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Photogrammetry and Traditional Bathymetry for High-Resolution Underwater Mapping in Shallow Waters

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Abstract

This study addresses the critical need for accurate mapping of submerged terrain, which is essential for hydraulic modeling, environmental monitoring, and water resource management. Traditional bathymetric techniques, such as topographic surveys and acoustic soundings, face spatial continuity and usability challenges in shallow or vegetated waters. Recent advances, including Uncrewed Surface Vessels (USVs) equipped with GNSS and acoustic sensors, along with UAV-based photogrammetry for 3D modeling in clear waters, have expanded capabilities. However, optical methods suffer from depth underestimation due to light refraction, requiring geometric corrections. To address these limitations, the paper proposes a multi-sensor fusion workflow that integrates high-precision topographic data from total stations and GNSS, depth measurements from a USV equipped with a single-beam echo sounder, and UAV-derived optical bathymetry corrected for refraction using Structure from Motion (SfM) techniques. The goal is to combine each method's strengths to overcome their weaknesses and produce an accurate, high-resolution bathymetric model. Validation against ground truth data demonstrated significant improvements in data quality, aligning with standards for shallow-water mapping. Notably, the use of corrected UAV photogrammetry extended effective depth measurements to 4–5 meters, exceeding typical optical limits. The combined methodology ensures robust spatial coverage, precise georeferencing, and transparent independent measurements, making it particularly well-suited for complex lacustrine (lake) environments. The results highlight the operational benefits of using complementary technologies and suggest potential for further enhancement through Machine Learning and Deep Learning techniques to refine data integration and analysis.

1. Introduction

Accurate knowledge of submerged morphology plays a crucial role in a wide range of applications, including hydraulic modelling, environmental monitoring, civil engineering planning, water resource management, and hydrogeological risk assessment (Marcus and Fonstad, 2008; Carbonneau et al., 2012). Traditionally, bathymetric data have been acquired through direct topographic surveys or acoustic measurements, such as single-beam or multi-beam echo sounders, which estimate depth based on the return time of acoustic pulses. While accurate and widely adopted, these methods exhibit intrinsic limitations regarding spatial continuity, operational constraints in shallow or vegetated waters, and the need for boat-based platforms (Westaway et al., 2001; Fonstad et al., 2013). Recent studies have also explored the use of topo-bathymetric LiDAR and multibeam systems for shallow water mapping, demonstrating their capability to capture continuous and high-resolution underwater topography, particularly in fluvial and transitional environments (Guo et al., 2023; Richter et al., 2024; Mandlburger et al., 2025). Current technological advancements have expanded the range of available solutions. In particular, robotic platforms such as Uncrewed Surface Vessels (USVs) equipped with GNSS and acoustic sensors now enable accurate bathymetric surveys even in difficult-to-access or small-scale aquatic environments (Almeida Del Savio et al., 2023; Sotelo-Torres et al., 2023; Makar, 2023). These platforms offer the possibility of high-density, autonomous data acquisition along predefined trajectories while enhancing operator safety and reducing field time. Parallel to the development of active sensors, photogrammetric techniques based on Structure from Motion (SfM) algorithms and UAV imagery have emerged as powerful tools for bathymetric mapping in shallow, clear-water environments (Dietrich, 2017; Fonstad et al., 2013; Menna, 2013). When favorable environmental conditions, such as minimal surface ripples and sufficient water transparency, UAV-photogrammetry can produce high-resolution 3D reconstructions of the submerged terrain. However, due to the refraction of light at the air–water interface, these reconstructions tend to underestimate actual depths. This results in “apparent” bathymetric models that require correction through specific geometric approaches. Among various correction methods, the geometric model proposed by Dietrich (2017), which integrates principles of photogrammetry with refraction physics based on Snell’s Law (Harvey et al., 1998), has proven effective in restoring accurate underwater elevations. Nonetheless, such photogrammetric methods are still susceptible to environmental factors and require robust ground control to ensure their reliability.

1.1 State of the Art and Research Objectives

Several recent contributions have demonstrated the feasibility of integrating UAV-based SfM photogrammetry with bathymetric data in shallow or clear-water contexts, confirming the potential of this approach for environmental and morphological analysis (Dietrich, 2017; Agrafiotis et al., 2019; Rossi et al., 2020; Almeida Del Savio et al., 2023). However, many of these studies have focused on the performance of individual techniques or applied the methods in relatively homogeneous and ideal conditions. There is a gap in the literature regarding structured multi-sensor fusion workflows that maximize spatial coverage, bathymetric accuracy, and adaptability in complex, real-world environments. This study addresses this gap by proposing and evaluating a fully integrated multi-sensor methodology that combines: high-precision topographic data acquired with

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traditional instruments such as total stations and GNSS; point-based depth measurements from a single-beam echo sounder mounted on a USV; and high-density optical bathymetry derived from UAV-photogrammetry, corrected for refraction. This approach aims to demonstrate how these complementary datasets can be effectively combined to generate accurate, continuous, and operationally feasible bathymetric models through comparative analysis and data fusion. The general objective of this study is to evaluate the effectiveness of an integrated multi-sensor approach for bathymetric surveying in shallow lacustrine environments, specifically demonstrating how the fusion of traditional topographic data, single-beam echo sounder measurements, and UAV-based photogrammetry can overcome the limitations of individual techniques to produce a comprehensive and accurate bathymetric model.

2. Study area and data acquisition

The research presented in this paper was conducted in a small lake located in the Piedmont region, Northern Italy (Figure 1). Specifically, the study site is the Biolago di Caraglio, an ornamental and bathing basin spanning approximately 4000 square meters, situated in the municipality of Caraglio. This biolake is distinguished by its natural water purification system, which utilizes plants, gravel, bacteria, phytoplankton, and zooplankton instead of traditional chemical treatments. This configuration creates an artificial ecosystem that simulates a natural environment for water purification, offering an ecological and sustainable alternative to conventional pools. As reported before, an accurate multi-sensor campaign was carried out for the 3D metric survey of the site. Based on integrating data from active and passive measurement instruments, the adopted approach represents the most appropriate methodology to ensure consistent three-dimensional metric documentation of the emerged and submerged parts. Operations commenced with a topographic survey of the geodetic control network and the measurement of the Ground Control Points (GCPs), both in the area surrounding the lake and in the submerged portions. Subsequently, bathymetric measurements were acquired using a single-beam echo sounder, which enabled the collection of point-based depth data along predefined cross-sections, employing a surface vessel. Concurrently, a photogrammetric survey was conducted using a UAV to obtain high-resolution data for the photogrammetric helpful process for the documentation of the area (Digital Surface Model- DSM and Orthoimages) and to support bathymetric reconstruction in shallow waters. The following sections detail each of these data acquisition methods.

2.1 Traditional Topographic Survey

In the context of 3D metric surveying, establishing a consistent reference system is of paramount importance. It ensures coordinate homogeneity for all measurements and derived products while enabling rigorous control over error propagation, guaranteeing adherence to the required accuracy. This aspect is particularly crucial for photogrammetric processing to obtain suitable and accurate outputs (in this case, related to the emerged and submerged area). Furthermore, measurements acquired in the submerged area allow for the validation of depths and bathymetric reconstruction obtained using different techniques. They also enable highly accurate measurement of the water surface elevation, which is essential information for subsequent processing phases. For the traditional topographic survey, two Leica System 1200 GNSS (Global Navigation Satellite System) receivers and a Leica Nova MS60 Total Station were employed (Figure 2). Initially, three topographic vertices were acquired using the GNSS receiver in static mode, with a 5-second sampling interval over approximately 2 hours of observation. Starting from the network vertices, traditional side shot measurements were performed in order to allow the acquisition of detailed points essential for both the processing of UAV data and for supporting the analysis of the submerged area of the Biolago (Figure 3). Specifically, 6 Ground Control Points (GCPs) were acquired for the photogrammetric process, 369 underwater points were collected for validating and integrating the bathymetric reconstruction obtained from the other acquisition methods; 15 points were measured on the water surface surrounding the biolake. These 15 points proved crucial for reconstructing the water surface, which is indispensable for applying the geometric bathymetric refraction correction method to the photogrammetric data.

Figure 1. Caraglio study area in Piedmont, north part of Italy

Figure 2. Instruments used for the topographic survey, Leica System 1200 GNSS receiver (left), Leica Nova MS60 Total Station (right)

Figure 3. Traditional topographic survey operations with a Total Station, during the acquisition of in-water points

2.2 Bathymetric Survey with USV and Single Beam Echo Sounder

For the bathymetric survey, an Uncrewed Surface Vessel (USV), the Blue Boat, manufactured by Blue Robotics (https://bluerobotics.com/store/boat/blueboat/blueboat/), was utilized (Figure 4). This surface platform, operable in autonomous or remotely controlled modes, is specifically designed for hydrographic and environmental surveys in inland waters, such as lakes, artificial basins, rivers, and shallow coastal zones. The Blue Boat features a maximum speed of 3 m/s, weighs 14.5 kg, and has an autonomy of approximately 62 hours with eight batteries. In the configuration used for this study, the Blue Boat was equipped with a Single Beam Galileo AL-WI Portable Echo Sounder, a single-beam acoustic echo sounder widely recognized and used in hydrographic applications for determining water depth and documenting bottom morphology. The Galileo AL-WI is a well-established and widely validated technology in professional practice, valued for its reliability, precision (with an accuracy of ± 2 cm), and ease of use even in complex operational contexts. The sensor operates within a depth range of 0.2 m to 200 m, with an acquisition angle of 8°. Measurements were continuously recorded along the USV's remotely controlled routes, providing point-based data describing the seabed morphology along the traversed trajectories (Figure 5). To ensure the accuracy of the measurements, fundamental aspects such as the distance and orientation between the echo sounder sensor and the GNSS antenna on board the USV were considered and calibrated. This calibration is essential for correctly referencing depth measurements to the precise planimetric position of the vessel.

Figure 4. Single Beam acquisition with the Blue Boat USV

Figure 5. Trajectory of bathymetric points acquired with the Blue Boat USV within the Biolago di Caraglio

2.3 UAV Photogrammetric Survey

Concurrently with other techniques, UAV acquisitions were carried out to support the study area's documentation, analysis, and graphical representation. A photogrammetric survey based on the SfM approach was conducted to assess the potential of photogrammetric techniques for bathymetric purposes. This method allowed for generating metrically bi- and three-dimensional accurate products, such as orthophotos and 3D models (point clouds and Digital Surface Models, DSMs). The drone used for acquisitions was a Matrice 350 RTK UAV equipped with a P1 camera with 45 Mpix of resolution and a 35 mm focal length. Flights were planned with longitudinal and transversal overlaps of 80% and 60%, respectively. Approximately 700 nadiral and oblique images were acquired at different altitudes (from 40 to 100 meters) to ensure optimal quality for photogrammetric orientation operations. The Ground Sample Distance (GSD) varies between 4 mm and 12.6 mm. It is crucial to note that optimal environmental conditions were sought for effective bathymetric reconstruction using photogrammetry, including clear water, minimal surface waves, and minimized surface glare. Figure 6 shows an example of the oblique acquired images.

Figure 6. Example of an oblique image acquired by the Matrice 350 RTK UAV for the photogrammetric survey

3. Data processing and fusion methodology

This section details the methodologies employed for processing the acquired data and their integration and fusion.

3.1 Topographic network data processing

The topographic network's processing, including the computation of baselines and detail points, was performed using Leica Infinity software v.4.2.1. Network compensation was achieved through a least-squares adjustment, ensuring overall precision optimization. The adopted geodetic reference system for all measurements is WGS84-ETRF2000. Subsequently, ellipsoidal heights were converted to orthometric heights using Convergo software and the GK2 grids provided by the Istituto Geografico Militare (IGM). Regarding precision, the coordinates of the three main vertices exhibited standard deviations not exceeding 5 mm for the planimetric components and 1 cm for the altimetric component. On the other hand, the precision of points measured through the total station using a side shot approach was determined to be ± 1 cm in XY and ± 2 cm in Z. These values confirm the high metric quality of the acquired data and their suitability for the survey's objectives. In Figure 7, an overview of the vertices and the acquired detailed points (about 370 points) in the emerged and submerged areas.

Figure 7. Orthophoto of the study area with superimposed spot heights acquired through traditional topographic survey

3.2 Single Beam data processing

The processing of the single-beam was conducted following a traditional approach. After data collection, sound velocity correction was applied to account for variations in the speed of sound in water, which can be influenced by temperature, salinity, and pressure. These values in the case of Caraglio were extracted from standard models. Depth readings are then adjusted accordingly to improve accuracy. After that the data were cleaning to remove outliers and noise. In the present research the noise was result from vegetation no debris or sonar signal distortions were noticed from the output of the single-beam. The filtering was performed combining manual inspection and automated filtering techniques. The final output (3300 points), georeferenced during the acquisition through the use of an RTK antenna that is part of the single-beam system, was employed for data fusion in order to generate the final bathymetry of the Caraglio lake. As is shown in Figure 5 only the central portion of the lake was covered by the blue-boat since in the low depth of the north and south part didn’t allow to navigate and acquire data with the single-beam. For this reason, in order to improve the number of points and to evaluate advanced methodology for bathymetric data collection, the approach of extracting underwater data was followed, as is reported in the next sections.

3.3 Photogrammetric-UAV data processing

For the processing of the acquired data, the traditional photogrammetric approach was adopted, using two of the widely used software: Agisoft Metashape v 2.2 and DJI Terra v 4.4, with the purpose of comparison and analysis of results. The key processing phases are common and aim at generating dense point clouds and other derived 2D products, such as DSM and orthophoto. The process begins with the import of images and the computation of their relative orientation. Subsequently, Ground Control Points (GCPs) and Check Points (CPs) are collimated directly onto the images. In the context of the Biolago di Caraglio, 4 GCPs and 2 CPs were used, supported by NRTK mode to ensure centimetric precision for camera orientation. Upon the adjustment of the global photogrammetric block optimization (Bundle Block Adjustment, Figure 8), and the camera calibration phase, the errors on GCPs were ≤ 1 cm, while on CPs ≤ 2 cm. These values confirm the adequate metric quality for a representation scale of 1:200, which was the research activity's initial objective (precision ± 4 cm). Based on the optimized photogrammetric block reconstruction, the dense 3D point cloud was generated (Figure 8), from which the Digital Surface Model of the area and the orthophoto were subsequently obtained.

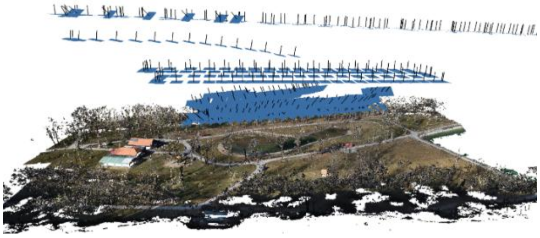

Figure 8. Photogrammetric Bundle Block Adjustment and dense point cloud generated by Agisoft Metashape software

A comparison between the point clouds generated by Metashape and DJI Terra revealed similar overall accuracy for the reconstruction in the emerged areas. However, regarding the submerged parts, a significant difference in the noise level of the point cloud was observed. As illustrated in Figure 9, the point cloud generated by DJI Terra exhibited higher noise both in shallower sections (around 30 cm) and in deeper areas, with noise progressively increasing with depth, ranging from 2 meters up to a maximum depth of around 4.6 meters. Figure 10, which shows a cross-section of the lake, clearly highlights this aspect, comparing the profile extracted from Metashape (in red) with that from DJI Terra (in white). Following this analysis, it was decided to proceed with the subsequent phases of refraction correction and data fusion with other methods using the point cloud processed with Metashape, due to its better noise management in submerged areas.

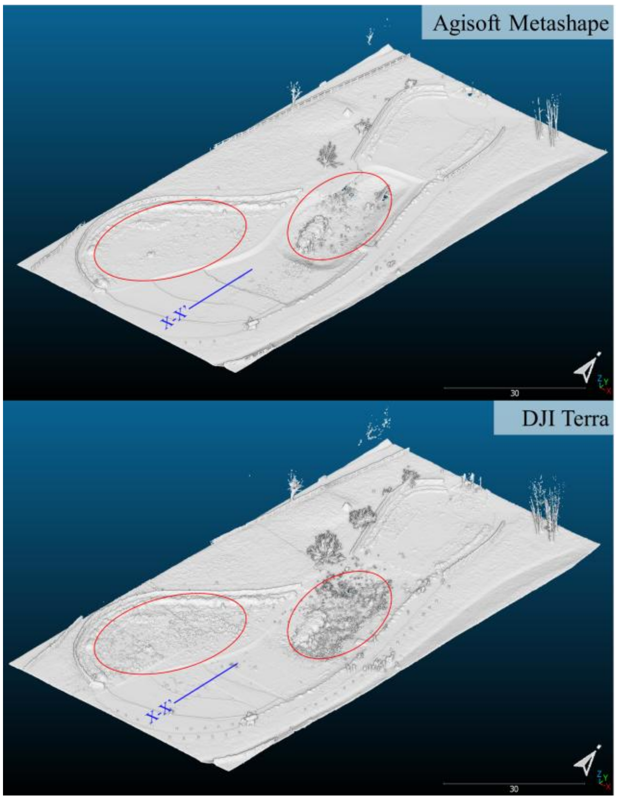

Figure 9. Comparison of dense point clouds generated by Agisoft Metashape (top) and DJI Terra (bottom) for the study area. Areas circled in red indicate regions with higher noise in the DJI Terra point cloud, particularly in submerged sections

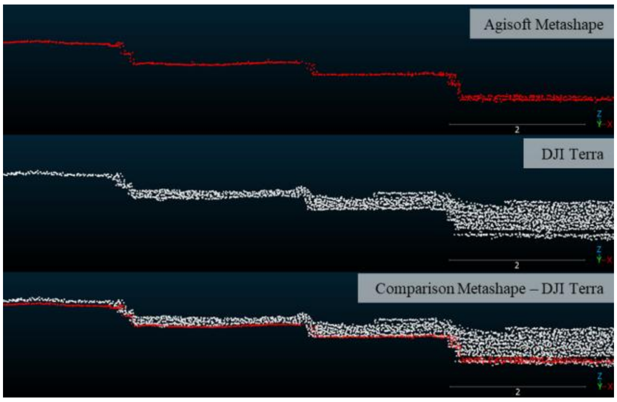

Figure 10. Section X-X', comparison of altimetric profiles extracted from Agisoft Metashape (red) and DJI Terra (white) point clouds, highlighting the increasing point noise with depth for DJI Terra

3.3.1 Refraction correction method

SfM photogrammetry with Uncrewed Aerial Systems is an effective method for acquiring high-resolution bathymetric data in shallow waters, provided conditions of water transparency, minimal wave presence, and absence of glare (Dietrich et al. 2017; He et al., 2021). However, refraction causes an underestimation of true depths, thus necessitating the application of a correction method to determine the actual depth by compensating for the error introduced by refraction. Therefore, the geometric method proposed by Dietrich was applied, which combines the principles of multi-view photogrammetry with the physics of refraction, based on Snell's Law (Harvey et al., 1998). The point cloud was subsampled (to 5 cm) in the CloudCompare software to reduce redundancy and noise. Subsequently, the apparent depth for each point is calculated as the difference between the water surface elevation (obtained from points measured with a total station) and the altimetric elevation of the point to be corrected. Finally, the correction algorithm, implemented in the Python script pyBathySfM (GitHub repository: http://github.com/geojames/py_sfm_depth), applies the refraction correction using the photogrammetry-based point cloud, the water surface model (Figure 11a), the external orientation parameters of the cameras, and the sensor characteristics as input data. The result is the underwater georeferenced point cloud (about 800,000 points with corrected altimetric elevations, corrected by refraction (Figure 11b). The detailed analysis of the results of this correction will be presented in Section 4. Results and Discussion.

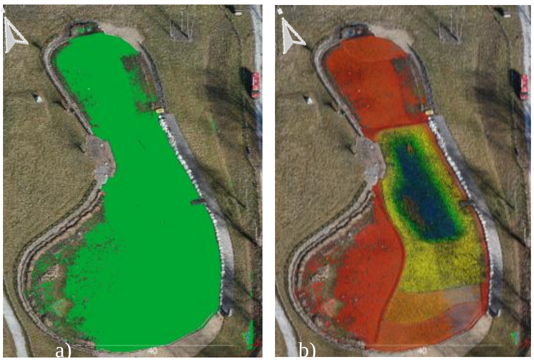

Figure 11. Creation of the water surface model and extraction of the underwater point cloud to be corrected for refraction. (a) Water surface model. (b) Extracted underwater point cloud

4. Results and discussion

This section presents the results obtained from each data acquisition method employed, followed by a comparative analysis and a discussion of the benefits of data fusion. The objective is to quantify the accuracy and complementarity of each technique, highlighting the added value of the integrated approach for creating a detailed and robust bathymetric model.

4.1 Overview of method outcomes

The results obtained from each data acquisition method were analysed to evaluate their planimetric and altimetric accuracy, coverage, and operational characteristics. The traditional topographic survey provided a high-precision reference, essential for overall georeferencing and creating an accurate water surface model (Figure 12a). Single-beam echo sounder acquisitions generated a dense bathymetric point cloud along predefined trajectories (Figure 12b), offering direct depth measurements, albeit with limited spatial coverage between lines. The UAV photogrammetric survey, processed with the photogrammetry approach, produced a dense point cloud of the entire study area, including the submerged part (Figure 12c), a Digital Surface Model, and a high-resolution orthophoto, although initial depths showed an underestimation due to refraction. Below is a summary Table 1 of the main outcomes for each method.

Acquisition Method	Accuracy (XY)	Accuracy (Z)	Coverage
Traditional Topographic Survey	≤ 5 mm (vertices) ± 1 cm (detail)	≤ 1 cm (vertices) ± 2 cm (detail)	Discrete points (370 points)
Single Beam Echo Sounder with USV	± 2 cm, depends on GNSS on USV	± 2 cm	Discrete lines (3.000 points)
Drone-based Photogrammetry	± 2 cm 7 mm average GSD	Underestimation function of depths (pre-correction)	Continuous, high-resolution (800.000 point, one each 5 cm)

Table 1. Summary of the main outcomes for each acquisition method, detailing planimetric and altimetric accuracy, and submerged area coverage

Additional considerations regarding the bathymetric DSM generated by each methodology. Concerning the topographic survey, the resulting DSM covers the entire submerged area (Figure 12d), but its accuracy and density critically depend on rigorous planning of point acquisition. This methodology proved highly effective for representing areas with minimal slope variations. However, its capability to provide a complete and detailed reconstruction is limited in zones characterized by steeper slopes. While functional in shallower portions, acquiring points in deeper sections revealed operational challenges. In terms of execution, this methodology is time-intensive and requires the deployment of highly qualified personnel; for instance, in the present case study, it was necessary to employ expert divers. Regarding the DSM obtained via USV with a single beam echo sounder not cover the whole submerged area (Figure 12e); the operability of this methodology is constrained by a minimum water depth, determined by both the echo sounder's minimum operational range and the minimum draft required for USV navigation. Despite this limitation, the methodology proved particularly effective in representing areas with high slope variations and in deeper parts of the seabed. In terms of efficiency, data acquisition is not excessively time-consuming but still requires trained, though not highly qualified, personnel. Finally, the DSM derived from UAV-based photogrammetry proved to be complete, covering both the entire emerged and submerged area, and high-resolution (Figure 12f), provided that acquisitions occur under optimal environmental conditions (e.g., low water turbidity, good visibility of the seabed). Field data acquisition is time-efficient. However, given the influence of the refraction phenomenon on light's trajectory through the air-water interface, the data post-processing phase requires significant time and expert, trained personnel to apply appropriate corrections. Analyses and comparisons, detailed in the subsequent sub-section (4.2), indicated that water depth does not constitute a limiting factor for this methodology, as refraction correction, under optimal conditions, proved effective even for depths exceeding 2 meters.

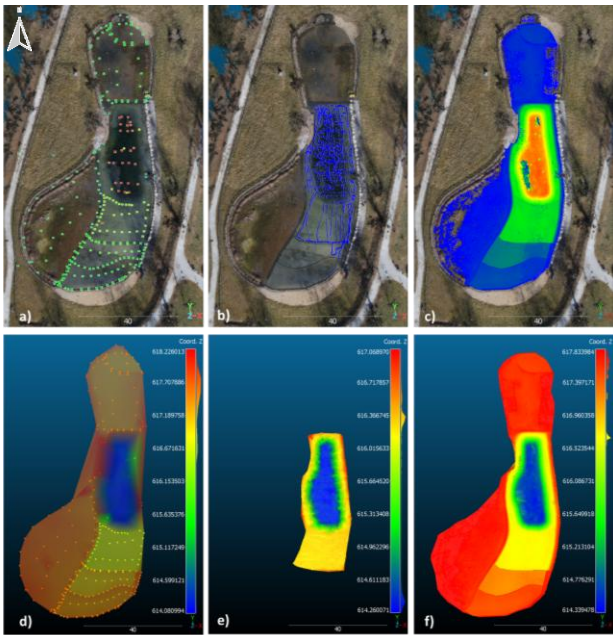

Figure 12. Overview of acquired data and derived Digital Surface Models (DSMs): a) In-water points acquired with total station; b) Bathymetric points acquired with single beam echo sounder; c) Photogrammetric point cloud. Corresponding derived DSMs: d) from total station; e) from single beam; f) from photogrammetry

4.2 Data Validation and Inter-Method Comparisons

A crucial aspect of this study was the validation of the corrected bathymetry through comparison with the DSM obtained from submerged points acquired with a total station. Figure 13 shows the Cloud-to-Cloud analysis of the uncorrected bathymetric point cloud (left) and the corrected one (right) with the surface model used as ground truth. Initially, uncorrected photogrammetric depths showed significant discrepancies compared to the ground truth, with an average RMSE of 41 cm. After applying Dietrich's geometric refraction correction method, the differences were drastically reduced. Statistical analysis revealed an RMSE of 4 cm, confirming the effectiveness of the correction process in restoring true depths with an accuracy compatible with bathymetric standards for shallow waters. For instance, at the deepest point, an initial underestimation of 1.4 meters was reduced to a difference of only 4 cm from the reference data after correction, perfectly in line with the 1:200 representation scale. In Figure 14, two sections are shown, at the point of maximum depth (A-A') and an average depth of 60 cm (B-B'); the green line represents the Topographic DSM used as reference; in red, the profile without refraction correction depth; in black, the refraction correction profile.

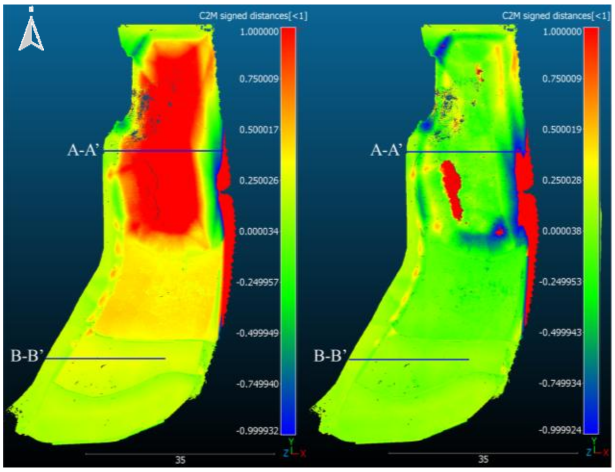

Figure 13. Cloud-to-Cloud (C2C) analysis of the uncorrected (left) and corrected (right) bathymetric point clouds against the reference surface model (ground truth).

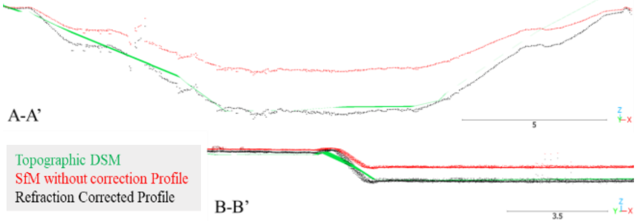

Figure 14. Sections A-A' and B-B' highlight the effectiveness of the correction even in greater depths.

The comparison between bathymetry acquired by the single beam and the topographic surface model, considered as ground truth in overlapping areas, showed good general consistency. The Cloud-to-Cloud (C2C) analysis between the single-beam data and the topographic reference revealed that 75% of the points have discrepancies below 10 cm (Figure 15).

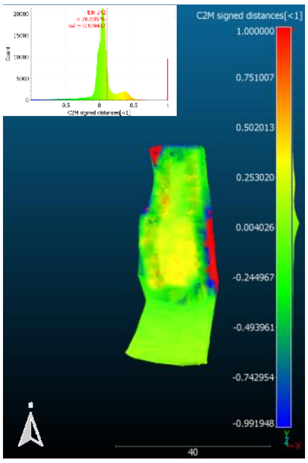

Figure 15. C2C analysis of the single-beam bathymetric point cloud against the topographic surface model (ground truth)

However, the profile comparison of all the methods shown in Figure 16 highlights significant agreement in seabed morphologies, although the corrected photogrammetric point cloud offers significantly higher density and spatial continuity than the discrete lines of the single beam. The average difference between single-beam and photogrammetric refraction-corrected bathymetry in overlapping areas was 3 cm, indicating good compatibility between the two techniques once photogrammetric correction was applied.

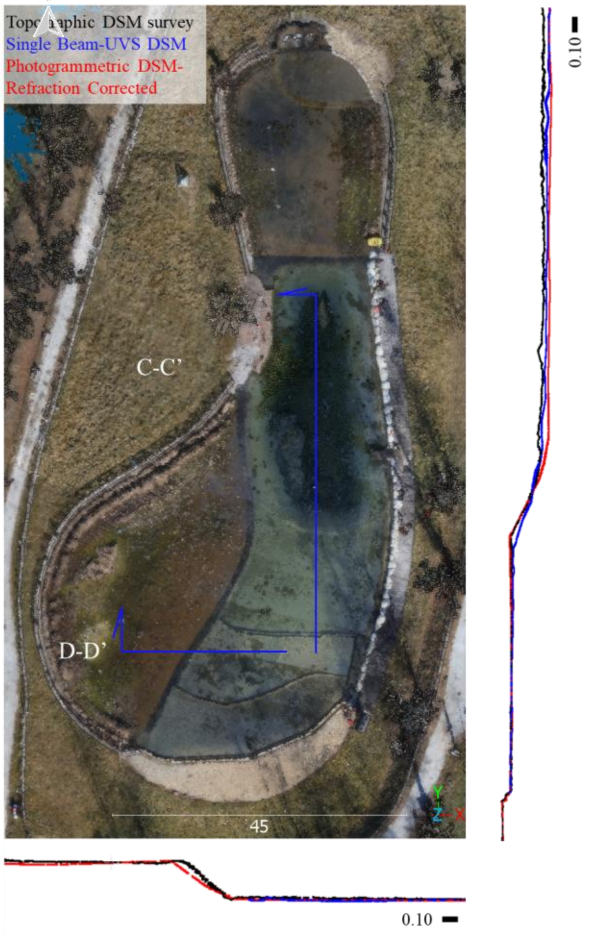

Figure 16. Altimetric profiles extracted from different datasets: Topographic DSM survey (black), Single Beam-UVS DSM (blue), Photogrammetric DSM-Refraction Corrected (red). Profiles C-C' and D-D' show the consistency between the models

4.3 Data fusion process and benefits

The fusion of data from various acquisition sources is a crucial step to obtain a complete and accurate bathymetric model, overcoming the inherent limitations of each single method. The computational integration of the datasets (total station, single-beam echo sounder, and corrected photogrammetry) was achieved through a strategy that capitalizes on the strengths of each technique. Data from the total station topographic survey played a fundamental role in the georeferencing and calibration of all datasets. The highly precise Ground Control Points (GCPs) and submerged detail points were used to georeference the photogrammetric 3D models and other 2D cartographic products, ensuring planimetric and altimetric accuracy. Furthermore, points measured on the water surface allowed for reconstructing an accurate water surface model, indispensable for applying refraction correction to the photogrammetric data. The corrected bathymetric point cloud obtained from UAV photogrammetry provides continuous, high-resolution spatial coverage of submerged areas with clear water. This dataset was integrated with the discrete depth measurements acquired by the single-beam echo sounder. Although the single beam offers direct measurements independent of transparency, its coverage is limited to linear profiles. Fusion was achieved through interpolation and registration techniques that allowed for combining the density and continuity of photogrammetry with the pointwise precision of the single beam. Specifically, single-beam data were used to calibrate and validate photogrammetric depths, especially in deeper areas or where photogrammetric image quality was less optimal. This data fusion strategy offers numerous advantages. Integrating high-precision total station data with direct single-beam measurements and dense, corrected photogrammetric coverage allowed for achieving a higher accuracy level than what is attainable with a single sensor. Moreover, the combination of techniques ensured exhaustive mapping of both emerged and submerged areas, overcoming the coverage limitations of each individual method. The final bathymetric model also benefits from the high spatial resolution provided by photogrammetry, integrated with the altimetric precision of direct topographic and bathymetric data. Finally, cross-validation and data integration from different sources enhance the overall reliability of the final bathymetric model, making it more robust and suitable for various applications. This synergistic integration not only enhances the precision and completeness of the model but also optimizes operational efficiency and survey versatility. For instance, while the traditional topographic survey proved ideal for extremely shallow waters (0-40 cm) and the shoreline, its application in greater depths is limited. The USV with a single-beam, although effective up to 200 meters, encounters difficulties in very shallow waters due to its draft. UAV photogrammetry, traditionally tested up to about 2 meters in depth, demonstrated in this study its effectiveness up to 4-5 meters under optimal bottom visibility conditions, significantly extending its operational range compared to previous studies. This operational complementarity offers an efficient and robust solution for the bathymetric mapping of complex lacustrine environments.

4.4 Discussion of implications and limitations

The obtained results clearly demonstrate the effectiveness of the proposed multi-sensor approach, with particular emphasis on photogrammetric refraction correction supported by robust topographic control. This method has proven to be extremely performant for bathymetric surveying in shallow lacustrine environments characterized by good water transparency. Such a methodology offers an efficient and inherently safe solution compared to traditional techniques for detailed seabed mapping. The implications of this capability are significant for various application sectors, including water resource management, environmental monitoring, and the planning of specific interventions in these contexts. Despite the notable advantages, it is crucial to acknowledge the inherent limitations. Photogrammetry, while ensuring high resolution and data density, remains subject to the necessity of favourable environmental conditions, such as adequate water transparency and the absence of cloud cover or precipitation that could alter image quality or light propagation through the water column. However, its integration with the single-beam echo sounder emerges as a crucial complementary solution, offering the capability to acquire bathymetric data even in less-than-ideal scenarios or areas where photogrammetry might be compromised.

5. Conclusion

This study demonstrated the effectiveness of an integrated multi-sensor approach for the bathymetric analysis and documentation of very shallow lacustrine environments, overcoming the inherent limitations of individual acquisition methods. The proposed data fusion methodology, combining the topographic precision of the total station with the high spatial resolution of UAV photogrammetry (corrected for refraction) and the direct measurements from the single-beam echo sounder, allowed for the generation of an accurate, comprehensive, and robust bathymetric model. In particular, the validation of the corrected photogrammetric bathymetry confirmed a significant reduction in discrepancies compared to the ground truth, achieving an RMSE of 4 cm, fully compliant with the accuracy limit for bathymetric products at a 1:200 scale that was the initial objective of the project. The synergistic integration of the three techniques not only improved the accuracy and completeness of the final model but also extended the operational range of UAV-based photogrammetry up to 4–5 meters depth under optimal water clarity conditions, outperforming the depth limits typically reported in literature. Beyond the quantitative results, this study highlights the operational advantages derived from the methods' complementarity: the topographic survey ensured accurate georeferencing and water surface modelling; the single-beam echo sounder provided direct measurements independent of water transparency; and UAV photogrammetry enabled continuous, high-density spatial coverage. The encouraging outcomes of this research pave the way for future developments. The implementation of Machine Learning (ML) and Deep Learning (DL) techniques could further enhance the automation and accuracy of the fusion process, for example, through intelligent point cloud denoising, adaptive weighting strategies among datasets based on local conditions, or the development of more generalizable refraction correction models. ML/DL methods could also support automatically classifying seabed morphology or submerged features, enriching the final product with additional thematic information. These advancements may make bathymetric surveys faster, more cost-effective, and more reliable across various environmental contexts.

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