Oecologia Montana 2023, **32,** 42-48

TECHNIQUES AND STRATEGIES

Analysis of a mountain lake using sonar with GPS

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Abstract. Mountain lakes are sensitive ecosystems that require detailed research using modern techniques. Little attention is paid to monitoring the morphology of alpine lakes in the Tatras. Therefore, in this work, we focused on diverse ways of monitoring the morphology of high mountain lakes and comparing the used techniques. Our main goal was to test procedures for monitoring the morphology of mountain lakes using sonar and remote-controlled boats at selected experimental locations (artificial: Ždiar, Žilina, natural: High and Western Tatras) over the course of two years (2021 – 2022). During the survey, we recorded and evaluated individual settings and environmental conditions that could influence the result of the measurements. To achieve satisfactory results, it is necessary to consider the choice of location in terms of size and depth, the type of mobile device in terms of load capacity, overall immersion, and manoeuvrability, as well as weather conditions that can reduce battery life. It is also important to process the collected sonar data and preserve quality of the GPS signal. In this work, we discuss the possibilities of changing the technique, the advantages, and disadvantages of their use, and offer recommendations suitable for smoothing when using this technique.

Key words: mountain lakes, morphology, sonar scanning, Tatra Mountains, testing, review

Introduction

Mountain lakes represent vulnerable ecosystems consistently influenced by ongoing natural processes, as well as by direct and indirect human activity, which change their natural development and stability (Moser *et al.* 2019). As mountain lake ecosystems are affected by various factors (Livingstone 2008), it is not surprising that they are often the site of rare endemic species (Niedrist *et al.* 2023). It is well known that past development of mountain landscape can be determined by a deeper analysis of lake sediments (Appleby and Piliposian 2006; Kopáček *et al.* 2006), which can also provide us information about global changes (Catalan *et al.* 2013) such as climate change, acidification, reactive nitrogen or carbon loading, pollution, and species introduction (Williamson *et al.* 2009; Catalan and Donata Rondón 2016).

Sediment analysis is critical to understand the functional relationships in mountain lakes. Inorganic and organic nutrients are continuously transported to lake bottoms by sedimentation and consequently, through biological, physical, chemical, and mechanical processes of certain nutrients, they can be reintroduced to the water. This cycling between sediments and water may be influenced by feeding patterns, lake morphology, temperature regimes, trophic level, and sediment type (Forsberg 1989). Sediments can consist of biological materials (live or decayed), nutrients, and pollutants released from higher cryogenic formations like glaciers, rock glaciers, and permafrost as well as from the direct atmospheric deposition of gases, aerosols, and particles (Nanus *et al.* 2012).

In this context we used two general approaches/analysis consisting of sample investigation and monitoring of lake morphology. In the past, analysis of the high mountain environment were complicated due to the remoteness of these areas. Today, we have modern technologies that facilitate and speed up work in the field. Thanks to remote sensing (LiDAR), the visualization of space is easier (Gao 2009). Bathymetry by sonar, despite its high operating cost and problematic applicability in shallow lakes, can provide more useful data, including depth of sediments or presence of life forms and their stratification. Each method has its own advantages and disadvantages, which can be observed immediately or over time with longer use (Dörnhöfer and Oppelt 2016).

Current bathymetry research using remote controlled vessels with sonar, is often utilized in larger and commonly accessible lakes, but can also by applied to alpine lakes. However, it is necessary to examine possible issues with scanning mountain lakes. Our main aim was testing a specific sonar mounted to a remote controlled boat and evaluating these sonar measurements in various mountain lakes in the Tatra Mountains. We focused on identifying obstacles and problems in the field that could impact the quality of scanning.

Material and Methods

In this study we tested sonar with a GPS system (HOOK 4, LOWRANCE, USA) which was attached to a fishing bait boat (Bait Liner, SPORTS, Slovakia) at the following study sites: artificial water bodies – Ždiar - Strednica, Žilina - dam reservoir (on the river Váh); mountain lakes in Tatra Mountains – Kolové pleso, Račkové pleso, Malé Hincovo pleso and Popradské pleso. All equipment, including the necessary accessories, weighs approximately 13.7 kg (Table 1), includes: backpack for carrying, sonar with accessories, fishing bait boat with controller, two accumulator batteries.

Used sonar with a GPS system HOOK 4 (LOWRANCE, USA) includes all the proven features introduced in the successful Elite HDI (Hybrid Dual Imaging) series with complemented CHIRP sonar technology. Sensor represented transom mounted transducers (Lowrance Skimmer HDI 83/200/455/800 kHz). CHIRP Sonar uses multiple frequencies (83 kHz/200 kHz) at once to a range of 305 m, but sonar is also able to use Down Scan Imaging (DSI) in frequencies 455 kHz or 800 kHz to the range of 91 m. The sonar offers several frequencies that must be known and understood for the result to be as accurate as possible. There are three frequencies to choose from: HIGH CHIRP is used most often in freshwater and shallow marine coastal areas. It provides the best details, such as bait or identification of fish in a school of small fish, or the proximity of obstacles and the bottom. LOW CHIRP provides the greatest penetration into depth when viewing fish in the entire water column. MEDIUM CHIRP has wide coverage; it is best to cover a large area when searching for obstacles or fish. The setting is not as detailed as High CHIRP and does not penetrate as deep as Low CHIRP. Due to the specific depth of the mountain lakes studied, we used HDI HIGH CHIRP frequencies (83/200 kHz) and the highly accurate (20 m RMS), built-in GPS antenna (DGPS, WAAS 16 channels).

The sonar sensor (Lowrance Skimmer HDI 83/200/455/800 kHz) was transom mounted to an aluminium console at the front of a fishing bait boat (Bait Liner, SPORTS, Slovakia). The boat weighs 5.3 kg (with battery) and has a load bait capacity of 1.5 kg. The dimensions of the boat are: 68 cm x 32 cm x 33 cm. The boat has an internal drive (low-consumption electromotor) powered by one accumulator battery (rechargeable lead-acid battery 12 V, 7 Ah, faston 4.7 mm). This battery is also suitable for sonar power supply. The boat should be able to stay in motion for 2-3 hours (without sonar consumption). Of course, this time may vary due to weather, thermal, and other conditions. An empty battery needs an average of 10 hours to recharge. The remote controller for the fishing bait boat weighs 0.6 kg even with eight batteries (NiMH AA 2600 mAh), and has a stated range of 350 meters, or up to 500 metres with a stronger antenna. There is approximately a half-second delay in response to a signal from the controller to the boat's antenna. The carrying capacity of boat is unknown with the exception of the bait container at 1.5 L. Therefore, it is important to distribute individual parts of sonar with respect to the balance of the boat, to avoid poor manoeuvrability of the boat. The battery charging time is approximately 3-4 hours depending on the capacity of mAh batteries.

Used equipment	Weight
Lowrance HOOK 4 controller	0.38 kg
Lowrance Skimmer HDI 83/200/455/800kHz with cable	0.73 kg
Lowrance HOOK 4 with Skimmer HDI Transducer	**1.11 kg**
Boat Bait Liner	5.30 kg
Bait Liner Controller	0.60 kg
Accumulator battery	1.82 kg
Total weight	**8.53 kg**
Maximum load capacity in the bait container	**1.50 kg**

Table 1. Weight of the used equipment.

Collected data were processed in ReefMaster (ReefMaster Software Ltd., UK). ReefMaster combines depth and location data from sonar record files to create highly detailed contour maps to view in 2D and 3D with several basic map options.

Results

Test site: Ždiar - Strednica

Site description: Fire-fighting reservoir on the stream Strednícky potok, close to Ždiar Strednica ski resort and the Belianske Tatras. Located at about 1000 m a.s.l. The reservoir has a maximum depth of 5 meters and a capacity of 20,000 m^3. This reservoir served as an easily accessible site to test proper ship coordination, sonar settings and data post processing.

Testing, data processing: Remote-control of the boat by was problematic due to lack of instruction in the manual; as a result, control skills needed to be developed through practice and time spent on the water. Our testing mode was hampered by battery capacity limitations, which did not allow us to scan the entire part of the lake during one trip. This is due to the sonar power, which reduces battery capacity to approximately one and one-half hours. Battery capacity and boat performance were also affected by wind and temperature, with strong winds draining the battery quickly and prolonged exposure to sunlight overheating the motor and resulting in inefficient boat movement. In windy weather, it was also difficult to control the boat (Fig. 1.).

Initially we tested various sonar settings, including CHIRP settings (Low, Medium, High) and DSI (455 kHz or 800 kHz). Despite efforts to resolve issues with settings, scan modes, and scan display quality, inaccurate depth measurements were observed, with readings indicating depths of 100 meters or more. Data analysis and interpretation was affected by the limitations of the software ReefMaster, including inconsistencies between scanned points, bottom cross-section records, and generated 3D models that had to be resolved in the field.

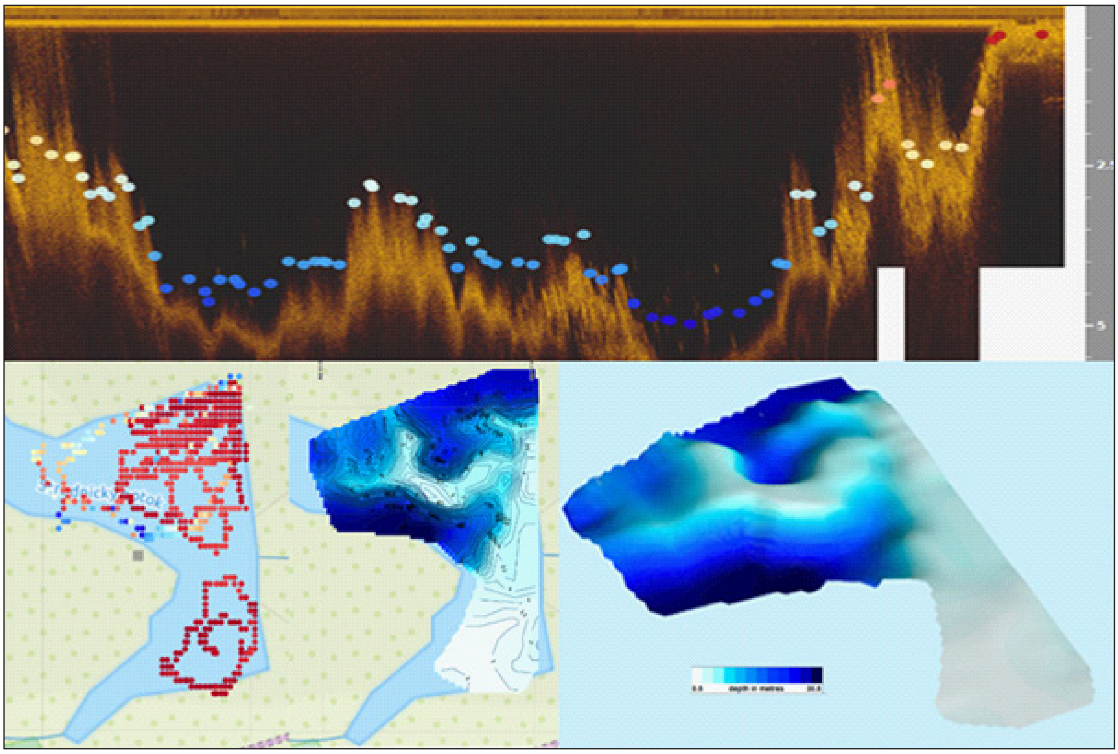

Fig. 1. Sonar scan imaging with automated node points which represented depth and GPS position measured in fire-fighting reservoir Ždiar Strednica. Visualization with final 3D model without modifications was performed via Reef Master program. Main errors consist of inconsistencies between scanned points with bottom cross-section records.

Other limitations included the lack of an SD card (2GB) in the device and interface issues.

Recommendation: Based on collected data and experience, we determined several important aspects which should be taken into consideration for sufficient bottom scanning. These include weather conditions, battery capacity limitations, accuracy of measurement at various depths, and knowledge of boat controls. Further study should consider improvements to increase battery capacity (backup spare battery), ensure boat coordination by towing the boat on a line or fishing rod (applicable also for safe return of boat to shore), increasing device accuracy by estimating maximal depth of the lake in order to successfully gather and analyze data. Additionally, the processing of scan nodes is particularly time consuming as they have to be fixed to the bottom of the lake according to recorded scan imaging.

Test site: Kolové pleso

Site description: Kolové pleso is a mountain tarn located on the edge of the High Tatra Mountains. It is located at an altitude of about 1565 m a.s.l., is 225 meters long, 123 meters wide and covers 1.67 ha. It is shallow, with a maximum depth of one meter. Kolové pleso was chosen due to its accessibility and especially for its low depth, to illustrate the shortcomings of sonar scanning in shallow mountain lakes.

Testing, data processing: Inaccuracies in depth measurement readings due to low water levels were observed. The sonar's GPS measurement was affected by signal interference from surrounding hills and final 3D modelling of the bottom's surface was complicated by inaccurate maps of the area (Fig. 2). Manipulating the boat was also problematic on the shallow lake. In many places, rocks protruded above the water surface and navigation was complicated by windy conditions. Finding appropriate spots for launching the boat may also be difficult due to shallow water and pebbles on the bottom.

Recommendation: This method is not well suited for shallow lakes (below 0.5 m). Future testing should include better selection of study sites that considers depth of the water, interference with the GPS signal, as well as better planning for weather conditions, especially as calm wind also limits waves on the water's surface. Overall, for efficient and precise data collection using the boat and sonar system, careful consideration of equipment setup, ambient factors, and data processing techniques are needed.

Test site: Žilina - dam reservoir

Site description: The Žilina dam lies on the river Váh in the north of Slovakia. It is located at an altitude of 339 m a.s.l. The reservoir is 7.5 kilometres long and its widest point, it is about 610 meters. The total volume of the tank is 18.15 million m^3. This dam reservoir was chosen as a test site for its easy accessibility, a large size, and unknown depth.

Testing, data processing: During testing we had issues with the sun reflecting on the sonar display.

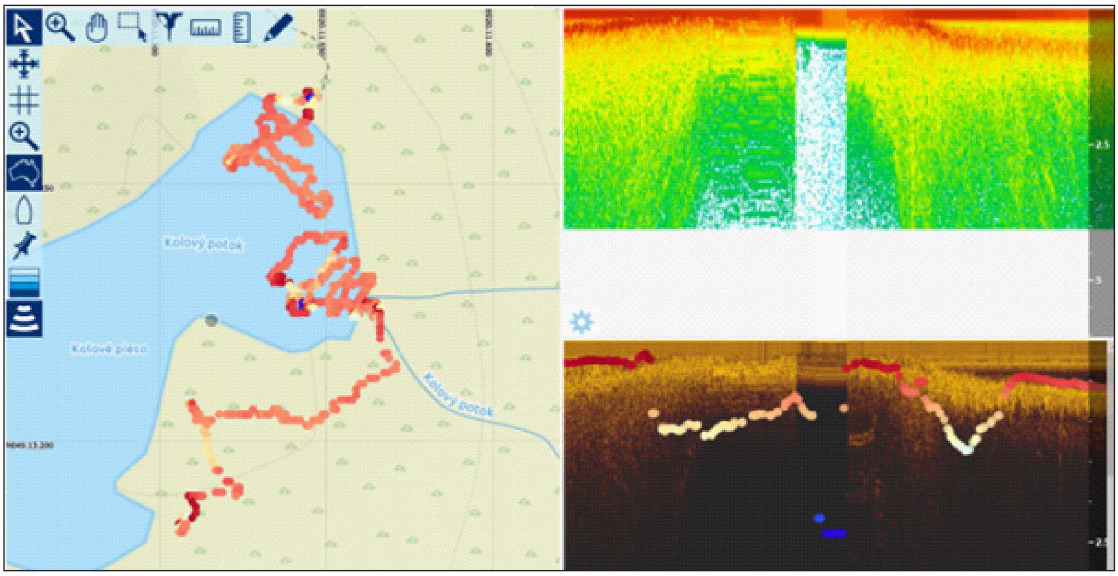

Fig. 2. Sonar scan imaging with automated node points which represented depth and GPS position measured in mountain lake Kolové pleso. Main errors consist of failure of depth measurement due to low water levels below 0.5 meter, inaccurate basic map, and slight GPS signal interference.

However, we achieved well recorded images of the bottom. In that site, we also tested the backup battery. Despite battery capacity improvement, we were not able cover this large water surface (a width of more than 600 m) in one trip. For data processing we used a new version (2.0) of the ReefMaster application, and dealt with an incorrect node point display, despite the use of a scan of the bottom's cross-section without scan errors of depth. This could be caused by faster movement of the boat due to the smooth bottom of the reservoir. The second version of the program was simpler to use.

Recommendation: For such large water areas it may be necessary to experiment with other measurement methods. For example, using a larger boat (light motorboat) managed by a single person could improve scanning of the lake bottom over the whole area. We determined that this version of the data processing software was better due to simplified controls and more efficient postprocessing to manage correction of scanned node points with depth parameters.

Test site: Račkové pleso

Site description: Račkova pleso is a mountain tarn placed in the Western Tatras. It is located at an altitude of 1697 m a.s.l. The tarn is 127 metres long, 83 metres wide and covers 0.74 ha. The maximum depth is estimated to be 12.3 metres, with a total volume of 27,058 m^3. The lake was chosen because of its accessibility, and optimal parameters (depth, area).

Testing, data processing: Due to the size and weight of the equipment and the long hike to reach the tarn, utilizing this site may be excessively physically taxing and impracticable for one person. Additional time spent finding the right location to launch the boat, unpacking, mounting and setting-up equipment added a significant delay. In total, it took 5 hours from starting the trip to initiate scanning. Apart from low visibility of measurement spots, on-site sonar measurements went smoothly. The data was loaded better using the new edition of ReefMaster. Although the measurement sites were accurately placed in the high mountain terrain according to base maps, it proved difficult to generate a 3D model before post-processing because of dips (errors) in the measured node points (Fig. 3). This issue will be a crucial area for additional research in the future, especially in the context of preliminary drawing results of scanning in situ.

Recommendation: Lightweight or portable equipment could be utilized due to the difficulty of field investigation in remote and high elevated areas. Using a lightweight portable computer (tablet) could improve decision making with repetitive scanning of lake bottom in case of frequent errors, and address difficulties in producing precise 3D models from the gathered data.

Test site: Račkové pleso second time

Testing, data processing: During a second visit to the Račkové pleso site, we tried to complete the model from the previous measurement and a larger portion of the mountain lake was investigated/scanned. The main aim was to enhance the 3D model from Račkové pleso. At the site, we experienced an increase in wind speed, which influenced boat handling and slowed down the entire process. Unfortunately, the limited GPS signal was also problematic. Due to a lack of validation of recorded scanning (via portable pc) and a limited timeline for detailed scanning of the entire lake bottom, we were not aware that the sonar had difficulty assigning GPS data, leading to the arrangement of node points in one straight line without spatial position. The recorded sonar scan was higher quality with minimal interference to depth, making it possible to distinguish between hard and soft bottom surfaces (depth of sediments).

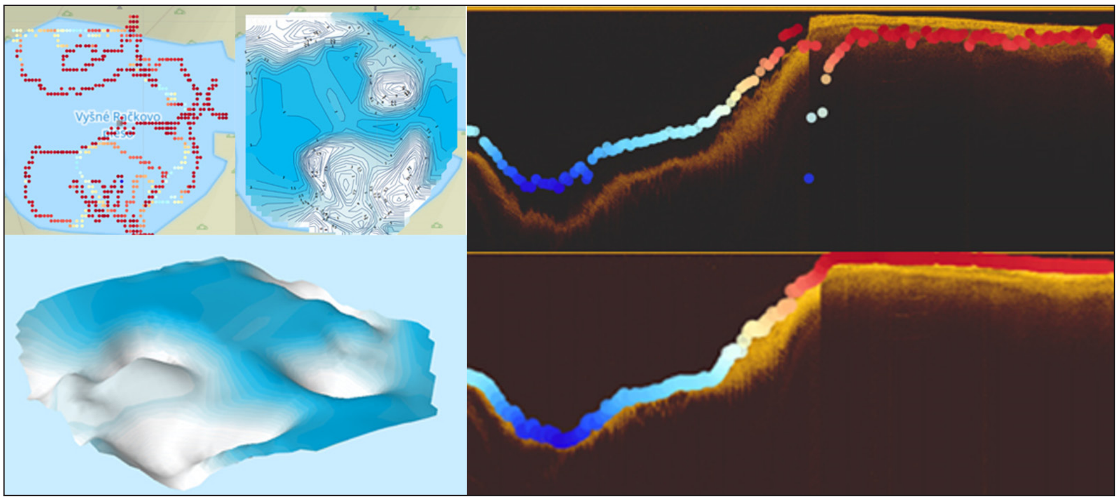

Fig. 3. Sonar scan imaging with automated node points which represented depth and GPS position measured in mountain lake Račkové pleso. Main errors consist of inconsistencies between scanned points with bottom cross-section records which were well adjusted by postprocessing and lack scanning of shallowed part close to shore.

Recommendation: Future research projects should carefully evaluate the potential effects of weather and strength of the GPS signal during measurement. Additionally, we can recommend using more lightweight GPS equipment, with a tracking function.

Test site: Malé Hincovo pleso

Site description: Malé Hincovo pleso is a mountain tarn located in the valley of Mengusovská dolina in the High Tatras. It is located at an altitude of 1921 m a.s.l. The tarn is 265 metres long, 130 metres wide and covers 2.23 ha. The maximum depth is estimated to be 6.4 metres with a total volume of 72,360 m^3. This mountain lake was chosen because of its remote location, size, rocky bottom, and the surrounding mountain peaks (which may degrade the GPS signal).

Testing, data processing: The sonar scan imaging with GPS signal interference was a crucial component of our testing. It was required to determine whether there would be a repeat of past complications produced by the lack of GPS signal or due to the rocky bottom. We carried out testing on a sunny, cloudless day, to avoid weather impact. Finally, we tested/scanned/processed only one pass of the boat close to shore. The GPS showed some deviation, but the scan and points were displayed satisfactorily. However, design of the device seemed unsuitable for transport to higher elevation sites, as we had to troubleshoot an issue with batteries in the remote controller and shifted the rudder of the boat during transport.

Recommendation: Despite satisfactory quality of imaging, the node points of bottom depths needed to be adjusted by software postprocessing. To troubleshoot common equipment issues, we recommend carrying the appropriate toolkit, including a screwdriver, hex keys etc.

Test site: Popradské pleso

Site description: Popradské pleso is a mountain lake located in the valley of Mengusovská dolina in the High Tatras. It is located at an altitude of 1494 m a.s.l. The lake is 380 metres long, 248 metres wide, and covers 6.88 ha. The maximum depth is estimated to be 17 metres with a total volume of 87,397 m^3. This lake is accessible by car and a larger size, so it was selected as a testing site.

Testing, data processing: Testing was conducted on a sunny, cloudless day, to avoid weather impact. First, we focused on testing the controller range to 300 meters. Unfortunately, stable moving control of the boat was only achieved to approximately 150 m. It was complicated by low visibility and uncertainty over the presence of roots and biological debris floating on the surface that made it difficult for the boat to progress. Additionally, in sunny conditions with higher air temperatures, we noticed that the motor was overheating, necessitating a pause in operation of approximately 30 minutes. Unfortunately, even after the pause the motor overheated a second time, resulting in the boat being pushed back to shore by the current. The scan imaging was precise despite the motor difficulties, and after updating the data points, the overall scan results were deemed accurate. Most of the differences/errors in depth measurements occurred in regions with depths under 5 meters. Similar outcomes were obtained when the scanning procedure was continued from the opposite side of Popradské pleso, with the overheating being the sole issue.

Recommendation: These results indicate that it is important to pay attention to possible obstacles on the water surface as well as to limit the distance the boat travels from the controller. Overheating of the engine can prolong the total time required to scan the bottom of the mountain lake.

Discussion

In this work, we investigated one of the methods of scanning the topography of mountain lakes using sonar with CHIRP technology and a GPS system. The sonar was mounted to a small fishing bait boat with remote control. We investigated various artificial and natural water bodies in the Tatra mountains. We dealt with appropriate site selection based on size and depth of lake as well as with accessibility due to the logistics of equipment transport. We considered the reliability of the technology and achieved outcomes. The results of the testing revealed to us several issues, both positive and negative, and we presented some recommendations for improvement.

Modern techniques are more efficient with respect to factors like time and accuracy. Most importantly, for environmental processes in mountain lakes that are spatially diverse and operate over long timescales, it is important to apply and combine advanced sensor systems such as in-depth sonar analysis with multiple imagining beams. In this context, it is necessary to prioritize the durability of sensor-based systems and their performance. In the high mountain environment of Slovakia, lakes are usually not deeper than a few meters, therefore their selection is essential (Müller *et al.* 2014).

Our testing boat has a draft of several centimetres, but the total draft can be greater if the total weight changes. However, the necessary accessories for measurement should be evenly loaded based on balance and coordination. For deeper draft of the boat, it is necessary to launch and navigate the boat to deeper waters. Apart from the first testing site we used a spare battery. The batteries were heavy to transport on the long trails and it was impossible mount them in tandem onto the boat due to size and overloading of boat. However, if we were to consider replacing them with a different type (smaller and lighter) of battery, this complication would disappear, and the boat would be able to operate for a longer time. To utilize a different type or model of battery (with the required voltage of 12 V), it is necessary to adapt the connections and charging interface. The capacity should be higher than 20 Ah to effectively power both the boat and the sonar. A battery with a higher capacity will likely exceed 12 V and would require a voltage converter.

Increasingly, newer, and more modern sonars such as the HOOK 4 sonar are used. A study by Levin *et al.* (2019) compared quality of the Lowrance HDS-7 and the EdgeTec2205 and provided a comprehensive review of scanning software testing. These are more expensive sonar systems that can offer superior performance, durability, and advanced capabilities. These sonars are ideal for specialized applications because of their excellent resolution, depth capabilities, and image quality. In addition, they often have additional features such as advanced mapping software and networking capabilities (EdgeTech 2023). Before purchasing one of these top sonar systems, it is important to evaluate your needs and budget (LOWRANCE 2021), as well as skillset and knowledge of technique. In Slovakia, mountain lakes do not reach depths greater than 60 m (Vološčuk *et al.* 1994; Bohuš *et al.* 1996). The deepest mountain lake in the Tatras is located on the Polish side and has a depth of 79.3 m (Radwańska-Paryska and Paryski 1995). Therefore, choosing equipment from a lower price range should not be problematic for the purpose of depth sonar imaging. However, more shallow lakes can present an issue. According to our results, a mountain lake should have a depth of at least 0.5 m for appropriate scanning and measurement of depth. While lakes that do not have a depth greater than 5 m can be tested, the ideal depth will help to avoid erroneous display of data and prevent damage to the device.

We visited testing sites during different weather conditions (sunny, windy, changeable, cloudy, and rainy), which led us to the conclusion that weather is a key factor. Wind can have a significant impact on boat control, while rainy weather makes it difficult to handle equipment and increases the risk of damage if equipment is poorly secured. Sunny weather results in poor visibility of the sonar display due to sun reflection, and overheating of the boat engine, leading to rapid discharge of the battery.

When collecting data, factors like weather conditions, battery limitations, depth range, user mode, and clarity of the displayed image or correct frequency must be considered. Data collection requires knowledge of sonar software. While the basic principle of each sonar device is the same, specific functionalities may differ. In some cases, the user manual does not provide comprehensive information, which requires the users of the technique to proceed with caution to avoid any complications. The better the sonar device, the better the preparation for the measurement should be.

Initially, we scanned too precisely, and did not emphasize the gaps and distances between individual points, resulting in a detailed analysis and a larger amount of data obtained from a smaller space. This can theoretically be an inefficient practice in terms of time for larger mountain lakes, but beneficial for measuring smaller lakes, thereby maximising the potential of smaller locations. During the measurements, we were unable to constantly observe the measured points, as our technology does not offer this capability. Observing real-time imaging during the measurement process on the external display of the sonar would improve ease of use, as measuring would not take place too close together or overlap data points. Other sonars have this functionality (Parnum *et al.* 2017). After data collection, the boat and recorded sonar imaging inspection are required. After the measurement, we checked the drive propeller and rudder which were often bent and needed to be straightened.

For data processing, we used the manufacturer's recommended program, ReefMaster. We used two versions of the program (the older 1.0 and newer 2.0), and compared them to determine which was more suitable for our research. In principle, they operate in the same way, despite visual changes. However, the layout of the functions has been updated to be simpler and more logical in design. The updated version of the program also supports the sonar file format: Lowrance SL3 (Biobasemaps 2023). Version 1.0 lacked many simple tools, including zooming in and out on the map or others specific functions. New functions have been added to version 2.0 such as: water level shift, point depths, and survey grids. Waypoint editing has been significantly improved. A simple click and drag with the cursor are all it takes to change several dozen points without jamming. Additionally, there is a cleaner visualization of the side scan (Sacarny *et al.* 2018), and the image export includes all image layers, producing a map in a much higher resolution. The improved layout, simplification of the program, and addition of new functions and removal of other make ReefMaster 2.0 simpler to use and more suitable for this type of work.

Our testing technique was able to provide us with enough measurements and thus information for evaluation and comparison. We conclude that it is especially important to have well developed skills related to the control of the technology. Factors like size and depth of the mountain lake, weather, transport distance, GPS signal strength and battery capacity can significantly influence sonar imaging results. Good decision making and light modification of equipment can prevent most encountered problems, but do little to mitigate the risk of other factors such as GPS signal interference or windy conditions.

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Received 3 June 2023; accepted 15 July 2023.