Bathymetric Survey and Digital Elevation Model, using an Echo Sounder/Acoustic Sonar: The Case of Dobra Lake (Hunedoara, Romania)

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Abstract: Bathymetric surveying represents a type of hydrographic survey that maps the details of underwater landforms such as rivers, lakes, seas or oceans. Data obtained from bathymetric surveys is especially important for DEM-based engineering applications such as river minerals exploration, flood risk map creation, safe travel determination, bridge construction, water energy management, etc. In bathymetric surveys, data can be collected on a variety of water bodies, including rivers, lakes, and estuaries. This article aims to describe the process of creating a bathymetric map for a small lake in Hunedoara District (Transylvania, Romania) using the Humminbird Helix 5 echo sounder. The proposed method of calculating the survey time can be successfully used by planners of academia, research centers, national hydrographic offices, maritime offices, and institutions and companies dealing with professional measurements in different water environments.

Keywords: bathymetric map; hydrographic survey; echo sounder; soundwaves; digital elevation model

1 Introduction

Water bodies cover more than 70% of our planet’s surface, helping to regulate mass and energy transfer between the biosphere, lithosphere, and atmosphere. Moreover, almost half of the world's population lives within 100 km of a coast. All these aspects, and many others, lead to the human need for a better understanding of the seabed [1].

Bathymetry is a part of hydrography, the underwater equivalent of hypsometry or topography. Bathymetry is the science that studies the underwater depths of water bodies (lakes, rivers, oceans), surveying their physical features. Hydrography includes not only bathymetry but also the study of shoreline shape and features, tidal characteristics, currents, waves, and the physical and chemical properties of the water itself [2] [3].

A bathymetric survey is the process of measuring underwater depths. It includes all the measurements, calculations, and representation of the underwater relief. It is particularly important in terms of aiding navigation and dredging activities and supporting land projects [2] [4]. A bathymetric survey is conducted to measure and map the underwater topography (bathymetry) of water bodies. The primary objectives include mapping the seafloor or riverbed, ensuring navigation safety, supporting engineering and infrastructure development, conducting environmental and ecological studies, resource exploration and managing floods/disasters [2] [4].

Bathymetric surveys use various techniques and instruments to measure underwater depths and create topographic maps of the seabed. The methodology generally includes data collection methods, positioning and navigation and data processing and interpretation. Generated depth models and contour maps can be used for further analysis [2] [4].

While acoustic sonar provides the raw depth measurements, bathymetric surveys process and refine this data, and the Digital Elevation Model (DEM) serves as the final product used for various scientific, engineering, and navigational applications [2] [4].

This paper will study the performance and accuracy of bathymetric measurements on a lake in Hunedoara County, Romania (Fig. 1) using acoustic sonar technology to create a representative bathymetric map of the underwater terrain in order to study water depths and sediment density.

Figure 1

The location of the lake from Dobra village, Hunedoara County, Romania

The present bathymetric surveys are conducted using an echo sounder attached to a survey boat for data acquisition, correlated with a GNSS system to link each measured distance to a particular depth on the surveying map [5] [6].

The next stage in the bathymetric survey involves converting the acquired raw data into an elevated digital model. For quality assessment, the model obtained in this study was tested to determine if it satisfies the imposed requirements, using various software tools such as AutoCAD, Global Mapper and Humminbird PC.

2 Materials and Methods

Traditional methods of monitoring and surveying water depths involved measuring points using hydrometric gauges. The use of bathometers has brought a multitude of advantages in the field of bathymetry, offering a much more advanced and precise technology [5]. Acoustic Sonar (Sound Navigation and Ranging) is a technology that uses sound waves to detect and measure underwater objects, distances, and topography. It is widely used for mapping the seafloor, navigation, underwater exploration, and detecting submerged objects. Nowadays, acoustic sonar is considered a crucial tool in oceanography, hydrography, and maritime industries, enabling precise underwater exploration and mapping [5].

The specific bathymetric instruments are divided into two categories: autonomous underwater vehicles (AUVs) and towed sonars. Underwater surveying methods are based on acoustic pulses, light propagation through water, or radio pulses, depending on the type of survey to be carried out (Fig. 2) [2] [3].

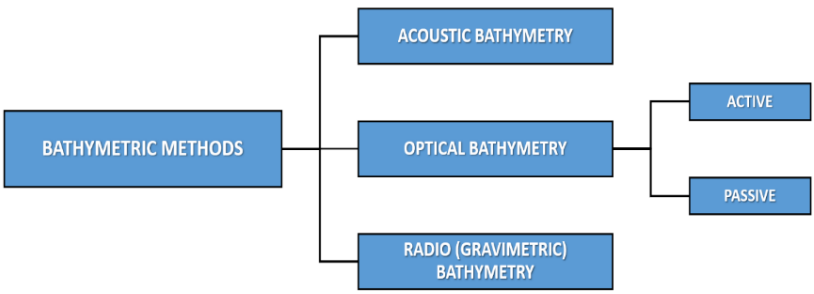

Figure 2
Underwater surveying methods

Underwater surveying methods should be chosen contingent on the type of project and it's goals (Fig. 2) [3] [6] [7]:

- **Acoustic method:** Frequently used for high resolution bathymetric maps in shallow waters

- **Optical method:** Based on the propagation of light through water. **Suitable for mapping coastal areas with depths less than 60 m:**
  - **Active:** Uses LiDAR systems with different wavelengths (similar to sonar but uses laser pulses instead of acoustic pulses), on a platform on the water's surface. Ideal for slightly deep waters (up to 60m; for depth and shore height determination)
  - **Passive:** Measuring the amount of reflected natural light with the help of aircraft or satellites. It is influenced by seabed color and composition, as well as water turbidity
- **Radio (gravimetric) method:** Uses radars placed on artificial satellites to measure the distance to the water surface. This principle works by detecting minor water surface rises over massive relief formations on the seabed. It uses radio pulses, and large variations (in kilometers) can be detected, especially in areas far from commercial maritime routes.

In the case of acoustic bathymetry, an echo sounder is used. The sonar emits short sound pulses, which are reflected by the relief on the bottom of the water. [3] [7].

The distance from the water surface to the seabed is determined measuring the delay time of the reflected acoustic pulse [3] [7]: $D=v\cdot T/2$, where: D – the distance from the water surface to the measured point on the seabed; v – sound speed in water (≈1500 m/s, depending on temperature, salinity, and pressure); T – the delay time measured from the acoustic pulse emission to the reception of the reflected pulse [3] [5].

The echo sounder source emits multiple survey pulses arranged in a perpendicular plane to the ship's movement direction. The pulses are emitted at different angles, similar to a fan. The acoustic pulses have frequencies between 12 KHz and 400 KHz. Low frequencies are used for deep-water bathymetry, while high frequencies are used for shallow waters [5] [7].

Acoustic bathymetry is often used for high-resolution bathymetric maps of shallow waters and low-resolution bathymetric maps of deep waters [5]. Acoustic bathymetric surveys require more time in shallow waters due to the narrow sound beam, which necessitates multiple crossovers to map a relatively small area. Therefore, acoustic bathymetry is not suitable for coastal or estuary areas, where there are rapid changes in the seabed morphology. However, it is recommended for shallow standing waters, essential for navigation, environmental studies and marine construction, due to the accuracy and efficiency [3] [5].

Underwater modeling is the process of developing a mathematical coordinate-based representation of any surface or object in three dimensions via specialized software. The main goal is to study, understand and predict surface behavior under different conditions [6].

A Digital Elevation Model (DEM) is a digital cartographic dataset that represents a continuous topographic elevation surface through a series of cells. Each cell represents the elevation of a feature at its location $Z= f(X,Y)$. Digital elevation models provide a "bare earth" representation because they only contain information about the elevation of geological (ground) features, such as valleys, mountains, and landslides. They do not include elevation data for non-ground features (natural or artificial structures, such as vegetation or buildings). DEMs can be used to create topographic and bathymetric maps, which illustrate underwater terrain [6] [8].

Once bathymetric data is collected, it undergoes extensive processing to create accurate underwater models, transforming into a DEM, a 3D representation of underwater topography for further analysis and applications. Through advancements in sonar technology and data processing techniques, modern bathymetric DEMs continue to improve in accuracy, resolution, and applicability [6] [8]. The activity is divided into certain phases (Fig. 3) [6] [8]:

- **Data acquisition:** The data acquisition methods should be chosen depending on the scale of the studied area, financial means, desired measurement accuracy, and additional variables. The sonar should follow a sinusoidal path on the water body, with a density of longitudinal axes depending on the water's mean depth
- **Preliminary processing:** Refers to taking corrective actions on raw data (correcting systematic errors, eliminating mistakes, filtering random error, editing codes, compensating for depth differences between scans, correcting for water level variations, and depth at which the sonar was located etc.), data compression, coordinate transformations, data registration
- **Data conversion:** Preprocessed raw data is converted and structured into a bathymetric digital model, interpreting the seabed hardness to visualize, locate and measure objects on the seabed, underwater relief structures, sediments, and area acoustic characterization and mapping
- **Quality assessment:** Required in certain phases. Ensures the bathymetric digital model meets imposed requirements
- **Results exploitation:** The bathymetric data is used via dedicated software and suitable procedures to solve various problems

The applicability of bathymetric products refers to their usage or to extracting information needed in human activities, such as observations, research, monitoring, designing future projects, using natural resources, and developing human activities, especially those related to water.

The study of underwater relief is crucial for understanding the morphology and dynamics of submerged landscapes.

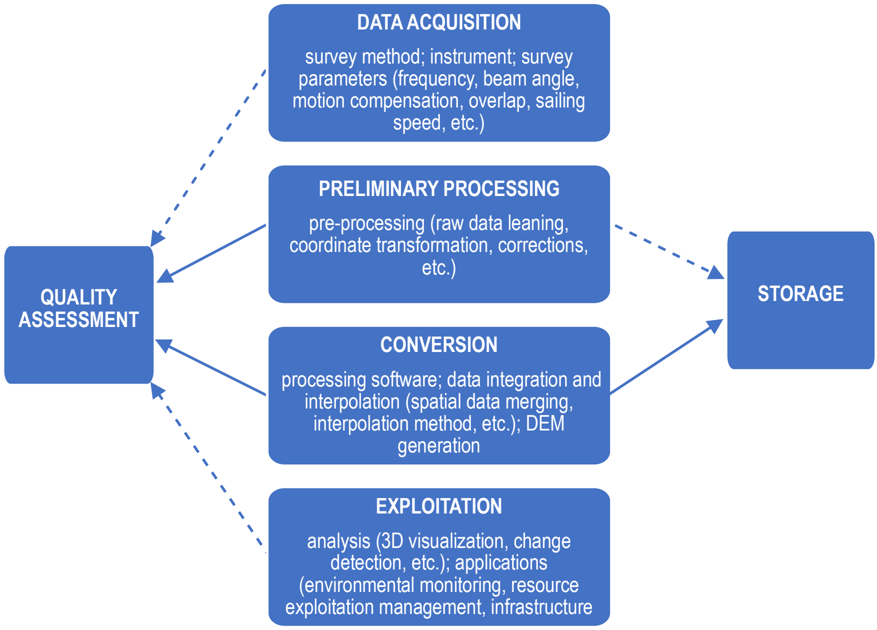

Figure 3
Modeling workflow

As shown in Fig. 3, by designing a survey session tailored to the characteristics of the lake, accurate and relevant data can be gathered. To achieve this, specific parameters are established beforehand. These parameters may include:

- **Method:** Acoustic sonar scanning
- **Instrument:** Humminbird Helix 5 Chirp
- **Frequency:** 200 kHz
- **Beam angle:** narrow mode
- **Motion compensation:** GPS + IMU
- **Overlap:** 30%
- **Sailing speed:** 8-10 km/h

To accurately study underwater relief, raw data collected from the survey session must undergo a rigorous data processing phase. This phase ensures that the final outputs, including DEM, are reliable, precise, and suitable for further analysis and decision-making. The integration of multiple data sources, advanced interpolation techniques, and GIS-based visualization ensures high accuracy in understanding and managing underwater relief dynamics. Below are the key stages in this process:

- **Software:** Humminbird PC, Global Mapper
- **Spatial data merging:** Acoustic sonar + GPS

- **Reference system:** ETRS-89
- **Projection system:** Stereographic 1970 (the Romanian official cartographic projection system)
- **Interpolation method:** Triangular Irregular Network (TIN)

This ensures the results are comprehensive and scientifically valid for both the study and further analysis, such as monitoring human activities (mineral or sediment extraction), helping to assess their impact on the aquatic ecosystem. Additionally, these findings can contribute to conservation efforts by identifying potential risks to biodiversity and water quality.

Human activities have diverse impacts on the environment, including the seabed. The main human impacts on the seabed include (Fig. 4) [2] [9-14]:

- **Exploration, research and monitoring:** Mapping the seabed using bathymetric technology, studying unique seabed ecosystems, observing and monitoring specific areas or phenomena, allowing scientists to discover and improve new underwater wealth – the future source for innovation and progress, leading to a better understanding of water body functions, informing people about the vulnerability of underwater ecosystems, and taking actions for environmental protection and responsible use and conservation of ocean resources
- **Exploitation:** Dredging construction materials from shallow waters, extracting valuable minerals via deep-sea mining. The high technology used in underwater mining, such as robotic mining machines, surface vessels, and refineries placed close to the exploitation area, causes damage to underwater ecosystems
- **Water pollution:** A global concern, including sources like industrial waste, marine dumping, sewage and wastewater, oil leaks and spills, agriculture, global warming, and radioactive waste.

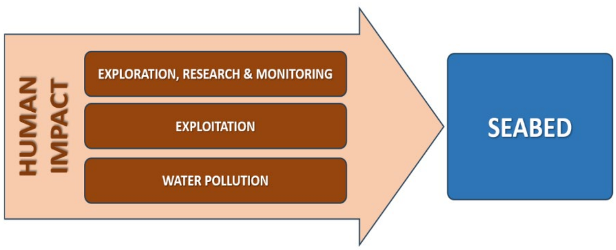

Figure 4
Human impact on the seabed

3 Results and Discussion

To perform the bathymetric survey for this study, the sounder used was a Humminbird Helix 5 Chirp GPS model (Fig. 5).

Figure 5
The echo sounder used for bathymetric survey

Before beginning the survey, the hydrographer must calibrate the multi-beam echo sounder through a patch test. This test helps identify measurement errors related to the mounting angles of the sonar head, allowing for necessary corrections to the transducer's initial angular values. Calibration should ideally take place in favorable weather conditions and in an area with depth and seabed characteristics similar to the planned survey site.

In order to obtain correct and precise results for the present case study, the following working methodology must be followed accurately:

Identifying the area of interest and choosing the right period for safe navigation.

Determining the spatial position of points using GNSS technology, related to the shores of the lake.

Sailing on the lake in a boat equipped with the Humminbird Helix 5 Chirp echo sounder.

Downloading the raw data from the sonar and georeferencing the points.

Importing the points into the Global Mapper software to obtain a 3D model of the underwater terrain.

Creating the bathymetric map with isobaths and depths.

When conducting a bathymetric survey using a multi-beam echo sounder, the line spacing (the distance between adjacent survey lines) is a critical factor that influences the efficiency and accuracy of the survey. The choice of line spacing is primarily influenced by water depth and data density, both of which impact the resolution and completeness of the final bathymetric map. Multi-beam echo sounders emit multiple acoustic beams in a fan shape, covering a wide swath of the seafloor. The width of this swath is directly proportional to the water depth.

To ensure seamless mapping, surveys aim for 20-30% overlap between adjacent swaths. In practice, line spacing is optimized based on survey objectives, seafloor conditions, and multi-beam echo sounder system specifications. Water depth determines swath width, while data density needs dictate the necessary overlap and resolution. Surveyors adjust line spacing accordingly to optimize efficiency without compromising data quality.

The ideal period for performing bathymetric measurements is during meteorologically stable weather. It is not recommended to navigate during the rainy or drought season.

The sonar offers two scanning modes: Wide Mode for maximum coverage and Narrow Mode for focusing on the smallest details. The improved base map provides a clear view of the underwater terrain and surrounding points of interest (Fig. 6).

Due to the low depths of the lake in this project and the need for a precise representation of the underwater terrain and vegetation, Narrow Mode was used for a detailed scan.

Once the sonar is attached to the boat, the survey navigation is initiated. The echo sounder sends out an array of beams across the seabed. When the beams are reflected back from the seabed, data is received and processed, allowing it to be viewed in real time during the survey on the sonar display. The sailing speed was maintained at 8-10 km/h. Using the GNSS technology implemented in the sonar, geospatial points are automatically recorded in the ETRS-89 system during navigation (Fig. 6).

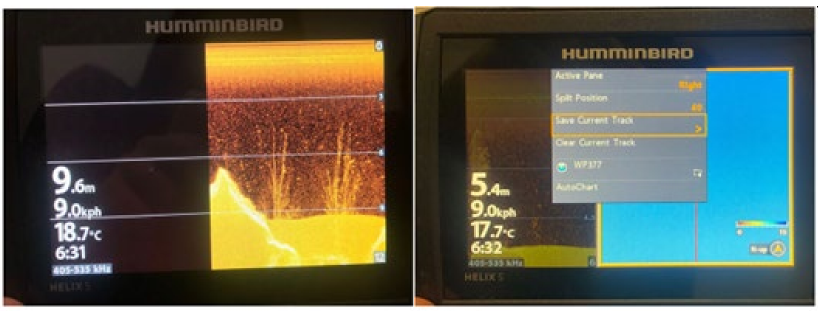

Figure 6

Real-time visualization of underwater vegetation and saving current track

Concurrent with recording the depths of the lake, topographical measurements were also taken along the shores of the lake and the surrounding areas, providing data points for the bathymetric contour map.

The topographical measurements were performed with a Trimble GNSS receiver connected to the ROMPOS Romanian national service (a real-time differential correction service that ensures positioning in ETRS-89 system). This service was used to collect a high number of topographical points for the digital elevation model.

After the field survey process, the raw data from the sonar was downloaded and the points georeferenced. The data obtained was then converted into the final product, as digital elevation model of the waterbody and bathymetric map.

Using the Humminbird PC compatible software, the coordinates were imported to be processed in the ETRS-89 reference system. They were then converted into the Stereographic 1970 projection system. For better visualization and raw data quality assessment, the software offers the option of viewing the sonar navigation route in Google Earth.

Once the spatial positions of the points were converted into the Stereographic 1970 projection system, the data was ready for conversion into bathymetric contour map (Fig. 7).

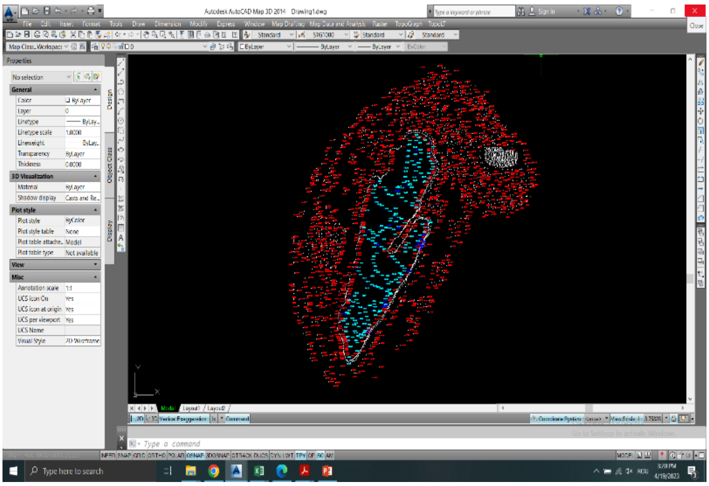

Figure 7

The georeferenced points in AutoCAD. The red points represent the altimetric points on the shores and terrain and the blue points represent the depths of the lake

The TIN (Triangular Irregular Network) triangle network was created to represent three-dimensional visualizations easily by rendering the triangular facets (Fig. 8). Data processing and conversion involved using the TIN data to create contour lines and isobaths. The software allows the selection of contour equidistance's, as well as the level of smoothing for contours to improve accuracy.

To create DEMs, there are various processing and editing software packages where the coordinates of points of interest are imported and then converted into DEMs. For this project, the software used was Global Mapper (Fig. 9). It is a geographic information system (GIS) software package, that handles vector, raster, and elevation data, providing visualization, conversion, and other general GIS features.

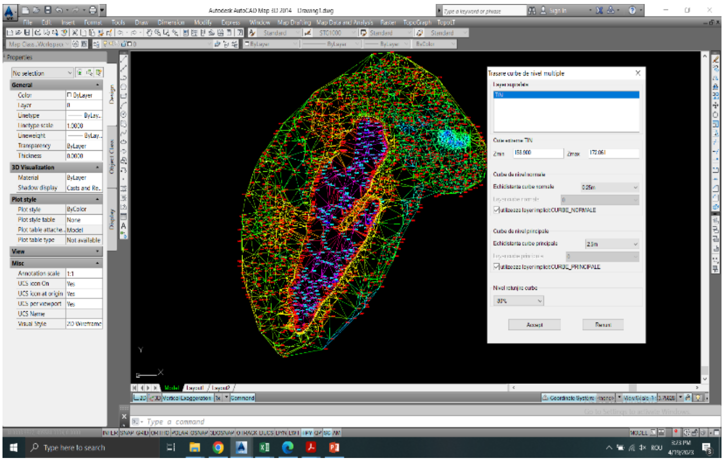

Figure 8
The Triangular Irregular Network created for 3D visualization

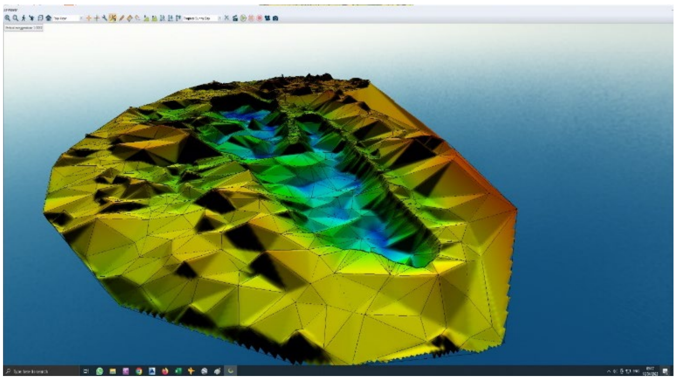

Figure 9
The lake and surroundings in 3D view

While topographic maps represent the three-dimensional features of terrain, bathymetric maps illustrate the underwater relief. Variations in underwater relief can be represented by color areas or contour lines called depth contours or isobaths.

The final result of this project is the bathymetric map, with a scale of altitudes and depths, as shown in Fig. 10.

In this case study, the use of acoustic sonar technology was essential for accurately mapping underwater terrain, determining water depths, and analyzing sediment density. By utilizing sonar techniques, a detailed and representative bathymetric map was generated, providing valuable insights for underwater research and further engineering projects.

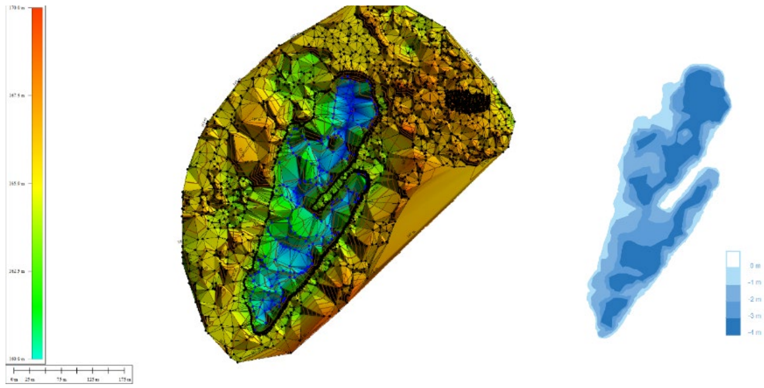

Figure 10
Final digital elevation model and bathymetric map of the lake

Dobra lake, being situated close to Mureș River, typically has a morphology influenced by fluvial and alluvial factors, formed by meandering river dynamics. The main morphological characteristics, derived from the present analysis, are:

- **Shape:** elongated
- **Depth:** shallow, with depth varying due to sediment deposition over time. Maximum depth: -3.96 m. Average depth: -2.62 m
- **Shoreline development:** irregular shorelines due to erosion and sedimentation
- **Sedimentation:** accumulated sediments from river floods, leading to gradual infilling and wetland formation
- **Water input:** direct precipitation, groundwater seepage, and overflow from the Mureș River during high discharge periods
- **Water levels:** fluctuate based on seasonal river flow and human interventions (e.g., raw materials exploitation)

Conclusions

Bathymetric surveys can be used for a wide range of applications and projects: studies on waterbody depths (bathymetric maps), description of sedimentary processes, before and after dredging, volume calculations for alluvial deposits, monitoring underwater landslides; nautical maps, underwater archaeological research, flood risk maps, ballast excavation monitoring, and environmental protection.

A proper establishment of the main phases and strict adherence to the workflow, in a bathymetric survey, are key criteria for obtaining accurate final results and efficiently achieving the project goals.

When conducting surveys with a multi-beam echo sounder, line spacing is influenced by water depth and data density. In practice, line spacing will vary across the survey area due to changes in water depth and terrain roughness. While the proposed method assumes uniform average depths within the survey region, such conditions are rare except in small bodies of water.

This proposed method for calculating survey time can be effectively utilized by planners, research institutions, national hydrographic offices, maritime authorities, and organizations specializing in professional measurements across various aquatic environments.

The bathymetry survey in this study is considered to be the optimal monitoring method, with sonar technology providing accurate and reliable results. In this case, the lake where the measurements were made, was formed by meandering river dynamics and influenced by quarry mining in the area. Bathymetric monitoring was necessary for this purpose.

The methodology for the bathymetric survey included area identification, GNSS positioning, surveying with the echo sounder, data processing, and 3D model generation. Ideal survey conditions are meteorologically stable weather, avoiding the rainy or drought seasons.

To ensure survey efficiency and accuracy, the requirement regarding overlap between adjacent swaths for seamless mapping has been fulfilled (20-30% overlap). Narrow mode was used in this case due to the lake's low depths. The GNSS technology integrated into the sonar automatically records geospatial points in the ETRS-89 system. Topographical measurements were also taken along the lake's shores using a Trimble GNSS receiver connected to the ROMPOS service, ensuring an accuracy of +/-3 cm.

Data processing and conversion consisted of raw data download, georeferencing, and conversion into a digital elevation model and bathymetric map. A TIN (Triangulated Irregular Network) was used to represent the 3D visualizations of the underwater terrain. Global Mapper software, used to process the data and create the digital elevation model, provided both vector and raster data. The final bathymetric map was created with depth contours, illustrating underwater relief.

According to this study, morphological characteristics of Dobra lake were established, such as depths ranging from -3.96 meters (maximum) to an average of -2.62 meters, irregular shorelines with sediment accumulation, and fluctuations in water levels.

The results obtained in this study are characterized by high accuracy, allowing precise determination of the mining parameters in the lake quarry for exploitation project design, future exploitation, and environmental protection according to the present legislation.

The study of Dobra lake's morphology through bathymetric surveys is crucial for raw material exploitation and mining monitoring for several reasons:

- **Raw materials exploitation:** Dobra lake contains valuable raw materials such as sand, gravel, and clay, which are essential for construction and industry. Understanding the lake's morphology helps in identifying deposits, planning sustainable extraction, ensuring water quality, and reducing contamination risks
- **Mining monitoring and environmental protection:** Studying lake morphology is essential for preventing water pollution from mining and heavy metal contamination due to runoff from nearby operations. Monitoring acid mine drainage by analyzing water depth, circulation, and sediment interaction, assessing structural stability, and predicting flooding and water level changes are also critical.

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