Geology, Geophysics & Environment 2023, vol. 49 (4): 401–418

# An inventory of opencast mining excavations recultivated in the form of water reservoirs as an example of activities increasing the retention potential of the natural environment: a case study from Poland

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Received: 30 March 2023; accepted: 15 July 2023; first published online: 15 December 2023

***Abstract:*** The article presents examples of the employment of various geodetic measuring tools used for a detailed inventory of lake basins and shorelines. The measurement and analysis covered three post-mining open pit excavations recultivated as water reservoirs: two in Krakow (Bagry Wielkie and Bagry Małe) and one in Piaseczno (Piaseczno Sulphur Mine). Attention was paid to the factors that reduce the accuracy of the inventory of some flooded post-mining excavations, which determine the degree of usefulness of the morphometric data set for later analyses. According to available estimates, only about one-third of all water reservoirs in Poland have detailed geodetic documentation in the form of bathymetric maps. This documentation usually does not include water reservoirs of anthropogenic origin formed after the flooding of post-mining excavations (mines: sand, gravel, clay, limestone, sulphur, aggregates, etc.). The authors suggest the introduction of a document known as a reservoir documentation card and the creation of a database covering all anthropogenic water reservoirs. Considering the water deficit in Poland, it may be necessary to develop a detailed database of water resources in the short term.

***Keywords:*** geodetic inventory, mining excavations, recultivation, retention, blue infrastructure

## INTRODUCTION

The ability to periodically retain water, otherwise known as retention, is 7.5% in Poland, while its average level in Europe is 20% (Vandecasteele et al. 2018). In the face of progressing climate change, increasing retention capacity is advisable to ensure adequate protection against both flooding and drought (Kõiv-Vainik et al. 2022). Uninterrupted access to water in the correct amounts affects the economy positively, and in particular is crucial for the functioning of agriculture. In terms of the latter, Poland is struggling with the problem of water shortages in a belt stretching from the western border of the country through the Greater Poland Lakeland, the Mazovian Lowland and further south-east to the eastern border of the country. Retention capacities are also fundamental for the energy market, where huge amounts of drinking water (3–4 $m^3$/MWh) are needed to generate energy. With periodic, prolonged periods of hydrological droughts, energy shortages should be feared in the future (*Czym jest retencja?* n.d.).

The existing conditions can be improved by replacing fast surface runoff with slow ground runoff (Zhou et al. 2023). As a result of this, water resources are increased and water balance improved. Considering the fact that Poland is at the bottom of the list of European countries in terms of water resources, care for optimal water retention is essential. To this end, the first strategic document "Water scarcity prevention program" (Ministerstwo Infrastruktury 2021) was created, which comprehensively discusses the possibilities and directions of activities in the field of water retention in Poland. It includes the identification and implementation of activities in the field of building an integrated system of natural and artificial water retention, creating conditions for the sustainable use of water resources, and strengthening social awareness in the context of the need to retain and save water.

Water retention (Zhang et al. 2022) can be divided according to the nature of water, the place of accumulation, or the state of aggregation. The distinction is also made between large- and small-scale retention, where the capacity of the retention reservoir in which water is stored is used as a criterion. The capacity of 5 million $m^3$ marks the border between small and large retention. Separately, micro retention is distinguished, aimed at managing precipitation and surface waters directly in the place of precipitation. The improvement of the local water balance has a significant impact on the water balance of the whole country.

Urban retention, recently a popular topic of research, is understood as a set of activities slowing down the outflow of rainwater and its accumulation in retention reservoirs in the city (Laurenson et al. 2013). The use of dry and wet retention reservoirs as possible options to reduce flood risk in cities is also being tested (Bezak et al. 2021), and in particular the impact of the designed retention reservoir on the flood protection of a given city (Laks & Walczak 2019). Municipal plans for adaptation to climate change include solutions in this area, including green roofs, rain gardens, flower meadows, drainage basins and ditches, permeable surfaces of communication routes and squares, rainwater tanks, and small retention reservoirs (Królikowska & Królikowski 2019).

Currently, analyses are being carried out in Poland to identify the most favourable water reservoirs that can be used in the design of small retention solutions. The research procedure proposed by Wiatkowski et al. (2021) not only includes the analysis of hydrological indicators (reservoir capacity, operation time, dependence on silting intensity, and flood risk index), but also water quality (phosphorus and nitrogen load), hydrogeological conditions (type of geological substrate of the reservoir basin and filtration losses), and the safety of reservoir dams.

Retention reservoirs are created as a result of the creation of a dam, but also due to the use of natural water reservoirs (lakes) by transforming them into retention reservoirs by increasing its size and flooding areas (Sender et al. 2021). Reservoir dams located in catchments with diverse anthropopressure are also the subject of research in terms of ecological risk analysis, in particular maintaining the safety of organisms feeding on their bottoms (Bartoszek et al. 2022). This is related to the accumulation of various heavy metals, granulometric fractions, and humic substances in the bottom sediments of small reservoirs.

In published papers (e.g. Stachowski et al. 2018) detailed concepts of the revitalization of mining areas characterized by water shortage can be found. The use of post-mining workings as water reservoirs fits perfectly into the Small Retention Program, opening up recreation opportunities for the inhabitants of the surrounding areas, shaping the landscape by creating water reservoirs in places where they did not occur naturally. It also improves the microclimate, increases retention (which has a positive effect on the irrigation of neighbouring agricultural areas), and also reduces economic and natural losses caused by possible floods. These activities also contribute to increasing the retention capacity of catchments, something which is particularly important in areas characterized by low water resources (Jawecki 2022).

The results of analyses of the Polish system of strategic and planning documents dedicated to the revitalization of post-industrial areas in Poland (Cała et al. 2019) indicate that it is characterized by an excessive number of studies at the national level, while investment decisions are mainly made at the local level, which lacks detailed guidelines. Developing them on a local scale could solve many problems in the field of reclamation and revitalization, while achieving the objectives of a given region related to, for example, increasing water retention.

Mining activity undeniably has negative consequences for the environment, however, post-mining areas could, with proper planning, provide the possibility of increased absorption of carbon dioxide from the atmosphere and improve regional water retention (Singh et al. 2022), which is confirmed by research on the retention properties of soils in reclaimed post-mining areas.

A comprehensive inventory of the littoral zone and the basins of the reservoirs was carried out using integrated geodetic and bathymetric technologies (Gawałkiewicz 2021). Among the methods of dimensioning retention reservoirs and hydrodynamic modelling, apart from the use of formulas and analytical tools, the use of artificial neural networks can also be distinguished (Pochwat & Słyś 2018).

Reclamation of the mining area of an opencast mine can be carried out by means of solutions from agriculture, forestry, or water (PKN 2022). The latter occurs when mining is carried out on elevations below the groundwater table. Reclamation is then limited to the appropriate shaping of the slopes and the bottom of the resulting water reservoir, taking into account the conditions of stability and load-bearing capacity of the slopes of water reservoirs and their optimal inclination (Kaźmierczak et al. 2022). It is also possible to control the sedimentation process in flood reservoirs by appropriately shaping the bottom of this reservoir (Wurms & Westrich 2008). Kanownik & Rajda (2010) indicate that the reclamation of excavations via water solutions can be one of the main aspects of increasing the retention capacity of catchments, particularly important in areas characterized by low water resources. It is possible to determine a specific value of increasing small-scale retention for the analyzed catchment and local area authority with hypothetical parameters of the exploitation reservoir (assumed for the reservoir after the end of exploitation).

According to Choiński & Ptak (2014), only about one-third of all water reservoirs in Poland have detailed bathymetric plans. A large part of these studies comes from the turn of the 1950s and 1960s, when the largest collection of morphometric information was collected at the request of the Inland Fisheries Institute (Instytut Rybactwa Śródlądowego) based in Olsztyn and illustrated in the form of detailed cartographic studies. In the following years, supplementary bathymetric measurements were carried out on a smaller scale for the purposes of the *Atlas of Polish Rivers and Lakes* (Awedyk et al. 2019), using simplified inventory methods. Such a relatively small set of data on lake water resources in Poland results from the laborious and time-consuming inventory processes of this type of objects and the high costs of obtaining topographic information. However, this is very valuable information that allows for the reliable estimation of real water resources and is the basis for assessing the scale and pace of changes in the parameters of subaquatic reservoirs (Jakubiak & Panek 2017).

A reliable assessment of the actual morphometric parameters of mining excavations recultivated in the form of water reservoirs is crucial for assessing the amount of accumulated water. Measuring technologies have changed over the years and the accuracy of the measuring equipment employed are of fundamental importance for the accuracy of the determined shape of the water reservoir's bottom. The research problem analyzed in this work is the accuracy of determining the depth of a water reservoir, which plays a major role in calculating the reservoir's volume. The accuracy of water column measurement declared by manufacturers of various types of single-beam echosounder (SBES) should not be accepted uncritically, since it depends on a number of factors analyzed by the authors in this article., For the assumed variant data, the authors determined the values of bottom shape measurement errors that occur during bathymetric measurements carried out using a single-beam echosounder both analytically and in the field.

## METHODS

Building a very precise, digital bathymetry elevation model is necessary to assess the amount of accumulated water. Existing bathymetric methods are analyzed and compared with each other in terms of data acquisition techniques, model accuracy, and interpolation algorithms for mapping underwater terrain (Ferreira et al. 2022).

The topography of the water reservoir bottom determined from a ship is the most commonly used topographic method, one which also ensures the high resolution of the obtained image.

A bathymetric set consisting of a single-beam echosounder and a GPS receiver can be mounted on platforms such as ships, unmanned surface vehicles (USV), or autonomous underwater vehicles (AUV) (Zongjian 2008, Samad et al. 2013, Rossi et al. 2020).

The key factors enabling the creation of correct bathymetric digital elevation models are measurement accuracy and resolution. The accuracy of the created model of a water reservoir bottom depends on the type of device used for measurement (calibrated and with the use of appropriate corrections), water depth, and bottom topography, factors which the authors have highlighted in this article. Moreover, to increase the resolution of bathymetric maps, interpolation is carried out using the kriging (Zhang et al. 2015) and inverse distance to a power (IDW) techniques (Amante & Eakins 2016). In recent years, machine learning techniques have also been used to improve the accuracy of bathymetric maps (Moran et al. 2022).

Environmental factors that may affect the accuracy and reliability of bathymetric data include: water transparency, turbidity, surface waves, currents, and bottom composition (Ernstsen et al. 2006, Stammer et al. 2014). The presence of these factors may affect the accuracy of the obtained data (by causing attenuation, scattering or refraction of the signal (Rowley et al. 2020)

In this study, three water reservoirs which were created as a result of the reclamation of opencast mining excavations were subjected to a detailed inventory: Piaseczno reservoir in Piaseczno, Bagry Lake (Bagry Wielkie) and Płaszów Pond (Bagry Małe) in Krakow (Fig. 1). These are water reservoirs without outflow and in which there is no water exchange.

For the reservoirs under consideration, a query of archival materials regarding the exploitation, method of reclamation, and possible geodetic inventory conducted by other authors in previous years was carried out, followed by a detailed geodetic inventory of the lake basins and the surrounding area together with an analysis of the factors affecting the accuracy of morphometric measurements.

The analytical methods employed are based on relationships known and used in geodetic calculations regarding the analysis of accuracy and summation of measurement errors in accordance with the law of error (Bouleau 2021).

The various measuring equipment used to measure depth (El-Hattab 2014) allows possible differences in the accuracy of measurements to be highlighted. These do not depend on the observer but rather on the measurement set used, something which is of great practical importance.

The added value of the article and which undoubtedly constitutes a contribution to the development of knowledge on the creation and monitoring of water reservoirs in former open-pit mine workings, is the collection of further experience obtained on the basis of field studies of physically existing facilities in specific environmental conditions (Gammons et al. 2009). The aspect of maintaining the stability of slopes at the time of the flooding of the excavation with water, as well as during the subsequent use of the reservoir, is of great practical importance when verified in situ. It is a constantly pertinent aspect, and taking into account the aspect of human health and life is an element requiring continuous research in order to increase the state of knowledge based on experiences in the field (Schultze et al. 2022).

The Płaszów Pond and Bagry Lake reservoirs are located in the Małopolskie Voivodship, within the administrative borders of the city of Krakow. They were created as a result of opencast mining activities which extracted sand, gravel and clay. The geological structure of the rock mass underlying the Płaszów Pond and the Bagry Lake is presented in the geological section (Fig. 2) prepared on the basis of the data of the Polish Geological Institute (Polski Instytut Geologiczny) and our own bathymetric measurements.


*Fig. 1.* Location of the analyzed water reservoirs created as a result of the reclamation of mining excavations against the outline of Polish voivodships

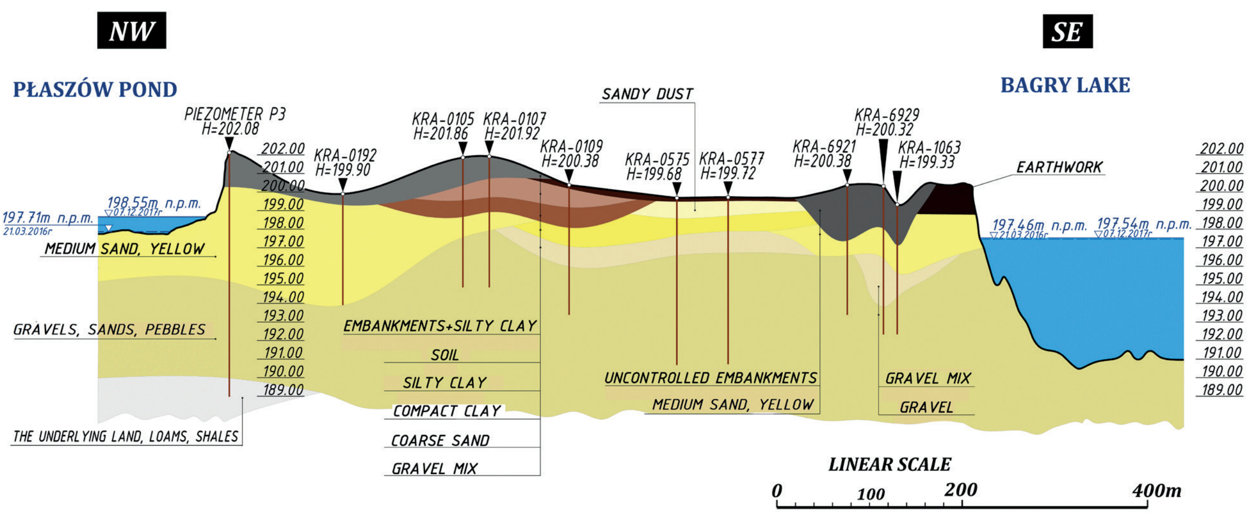


*Fig. 2.* Geological cross-section of the area from Płaszów Pond to Bagry Lake

The geological cross-section was drawn according to the profile line (Fig. 3) presented against the background of the communication outline of housing estates of the city of Krakow, where the reservoirs are located.

The Piaseczno reservoir is located in the Świętokrzyskie Voivodship, in the town of Piaseczno. It was created as a result of opencast mining activities in which sulphur ore was extracted. The choice of the mining method for one of the two identified patches of chemical sediments Świniary – Piaseczno (located along the left bank of the Vistula River) resulted from the geological structure and small deposit depths not exceeding 100 m (Pawłowski 1956, Kwiecień 1979, Sokołowski et al. 2016) (Fig. 4).

For the selected reservoirs, a detailed inventory of the shoreline and the adjacent area was made, and models of lake basins constructed in order to determine possible changes in the volume of the reservoir. These measurements were made using integrated geodetic measurement technologies (Gawałkiewicz 2018), including an ultrasonic echo sounder, *XY* positioning module and a vessel (Gawałkiewicz & Madusiok 2018), as characterized in Table 1. Measurement ranges and accuracy of individual instruments were determined on the basis of information provided by equipment manufacturers (Eagle Electronics 1992, Lowrance 2011a, 2011b, OHMEX Instrumentation 2016) and the results of field research (Wicher 2009).

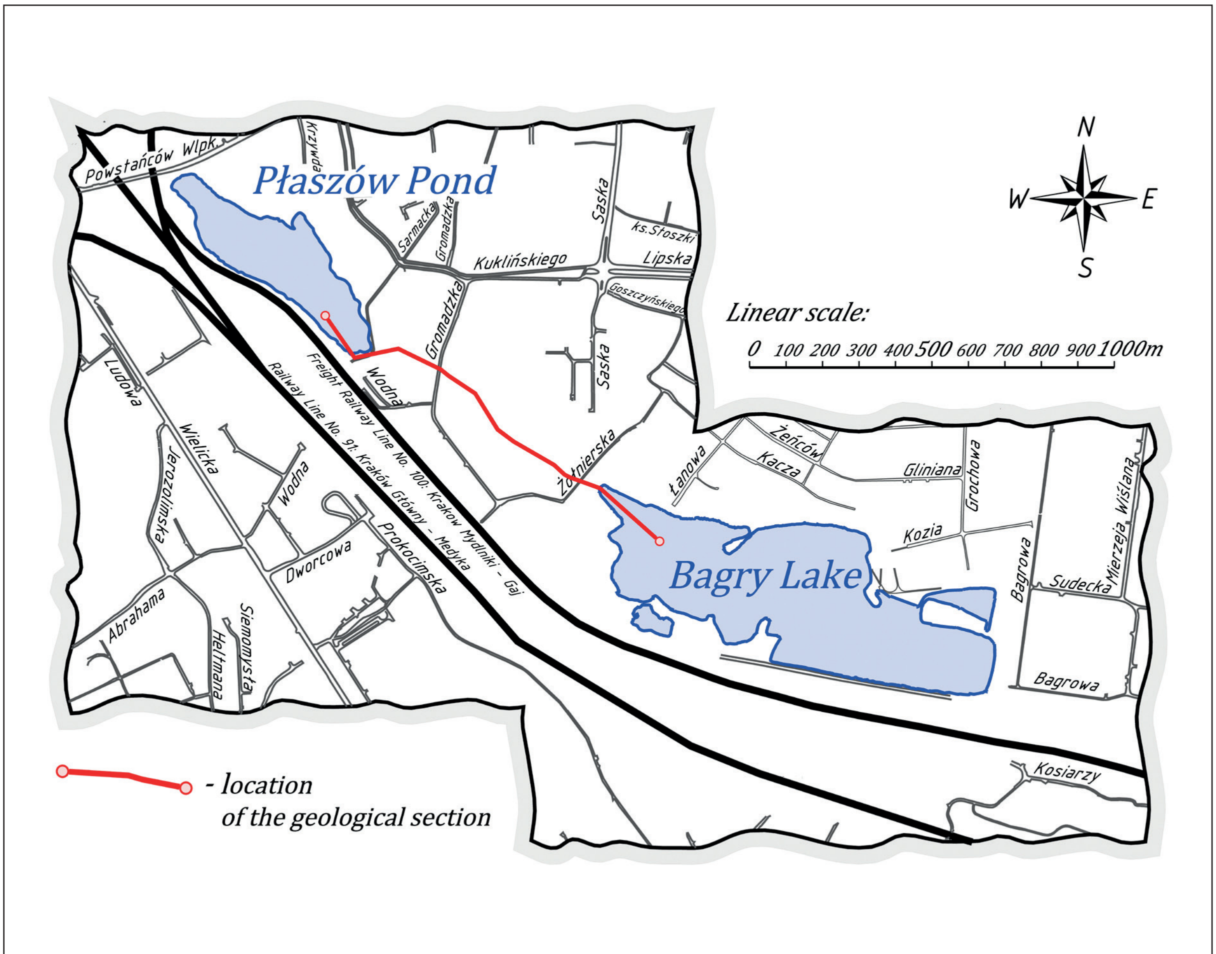


*Fig. 3. Location of the geological profile and water reservoirs: Płaszów Pond and Bagry Lake against the background of the communication outline of the area of housing estates: Płaszów and Prokocim of the city of Krakow*

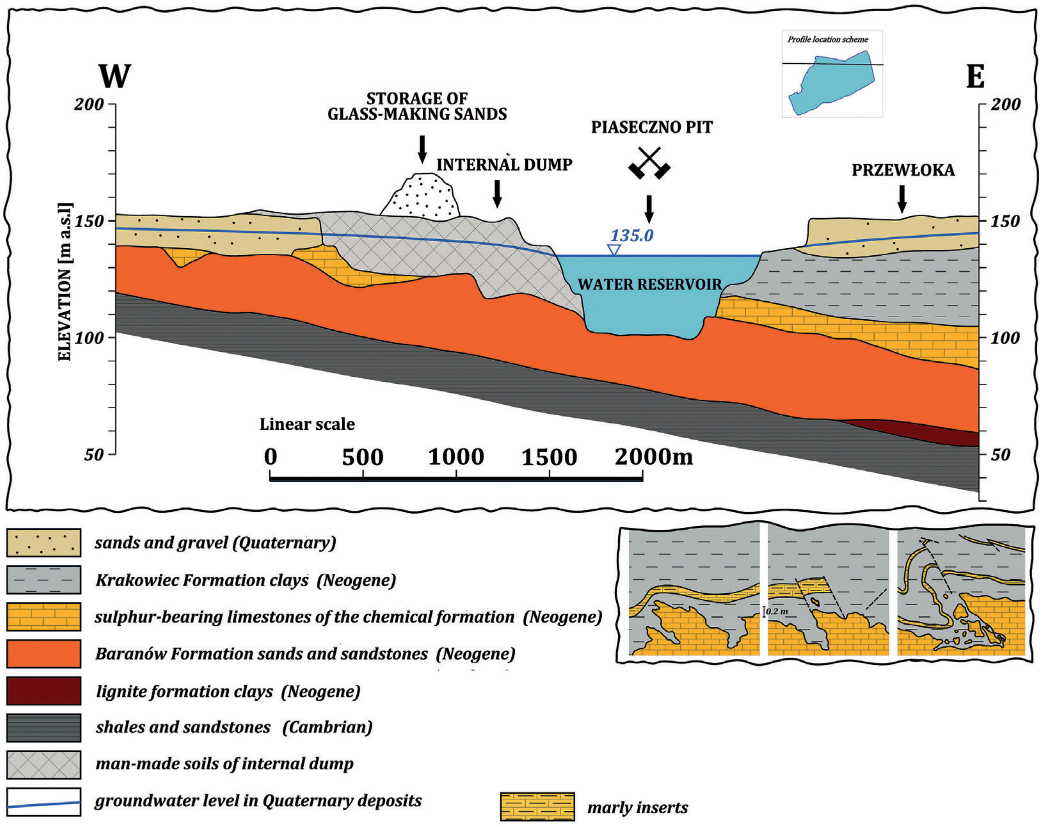


***Fig. 4.*** *Geological cross-section through the Piaseczno excavation in the W-E direction*

***Table 1***
*Basic technical parameters of measurement sets used in the inventory of water resources of water reservoirs Bagry Lake and Płaszów Pond (Krakow) and a post-sulphur pit Piaseczno (Piaseczno)*

| Set data | Bagry Lake | | Płaszów Pond | Piaseczno |
|---|---|---|---|---|
| | Large body of water | Small body of water | | |
| Depth probe $G$ | Lowrance Elite 4x-HDI | Lowrance Mark-4 | Eagle Ultra II | OHMEX / P66 / SonarMite BTX |
| Depth measurement range [m] | 0.2–229.0 | 0.0–305.0 | 0.0–100.0 | 0.3–75.0 |
| Width of the ultrasonic beam cone [°] | 60 (83 kHz), 120 (200 kHz), 55 (455 kHz), 30 (800 kHz) | 60 (50 kHz), 120 (200 kHz), 55 (455 kHz), 30 (800 kHz) | 8 or 20 | ±4 |
| Type of echosounder / Operating frequency | one-beam 83/200/455/800 kHz | one-beam 50/200/455/800 kHz | one-beam | one-beam 235 kHz |
| Depth measurement accuracy $m_G$ [m] | ±0.10 | | | ±0.025 |
| Bathymetric pickets $XY$ positioning module (external) | GPS Receiver R8s Trimble | | parallel profile method | GPS Receiver R8s Trimble |
| Accuracy of (external) GPS positioning $m_{XY}$ [m] | ±0.03 (ASG-EUPOS) | | – | ±0.03 (ASG-EUPOS) |
| GIS (internal) positioning accuracy $m_{XY}$ [m] | ±2.1 | ±1.0–3.0 ±2.7 | <0.5 | – |
| Watercraft | pedalo | hydrodrone smart-sonar-boat | pontoon | hydrodrone seefloor |

A full inventory of the reservoirs was carried out using the following sets:

- Large reservoir (Bagry Lake): using the Lowrance Elite-4x HDI acoustic probe with a built-in GPS module (a popular device dedicated to anglers and sailors), mounted on a pedal boat.
- Small reservoir (Płaszów Pond): using the SmartSonar-Boat hydrodrone, equipped with a GNSS positioning module, i.e. the R8s Trimble antenna.
- Piaseczno reservoir: using a modular system based on two cooperating components: hydrographic and positioning. The hydrographic component consisted of a catamaran (by Seafloor Systems) and an echo sounder consisting of a digital (active) P66 transducer equipped with a microprocessor, used for filtering (signal denoising) of the transmitted frequencies and interpretation of return signals in real time. The applied echo sounder with a transducer with a frequency of 235 kHz, with a focused, narrow width of the ultrasonic pulse beam (±4°) prevents the averaging of the returning signal. This guarantees the high degree of accuracy of the depth measurements given by the RMSE (root mean square error) at the level of ±0.025 m signals coming from both components (Bluetooth wireless connection).

## RESULTS

The query of archive materials of the Płaszów Pond area allowed for the analysis of changes in the shape and surface of the basin. Despite the end of its operations falling in 1945, it was only in 1999 that a full inventory of the reservoir was made, using the Eagle Ultra II probe from a pontoon deck and employing the transverse profile method (signalled with a rope, with starting and ending points of the profiles determined tacheometrically). As a result of the geodetic inventory of the coastline made in previous years, it was possible to compare the shape of the coastline and its changes over the course of the last 34 years. At that time, according to Figure 5, the coastline underwent significant changes resulting from the need to expand the Krakowskie Centrum Handlowo-Targowe complex (commonly known as "Tandeta").

The Bagry Lake is originally an excavation pit of clay used for the production of ceramics by local brickyards, the beginnings of which date back to the 1920s and 1930s. Intensified exploitation of sands and gravels underlying the clay layer was carried out during the war with the use of traditional excavators and a narrow-gauge railway. It was possible thanks to the use of pumps that drew rainwater and groundwater from the bottom of the excavation and discharged it through pipelines into the nearby Vistula River. This exploitation system enabled an efficient and orderly system of aggregate acquisition, which translated into a relatively regular geometry of the lake basin. In the post-war period, the mining system was changed to adapt the method to the prevailing situation in the field, when the excavation was partially filled with water. Using excavators located on barges, the aggregate was taken from under the water table without controlling the morphometric model of the bottom. Therefore, a significant variation in depth is observed in the western part, which abounds in numerous thresholds and pits. The exploitation of sands and gravels was completed in the 1970s. During the liquidation of the mine, no particular attention was paid to reclamation issues. Over the years, thanks to the natural succession of vegetation in the area of the present reservoir and adjacent areas, an area of biodiversity has spontaneously been created. Since the end of its period of exploitation, the geometry of the reservoir (shoreline) has also been modified. In the 1960s, Bagry formed three separate bodies of water. In the 1970s, two of them were connected during operation. In the southern part, along the railway siding, the reservoir was partially filled in. Also, a small pond in the south-western part was clearly corrected (Fig. 6).

The Piaseczno reservoir is the result of spontaneous filling of the excavation with rainwater and groundwater after the completion of the opencast exploitation of sulphur ore conducted until 1971. The unfavourable topography of the areas directly adjacent to the excavation and their long-term development and the lack of a drainage network in the communes of Łoniów, Koprzywnica and Samborzec compelled the permanent maintenance of a relatively constant water level with an elevation of approx. 138 m a.s.l. with the use of pumps, which is a value of about 8 m lower than the level of the Vistula River and the Tarnobrzeskie Lake (approx. 146 m a.s.l.) which are also located in the vicinity.

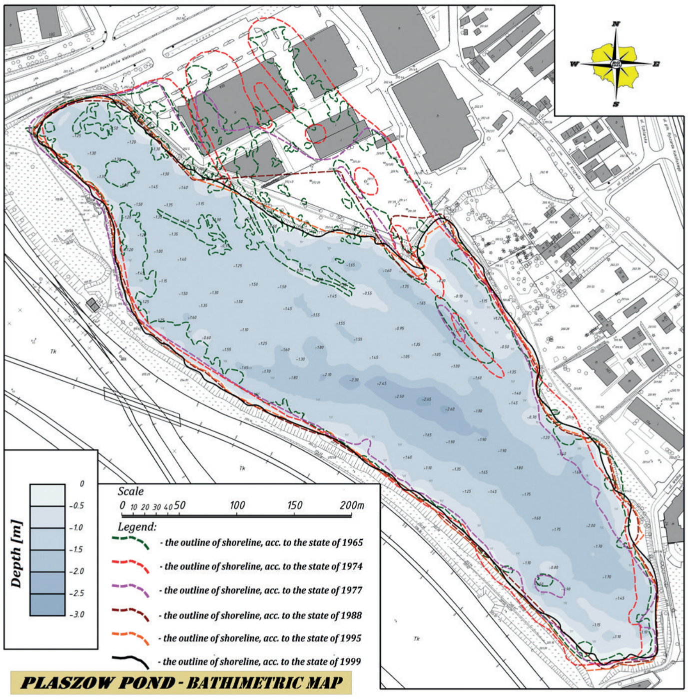


***Fig. 5.*** *Map of the Płaszów Pond area with a bathymetric map and interpretation of changes in the outline of the reservoir in the period 1965–1999*

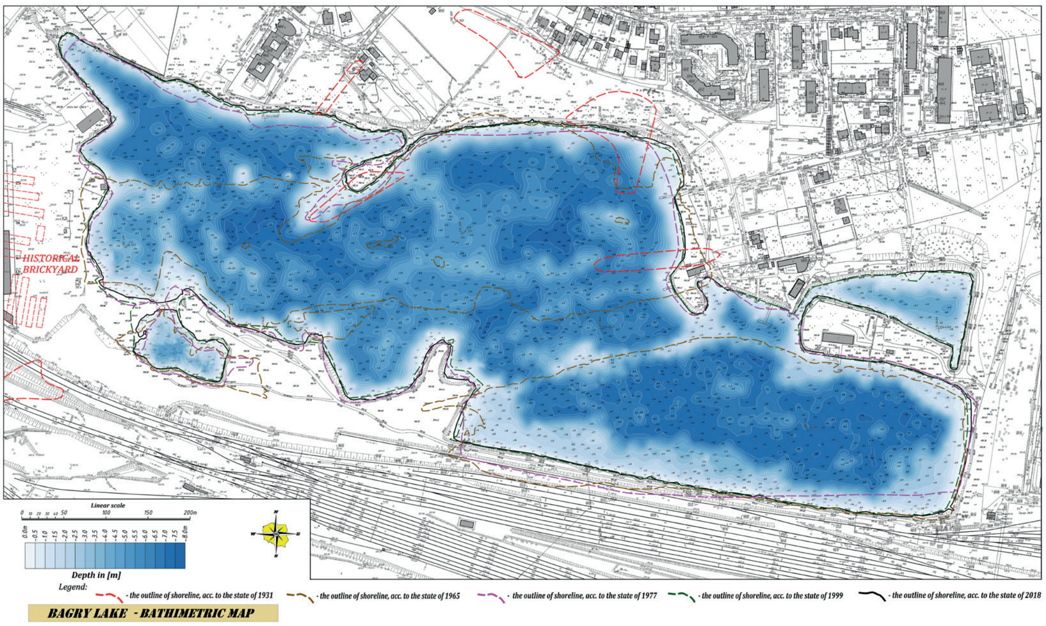


***Fig. 6.*** *Map of the Bagry Lake area with a bathymetric map and interpretation of changes in the outline of the reservoir in the period 1931–2018*

Such action inhibits the process of rebuilding water conditions by maintaining the depression cone. Unfortunately, the liquidation of the depression cone and the restoration of the original water level to the value of approx. 146 m a.s.l., today poses a potential threat to the areas and elements of their development, covering three communes of the Sandomierz County. The excavation itself is still able to accept about 12 million $m^3$ of water but bringing it to a state of equilibrium would involve the problem of flooding (Szmuc & Madej 2010). Due to the size of the registered water resources, the Piaseczno reservoir is classified as a large retention facility. The bathymetric map of the Piaseczno reservoir with the interpretation of changes in the reservoir outline is shown in Figure 7.

The basic morphometric parameters of the reservoirs, obtained as a result of bathymetric and situational-height measurements, are presented in Table 2. The table lists the areas of water bodies, lengths of coastlines, volumes of water resources, and the average and maximum depths of the reservoirs.

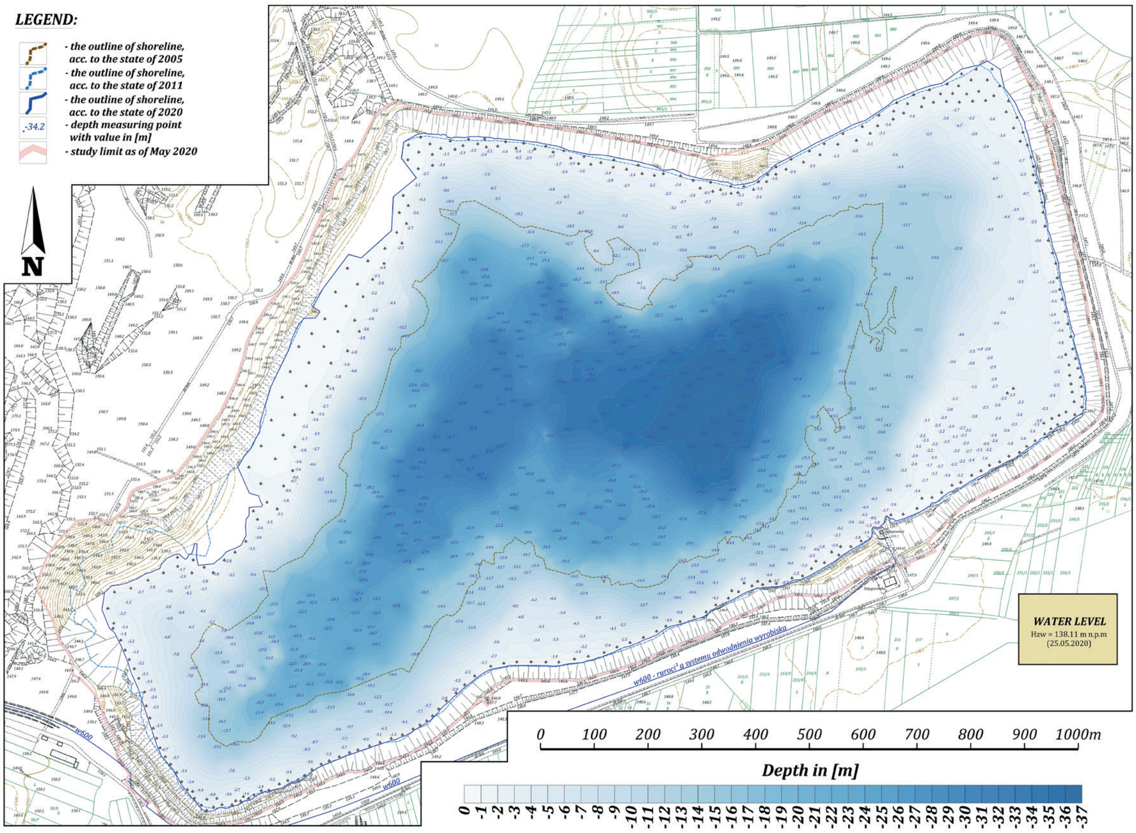


***Fig. 7.*** *Map of the Piaseczno reservoir area with a bathymetric map and interpretation of changes in the outline of the reservoir in the period 2005–2020*

***Table 2***
*Basic morphometric parameters of the water reservoir Bagry Lake and Płaszów Pond (Krakow) and a post-sulphur pit Piaseczno (Piaseczno)*

| Morphometric parameter | Bagry Lake | | Płaszów Pond | Piaseczno |
|---|---|---|---|---|
| | Large body of water | Small body of water | | |
| | State for 2016 | State for 2018 | State for 1999 | State for 2021 |
| Water area [ha] | 30.03 | 0.60 | 8.96 | 137.15 |
| Shoreline length [m] | 4,066.7 | 364.6 | 1,700.9 | 5,511.0 |
| The volume of water resources [m$^3$] | 1,405,762 | 11,505 | 94,985 | 20,679,639 |
| Maximum depth [m] | −7.80 | −5.24 | −2.47 | −36.83 |
| Average depth (GRID 5 m × 5 m) | −4.66 | −2.04 | −1.06 | −14.88 |
| Reservoir status – retention | small | small | small | big |

The following components affect the accuracy of bathymetric (single point) measurements:

– $m_{Pi}$ sonar situational positioning error (depending on the class of the GPS receiver);
– error of the momentary deflection of the sonar axis by the angle a resulting from the waving of the water table affecting the behaviour of the vessel (minimization of this factor is possible by adjusting the measurement time to weather conditions – windless season);
– $m_G$ depth measurement error resulting from the design of the transducer, determined individually by the manufacturer or determined by the user through tests.

The influence of the situational positioning error of the sonar $m_{Pi}$, assuming a uniform slope of the lake basin at the measurement point, on the values of the depth measurement errors $\Delta g_{i'}$ and $\Delta g_{i''}$ is determined from Formula (1):

$$\Delta g_i = \pm m_{P_i} \cdot \mathrm{tg}\,\beta_2 \qquad (1)$$

the components of which are xplained in Figure 8.

In the case of water reservoirs created as a result of the reclamation of mining excavations, the inclination of slopes located below the water table usually does not exceed the angle of the natural fall, which guarantees their stability. On the basis of the selected profile of the bottom of the reservoir, with an extreme drop of 63°, the values of depth errors resulting from the sonar positioning error were determined (Table 3). The analysis shows that the accuracy of sonar positioning has a significant impact on the result of measuring the depth of the reservoir. Depending on the accuracy of the GPS positioning of a given probe, different degrees of depth determination accuracy are obtained. Probes with low positioning accuracy (single-frequency receivers) should only be used for shallow water bodies after the exploitation of natural aggregates with undifferentiated bottom morphology. Probes with a high degree of positioning accuracy (see the OHMEX + GNSS R8s measurement set) guarantee decimetre accuracy in determining the depth, even in the case of extremely unfavourable geometry, recorded by the authors.

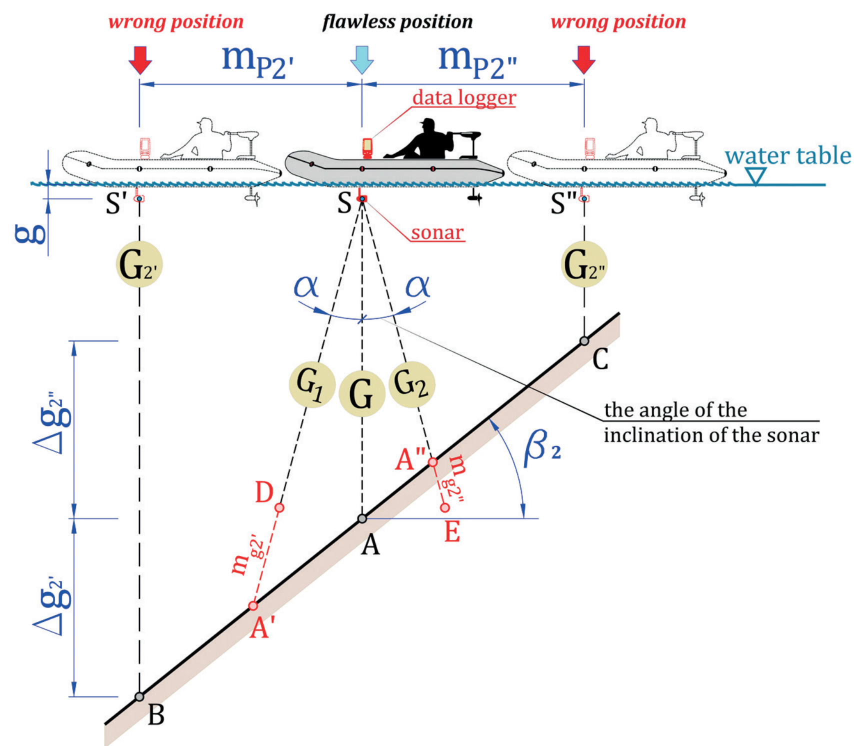


***Fig. 8.** Analysis of the impact of $m_{P_i}$ sonar situational positioning errors and sonar axis deflection α on the magnitude of errors $\Delta g_{i'}$, $\Delta g_{i''}$, $m_{g2'}$ and $m_{g2''}$ in determining the depth G for a uniform bottom slope*

***Table 3***
*Examples of depth measurement errors $\Delta g_{i'}$ and $\Delta g_{i''}$ for selected conditions of the bottom morphology (uniform bottom inclination and real profile) and technical parameters of the measurement sets used on the example of a selected fragment of the Piaseczno reservoir profile*

| **Parameter** | **LOWRANCE** | | | | | |
|---|---|---|---|---|---|---|
| | **uniform bottom inclination**<br>**real profile** | | | | | |
| | **Value** | **$\Delta g_{i'}$ [m]** | **$\Delta g_{i''}$ [m]** | **Value** | **$\Delta g_{i'}$ [m]** | **$\Delta g_{i''}$ [m]** |
| Bottom slope $\beta_2$ [°] | 63 | 5.30 | −5.30 | 6 | 0.28 | −0.28 |
| Actual depth $G$ [m] | 28.44 | | | 24.06 | | |
| Horizontal positioning error $m_{P2'}/m_{P2''}$ [m] | ±2.7 | 2.22 | −1.80 | ±2.7 | 0.38 | −0.39 |
| Sonar axis deflection α [°] | 0 | | | 0 | | |
| **Parameter** | **OHMEX + GNSS R8s** | | | | | |
| | **uniform bottom inclination**<br>**real profile** | | | | | |
| | **Value** | **$\Delta g_{i'}$ [m]** | **$\Delta g_{i''}$ [m]** | **Value** | **$\Delta g_{i'}$ [m]** | **$\Delta g_{i''}$ [m]** |
| Bottom slope $\beta_2$ [°] | 63 | 0.20 | −0.20 | 6 | 0.01 | −0.01 |
| Actual depth $G$ [m] | 28.44 | | | 24.06 | | |
| Horizontal positioning error $m_{P2'}/m_{P2''}$ [m] | ±0.1 | 0.20 | −0.18 | ±0.1 | 0.01 | −0.01 |
| Sonar axis deflection α [°] | 0 | | | 0 | | |

The values in Table 3 indicate that the depth error $\Delta g_{i'}$ and $\Delta g_{i''}$ at a uniform bottom slope is about twice the sonar positioning error.

The linear value of the depth change resulting from the instantaneous deviation of the ultrasonic transducer from the vertical can be mathematically determined according to the following formulas, according to the marks shown in Figures 8 and 9:

$$m_{g2'(A'D)} = G \cdot \frac{\cos\beta_2}{\cos(\alpha + \beta_2)} - G \tag{2}$$

$$m_{g2''(A''E)} = G \cdot \frac{\cos\beta_2}{\cos(\alpha - \beta_2)} - G \tag{3}$$

where:

- $G$ – actual depth of the reservoir at the measurement site,
- $\alpha$ – exemplary angle of instantaneous deflection of the sonar axis for light hydro drone-type vessels,
- $\beta_2$ – angle of inclination of the bottom at the measurement point.

Example values of depth errors $mg_{i'}$ and $mg_{i''}$ determined with the assumption of a uniform slope and the actual bottom profile (see Fig. 9) determined on the basis of Formulas (2) and (3) for the selected measurement profile A-B in Piaseczno for selected depths and slopes are presented in Table 4.

The impact of the momentary deflection of the sonar from the vertical, causes significant changes in the depth value indications, especially in extreme situations, uniform bottom slopes determined in accordance with Formulas (2) and (3). In fact, in the case of the considered measurement site, the morphometric characteristics of the bottom can significantly reduce the error value, as evidenced by those included in Table 4. For the extremely inclined slopes recorded on the Piaseczno reservoir, in accordance with mathematical Relationships (2) and (3), the depth error values of the order of several meters were obtained. This practically disqualifies the measurement set based on light vessels (hydro drones) for use in excavations, with characteristic profiles in the form of escarpments and ledges resulting from the exploitation system used.

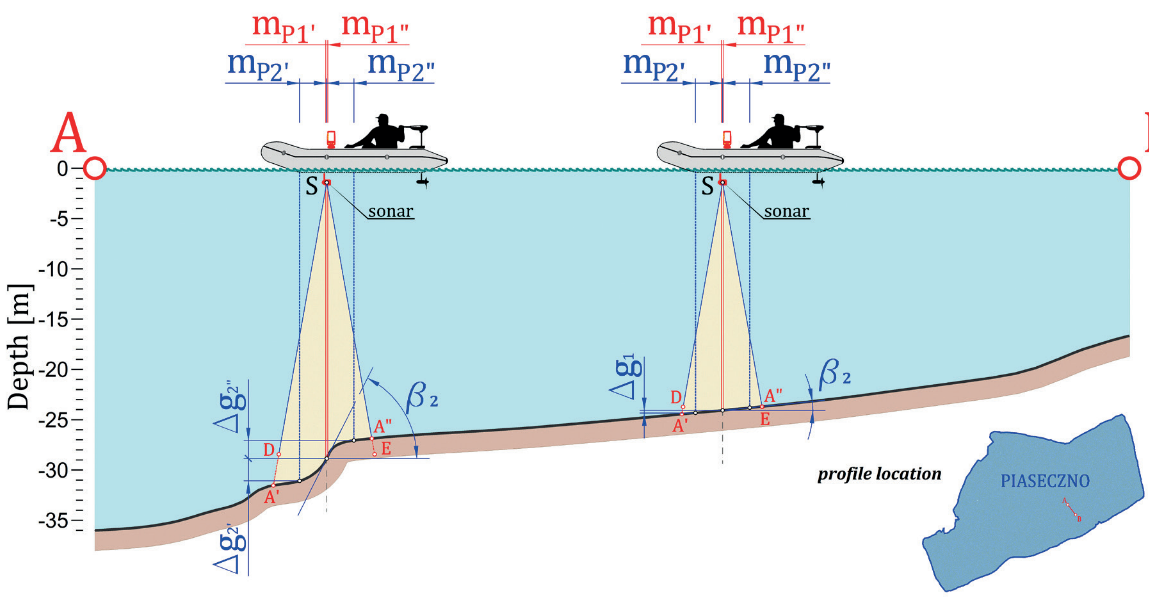


***Fig. 9.** Analysis of the impact of $m_P$ sonar situational positioning errors and sonar axis deflection α on the size of errors $\Delta g_{i'}$, $\Delta g_{i''}$, $m_{g2'}$ and $m_{g2''}$ in determining the depth G in the case of knowledge of the actual bottom morphology*

***Table 4***
*Exemplary errors for selected conditions of the bottom morphology and technical parameters of the measurement sets used on the example of a selected fragment of the Piaseczno reservoir profile acc. to the Formulas (2) and (3)*

| **Parameter** | **Uniform bottom inclination** | | | **Real bottom morphology model** | | |
|---|---|---|---|---|---|---|
| | **Value** | **$g_{i'}$ [m]** | **$g_{i''}$ [m]** | **Value** | **$g_{i'}$ [m]** | **$g_{i''}$ [m]** |
| Bottom slope $\beta_2$ [°] | 63 | 15.72 | −6.98 | 6 | 0.83 | −0.07 |
| Actual depth $G$ [m] | 28.44 | | | 24.06 | | |
| Sonar axis deflection α [°] | 10 | 3.15 | −1.60 | 10 | 0.63 | −0.03 |

Metrological tests conducted on the basis of single-beam probes by Gołuch et al. (2010) on reservoirs with a small morphological differentiation of the basin, proved that the $m_G$ depth measurement errors ranged between ±0.11 m (pelagial zone) and ±0.19 m (littoral zone).

In turn, Popielarczyk & Templin (2014) emphasize that the accuracy of determining the depth depends on:
- signal transducer frequency;
- characteristics of the water environment (temperature and the influence of the thermocline on the speed of sound in water);
- degree of salinity and water turbidity (content of dusty and clayey particles);
- the effect of Karman vortices around the transducer caused by the propellers of the vessel;
- type of bottom (silted bottom covered with aquatic vegetation may decrease in the accuracy of depth readings in the littoral zone, and a hard bottom covered with sand or clay in the pelagic zone guarantee high measurement accuracy).

Laboratory tests conducted by Lymtech (Ohmex Instrumentation 2016) confirm that the salinity of water and the change in water characteristics (warm fresh water – cold salt water) can only cause distortion of sonar indications at the level of about ±20 cm at a depth of 10 m. A light vessel (hydro drone) is designed for bathymetric measurements in the range of small depths, therefore it does not have a gyroscopic system whose role is to compensate for the impact of the motion of the vessel subjected to wave pressure on the stability of the measurement system.

## DISCUSSION

In the case of the discussed water bodies in Krakow, the reclamation of post-mining areas was not carried out in accordance with the contemporary canons of revitalization. In fact, the depression slowly filling with water resulted in the spontaneous regulation of water relations and the stabilization of the water table. For years, cartographic documentation on historical topographic maps and orthophoto maps consisted of only drawing the course of the shoreline, which made it possible to assess the scope and directions of the city's investment. Especially in the case of the Płaszów Pond, this significantly changed the geometric characteristics of the reservoir and depleted its water resources, as illustrated in Figure 5.

Today, measurement tools as well as IT, mathematical and graphic tools provide the basis for creating very detailed environmental studies, including water reservoirs and their parameterization, as part of the inventory and monitoring of water resources in Poland. The increasing water deficit in Poland will require quantitative analyses of water resources and qualitative assessment. Therefore, each body of water and its adjacent areas should be inventoried in such a way as to enable a reliable assessment of their condition over time. This should not only concern changes in the amount of water, the geometric characteristics of the lake basin, but also biodiversity, which determine the increase or loss of natural values. It is important that the base inventory is made with the highest possible accuracy and properly parameterized. It seems necessary to build databases in a descriptive form (location, history, and origin), graphic (cartographic in the form of maps and profiles) and parametric (quantitative and qualitative characteristics of the object) of all water reservoirs, regardless of the size of retention resources and the origin of reservoirs. Attempts at qualitative assessment usually concern a small area with a limited scope of collected information, as exemplified by the studies of Jakubiak & Panek (2017).

Determination of water resources retained in reservoirs on the basis of time-integrated bathymetric data and GNSS observations, is carried out today with the use of IT and mathematical GRID based tools. The multitude of data obtained from the decks of vessels, regardless of the type of carrier, enables an accurate description of the bottom morphology, regardless of the characteristics of the point distribution. The following methods are most often used for the mathematical description of the bottom: triangulation with linear interpolation (regular longitudinal and transverse profiles) or kriging (irregular distribution of points). The description of the bottom geometry through the use of GRID allows for easy assessment of changes in resources and the shape of the lake basin in the case of repeatability of measurements over time (control measurements carried out as part of environmental monitoring), by comparing identical models (with the same locations of grid nodes).

As a result, errors in the lake basin model result mainly from the accuracy of bathymetric measurements and sonar positioning. The accuracy of the situational positioning of the probe is not the only reason for the distortion of the morphometric description of the lake basin. The measurement conditions (wind and water waves) and the characteristics of the vessel (dimensions, weight, structure) may affect the stability of the vessel and the maintenance of the specified geometric arrangement of the measuring devices, which affects the accuracy of determining the depth at the measurement point. An important component is the value of the angle of deflection of the probe axis by angle a from the vertical (Fig. 8). The wave motion, especially in the case of a light craft (hydro drone), which is not equipped with gyro modules, causes the sonar axis to be knocked out of the vertical position, leading to the registration of distorted depths with the value of distortions $m_{g2'}$ and $m_{g2''}$. Distortion values of the depth indications by the sounder are particularly significant in directions consistent with the maximum slope of the bottom at the measurement point.

Therefore, one of the methods of data control and an indicator of their quality is "crossing" the vessel's trajectory, especially in the case of greater depths and morphometric diversity. High consistency of depth data in such zones provides an initial qualitative picture. The second binding parameter is to determine the value of the residuals at the measurement locations as the difference between the directly measured depth at the point and the depth of the model surface (regardless of the algorithm used) at this point. Based on the measurement data set and the developed bowl surface model in the Surfer program, it is possible to determine the root mean square error RMSE as an indicator of the accuracy of mapping the topographic surface of the bottom given by the formula:

$$\mathrm{RMSE} = \pm\sqrt{\frac{\sum_{i=1}^{n}\left[R(x_i)\right]^2}{n}} \quad (4)$$

where $R(x_i)$ – value of the residuum (residual error) at the point of direct hydrographical measurement; this number makes the difference between the value of the depth of the interpolated point and the corresponding value of the depth of the measurement (control) point.

Thus, the error of determining the reservoir basin is:

$$m_V = \pm\sqrt{\left(\mathrm{RMSE}\cdot\sqrt{P\cdot P_o}\right)^2 + \left(m_o\cdot\sqrt{\frac{P}{4}}\right)^2 + \left(\frac{1}{2}\cdot\varepsilon_{\max}\cdot P_o\cdot\sqrt{n}\right)^2} \quad (5)$$

where:

RMSE – root mean square error, which was taken as the value of the average residual determining the degree of adjustment of the GRID model to the distribution of bathymetric measurement points (for example, for the Piaseczno reservoir RMSE = ±0.131 m, and for the Bagry Lake RMSE = ±0.097 m),

$P$ – surface area of the reservoir,

$P_o$ – surface area of a single GRID quadrilateral,

$m_o$ – average depth measurement error, resulting from the specifications used to measure the ultrasonic echo sounder:

$m_o$ = ±0.025 m (OHMEX) and $m_o$ = ±0.10 m (Lowrance Elite-4x/ Lowrance Mark-4/ Eagle Ultra II),

$e_{max}$ – the greatest distance between the spherical surface and the square surface, identical to the maximum depth value,

$n$ – the number of quadrilaterals with dimensions of 5 m × 5 m (assumed for models) filling the area.

Formula (5) shows that, for example, with a reservoir volume of $V$ = 20 679 639 m$^3$ (Piaseczno), the average volume error is $m_V$ = ±107 210 m$^3$, which is a relative error of ±0.52%, and for the Bagry Lake with a volume of $V$ = 1 405 762 m$^3$, the average volume error is $m_V$ = ±4 239 m$^3$, which is a relative error of ±0.30%. The obtained error values suggest that, with a fifteen-fold difference in the $V$ parameter of both reservoirs, the relative error in determining the volume differs only by 42% with similar RMSE parameters, despite large differences in the morphometric characteristics of both objects (depth, surface, degree of geometric diversity of the bottom).

In the case of tank measurements for scientific and research purposes in terms of determining:

- changes in morphometric characteristics over time as a result of e.g. climate changes,
- the amount of silting of the reservoir (especially important for septic tanks) and sediments,
- registration of underwater landslides resulting from large fluctuations in the elevation of the water table or water damming,

obtaining high accuracy of the model will require the preliminary identification of the morphological characteristics of the bottom (preliminary measurement) and carrying out a basic measurement taking into account zones of large changes in bottom geometry and depth (planning changes in the density of recorded data and the course of the vessel's trajectory).

## CONCLUSION

The use of mining excavations created after the opencast mining of minerals in urban areas as water storage sites not only increases water retention, but also has a positive effect on the living standards of city dwellers by lowering the air temperature in the vicinity of the reservoir. The advantage of this solution is also the reduction of the maintenance costs of green areas. Undoubtedly, however, the most important role of the presented solution is to increase Krakow's resistance to climate change by locally reducing the effects of torrential rains and flash floods. The work carried out was aimed at inventorying the initial state for the assessment of water resources and the state of the environment in the analyzed area. According to the authors, it would be advisable to carry out this type of inventory on all reservoirs in Poland and create a database of objects for the implementation of many goals in the fields of spatial planning, water management, and protection against drought and floods.

According to the authors, water reservoirs should have information and scientific cards that can contain a number of important information of an interdisciplinary nature regarding, among others: the institution that owns the prepared documentation (address), the genesis of the reservoir, the assigned functions and method of development, the detailed location of the reservoir, the nature of measurement data (density of measurement data, accuracy, elevation of the water table and its change over time, raw data/processed in the form of a GRID grid), morphometric characteristics of the lake basin (bathymetric maps that can be the starting point for assessing the size of water resources), or also morphometric parameters.

In the case of morphometric indicators, an important role in the description of the reservoir is played by: the volume of retained water (the method of determining the amount of resources and the error in determining this parameter), the surface of the reservoir and the geometry of the shoreline, the elevation of the water table determined during hydrographic measurements (knowledge of the bottom model and the elevation of the water table is a necessary condition for precise determination of, among others, the rate of silting up of the reservoir, registration of underwater landslides resulting from damming water – assessment of the costs of the revitalization and protection of the reservoir). In addition, a full interdisciplinary description of the reservoir's characteristics should include information on threats (ecological disasters), geohazards (landslides in the above-water and underwater parts) or events posing a danger to water resources (hydrological droughts, investments near the reservoir that may affect the volume of water resources) and the characteristics of its biodiversity and its protection.

*The article was financed by a research grant from the Department of Mining Areas Protection, Geoinformatics and Mining Surveying, Faculty of Geo-Data Science, Geodesy, and Environmental Engineering, AGH University of Krakow.*

*The article was financed by a research grant from the Department of Geoengineering and Water Management, Faculty of Environmental Engineering and Energy, Cracow University of Technology.*

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