

Satellite-derived bathymetry and rock detection for maritime archaeology using VENμS imagery

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ABSTRACT

Since its beginnings in 1975, deriving bathymetry by means of multispectral satellite imagery has been a method that has not yet been fully exploited in the maritime archaeology realm. It focuses on using the blue and green bands for their water penetration capabilities to later convert each pixel into depth values. This method can be replicated in time and space, while keeping costs low and covering large areas. In this research, two high-resolution bathymetric maps using VENμS satellite imagery and a variation of Stumpf's equation were produced. Two archaeological sites were selected: the harbour of Sebastos (built by King Herod) and the Achziv ridges on the northern coast of Israel. The importance of collecting satellite imagery under low Chl-a [mg/m³] conditions is addressed, and an algorithm for identifying shallow rocks above and below the water level is included. Our research suggests that satellite-derived bathymetry mapping along the Israeli coast is more efficient for satellite images taken between March and September, when Chl-a concentrations are likely to be lower; maximum depth penetration using VENμS is found to be approximately up to 23 m depth with a Root Mean Square Error (RMSE) of 0.53.

Keywords: VENμS; bathymetry; chlorophyll-a; rock identification

List of Abbreviations

Red, Green and Blue	RGB
Satellite-Derived Bathymetry	SDB
Chlorophyll-a	Chl-a

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INTRODUCTION

Most common approaches for deriving bathymetry rely on acoustic systems (such as sonar) or aerial alternatives such as LiDAR. However, these methods are expensive, labour-intensive and difficult to scale them into large areas (Stumpf et al. 2003, 547; Traganos et al. 2018, 2). In contrast, in recent years, Satellite-Derived Bathymetry (SDB) has been suggested as cost-effective for regions where traditional methods are either impractical to operate or highly expensive (Jagalingam et al. 2015, 565; Sam et al. 2018, 750), or there is poor or no data at all (Westley 2021, 17). The use of satellites to derive bathymetric maps has been proven to be not only reliable (Jagalingam et al. 2015, 560-566; Guzinski et al. 2016, 243-263; Sam et al. 2018, 1-14) but also cheaper in comparison with the technologies mentioned above (Jagalingam et al. 2015, 561).

Bathymetric mapping highly benefits maritime and underwater archaeologists by facilitating them to understand site formation processes, shipwreck scours (Caston 1979, 193-204; Quinn 2006, 1419-1432); reconstruct paleo-landscapes (Westley et al. 2014, 411-430; Westley 2021, 12-14) as well as to

conserve, protect, and preserve underwater cultural heritage (Maarvelend et al. 2013, 191-192). In this paper, near-shore landscape reconstruction is assessed through SDB and rock identification through VENμS satellite imagery. The study incorporates a procedural framework encompassing sea conditions such as low Chl-a content prior to acquiring high-resolution satellite imagery over the area of interest, and two algorithms capable of identifying rocks above and below the water. The significance of this approach stems from its replicability in oligotrophic waters of the Pacific Ocean, as well as the potential utility of the proposed algorithms in coastal environments exhibiting analogous reflectance properties.

CASE STUDIES

For the application of SDB, two different areas were selected along the coast of Israel. The underwater aeolian Achziv ridges, located off the coast of the North District (Figure 1A), were chosen due to their proximity to Shikmona (Haifa), where a 6-year record of Chl-a content is available, and low-bathymetric data is accessible. With respect to important archaeological sites, only Tel Achziv is known (c. 5 km south of the Israeli border with Lebanon). This site was a Phoenician city that rose at the end of the 8th century BCE and was also a maritime stop thanks to its convenient seaside location and easily accessible sand beach for landing (Jasmin et al. 2016, 276).

The second area includes the Roman harbour of Sebastos and the modern port of Hadera (Figure 1A). The former was chosen because it is a very well-studied harbour (Raban et al. 2009; Bergin 2018; Galili et al. 2021, 8-16) and *in situ* depths are available. The latter because it contains low-resolution bathymetry, which serves as ground-truth data. The harbour of Sebastos, now fully submerged, was built by King Herod in 21 BCE. It took more than five years to construct, and when completed, it was the largest artificial harbour of its time in the Mediterranean (Raban 1992). Hadera is a medium-sized port, located around 3.7 km south of the previous. This port was completed in the early 1960s, and it currently specialises in coal and fuel oil products and serves the two adjacent power stations (MarineTraffic 2023; Shipnext 2023).

RESOURCES

The resources available to conduct this work include:

Sonar Data

Sonar bathymetric data was collected between 2001 and 2006. Horizontal resolution is 50x50 m and one metre vertically. Although this data is highly reliable, its spatial resolution is too broad, and it does not cover near-shore areas and regions proximate to harbours, which makes it impractical for maritime archaeology applications.

Chl-a Field Observations

Although there is some research including Chl-a concentrations to produce SDB maps (Li et al. 2019, 4; Li et al. 2021, 4), they do not evaluate how high concentrations can mislead SDB calculations. To estimate the sensitivity of SDB to fluctuating Chl-a concentrations, a series of measurements were taken from 2013 – 2019 on a weekly to monthly basis at the Shikmona station (Raveh 2015, 1-23; Rahav 2018, 10). Two notable contrasting periods were identified: one, during the Israeli summer season on 25 July 2018 (low Chl-a concentrations), and another on 14 December 2018 (high Chl-a content).

In-situ Depth Measurements

In December 2017, underwater excavations took place in Caesarea, in the northern part of the bay, around 60 m offshore (Derenne et al. 2019, 77). The investigation was led by Prof. Emmanuel Nantet from the University of Haifa. The excavation was aimed at conducting a reappraisal of a shipwreck discovered in 1976, briefly explored by Avner Raban (2008, 129; 2009, 69-149) and subsequently

studied by Michael Fitzgerald (1989a, 4-9; 1989b, 184-190; 1989c; 1994, 163-223; 1995). Due to the important dimensions of her hull components, especially the 10-cm thick planking, it seems that she was initially a large merchantman, that sank in the Early Roman Period (Nantet 2020). Ten hull points were recorded from the ship, using a Total Station following the technique specified by Bowens (2009, 92). These points were later used to validate SDB depths in the Harbour of Sebastos.

VEN μ S Satellite Imagery

VEN μ S (Vegetation and Environment monitoring New Micro-Satellite) is a recent initiative between the Israeli Space Agency (ISA) and the French Space Agency (CNES) aimed at developing, manufacturing, and operating a new Earth observing satellite using a superspectral camera that provides high resolution imagery in both space and time (VEN μ S, 3). VEN μ S acquires satellite imagery at four, five, and 10 m resolution with a revisit period of every two days. VEN μ S can be accessed at <https://venus.bgu.ac.il/venus/>. It provides three levels of products: L1 (TOA reflectance), L2, and L3 (surface reflectance). Two L3 products for the Achziv ridges were employed, one on 25 July 2018, and another on 14 December 2018 for low and high Chl-a content, respectively. The other product (L2) was used for the Caesarea and Hadera ports under low Chl-a conditions and was taken on 21 May 2020.

Drone Imagery

Although the harbour of Sebastos was the main commercial maritime trading place during the Roman and Byzantine periods, natural anchorages were highly utilised as well. The Sebastos harbour complex has two natural anchorages, which have been thoroughly studied by Ratzlaff et al. (2017), Galili (2017), and Galili et al. (2021). These two natural anchorages are commonly labelled as Northern and Southern anchorages. In this area, one set of aerial imagery was collected. The UAV deployed was a DJI Mavic Mini at 50-m above sea level to qualitatively validate the presence of these anchorages as well as some other underwater and above-water rocks along the study area. Images were taken on 10 February 2021 before the Israeli oil spill (16 February 2021). The images were then converted into orthomosaics by using the professional 3D modelling software Agisoft Metashape.

FRAMEWORK

The research questions for this paper are:

- Which climate and water conditions should be considered to derive bathymetry from satellite sensors?
- Up to what depth is satellite-derived bathymetry still reliable along the Israeli coast?
- What is the reliability of the method in comparison with *in-situ* measurements?
- How can one easily highlight both above-water and shallow underwater rocks?
- How do underwater archaeologists benefit from this?

RESULTS

Except for L1 products, VEN μ S does not require a long pre-processing stage (e.g., DN to radiance and radiance to reflectance) or atmospheric corrections. The spectral band ratio model used in this research is based on Stumpf's linear algorithm (Equation 1). The algorithm requires tunable constants m_o and m_1 to scale the ratio to absolute depth values (Stumpf et al. 2003, 550); n is generally taken as 1000 (Sam et al. 2018, 8; Li et al. 2021, 4; Traganos et al. 2018, 5) to ensure a positive outcome. Bands blue and green are used due to their maximum penetration capabilities, which correspond to bands two and four for VEN μ S. For this research, a variation of Stumpf's equation was used (Equation 2) as proposed by Sam et al. (2018, 4) for relative depths where no tunable parameters are needed but ground-truth data is employed instead.

$$Z = m_0 \frac{\ln(n \cdot B2)}{\ln(n \cdot B4)} - m_1 \dots \dots \dots \text{Equation 1}$$

$$Z_r = \frac{\ln(n \cdot B2)}{\ln(n \cdot B4)} \dots \dots \dots \text{Equation 2}$$

First, Equation 2 is applied in a training area where sonar data near the shore is available (Figures 1B and 1D). The values obtained from this band ratio underwent a low-filter convolution to smooth and decrease the disparity between pixel values. Then, all pixel values were converted from five to 50 m pixel size to match the sonar's spatial resolution. A scatter plot is produced between sonar (x-axis) and spectral (y-axis) data, and a quadratic regression model is obtained to ensure the best fitting model (Figures 1C and 1E).

Second, a new band ratio is applied in a near-shore region of interest, and depth values are derived from the quadratic model, from which only positive and real values are considered. These values are assigned to a $n \times 1$ matrix labelled as Z. An additional $n \times 2$ matrix containing values for latitude (X) and longitude (Y) (in UTM coordinates) is adjoined to the previous matrix. These points are then exported to ArcGIS 18.0, and an SDB map is obtained by using kriging interpolation (Amante 2016, 123-133).

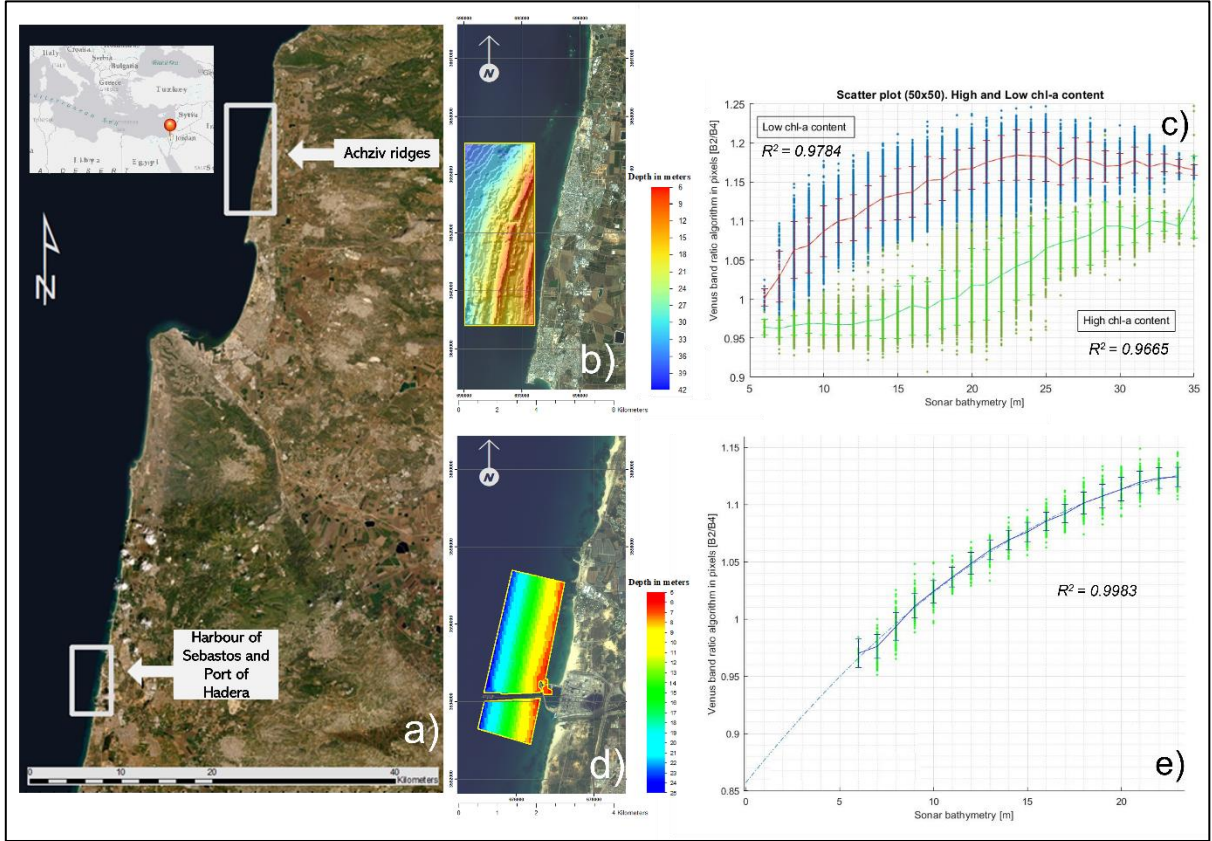


Figure 1: Study Areas and Ground-truth data in comparison with VENUS satellite imagery. a) Study Areas; b) Sonar bathymetry map for the Achziv ridges; c) Scatter plot and regression analysis between sonar bathymetry (x-axis), and band ratio values (y-axis). For high Chl-a content: $Y = 0.00009X^2 + 0.00224X + 0.93679$. For low Chl-a content, $Y = -0.00039X^2 + 0.02046X + 0.91304$; d) Sonar bathymetry map for the Harbour system of Caesarea; e) Scatter plot and regression analysis between sonar bathymetry and band ratio values, $Y = -0.0003816X^2 + 0.020445X + 0.856941$.

SDB Performance under Different Chl-a Concentrations: The Achziv Ridges

Two bathymetric maps were generated for the Achziv ridges, its closeness to Shikmona makes them ideal for relating Chl-a measurements to specific dates. RGB colour composition is shown for low and high Chl-a content (Figures 2A and 2B). Maximum depths reach 23 m during July, as shown in Figure 1C, when Chl-a concentrations are likely to be low. In contrast, although the coefficient of

determination ($R^2 = 0.9784$) derived from sonar and spectral values was high during high Chl-a content (Figure 1C), SDB mapping was demonstrated to be entirely ineffective by not only concealing the aeolianite ridges but also misleading water depth values (Figure 2D) of up to 62.3-m. Additionally, white pixels represented erroneous and false bathymetry by showing values up to 12 m above sea-level.

Conversely, SDB for July displays the ridges in detail. A major ridge expanding in a NNE-SSW direction, and two minor ridges closer to the shore at depths of 6–10 m were visible. Additionally, SDB proved to be useful for identifying shallow coastal geomorphological features such as a possible basin at 10–13 m depth, and an isolated rounded feature around the middle of the main ridge (Figure 2C), all of them not visible on the sonar data.

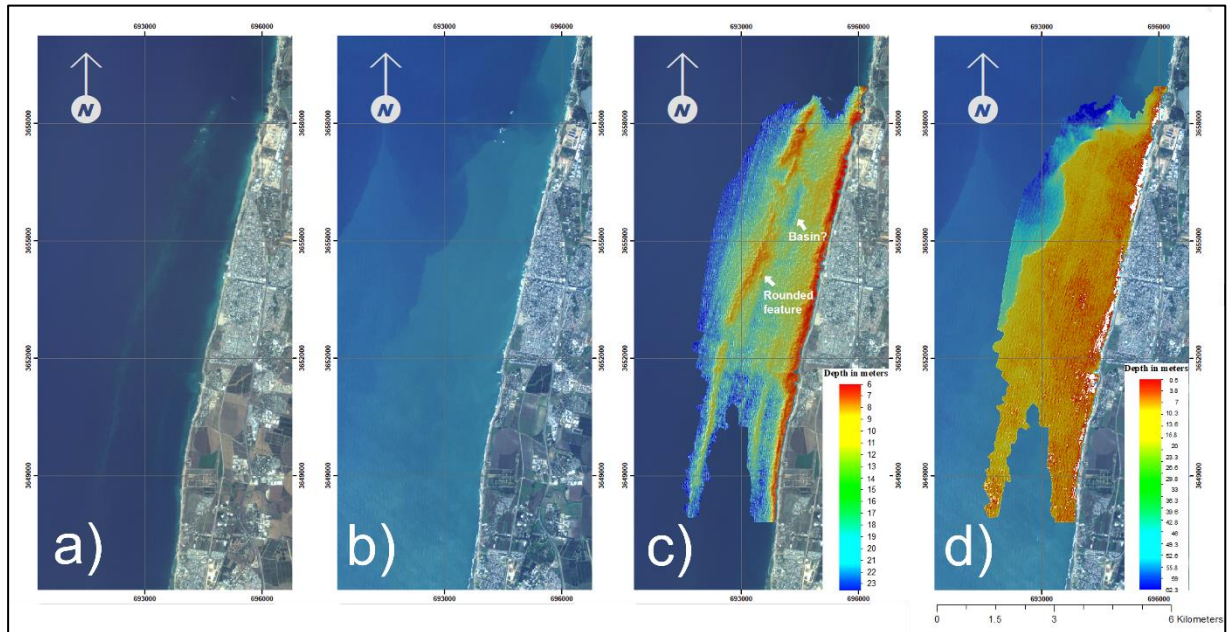


Figure 2. SDB results for low and high Chl-a content for the Achziv ridges; a) low Chl-a RGB; b) high Chl-a RGB; c) low Chl-a SDB, two features; d) high Chl-a SDB, pixels in white denote false bathymetry above mean sea level.

SDB and Rock Identification: The Harbour of Sebastos and the Hadera port

The previous methodology was followed for the second study area (Figure 3A), obtaining a point grid matrix of $n \times 3$, containing latitude, longitude, and depths derived from the quadratic equation (Figure 1E), from which a high-resolution (five m/pixel) georeferenced bathymetric map was generated, covering a total area of 15,770 km² (Figure 3B). Shallow areas were found between Hadera port and Sebastos harbour. Within these regions, traditional ship-based measurements would be almost inaccessible due to high expenses and complicated logistics in comparison with SDB. The algorithm's final limitation went up to 23 m (Figure 1E), similar to the Achziv ridges (Figure 2).

In general, SDB has better performance between four and ten metres deep. Uncertainties appear below four metres deep because the water column attenuation becomes very weak due to the short light transfer path (Dekker et al. 2011, 405, 415; Li et al. 2019, 11), which can lead to small discrepancies between the blue (band two) and green (band three). Moreover, the reflective properties of bottom substrates and bottom albedo also affect its accuracy (Green et al. 2000, 220-233). Above 10 m, light is attenuated, which can lead to weak signals (Lee et al. 2012, 2578).

To evaluate the SDB's performance, satellite depths were compared with the data mentioned in the Resources Section. Comparison between these measurements taken *in situ* and SDB depths (Figure 3C) yielded an outstanding RMSE of 0.52 m (Table 1), which is remarkably good if compared with similar studies (Westley 2021, 8), where the best RMSE was 2.56 m using Sentinel 2 data (10 m/pixel) and a polynomial fitting, or Li et al. (2019, 8), who reported an RMSE of 1.67 m using Planet Dove

satellites (four m/pixel). Note that the shipwreck was again covered by sand during the SDB approach; thus, satellite depths should be slightly larger to reach the hull.

Concerning rock identification, it was found that due to their water penetration capabilities, by multiplying bands three (cyan) and four (green), submerged rocks in shallow waters were enhanced. Likewise, rocks above the water were identified by subtracting band eight (red edge) from band seven (red). The results of applying both algorithms for rock identification are integrated in Figure 3. Underwater rocks are displayed in red, while rocks above the water are shown in yellow. Validation of the proposed algorithms for identifying rocks above and below the water was qualitatively corroborated in Figure 3D by overlying drone imagery over the rocky areas.

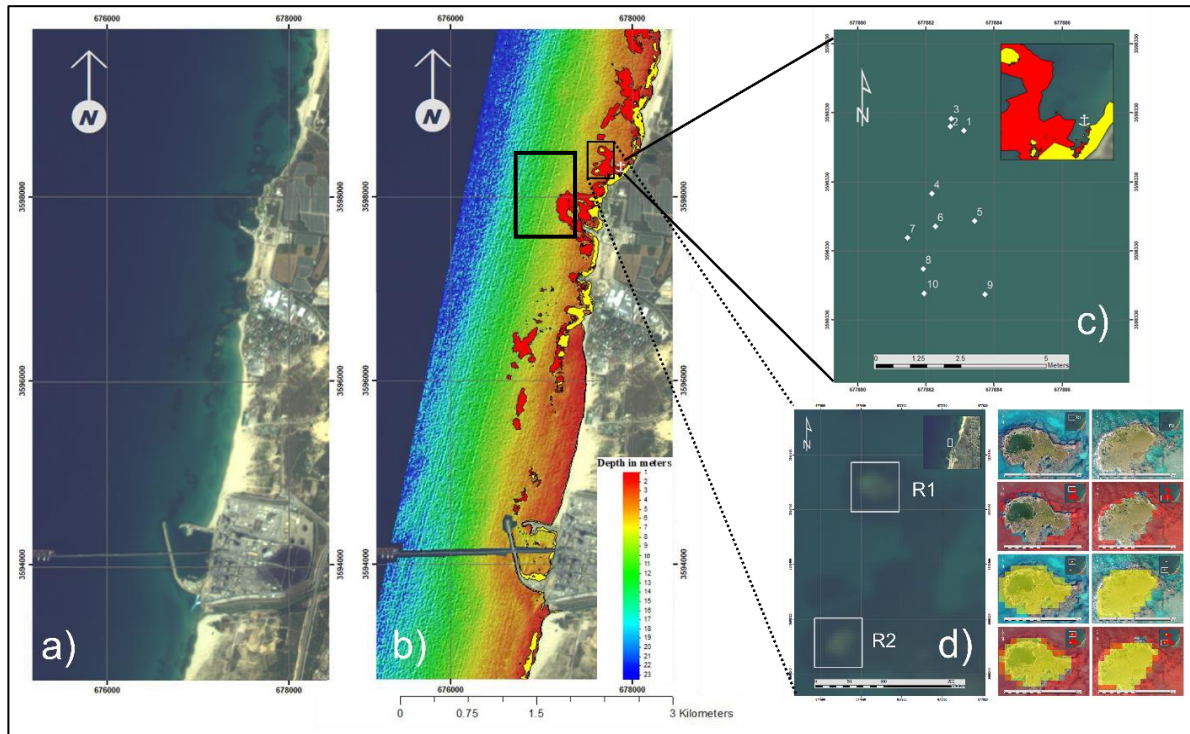


Figure 3. SDB results for the Harbour of Sebastos and the Hader port a) RGB; b) SDB map and rock identification map; c) location of the Caesarea shipwreck points; d) location and validation of the Northern anchorages; Southern anchorages are enclosed in the white box.

Table 1: Comparison between in situ depth points taken during the Caesarea shipwreck excavation of December 2017 and the SDB map from May 2020.

Measurement number	Measured depths <i>in situ</i> (m)	SDB depths (m)	Depth Difference (m)
1	2.5441	3.021	0.4769
2	2.5771	3.021	0.4439
3	2.7984	3.021	0.2226
4	2.6654	3.139	0.4736
5	2.5230	3.139	0.716
6	2.8519	3.139	0.2871
7	2.8090	3.118	0.309
8	2.5481	3.118	0.5699
9	2.1775	3.139	0.9615
10	2.7698	3.118	0.3482

RMSE = 0.5253 m

CONCLUSIONS

The results can be used to comprehend the geological and archaeological landscape of the ancient harbour of Sebastos as well as the northern ridges of Achziv. This approach can be easily replicated in other regions as long as Chl-a concentrations remain low using any other multispectral set of imagery (preferably high resolution). The following conclusions can be drawn from this research:

- For the Israeli coast, SDB mapping should be done for images taken between March and September, when Chl-a concentrations are likely lower.
- Results show that a high R^2 coefficient between ground-truth and spectral data does not necessarily mean that SDB values will be accurate or trustworthy; hence, special attention should be given to the environmental conditions at the time of image acquisition.
- Both VENμS products (L3 and L2) yielded highly reliable results and are highly recommended for SDB bathymetry studies.
- The maximum light penetration depth for the coast of Israel was up to 23 m. Errors likely below this depth.
- The product obtained from multiplying bands three and four from VENμS can be used for identifying rocks submerged in shallow waters.
- The subtraction of band eight from band seven is suitable for detecting rocks above the water level.
- It is strongly recommended to integrate rock identification with SDB for future research projects.

It will be of special interest to replicate this method in the Asian Pacific to test both light penetration capabilities and the ideal yearly timing for multispectral image acquisition based on the Chl-a content of a proposed study area. Likewise, rock detection using other sensors should be examined as well.

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