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Optical Remote Sensing of Shallow-Water Benthic Habitats: An Overview of Advances and Future Directions

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Abstract Summary

This brief review focuses on the use of optical remote sensing for benthic habitat mapping and monitoring in shallow waters. Significant progress has been made over the past decade, particularly with the adoption of multi- and hyperspectral sensors deployed on airborne and satellite platforms. These technologies enable the detection of seafloor habitats by capturing bottom reflectance, supporting a variety of methods that combine empirical models or radiative transfer simulations with classification or regression algorithms. High spatial and spectral resolution has been shown to greatly improve the accuracy of benthic feature detection and quantification. However, challenges remain, particularly in turbid waters and areas affected by atmospheric variability. Mapping also becomes more difficult in regions with complex and heterogeneous bottom types. Thus, further effort is required to advance toward fully operational applications, especially leveraging upcoming drone- and satellite-based hyperspectral systems.

Introduction

The emerging demand for sustainable solutions amid climate change and energy transition underscores the need for a deeper understanding of marine ecosystems (Misiuk & Brown, 2024). By delivering detailed seafloor data, optical remote sensing has been widely used in benthic habitats mapping over the last decades, providing critical data to support marine conservation, sustainable development, and policy-making. Although encouraging perspectives of operational applications have emerged in this field, important limits remain in shallow-water benthic habitat mapping. Indeed, attenuation of light by water molecules is the fundamental limiting factor in benthic mapping by optical remote sensing. However, recent advances in sensor technology and processing techniques offer promising avenues to fully exploit correlations between substrate features and their spectral signatures (Kutser et al., 2020). These advances allow more accurate and scalable habitat mapping using airborne and satellite-based imagery. Various methods have been developed for this purpose recently, making it possible to map benthic habitats accurately from multi- and hyperspectral sensors (He et al., 2024). To succeed, these methods imply that the specifications of the sensor (e.g. the spatial and spectral resolutions) comply with those needed to track differences in seafloor reflectance induced by different benthic features. This approach sparked a growing attention in the last decade. Since then, the development of drone- to satellite-embedded optical sensors is encouraging the hydrographic community to make remote sensing an operational tool for mapping and monitoring benthic habitats in shallow water regions. This short review aims at summarizing the last advances and future challenges in this field.

Overview of recent advances

Over the last decades, optical remote sensing has emerged as a widely adopted method for mapping benthic habitats in shallow waters (Figure 1). In contrast to traditional acoustic surveys, which are often constrained by cost and shallow depth limitations, airborne and satellite platforms now provide non-invasive, spatially extensive and temporally frequent data collection, which provides scalable alternatives aligned with modern analytical frameworks (Kutser et al., 2020; Misiuk & Brown, 2024).

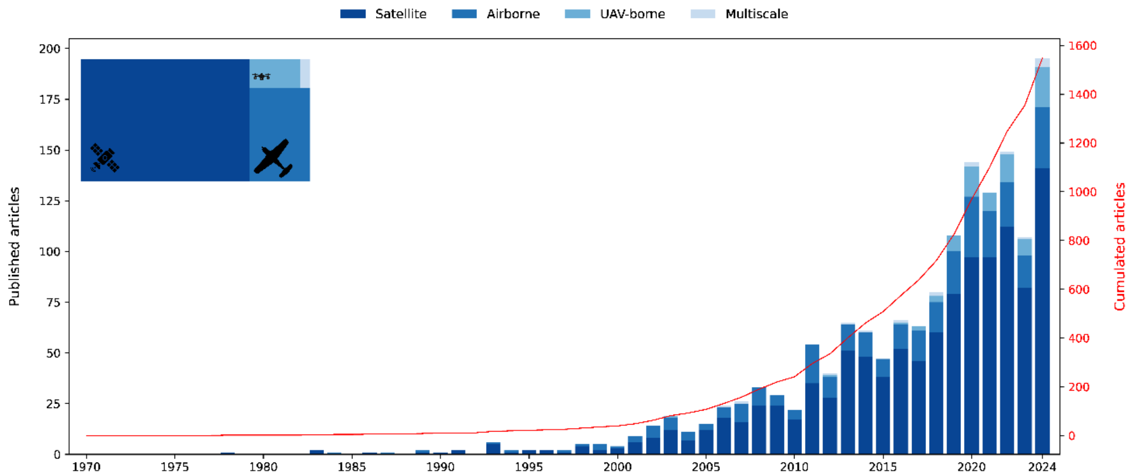

Figure 1: Evolution of publications reporting the use of optical remote sensing for monitoring benthic habitats (1970 – 2024), categorized by the imaging platform. The counts are based on systematic literature search results from Web of Science and Scopus.

Multi- and hyperspectral sensors have demonstrated increasing success in seafloor classification. Multispectral sensors remain the most widely used due to their accessibility and spatial coverage. For instance, Araujo et al. (2023) mapped seafloor geomorphology features, achieving an RMSE of 2.98 m, by integrating Sentinel-2 imagery with field observations, within a large Brazilian Marine Protected Area (MPA). While most applications focus on regional-scale habitat distribution, fewer studies have addressed the spectral differentiation of benthic substrates under optically complex conditions. Recent advances in hyperspectral satellite missions, such as PRISMA and DESIS, offer new opportunities to close these gaps. In the Caribbean, Alevizos et al. (2022) successfully distinguished sand, silt, and macrophytes using PRISMA imagery. These advances in detecting subtle spectral differences among benthic substrates enable more nuanced habitat discrimination, even under variable water conditions (Burns et al., 2022).

The spectral similarity among substrates and water turbidity remains inherently challenging, resulting in misclassifications (Caballero & Stumpf, 2023). Technical advances suggest high spatial and spectral resolution imagery as effective solutions to overcome these issues, allowing better discrimination of habitats even under optically complex conditions (Ashphaq et al., 2021). However, current satellite-based sensors rarely provide simultaneously high spatial and spectral resolutions, limiting their operational efficacy. While hyperspectral missions like PRISMA offer promising spectral detail, their lower revisit frequency and limited spatial coverage restrict widespread operational application compared to multispectral sensors such as Sentinel-2(Hartmann et al., 2025). As a practical consequence, benthic habitat mapping often still requires extensive in situ validation to mitigate misclassification errors, especially in heterogeneous regions where different habitats exhibit similar spectral signatures (Lutzenkirchen et al., 2024). Therefore, integrating detailed ecological field measurements with satellite and airborne remote sensing methods remains essential to enhance operational reliability and accuracy for broader-scale applications.

To address these limitations, research has shifted toward advanced processing techniques, spectral transformations, and sophisticated analytical tools. Traditional empirical models, such as band-ratio approaches, continue to serve as baselines due to their simplicity, contemporary research prioritizes semi-analytical models and machine learning algorithms which better exploit the spatial structure of optical data (Ashphaq et al., 2021). These newer methods, like Convolutional Neural Networks (CNN), have shown superior performance in handling complex, spatially structured data(Hartmann et al., 2025). Additionally, data-driven approaches that combine remote sensing imagery with auxiliary datasets, such as LiDAR geomorphometric models, and water quality data, further improve classification accuracy and operational robustness (Misiuk & Brown, 2024).

Together, these advances have significantly improved the resolution, accuracy, and interpretability of benthic habitat maps derived from optical imagery. Remote sensing products are now being used not only for ecological studies but also in operational contexts such as marine spatial planning, impact assessments, and habitat monitoring (He et al., 2024; Kutser et al., 2020).

Perspectives of application

To support broader operational use, optical remote sensing must enable the mapping of benthic habitats across large areas while overcoming environmental variability and limited validation data. Most current frameworks perform well in localized, well-characterized settings, where supporting datasets such as multibeam bathymetry are available. However, these models often lose effectiveness when transferred to turbid or heterogeneous regions. Expanding applicability requires site-independent calibrations, regionally tuned spectral libraries, and integration of ancillary data such as geomorphometric layers. Satellite imagery remains a preferred option for regional-scale assessments due to its broad coverage and regular revisit cycles. In contrast, high-resolution airborne sensors (<1 m) are ideal for capturing complex habitat structures but are limited in availability and spatial extent. Drone-embedded multispectral and hyperspectral sensors bridge this gap by offering ultra-high spatial resolution and flexible deployment. Their integration with satellite imagery allows for hierarchical, multi-scale monitoring strategies (He et al., 2024; Kutser et al., 2020). To further improve the reliability of classification outputs, particularly in optically complex or poorly characterized environments, the integration of optical imagery with complementary data sources such as LiDAR bathymetry, spaceborne SAR, and numerical oceanographic models is likely to become standard. These fused approaches help mitigate spectral ambiguities, enhance spatial context, and reduce dependence on field surveys. Cloud-based processing and open-source platforms also enabling near-real-time analysis, improving responsiveness for environmental planning (He et al., 2024)

Accurately mapping the seafloor at large scales remains a significant challenge, particularly in areas with high habitat diversity and limited prior knowledge of the benthic types present. This difficulty is compounded when using moderate-resolution satellite imagery due to mixed pixels. In such cases, spectral unmixing techniques can be employed to estimate the proportion of different substrate types within a single pixel, serving as a preliminary classification prior to high-resolution mapping. Drone imagery might also help identifying habitat types of interest on the sites. while hyperspectral data enables extraction of ecological metrics such as benthic health indicators—useful for monitoring, impact assessments, and habitat modeling (Alevizos et al., 2022; Burns et al., 2022). Despite promising results in clear coastal zones, optical remote sensing is under-tested in several operationally relevant contexts such as MPAs and offshore wind farms. Operational adoption will depend on cross-site validations, robust sensor-model frameworks, and alignment with regulatory needs. With increasing sensor availability and data accessibility, and mounting demand for scalable, cost-effective monitoring tools, remote sensing is well-positioned to support international marine conservation goals provided that ecological relevance, adaptability, and end-user needs remain central to future developments. Optical remote sensing, especially when used in synergy with other technologies, is poised to support applications ranging from marine spatial planning to habitat monitoring and impact assessments.

Conclusions

This brief review aimed at summarizing the last advances and challenges in using optical remote sensing for mapping benthic habitats in shallow waters. Although significant progress has been made in this field during the last decade, further research is needed to operationalize the methods of seafloor mapping and monitoring proposed in the literature. Promising perspectives of satellite and drone applications opened in previous studies should be addressed in future research.

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