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Case Study

Satellite derived bathymetry for rapid investigation for possible navigational channel design for coastal wind farm installation: a case study at Silavathurai, Sri Lanka

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Abstract

A rapid bathymetric survey was required for the transportation of wind turbines and blades to the Silavathurai coastline, Sri Lanka via sea. This area is a shallow uncharted area which makes this task a challenge. To overcome this limitation, remote sensing techniques were used to derive the bathymetry of the area using Sentinel-2 satellite images because of its high-resolution capabilities. The empirical bathymetric method was used by incorporating band ratio techniques that involves comparing different bands of the satellite imagery in estimating water depths. Three band combinations (Green–Blue, Red–Blue and Red–Green) were used and evaluated for their effectiveness in estimating water depths. The findings showed varying degrees of correlations between the in-situ measurements and bathymetry values. Green–Blue band combination gave the strongest correlation ($R^2 = 0.91$) among the band combinations, indicating that it is most suitable for bathymetry estimation in such situations. Further, various depth zones were also tested for correlation analysis, which reveals higher correlation values for shallower depths. Then, accuracy analysis was done based on the computed Root Mean Square Error (RMSE) values and Green–Blue combination gave the least overall RMSE value (1.06 m) with the measured depths. Finally, the derived bathymetry data from the satellite images played a vital role in designing the navigation channel, ensuring safe transport of wind turbines for the Silavathurai wind farm project. The study emphasises the effectiveness of the remote sensing approach in determining bathymetry for shallow areas, offering insightful information for coastal renewable energy projects.

Article Highlights

- Silavathurai is an unchartered area and a quick bathymetric method was required designing a channel to transport the large equipment to the wind farm site over the water.
- Sentinel-2 multispectral satellite images were used and the Green–Blue band combination given best band combination to derive the bathymetry.
- The validation results from the echosounder data provided a very good correlation with the satellite derived bathymetry for the shallow depths up to 10 m.

1 Introduction

In recent years, the global demand for electricity has witnessed a significant rise due to the growing world population, industry demand and increasing prosperity. To meet this demand while addressing the environmental concerns almost every country is now shifting their focus towards renewable energy sources. Sri Lanka, too, has embarked on a path towards a sustainable energy future, aiming to become an energy-self-sufficient nation by 2030. As part of this endeavour, the Sri Lankan government has set a target to increase the country's power generation capacity from the existing 4043–6900 MW by 2025, with a substantial emphasis on renewable energy sources [1]. Sri Lanka's enthusiasm for wind power aligns with global efforts to reduce reliance on polluting traditional energy sources. The imperative for decreasing air pollution, greenhouse gas emissions, and ecosystem degradation associated with fossil fuels drives the shift to renewables. Sri Lanka hopes to meet its energy goals while also contributing significantly to a cleaner, more sustainable global energy landscape.

In the pursuit of harnessing renewable energy, wind power has emerged as a viable option for Sri Lanka. The country benefits from its strategic location in the Indian Ocean, providing vast resources for solar and wind energy. These prevailing winds, such as the well-known "North-east" and "South-west" monsoons, produce consistent and predictable wind patterns, making Sri Lanka ideal for the effective deployment of wind turbines to generate sustainable and reliable renewable energy. As part of its renewable energy expansion plans, Sri Lanka has already connected eleven wind power plants to the national grid, with further ambitions to add 780 MW of wind power between 2020 and 2025. In line with these efforts, a new wind farm project is currently underway along the coastline of Silavathurai area [2].

Transporting wind turbines and its large accessories for the installation of a wind farm presents unique logistical challenges. While smaller components can be transported relatively easily, the transportation of larger components, such as wind blades and towers proves to be more complex due to the nature of the existing land transportation network. In light of these challenges, alternative modes of transportation is essential. Ground transportation is often impossible due to the sheer size and weight of the wind turbine components. Consequently, the transportation of wind turbines through the ocean has become a favourable option for the Silavathurai wind farm project [3].

A crucial factor that needs to be taken into account when transporting wind turbines through the ocean using carrier barges is the bathymetry of the seabed. Bathymetry refers to the measurement of water depths and the topography of the underwater terrain. In shallow waters, conventional bathymetric survey methods such as Sound Navigation and Ranging (SONAR) and Light Detection and Ranging (LiDAR) face limitations in terms of accuracy, coverage and practical constrains such as time & cost. To overcome these challenges, remote sensing approach utilizing the satellite derived bathymetry (SDB) technology has gained prominence since recently [3, 4].

To estimate bathymetry values in shallow water regions, SDB utilizes satellite imageries from various spectral bands. SDB provides valuable understandings into the depths of near shore waters by analysing the characteristics of the optical properties of the water column. The band ratio method is a commonly used method that estimates bathymetry using modelling of the specific bands of the electromagnetic spectrum [5]. This approach has shown promising results in calculating bathymetry in shallow water areas.

The objective of this study was to investigate the potential of SDB as a promising approach for determining bathymetry in shallow coastal waters in supporting in designing of a navigation channel for the transportation of wind turbines to Silavathurai, Sri Lanka.

2 Methodology

Silavathurai in Sri Lanka, boasts unique geographical features characterized by its strategic location on the North West coast and renowned for its high wind power potential attributed to favourable wind conditions. The site positioned between latitudes 8°38′08″ N to 8°43′52″ N and longitudes 79°46′05″ E to 79°58′14″ E, spans approximately 2500 hectares (Fig. 1). The bathymetry of the Silavathurai coastal area is varying between 0 and 13 m. Notably, the area is subject to the influential forces of both wind and tidal currents, marked by prevailing winds from the northeast and tidal currents flowing in a northwest to southeast direction.

2.1 Satellite data

This study used the Sentinel-2 satellite images to derive the bathymetry using Band Ratio method. The Sentinel-2 satellite mission opened a new era in coastal bathymetric mapping thanks to high resolution, a 5 days revisit time and its open access policy. These capabilities are especially advantageous for bathymetric studies in coastal areas. Two identical satellites (Sentinel 2A and 2B) placed in the same sun synchronous orbit and phased at 180° to each other, carry a multispectral instrument that samples 13 spectral bands. The Copernicus Open Access Hub (COAH) provides Sentinel-2 data as two products: Level 1C as Top-of-Atmosphere (TOA) reflectance and Level 2A as Bottom-of-Atmosphere (BOA) reflectance [6].

The Sentinel-2 satellite images were obtained from the COAH, powered by European Space Agency (ESA). The images were captured on 29th June 2022 and falls under the product type "S2MSI2A" with a processing level of Level-2A. The assessment of cloud coverage for the image was determined to be 3.8277. The Sentinel-2 MSI capture data in 13 spectral bands, including four bands at 10 m, six bands at 20 m, and three bands at 60 m spatial resolution (Table 1). The coordinate system used for the satellite images was World Geodetic Datum 1984 (WGS 84) Universal Transverse Mercator (UTM) Zone 44. Then, the image is ortho-corrected to the BOA reflectance. The ESA atmospheric processing consists of combining the latest techniques for performing atmospheric corrections including cirrus clouds customized to the Sentinel-2 environment. Therefore, this correction is distinctive of the atmospheric and climate circumstances in the project area.
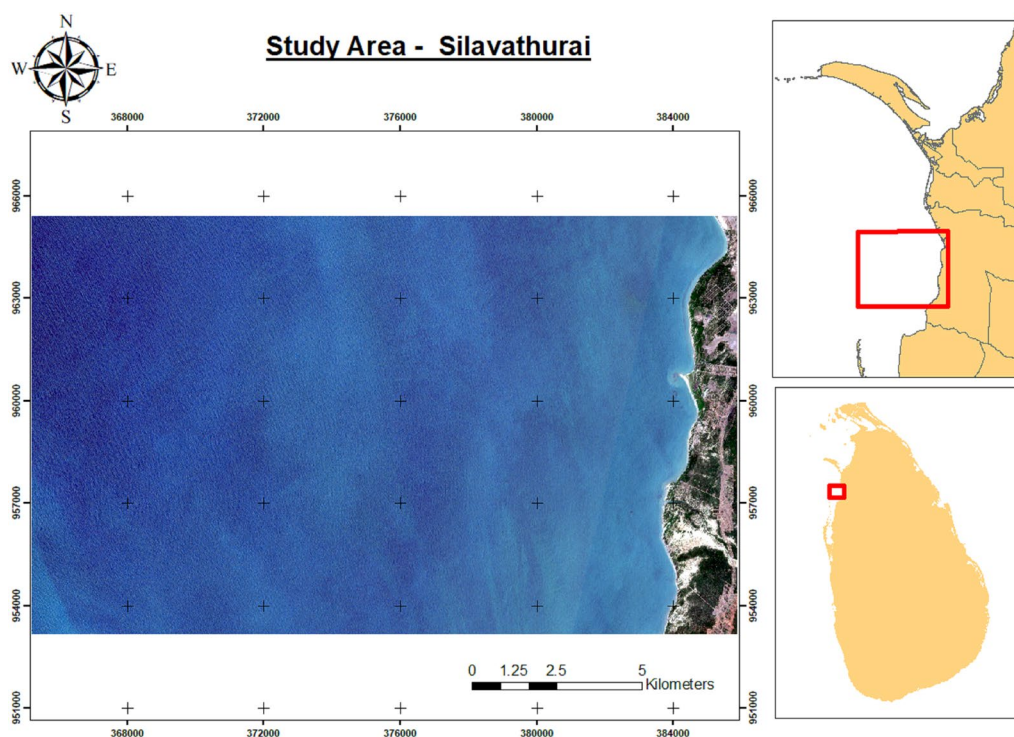

Fig. 1 Location of the study area, Silavathurai (*Source*: Google Earth Pro)

Table 1 Sentinel-2 Band List [7]

Bands	Spectral region	Spatial resolution (m)	Central wavelength (nm)	Specific characteristics
B1	Coastal aerosol (CB)	60	443	Captures information on suspended sediments and coastal aerosols
B2	Blue	10	490	Penetrates clear water, providing information on water depth and clarity
B3	Green	10	560	Penetrates water with abundant vegetation, offering insights into submerged features
B4	Red	10	665	Detects chlorophyll absorption, aiding in the identification of algae and aquatic vegetation
B5	Red edge 1	20	705	Sensitive to changes in chlorophyll content, supporting vegetation mapping
B6	Red edge 2	20	740	It aids in vegetation health assessment
B7	Red edge	20	783	Provides additional information on vegetation health
B8	Near infrared	10	842	Penetrates water to a certain depth, useful for studying submerged structures
B8A	Near infrared narrow	20	865	Sensitive to chlorophyll content and useful for vegetation monitoring
B9	Water vapour	60	945	Measures atmospheric water vapor content
B10	Shortwave infrared/cirrus	60	1375	Penetrates atmospheric effects to capture details on underwater features
B11	Shortwave infrared 1 (SWIR1)	20	1610	Penetrates water, providing information on water quality and depth
B12	Shortwave infrared 1 (SWIR1)	20	2190	Sensitive to water vapour and offers insights into atmospheric conditions

2.2 In-situ data

Single Beam Echo Sounding (SBES) technology was used to collect the in-situ bathymetry data at Silavathurai to train the SDB process and also to validate results. SBES is a hydrographic surveying technique used to measure water depths by emitting an acoustic beam downward from a survey vessel. Here, a total of four survey lines data was acquired such a way that they adequately represent the project area. Later, these data was corrected for tidal correction prior to the analysis. The depths of the survey lines varying between 1 and 13 m.

2.3 Satellite image processing and band ratio method

To process and visualize the satellite data, Sentinel Application Platform (SNAP) DESKTOP and ArcGIS software were used. SNAP Desktop was utilized for the processing and analysis of Sentinel-2 satellite imagery, providing essential tools for atmospheric correction, band ratio calculations, and image enhancement. ArcGIS played a pivotal role in spatial data integration, mapping, and the visualization of bathymetric results within a geographic information system (GIS) framework. The Sentinel-2 satellite image underwent several pre-processing techniques to prepare it for final analysis. These included land mask, sun glint correction, and dark object subtraction. The land mask method was employed to distinguish between land and water areas in the image. It involved generating a binary mask based on the spectral properties of the image. This technique is crucial for various remote sensing applications, including bathymetry estimation and coastal zone management [7].

The Near Infrared (NIR) band is included in this study for a specific purpose, despite its general limitations in water property analysis. While NIR wavelengths are typically absorbed by water and do not penetrate deeply into water bodies, their application in this study is primarily aimed at mitigating atmospheric and surface effects, particularly sun glint. Sun glint occurs when sunlight is directly reflected off the water surface back to the satellite sensor, resulting in inaccuracies in the data. In the context of bathymetric estimation, this correction is critical for obtaining accurate water depth measurements [8]. The proposed method by [8] was utilized and this linear regression based on a sample of image pixels to establish the relationship between the Near Infrared (NIR) and visible bands [9]. Dark Object Subtraction (DOS) was employed as an empirical atmospheric correction method. It assumed that reflectance from dark objects contained a significant atmospheric scattering component. By subtracting the atmospheric offset value, estimated from the image itself, from each pixel in the band, the atmospheric effects were mitigated [8].

Following post processing was performed to identify the optimal band combination for deriving bathymetry using the Band Ratio Method. The log-band ratio method proposed by [9] was implemented, creating new band combinations (B3B2, B4B2, and B4B3) incorporating sun glint and DOS corrections.

The ratio model of [9] is given in the following equation,

$$z = m_1 * \frac{\ln\left(n * R_i\right)}{\ln\left(n * R_j\right)} - m_0 \tag{1}$$

where z is the water depth, R_i and R_j are the reflectance of bands i and j, m_1 is scaling the ratio to depth constant, and m_0 is the offset for z = 0. n-factor is a fixed value between 500 and 10 000, confirming that the logarithm remains positive under any seabed type.

In the study area, regression analysis was conducted between the logarithm of the ratio of different band combinations of sun glint-corrected bands and the in-situ data. The band combination that demonstrated the highest correlation value was selected as the optimal band combination. Using this optimal band combination, the bathymetry was derived by applying Eq. (1). This equation utilizes the ratios of the bands (R_i and R_j) along with tuneable constants (m_1 and m_0) to estimate the absolute water depth (Z) [10].

Following is the identification of the best band combination. Then, the data was further processed to determine the best depth range for using satellite-derived bathymetry (SDB) techniques. Depths were divided into three categories: 0–5 m, 5–10 m, and 10–15 m. To determine the appropriate depth range, regression analysis was performed between the logarithm of the ratio of the optimal band combinations and the in-situ data. Later to assess the accuracy of the generated models, the Root Mean Square Error (RMSE) was used [11].

After deriving the bathymetry using band ratio method, a navigational channel was designed based on the obtained bathymetric data. In designing of the navigational channel, it was exclusively took into account the total navigational

depth required for safe passage and unloading location. Further, it was determined that the barges carrying the wind turbines and accessories must have a minimum depth requirement of 5 m [12].

3 Results of the satellite derived bathymetry

The analysis of different band combinations using scatterplots revealed varying correlation values between the logarithm of the ratio of band combinations and the in-situ data. Among these combinations, it was observed that the highest correlation value was obtained when using Band 2 (Blue) and Band 3 (Green). This finding indicates that the combination of these two bands is particularly effective in estimating water depths adequately (Fig. 2).

   This results showed that the optimal band combination for deriving bathymetry using the band ratio method is the combination of the Blue band (band 2) and the Green band (band 3) of the Sentinel-2 satellite image as this gave the highest correlation of 0.91 (Fig. 2).

3.1 Checking the most suitable depth range

The depths were divided into three distinct ranges (0–5 m, 5–10 m, and 10–15 m) to determine the most appropriate depth range for the band ratio method. The results of the analysis indicated that the band ratio method is particularly well-suited for shallow areas with depths less than 10 m (Fig. 3). Water turbidity, bottom features, and wave refraction
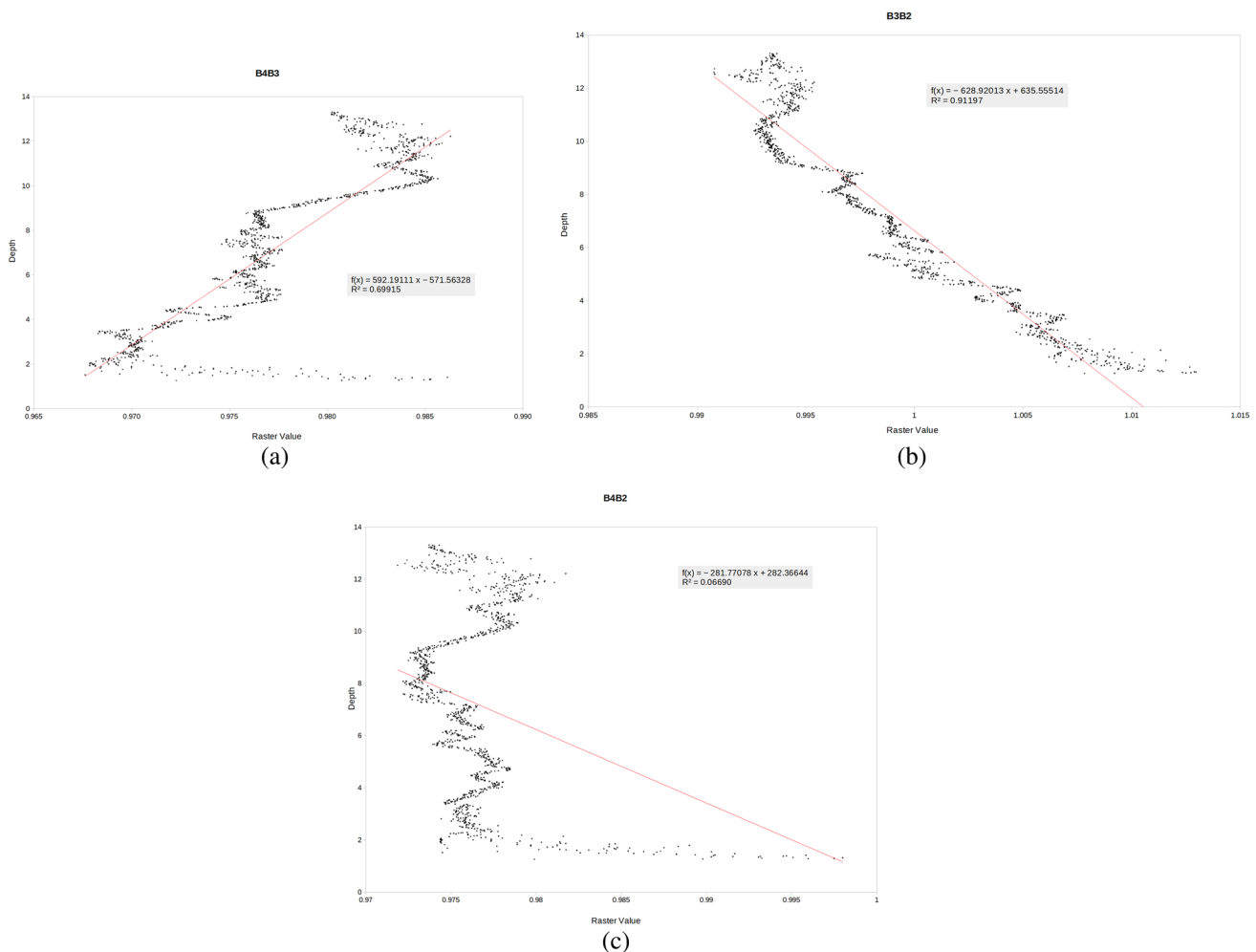

Fig. 2 Regression analysis in the study area between in situ data (depth in m) and the logarithm of the ratio between the sun glint corrected (**a**) B3 and B4 bands (**b**) B2 and B3 bands (**c**) B2 and B4 bands
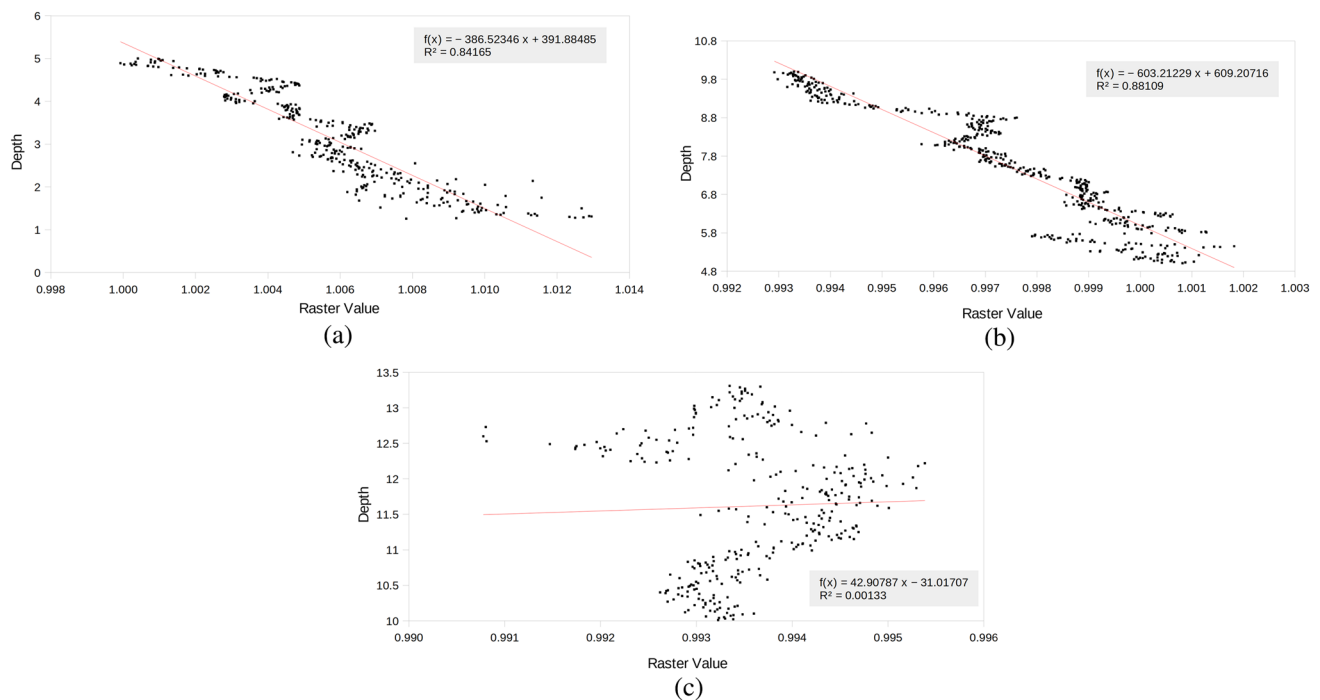
Fig. 3 Scatterplot of satellite-derived depth using the band ratio method versus the in-situ depth ranges (**a**) less than or equal 5 m (**b**) between 5 and 10 m (**c**) greater than 10 m

may all contribute to the lower R^2 value in the 0–5 m depth range compared to 5–10 m depth range. These complexities can influence light penetration and cause differences in remote sensing measurements. Mitigating these issues is critical for accurate and dependable bathymetric estimation in shallow water areas [12].

The significant presence of sun glint in the image may have affected to the low R^2 value obtained for depths greater than 10 m. Correction techniques for sun glint may not adequately compensate for its impact in deeper areas, resulting in a weaker correlation with ground truth data. The presence of vegetation or sediment may also contributed to the low R^2 value by complicating the remote sensing signals. Vegetation absorbs or scatters light, whereas suspended sediment attenuates and scatters light, both of which affect bathymetric estimation accuracy. It is critical to consider and address the influence of sun glint, vegetation, and sediment using appropriate correction techniques and algorithms to improve accuracy [10]. Utilizing Eq. (1) and the constant values, m1 and m0, derived from the regression line equation obtained through regression analysis using band 2 and band 3, the bathymetry map at Silavathurai was derived (Fig. 4).

3.2 Validation of the bathymetry model

The statistical results were analysed with an emphasis on the method's accuracy and alignment with in-situ measurements. The robust validation reinforces the credibility of the derived bathymetric data, inculcate confidence in its use in maritime activities [13]. By comparing the bathymetric values obtained from the derived map with the corresponding depths measured in the field, the suitability of the satellite derived bathymetry method was assessed (Table 2). These findings demonstrate that SDB can effectively provide bathymetric information in shallow water regions with an acceptable level of accuracy and reliability [14].

3.3 Proposed navigational channel

The proposed navigation channel is given in the Fig. 5. This is the most economical route to deliver the items from loading site to landing site and a detailed investigation was proposed with SONAR technology to ensure the safety of the navigability and if any dredging work required to maintain the channel depth. The width of the designed channel is 400 m and length of the channel is close to 5 km, ensuring a safe and efficient passage for vessels. This practical application demonstrates the real-world significance of the study's findings.
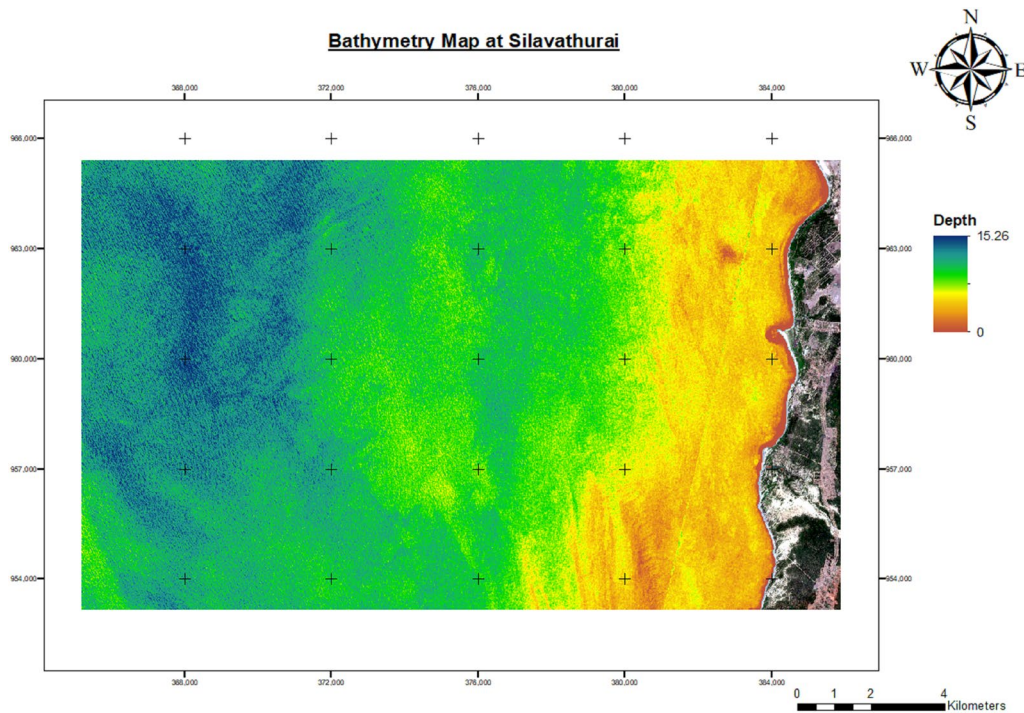
Fig. 4 Bathymetry Map of Silavathurai

Table 2 Statistical results of the band ratio model at different depth ranges at Silavathurai

Depth range	No. of points	R^2	RMSE (m)
≤5	4143	0.75	1.09
5–10	10,314	0.86	0.89
≥10	2936	0.01	1.39
Overall	17,393	0.90	1.06

4 Discussion

As a requirement of an ongoing renewable energy project of Sri Lanka, the use of SDB with Sentinel-2 satellite images has proven to be a useful method for rapid investigating in designing of a suitable navigational channel for the Silavathurai area. The findings of this study illustrated that the empirical bathymetry method that utilises regression analysis and band ratio techniques to estimate water depth in coastal and marine environments is adequate for rapid investigations. Here, blue and green bands in particularly demonstrated a strong correlation ($R^2 = 0.91$) with measured depths, demonstrating its suitability for bathymetric mapping. Overall estimated depth accuracy was 1.06 m (RMSE). In conclusion, this research highlights the potential of remote sensing approaches, specifically SDB, in addressing the challenges associated with rapid bathymetric mapping in shallow water regions [15]. Further advancements in this field will pave the way for more accurate and reliable bathymetric mapping, benefiting a wide range of maritime activities and environmental monitoring efforts. As renewable energy projects continue to expand globally, the application of SDB can contribute to improved decision making processes and sustainable development in coastal and marine environments [16].

Further, it is important to note that the success of the SDB method relies on several pre-processing steps, including land mask, sun glint correction, and dark object subtraction. These steps play a crucial role in enhancing data quality and improving the accuracy of the bathymetric estimates. However, certain limitations associated with atmospheric conditions, water turbidity, and the availability of high-quality in-situ data should be considered when interpreting the results. Therefore, it is recommended to include more sophisticated validation processes and look into the integration of other remote sensing techniques in order to advance research in this field and address the aforementioned limitations [17].
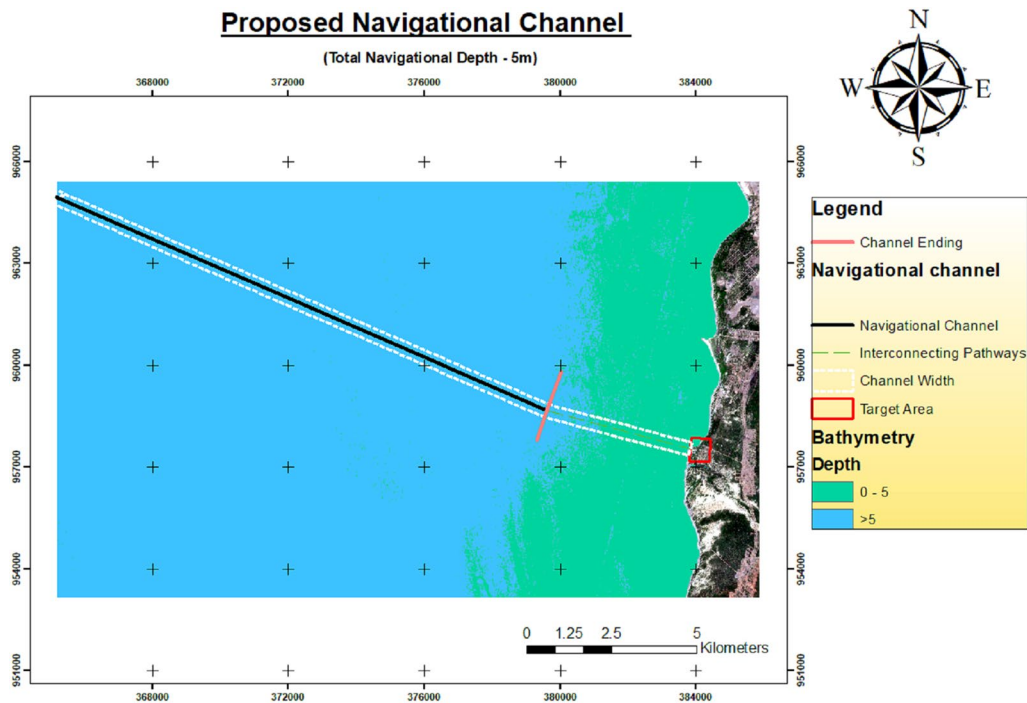
Fig. 5 Proposed navigational channel for the vessel of total navigational depth of 5 m

5 Conclusions

In conclusion, the study successfully exploited the capabilities of Sentinel-2 satellite images for satellite-derived bathymetry, resulting in a robust methodology for estimating water depth in coastal and marine environments. The empirical bathymetry method, which was strengthened by rigorous pre-processing steps, proved effective in producing accurate bathymetric maps. The practical application of the derived bathymetry data, as demonstrated by the navigational channel design, demonstrates the research's tangible impact on maritime activities, particularly in the context of renewable energy projects.

While the study has achieved significant milestones, it is critical to recognize the study's limitations, which include the influence of atmospheric conditions, water turbidity, and reliance on high-quality in-situ data. These considerations pave the way for future research efforts to improve the accuracy and applicability of satellite-derived bathymetry by refining methodologies, integrating advanced algorithms, and conducting extensive validations.

In essence, the research not only advances the field of remote sensing, but also provides valuable insights for coastal zone management, marine resource exploration, and infrastructure development in similar regions. The study establishes a precedent for leveraging advanced technologies to address critical challenges in maritime and coastal environments as renewable energy projects evolve.

Declarations

Competing interests The authors declare no competing interests.

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