Shallow Water Bathymetry Derivation, Using Medium Resolution Imagery Case Study: Obhur Creek, Red Sea, Saudi Arabia

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Abstract: Researchers can utilize remote sensing imagery to derive bathymetric data for shallow water. The quality of the derived data depends on the resolution of the imagery, the Satellite Derivation Bathymetry (SDB) method, and the modelling of the variations in the bottom cover of water and water column effects. The latter is a very sophisticated issue that requires various measurements, time, and effort. This leads to the adoption of empirical methods. These are based on the relationship between the recorded satellite imagery spectral reflectance and the measured depth value. In this research, a detailed investigation was carried out using the single band (SDB) method and medium resolution satellite imagery (10 m) with different shallow water depth ranges. The aim is to evaluate the optimal depth range and band selection for the single band SDB method and its applicability to shallow water areas. The accuracies reported in the investigation are considered acceptable compared to similar studies. The best results are associated with the depth range of 5-10 meters, with an accuracy of ± 2.189 m, ± 2.158 m, and ± 2.221 m, for the blue, green, and red bands, respectively. Such investigations are significant for satellite-based shallow water depth derivation applications, in general and the single band method in particular. This method is more economical than conventional and advanced technology-based echosounder methods

Keywords: Obhur Creek, single band method, Sentinel 2A, depth range, shallow water, RMSE.

1. Introduction

Reliable bathymetry data is a requirement for a wide range of marine and coastal applications. To name but a few, the fields include mapping of coral reef habitats, physical oceanography, marine geology, geophysics, and biology. Different techniques were used for obtaining shallow water depth, ranging from the lead-line conventional method to the advanced technology-based echosounder methods. However, compared to the satellite-based bathymetry methods, "they are constrained by access, speed, deployment, cost, and efficiency in shallow waters" [1]. However, the echo sounder survey is constrained by its time-consuming nature and the high operational cost [4]. The effort made in this research was directed towards a multi-spectral imagery-based shallow water depth derivation area. Numerous Satellite-based Derivation Bathymetry (SDB) methods are available in the literature. In general, the difficulties, errors, and limitations associated with these methods are mainly due to water attenuation, bottom reflectance, scattering, and absorption effects. However, the challenges in evaluating these effects, which require field measurements, have outweighed the use of empirical models compared to the analytical ones. Analytical models depend on several shallow water optical properties. "Meanwhile, empirical methods require training data since the models are developed based on the assumption that the total water reflectance is related to water depth" [15] Training data is required for calibration and validation of the model. Though bathymetric measurements are preferred, previous survey data can be used as well. Typical examples of these are the digital databases and digital nautical charts, with accuracies adequate for the satellite imagery resolution. However, models relying on coefficients obtained through regression with *in-situ* depth points assume a linear relationship between depth and water surface reflectance, presuming homogeneous water columns with high transparency both vertically and spatially, and uniform bottom types across the image [1].

This study investigated the relationship between the single band (SDB) model, the shallow water depth range, the imagery resolution, and the image band. Sentinel 2A, color bands (medium resolution, 10 m), the single band (SDB) model, a multi-beam echosounder data set (MBES), and five shallow water depth ranges were used. Both Sentinel 2A data and MBES data were acquired in February 2023. The use of the single band empirical method allows the assessment of the individual color bands in deriving shallow water bathometry data. The single band SDB model was implemented on Obhur Creek shallow waters. These waters vary significantly in terms of bottom substrate types and water quality. "The substrate types are composed of gravel, sand, and mud, ranging from clay to very fine silt", [7]. Also, coral reefs present a significant marine ecosystem in the creek. Though Obhur water is relatively clean, the creek is exposed to heavy tourism activity that may affect the turbidity of the water. The single-band method is cost-effective compared to other satellite-based methods, as it assumes a constant water attenuation and uniform bottom types across the image. It presents an easy-to-apply, economic, and fast solution for broad shallow water areas. It is significant for coastal zone activities that do not require high-accuracy bathymetry data and focus on trends to understand patterns. Typical examples of these include broad-scale seafloor topography assessment, coastal flooding prediction, and general hydrodynamic modeling. This method is not sufficiently addressed in the literature. There are not enough real-world data or case studies, specifically related to the applicability of the method over broad shallow water areas. This study aims to examine its performance against the difficult-to-apply and time-consuming empirical methods and other sophisticated SDB methods. The novelty of this study lies in its contribution to the ongoing research in satellite-based bathymetry in general and highlighting the significance and applicability of the advantageous single band method in shallow water areas in particular.

2. Previous work

Figliomeni F.G. et al. experimented on Sentinel-2 imagery, including Blue, Green, Red, and Near Infrared bands, with 10 m resolution. Three methods were applied: Band Ratio method (BRM), 3rd-Degree Polynomial regression line Method (3DPM), and Principal Component Analysis Method (PCAM). RMSE accuracy values reported are 1.950 m, 2.603 m, and 2.934 m for the 3DPM, PCAM, and BRM, respectively [6]. AL Najar et al. demonstrated a first application of deep learning to satellite derived bathymetry using synthetic cases, and estimated depths down to $\simeq$ 70 m while maintaining an error rate of $\simeq$ 3 m [12]. Ratna Sari Dewi and Aldino Rizaldy reported accuracies of 5.19 m, 2.999 m, and 3.882 m for the blue, green, and red bands, using the single band method and Sentinel 2A data [15]. Luhur Moekti Prayogo, Abdul Basith, carried out a 0-25 m depth range (five equal intervals) investigation using the single band method, Sentinel 2A data, and reported a RMSE value of 2.373 m at a depth range of 0-5 m for the green band [10]. Nguyen Hao Quanga et al. implemented the Stumpf and multi-linear regression models, using Sentinel 2 temporal resolution data (2016, 2018, and 2020) and reported RMSE accuracy values of 1.37, 2.46, and 2.17 m for the years 2016, 2018, and 2020, respectively, [14]. In this detailed research, the results were reported for the five depth intervals (0.297-2.016, 2.084-5.027, 5.03-10.003, 10.054-20.09, and >20 meters) used in the study.

3. Materials and methods

3.1 The study area

The study area is located in a coastal lagoon called Sharm Obour, situated along the Jeddah Red Sea coastal stretch. It is roughly 30 kilometers north of Jeddah City on the eastern shore of the Red Sea in western Saudi Arabia. This Sharm serves as a major sea tourism hub in the Jeddah region. It is well known as a popular tourist destination and is increasingly becoming a desirable residential area for both locals and businesses. The lagoon extends about ten kilometers, with depths reaching up to 30 meters. Figure 1 shows the location of the study area.

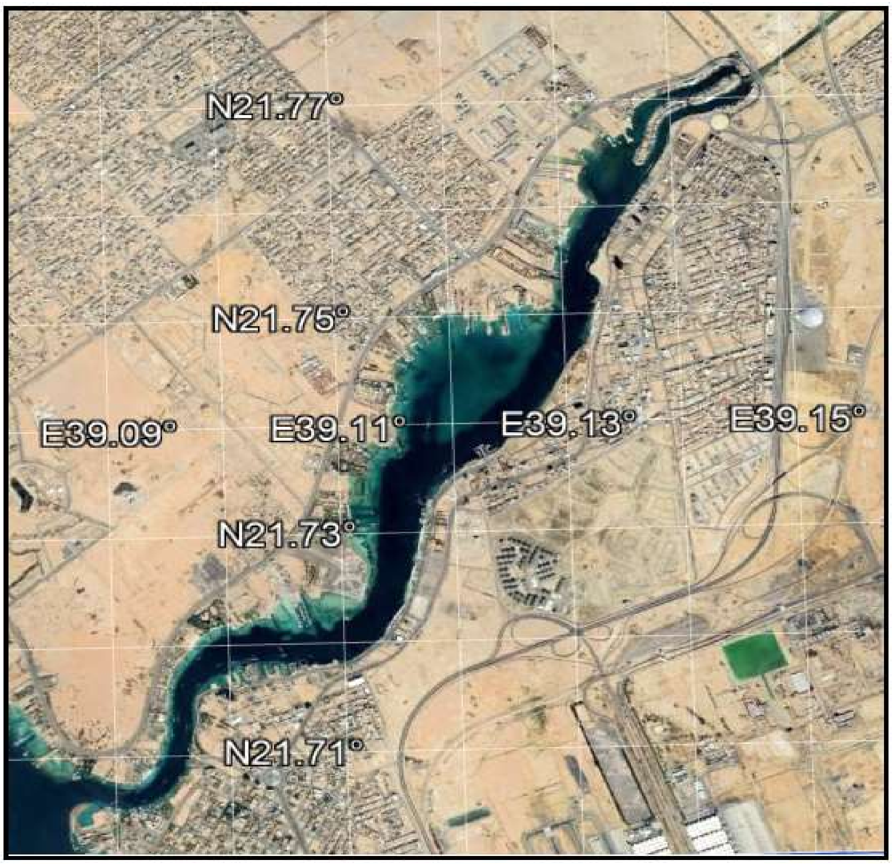

Figure 1. The Study Area Geographical Location (Obhur C reek)

Source: Google Pro image

3.2 Data sets

The data sets used in this study consist of multispectral imagery (MSI) data and multi-beam echo-sounding points (MBES). The MSI data include Sentinel-2A true color image bands and one near-infrared band, as described in Table 1. Radiometrically and geometrically corrected (BoA) level 2A Sentinel-2 data products were downloaded from the ESA Copernicus Open Access Hub, [5]. The imagery was acquired in February 2023. Table 1 details the specifications of the data sets used in the study. The correlation analysis models and results for Sentinel-2A true color bands are shown in Figure 2 and Table 2. Results reveal that all three bands are correlated with water depth in the study area and can be used to derive bathymetry. The red band shows a high correlation coefficient, while the green band has the lowest. However, the correlation for the green band is weaker compared to the other bands, as clearly seen in Figure 2.

Table 1 The Sentinel 2A Data Sets used in the Study

Band	Spectral Wavelength (nm)	Spectral Bandwidth (nm)	Resolution (m)
Blue	490	65	10
Green	560	35	10
Red	665	30	10
NIR	842	115	10

Source: ESA SENTINEL-2 User Handbook 2015

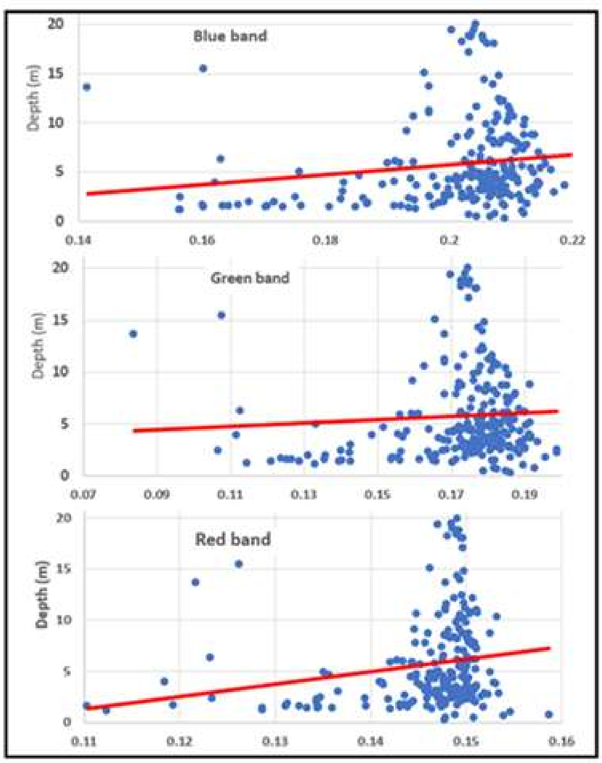

Figure 2. Regression Analysis for the True Color Sentinel 2 A bands, The X-axis represents the Band reflectance, and The Y-axis represents the Calibration Points Depth values

Table 2 Linear Regression and Correlation Analysis Results for Sentinel 2A color Bands (95% significance level)

Band	Correlation coefficient (r)	R -squared (R^2)	β_0	β_1	No. of calibration points
Blue	0.154	0.0238	-4.297442241	49.9296483	225
Green	0.067	0.004	2.935327855	16.36546755	225
Red	0.191	0.036	-12.06046962	121.9036313	225

"The MBES data points were collected using the SeaBat T50-P system (KAU Hydrography 1 Vessel). These data points were acquired in February 2023. The data were processed using Teledyne PDS software, which provided robust tools for managing, visualizing, and ensuring the quality of hydrographic datasets. The software facilitated seamless data handling, high-resolution 3D visualization, and rigorous quality control, ensuring the accuracy and reliability of the collected data for further modeling purposes" [7],[11]. The survey was carried out by an IHO Category A–recognized department in accordance with IHO standards and quality control procedures, with data collected under Special Order specifications ensuring vertical accuracy of about ±25 cm in shallow water (increasing slightly with depth) and horizontal accuracy better than 2 m at the 95% confidence level [9]. A total of 225 calibration and 439 validation points, evenly distributed in the study area, were used in the investigation (Figures 4 and 5). The calibration and validation points are spaced by 150 m and 25 m, respectively. The KAU-HYDROGRAPHY-1 vessel is illustrated in Figure 3.

Figure 3. Survey Vessel KAU- HYDROGRAPHY 1

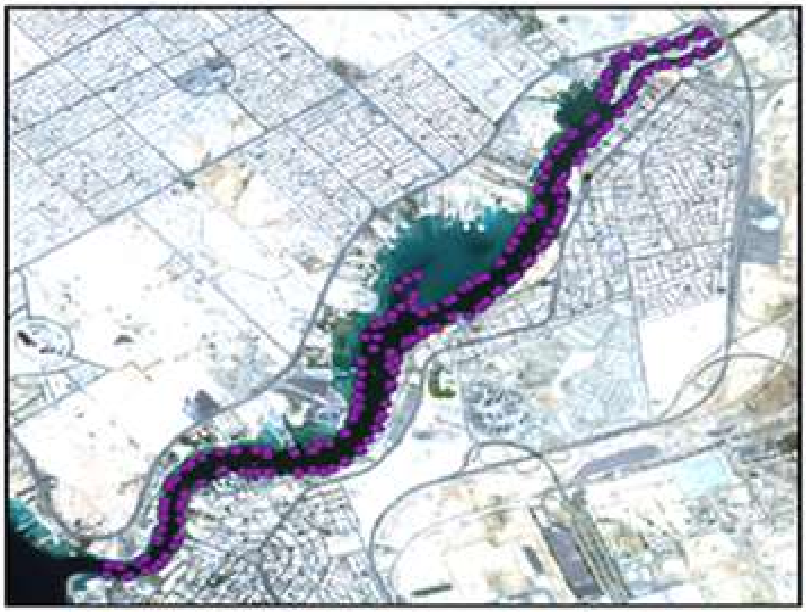

Figure 4. Locations and Distribution of the Calibration MBES Points

Figure 5. Locations and Distribution of the MBES Validation points

3.3 Workflow

The data processing of the study involved various types of software. The ESA Sentinel 2 SNAP application program was used for image processing operations. QGIS and Paint were used to create and display

Plots/figures. Microsoft Excel sheets' data processing facilities were used for regression analysis and statistical analysis. The bathymetric models generated from the satellite image involved many steps. The satellite image was downloaded from the Copernicus Scientific Data Hub website (https://scihub.copernicus.eu/dhus/ #/home). The image was preprocessed to separate the water body from the land and remove the glint noise. The glint was removed by the glint processor module available in SNAP, which is based on the ESA Sen2Cor. The single-band SBD model was applied in two steps. Firstly, the Excel Sheet regression analysis facilities were used to calculate the model parameters, using the MBES calibration points. Secondly, the bathymetry models were obtained via the BANDMath module available in Sentinel 2 SNAP program. Finally, the derived digital bathymetry models were tested with the MBES validation data to verify the accuracy level. The workflow of the bathymetry model's derivation process is presented in Figure 6.

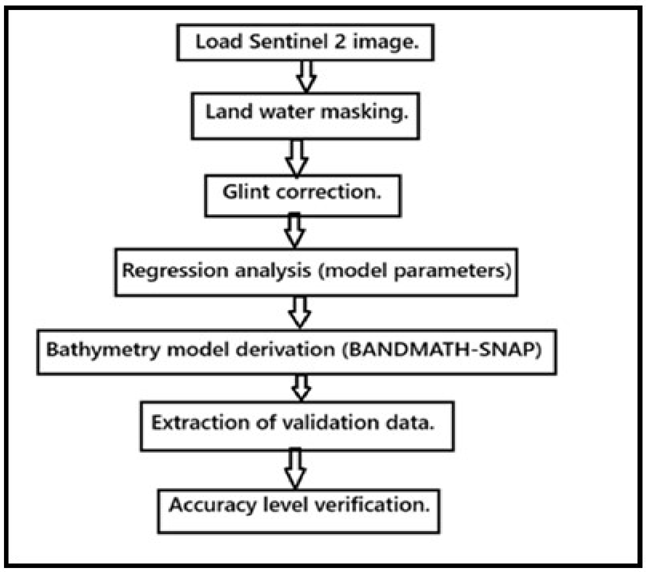

Figure 6. Workflow of Bathymetry Models' Derivation

3.4 Derivation of satellite bathymetry models

The empirical single band (SDB) method was used to derive the bathymetry models required for the investigation. "Estimating depth by using one band is possible by using the assumption that bottom reflectance and water attenuation are constant throughout the image" [3]. "The Empirical method involves extracting the water depth value by connecting the pixel value to the measured depth" [13]. For this method, water depth was estimated by means of linear regression analysis as follows [15]:

$$Wi = \beta 0 + \beta 1 \Sigma xi \qquad (1)$$

Where xi is the reflectance value of the band, n is the number of calibration points, and $\beta 0$ and $\beta 1$ are the model coefficients.

Microsoft Excel sheets were used for the regression analysis operations and the model parameters obtained for the de-glinted blue, green, and red bands are presented in Table 2. The glint processor module available in SNAP (Sen2Coral snap) was used to eliminate the effect of atmospheric scattering, surface reflection, and in-water scattering, using regression analysis and NIR band eight at selected regions. The module is based on “European Space Agency (ESA) Sen2Cor, an algorithm designed specifically for Sentinel-2 imagery that uses scene classification data and LibRadtran radiance transfer model look-up tables for AC” [8]. The single-band method was applied to derive SDB models. A bathymetry model was derived for each of the three-color bands, for the five data sets (a total of 15 SDB models).

3.5 Extraction of the validation depth values

An MBES set of validation points with depths ranging between 0.4 and 27.4 m was used in the study (Figure 4). These validation points were grouped in five depth intervals: 0.297-2.016, 2.084-5.027, 5.03-10.003, 10.054-20.09, and >20 m. The depth values at the locations of the validation points were derived from each of the SDB models (a total of 15 calibration data sets).

3.6 Data validation

The data validation was achieved by accuracy assessment, where the MBES depth values at the validation locations were compared with their corresponding depth values derived from the SDB models, using Microsoft Excel sheets' data analysis facilities. The accuracy for each data set was calculated, using the Root Mean Square Error statistic model as follows: -

$$RMSE = \text{Sqrt}\ \Sigma\ r_i^2 / (n-1) \qquad (2)$$

Where r_i = residual value at validation points i (difference between MBES value and derived SDB model value) and n is the number of validation point.

4. Results

Below, we provide the linear regression model and the correlation analysis results obtained for the glint-corrected blue, green, and red bands, for the different data sets. The results for the depth range (0.297-2.016) are presented in Table 3 and Figure 7. The highest and lowest correlations were associated with the green and red bands, respectively. The red band obtained the highest accuracy, (the lowest RMSE 4.356 m). Figure 7 demonstrated under-prediction pattern between the validation and the SDB models. This is revealed by the negative residuals associated with the validation points in the three models.

Table 3. Analysis Results for de-glinted color Bands for Depth Range 0.297-2.016 m (95% significance level)

Band	Blue	Green	Red
Validation points	54	54	54
RMSE	4.047	4.046	4.356
Correlation coefficient (r)	0.271	0.282	0.231
R-squared (R^2)	0.073	0.080	0.053

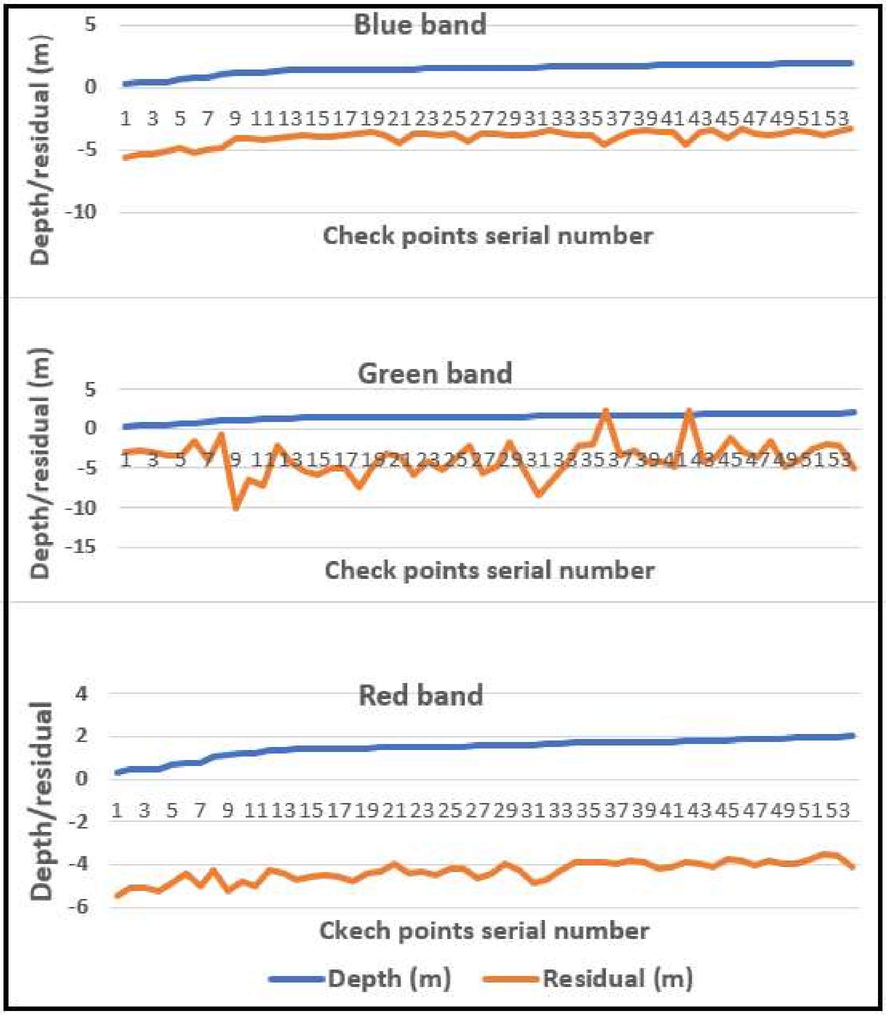

Figure 7. Sentinel 2A color Bands, Depths vs Residuals for Range (0.297-2.016 m)

The results for depth range (2.084-5.027) m are presented in Table 4 and Figure 8. The highest and lowest correlations were associated with the blue, and red bands, respectively. The red band provided the highest accuracy, (the lowest RMSE 2.428 m). The blue band provided the highest residual value (-4.434 m). The blue, green, and red bands' provided accuracies of ± 2.457 m, ± 2.539 m, and ± 2.428 m, respectively.

Table 4. Analysis Results for de-glinted color Bands for Depth range 2.084-5.027 m (95% significance level)

Band	Blue	Green	Red
Validation points	147	147	147
RMSE	2.457	2.539	2.428
Correlation coefficient (r)	0.150	0.118	0.072
R-squared (R^2)	0.0226	0.014	0.005

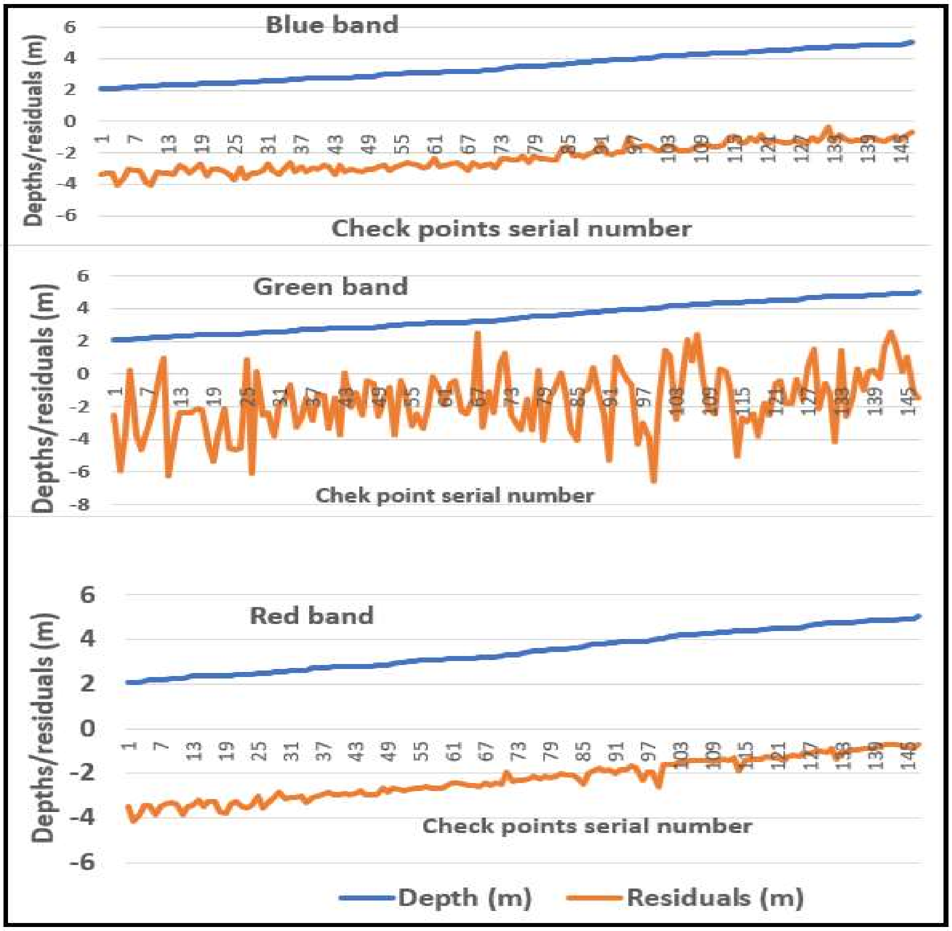

Figure 8. Sentinel 2A color Bands, Depths vs Residuals for Range (2.084- 5.027 m)

The results for depth range (5.03-10.003) m are presented in Table 5 and Figure 9. The highest and lowest correlations were associated with the red and green bands, respectively. The green band provided the highest accuracy (lowest RMSE 2.158m). The blue band provided the highest residual value (4.289 m). The blue, green, and red bands' provided accuracies of ± 2.189 m, ± 2.158 m, and ± 2.221 m, respectively.

Table 5 Analysis Results for de-glinted color Bands for Depth Range 5.03-10.003 m (95% significance level)

Band	Blue	Green	Red
Validation points	113	113	113
RMSE	2.189	2.158	2.221
Correlation coefficient (r)	0.101	0.051	0.143
R-squared (R^2)	0.010	0.003	0.021

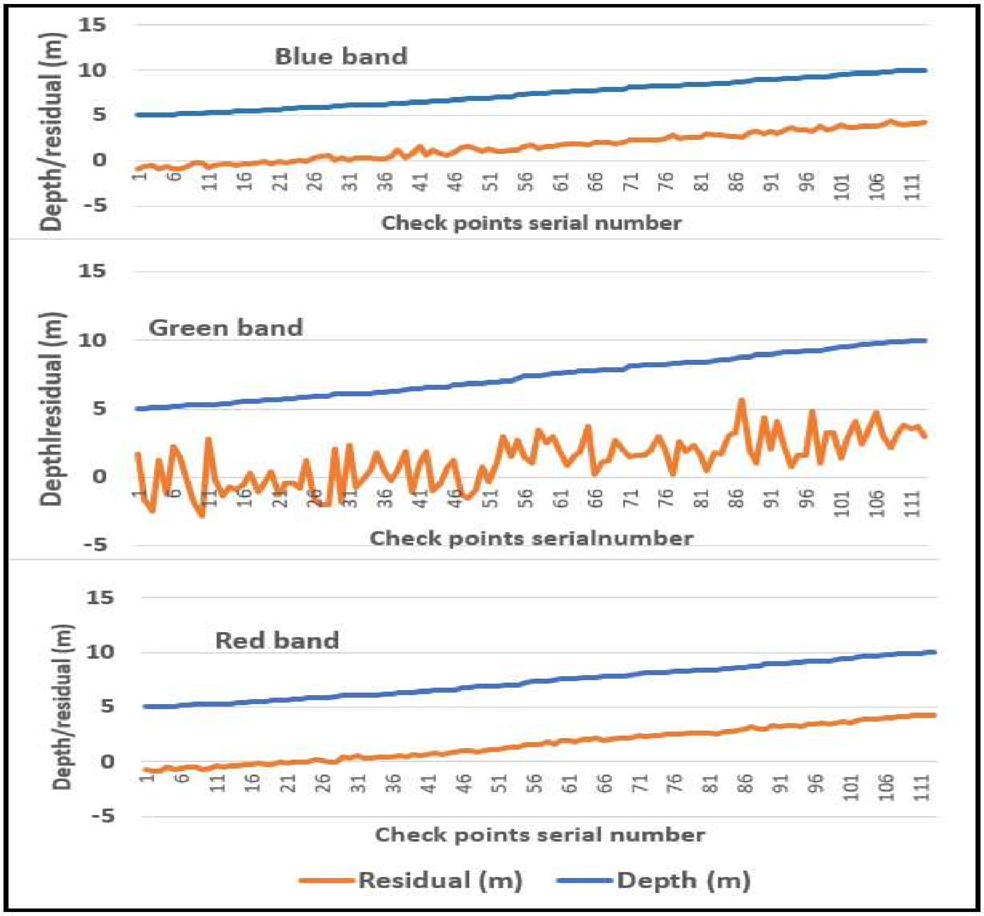

Figure 9. Sentinel 2A color bands, Depths vs Residuals for Range (5.03-10.003 m)

The results for depth range (10.054-20.09) m are presented in Table 6 and Figure 10. The highest and lowest correlations were associated with the blue and red bands, respectively. The green band obtained the highest accuracy (lowest RMSE 7.698 m). The green band provided the highest residual value (14.292 m). The blue, green, and red provided accuracies of ± 9.158 m, ± 7.698 m, and ± 9.132 m RMSE values, respectively.

Table 6 Analysis Results for de-glinted color Bands for Depth Range 10.054-20.09 m (95% significance level)

Band	Blue	Green	Red
Validation points	95	95	95
RMSE	9.158	7.698	9.132
Correlation coefficient (r)	0.183	0.176	0.092
R-squared (R^2)	0.033	0.031	0.009

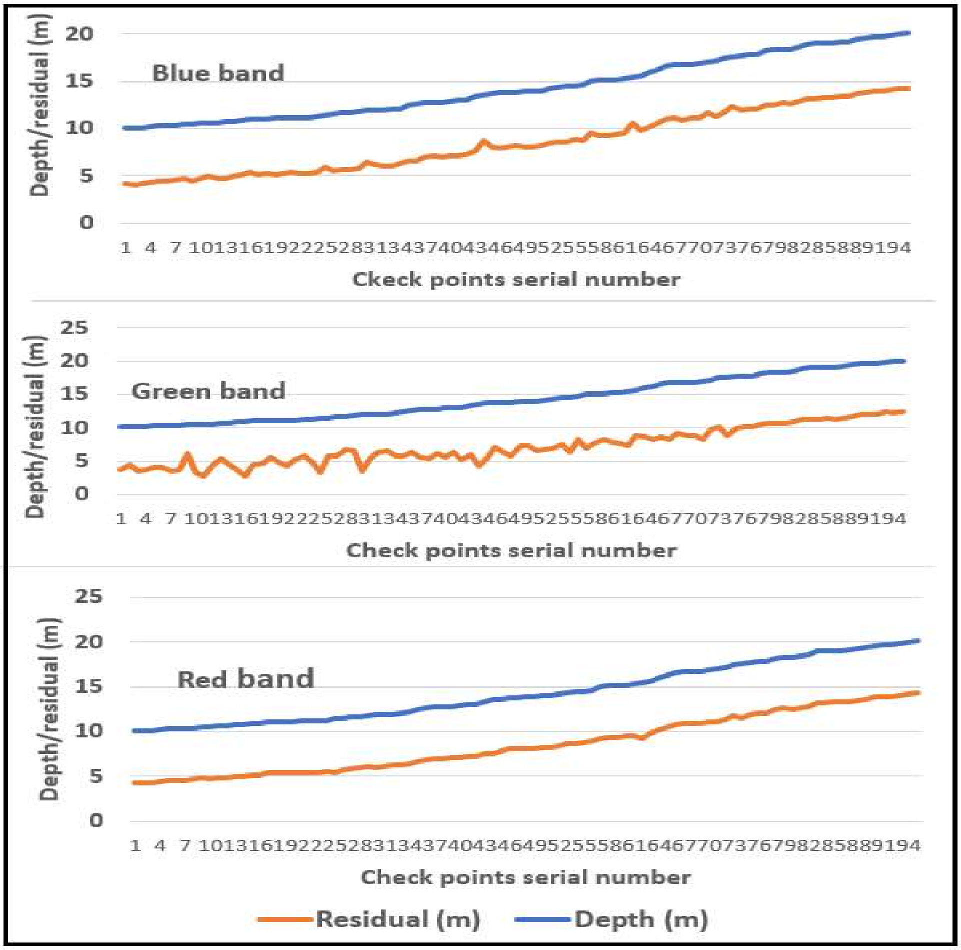

Figure 10. Sentinel 2A color Bands, Depths, vs Residuals for Range (10.054-20.09 m)

The results for depth range > 20 m are presented in Table 7 and Figure11. The highest and lowest correlations were associated with the blue and red bands, respectively. The green band obtained the highest accuracy (Lowest RMSE 14.784 m). The blue band provided the highest residual value (21.728 m). The blue, green, and red bands' provided accuracies of ± 17.092 m, ± 14.784 m, and ± 17.009 m, respectively. These results clearly demonstrated that using the method with 10 m resolution imagery for shallow water depths greater than 20 m gives unreliable depth values. This is mainly attributed to the fact that the method does not consider the water column attenuation and the bottom reflection effects.

Table 7 Analysis Results for de-glinted color Bands for Depth Range > 20 m (95% significance level)

Band	Blue	Green	Red
Validation points	30	30	30
RMSE	17.092	14.784	17.009
Correlation coefficient (r)	0.434	0.349	0.296
R-squared (R^2)	0.188	0.122	0.087

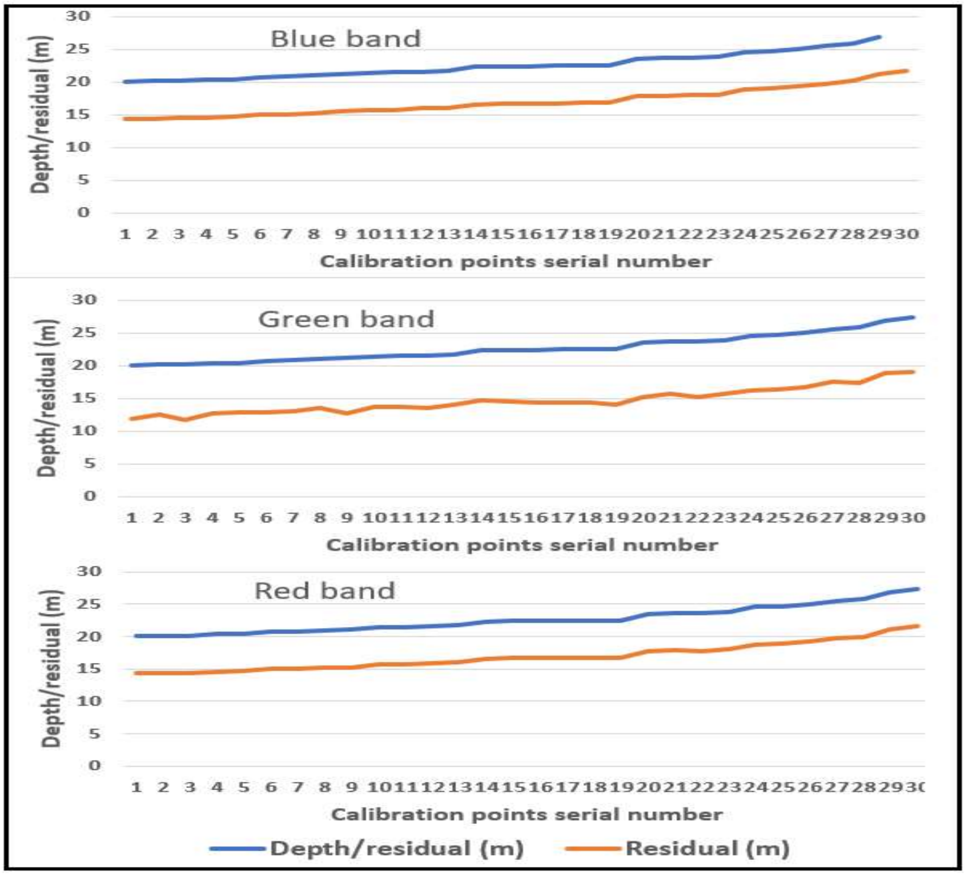

Figure 11. Sentinel 2A color Bands, Depths vs Residuals for Range (>20 m)

5. Discussion

Table 8 and Figure 12 show the accuracies for the blue, green, and red color bands for the different data sets.

Table 8: Summary of the Results provided by the color Bands for the different Data Sets.

	Accuracy RMSE (m)		
Depth range (m)	Blue	Green	Red
0.297-2.016	4.047	4.406	4.356
2.084-5.027	2.457	2.539	2.429
5.03-10.003	2.189	2.158	2.221
10.054-20.09	9.158	7.698	9.132
> 20	17.092	14.784	17.009

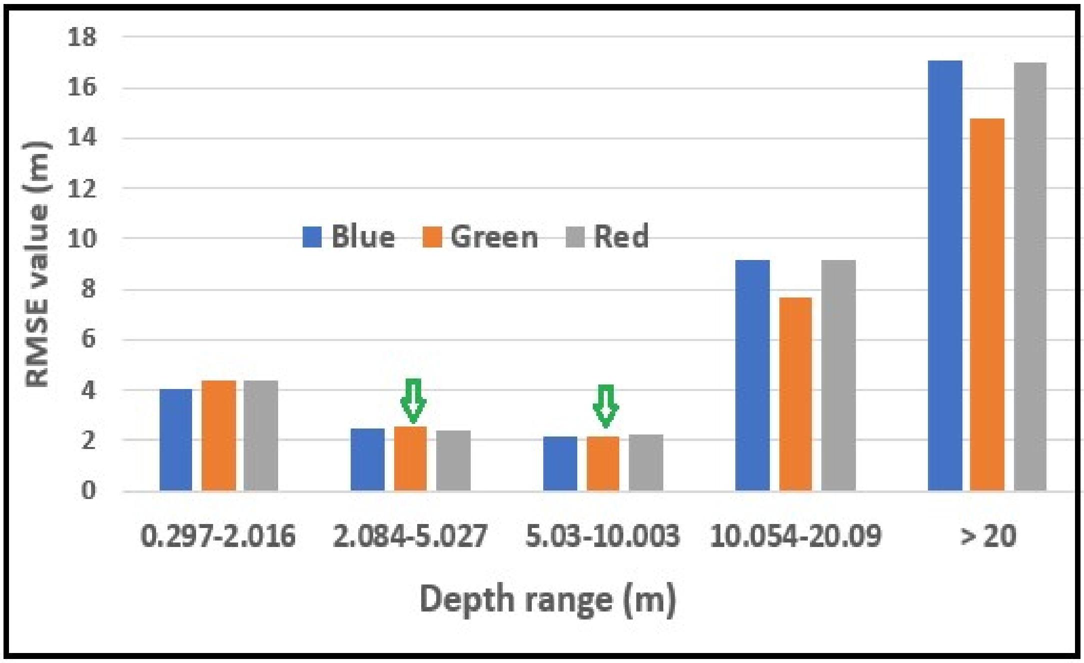

Figure 12. Sentinel 2A color Bands, Depths vs Residual values for all Depth Ranges

The (0.297-2.016) m depth range results may rule out the possibility of using the method with a 10 m resolution imagery, and the utilization of a SDB method that considers, water column attenuation and bottom reflectance is a necessity. The reason for this is twofold. Firstly, it is not practical to use depth values with an accuracy of ± double the maximum depth in the area. Secondly, all the bands provided SDB models (3.7-4.1 m) meters below the validation model (under-prediction pattern). This poor performance can be attributed to the variation in the bottom cover, such as sea grass and coral reefs. In this depth range, the coral reefs and sea grass can couple together to create strong bottom and water column reflections, and result in significant impact on the recorded signal. The (2.084-5.027) m depth range results with an average accuracy of 2.475 m RMSE value, represented a good performance for the method as compared to the results reported by, [6], [10] and, [15]. The (5.03-10.003) depth range results, with an average accuracy of 2.189 m RMSE value, demonstrated a significant performance for the method. This may be attributed to the weak seafloor influence and water column attenuation as compared to the lower and higher depth ranges, as the water column attenuation and bottom reflections, increase with the depth increase and decrease, respectively. The performance of the method for the (10-20 m) and >20 m ranges was very poor (Figure 12). This may relate to the strong water column attenuations associated with the increase in depth. These findings demonstrated the suitability of the method for the rapid bathymetry mapping of the coastal zone shallow waters with a depth range 2-10 m. The results obtained demonstrated an under-prediction pattern, with the water depth increase (retrieval depth less than actual depth). This is expected as the under-prediction and over-prediction patterns are reported in the literature. Chunzhu Wei, C. et al. applied the linear band model and the log-transformed band ratio model, using L8 and S2 images, and reported an under-prediction pattern for depths (<6 m) and an over-prediction pattern for depths (6-30 m), [4]. An in-depth discussion of these results is presented in Tables 9, 10 and Figure 13. These Tables present comparisons between the method and previous single-band, and other SBD methods, respectively, and are summarized in Figure 13.

Table 9. Comparison between the Research Results and previous Works (SBM method)

Band	Current Research (2025)		Ratna S. D. at al. (2021)	Luhur M. P. at al. (2020)
Blue	2.457	2.189	5.019	-
Green	2.539	2.158	2.999	2.373
Red	2.429	2.221	3.882	-
Depth range (m)	2-5	5-10	0-20	0-5
Satellite data	Sentinel 2, 10 Resolution		Sentinel 2, 10 m resolution	Worldview 3
Calibration data	MBES points		SBES points	SBES points
Image correction	Glint correction		Average deep-water correction	Radiometric AComp

Table 10. Comparison between the Research Results and previous Works (Other methods)

Method	Satellite data	Calibration data	Validation data	Accuracy (RMSE) (m)	Depth Range (m)	Source
(BRM)	Worldview 3(B/G bands)	SBES	SBES	1.669	0-5	Luhur M. P. atal. (2020)
DL-based	S2, 10 m	Bathy-survey data	Bathy-survey data	3.26	Up to 70	Al Najar et al. (2021)
(3DPM)	S2, 10 m	1:7500, ENC	1:7500, ENC	1.950	0-23	F.G. Figliomeni, C. et al. (2024)
(PCAM)	S2, 10 m	1:7500, ENC	1:7500, ENC	2.603	0-23	F.G. Figliomeni, C. et al. (2024)
(GEE)	S2, 10 m	SBES	SBES	1.39-1.67	0-17 M	F.G. Figliomeni C. et ai. (2024)

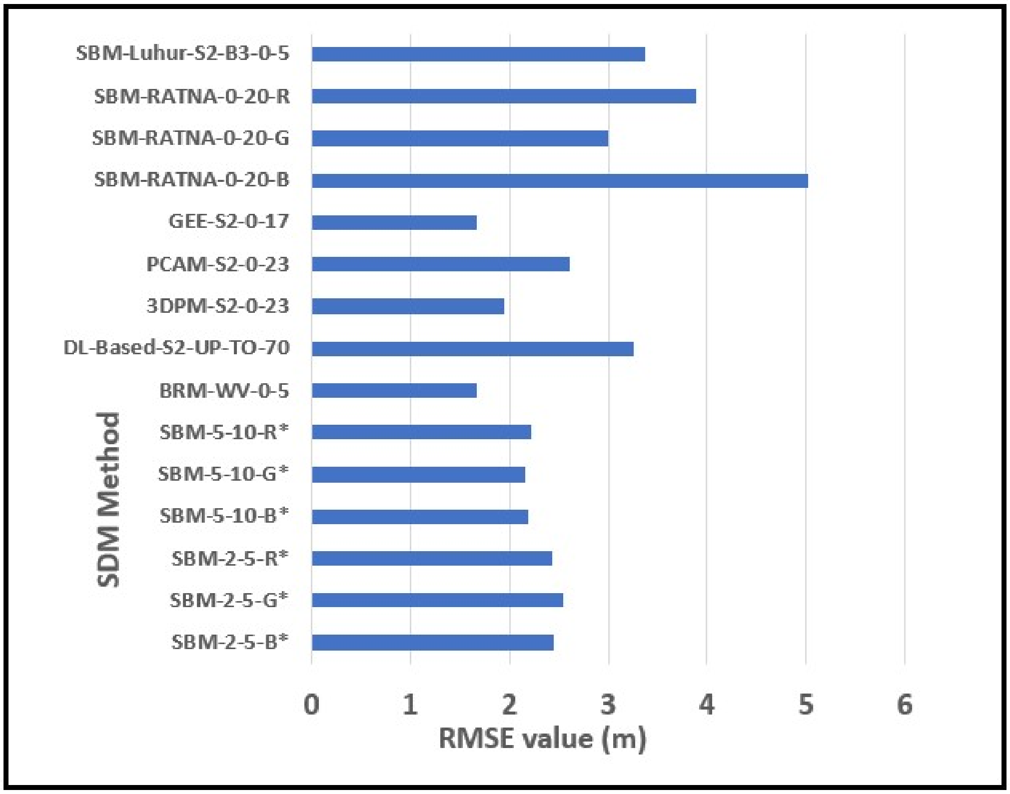

Figure 13. A flowchart showing the performance of the Method compared to Single Band and other SDB methods

Table 9 provided the methods results compared to similar previous works. It shows reasonable differences, even with the high-resolution Worldview data for the range 0-5 m. Particularly, the green band results show significant performance. Notably, the RMSE value decreased by 18% for the 2-5 m depth range and by 39% for the 5-10 m range, as compared to Ratna S. D. et al. results, [15]. Meanwhile, the RMSE value increased by 17% for the depth range 2-5 m and decreased by 10% for range 5-10 m, as compared to Luhur M. P. et al., [10]. These findings truly represent significant performance of the method. Table 10 provides an overview of the performance levels of various SDB methods, compared to the method, showcasing a spectrum that ranges from simple to sophisticated methods. These methods consist of the Band Ratio (BRM), the Deep Learning (DL-based), the 3D Polynomial (3DPM), the Principal Component Analysis, and the Google Earth Engine (GEE). The RMSE values reported for these methods and the method, ranged between 1.39-3.26 m, for depths up to 70 m, and 2.189-2.539 m, for range 2-10 m, respectively. Figure 13 provides a graphical summary of Tables 9 and 10, where the methods bars are indicated by a star and abbreviations WV, SBM, and S2 stand for WorldView, Single Band Method, and Sentinel 2, respectively. It demonstrates the significant performance advantages of this method compared to single band and other SDB methods. This strong performance, along with its advantages, justifies its further investigation. The method is straightforward, simple, fast and easy to apply. While it may not match sophisticated approaches in terms of accuracy and resolution, the findings from this detailed research support its use for surveys with low requirements for accuracy and resolution. A self-explanatory example is the determination of the multi-beam survey area, as this can help avoid issues in shallow water and reduce cost.

6. Conclusions and recommendations

This study provided a detailed investigation related to satellite-based shallow water bathymetry. Though it is not possible to generalize for the use of the single band (SDB) method, without more elaboration on the issue, particularly when using data from different sources. The depth range 5-10 m, provided the best results, with an accuracy of ± 2.189 m, 2.158 m, and 2.221 m, RMSE values for the blue, green, and red bands, respectively. The accuracies reported in the investigation are considered acceptable, compared to similar studies using the single band and other SDB methods, as presented in Tables 9, 10 and Figure 13. The use of satellite-based bathymetry is promising, as numerous open data sources provide more temporally resolved free-of-charge satellite images. However, rapid collection of shallow water bathymetric information without the mobilization of personnel/equipment is economic, significant for mapping inaccessible areas, and deserves more attention. The study has demonstrated the applicability of the method over shallow water areas (2-10 m) for projects with low accuracy requirements. The findings add to the rapid, cost-effective, easy-to-apply single band SDB method. This comprehensive investigation, along with the comparison to similar and other SDB methods, contributes valuable insights to the SDB field, particularly, regarding the single band method. The study should encourage future research in this subject. Further investigations, utilizing medium-resolution images from different data sources, over shallow water areas with diverse bottom terrain complexities, should add to the subject.

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