Enhancing Satellite-Derived Bathymetry Using the Different Sentinel-2 Spectral Bands in the Middle Adriatic

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Abstract: Bathymetry, the measurement of seafloor depths, underpins numerous marine research and navigation safety. However, less than 25% of global oceans and seas are mapped at high resolution due to the high-cost of traditional ship or airplane-based survey methods. Satellite Derived Bathymetry (SDB) offers a rapid, cost-effective alternative for shallow marine areas using optical satellite data. This study augments existing SDB algorithms by incorporating the Sentinel-2 Band 1 (Coastal Aerosol) with Band 4 (Red) in the Log-Band Ratio (LBR) algorithm for the Middle Adriatic's shallow waters. Using a one-year dataset of Sentinel-2 imagery for the Šibenik channel, the study evaluates the new spectral combination's effectiveness. Results indicate that the Coastal Aerosol band, despite its lower spatial resolution, improves bathymetric accuracy in shallow waters (0-5 meters) compared to traditional blue/green ratio. The new combination achieved a NMedAE of 0.22, outperforming the green/blue model's 0,79 NMedAE in the same depth range. The switch SDB model, integrating both spectral combinations, provided bathymetric coverage up to 20 meters depth, ensuring improved accuracy in coastal areas.

Keywords: remote sensing; earth observation; seafloor mapping; optical bathymetry; switch model.

1 Introduction

Bathymetry refers to the measurement of depths to model the topography of the seafloor. Bathymetric data provide a framework for almost all marine-related research from geodynamics to the safety of navigation, supporting activities related to blue growth (Wölfl et al. 2019).

Currently, less than 25% of the world's seas and oceans are mapped at high resolution due to high cost and/or duration of traditional survey techniques, which rely on ships (acoustic systems) or airplanes (LiDAR) as survey platforms (Seabed 2030, 2024).

Compared to traditional survey methods, Satellite Derived Bathymetry (SDB) is recognized as a rapid and cost-effective method for estimating bathymetry in shallow parts of the seas using data collected by the optical satellite sensors (IHO 2024). Since the 1970s, SDB methods have significantly evolved in accuracy and popularity, largely due to the availability of extensive multispectral image (MSI) databases from Earth observation missions such as Landsat and Sentinel.

Compared to other two main concepts of SDB—the photogrammetric approach and the 'physics-based' approach, empirical methods known as the 'ratio approach' feature simpler algorithms, though they require a set of known depths for model calibration. The log-band ratio (LBR) algorithm applies the linear regression to model the mathematical relations between the ratio of the green and blue bands (pseudo-depth model pSDB) and prerequisite survey data (Stumpf and Holderied 2003). This method is independent of changes in the seafloor substrate, can be adapted to other combinations of visible light (VIS) bands, and different satellite images.

Previous studies demonstrated the potential of using other combinations of spectral bands, beyond the classical blue and green, to minimize negative effect of higher turbidity, submerged vegetation, or water attenuation on SDB (Dierssen et al. 2003, Poursanidis et al. 2019, Caballero and Stumpf 2020, Vrdoljak and Kilić-Pamuković 2022).

Proximity to the shoreline, where various human activities and wave action occur, often resuspends sediments from the seabed into the water column, contributing to higher turbidity in the shallowest marine areas. In previous research (Vrdoljak and Kilić-Pamuković 2022), a switch algorithm for SDB (Caballero and Stumpf, 2020) was adapted using a combination of spectral Band 2 – Blue (B2), Band 3 – Green (B3), and Band 4 – Red (B4) from Sentinel-2 MSI, which proved effective for the shallowest marine areas in the Middle Adriatic.

The aim of this study is to extend the existing algorithm by combining Band 1 – Coastal aerosol (B1) and B4 of the Sentinel-2 MSI. The focus of the research was on the shallowest parts of the marine areas where traditional methods are less effective. Using the LBR algorithm as the base of the switch algorithm, analysis and comparison of the results were performed to assess the effectiveness of the new spectral combination in the marine areas of the Middle Adriatic.

2 Materials and methods

In this study, a switch SDB algorithm (Caballero and Stumpf 2020), adapted to Middle Adriatic (Vrdoljak and Kilić-Pamuković 2022) was used to predict bathymetry from Sentinel-2 MSI.

Study area was marine area of Šibenik channel located in Middle Adriatic (Figure 1a). Part of the Šibenik channel was surveyed with Kongsberg EM-3002 D multibeam system to assure safety of navigation by Hydrographic Institute of the Republic of Croatia in 2014. Collected data, categorized as Special-Order Survey (IHO, 2022) and referenced to Mean Low Lower Water (MLLW), was used for vertical calibration and validation of SDB (Figure 1b). For the area of Šibenik channel, a one-year period (2017 -2018) of Sentinel-2 MSI was evaluated for estimation of SDB and based on quality statistics an optimal image was depicted. A workflow for SDB estimation (Vrdoljak and Kilić Pamuković 2022) was adapted (Figure 2).

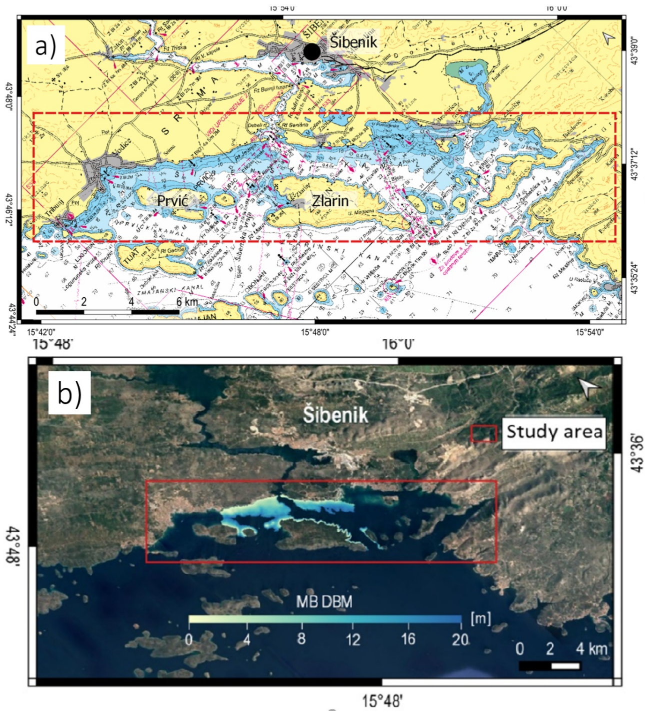

Figure 1. Location of study area in Middle Adriatic. (a) Red line on a nautical chart (GeoAdriatic, 2022) indicates the marine area of interest for SDB estimation. (b) In-situ MB survey data, randomly chosen 25% were control points, the remaining 75% were denoted as check points.

All scenes were processed with ACOLITE Dark Spectrum Fitting algorithm for atmospheric correction to obtain Bottom of the Atmosphere reflectance (BOA) (Vanhellemont and Ruddick 2018). In addition, ACOLITE DSF corrected the MSIs for sun glint and masked the land areas. Median filter was applied to reduce remaining noise in the MSIs. Two spectral combinations were chosen Green (G) combining B2 and B3, and Red (R) combining B1 and B4. Multibeam bathymetry model (MB DBM) and B1 were interpolated using bilinear interpolation to match the 10-meter resolution of B2, B3, and B4. PSDB models were estimated using LBR algorithm (Stumpf and Holderied 2003) in both spectral combinations for all the MSIs. Randomly chosen 25 % of MB DBM were used as control points for the vertical calibration

of pSDB performed by linear regression. Rest of the points were set as check data. Resulting R SDBs and G SDBs were validated against check data. Following statistics were used for quality assessment: Mean absolute error (MAE), Median absolute error (MedAE), and Standard deviation (St.dev.). Upon the results, an optimal MSI for SDB estimation was chosen. G SDB and R SDB of the optimal image were compared using Normalized Median of Absolute Error (NMedAE) to determine coefficients for the switch SDB. Switch SDB was calculated by the weighted mean (Caballero and Stumpf 2020, Vrdoljak and Kilić-Pamuković 2022):

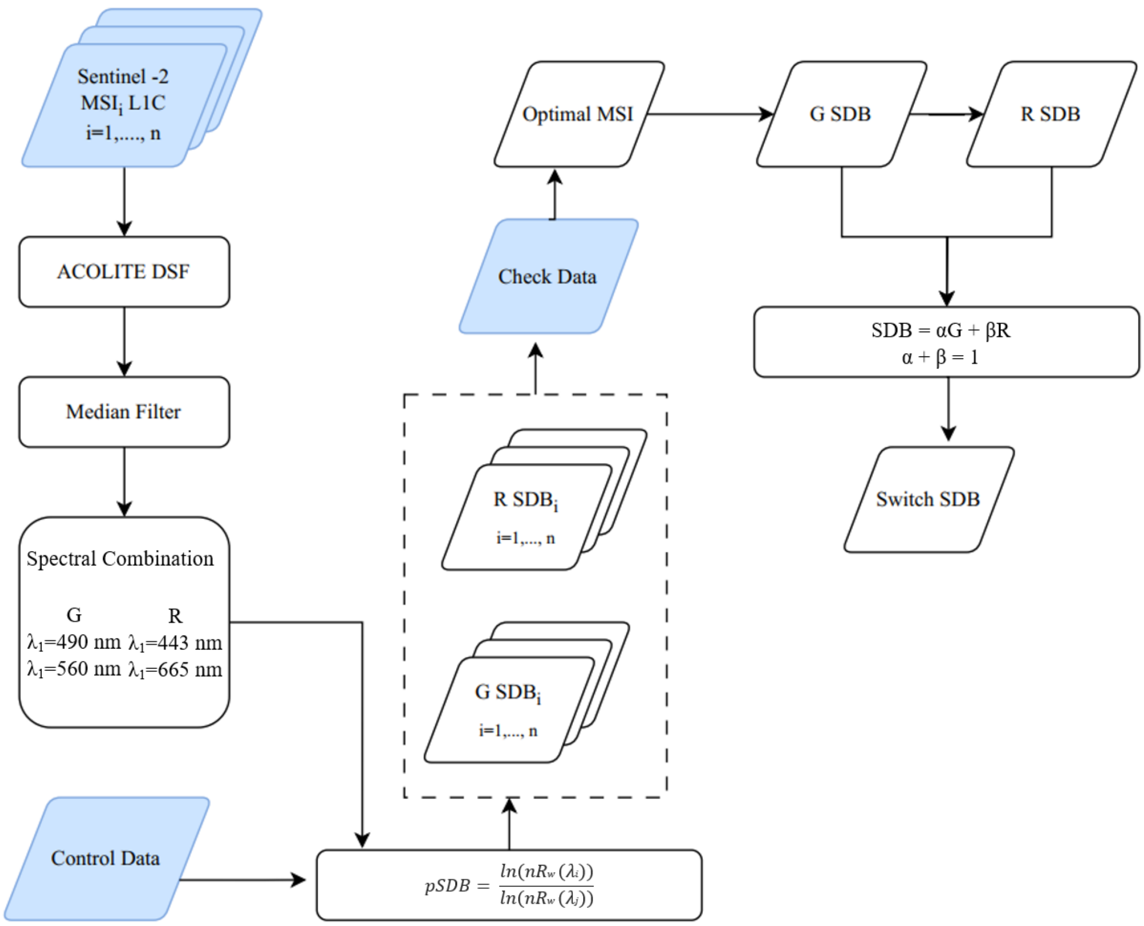

Figure 2. Procedure for the SDB estimation (adapted after Vrdoljak and Kilić-Pamuković, 2022).

$$\text{switch SDB} = \begin{cases} \text{SDB R for SDB R} < 3 \\ \text{SDB G for SDB R} > 3 \text{ AND SDB G} > 5 \\ \alpha\text{SDB G} + \beta\text{SDB R for SDB R} \geq 3 \text{ AND SDB G} \leq 5 \end{cases} \quad (1)$$

while

$$\alpha = \frac{5 - \text{SDB R}}{3}, \beta = 1 - \alpha. \quad (2)$$

3 Results

In this research, the possibility of using the Sentinel-2 B1 for SDB retrieval in shallow coastal parts of marine areas was analyzed.

Based on SDB quality statistics, MSIS2A20170329 was selected as the optimal one. The G SDB model covered marine areas up to 20 meters in depth with a MAE of 1.55 m, a MedAE of 1.14 m, and a standard deviation of 2.13 m. The R SDB model covered areas up to 5 meters in depth with a MAE of 0.44 m, a MedAE of 0.33 m, and a standard deviation of 0.62 m. To evaluate the performance of each spectral combination, comparisons were made within the same depth ranges (Table 1).

The G DBM model showed varying NMedAE with depth, ranging from 79% for depths of 0–3 meters to 10% for 15–20 meters. Conversely, the R DBM model showed lower changes in NMedAE values for the shallow depths of 0–3 meters (22%) and 3–5 meters (10%). In comparison with the G SDB, the R DBM model demonstrated better performance in the shallowest depth range of 0–5 meters in terms of depth quality. The combined SDB model, which integrates G SDB and R SDB, is presented in Figure 3. Compared to G SDB alone, the combined model shows residuals up to twice as small in the shallowest depths. Specifically, the NMedAE is 39% for the 0 to 3–meter range and 18% for the 3 to 5–meter range. The R SDB model achieved higher accuracy in the shallowest parts (up to 5 meters), while the G SDB model extended coverage and maintained quality to depths of up to 20 meters, ensuring continuous bathymetric estimation throughout the study area.

Table 1. NMedAE (%) of G DBM and R DBM in different depth ranges.

NMedAE (%)					
Spectral Combination	**Depth Range**				
	0–3	3–5	5–10	10–15	15–20
G	79	29	20	12	10
R	22	10	-	-	-

4 Discussion and conclusions

The present study evaluated the potential of downscaled Sentinel-2 B1 for bathymetry estimation in the shallowest marine areas of the Middle Adriatic.

Previous research (Vrdoljak and Kilić-Pamuković 2022) using a switch algorithm (Caballero and Stumpf 2019) adjusted for the Middle Adriatic, combined spectral bands B2, B3, and B4, resulting in a model with lower residuals in the shallowest marine areas (Figure 4).

Compared to other VIS bands of Sentinel-2 MSI, B1 has the lowest spatial resolution and a higher signal-to-noise ratio.

This study demonstrated that despite its limitations B1, when downscaled to a 10-meters resolution, enhanced bathymetric estimation in the shallowest marine areas.

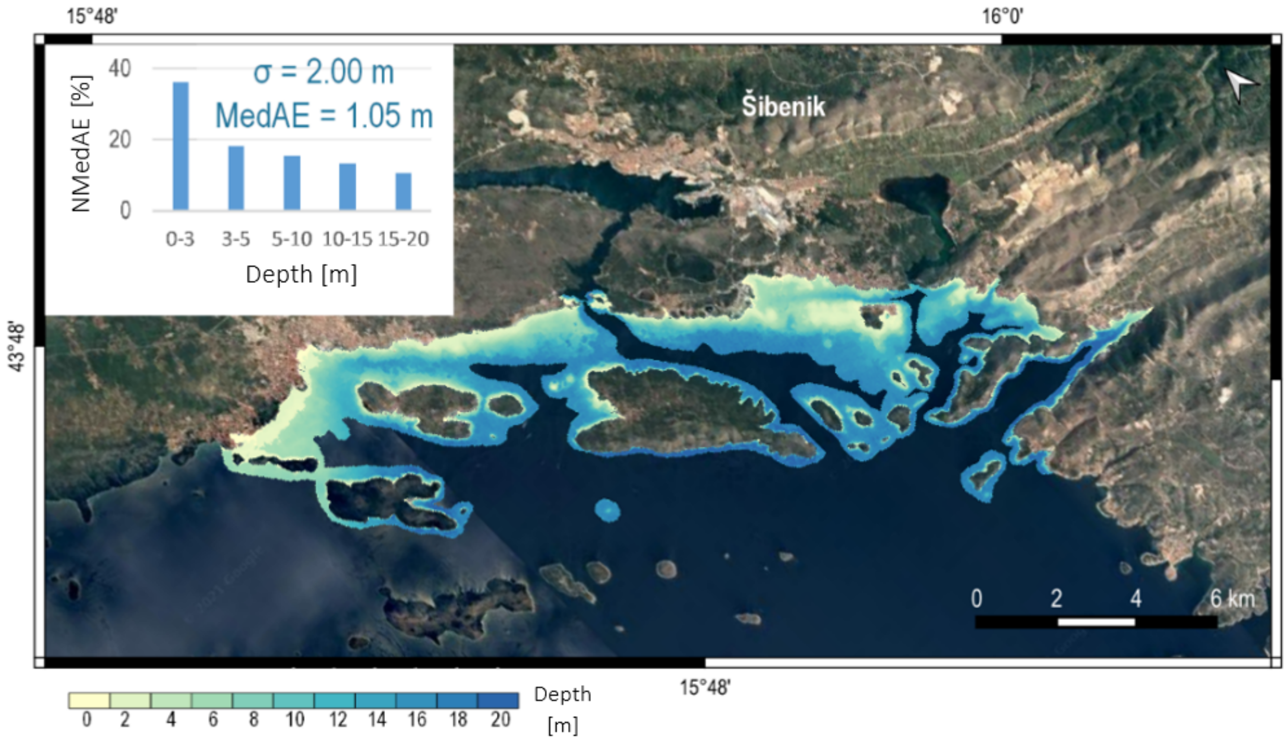

Figure 3. Switch SDB in Šibenik channel.

The LBR algorithm incorporating B1 and B4 improved coastal bathymetry accuracy in the shallowest depth range (0-5 m), with NMedAE of 22% in the 0-3 m depth range and NMedAE of 10% in the 3-5 m depth range. Compared to results from previous research (Figure 4), the spectral combination of B1/B4 showed a negligible but better performance.

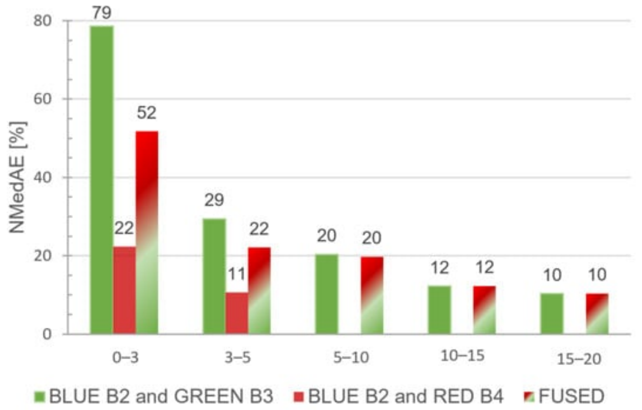

Figure 4. Results of SDB validation from previous research by Vrdoljak and Kilić-Pamuković (2022) show NMedAE values for B2 and B3, B2 and B4, and fused (switch) SDB across different depth ranges.

The model was augmented by the classic B2/B3 ratio with the switch SDB algorithm to ensure continuous SDB estimation up to 20 meters depth in the Šibenik channel. The result was a switch SDB model covering marine areas up to 20 meters with improved quality in coastal parts with depths up to 5 meters.

These improvements underline the importance of selecting the optimal spectral band for bathymetry estimation, which is important for many marine-related research projects needing up-to-date bathymetry.

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