-head devices (e.g., SES 2000 Quattro) with a simultaneous 20-fold density of guided profiles (Missiaen et al., 2018). Such devices deliver results that are much more useful for archaeological interpretation (Pydyn et al., 2019; Pydyn et al., 2021).

As mentioned earlier, the sediment profiler system (SBP) requires even denser coverage by the survey boat than does the multibeam echosounder. This is especially true when working on relatively small objects such as piles driven vertically or obliquely into the bottom.

A positive result of the SBP scanning was that it demonstrated the effectiveness of the seismic method in searching for objects that are not visible on the bottom surface while also not interfering with the sediment structure. It is worth noting that this is currently the only non-invasive method for searching for non-magnetic objects embedded in the bottom (Jones et al., 2005).

Fig. 5. Visualisation of magnetometer scan, with magnetic anomalies (M. Popek).

1.4. Caesium magnetometer

At Lake Lednica, a G858 onshore caesium magnetometer and a G882 offshore magnetometer were used to locate potential anthropogenic objects with ferromagnetic properties (objects with a magnetic signature) deposited on the bottom of the study area. The devices' sensitivity of 0.004 nT to 0.05 nT allowed the detection of even small metal objects with a magnetic signature deposited on the surface or in the lake bottom sediments (Fig. 5). Unfortunately, the detection range decreases by the cube of the increase in distance. This means that the further away from the sensor, the larger the magnetic mass must be in order to be detected (Hac, 2017: 35; Pydyn et al., 2019; Pydyn and Popek, 2022).

Measurements on Lake Lednica were carried out in two stages: first, along the shores of the lake with a land-based magnetometer (G858), and then in the area of waters deeper than 2 m with a device adapted for use in water. Profiles in the shallow zone were run parallel to the shoreline at 2- to 5-metre intervals. In areas deeper than 2 m, a marine magnetometer (Magnetometer G882) was used, which was towed behind a vessel. Profiles were taken parallel at fixed intervals of 5 m on a north–south axis. At bridge relics, the profiles were performed at narrower intervals to increase measurement accuracy. The data collected during the magnetic profiling was filtered. Signals were removed from the records where the instrument struck the bottom, and a point cloud was created from them to determine the position of ferromagnetic objects (Hac, 2017: 35; Pydyn et al., 2019: Fig. 3; Pydyn and Popek, 2022).

Due to the project's non-invasive nature, it was impossible to check all the anomalies determined during the magnetometer scan. A dozen points located in the shallow water were selected for checking. Approximately 70 % of the items checked were metal objects of modern origin. Therefore, it is reasonable to assume that the magnetic anomalies, which could be archaeological objects, will be located deeper and give a much weaker signal (Pydyn et al., 2019; Pydyn and Popek, 2022). However, a few archaeological artefacts (axes and a spear) were found during the survey close to the medieval bridge to Ledniczka Island. The artefacts can be associated with both phases of the bridge, dating to the 10th and 14th centuries.

Magnetometric survey technology is irreplaceable when conducting non-invasive, large-area searches for metallic objects with magnetic signatures, such as those made of iron or steel. The disadvantage of the system is that the sensors have to be guided at a constant height above the bottom and, simultaneously, as close to the bottom as possible, which creates a risk of damage to the sensors. In addition, the intervals between the measurement profiles have to be very small, e.g. at about 80 cm, which further increases the survey cost. At the same time, the process requires very accurate positioning of equipment towed astern of the vessel in real-time mode (Pydyn et al., 2019; Pydyn and Popek, 2022).

The usefulness of this technology for underwater archaeology is undeniable, but there are also drawbacks to this method. The number of modern magnetic objects on the bottom of the lakes and the depth of deposition of archaeological objects cause artefacts to be "lost" and covered by other signals. In order to increase the suitability for underwater research, it would be necessary to clear the body of water of objects with a ferromagnetic signature. Another scan should follow this. This would need to be repeated until the bottom was completely cleared of unwanted signals. Evidence of this is the large number of magnetic artefacts found during the exploration of the bridge to Ledniczka Island that had previously gone "unnoticed" by the magnetometer (Pydyn et al., 2018; Pydyn and Popek, 2020; Kucypera et al., 2021). Applying the above-described method could lead to the location of these objects, but the high cost of such a tactic makes its application impossible in practice.

1.5. Airborne laser scanning (ALS)

Additional complementary types of prospection for underwater archaeology should include ALS scans. This method allows us to record the wider context of submerged objects, especially in the lake's shallow shore zone (Fig. 1) (Štular et al., 2021; Štular and Lozić, 2022). In the case of Lake Lednica, an aerial laser scanner mounted on an unmanned aerial vehicle (AUV) was used. A significant benefit of adopting such a solution was that it allows more flexibility in selecting a date and in determining the density of measurement points. The choice of timing was important in terms of vegetation that could interfere with the scanning. The aerial survey was carried out using a Riegl RiCOPTER UAV equipped with a Riegl2 scanner. The projected cloud density was 400 pts/m^2. The aerial pass resulted in a classified point cloud that was saved as an LAS file with 1-cm spatial precision (Kostyrko et al., 2022).

A significant advantage of using a UAV is that the apparatus collects more accurate data. The spot of light reaching the scanned object can be measured in millimetres. In the case of aircraft laser scanning, this is approximately 20 cm, which directly affects the measurement's precision (Kostyrko et al., 2022). The data obtained for Ledniczka Island were characterised by a point density of 562 points/m^2 (average spacing 4 cm). In contrast, ground-level density was ten times lower, at 5.86 points/m^2 (spacing every 41 cm). Further data processing using the specialised point cloud analysis software LAStools allowed its reclassification. This led to a much better ground-level result, averaged to 43 pts/m^2 (spacing every 15 cm). The digital terrain model obtained as a result of the in-house transformations was characterised by a higher number of points classified having been reflected from the ground surface, which translated into visual "noise" (uncertain measurements, some of which may have reflected from plants in the early vegetation stage) that negatively affected the visual assessment or interpretation of the study area (Kostyrko et al., 2022).

The number of measurement points in the data provided for Ostrów Lednicki that were classified as having been reflected from the ground surface differed from the measurements obtained for Ledniczka. The density of the point cloud was 575 pts/m^2 (average spacing 4 cm), of which 15 pts/m^2 (average spacing 25 cm) were assigned to the ground. It should be emphasised that, although a model with a spatial resolution of 10 cm may be visually more attractive, its scientific value is not necessarily greater than one with a resolution of 50 or 100 cm. This is due to the size of objects of interest to archaeologists (earthwork structures) that are possible to identify (interpret) with this type of data. Fig. 6 shows a depression in the structure of the island. After correlating this 'object' with archival data, it can be concluded with a high degree of certainty that this is the remains of an archaeological excavation from the 1980s (Kostyrko et al., 2022; Štular et al., 2021; Štular and Lozić, 2022; Štula et al., 2023).

Indeed, the higher spatial resolution of the Digital Terrain Model (DTM) derived from Airborne Laser Scanning (ALS) measurements may enable the detection of small archaeological objects, such as logs, piles, or wooden structural elements. However, this increased spatial detail may be associated with a greater presence of noise, leading to a higher occurrence of measurement artefacts. These artefacts can take various geometric forms that may occasionally be mistaken for actual archaeological objects. Therefore, it is prudent to adjust the spatial resolution of the DTM based on the scale of the archaeological structures being sought. For instance, the archaeologically significant negative of the old trench shown in Fig. 6 is approximately 30 m long. The prospecting of structures of this size does not justify the use of very high-resolution remote-sensing measurements, which can be quite noisy.

1.6. Geo-referencing of archive data

The basic data on which the geo-referencing of the archival plans was based was the orthophotomap and the archaeological excavation plan. The basic challenge, however, was to find points common to both cases to which reference data could be assigned. The points should be fixed and stable enough to be sure that there was no shift in the time between the creation of the archive plans and the production of the orthophotos.

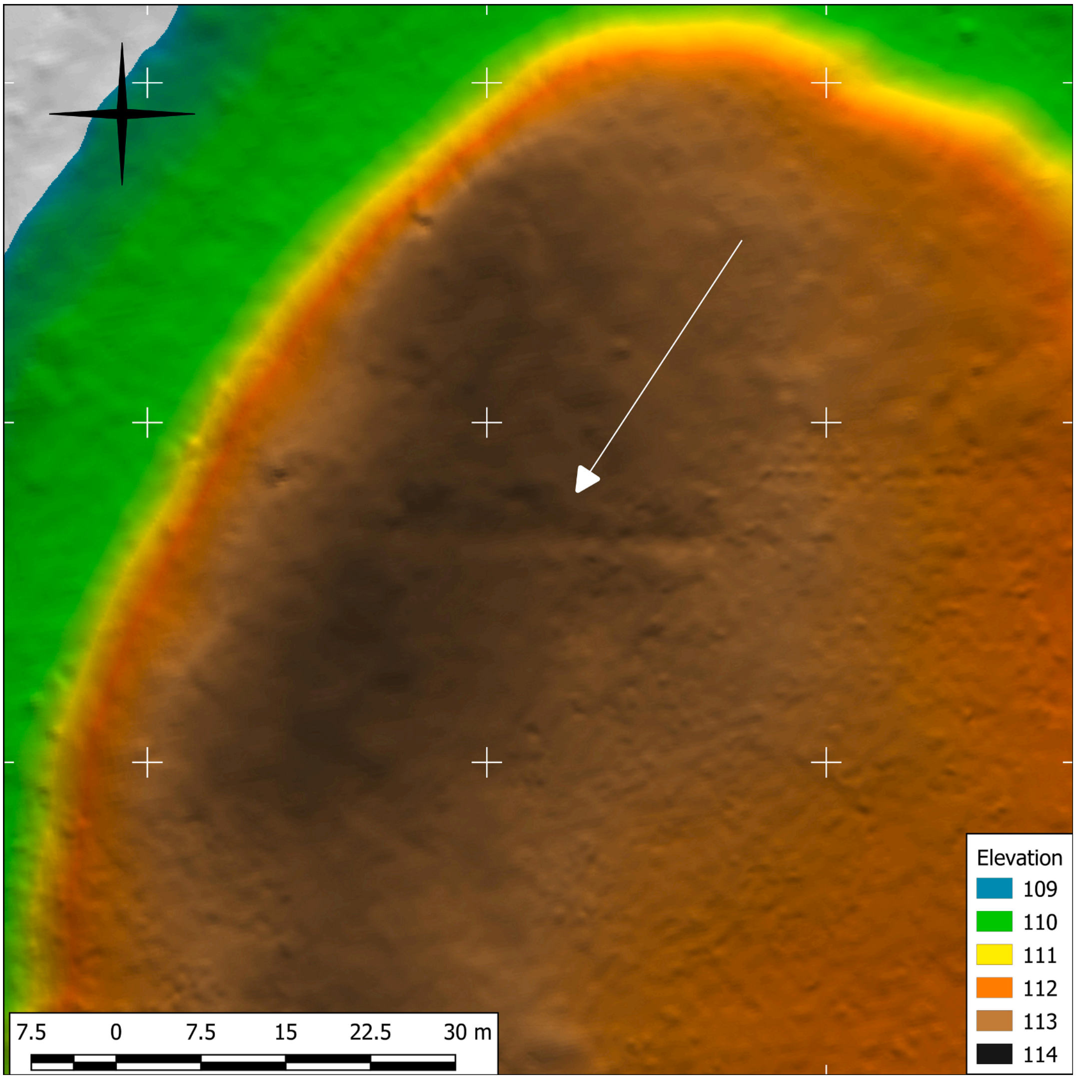

Fig. 6. Negative of the old trench visible on the ALS scan (M. Popek, L. Żuk, M. Kostyrko).

Within the stronghold, the only option was to use the remains of the *Palatium*, as the other fixed objects included on the plan did not coincide with the contemporary orthophotoplan. The georeferencing used the corners of the ruins, which were clearly visible on both the set of excavation plans and the orthophotoplan. At the same time, it was assumed that they had not been altered over the last few decades. The processing was carried out in QGIS using the "Tiling function (TPS)" transformation. For both parts of the plan, the averaged transformation error was 4 pixels, which translates into a real size of 6.68 cm.

The accuracy of the georeferencing was checked on two objects: the foundations of the church and the remains of the *Palatium*. The difference in location between the points measured with the GPS RTK and the church corners visible on the archive plans ranged from 12 to 35 cm. In the case of the *Palatium*, the corners of the building were marked on the orthophotoplan and then compared with the documentation on the georeferenced plan. The difference between the two was between 6 and 33 cm. These differences may be due to various factors, including the accuracy of the archival measurements. However, it should be borne in mind that, on a per-plan scale, this error is minimal.

1.7. Connecting the data

The primary platform for combining underwater and aerial survey data was the GIS environment. This software made it possible to compare and correlate prospecting, magnetic, seismic, acoustic and laser data. This provided a comprehensive picture of Ostrów Lednicki and the surrounding area in a broader context.

QuantumGIS software was used in the project. This open-sourced software, which is still under development, allows for the import of multiple data types. The basis for combining the data was the georeferencing contained in the different survey types. ALS, MBES and magnetometer surveys had their own georeferencing, which allowed automatic import and positioning in the software. Orthophotos based on aerial photographs were positioned based on reference points distributed over the island. The reference points were measured using a differential GPS. This allowed the creation of an orthophoto with a high degree of accuracy. The photogrammetric models were georeferenced after surveying with a total station. The orthophotos produced from the 3D models could thus be easily imported into the software. The biggest challenge was the positioning of the archived plans. This required the reconstruction of the archival survey grid, on the basis of which the plans were positioned.

Integrating bathymetric data for the lake bottom and a height model for the islands in the GIS system allowed the identification of methodological problems for the archaeological identification of the sites (Fig. 1). These problems concerned the water reed belt and the coastal part of the lake out to a depth of 1 m. The multibeam echosounder system (MBES) does not allow a bottom at a depth of less than 1 m to be scanned (Pydyn and Popek, 2022). For airborne laser scanning, the water line is the boundary line for the laser range. Water prevents the reflection of the standard laser beam, and consequently, the method is unsuitable for the identification of aquatic areas (Crutchley and Crow, 2018). For these reasons, a strip of methodological “no man’s land”, inaccessible by the methods mentioned above, appeared in the survey of the two islands in these shallow areas.

Despite noting the above difficulties, the confrontation of the results from the two types of prospection allowed the identification of sites in the water reed belt where medieval structures may be present. The test trench opened by the underwater archaeology team exposed timber structures in this area.

1.8. On the border of land and water

The confrontation and correlation of various prospecting methods, both underwater and on land, allowed the location of timber structures in the water reed belt to be identified. Subsequent test excavations allowed the structures to be exposed and documented. This trench was documented using photogrammetry. Based on numerous photographs, point clouds were built, followed by three-dimensional models of the discovered objects (Fig. 7). Once these models were georeferenced, orthophotos and elevation models of the terrain were produced. The data thus-prepared was suitable to be placed in a GIS environment and combined with MBES and ALS data. This approach to data analysis allowed the structures discovered underwater to be put into a broad context.

Grounded on the data acquired, some anomalies were found that helped to discover structures located offshore. Several of them were noted on the MBES maps, one of which was a wooden yoke beam found during the 2019 prospection. There were no other artefacts around it, which may indicate that it had slid down the slope of the lake. No wooden structures were discovered underwater at this location. However, magnetometric surveys showed some anomalies at this location that could be of anthropogenic origin. ALS analysis, on the other hand, showed that, at this location, the rampart of the fortified settlement was much narrower and had a different shape. This could suggest that it had been destroyed in some way.

Based on these indications, in the year 2020, a survey trench was opened in the discussed shore area. As a result, a significant number of wooden structures associated with the early medieval hillfort were found.

An additional source of information that helped to broaden the context of the structures was the georeferencing and mapping of plans of land excavations explored in the immediate vicinity 30 years ago. This provided a comprehensive picture of the investigated structures. Site topographies, bottom topography and archival data were used for possible interpretation. This broad context was needed to attempt to answer the fundamental research question of whether the relics discovered were land or water structures.

The current state of research allows us to conclude that the study site has two construction phases. One was based on a box structure, while the other was based on driven piles, onto which yoke beams were fitted. It can also be concluded that there were destructs of these structures in the survey trench, but it cannot be determined whether they collapsed during use or as a result of post-depositional processes.

2. Summary and conclusion

Underwater objects must not be surveyed without regard for their terrestrial context. Therefore, combining data obtained from land surveys and underwater prospection plays a major role in the research process. The ideal environment for combining such data is GIS software, which allows the input of both underwater prospection information such as MBES, SBP or magnetometer. The same is true for the input of ALS data. In this way, very detailed and extensive topographic data can be obtained and combined.

The development of underwater photography and photogrammetry software has allowed documentation of structures investigated underwater to be placed in this GIS environment. Relevant software options also allow the placement of geodetic archive data in an analysed space. Such a comprehensive approach to the study of structures found

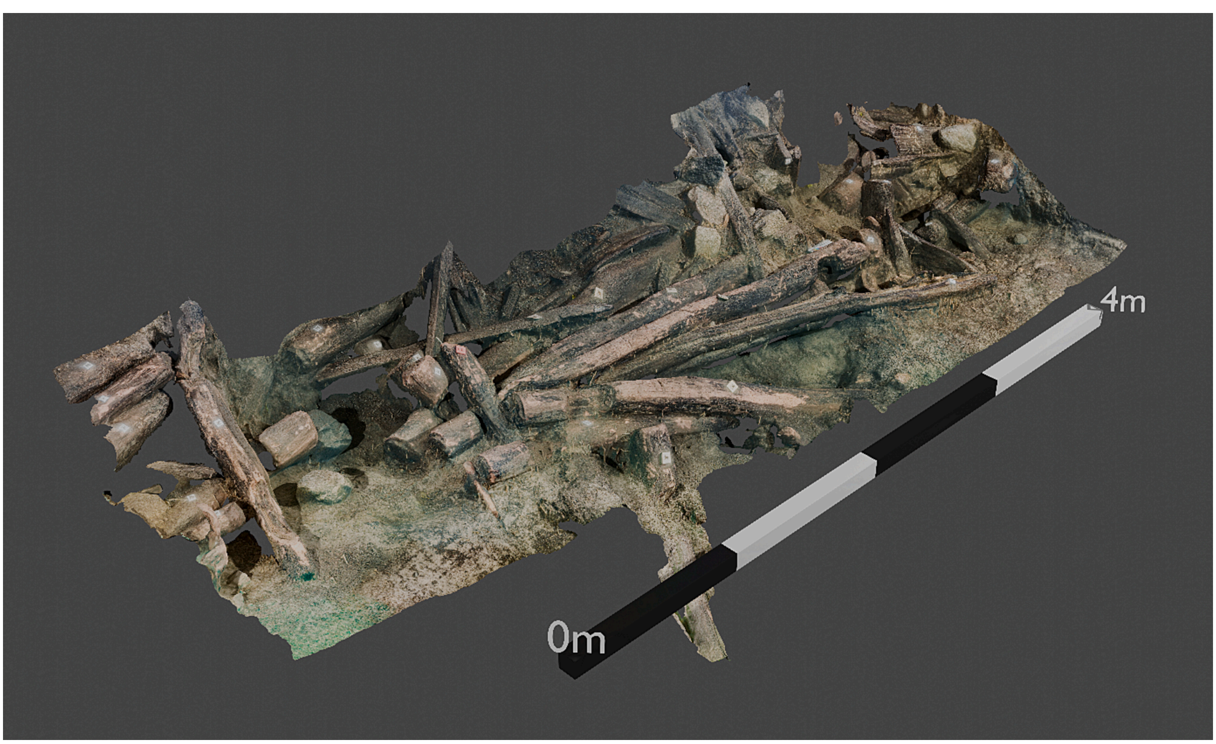

Fig. 7. Photogrammetric model of the excavated structures (M. Popek).

underwater yields tangible results. By combining and correlating data obtained by many methods of prospection, it was possible to locate and preliminarily examine a very interesting wooden structure located on the shoreline of the island Ostrów Lednicki. A combination of these methods can be successfully implemented at other archaeological sites.

CRediT authorship contribution statement

Andrzej Pydyn: Investigation, Project administration. **Mateusz Popek:** Formal analysis, Visualization, Writing – original draft. **Łukasz Janowski:** Formal analysis, Methodology, Writing – original draft. **Andrzej Kowalczyk:** Investigation, Project administration. **Lidia Żuk:** Data curation, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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