UDC 556.55:528.47:528.94 https://doi.org/10.15407/vidbir2024.52.032

COMPARISON OF GIS-BASED SOLUTIONS FOR THE ASSESSMENT OF LAKES WATER VOLUME: A CASE STUDY OF BIOSPHERE RESERVE “SHATSKYI”

O. V. Alokhina, B. P. Rusyn, M. M. Korus, D. V. Ivchenko, N. A. Pits

H. V. Karpenko Physico-Mechanical Institute of the NAS of Ukraine, Lviv

E-mail: alokhina2011@gmail.com

Understanding the volume of water in a lake is essential for assessing the health of the ecosystem. Geographic Information Systems offer valuable tools for evaluating water volume in lakes, employing such methods as remote sensing for surface data and bathymetric surveys for lakebed data. By integrating techniques like sonar-based bathymetric surveys, precise depth measurements can be obtained to accurately calculate water volume. Based on the survey results, depth maps of three lakes of different sizes, depths, and origins within the Biosphere Reserve were created. Key morphometric characteristics and the volume of water mass were calculated from these surveys. However, it is important to note that these investigations can be expensive and time-consuming, especially for large lakes. It may not be feasible for lakes in remote or inaccessible areas. Hollister JW’s (2010) bathymetry modelling method was applied, as an alternative to ground-based bathymetry survey results, to calculate the water volume of the above-mentioned lakes. The method is based on the assumption that the depth of the reservoir is a function of distance from the shoreline. The advantage of the method is the limited amount of input data, namely the area and maximum depth of the reservoir. The modeling bathymetry method is not suitable for very deep lakes like Svitiaz Lake, with complicated lake basin shapes, as demonstrated by comparing the results with ground-based bathymetric survey data. The lake with the smallest depth and more regular lake basin form, which is closer to a circular shape, such as Liutzimer Lake, provided the best results. Using the bathymetric modelling approach for other medium and small Bioreserve lakes could help to define the characteristics of water bodies for which this method can be extremely useful.

Keywords: *GIS, bathymetry modeling method, lake basin, water volume, lake morphometry.*

ПОРІВНЯННЯ ГІС-РІШЕНЬ ДЛЯ ОЦІНКИ ОБ’ЄМУ ВОДИ В ОЗЕРАХ: ПРИКЛАД БІОСФЕРНОГО РЕЗЕРВАТУ “ШАЦЬКИЙ”

О. В. Альохіна, Б. П. Русин, М. М. Корусь, Д. В. Івченко, Н. А. Піць

Фізико-механічний інститут ім. Г. В. Карпенка НАН України, Львів

Розуміння об’єму води в озері має важливе значення для оцінки здоров’я екосистеми. Географічні інформаційні системи пропонують цінні інструменти для оцінки об’єму води в озерах, використовуючи такі методи, як дистанційне зондування для отримання даних про поверхню та батиметричні дані отримані з дна озера. Завдяки батиметричним дослідженням з використанням сонара, можна отримати точні вимірювання глибини для якіснішого обчислення об’єму води. За результатами досліджень створено батиметричні карти для трьох озер біосферного резервату, різних за розмірами, глибиною та походженням. Розраховано ключові морфологічні характеристики та об'єми води. Однак такі дослідження, зазвичай, є дорогими і трудомісткими, особливо для великих озер. Метод батиметричного моделювання Холістера (2010) застосовано для розрахунку об'ємів води у вищезгаданих озерах як альтернатива результатам наземних батиметричних вимірювань. Цей метод базується на припущенні, що глибина водойми є функцією відстані від берегової лінії. Перевагою цього методу є обмеженість вхідних даних (площа водойми та її максимальна глибина). Порівняння отриманих результатів показує, що метод батиметричного моделювання важко застосувати до дуже великих і глибоких озер (таких як Світязь) зі складною геометрією озерної улоговини. Найкращі результати отримано для озера Люцимер, яке має правильнішу форму озерної улоговини і невелику глибину. Метод батиметричного моделювання для інших, середніх і малих, озер біосферного резервату може допомогти визначити особливості водних об'єктів, для яких використання саме цього методу буде достатньо ефективним.

Ключові слова: *ГІС, метод батиметричного моделювання, озерна улоговина, об’єм води, морфометрія озера*.

Introduction. Estimating the volume of water is crucial for monitoring and preserving the natural environment. By examining the balance between water inflows and outflows, we can identify which processes affect the water level and environment of a lake. The volume of water in a lake is a vital indicator of the health of its aquatic ecosystem. Fluctuations in volume can have significant consequences for aquatic flora and fauna. A drop in water level can lead to bank drying, disturb the reproduction of fish and other aquatic organisms, alter the physical and chemical properties of water, and pollute the environment. Determining the water volume enables us to detect such changes and take necessary precautions to safeguard biodiversity and promote the balanced development of ecosystems. Analyzing changes in the volume of water masses is also essential for water resource management. It enables us to solve such problems as water supply to local consumers, water usage in agriculture and industry, flood control, and water security. This is particularly important for areas with a significant number of aquatic complexes, as the impact of climate change intensifies.

The lakes in Biosphere Reserve (BR) “Shatskyi” are crucial to the region ecosystem and the lives of locals. They are the primary source of drinking water and a valuable resource for industries. The lakes are protected areas, vital to the environment [1–2], and home to plant and animal species. They regulate groundwater and moisture and filter water. Water resources are crucial to a country wealth.

Calculating the volume of a lake is typically done using a planimeter to determine the area of depth contours on paper maps [3]. This approach assumes that the lake contains multiple conic sections, and a full bathymetric survey is required to create an isobaths map. This map is then used to estimate the area of the depth contours, which in turn allows for the calculation of the lake volume. A newer approach involves using the triangulated irregular network (TIN) formed from bathymetric survey points, which can be analyzed using geographic information systems (GIS) to estimate the lake volume [4–7].

Developing less energy- and resource-intensive algorithms for calculating water volume with minimum input data can help to overcome the high costs and infeasibility of collecting accurate bathymetric data, particularly when dealing with a large number of lakes. In the scientific community, the issue of developing and testing methods for estimating the depth and volume of lakes without the use of in-situ bathymetric measurements is widely discussed. Xiao [8] proposed a technique for estimating lake bathymetry from SRTM DEM (digital elevation model created based on data collected during the Shuttle Radar Topography Mission mission) data based on the assumption that the underwater topography of lakes is a continuation of the surrounding topography. Similarly, Martinsen [9] described a technique for predicting lake bathymetry using deep learning and DEM data. Zhan [10] proposed an effective method for estimating lake mean depth/volume based on the lake deepest record using machine learning methods. Hollister [11] provided a GIS approach for calculating lake water volume that integrates a better degree of realism and utilizes accessible data, such as lake area and maximum depth.

The Biosphere Reserve territory has a flat topography with very few differences in elevation. More than 50% of the area is covered by forests, which makes it difficult to use SRTM DEM. The lakes within the reserve are mostly of karst origin, and their bottom relief is complex due to the activity of the oldest glaciers. This greatly complicates the application of lake bathymetry assessment techniques based on the surrounding topography. Given the limited access to most of the lakes in the region due to shoreline waterlogging and military restrictions, it is essential to explore alternative methods for accurately determining water volume. This is currently a critical issue that needs to be addressed, taking into account the existing and realistic possibilities available.

The method of modeling bathymetry (distance method) was chosen for its effectiveness, as demonstrated in Hollister's [11] work on 129 lakes in New Hampshire with depths ranging from 1 m to 38 m. This method has also methodological advantages, including the use of standard procedures provided by geographic information systems. An additional advantage of this method is the availability of resources, such as the use of the most reliable data we have for all lakes, namely, the GIS shoreline layers [12] and the maximum depth estimates [13]. Furthermore, compared to in-situ bathymetric surveys, the distance method is cost-effective. However, there are questions about the effectiveness of using this method to determine the volume of the BR "Shatskyi" lakes, given their specificity, which justifies the purpose accurately of these studies.

Therefore, this study is aimed at a comprehensive evaluation of the key features of the lakes mentioned above, using GIS. Based on this evaluation, the water volume of these lakes was determined using two methods: data obtained from a bathymetric survey and the distance method [11].

The following tasks have been assigned:

– conduct an in-situ survey of Svityaz, Pulemetske, and Liutsymer lakes to determine their depth, and create corresponding depth maps using GIS;

– calculate and estimate the key morphometric properties of the lakes;

– create a lake basin and calculate the water mass volume for the above-mentioned three lakes using two methods, i.e. via data from an in-situ bathymetric survey and distance method, estimating the volume of the lake based on two input parameters [11];

– compare and evaluate the results on the lake basin shapes and the values of volume water masses, obtained via two methods;

– conclude if the distance method, which uses a limited set of input data (as described in [11]), can be applied to estimate water volumes in various basin shapes accurately and determine whether this method can be an alternative. Could this method be an alternative to in-situ surveys for estimating water volume in the other 28 biosphere reserve lakes?

Study area. The studied lakes can be found on the borders of the Shatsk National Nature Park, which is a part of the 75 000 ha BR "Shatskyi". The latter is a nature preserve located in Ukrainian West Polissia and it joined the Transboundary BR "West Polissia" in 2012, which encompasses Poland, Ukraine, and Belarus. Due to its unique combination of lake, woodland, and marsh ecosystems, the BR region plays a crucial role in shaping the climate of a vast part of the European continent.

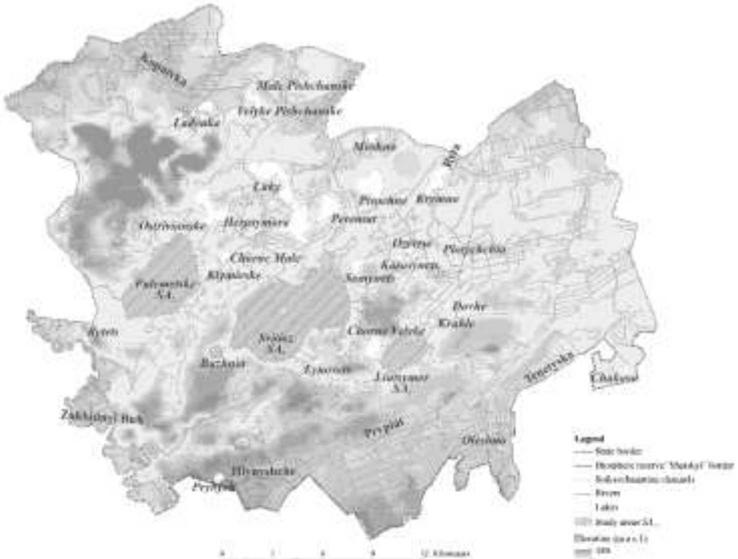

Fig. 1. Study area within the hydrological network of the "Shatskyi" BR.

The hydrological network in BR comprises rivers and streams with permanent water flow, spanning over a total length of 114 km as shown in Fig. 1. The territory has also a lake complex consisting of 31 lakes, predominantly of karst origin, covering an area of approximately 5 928 ha. There are four groups of lakes in the BR based on their size: large (>500 ha), medium (100...500 ha), small (10...100 ha), and very small (<10 ha).

During the late nineteenth century, various studies on the Shatsk Lakeland began to appear in scientific literature. Over the years, numerous researchers such as Tutkovskiy [14], Lenzewicz [15], Rühle [16], Yakushko and Kalechic [17], Prots-Kravchuk [18], Karpenko [19], Ilyin and Molchak [20], and Choiński [21] have published papers on this group of lakes, covering a wide range of scientific fields.

Lake Svitiaz, study area SA_1, is the largest and deepest natural lake in Ukraine. Its central position has geographical coordinates of 51° 29′ 49.0″ N, 23° 50′ 20.0″. The Lake Svitiaz is a unique body of water that has never been connected to the World Ocean. It is fed by both precipitation and subterranean sources [22]. The water in the lake is lost through evaporation and infiltration. Additionally, the slopes around the lake indicate a natural water flow due to groundwater inflow and outflow.

Lake Pulemetske, SA_2, is the second largest lake in BR and belongs to the group of large lakes. Its central position geographical coordinates are 51° 31′ 20.0″ N, 23° 44′ 00.0′ (Fig. 1). This lake is fed by groundwater, precipitation, and surface runoff and is known for its abundant underwater and surface plant life. Despite the abundance of plants, they only take up a small amount of space. The types of sediment found at the bottom of the lake (such as clay, sand, gravel, redeposited peat, and limestone deposits) are directly related to the current topography of the lake basin. The organic deposits in the lake consist of sapropel and peat [13].

Lake Liutsymer, SA_3, belongs to the group of medium lakes in BR (Fig. 1) with geographical coordinates of 51° 28′ 36.0″ N, 23° 56′ 10.0″ E. The lake is primarily filled by rainwater. The consumed water is either evaporated or absorbed into the ground. The lake drainage system consists of various wetlands that serve as natural water sources. In addition, the groundwater also contributes to the water levels. Furthermore, an artificial waterway connects Lake Velyke Chorne, adding to the lake surface inflow. The lake water-regulating structure helps to maintain the water levels during periods of significant inflow and also controls the outflow to other connected lakes.

Bathymetric data collection. Advancement in surveying technology, combined with hydroacoustic equipment, now offer a fast and detailed description of the underwater environment [23–24].

In our case, the bathymetric survey technique consisted of three stages: preparation, measurement, and data processing. During the preparation stage, we analyzed satellite imagery data and generated a network of measurement points and tracks using the GIS of the BR “Shatskyi” [25, 12]. To determine the distance between the longitudinal and transverse tracks, we followed a specific task. For SA_{1-3}, the longitudinal discreteness was set to 200 m. We chose a spatial discreteness of measurements that considered the relatively low speed of the navigator. For recording sonar and GPS receiver data, we set the discreteness at 1 m for SA_2 and SA_3, while the speed did not exceed 4 to 5 km/h^{-1}. For SA_1, the speed did not exceed 3.6 km/h^{-1}. This was especially significant when investigating the complicated topography of Lake Svitiaz’s bottom.

The second stage includes in-situ measurements within the lakes. Bathymetric measurements are carried out on a boat which is equipped with an electric motor, an echo-sounder with a sensor, and built-in GPS, along with batteries which power the sensors. The HEIBO electric motor is designed for use in freshwater and comes with three propellers. It provides seven different motor speeds to choose from, allowing us to select the most appropriate one for the task at hand. Since the motor control is manual, all bathymetric measurements are taken in calm waters to eliminate the impact of water fluctuations on the measurement results. We collected depth data using a Lowrance LMS-527cDF echo-sounder with a built-in GPS. The frequency used for measurements was 200 kHz and the ultrasonic transducer diagram had an angle of 12 degrees. Although the echo-sounder has a maximum working depth of 760 m, our investigation needed depth data only up to approximately 60 m. The device features an internal GPS with a 12 parallel channel NMEA 2000-compatible GPS/WAAS receiver/antenna. The third stage involves converting sonar data into a format that can be viewed and processed using Lowrance Sonar Viewer Software. The processed data can be exported to AcrMap$^{\text{TM}}$ and XLSTAT software packages. The primary task for additional data work is the coordinate system conversion. The Universal Transverse Mercator (UTM) Zone 34N coordinate system is used to reference the latitude and longitude of the area of study map in Fig. 1 and other data in our GIS. As GIS software cannot understand Lowrance proprietary coordinate system, the sonar information is recorded in Lowrance Mercator coordinates. These coordinates must be converted to standard UTM coordinates, using the following parameters: Semimajor Axis 6356752.3142, Semiminor Axis 6356752.3142, Prime Meridian Greenwich (0.0), and Inverse Flattening 0.0. The number of *XYZ* points obtained during echogram conversion is used to generate a digital model of the bottom relief and depth maps, compute morphometric characteristics, and calculate the lake water volume.

Surface interpolation and contour map. To generate regular grid data for the entire lake, the geographical data collected through the survey needs to be interpolated. Interpolation is a technique used to determine data for unknown locations between the recorded data points. In this method, the original data gathered in the field, which is an *XYZ* file containing position and depth information, is used to calculate data points on a regularly spaced grid. These calculated data points enable us to generate a complete map of the lake.

Fig. 2 shows the number of *XYZ* points, obtained as a result of echogram processing: SA_1 – 350 000; SA_2 – 78 000, and SA_3 – 23 000.

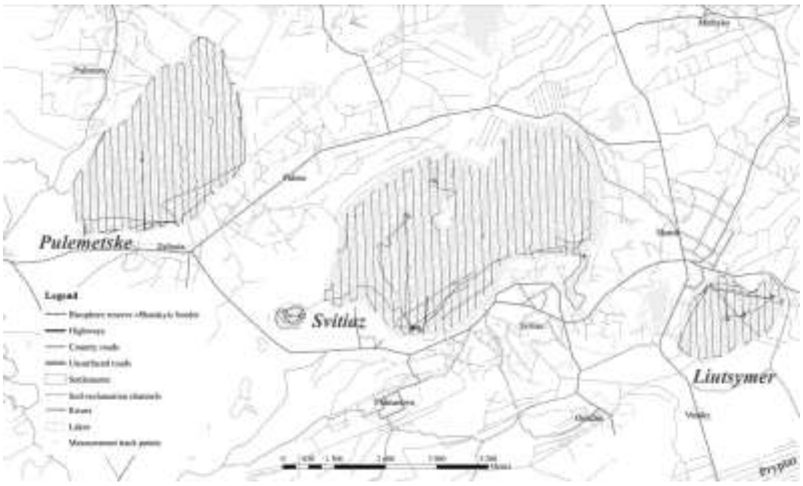

Fig. 2. Data cloud (*XYZ* points) from field bathymetric surveys of study areas.

To create bottom relief maps, depth maps, and isobaths, we used the AcrMap$^{\text{TM}}$ software from the ArcView 9.2$^{\text{TM}}$ software package. Firstly, a cloud of points generated from the echo sounder was used to build the TIN of the relief model. This TIN was constructed by integrating known point values into a series of triangles through the application of the Delaunay triangulation algorithm [4].

The model is made up of a set of connected triangular faces that do not overlap. The algorithm used to create the triangles aims to make them as close to equilateral as possible using depth markers – Z coordinate values – for each point. A TIN model was created and then converted into a GRID model for further processing and the creation of lake isobaths. Unlike the TIN model, the GRID model is formed of squares or rectangles and is more regular in shape. Once converted to a GRID model, one can collect depth values for each cell, allowing one to solve a variety of problems using the resulting model.

During the conversion of TIN to GRID, Natural Neighbor interpolation was used to provide a smoother raster when compared to the Linear interpolation method. The result may be affected by sharp bends in the TIN not being smoothed when using Natural Neighbor interpolation for surface construction. However, this is not a concern for us as the depth changes in the lakes are gradual, and there are no such sharp bends. The CELLSIZE Sample Distance is used to display the original pixel size. For SA_1, the cell size is 33, while for SA_2 and SA_3, it is 22 and 10, respectively.

Defining the shoreline is a crucial step in creating a bathymetric chart. This line is comprised of several points that have geographic coordinates, where Z is zero. However, we used a different method to obtain these coordinates, since no echo sounder could provide them. Instead, we derived the shoreline points from data obtained from satellite images. Specifically, we used images from the Sentinel-2 A and B satellites.

Estimating the morphometric characteristics. Bathymetry and morphometry are two branches of limnology that focus on studying the physical shape of internal waters. Morphometric markers are used to determine the morphology of a lake, which describes its size and shape. Lake morphometry involves studying various factors such as the area, volume, maximum and average depth, shape and length of shoreline, bottom topography, and the relief in the surrounding areas of the lake [26–29].

The morphometric characteristics were estimated using both field data and satellite imagery. The maximum depth ($H_{\text{max.}}$, m) was read directly from the field-data matrix, allowing the calculation of a lake average depth ($H_{\text{avr.}}$, m). The lake area (F_0, km^2), length (L, km), maximum ($B_{\text{max.}}$, km), and average ($B_{\text{avr.}}$, km) width were calculated using satellite imagery and ArcMap™.

The coefficient of the relative length of the lake indicates how elongated the above-water basin is:

$$K_{\text{length}} = \frac{L}{B_{\text{avr.}}} \tag{1}$$

The sinuosity coefficient of a lake shoreline indicates how irregular the shoreline is. It is calculated by dividing the length of the shoreline by the circumference of a circle with an area equal to that of the lake water surface:

$$K_{\sin\text{uos.}} = \frac{L}{2\sqrt{F \cdot \pi}} \tag{2}$$

The openness of the basin serves as an indicator of the degree of water mixing and stratification possibility:

$$K_{\text{open.}} = \frac{F_0}{H_{\text{avr.}}} \tag{3}$$

The capacity of a lake basin can be determined by calculating the ratio of its average depth to its highest depth. This allows for easy comparison of the lake basin with bodies of rotation. The value of this ratio is 1 for a cylinder, 0.5 for a parabolic shape, 0.66 for a semi-ellipsoid shape, and 0.33 for a cone. However, there is another shape, a concave cone, which has a ratio of less than 0.33 ($C < 0.33$) [30].

Water volumes were determined using isobath maps, developed earlier, as well as the “prism technique”. If areas restricted by isobaths are $f_1, f_2, f_3, ..., f_n$, and vertical distances between isobaths planes are $h_1, h_2, h_3, \ldots$, so lake volume (V) will be calculated according to the:

$$V = \frac{h_1(f_1 + f_2)}{2} + \frac{h_2(f_2 + f_3)}{2} + \ldots + \frac{h_{n-2}(f_{n-2} + f_{n-1})}{2} + \frac{h_{n-1}(f_{n-1} + f_n)}{2} \quad (4)$$

Satellite imagery. Scientific research in Ukraine is facing the challenge of limited funding, which has made it difficult for us to obtain the necessary RS data. We have been actively searching for open-access sources and after considering various options, we have concluded that the European Sentinel-2 mission provides the best accessibility and spatial-temporal coverage for our research area of around 75 000 ha. This mission offers high-resolution optical imagery of agriculture, forests, land-use change, and land-cover change globally every 10 days, with the first spacecraft, and every 5 days once both are in orbit.

The satellite is equipped with a multispectral sensor which can capture visible, near-infrared, and short-wave infrared spectral zones. It includes 13 spectral channels and provides a resolution of 10 to 60 m. We use Level-1C data, which has top-of-atmosphere reflectance in fixed cartographic geometry. This includes a combined UTM projection and WGS84 geodetic system, and corrections applied for radiometric and geometric factors (including orthorectification and spatial registration). For analyzing the shorelines of large lakes, we utilize the blue, green, red, and near-infrared spectral channels. The spatial resolution provided is 10 m.

The shoreline of a lake changes throughout the year. This process is primarily influenced by the climate, specifically the amount of precipitation and evaporation from the lake surface. To calculate the area of the water, as well as other morphometric characteristics of the lake basin, it is necessary to determine the shoreline contours and identify the zero level (isobath) of the lake.

Data from various satellites, depending on their availability and the task at hand, allow us to quickly identify the shorelines of water bodies, calculate their area, and assess their change over time [31–33].

The contours of the lake shoreline were estimated using Sentinel-2 satellite images from space. There are two commonly used methods for determining the area of the lake water surface: manual digitization and image ratio. The third and last method used to obtain the shoreline contours is the normalized difference water index (NDWI) (5). This index works by calculating the difference in the coefficients of light reflection from objects at different wavelengths, specifically the green and near-infrared reflection channels:

$$\mathrm{NDWI} = \frac{X_{\mathrm{green}} - X_{\mathrm{nir}}}{X_{\mathrm{green}} + X_{\mathrm{nir}}} \quad (5)$$

where X_{green}, X_{nir} – absorption coefficients of the 3rd and 8th channels of the Sentinel-2 satellite. The process for getting the outlines of the lake in the ArcGIS software system is depicted in Fig. 3.

To transform a satellite image into a shoreline, a surface water mask was created using NDWI, raster to polygon, raster to polyline, and object-to-point tools. Then, the point objects from the bathymetric survey and this class of point objects are combined (Fig. 2).

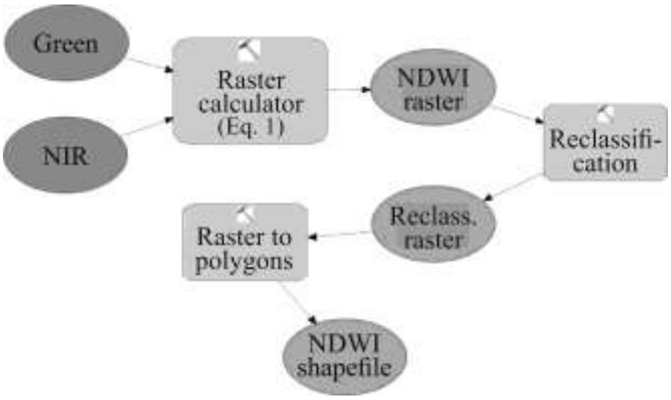

Fig. 3. The model of the process for getting the outlines of the lake in the ArcGIS.

Estimating volume using the bathymetry modeling method. Hollister JW's [11] distance method was used for calculating water volume. For this, the lake area and, consequently, shorelines were obtained from satellite data, namely the Sentinel-2 satellite. The lake maximum depth was taken from in-situ bathymetric surveys.

Assessment method. A percent of difference (PD) for each *SA* between the distance method and the true volume (i.e., measured depth) was calculated as follows:

$$\mathrm{PD} = \frac{Calculated_{\mathrm{vol}} - True_{\mathrm{vol}}}{True_{\mathrm{vol}}}. \tag{6}$$

Lakes morphometry and depth maps. Table 1 shows the key morphometric characteristics for $SA_{1–3}$ as part of the calculation.

Table 1. Morphometric characteristics of $SA_{1–3}$
(*averaged over estimated seasonal data of 2021)

Name	F_0, km^2	L, km	$B_{\max}$, km	$B_{\mathrm{avr.}}$, km
SA_1	25.0	7.76	4.29	3.19
SA_2	14.5	6.03	3.26	2.38
SA_3	4.2	3.08	1.90	2.16

One of the most important characteristics is the area of the water mirror. According to the categorization [1–2], the results of measurements of the water mirror area enable us to attribute SA_1 to a very large lake with a surface area of more than 20 km^2, SA_2 to large ones with a surface area from 10 up to 20 km^2 and SA_3 to medium ones with a surface area from 1up to 10 km^2.

According to the coefficient of the relative length of the lakes, the right contours are primarily typical of suffosion, karst-suffosion, and some artificial reservoirs. SA_1 and SA_2 have an elongated basin shape with index values of 2.43 and 2.53 [34]. However, the SA_3 basin is circular with a value of 1.42.

The shorelines of $SA_{1–3}$ are classified as undeveloped water bodies with values of 0.44, 0.45, and 0.43, respectively.

The maximum depths of lakes can provide clues about how they were formed. For instance, lakes that are created through karst processes often have deep maximum depths. While maximum lake depths are usually measured in situ, average depths are calculated. In the case of SA_1, the maximum depth is 58.4 m (in-situ data) and the average depth is 6.8 m (calculated). Fig. 4 provides a visual representation of this data.

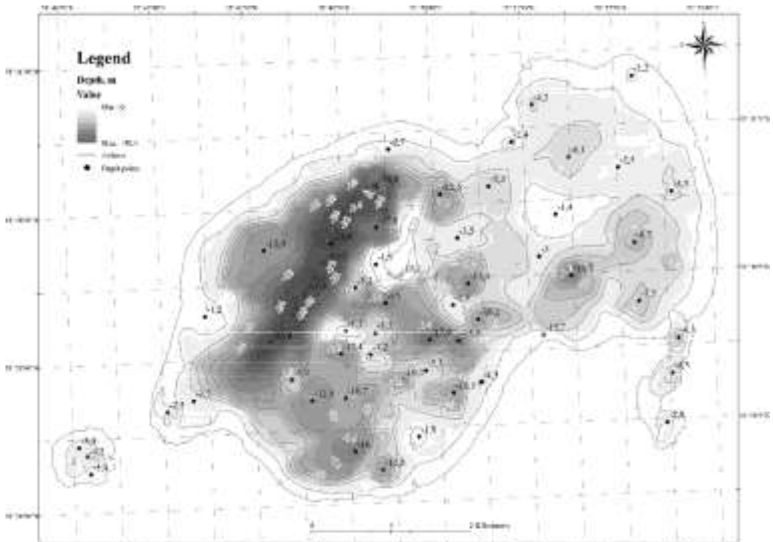

Fig. 4. Depth map of SA_1.

The depth maps of two other lakes indicate that the SA_2 lake has a maximum depth of 19.2 m and an average depth of 4.18 m, as shown in Fig. 5. On the other hand, SA_3 has a maximum depth of 8.04 m and an average depth of 3.40 m, as depicted in Fig. 6.

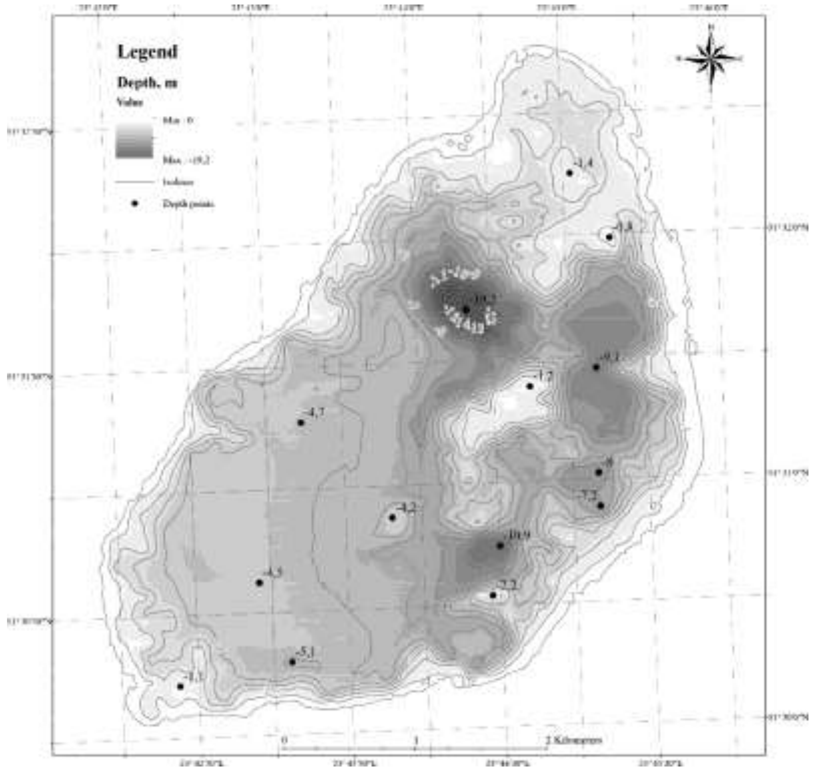

Fig. 5. Depth map of SA_2.

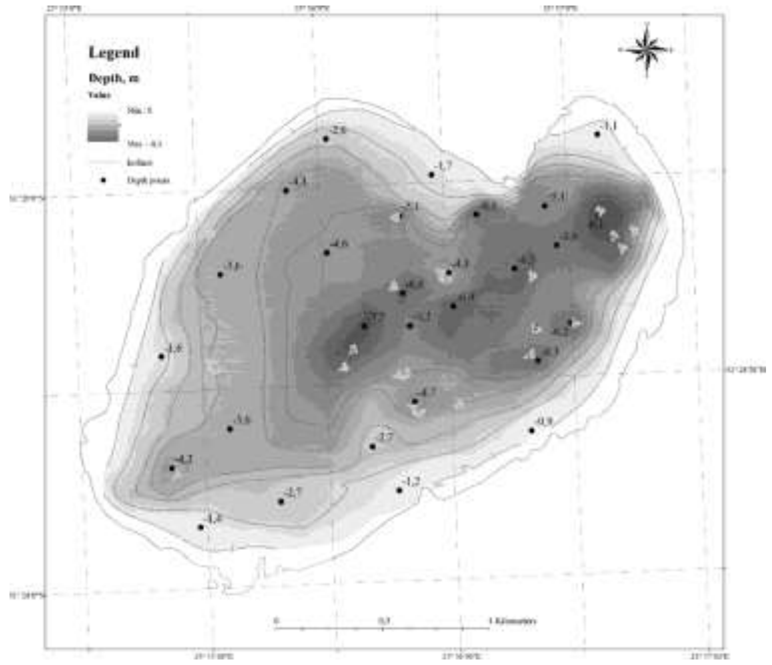

Fig. 6. Depth map of SA_3.

It should be noted that, despite the slight difference in average depths for $SA_{1–3}$, the maximum depths for these lakes range from ≈8 up to ≈58 m. This already refers to the specificity of the basin structures of the aforementioned lakes.

Based on performed calculations, Table 2 presents the organization of study areas according to lake depth classification.

Table 2. Classification based on lake depth

Name	Class based on average depth, m	Class based on maximum depth, m
SA_1	Medium	Very large
SA_2	Small	Large
SA_3	Small	Not Large

The basin openness coefficient helps us to determine the extent of water mass mixing and stratification possibilities. When the reservoir area is large and the water is shallow, the wind processes mix the water, enhancing the internal circulation of the water mass.

The $K_{open.}$ indicator has values of 3.62 and 1.21 for SA_1 and SA_3, respectively, allowing them to be categorized as open areas according to the proper categorization [35]. SA_2 is classified as a medium-sized open lake, with an indication value of 0.35.

When studying a lake, it is important to consider the shape of its basin. This is because the shape affects various dynamic processes that occur in the lake, such as mixing and heating. In addition, the size and shape of the basin are closely related to the duration of the ice period. If the basin is larger, the volume of water is greater, which takes a longer time to cool down in fall and warm up in spring. Table 3 shows the capacity indices and basin types for all the areas that were studied. However, it is important to remember that the study of lake basins should not only focus on their shape but also the bottom topography. A basin can either be a single simple depression or a complex depression made up of several depressions.

Table 3. Distribution of lakes based on the values of basin capacity indicators

Name	Lake basin capacity indicator, *C*	The shape of the lake basin
SA_1	0.12	Concave cone
SA_2	0.22	Concave cone
SA_3	0.41	Parabolic

Water volume estimation. Data from in-situ bathymetric surveys, along with morphometric characteristics, were utilized to determine the water volume of $SA_{1–3}$. The area of the reservoir plays a crucial role in computing the volume of a water mass in a reservoir. Due to the increasing impact of various natural and anthropogenic factors, as well as regular seasonal fluctuations in water levels, changes in the area of water bodies and subsequently in the volume of their water mass may have occurred over the past few decades. However, our aim was not to compare the volume of lakes over time but rather to approbate an alternative technique for estimating volume. Therefore, we used the average values of the lake area obtained for the year 2021 as input data for both methods.

The method of assessment chosen depends on the origin, basin shape, and depth of the lakes. In-situ bathymetric technique was used to obtain true basin shapes. This method provides accurate measurements and allows for control of conditions, resulting in real-time data collection. This approach eliminates errors that may occur during data collection from satellites or acoustic systems. Direct measurements also enable the collection of detailed relief data in hard-to-reach areas where other methods may not be effective.

The origins of all BR “Shatskyi” lakes are complicated. In the case of SA_1 and SA_2 (Fig. 7), we deal with lakes whose basins were formed by a combination of relief-forming forces (glacial and karst), resulting in a complicated structure and layering of different rocks. Smaller and shallower BR lakes, such as SA_3, have a simpler basin formed by a single component (karst funnel) (Fig. 7).

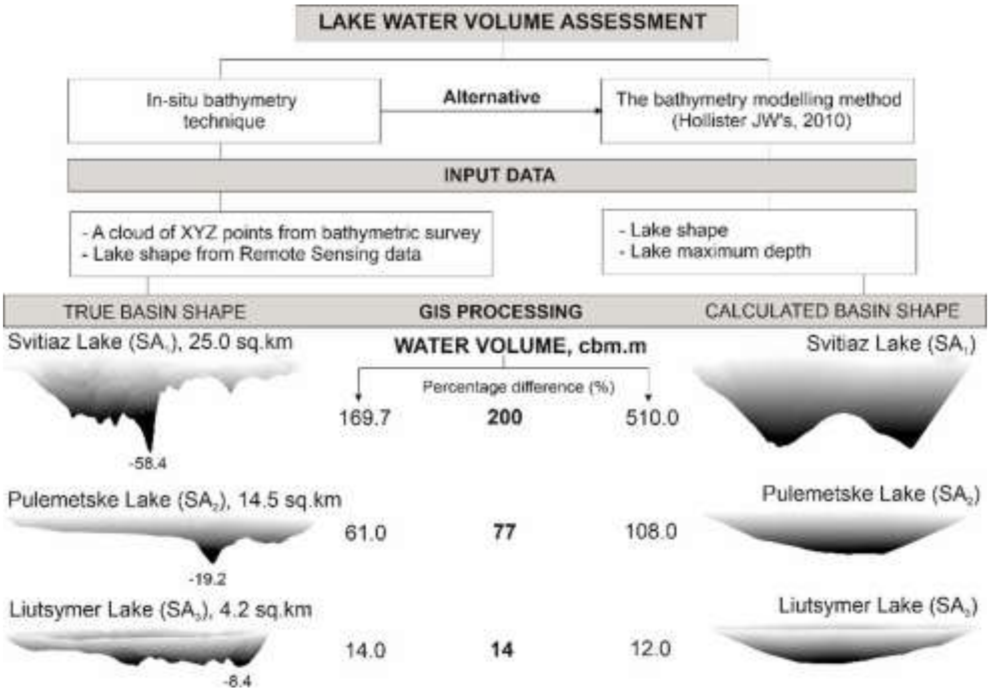

Fig. 7. Comparison scheme for assessing lakes water volume results.

Based on the distance method [11], the shape of the basins for all three lakes appears to be a cone or, for SA_1, two cones, as shown in Fig. 7.

A percentage difference was computed between the distance method and in-situ bathymetry results to calculate the difference between the water mass volumes.

When the true volume for SA_1 (lake area is 25 km^2) is 169.7 Mm^3, a distance method estimates a volume of 510 Mm^3, resulting in a *PD* of 200%. This lake has a complicated basin structure. Most of the lake is presented in the form of a flat “plate”, while the north-western part can be recognized by the presence of a fault with a depth of 58.4 m (Fig. 8).

In SA_2, the lake covers an area of 14.5 km^2 and has a true volume of 61 Mm^3. However, when using the distance method, the volume increases to 108 Mm^3, resulting in a percentage difference (PD) of 77% (Fig. 7).

SA_3 is a small lake with an area of only 4.2 km^2. It is circular due to its sinuosity coefficient and shallowest depth of 8.4 m. The true water volume of the lake is 14 Mm^3, but the distance method estimated the volume to be 12 Mm^3, resulting in a percentage difference of only 14% (Fig. 7).

CONCLUSIONS

The following research discusses the results of a study on three lakes in the Ukrainian Biosphere Reserve. The study aimed at determining the volume of water in these lakes using an in-situ bathymetric survey and the distance method, a GIS-based solution that estimates the volume of water in a reservoir based on two input parameters. The distance method is ideal for calculating water volume in reservoirs with limited input data and restricted access to conduction-situ bathymetric surveys.

It’s worth noting that the lakes in the Ukrainian Biosphere Reserve had not been extensively studied, and there was no detailed information available about their underwater features. The in-situ bathymetry surveys conducted as part of this study were the first to reveal the topography of the lake bottom and depth maps. Therefore, to use the data as a model, we cross-checked our results on morphometry with archival materials from the Biosphere Reserve that provided data on the main morphometric characteristics of the lakes.

After comparing the two methods, we found that the distance method has certain advantages, such as use of standardized procedures, a limited amount of input data, and being cost-effective. However, it is not suitable for deep lakes with complex bottom topography. The distance method produced the poorest results for lakes with a complex basin shape and significant depth, such as SA_1 (maximum depth 58.4 m) and SA_2 (maximum depth 19.2 m). In contrast, lake SA_3, which has a circular shape and a maximum depth of only 8 m, produced a more accurate result.

It is evident that the use of satellite data and deep learning techniques in studying aquatic ecosystems, especially in determining water volumes in reservoirs, is very promising. However, each of these methods has its limitations and risks when applied to a particular territory and a specific water body. Therefore, for practical purposes, our future research will focus on testing the distance method on smaller lakes in the Biosphere Reserve area. We plan to improve the distance method for lakes with more complex topography.

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Received 16.07.2024