BATHYMETRIC SURVEYS OF TATRAS GLACIAL LAKES:
CASE STUDY – BATIZOVSKÉ PLESO

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The Tatras Mountain, located on the border between Slovakia and Poland, are the highest and the most significant mountains range within the Carpathian Mountains of Central Europe. Because of their altitude and former glaciations the Tatras Mountain are classified as an alpine massif. The most important and interesting natural elements of the Tatras Mountain alpine landscape represent glacial lakes. There are about 87 lakes of glacial origin in the Slovak part of the Tatras Mountain, the most of them are situated in the alpine zone (1 800–2 200 m a.s.l.) above the upper forest line. Hydrographic research of the glacial lakes in the Tatras Mountain has a long history since 1925, however the results of the surveys were different over the years due to technical limits of the survey instruments, their low precision as well as the extreme climate conditions with high altitude. The aim of this paper is to demonstrate the application of modern hydrographic and geodetic instruments for bathymetric survey in the condition of the Tatras Mountain, which unlike the traditional instruments and techniques are characterized by high precension and efficiency. In the case study we demonstrate yet the most precise digital terrain model (DTM) of the glacial lake Batizovske pleso, created in software environment ArcGIS and based on the data from the bathymetric survey performed in 2018 by Autonomous Underwater Vehicle (AUV) EcoMapper and geodetic instrument GNSS Stonex.

KEY WORDS: bathymetry, lake, Tatras Mountain, EcoMapper, DTM

Introduction

The Tatras Mountain are the part of Western Carpathians and they are situated on the territory of two states – the Slovak Republic and the Polish Republic along the border between 20°10’ E and 49°10’ N. The Tatras Mountain stretch longitudinally over a distance of 50 km and occupy about 778 km² of area divided between Slovakia (78%) and Poland (22%) (Fig. 1). The Tatra range can be divided into four geomorphological unit: the High Tatra, the Western Tatra, the Belianske Tatra and Reglowe Tatra (Klimaszewski, 1988). In Pleistocene, the Tatras Mountain were covered several times with ice and the glaciation imprinted the present shape to the mountains on both sides of the state border by forming peaks, glacial valleys, cirques, amphitheatres; waterfalls and lakes. The alpine glacial lakes – as the relics of the last Ice Age, which ended up some 10 to 8 thousand years ago, are the typical elements of the Tatras Mountains nature. Many small and larger lakes form the alpine scenery of the Tatras, while the majority of them indicate the closure of individual glaciers’ branches, the formation of which started in cirques. Considering the genesis; the glacial lakes had been either hollowed out (kar lakes) or dammed by moraines (moraine lakes). However, the majority of the Tatras lakes were formed by the combination of both genesis types, when the originally hollowed out lakes were later dammed by the moraine detritus (UNESCO, 2002). Nowadays, there is about 150–230 lakes of various sizes and depths (depending on the size and periodicity criteria) in the Tatras. Approximately half of them are periodic. In addition, there is a significant number of already extinct, fully overgrown lakes and peat bogs. Mostly, there are small lakes with a surface of less than 1 ha and depth up to 2 m (Gregor and Pacl, 2005), (Kapusta et al., 2018). The lakes are situated mainly in the West Tatras Mountain and the High Tatras Mountain at elevations between 1089 and 2189 m above sea level (a.s.l.). About 70% of the lakes are in an alpine zone above 1800 m a.s.l., 19% in subalpine zone and 11% in mountain zone. The total area of the glacial lakes in Slovak part of Tatras Mountain is 3 km² and they have volume of about 10 million cubic meters (Štefková et al., 2001). The largest lake of the Slovak part of the Tatras Mountain and also the deepest one is Velké Hincovo pleso. The highest located lakes are Modre pleso (2192 m a.s.l.), and Baranie plesie (2 207 m a.s.l.). However, Baranie plesie dries up at the end of the summer and has no water. It should also be noted that 20 lakes of the total number are located in the Western Tatras, however they are shallower and relatively small (2.1 ha max.) Altitu-
Fig. 1. The Tatras Mountain – location of representative lakes.

ides of the Tatras lakes are connected with individual stages of valley glaciers. Therefore, the highest located lakes are the youngest ones and the lowest located are lakes in the advanced stage of the development. The fluctuation of the kar lakes water level with the surface runoff is small, max 0.5 m (UNESCO, 2002).

Previous research

Bathymetric measurements of the Tatras Mountain lakes commenced by Josef Schaffer in 1927 and Franz Stummer in 1931. The cooperation of these two explorers resulted in the Atlas of the High Tatras lakes that was published in three volumes (Schaffer & Stummer 1929, 1930, 1932). It comprises bathymetric plans of 31 Tatras lakes with a number of longitudinal and cross sections. Another researcher who dealt with the lakes of the West Tatras was Eduard Kříž in his doctoral thesis. He carried out plan and depth measurement of twelve lakes in the area. It was the first survey of morphographical and hydrographical conditions (Kříž, 1970). In the years 1961–1964 measurements were performed by Gregor and Pacl (2005) on the areas, depths and altitudes. In 2001, bathymetric measurements of some High Tatras lakes were carried out within the EMERGE project and in 2006 measurement of eighth lakes were performed by Šobr and Česář (2006). To construct these maps a series of transects were run across the lake using the manual method or an echo sounder to measure water depth. Depth was transcribed onto a corresponding transect map. When all the depths had been transcribed, then the points of equal depth were joined on the map to create contours. The quality of the maps depended on a variety of factors including the number of transects that were run, the accuracy of the transect map, the number of depths transcribed and the interpretive skills of the drawer. At the best, only a moderately accurate bathymetric map could be produced and it was inevitable that many underwater features would be missed (Monroe and Betteridge, 2000). In the recent years, a new technology became available that was used in the collection of bathymetric data. Applying GPS (Global Positioning System) technology significantly improved the efficiency and speed of data collection. The quality of data also improved from using GPS, and the integration with GIS to produce maps also became much more efficient. Combination of the GPS unit and single beam echo sounder for hydrographic measurement of selected Tatras lakes used Kapusta (2018) in his dissertation thesis which deals detailed analysis of changes of glacial lakes in the High Tatras Mts.

Material and methods

For the hydrographic research and data mapping, the Autonomous Underwater Vehicle (AUV) Eco Mapper device was used. AUVs represent devices which are currently used in a wide range of hydrographic research, marine geosciences, and the military, commercial, and policy sectors. EcoMapper was developed by YSI Company (USA) and is designed for the quick and easy collection of bathymetric, sonar, and water quality data. EcoMapper is capable of moving on surface and subsurface water levels independently and performing data logging. This device is ideal for coastal and shallow water applications such as hydrographic surveys and spatial environmental monitoring. A survey mission by EcoMapper can be performed in water with a depth of more than one meter, and it is fully capable of subsurface operations down to 100 m. The EcoMapper device consists of a hardware part and the Vector Maps software program, which is designed for mission planning and for
the partial analysis of measured data. Physically, the vehicle can be divided into 3 distinct parts. The bow section contains water quality sensors that interact with the aquatic environment and a Doppler Velocity Log (DVL) for navigation under water surface. The middle section includes an onboard computer, electronic components, batteries, and weights to balance the vehicle. The tail section contains a propulsion system and GPS antennas for navigating on the water’s surface. The device uses a frequency of 500 kHz and has a range of measurement depth from 0.5 to 100 m and a measurement accuracy ±0.003 m. While it is measuring (its mission), the EcoMapper collects predetermined parameters in one second intervals and they are automatically associated with geographic coordinates (latitude, longitude). Water quality measurements include information such as the water temperature, dissolved oxygen, turbidity, pH, chlorophyll, salinity, etc.

**Acoustic bathymetry profiling**

The EcoMapper follows a predefined mission plan pre-programmed by the operator. The mission plan is created in the graphic user environment of the Vector Map Software. Geo-referenced charts, maps or satellite images are imported into the Vector Maps planning software and the mission plan continues by setting positions of waypoints for the vehicle’s navigation. The mission planning includes set points for each leg to a waypoint, speed, depth or undulates for data collection (Fig. 2). This parameter programming tool can be separately utilized for vehicle and sensors pre-programming of each leg or for a complete survey. The software output of the mission planning is an ASCII file that is uploaded to the EcoMapper via a wireless interface prior to the mission’s start. Once the vehicle has started its mission, it operates independently and uses GPS waypoints and DVL navigation to complete its pre-programmed course. Throughout the course, the vehicle constantly steers toward the line drawn in the mission planning software and essentially follows more accurate course of coordinates instead of traversing waypoint-to-waypoint. Upon completing its mission, the vehicle uses Windows Remote Desktop to relay the collected data via a WiFi connection, which is facilitated by the Communications Box, to the user’s computer.

Two missions in total were planned for Batizovske pleso. First mission were planned in transverse direction and second mission in longitudinal direction. The navigation path was created by linking 61 waypoints for the first mission and 53 waypoints for the second mission (Table 1). The average vehicle speed was set to 3.7 km/hour and the acquisition frequency to 1 point per second, resulting in 7,886 points. Total length of both survey missions was 7493 m and duration 121 minutes. The position fixing was guaranteed by an average of nine satellites. In addition a combination of GNSS Stonex S9II and control unit Ashtech Mobile Mapper 100 was used for the data collecting of the Batizovske pleso shore line and the altitude of the lake surface. Phase measurements

![Mission planning in software program Vector Map.](image)

**Table 1.** Type of performed mission for location Batizovske pleso and measured parameters

| No. of mission | No. of waypoint | Total length of survey [m] | Duration [min] | No. of measured points |
|----------------|----------------|---------------------------|----------------|-----------------------|
| Mission 1 (EcoMapper) | 69             | 3487                      | 56:29:00       | 4177                  |
| Mission 2 (EcoMapper) | 53             | 4006                      | 64:54:00       | 3709                  |
| GNSS (Stonex S9II)   | -              | -                         | -              | 142                   |
SKPOS were used for higher accuracy. SKPOS service provides differential corrections for real-time phase measurements (RTK) in the virtual reference station (VRS) concept. To use this service a dual-frequency GNSS receiver is necessary, which is able to process RTK corrections in one of RTCM 2.3, RTCM 3.1, CMRx, CMR+ formats. The service delivers 0.020–0.040 m level accuracy. During the data collection, only measured parameter which fulfilled the accuracy <0.025 were saved. Total number of measured points by GNSS Stonex was 142. Trajectory of both mission and measured points by EcoMapper and GNSS Stonex shows Fig. 3.

Post-processing

Post processing and data analysis were accomplished using Esri’s ArcGIS software. The majority of data obtained was in point form and imported as x, y, z files. The vertical datum and horizontal projection were provided with the metadata and were assigned to the ESRI ArcGIS 10.1 working files. The optimum gridded resolution was determined based on the density of the data. ArcGIS provides advanced and various options to interpolate surfaces using two extensions: Spatial Analyst and Geostatistical Analyst. Digital Elevation Model (DEM) of Batizovske pleso was created by geostatistical analyst tool through the Topo to Raster. Topo to Raster provides the functionality of incorporating other types of geographic features, which can assist in the creation of a DEM. The parameters required for topo to raster are mostly optional to change from the default. Spot elevation, contours, cliffs, lakes, coasts and other boundary information can be inputted and can be utilized in creation of the final raster surface. The drainage enforcement within the tool will ensure a mostly hydrological correct surface. Overall, these interpolation methodologies provide the basic requirements of testing the integration of the topographic and bathymetric point elevation values in order to create a single raster elevation surface (Rodriguez 2015).

Results and discussion

Based on the analysis and post-processing of measured data in GIS software ArcGIS 10.1 Digital Elevation Models of the lake Batizovske pleso was produced (Fig. 4, Fig. 5). The area and volume were calculated with the 3-D surface analysis package in ArcGIS 10.1. For each altitude, the triangulated irregular network was examined to determine the area and volume of each triangle contained within the limits of that particular altitude. The sum of these triangles is used for the output of area and volume (Baskin, 2005). The output from the calculations of area and volume is shown in Table 2. The calculations of area and volume for the Batizovske pleso show the maximum area of 33 011 square meters and the maximum volume of 158 787 cubic meters at a water-surface altitude of 1 884.7 meters above sea level. Another outcome was a comparison (Table 2) of our

![Fig. 3. Trajectory of the survey and measured bottom points.](image)
Fig. 4. Digital elevation model (bathymetry) of the Batizovske pleso.

Table 2. Comparison of the survey results performed by Gregor and Pacl (2005) and by our measurements in 2018

| Author                  | Water surface [m a.s.l.] | Surface Area [m²] | Circumference - shape length [m] | Max. depth [m] | Lake volume [m³] |
|-------------------------|--------------------------|-------------------|----------------------------------|---------------|-----------------|
| Gregor, Pacl, (2005)    | 1884.2                   | 34775             | 885                              | 10.5          | 232089          |
| Our measurements (2018) | 1884.7                   | 33011             | 783                              | 10.4          | 158787          |

Fig. 5. 3D model of the lake Batizovske pleso.
results with 50 year old measurements performed by Gregor and Pacl (2005). Differences between lakes morphometrical characteristics are mostly in volume calculation. The difference at lake volume is very likely result of different methods and density of depth measurements. It is very disputable how many depth measurements used Gregor and Pacl to bathymetric maps construction. Difference of elevation of water surface is 0.5 m so differences at calculation of lake area and circumference should be caused by different water level in lake at the time of both measurements.

Conclusion

The purpose of bathymetric survey is to describe the physical characteristics of the body water bottom. Bathymetric data are used to produce a map showing depth contours, underwater structure, maximum and minimum depth. Data are used to calculate lake volume and mean depth, too. This information is important for understanding the ecology of lake systems, evaluating the limnology process in lakes or for evaluating habitat suitability of lakes for various aquatic species. However, gaining access to these data especially from the mountains terrain is often challenging. Significant potential for the bathymetric survey mountain lakes is application autonomous survey vehicles which are characterized by high precession and efficiency of the survey. The survey had two objectives: (1) to acquire a modern bathymetric dataset of lake Batizovske pleso that can serve as a reference for future investigations of the lake dynamics and (2) to demonstrate application of Autonomous Underwater Vehicle EcoMapper in condition of alpine mountain terrain. The outcomes of the bathymetric survey in this case study deliver the high precious results with utilization of the newest bathymetric instruments and post-processing software methods.

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