

Accuracy Of Shallow Water Bathymetry Mapping Based On Landsat 8 Satellite Imagery Data In Prigi Bay, Trenggalek Regency

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Abstract

Bathymetry plays a crucial role in supporting navigation routes within Indonesian waters. Given the highly dynamic nature of the marine environment, continuous bathymetric mapping is essential. Particularly in Prigi Bay, which holds considerable potential in terms of natural resources, tourism, and serves as the location of the Nusantara Fisheries Port (PPN Prigi). Conventional methods such as echosounders still face limitations in terms of spatial coverage and operational efficiency. A more advanced alternative is Satellite Derived Bathymetry (SDB), which utilizes satellite imagery combined with digital processing algorithms. This study employs Landsat 8 imagery to map seafloor depth and topography using the Stumpf algorithm. The analysis involves comparing band ratio outputs from the Landsat 8 imagery with in-situ depth measurements to evaluate the accuracy of depth estimation. Results indicate that actual water depths in Prigi Bay range from 4.92 m to 67.61 m, while estimations derived from Landsat 8 imagery range from 7.05 m to 57.10 m. The regression model between Landsat 8-derived depths and in-situ measurements produced a coefficient of determination (R^2) of 0.6287, a correlation coefficient (r) of 0.792, a Root Mean Square Error (RMSE) of 12.697, and a Normalized Mean Absolute Error (NMAE) of 28.48, indicating a reasonably reliable level of accuracy for satellite-based bathymetric estimations in coastal waters.

Keywords: Stumpt Algorithm, Bathymetry, Landsat 8, Shallow Waters

INTRODUCTION

Indonesia, as an archipelagic country, possesses an extensive marine territory covering approximately 3,110,000 km² of both deep and shallow waters, accounting for about 77% of the total national area. The country also has a coastline of approximately 108,000 km and consists of around 17,504 islands (Setiawan et al., 2021). With such maritime characteristics, bathymetric information in shallow waters is highly needed, particularly to support port development, shoreline delineation, seabed habitat mapping, aquaculture spatial planning, and integrated coastal zone management. The availability of bathymetric data is also essential for supporting navigation safety and the management of maritime transportation (Febrianto et al., 2015). Bathymetry itself refers to the study of the depth and topography of underwater bodies such as rivers, lakes, and oceans, which plays an important role in ensuring safe navigation (Pambuko et al., 2013).

Traditionally, bathymetric data have been

collected using manual methods such as ropes and weighted lines. However, this technique is considered inefficient because measurements are limited to specific points and are highly constrained by time and vessel movement. Currently, echosounder technology is more commonly used, where water depth is calculated based on the travel time of acoustic or light signals reflected from the seabed back to the sensor of the instrument (Pambuko et al., 2013). The limitations of conventional methods have encouraged the development of alternative approaches to obtain water depth data that are more efficient and accurate (Prayogo & Basith, 2020). One of the emerging innovations is the Satellite Derived Bathymetry (SDB) method, which utilizes satellite imagery and digital processing algorithms to extract bathymetric information (Suwargana & Setiawan, 2017). Remote sensing techniques have proven effective for mapping shallow waters and supporting the identification of safe navigation routes (Bobsaid & Jaelani, 2017).

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This study focuses on Prigi Bay, located in Trenggalek Regency, East Java Province. The bay has significant potential in the tourism and recreational sectors, as well as serving as a center for fisheries activities, including the presence of the Nusantara Fishing Port (PPN Prigi), which is the largest fishing port in the region (Julianinda et al., 2026). Fisheries and tourism activities around the bay, such as those in Prigi Beach, Pasir Putih Beach, Karanggongso Beach, and Damas Beach, indicate the importance of accurate bathymetric mapping, especially considering the discharge of the Cengkong River into Prigi Bay, which may influence sedimentation processes and seabed morphology (Sidabutar, 2019). The dynamic characteristics of the marine environment make it necessary to conduct bathymetric mapping periodically and continuously. Prigi Bay is the main landing site for lemuru fish (*Sardinella lemuru*) catches in Trenggalek and East Java, where production even exceeds catches from the Bali Strait due to the high productivity cycle of the waters, indicated by the abundance of phytoplankton and zooplankton (Sartimbul et al., 2021). Therefore, depth mapping is crucial to support marine activities and optimize the utilization of marine resources by local fishermen.

Previous SDB studies have shown that band-ratio approaches can be applied effectively to a range of sensors, including Landsat 8, Sentinel-2, QuickBird, SPOT-7, and Pleiades, although the results are still sensitive to seabed reflectance, water clarity, and calibration quality (Bobsaid & Jaelani, 2017; Jaelani & Putri, 2019; Nugraha et al., 2022; Nurkhayati, 2013; Suwargana, N., & Setiawan, 2017). Many studies still emphasize spectral correlation without fully validating the estimates against field measurements. Therefore, this study compares Landsat 8-derived bathymetry with tide-corrected in-situ depth data in Prigi Bay and evaluates accuracy using RMSE and NMAE. Landsat 8 was selected because its visible bands and 30 m spatial resolution are adequate for mapping shallow-water depth patterns at regional scale, while the Stumpf algorithm improves the separation of depth zones through the blue and green bands (Masykur, 2021; Stumpf et al., 2003).

MATERIAL AND METHODS

Study Area and Data

The study area for water depth modeling is in Prigi Bay, Trenggalek Regency, East Java

Province, Indonesia. This study utilized sounding data obtained from a field survey conducted on 19–20 September 2018, during the second transitional season, using an echosounder instrument (Figure 1). The dataset represents a continuation of an ongoing research program conducted by the same research group. A total of 27 sounding station points were specifically used as control data in this study, representing a subsequent phase of data utilization for model development and validation. In addition, the full sounding dataset comprised 7,087 observation points, which were corrected for tidal fluctuations to improve the accuracy of the depth measurements. The remote sensing data used in this study were derived from Landsat 8 satellite imagery acquired on 5 October 2018. The combination of image bands applied in the data processing is presented in Table 1, with a spatial resolution of 30 meters.

Research Workflow

This study followed three stages (Wicaksono et al., 2024): pre-processing, SDB modeling, and validation. Pre-processing included study-area selection, Landsat 8 radiometric correction, image cropping, land masking, and preparation of the tide-corrected sounding data. The modeling stage applied the Stumpf band ratio to generate relative depth, which was then calibrated with in-situ depth data to produce absolute depth. The validation stage compared observed and estimated depths using RMSE, bias, and NMAE, and the final output was a bathymetric map.

The Landsat 8 image processing stage utilized a combination of spectral bands, specifically band 2 (blue) and band 3 (green), with a spatial resolution of 30 meters. The sounding dataset consisted of 7,087 points obtained from measurements using a Echosounder GPS Map 178 C. The dataset was then divided into two groups: data for model development and data for accuracy testing, with a ratio of 60% and 40%, respectively. A total of 4,250 points were used for relative depth validation, while 2,838 points were used for absolute depth accuracy assessment. The overall processing results produced a bathymetric map. The final stage involved accuracy evaluation and comparison between in-situ depth measurements and depth estimates derived from Landsat 8 imagery. Depth estimation using the Stumpf algorithm was conducted through a statistical regression approach to determine the strength of

the relationship (R^2) between the actual sounding values and the estimated values obtained from satellite imagery.

Data Processing

The data analysis followed the logarithmic band-ratio approach proposed by (Stumpf et al., 2003). Complete methodology can be seen on Figure 2. The method assumes that the blue and green spectral bands are attenuated differently as water depth increases, so the ratio between the two bands changes in a consistent way with depth. This makes the band-ratio model less sensitive to bottom reflectance than a single-band approach.

$$Z = m_1 \times \frac{\ln(R(\lambda_B))}{\ln(R(\lambda_G))} - m_0$$

The Stumpf model can be written as $Z = m_1 \ln(R_{\text{blue}} / R_{\text{green}}) + m_0$, where Z is relative depth, m_1 and m_0 are calibration coefficients, and

R_{blue} and R_{green} are the reflectance values of Landsat 8 Bands 2 and 3.

Relative depth derived from the Landsat 8 ratio image was then calibrated against tide-corrected in-situ depths using simple linear regression. In this step, the relative output from the image was converted into absolute depth so that the satellite estimate could be directly compared with field measurements..

$$Y = ax + b$$

Where y represents the dependent variable, a is the constant (intercept), x denotes the independent variable, and b is the regression coefficient that indicates the magnitude and direction of the relationship between the independent and dependent variables.

Table 1. Image Band Combination

Satellite Image	Landsat 8
Wavelength Bands	Band 2 – Blue (0.452–0.512 μm) Band 3 – Green (0.533–0.590 μm) Band 5 – Near Infrared (0.851–0.879 μm)
Spatial Resolution	30 meters

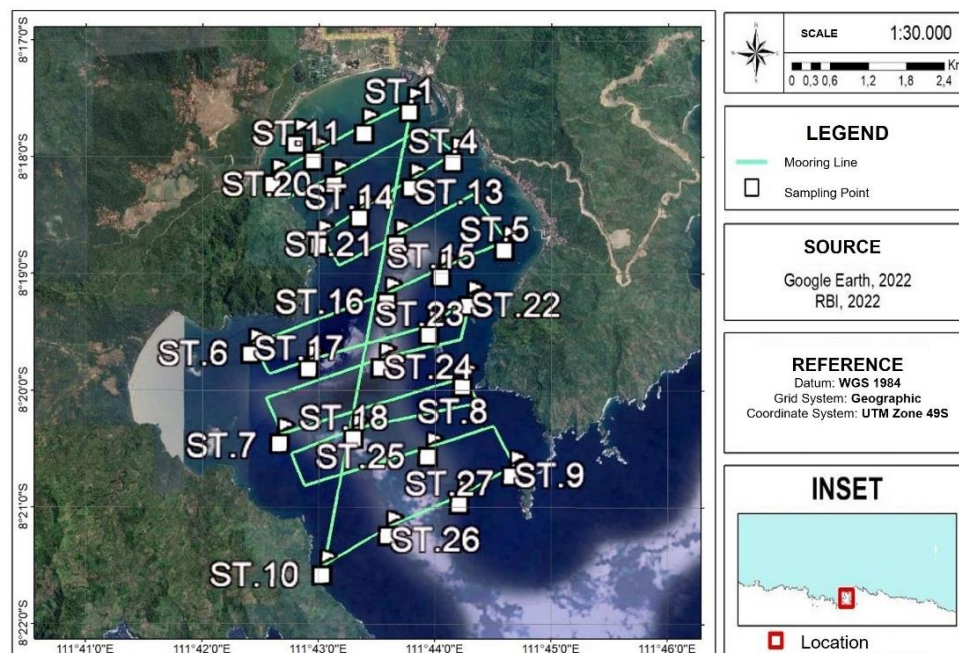


Figure 1. Spatial distribution of bathymetric survey tracks used for depth modeling in Prigi Bay, East Java, Indonesia.

Model performance was assessed using the coefficient of determination (R^2), RMSE, and NMAE. R^2 describes the goodness of fit between observed and estimated depths, RMSE quantifies the average magnitude of the error, and NMAE expresses the error in percentage form for easier comparison with other studies (Fadilah et al., 2018).

$$R^2 = 1 - \frac{\sum_{i=1}^n (h_i - \hat{h}_i)^2}{\sum_{i=1}^n (h_i - \bar{h})^2}$$

Where h_i represents the measured depth, $\hat{h}_i$ denotes the estimated water depth, $\bar{h}$ is the mean depth value, n indicates the number of data points, and R^2 is the coefficient of determination, which measures how well the estimated values explain the variability of the observed data.

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (\Delta h_i - \Delta \hat{h}_i)^2}{n}}$$

Where Δh_i represents the difference in in-situ depth, $\Delta \hat{h}_i$ denotes the difference in predicted depth, n is the number of observations. RMSE was calculated from the differences between observed and predicted depths, with a smaller value indicating a better fit.

Correlation coefficient (r) was calculated only as a supplementary descriptor of linear association and was not used as the main accuracy criterion in this study (Nuryadi et al., 2017; Wicaksono et al., 2026).

$$r = \frac{n\sum xy - (\sum x)(\sum y)}{\sqrt{[n\sum x^2 - (\sum x)^2][n\sum y^2 - (\sum y)^2]}}$$

Where r represents the correlation coefficient between variables, x denotes the independent variable, y represents the dependent variable, and n indicates the number of data points used in the analysis.

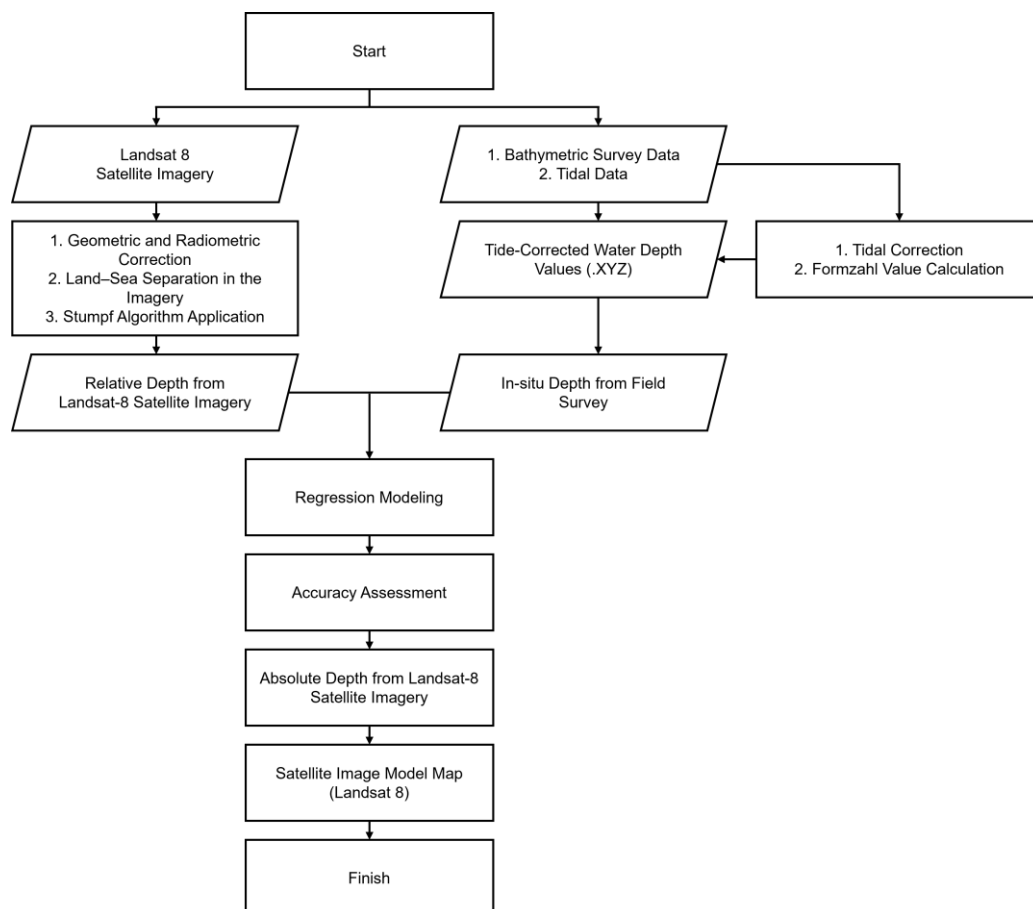


Figure 2. Research Flow Diagram

NMAE is a normalized error indicator commonly used in bathymetric assessment. A lower NMAE value indicates better agreement between estimated and measured depths and allows the result to be compared across different datasets (Jaelani & Putri, 2019). The formulation used in this study followed (Wahyuningrum et al., 2008), and Steven C. Chapra (1988).

$$\varepsilon_a = \left| \frac{A_1 - A_0}{A_1} \right| \times 100\%$$

Where ε_a represents the absolute percentage error, A_1 denotes the depth measured with the echosounder, and A_0 refers to the predicted depth from remote sensing data.

The absolute-depth results were grouped into four classes to examine the spatial pattern of model error across depth ranges (Sesama et al., 2020).

RESULTS AND DISCUSSION

The tide analysis used 29 days of observations from the Geospatial Information Agency (BIG) can be accessed at <https://srgi.big.go.id/tides> (Figure 3). The

harmonic constants in Table 2 produced a Formzahl value of 1.50, indicating a mixed semidiurnal tide in Prigi Bay. The tidal graph was also used to derive the Lowest Water Surface (LWS) datum of -0.33 m (Table 3). Sounding depths were reduced to LWS using tidal correction so that all measurements shared the same vertical reference. In simplified form, the correction can be written as $H_{LWS} = H_{obs} + (\eta_t - \eta_{LWS})$, where H_{obs} is the observed depth, η_t is the tide level during the survey, and η_{LWS} is the vertical datum. This correction was applied before the depths were used in the SDB analysis.

The bathymetry model from the Landsat 8 image acquired on 5 October 2018 was generated using the blue-to-green band ratio. After the ratio between Bands 2 and 3 was calculated, the resulting values were sampled at the tide-corrected in-situ points to compare the image-derived index with the measured depths.

The blue-green ratio was selected to reduce the effect of bottom reflectance variation caused by the water column. The Landsat 8 ratio image produced index values from 0.91 to 1.02, as shown in Figure 5 and Table 4. Lower values occur near the shoreline and represent shallower water, whereas higher values occur farther offshore and indicate deeper water.

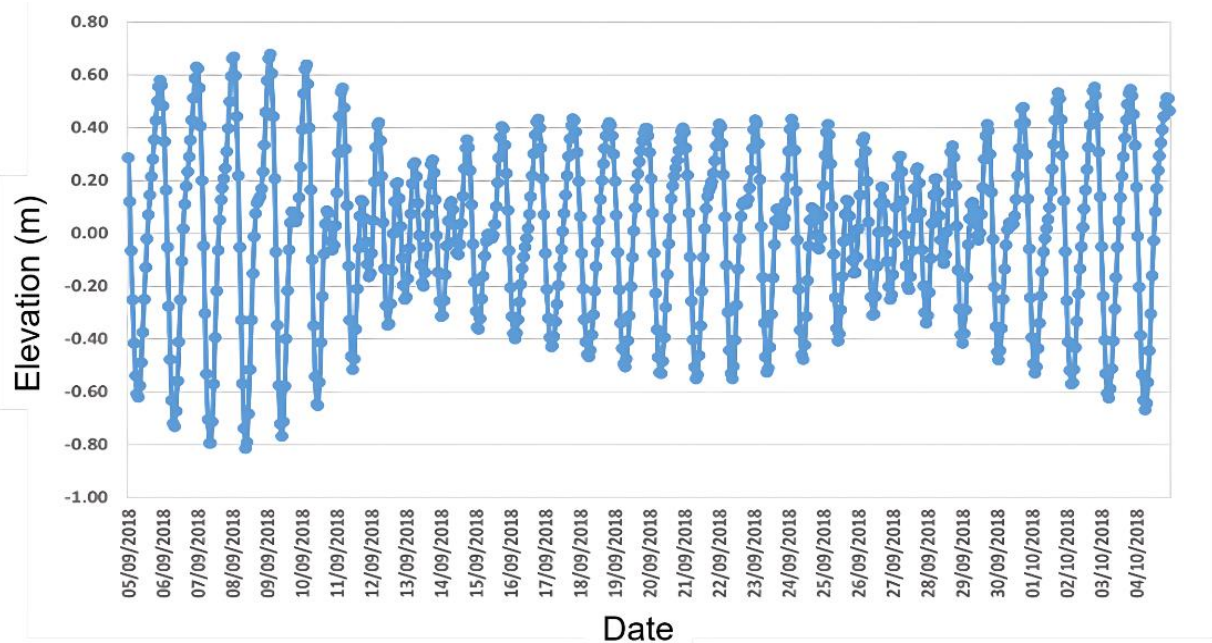


Figure 3. Tidal Graph Period
Source: srgi.big.go.id and (Hutomo, 2019)

Table 2. Harmonic Constant Values

No.	Harmonic Constant	Amplitude (m)
1	K1	0.18
2	O1	0.27
3	S2	0.12
4	M2	0.18
5	N2	0.03

Table 3. Vertical Datum Values

No.	Vertical Datum	Amplitude (m)
1	HHWL	1.62
2	LLWL	0.12
3	Zo	0.87
4	MSL	1.20
5	HWS	0.75
6	LWS	−0.33

Table 4. Index Values and Regression Equation

Satellite Image	Landsat 8
Index Value	High: 0.91 Low: 1.02
Regression R^2	$Y = -874.24x + 820.47$ 0.373

The Landsat 8 ratio image produced a relative-depth model with the regression equation $Y = -874.24x + 820.47$ and $R^2 = 0.374$ (Figure 4). This indicates a moderate relationship between the image-derived ratio and the measured depth, but it also shows that the relative model alone is not sufficient for final depth reporting. For this reason, the regression calibration step was necessary before the results were used as absolute bathymetry (Masykur, 2021; Stumpf et al., 2003).

Absolute Depth Estimation and Satellite Image Accuracy Assessment

The accuracy of SDB is strongly influenced by water clarity and seabed reflectance. Although in-situ turbidity was not measured in this study, previous work in Prigi Bay reported turbidity values of 0.3–4.32 NTU and water clarity of 2–6 m, suggesting that suspended particles may reduce bottom reflectance and affect SDB performance (Isdianto et al., 2020). In addition, seabed substrate was not directly measured, so the result should be

interpreted as a regional bathymetric estimate rather than a definitive hydrographic chart. The accuracy test compared the SDB estimates with sounding data, and the regression output was then used to generate absolute depth, as shown in Figure 6. To obtain the coefficient of determination, a regression equation was applied. The Landsat 8 imagery produced the linear equation $Y = 0.474x - 17.365$ with $R^2 = 0.6287$ (Figure 7), indicating moderate agreement between observed and estimated depths. The negative intercept and slope below 1 suggest a negative bias, meaning that the model tends to underestimate deeper areas. Similar accuracy levels were reported by (Nurkhayati, 2013), who obtained $R^2 = 0.711$ from QuickBird imagery, and by (Nugraha et al., 2022), who reported $R^2 = 0.6205$ from SPOT-7 imagery. The depth-class map was derived from the absolute-depth results and divided into four categories. The RMSE values showed that the shallowest class (0 to −20 m) had an RMSE of 10.38 m, the 20.01 to −40 m class had the lowest

RMSE at 6.37 m, and the deepest class (60.01 to –80 m) had the largest RMSE at 22.23 m (Table 5). Although the shallowest class showed the strongest correlation in the original scatter plot, the relatively large RMSE indicates that it still contains considerable error. Therefore, class-wise correlation should be treated as supplementary information, while RMSE remains the primary indicator of accuracy. These results are consistent with Masykur (2021) and Wicaksono et al., (2025), who found that the blue-green ratio was the most responsive combination for shallow-water depth retrieval, but the error increased as depth increased.

These findings are consistent with the study conducted by (Masykur, 2021), which used Sentinel-2 imagery and the Stumpf Algorithm

evaluated through spectral band ratio combinations between band 2 and 3, band 2 and 4, and band 3 and 4. The results showed that the band 2 and band 3 ratio exhibited the strongest relationship with depth data, indicated by the highest coefficient of determination ($r^2 = 0.78$), followed by the band 3 and band 4 ratio ($r^2 = 0.75$) and band 2 and band 4 ratio ($r^2 = 0.54$). Based on these results, the band 2 and band 3 ratio was selected as the primary parameter for bathymetric modeling. The Root Mean Square Error (RMSE) at the maximum depth of extinction (20 m) was 2.35 m, indicating a relatively low estimation error.

The number of spectral bands used in the model essentially influences the algorithm's ability to distinguish between seabed topography and the

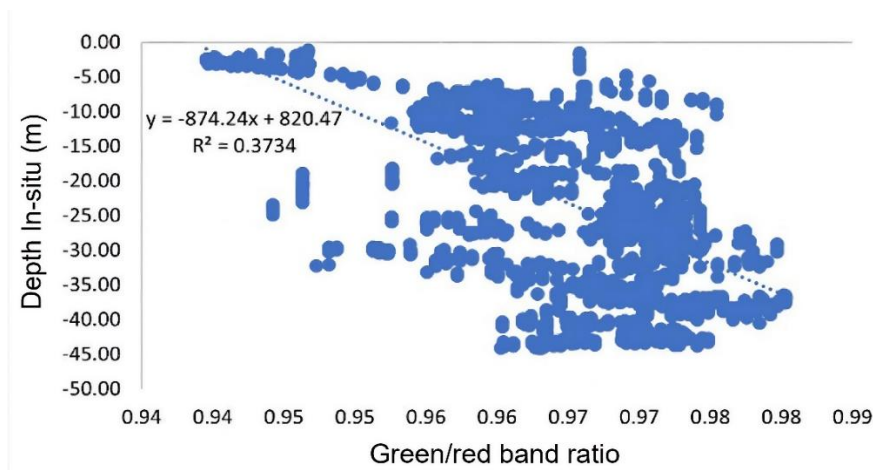


Figure 4. Landsat 8 Stumpf Algorithm Ratio Graph

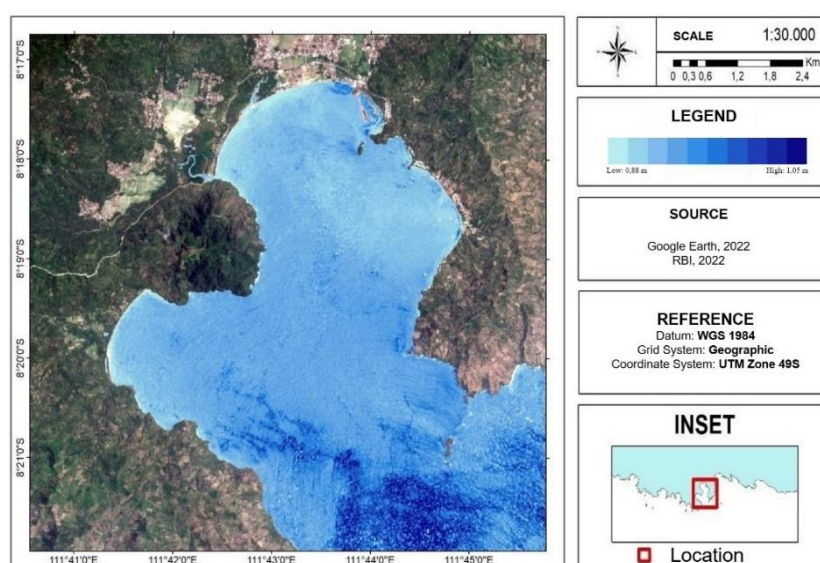


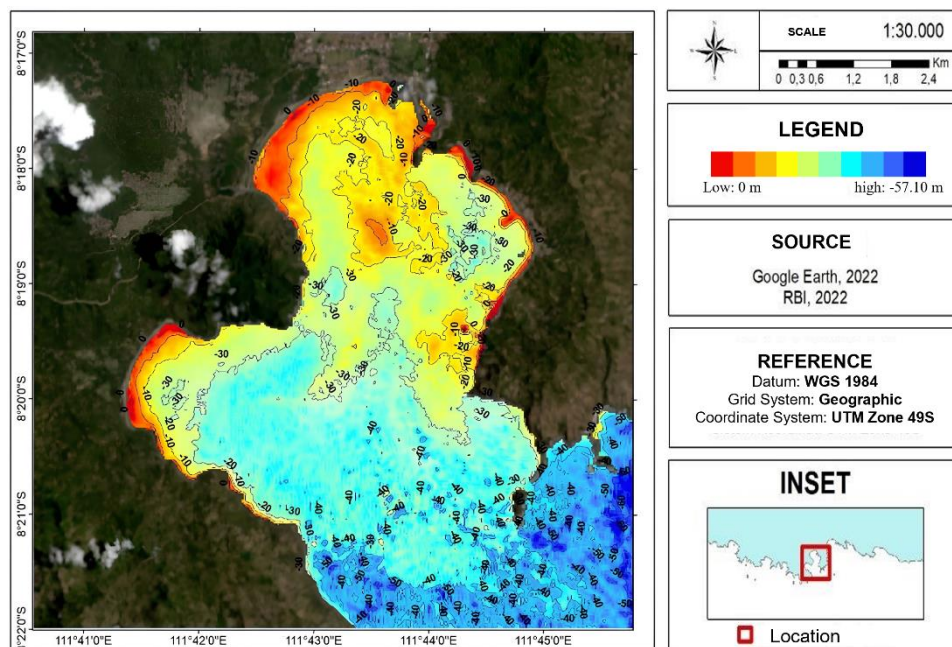
Figure 5. Relative Depth Map Derived from Landsat 8

Table 5. Depth Classification from Landsat 8 Imagery

Depth (m)	RMSE	Correlation
(0) – (–20)	10.37837	0.92
(–20.01) – (–40)	6.373335	–0.57
(–40.01) – (–60)	9.554646	0.15
(–60.01) – (–80)	22.23419	0.21

Table 6. Comparison Between Satellite Image Data and In-Situ Measurements

Image Data	Minimum Depth (m)	Maximum Depth (m)	R ²	Correlation	Error (%)
Landsat 8	7.05	57.10	0.628	0.792	28.48
In-situ Depth	4.92	67.61	–	–	–

**Figure 6.** Absolute Depth Derived from Landsat 8 Satellite Imagery

water column; therefore, the greater the number of bands utilized, the more accurate the resulting model tends to be (Safi'i & Dewi, 2020). This occurs because not all seabed topographic structures can be fully captured by the echosounder instrument. Furthermore, the correlation coefficient has a relationship range between 0 and 1. The closer the value is to 1, the stronger the relationship between the two variables. A negative sign (–) in the correlation value in the classification table indicates a tendency toward seabed shallowing, while a positive sign (+) indicates a direct relationship between variables—meaning

that when one variable increases, the other tends to increase as well (Nuryadi et al., 2017). Differences in RMSE and correlation values among the depth classes derived from satellite imagery may be caused by variations in the number of data points within each depth range during the processing stage, as well as the spatial extent of the study area.

Based on the image data processing results, differences (errors) were identified between the depth values obtained from sounding measurements and those used in the accuracy testing process, with a total of 2,837 sample points. This number does not include the points used in

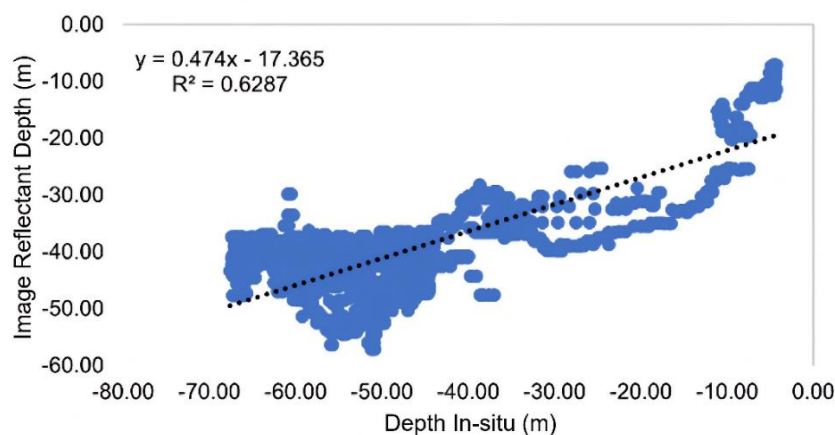


Figure 7. Plot Scatter and Regression Results Regression Results of Depth in Situ Versus Image Reflectant Depth

constructing the regression model. The evaluation was conducted using the Normalized Mean Absolute Error (NMAE), the coefficient of determination (R^2), and the correlation coefficient (r) through a simple linear regression analysis. The results are presented in Table 6.

The results obtained from Landsat 8 image processing indicate a relatively high level of accuracy when compared with in-situ depth data collected through field surveys. The minimum depth derived from the imagery was 7.05 m, while the maximum depth reached 85.27 m. The coefficient of determination (R^2) was 0.628, the data agreement level of 78.77%, reflecting the capability of SPOT-7 imagery to represent bathymetric depth conditions with good accuracy.

CONCLUSION

The bathymetric mapping and accuracy assessment for Prigi Bay, Trenggalek Regency, based on Landsat 8 imagery, indicate moderate accuracy rather than high-precision mapping. The final validation produced $R^2 = 0.6287$, RMSE = 12.697 m, and NMAE = 28.48%, which means that the method is suitable for preliminary shallow-water bathymetric mapping but still requires field surveys for operational use. The negative bias observed in the calibration curve indicates that deeper waters tend to be underestimated. The main source of error is likely the variation in reflectance caused by water clarity, suspended sediment, and seabed substrate conditions. Even so, the method provides a cost-effective way to generate regional bathymetric information to support coastal

correlation coefficient (r) was 0.792, and the Normalized Mean Absolute Error (NMAE) was 28.48%. According to (Jaelani & Tyastiti, 2019), the acceptable minimum standard for accuracy is an NMAE value below 30%, indicating that the results of this study are suitable for extracting water depth information using remote sensing technology. This finding is also supported by (Nugraha et al., 2022), who reported that accuracy evaluation using SPOT-7 imagery in a Lombok case study produced a coefficient of determination of $R^2 = 0.6205$, with a correlation coefficient (R) reaching 0.7877. These values indicate a model—planning, marine resource management, and navigation safety in Prigi Bay. The Landsat 8 results show moderate agreement with the in-situ data. The minimum estimated depth was 7.05 m, and the maximum estimated depth was 57.10 m. The overall validation gave $R^2 = 0.6287$, RMSE = 12.697 m, and NMAE = 28.48%. According to Jaelani & Tyastiti (2019), an NMAE below 30% is generally acceptable for preliminary remote-sensing-based depth extraction, so the present model can be used for regional-scale shallow-water mapping, although it is not yet precise enough for detailed navigational charting. This finding is also consistent with Nugraha et al. (2022), who reported comparable accuracy from SPOT-7 imagery.

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