The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLVIII-2/W10-2025
3D Underwater Mapping from Above and Below – 3rd International Workshop, 8–11 July 2025, TU Wien, Vienna, Austria

Underwater Mapping in Shallow Coastal Waters Using MBES and Photogrammetry: Applications in Archaeology and Marine Habitat Monitoring

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Keywords: underwater mapping, MBES, photogrammetry, marine archaeology, habitat mapping, *Posidonia oceanica*

Abstract

This study explores the combined use of Multibeam Echosounder (MBES) and Structure-from-Motion (SfM) photogrammetry for high-resolution underwater mapping in shallow coastal environments. Focusing on Slovenian waters, the methodology was tested in two case studies: the *Posidonia oceanica* seagrass meadows near Koper, and the submerged archaeological site of Fizine. By integrating MBES and optical photogrammetry, the approach combined the spatial precision of sonar data with the detailed visual reconstruction capabilities of photogrammetry. In the case of *Posidonia oceanica* mapping, this integration enabled the detection of broader meadow structures through MBES, while photogrammetry—both underwater and aerial—allowed for the accurate delineation of meadow boundaries, especially in shallow or visually complex areas. The complementary strengths of the two methods improved the reliability of habitat classification across varying depths and environmental conditions. At the archaeological site of Fizine, MBES provided high-resolution bathymetry and structural layout of the submerged features, while underwater photogrammetry enhanced the spatial detail, capturing fine architectural elements such as stone alignments and basin walls that were not visible in acoustic data alone. Together, the methods produced comprehensive, georeferenced models well-suited for both habitat monitoring and cultural heritage documentation.

1. Introduction

High-resolution underwater mapping technologies have greatly enhanced our ability to document submerged environments, particularly in shallow coastal areas where traditional methods—such as single-beam echosounders (SBES) and diver-based observations—offer limited spatial coverage and resolution (Finkl and Makowski, 2014; Sahla et al., 2016). Advances in Multibeam Echosounder (MBES) systems and Structure-from-Motion (SfM) photogrammetry now allow for dense bathymetric data and ultra-high-resolution 3D modelling, respectively, both in archaeological (Poglajen, 2008; Drap, 2012; Erič and Poglajen, 2014) and ecological (Marre et al., 2019; Poklar, 2020; Rende et al., 2020; 2022) applications.

This study explores the integration of MBES and SfM photogrammetry for underwater mapping in shallow coastal waters along the Slovenian coast. Two case studies demonstrate the method's application in contrasting contexts: (1) *Posidonia oceanica* seagrass meadows near Koper, and (2) a submerged Roman archaeological site at Fizine (Fig. 1).

While prior studies in Slovenian waters have employed remote sensing tools individually (e.g., Berden Zrimec et al., 2015; Moškon et al., 2015; Poklar, 2020), this work presents their combined use, aiming to assess the strengths and complementarity of MBES and SfM photogrammetry in resolving both ecological and archaeological underwater features.

The specific objective of the underwater photogrammetry survey at the Fizine site was to generate a high-resolution digital terrain model that improves on sonar-derived bathymetry by capturing detailed architectural elements. For the *Posidonia oceanica* site, the goal was to produce a seamless orthomosaic that reveals the spatial distribution and patch structure of the seagrass meadows in high visual detail.

1.1 Study Areas

1.1.1 Posidonia Oceanica Site: The study area covered a coastal strip up to 150 meters from shore along a 1.5 km stretch between the towns of Koper and Izola, where the only known meadow of *Posidonia oceanica* in Slovenian waters is located. This seagrass habitat occurs at depths between 0.2 and 4 meters, but rather than forming a continuous meadow, *P. oceanica* appears as scattered patches or "islands" of varying shapes and sizes, growing on silty and sandy substrates. Given its restricted and fragmented distribution, this meadow is likely the only significant *Posidonia oceanica* habitat remaining in the Gulf of Trieste. Aside from a negligible remnant near Grado, Italy (~2 m²), no other viable meadows are currently documented in this northernmost part of the Adriatic (Turk, 2003).

All seagrass meadows are of great importance due to their widely recognised function in the marine ecosystem (Hemminga and Duarte, 2000). That is why this habitat is recognized as a priority conservation type under the EU Habitats Directive and the Barcelona Convention. In Slovenia, *Posidonia oceanica* has been classified as a rare and endangered species since 2002 (Turk, 2003) and it is included in Natura 2000 network for the conservation of habitat types and species (Slovenian Environment Agency 2018). Despite its ecological importance, the meadow is situated in an urbanized coastal zone facing pressures from port operations, coastal development, and recreational use. To support conservation and management efforts, detailed mapping of its extent was undertaken as part of an environmental monitoring project commissioned by the Port of Koper, aimed at assessing the impact of increased sediment deposition in the Gulf of Koper.

1.1.2 Fizine Site: The archaeological site of Fizine is located along Slovenia's coast between Piran and Portorož. Known in antiquity as *Ad Figulinas*, this coastal settlement was continuously inhabited from the late 1st century BC through the 6th or 7th century AD. The site includes a range of well-preserved Roman maritime structures, with the underwater portion featuring a large rectangular stone complex interpreted as a *piscina vivarium*, a Roman fishpond composed of two enclosed basins constructed with massive sandstone blocks. Likely used for breeding or storing marine animals, this facility remained in use until at least the 5th century AD. Adjacent features such as piers, breakwaters, and mooring installations further suggest the existence of a small harbour that supported local trade and fishing activities (Gaspari et al., 2006).

Our survey at Fizine represents a significant step forward in a continuum of site investigations that span more than two decades. Previous documentation efforts included diver-based visual inspections, targeted underwater excavations, single-beam echosounder (SBES) surveys, and high-precision measurements using total station instruments. A wide-area MBES survey conducted in 2007 provided the first digital bathymetric baseline of the site. Building on these foundations, the 2023 survey focused on documenting the two submerged basins using an integrated approach that combined high-resolution MBES and Structure-from-Motion (SfM) photogrammetry. This recent work was undertaken primarily as a technical demonstration and test of advanced mapping methodologies, rather than as part of a broader archaeological research campaign. It reflects an ongoing commitment to applying state-of-the-art technologies in underwater archaeology.

2. Methods

This study employed a dual-sensor approach integrating Multibeam Echosounder (MBES) and Structure-from-Motion (SfM) photogrammetry techniques for underwater mapping in shallow coastal areas. The method aimed to combine the high spatial resolution and coverage of acoustic data with the detailed textural and structural representation achievable via optical imaging. Despite differences in application objectives (archaeological site documentation vs. habitat monitoring), the overall workflow was consistent across both case studies. However, there were some variations in the equipment used and in the execution of the surveys, tailored to the specific conditions and goals of each site. In contrast, the processing procedures, from image extraction to photogrammetric modelling, were standardized across both case studies.

Figure 2. Lyra boat for hydrographical surveys equipped with over the side pole for sonar mount and electric winch at the stern for towing the camera rig.

2.1 Field Survey Equipment for Habitat mapping and Implementation

2.1.1 Acoustic Bathymetry: For habitat mapping of *Posidonia oceanica*, bathymetric data were collected using a high-frequency MBES system deployed from an 8-meter vessel with cabin (Lyra). The system included a RESON SeaBat 8125 sonar operating at 455 kHz and an SBG Navsight Apogee INS for navigation data. The sonar was mounted on an over-the-side pole, with Teledyne PDS used for real-time data acquisition (Teledyne Reson, 2023). This configuration enabled mapping of *Posidonia oceanica* meadows at a resolution of 10–20 cm, usually sufficient for identifying the boundaries and textures of the seagrass meadows.

2.1.2 Underwater photogrammetry: Optical video was captured using five off-the-shelf GoPro Hero 6 cameras, which are widely used in underwater photogrammetry applications within the scientific community (Hamal and Ulvi, 2024). The Hero 6 features a 12-megapixel (4000 × 3000 pixels) 1/2.3" CMOS sensor with an approximate pixel size of 1.55 µm. For underwater deployment, each camera was enclosed in a standard waterproof acrylic housing. The custom five-camera rig consisted of a winch and a horizontal pole, which was towed from the survey vessel Lyra. The cameras, spaced 70 cm apart, were suspended from the vessel using ropes, enabling adjustable depth control (Fig. 2). The ropes were attached and tightened at three points and the sailing speed was constant thus minimizing the unwanted motion of the camera rig. To reduce motion blur effect on the underwater images the sailing speed was limited to 2 knots.

2.1.3 Aerial Photogrammetry: To bridge the nearshore gap, where water depths of less than 1 meter made vessel-based surveys impractical, an aerial photogrammetry campaign was conducted using a DJI Air 2S drone. This consumer-grade UAV is equipped with a 1-inch CMOS sensor capable of capturing 20-megapixel still images (5472 × 3648 pixels), making it well-suited for high-resolution coastal mapping.

2.1.4 Survey execution: The habitat mapping survey was carried out in three complementary phases to ensure full spatial coverage from open water to the shoreline. The first phase involved an MBES survey conducted in November 2022 during an exceptionally high tide, which allowed bathymetric data collection as close to the shoreline as possible. The survey of a 10 hectares' area was completed in approximately three hours, resulting in complete coverage from a depth of 5 m (MSL) to a depth of 0.6 m (MSL). In the second phase, conducted over three survey days in December 2022 and January 2023, an underwater video survey was performed using a five-camera rig. The rig was lowered to maintain an altitude of approximately 1.5 meters above the seabed, ensuring optimal image quality and spatial coverage across the study area. The third phase (aerial survey) took place over two clear mornings in November 2022, with flights conducted at an altitude of approximately 40 meters. This setup yielded a ground sampling distance (GSD) of better than 1.5 cm. Images were acquired in nadir orientation with sufficient forward and side overlap to support later SfM photogrammetric processing. A total of 470 photographs were captured, effectively filling the data gap between underwater imagery and the land interface, and enabling seamless integration with the bathymetric and underwater datasets for comprehensive mapping of *Posidonia oceanica* meadows.

2.2 Equipment and Execution of Archaeological Site Documentation

2.2.1 Acoustic Bathymetry: For archaeological mapping, the survey system was integrated on a smaller, agile 4.5-meter rigid inflatable boat (RIB), suited for manoeuvring in extremely shallow waters (Fig. 3). It featured an R2Sonic 2022 MBES operating at 400 kHz, paired with two Javad GNSS receivers and a Teledyne DMS-05 IMU. The sonar was mounted through a moon pool in the vessel, allowing for efficient deployment and recovery. All sensors were integrated into a laptop running Teledyne PDS hydrographic software, enabling synchronized acquisition of sonar and navigation data.

2.2.2 Underwater photogrammetry: For the purpose of photogrammetric documentation, an additional vertical mounting pole was rigidly fixed at the bow of the boat. This served as a mounting point for a horizontal pole with three GoPro Hero 6 cameras, spaced 70 cm apart and lowered 0.6 m below water surface. This proved to be an optimal platform to record data from depths of about 1 m to 3 m.

2.2.3 Survey execution: At the Fizine site, the survey was conducted in February 2023, simultaneously with a dual-sensor approach, combining sonar and underwater video. Since the camera coverage was narrower than that of the sonar, the survey pattern was carefully planned to ensure full visual coverage. A criss-cross survey layout was used to document submerged structures from multiple angles, while

Figure 3. Small RIB customized for mobile mapping. The pole at the bow serves as a mounting point for camera rig.

also providing high redundancy in the MBES data through extensive overlap. The video data logging part of the survey was accomplished in two hours, producing about 6 hours of video footage, which resulted in more than 52,000 individual frames. The sonar survey extended slightly to encompass wider and deeper area of the site.

2.3 Photogrammetry workflow

The photogrammetric workflow involved five main stages: (1) video capture, (2) frame extraction, (3) image enhancement, (4) 3D model generation using Structure-from-Motion (SfM), and (5) georeferencing. The setup used five GoPro Hero 6 cameras mounted on a custom horizontal pole designed for stable image acquisition in shallow waters. Each camera recorded video at 2.7K resolution and 30 frames per second.

Video footage was processed by extracting still frames at a rate of three images per second—balancing sufficient spatial overlap with computational efficiency. Prior to photogrammetric processing, image enhancement techniques were applied to reduce the effects of water turbidity and improve visual clarity. These included Contrast Limited Adaptive Histogram Equalization (CLAHE), Unsharp Masking, and white balance correction.

The enhanced frames were processed in Agisoft Metashape Professional (Agisoft LLC, 2022) following a standard Structure-from-Motion (SfM) pipeline. Initially, sparse point clouds were generated, then optimized and filtered to create depth maps. These were used to construct digital elevation models (DEMs) with a spatial resolution of approximately 1–2 cm, and orthomosaics with centimetre or sub-centimetre detail.

Accurate georeferencing of imagery was achieved by synchronizing video timestamps with navigation data recorded in Teledyne PDS software, using the vessel's navigation system. UNIX UTC time was manually logged at the start and end of each video, allowing interpolation of timestamps for individual frames. These were matched with position and orientation data via a spreadsheet-based workflow. A consistent drift in the GoPro internal clocks of about 0.2 seconds per hour, was observed and corrected with a linear adjustment across each recording. This ensured temporal alignment between imagery and positional logs, which was critical for accurate georeferencing. The final photogrammetric outputs were superimposed in GIS with MBES-derived terrain models, enabling integrated analysis and interpretation of submerged archaeological structures and marine habitats.

The aerial photogrammetry workflow followed a similar processing approach to that of the underwater photogrammetry, including frame extraction, image enhancement, and 3D reconstruction using SfM techniques. However, because data were captured above the sea surface, light refraction at the air–water interface introduced additional challenges. This effect caused visual distortions in some images, particularly for submerged features viewed at greater depths or oblique angles, potentially reducing geometric accuracy.

In this workflow, refraction was not explicitly corrected. However, since our primary georeferenced reference layer was

This contribution has been peer-reviewed.
https://doi.org/10.5194/isprs-archives-XLVIII-2-W10-2025-223-2025

the MBES-derived DTM, the aerial imagery was used primarily as a qualitative layer to support visual interpretation and delineation of nearshore features. As such, the lack of refraction correction did not significantly impact the overall integration or interpretation of the dataset.

verified against raw sonar data and the visual inspection of bathymetric models (Fig. 5).

While MBES performed well in identifying larger, dense seagrass patches, it proved less reliable in detecting sparse or fragmented meadows. In such areas, where elevation differences between vegetated and bare substrate were minimal, the contrast in sonar returns was too low to delineate meadow boundaries accurately. This occasionally led to an overestimation of seagrass extent, particularly in flat or silty zones lacking sharp morphological transitions, where subtle elevation differences failed to provide sufficient acoustic contrast. Overestimation also occurred in areas with highly irregular seafloor topography, such as rocky substrates, where MBES data could not reliably distinguish between actual seagrass meadows and complex hard-bottom features. These limitations underlined the need for complementary optical methods, capable of capturing textural and visual cues that sonar alone cannot resolve.

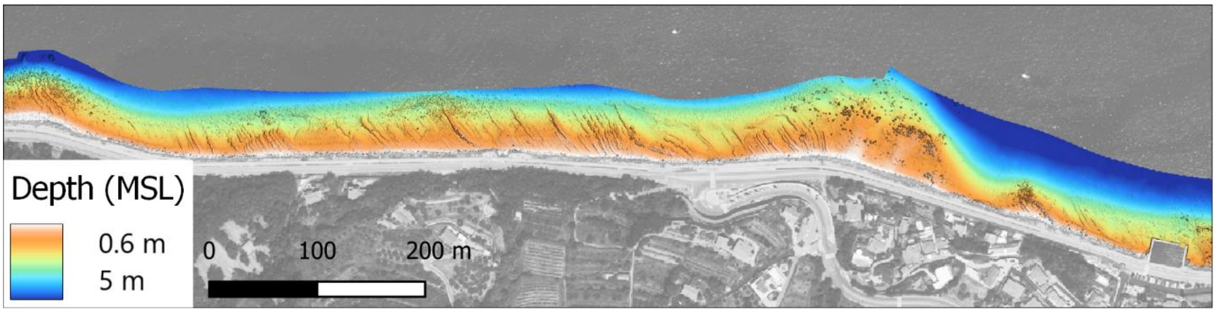

Figure 4. Bathymetric map of the coastal (nearshore) area near Koper with *Posidonia oceanica* meadows (scale 1:7000).

3. Results and Discussion

3.1 Habitat Mapping – *Posidonia oceanica*

MBES survey provided a georeferenced point cloud, which was manually examined in order to avoid incorrect data that occasionally arise due to disturbances in measurements. From processed and systematically organized data, containing more than 20 million individual 3D points, bathymetric digital terrain models (DTMs) at 10 cm resolutions was created (Fig. 4). The resulting DTM covers an area of approximately 10 hectares. Each cell value represents the average recorded depth within that grid cell, referenced to mean sea level (MSL, height datum Koper 2010).

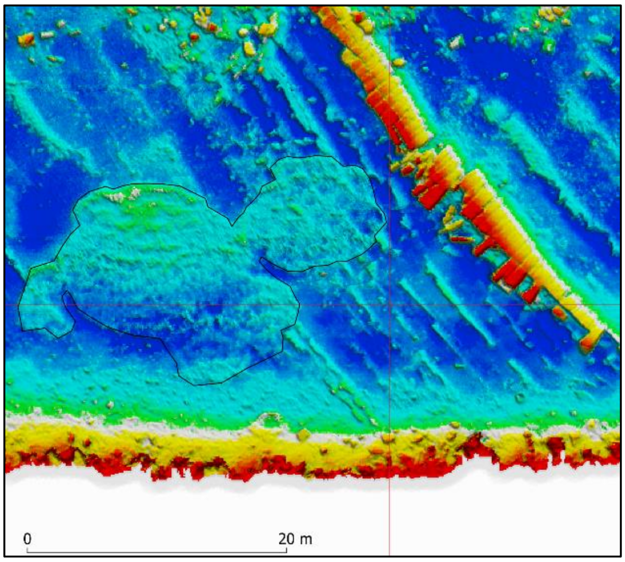

Figure 5. A close-up of the part of the bathymetry with visible *Posidonia oceanica* meadows.

The DTM provided a detailed representation of the seabed morphology and served as a basis for slope analysis, which was used to identify potential *Posidonia oceanica* meadow boundaries. As seagrass meadows typically form slightly elevated features above surrounding sediments, slope gradients exceeding 10° were extracted from the DTM to identify their edges. These slope-derived contours were further

Processing of underwater photogrammetric data allowed us to obtain an orthomosaic with a spatial resolution of 1 cm and a

Figure 6. *Posidonia oceanica* meadows depicted on aerial (bottom) and underwater (top) orthomosaics.

total coverage of almost 4 hectares. This method allowed for detailed visual analysis of the seabed, enabling the dentification of meadow structures, shoot density variations, and the distinction between *Posidonia oceanica* and similar features such as macroalgae or detrital mats. Underwater photogrammetry was most effective in moderate depths (1–4), but its use in very shallow water was limited by the vessel's draft. Additionally, the success of this method was highly dependent on water clarity, and surveys were conducted during periods of maximum transparency to ensure sufficient image quality.

Aerial photogrammetry was employed to map the shallowest nearshore areas where vessel-based systems were difficult to operate due to limited manoeuvrability and data quality constraints caused by the vessel's draft. Surveys in these zones required exceptional conditions, including very high tides, calm sea, and high water transparency, which made consistent coverage challenging using boat-based methods. A set of 470 nadir-oriented images were processed into a 1.5 cm resolution orthomosaic. Aerial imagery provided extensive coverage in shallow zones (0–2.5 m depth), and the visual characteristics of *Posidonia oceanica,* especially its growth pattern, enabled effective classification of larger, continuous patches. However, detection accuracy decreased for small or isolated beds, particularly in areas with low contrast or reflection from water surface.

For both photogrammetry datasets, *Posidonia oceanica* meadows were delineated through supervised image classification, refined by manual interpretation (Fig. 6). By integrating these results with slope-based contours extracted from MBES data, a comprehensive vector layer of *P. oceanica* meadow distribution was generated. The total delineated area of *P. oceanica* seagrass meadows in the study site was calculated at 0.63 hectares.

To evaluate the comparative performance of the three methods (MBES, underwater photogrammetry, and aerial photogrammetry) a representative test meadow was selected (Fig. 7). MBES data, based on slope analysis, indicated a seagrass extent of 58 m². Underwater photogrammetry delineated the meadow at 48.4 m², while aerial photogrammetry yielded a similar result of 48.3 m². These findings demonstrate that MBES tended to overestimate meadow boundaries in flat or low-contrast areas due to the lower ability to detect subtle textural or spectral differences. However, MBES proved to be the more robust and reliable method due to its consistent performance across diverse environmental conditions, where optical methods tend to be less effective. In contrast, optical methods, though can be limited by depth, visibility, and lighting, provided more constrained and visually accurate delineations. Spatial comparison of the delineated outlines revealed mean positional offsets of 22 to 26 cm between MBES and photogrammetry, with MBES consistently mapping broader meadow extents. The agreement between aerial and underwater photogrammetry was notably higher, with mean offsets between 12 and 14 cm.

3.2 Archaeological Mapping – Fizine Site

The bathymetric survey of the wider Fizine site produced a dense point cloud comprising nearly 43 million individual depth measurements covering about 1.6-hectare area. The depth density over main part of the site was at least 2,500 points/m². These data were interpolated into a high-resolution digital terrain model (DTM) with a grid resolution of 5 cm. As expected from an MBES, the resulting DTM offers exceptional

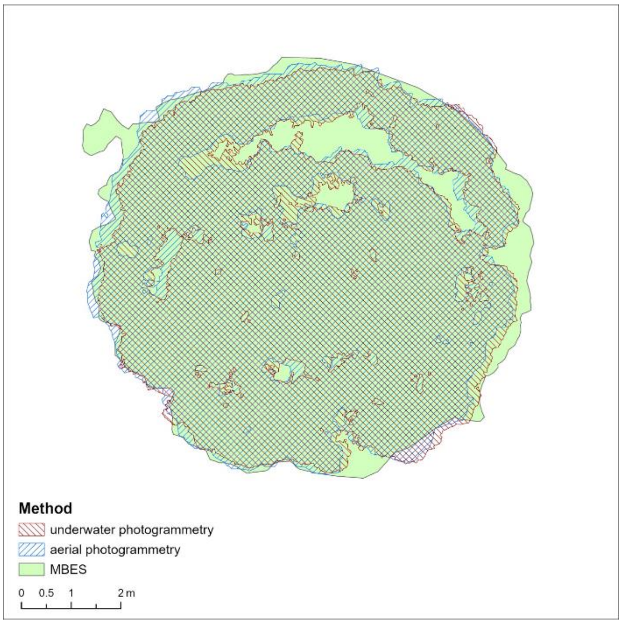

Figure 7. Comparison of delineated *Posidonia oceanica* meadow outlines obtained from MBES, underwater and aerial photogrammetry for a selected test area. The figure illustrates spatial discrepancies between methods and highlights differences in boundary precision and surface extent.

detail and accuracy, clearly revealing the seabed configuration and the architectural layout of the submerged features (Fig. 8).

The structural elements of the *piscina vivarium,* including the outlines of the two large rectangular basins, are distinctly visible, with well-defined internal divisions and surrounding features. Notably, individual in-situ sandstone blocks linear alignments are identifiable in the data. The MBES-derived model thus provides a highly reliable and spatially accurate representation of site morphology, serving not only as a precise record of current conditions but also as a valuable base layer for future archaeological investigations and interpretation.

Underwater video data (i.e. 52,000 individual frames) went through a processing pipeline which generated a DTM surface and an orthomosaic over an area of 6,800 m². Compared to the MBES-derived bathymetry, the SfM photogrammetry provides significantly higher spatial resolution and visual richness. While the MBES offered accurate large-scale morphology, the optical data allowed for sub-centimetre level surface reconstructions, which are essential for documenting archaeological elements that depend on fine textural detail.

The level of detail achieved in the final products is remarkable. Orthophoto mosaic, with a ground resolution of 2.5 mm, offers a visually coherent and spatially accurate representation of the site, suitable for both analytical interpretation and archival documentation (Fig. 9). The photogrammetric DTM reveals subtle topographic features and fine-scale archaeological structures, such as building outlines, stone alignments, and sediment patterns, that were not visible in the corresponding MBES data (Fig. 10).

These results demonstrate the clear advantage of underwater photogrammetry in extremely shallow, clear-water environments where high-resolution imaging is feasible. In the

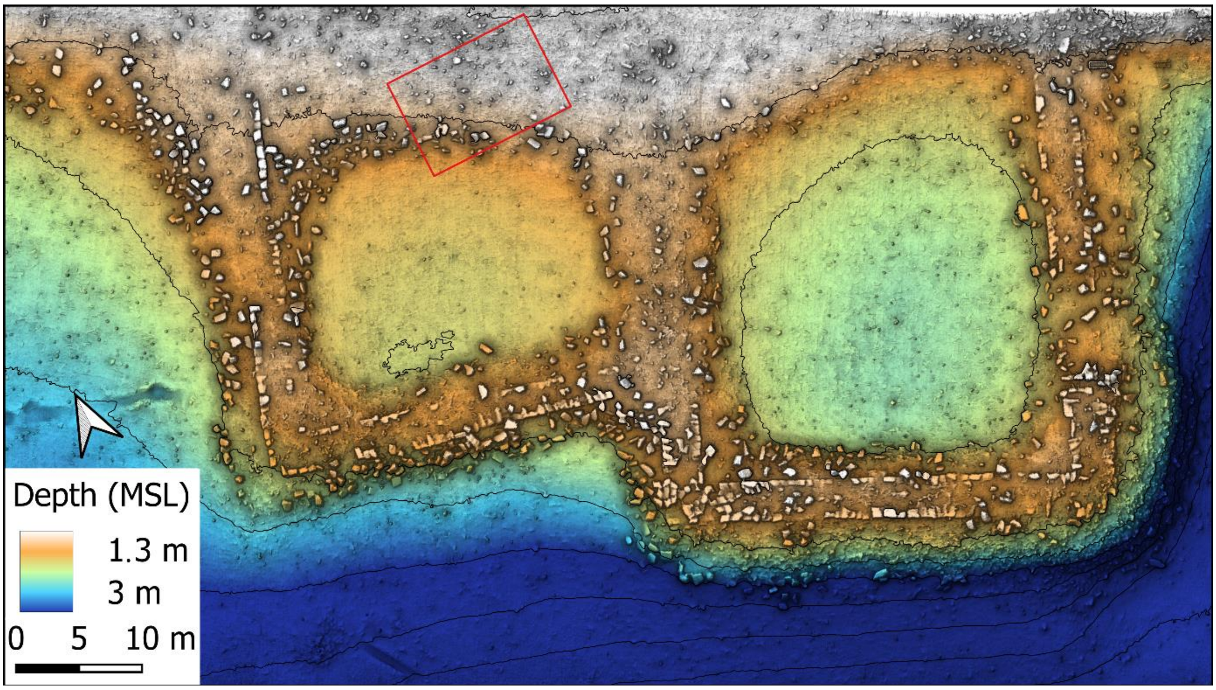

Figure 8. MBES-derived DTM of Fizine underwater site, isobaths are spaced at 0.5 m, scale is 1:600. The red rectangle indicates the extent of the detailed view presented in Fig. 9 and Fig. 10.

case of Fizine, this approach not only captured the archaeological features in unprecedented detail but also complemented acoustic data, enabling a more complete and multidimensional understanding of the submerged cultural landscape.

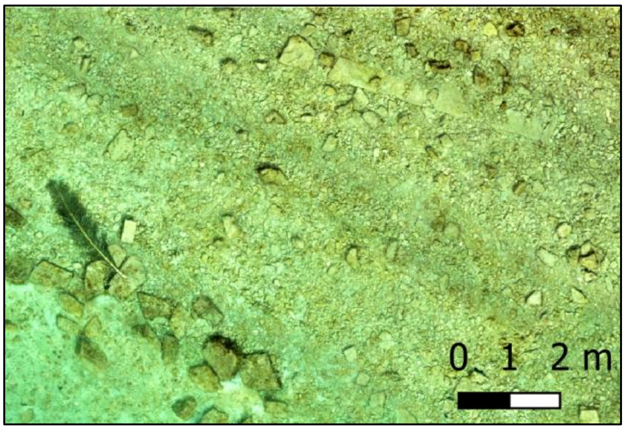

Figure 9. Detail view of the site represented as orthophoto, scale 1:150.

4. Conclusion

This study demonstrated that integrating Multibeam Echosounder (MBES) and Structure-from-Motion (SfM) photogrammetry provides a powerful approach for high-resolution mapping in shallow coastal waters. The complementary nature of the two methods—MBES offering reliable bathymetric coverage and SfM delivering fine-scale visual detail—proved essential for accurate and repeatable documentation of both seagrass habitats and submerged archaeological features.

Across both case studies, delineation errors between methods remained within an acceptable range, supporting the use of this dual-sensor approach in long-term, cyclic monitoring efforts. However, optical methods remain sensitive to environmental constraints such as turbidity, light penetration, and seafloor complexity—factors particularly relevant in optically variable zones like the northern Adriatic.

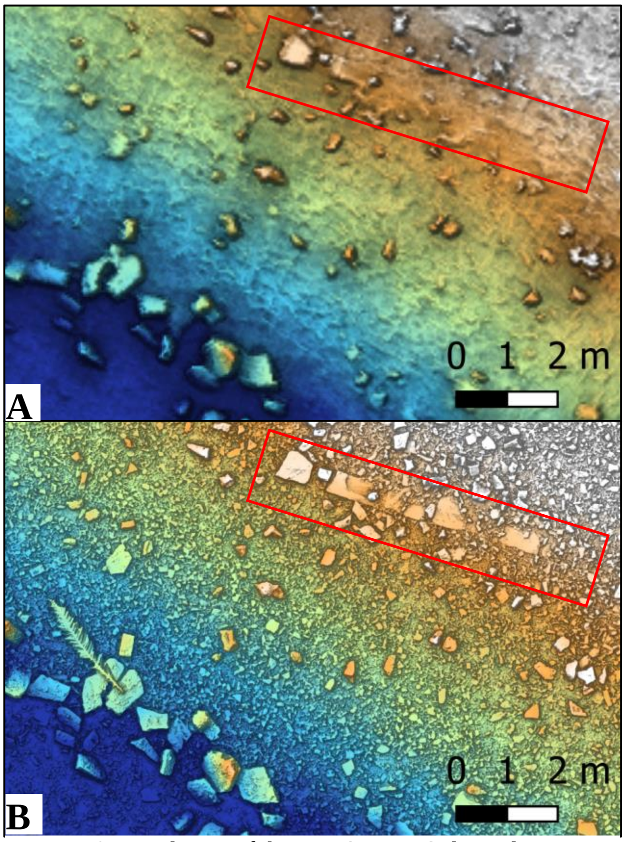

Figure 10. Detail view of the site. A: MBES-derived DTM, B: SfM-derived DTM, depth rage 1.1 m – 1.6 m, scale 1:150.

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In both habitat and archaeological mapping, MBES proved to be the more robust and reliable method due to its consistent performance across diverse environmental conditions. In contrast, SfM photogrammetry is more affected by water clarity, lighting, and bottom texture, which can limit its applicability. However, when conditions are favourable and processing is successful, SfM provides superior spatial resolution and captures fine-scale features—such as meadow patch structure or architectural elements—that are not visible in sonar data alone. The two approaches are therefore best used in combination: MBES ensures dependable baseline coverage, while SfM enhances spatial detail where and when environmental conditions permit.

Together, these methods form a scalable, adaptable toolset suitable for habitat monitoring, cultural heritage documentation, and integrated coastal zone management, particularly in complex and dynamic shallow-water environments.

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