

Satellite-Derived Relative Bathymetry Mapping of Kopa Dam Using Sentinel-2 Level-2A Imagery and GIS Techniques

Musa Abdulmumin^{id}; Abubakar Sunusi; Dauda Waziri Abdullahi and Abubakar Zalkiflu Idris

Department of Surveying and Geoinformatics, Nigerian Army University Biu, Borno State, Nigeria.

Corresponding author: musaabdulmuminjr@gmail.com

DOI: <https://doi.org/10.62154/ajesre.2026.023.01023>

Abstract

Satellite-derived bathymetry (SDB) provides a remote-sensing approach for characterizing spatial variations in water depth-related information without requiring complete conventional hydrographic coverage. This study developed a relative satellite-derived bathymetry map of Kopa Dam, Tafa Local Government Area, Niger State, Nigeria, using Sentinel-2 Level-2A imagery and ArcGIS 10.8. Sentinel-2 Bands 2 and 3, representing the blue and green portions of the visible spectrum, were used to derive a logarithmic spectral-ratio called Relative Bathymetry Index (RBI). The RBI is an uncalibrated, unitless spectral index representing relative bathymetric variation rather than measured water depth in metres. A water mask was developed and applied to restrict the RBI to the water body, after which descriptive statistics were calculated. The RBI was subsequently classified into four relative bathymetric classes and processed using a Majority Filter to improve spatial coherence. The resulting RBI ranged from 0.386808 to 1.000235, with a mean of 0.777053, standard deviation of 0.058869, and range of 0.613426. The final classification contained 37,845 valid water pixels, equivalent to 378.45 ha at 10-m spatial resolution. Moderate depth class was dominant, covering 249.60 ha (65.95%), followed by deep zone class with 127.29 ha (33.63%), while very shallow and shallow class accounted for 0.02 ha (0.01%) and 1.54 ha (0.41%), respectively. The study demonstrates the usefulness of Sentinel-2 multispectral imagery and GIS-based spectral-ratio processing for preliminary spatial characterization of relative bathymetric variation in an inland water body. Future studies should incorporate field-based bathymetric calibration to enable conversion of the RBI into quantitative water-depth estimates.

Keywords: Bathymetry, GIS, Kopa Dam, RBI, Sentinel-2, Spectral Ratio.

Introduction

Bathymetric information is fundamental to the understanding and management of aquatic environments. Knowledge of the spatial distribution of water depth supports reservoir management, environmental monitoring, habitat assessment, hydraulic studies, navigation, and other water-resource applications. Conventional bathymetric surveying can provide direct measurements of water depth, but extensive field surveys may require considerable equipment, time, personnel, and financial resources. Satellite-derived bathymetry has consequently developed as a complementary approach for obtaining

spatial information about shallow-water environments from remotely sensed observations (Ashphaq et al., 2021).

Optical satellite-derived bathymetry is based on the interaction between electromagnetic radiation and the water column. As light penetrates water, it undergoes absorption and scattering, causing its intensity to decrease with increasing water-column path length. The spectral response recorded by an optical sensor can therefore contain information related to water depth and bottom characteristics. Lyzenga (1978) demonstrated the use of passive multispectral remote sensing for extracting water-depth and bottom-feature information and reviewed ratio-based approaches for shallow-water environments.

Spectral-ratio methods subsequently provided an important development in optical bathymetry. Stumpf et al. (2003) developed an empirical ratio transform based on logarithmically transformed reflectance from two spectral bands. Their approach was designed to reduce the influence of variable bottom albedo while maintaining sensitivity to depth-related changes in the water-column signal. The ratio algorithm was evaluated against lidar bathymetry and demonstrated its potential for estimating bathymetry in clear water, although calibration coefficients are required when the spectral ratio is converted to quantitative depth.

The Sentinel-2 MultiSpectral Instrument (MSI) provides multispectral observations suitable for environmental and Earth-observation applications. The mission comprises 13 spectral bands at spatial resolutions of 10, 20, and 60 m, with four bands available at 10-m spatial resolution (Drusch et al., 2012; European Space Agency, 2015). Sentinel-2's blue and green bands provide visible-spectrum observations that can be used in spectral-ratio analyses of water bodies.

The development of satellite-derived bathymetry has included empirical, analytical, spectral-ratio, and machine-learning approaches. A review by Ashphaq et al. (2021) documented the development of SDB techniques and highlighted the importance of sensor characteristics, environmental conditions, reference data, algorithms, and required accuracy in determining the suitability of different SDB approaches.

Recent studies have also demonstrated the importance of independent bathymetric observations for quantitative SDB. Ma et al. (2020), for example, combined ICESat-2 lidar observations and Sentinel-2 multispectral imagery to develop and validate satellite-derived bathymetry, illustrating how independent bathymetric observations can be used to establish a relationship between remotely sensed spectral information and water depth.

A distinction must therefore be made between relative bathymetry and absolute bathymetry. A spectral ratio can provide a continuous depth-related index, but conversion of that index into actual water depth requires calibration against known depth observations. Since suitable independent bathymetric observations were not available for Kopa Dam, the present study focuses on deriving and spatially classifying a Relative Bathymetry Index rather than producing calibrated water depths in metres. The aim of this study is to develop and spatially characterize a relative satellite-derived bathymetry map of

Kopa Dam using Sentinel-2 Level-2A multispectral imagery and GIS techniques. The specific objectives of this study are; (i) To acquire and preprocess Sentinel-2 Level-2A imagery of Kopa Dam, including the preparation and conversion of the relevant spectral bands to surface reflectance for subsequent bathymetric analysis. (ii) To derive and spatially characterize the Relative Bathymetry Index (RBI) of Kopa Dam using a logarithmic spectral-ratio approach applied to Sentinel-2 blue and green surface-reflectance bands within the delineated water body. (iii) To characterize the spatial distribution of the relative bathymetric classes within Kopa Dam. (iv) To evaluate the areal extent and statistical distribution of the relative bathymetric classes across Kopa Dam.

Sentinel-2 has become an important platform for empirical satellite-derived bathymetry (SDB) because it provides freely accessible multispectral imagery with suitable spatial and temporal resolution for shallow-water mapping. Vrdoljak and Kilić Pamuković (2022) evaluated several atmospheric-correction processors for Sentinel-2 SDB in the Middle Adriatic and demonstrated that the choice of atmospheric-correction method influences bathymetric results. Their findings highlight the importance of appropriate atmospheric correction when applying empirical SDB methods. Gafoor et al. (2022) compared the conventional green-to-blue band ratio with a newly proposed four-band ratio and gradient-boosting models using Sentinel-2 imagery. The four-band ratio and gradient-boosting approach produced better bathymetric estimates than the conventional ratio and linear regression, respectively, although the conventional ratio provided a useful baseline for comparison. Prasetya et al. (2023) evaluated Lyzenga, Stumpf, and support-vector-machine approaches using Sentinel-2 imagery and field-observed depths. The support-vector-machine model produced the highest performance, followed by the Stumpf and Lyzenga methods, demonstrating the continued applicability of ratio-based approaches for empirical bathymetric estimation when suitable calibration data are available. Bernardis et al. (2023) demonstrated the potential to derive bathymetric information using open satellite data by combining Sentinel-2 imagery with ICESat-2 bathymetric observations, providing an alternative source of depth information where conventional field surveys are limited. Figliomeni and Parente (2024) further compared band-ratio, third-degree polynomial, and principal-component approaches using Sentinel-2 imagery. Their results showed that the third-degree polynomial approach produced a more precise bathymetric model than the conventional band-ratio method, while also demonstrating the continued use of band-ratio approaches in Sentinel-2 SDB research.

Collectively, these studies demonstrate that empirical ratio-based SDB remains an established approach for extracting shallow-water depth information from multispectral imagery. They also show that its performance can vary with atmospheric correction, spectral-band selection, calibration data, and environmental conditions affecting the water column and bottom reflectance. These considerations are particularly relevant when transferring methods developed largely in coastal environments to inland reservoirs. This present study therefore applies a Blue-to-Green spectral-ratio approach to Sentinel-2

imagery over Kopa Dam. Because no suitable field-measured bathymetric depths were available for calibration to absolute water depth, the resulting product is interpreted as a relative bathymetric index rather than an absolute depth model. This distinction limits direct comparison with calibrated SDB studies but allows the spatial pattern of relative bathymetric variation within the reservoir to be examined.

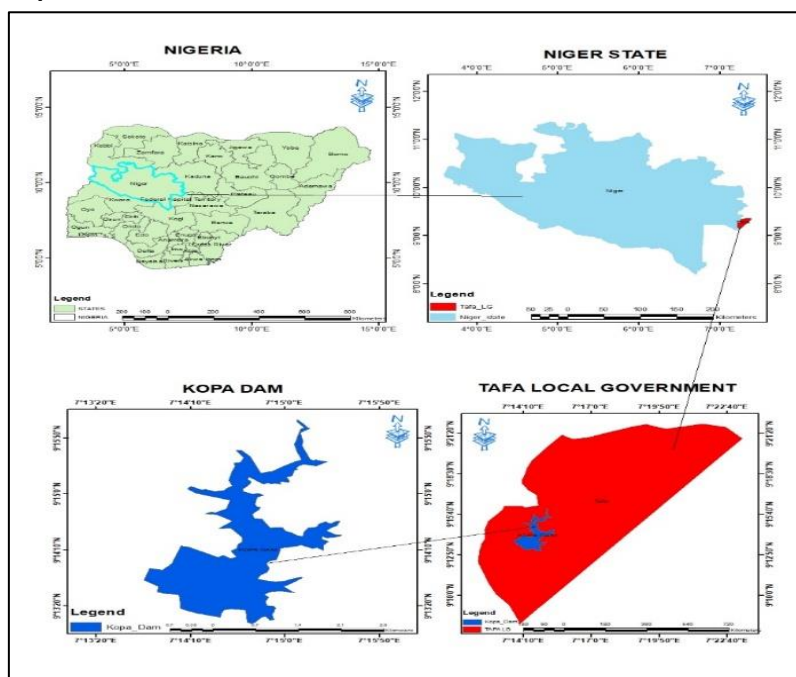
Materials and Methods

Study Area

The study was conducted at Kopa Dam, situated in Tafa Local Government Area of Niger State, Nigeria, centred at approximately $9^{\circ}14'10''\text{N}$, $7^{\circ}14'45''\text{E}$. The dam was initiated by the Niger State Government in 1990 to provide a reservoir for the people of Suleja, Abuja, and its environs, with an original design capacity of approximately 34.7 million m^3 and a catchment area of about 143 km^2 . Kopa Dam serves as a major source of raw water for Suleja Local Government Area and its surrounding communities, with treated water supply managed by the Niger State Water Board, which serves Tafa and Suleja.

Beyond domestic water supply, the reservoir supports irrigation, flood control, and fisheries for the surrounding communities, and its shoreline is increasingly used for recreational activities such as fishing and picnicking.

Figure1: Study Area



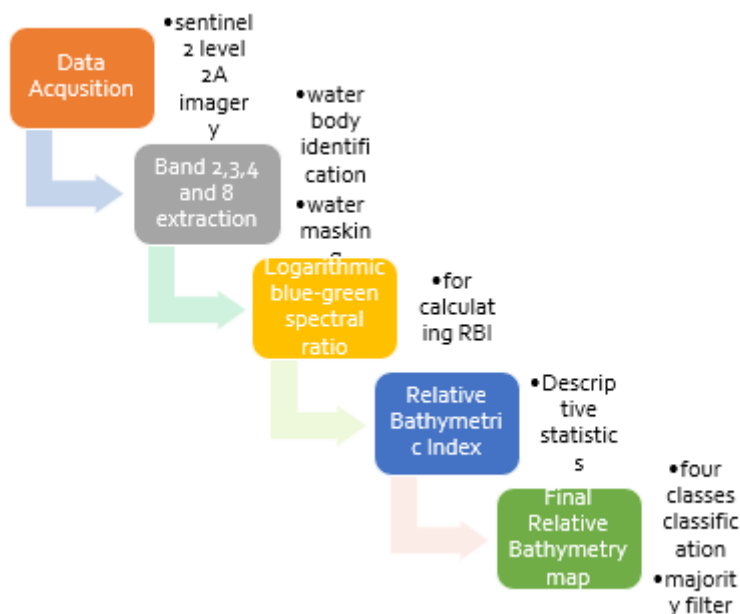
Source: Author, 2026.

Data and Analytical Workflow

The study adopted a quantitative remote-sensing and GIS-based approach for deriving and analysing relative bathymetric information from Sentinel-2 Level-2A imagery.

The methodological workflow comprised.

Figure 2: Methodological-workflow



Source: Author, 2026.

Data Used

The principal dataset was a Sentinel-2 Level-2A multispectral image. Sentinel-2 provides multispectral observations from the visible to shortwave-infrared portions of the electromagnetic spectrum and includes four 10-m bands, six 20-m bands, and three 60-m bands (Drusch et al., 2012).

The analysis specifically used

Table 1. Sentinel-2 bands used for relative bathymetry derivation

Band	Spectral region	Approximate central wavelength	Spatial resolution	Purpose
B2	Blue	490 nm	10 m	RBI calculation
B3	Green	560 nm	10 m	NDWI and RBI calculation
B4	Red	665 nm	10 m	NDVI calculation

Band	Spectral region	Approximate central wavelength	Spatial resolution	Purpose
B8	Near-infrared	842 nm	10 m	NDWI and NDVI calculation

Source: Author, 2026.

The four bands were selected because they provide the spectral information required for both water-body delineation and the subsequent blue-green spectral-ratio analysis.

Image Preprocessing and Band Extraction

The Sentinel-2 Level-2A imagery was imported into ArcGIS 10.8 and Bands 2, 3, 4, and 8 were extracted from the Level-2A product.

The four bands have a common 10-m spatial resolution, allowing their direct use in raster calculations without resampling between the selected bands. The bands were visually inspected to ensure that they were spatially aligned and that the study area was clearly represented.

The Sentinel-2 Level-2A product provides atmospherically corrected bottom-of-atmosphere (BOA) reflectance data stored as scaled digital values. The extracted Bands 2, 3, 4, and 8 were therefore converted to surface reflectance values by dividing the pixel values by the scaling factor of 10,000 prior to subsequent spectral-index and bathymetric analyses. The conversion was expressed as:

$$\rho = \text{DN} / 10000$$

Where:

- ρ = surface reflectance value
- DN = original Sentinel-2 Level-2A pixel value
- 10,000 = Sentinel-2 reflectance scaling factor

The resulting reflectance bands were subsequently used for NDWI, NDVI, water-mask development, and Relative Bathymetry Index calculations.

Normalized Difference Water Index

The Normalized Difference Water Index was calculated to enhance the water body and distinguish it from surrounding terrestrial surfaces.

Following McFeeters (1996), NDWI was calculated from green and near-infrared reflectance:

$$\text{NDWI} = \frac{\rho_{B3} - \rho_{B8}}{\rho_{B3} + \rho_{B8}}$$

Where:

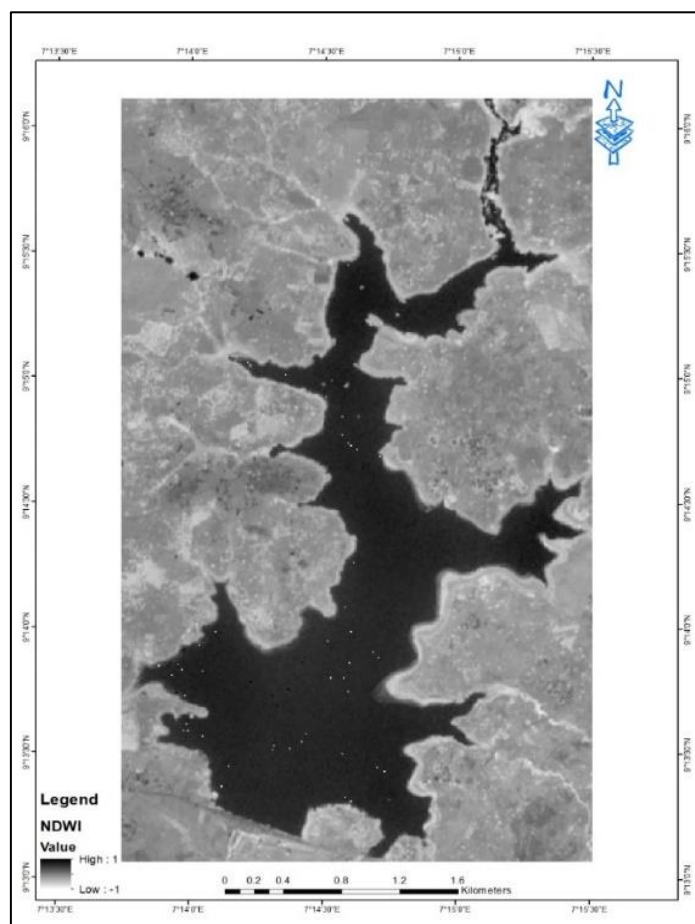
- ρ_{B3} = Sentinel-2 green-band surface reflectance;
- ρ_{B8} = Sentinel-2 near-infrared surface reflectance.

McFeeters (1996) developed NDWI specifically to enhance open-water features using visible green and near-infrared information.

The NDWI raster was generated using Raster Calculator in ArcGIS 10.8.

The resulting NDWI image provided an initial basis for distinguishing water pixels from non-water surfaces.

Figure 3: NDWI. (WGS 1984 UTM ZONE 32).



Source: Author, 2026.

Normalized Difference Vegetation Index

NDVI was calculated to identify vegetation within and around the water-body boundary.

The index was calculated using the red and near-infrared bands:

$$NDVI = \frac{\rho_{B8} - \rho_{B4}}{\rho_{B8} + \rho_{B4}}$$

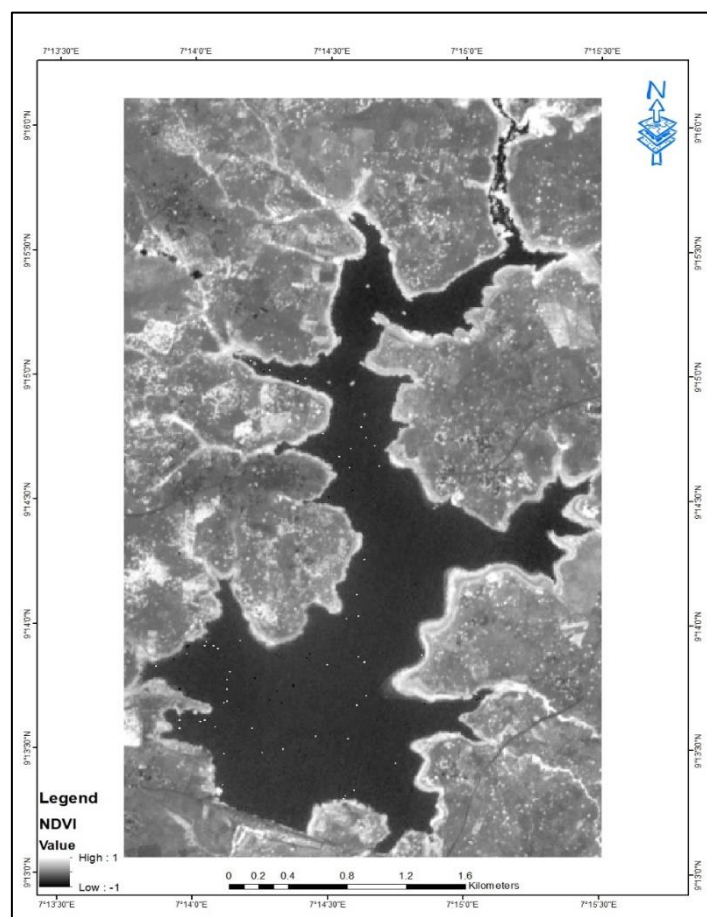
Where:

- ρ_{B8} = Sentinel-2 near-infrared surface reflectance;
- ρ_{B4} = Sentinel-2 red surface reflectance.

The NDVI calculation follows the established principle of using the contrast between red and near-infrared reflectance to characterize vegetation response. The foundational ERTS

work by Rouse et al. (1974) demonstrated the use of red and near-infrared spectral information for vegetation-condition assessment.

Figure 4: NDVI. (WGS 1984 UTM ZONE 32).



Source: Author, 2026.

Water Mask

The NDWI and NDVI outputs were used together to develop a more reliable water mask. The NDWI provided the primary water-sensitive information, while the NDVI helped identify and exclude vegetation and terrestrial pixels that could otherwise remain attached to the water-body boundary.

The initial water classification derived from the NDWI was examined against the NDVI result and the original multispectral imagery. Areas representing vegetation or land were removed from the water class.

The resulting water mask contained:

- **1 = water**
- **0 = non-water/land**

The final water mask was visually inspected to ensure that the water body was spatially continuous and that terrestrial areas were excluded.

This step was particularly important because the subsequent bathymetric analysis was intended to operate only on water pixels. The use of NDWI for water delineation is consistent with McFeeters' (1996) original application of the index to open-water extraction.

The water mask was subsequently applied to the RBI raster using the water class as the retained area. In ArcGIS Raster Calculator, the masking logic can be expressed as:

SetNull("WaterMask" == 0, "RBI")

Means:

- Wherever WaterMask = 0 → assign NoData
- Wherever WaterMask ≠ 0 (i.e., 1) → retain the RBI value

Therefore, the resulting raster contains RBI values only inside the water body, while land becomes NoData.

Water masking was necessary because the optical bathymetric relationship is based on the interaction of light with the water column and submerged bottom, whereas terrestrial surfaces have different spectral responses (Lyzenga, 1978).

Relative Bathymetry Index

In this study, the RBI is treated as a relative depth-related spectral index rather than as absolute water depth. Because no independent in-situ depth observations were available for calibration, the derived index was not converted to metres. The exact class boundaries used in the four-class reclassification should be reported from the ArcGIS reclassification table to ensure reproducibility.

The continuous Relative Bathymetry Index was derived from the logarithmic ratio of Sentinel-2 blue and green reflectance. The spectral-ratio approach follows the formulation proposed by Stumpf et al. (2003):

$$R = \frac{\ln(nR_w(\lambda_i))}{\ln(nR_w(\lambda_j))}$$

and the calibrated depth relationship:

$$Z = m_1 R - m_0$$

Where:

- R = logarithmic spectral ratio
- n = constant used in the logarithmic transformation
- $R_w(\lambda_i)$ and $R_w(\lambda_j)$ = water-leaving reflectances at two wavelengths

- Z = estimated water depth
- m₁ = calibration coefficient
- m₀ = calibration offset

For the Sentinel-2 implementation in this study, Bands 2 and 3 were used to calculate the Blue-to-Green ratio model and finally the Relative bathymetric index:

Blue to Green ratio was calculated using the formula below

$$R = \rho_{B2} / \rho_{B3}$$

Where:

- ρ_{B2} = Sentinel-2 Band 2 (Blue) surface reflectance
- ρ_{B3} = Sentinel-2 Band 3 (Green) surface reflectance

In ArcGIS Raster Calculator, the exact expression entered was: "B2" / "B3" (Green-band reflectance divided by Blue-band reflectance), consistent with the formula above.

While the Relative Bathymetric Index was calculated using the formula below:

$$RBI = \ln \left(\frac{\rho_{B2}}{\rho_{B3}} \right)$$

Where:

ρ_{B2} = Sentinel-2 blue-band reflectance;

ρ_{B3} = Sentinel-2 green-band reflectance.

The RBI was calculated using Raster Calculator in ArcGIS 10.8. The resulting raster represented continuous spatial variation in the depth-related spectral response of the water body.

The use of the logarithmic ratio is consistent with the ratio transform developed by Stumpf et al. (2003), which showed that the approach can provide bathymetric information while accounting for variation in bottom type and albedo.

The spectral ratio derived above represents a depth-related index. To obtain absolute water depth, the Stumpf approach requires calibration parameters derived from known depth observations.

The calibrated relationship can be represented as:

$$Z = m_1 R - m_0$$

Where:

(Z) represents estimated water depth and (m₁) and (m₀) are calibration parameters.

The original study by Stumpf et al. (2003) used known depth information to tune the ratio algorithm and evaluate the resulting bathymetric estimates.

However, no suitable independent depth measurements were available over Kopa Dam for calibration and validation in the present study. Therefore, calibration parameters were not estimated, and the continuous spectral ratio was retained as a Relative Bathymetry Index.

Accordingly:

The RBI values are not water depths in meters. Likewise, the four resulting classes are relative bathymetric classes. This distinction is necessary for scientifically accurate interpretation of the results.

Descriptive Statistical Analysis and classification of the RBI

Descriptive Statistical Analysis

The water-restricted RBI raster was subjected to descriptive statistical analysis.

The minimum, maximum, mean, standard deviation, and range were determined.

The mean was calculated as:

$$\bar{x} = \sum_{i=1}^N x_i / N$$

Where $\bar{x}$ is the mean RBI, x_i represents each valid RBI observation, and N is the number of valid observations.

The standard deviation was calculated as:

$$SD = \sqrt{\frac{\sum_{i=1}^N (x_i - \bar{x})^2}{N}}$$

The range was calculated as:

Range=Maximum-Minimum

The mean describes the central tendency of the RBI distribution, while the standard deviation indicates the dispersion of the values around the mean. The range represents the overall difference between the minimum and maximum observed RBI values.

Four-Class Reclassification

The continuous RBI raster was reclassified into four classes to facilitate spatial interpretation and statistical summarization.

The resulting classes were:

Very shallow (class 1)

Shallow (class 2)

Moderate (class 3)

Deep Zone (class 4)

Table 2: Comparison of Original and Revised RBI Class Intervals for Satellite-Derived Bathymetry

RBI range	New class
0.386808–0.704451	1
0.704451–0.767435	2
0.767435–0.824694	3

RBI range	New class
0.824694–1.000235	4

Source: Author, 2026.

The class numbers represent classification codes generated during the GIS analysis and do not represent water depths in metres.

The purpose of the classification was to convert the continuous RBI surface into a simplified categorical representation of relative bathymetric variation.

Majority Filtering

The initial four-class raster contained isolated pixels and small spatial irregularities. A Majority Filter was therefore applied in ArcGIS 10.8. The Majority Filter is a spatial post-classification operation that replaces isolated cells according to the dominant neighbouring class.

In this study, the operation was used to reduce isolated classification artefacts and improve the spatial coherence of the final map.

The filtered raster was visually inspected and retained as the final four-class relative bathymetry map.

The Majority Filter was considered a cartographic and spatial-smoothing operation and was not treated as an accuracy-validation procedure.

Calculation of Class Area

The selected Sentinel-2 Bands 2 and 3 have a spatial resolution of 10 m. The area of each relative bathymetry class was therefore calculated using:

$$A_p = 10 \times 10 = 100 \text{ m}^2$$

and:

$$1 \text{ ha} = 10,000 \text{ m}^2$$

Therefore:

$$A_p = 0.01 \text{ ha}$$

The area of each class was calculated as:

$$A_c = N_c \times 0.01$$

where N_c is the number of pixels in class c .

Calculation of Class Percentage

The percentage contribution of each class was calculated using:

$$P_c = \frac{N_c}{N_T} \times 100$$

Where:

- P_c = percentage area of class c
- N_c = number of pixels in class c
- N_T = total number of valid water pixels

Results

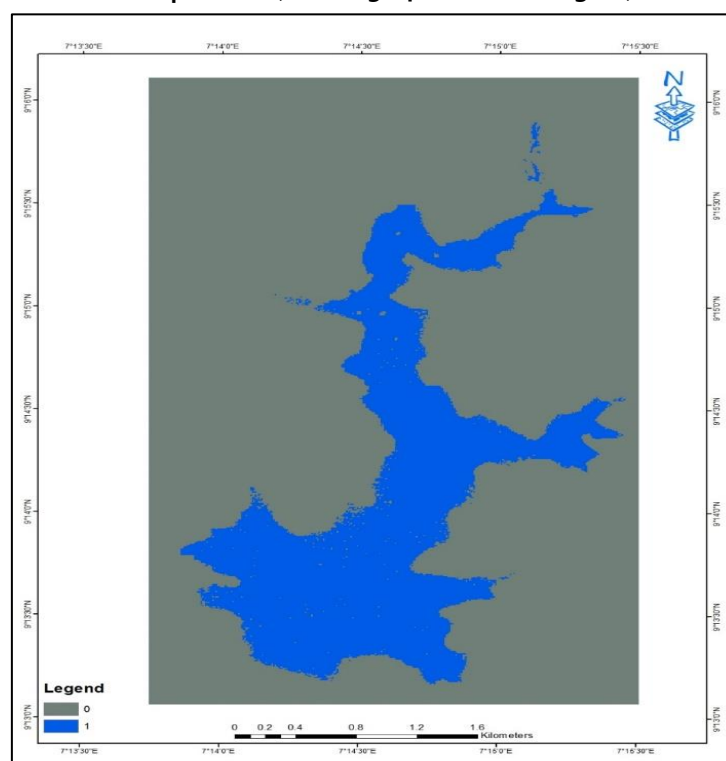
Water-Body Delineation

The NDWI successfully enhanced the water body relative to surrounding land surfaces. However, because vegetation and other terrestrial features occurred around portions of the reservoir boundary, NDVI was additionally used to identify vegetation-related pixels.

The combined interpretation of NDWI, NDVI, and the original Sentinel-2 imagery enabled the development of a refined water mask.

The final water mask contained water pixels coded as 1 and non-water pixels coded as 0.

Figure 5: Water mask of Kopa Dam (WGS 1984 / UTM Zone 32N).



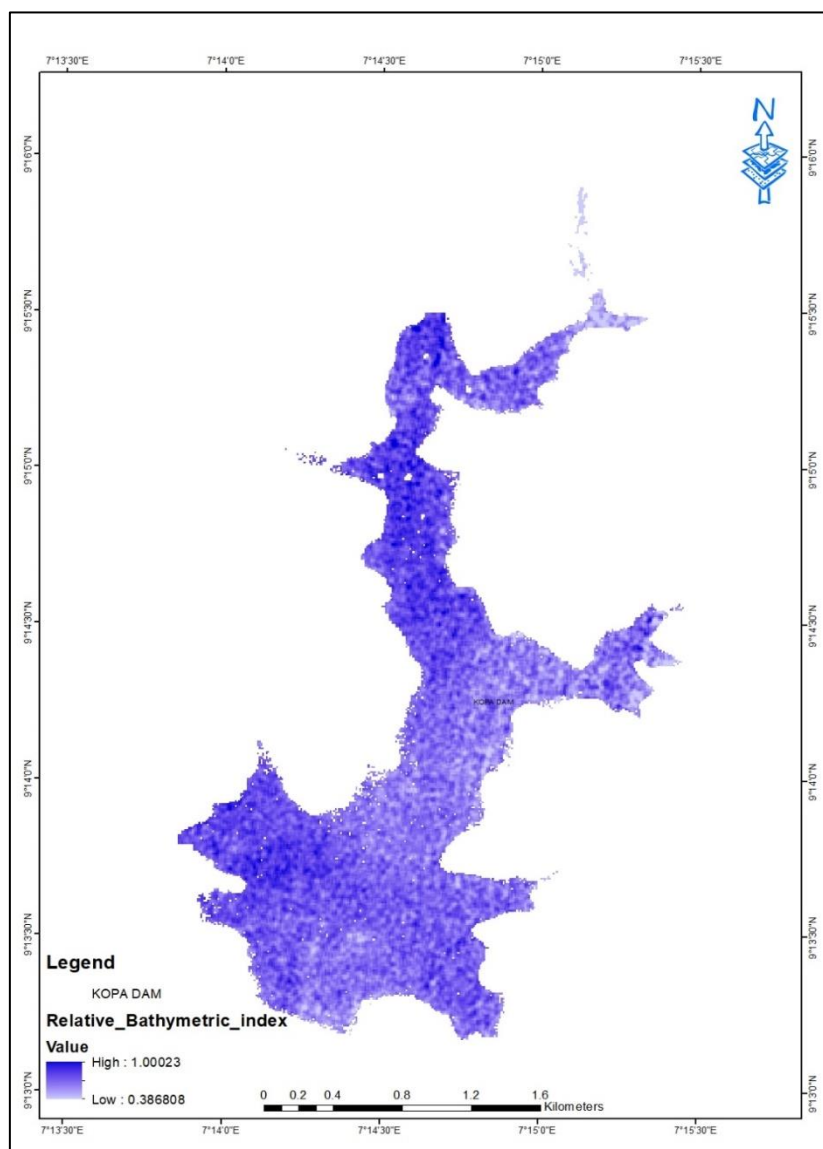
Source: Author, 2026.

The final mask was subsequently used to restrict the blue and green bands to the water body before calculation of the RBI.

Relative Bathymetry Index

The water-restricted RBI showed continuous spatial variation across Kopa Dam.

Figure 6: Relative Bathymetry Index map of Kopa Dam (WGS 1984 UTM Zone 32N).



Source: Author, 2026.

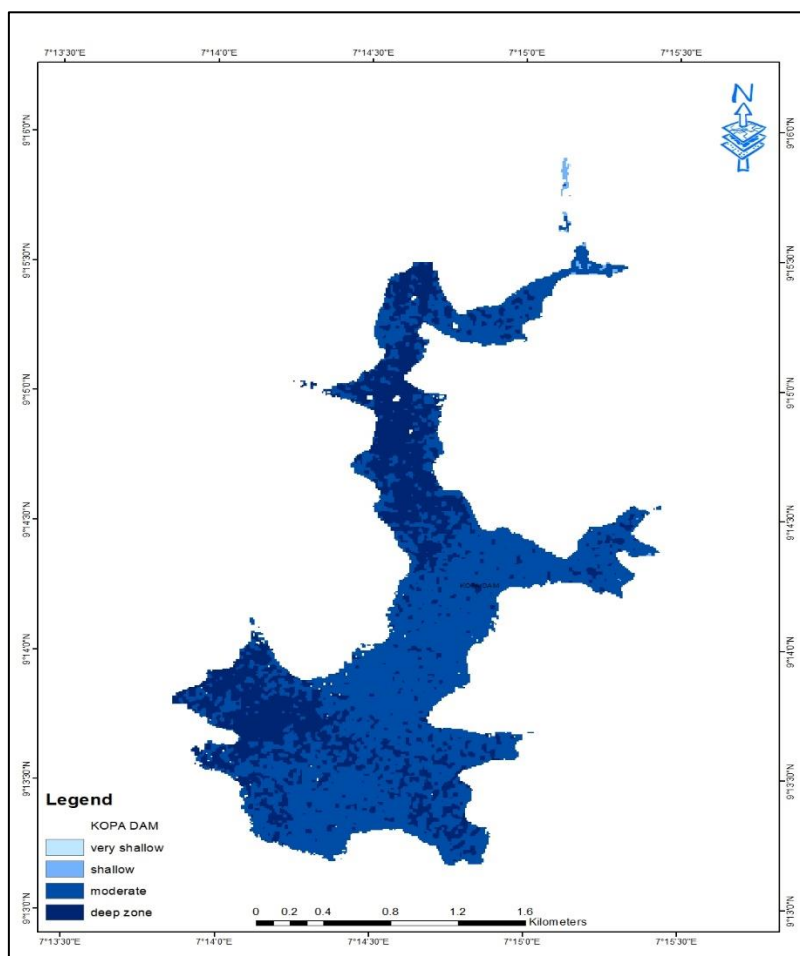
The continuous RBI map provides the most detailed representation of the spatial variability obtained from the spectral-ratio analysis. Unlike the classified map, it preserves the full range of continuous index values.

Relative Bathymetry Map

The continuous RBI was classified into four relative bathymetric classes and subsequently processed using a Majority Filter.

The final classification contained 37,845 valid water pixels.

Figure 7: Final four-class relative bathymetry map of Kopa Dam (WGS 1984 UTM Zone 32N).



Source: Author, 2026.

The final map illustrates the spatial organization of the four relative bathymetric classes. The classes represent relative differences in the derived RBI and should not be interpreted as absolute depth intervals.

Area Distribution of Relative Bathymetry Classes

The total area represented by the valid water pixels was: 37,845=378.45ha, Moderate class had the largest spatial extent, covering 249.60 ha, equivalent to 65.95% of the mapped water area, The Deep Zone class covered 127.29 ha, corresponding to 33.63%.

Shallow class occupied 1.54 ha, equivalent to 0.41%, whereas Very shallow class occupied only 0.02 ha, equivalent to 0.01%.

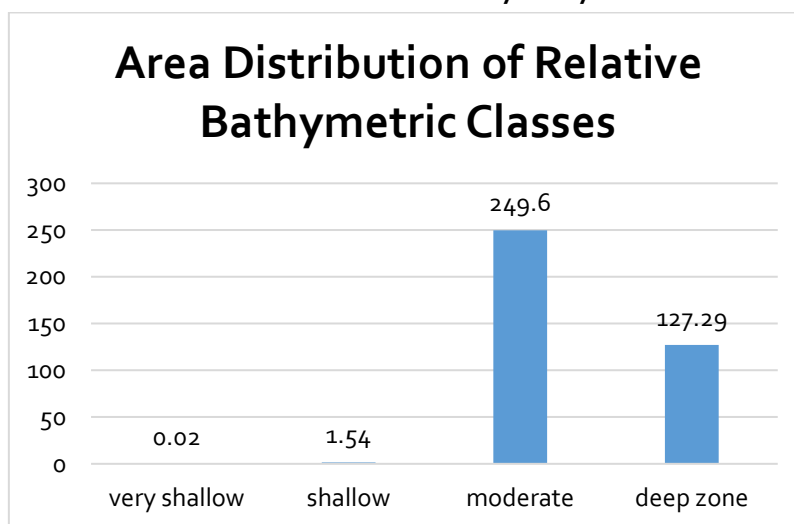
The calculated area and percentage statistics are presented in Table 3.

Table 3. Area and percentage distribution of relative bathymetry classes

Relative bathymetry class	Pixel count	Area (ha)	Percentage (%)
Very shallow	2	0.02	0.01
Shallow	154	1.54	0.41
Moderate	24,960	249.60	65.95
Deep Zone	12,729	127.29	33.63
Total	37,845	378.45	100.00

Source: Author, 2026.

Figure 8: Area distribution of the four relative bathymetry classes.



Source: Author, 2026.

A bar chart provides a direct comparison of the spatial area represented by each class.

Percentage Distribution

The percentage distribution demonstrates that Classes 3 and 4 were overwhelmingly dominant.

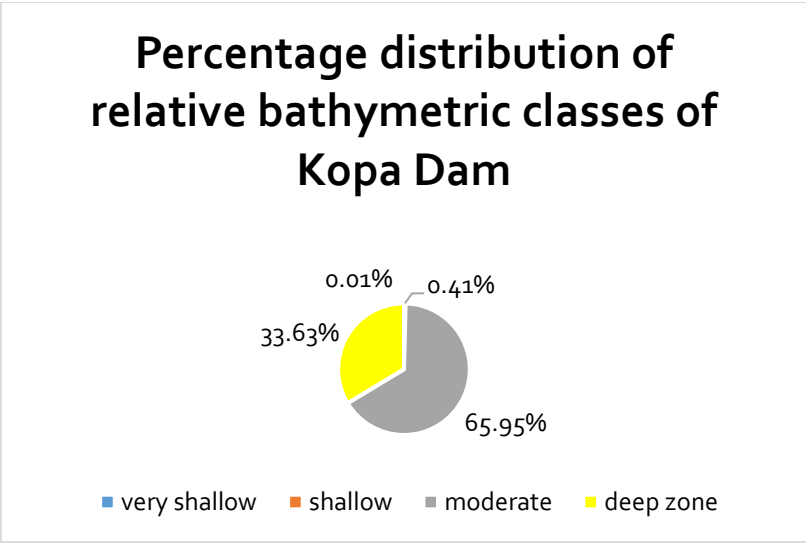
Moderate class represented 65.95% of the mapped water area, while Deep Zone class represented 33.63%.

Together: $[65.95 + 33.63 = 99.58\%]$

Thus, Moderate Class and Deep Zone class collectively represented approximately 99.58% of the mapped water area.

Very shallow class and Shallow class represented only 0.01% and 0.41%, respectively.

Figure 9: Percentage distribution of the four relative bathymetry classes.



Source: Author, 2026.

Descriptive Statistics of the RBI

The descriptive statistics indicate that the RBI had a minimum of 0.386808, maximum of 1.000235, mean of 0.777053, standard deviation of 0.058869, and range of 0.613426. The relatively small standard deviation compared with the mean indicates that a substantial proportion of the RBI observations were concentrated around the central part of the observed distribution. However, the range demonstrates that measurable spatial variability existed within the water body. The resulting statistics are presented in Table 3.

Table 4. Descriptive Statistics of the Relative Bathymetry Index

Statistic	Value
Minimum	0.3868084847927094
Maximum	1.000234842300415
Mean	0.7770526739878992
Standard deviation	0.05886907936250115
Range	0.6134263575077056

Source: Author, 2026.

Discussion

The Sentinel-2-based workflow successfully provided a spatially continuous representation of relative bathymetric variation within Kopa Dam. NDWI and NDVI were integrated to develop a refined water mask and minimize the inclusion of terrestrial and vegetated pixels. The logarithmic blue-green spectral approach produced a continuous Relative Bathymetry Index (RBI) ranging from 0.386808 to 1.000235, representing relative spectral variation associated with bathymetric conditions rather than absolute water depth. The four-class

classification showed a strong dominance of Class 3, which covered 65.95% of the mapped water area, followed by Class 4 with 33.63%, while Classes 1 and 2 represented only 0.01% and 0.41%, respectively. The continuous RBI map preserved detailed spectral variability, whereas the four-class map provided a simplified representation suitable for spatial visualization and area-based statistical analysis.

Majority filtering improved the spatial coherence and cartographic quality of the classified relative bathymetry map by reducing isolated pixels. However, the absence of independent bathymetric reference data prevented calibration of the RBI into absolute water-depth values and consequently limited quantitative accuracy assessment using R_2 , RMSE, and MAE. The results should therefore be interpreted as relative bathymetric zones rather than measured depth classes. Overall, the study demonstrates that freely available Sentinel-2 imagery can provide a practical and spatially explicit approach for preliminary relative bathymetric characterization of inland water bodies such as Kopa Dam, particularly where field-based bathymetric measurements are unavailable.

A further consideration relates to the transferability of the Stumpf (2003) ratio model, which was originally developed and validated in optically shallow coastal waters, to an inland reservoir setting such as Kopa Dam. Inland reservoirs commonly experience higher turbidity and suspended-sediment loads than open coastal waters, and these constituents can elevate green-band (B_3) reflectance independently of actual water depth. Because the RBI in this study is derived directly from the green-to-blue reflectance ratio, elevated turbidity in shallower nearshore zones could partially offset the depth-related decline expected in the ratio, potentially causing turbid shallow areas to be misclassified as deeper zones. Vrdoljak and Kilić Pamuković (2022) similarly showed that atmospheric-correction choice and band selection strongly influence ratio-based SDB accuracy, while Gafoor et al. (2022) reported that the conventional green-to-blue ratio is sensitive to water-quality variation and can be outperformed by multi-band alternatives in optically complex waters. These findings reinforce that the RBI values reported here should be interpreted as relative spectral indicators rather than direct proxies for depth, and that turbidity-related confounding is a plausible explanation for anomalies in the classified map, particularly along the reservoir margins.

The present findings are broadly consistent with recent Sentinel-2 SDB studies. Prasetya et al. (2023) and Figliomeni and Parente (2024) both found that simple band-ratio approaches, including the Stumpf-type ratio applied here, remain competitive with more complex alternatives when independent calibration data are unavailable, although all such studies caution that ratio-based methods are sensitive to atmospheric correction and water-column optical properties. Similarly, Bernardis et al. (2023) demonstrated that Sentinel-2 ratio-based bathymetry can be derived reliably using open satellite data alone, supporting the practicality of the Sentinel-2-only workflow adopted for Kopa Dam. Unlike these coastal and lagoon-based studies, however, the present work addresses an inland freshwater reservoir, for which comparable Sentinel-2 ratio-based case studies remain

scarce, underscoring the exploratory contribution of this study to inland-water SDB applications in a West African context.

Conclusion

This study developed a GIS-based workflow for deriving and spatially characterizing relative bathymetric variation in Kopa Dam using Sentinel-2 Level-2A imagery.

The methodology integrated Sentinel-2 Bands 2 and 3, water-body masking, logarithmic blue-green spectral-ratio processing, descriptive statistical analysis, four-class reclassification, Majority Filtering, and spatial quantification of the resulting classes.

The derived Relative Bathymetry Index ranged from 0.386808 to 1.000235, with a mean of 0.777053, standard deviation of 0.058869, and range of 0.613426.

The final four-class classification contained 37,845 valid water pixels, representing approximately 378.45 ha. Moderate depth class was dominant, covering 249.60 ha (65.95%), followed by deep zone class with 127.29 ha (33.63%). Shallow class covered 1.54 ha (0.41%), while very shallow class covered 0.02 ha (0.01%).

The results demonstrate that Sentinel-2 multispectral imagery combined with GIS-based spectral-ratio processing can provide a practical means of spatially characterizing relative bathymetric variation in an inland water body.

However, because suitable independent depth observations were unavailable, the resulting RBI was not calibrated to absolute water depth. The final four classes therefore represent relative bathymetric zones rather than measured depth intervals.

Recommendations

Future research should incorporate field-based bathymetric observations or suitable independent satellite-derived bathymetric measurements to calibrate the RBI and establish a quantitative relationship between the spectral index and actual water depth. Such reference data would also enable independent validation using (R^2), MAE, RMSE, and other standard bathymetric accuracy measures.

For practical purposes, reservoir managers should treat the current classified map as suitable for preliminary spatial planning only; it should not be used for engineering design, dredging, or navigation purposes without prior field-based calibration and validation.

The methodology presented in this study provides a reproducible foundation for preliminary bathymetric assessment of inland water bodies in areas where conventional bathymetric datasets are limited or unavailable.

Conflict of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this article.

Funding Declaration

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Author's Contribution (CRediT)

Musa, A.: Conceptualisation, Methodology, Writing – Original Draft, Data Curation, Analysis. Sunusi, A.: Writing – Review & Editing. Dauda, W.A.: Supervision. Abubakar, Z.1.: Investigation.

Data Availability

The datasets generated and analysed during the current study are available from the corresponding author on reasonable request.

Disclosure Statement

"The authors used ChatGPT browser (OpenAI, August 2025) for language editing and grammar correction of the manuscript draft.

References

- Ashphaq, M., Srivastava, P. K., & Mitra, D. (2021). Review of near-shore satellite derived bathymetry: Classification and account of five decades of coastal bathymetry research. *Journal of Ocean Engineering and Science*, 6(4), 340–359. <https://doi.org/10.1016/j.joes.2021.02.006>
- Bernardis, M., Nardini, R., Apicella, L., Demarte, M., Guideri, M., Federici, B., Quarati, A., & De Martino, M. (2023). Use of ICESat-2 and Sentinel-2 open data for the derivation of bathymetry in shallow waters: Case studies in Sardinia and in the Venice Lagoon. *Remote Sensing*, 15(11), 2944. <https://doi.org/10.3390/rs15112944>
- Drusch, M., Del Bello, U., Carlier, S., Colin, O., Fernandez, V., Gascon, F., Hoersch, B., Isola, C., Laberinti, P., Martimort, P., Meygret, A., Spoto, F., Sy, O., Marchese, F., & Bargellini, P. (2012). Sentinel-2: ESA's optical high-resolution mission for GMES operational services. *Remote Sensing of Environment*, 120, 25–36. <https://doi.org/10.1016/j.rse.2011.11.026>
- European Space Agency. (2015). *Sentinel-2 user handbook*. European Space Agency.
- Figliomeni, F. G., & Parente, C. (2024). Methods for satellite derived bathymetry from Sentinel-2 images: A comparison. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLVIII-4/W9-2024, 165–173. <https://doi.org/10.5194/isprs-archives-XLVIII-4-W9-2024-165-2024>
- Gafoor, F. A., Al-Shehhi, M. R., Cho, C.-S., & Ghedira, H. (2022). Gradient boosting and linear regression for estimating coastal bathymetry based on Sentinel-2 images. *Remote Sensing*, 14(19), 5037. <https://doi.org/10.3390/rs14195037>
- Lyzenga, D. R. (1978). Passive remote sensing techniques for mapping water depth and bottom features. *Applied Optics*, 17(3), 379–383. <https://doi.org/10.1364/AO.17.000379>
- Ma, Y., Xu, N., Liu, Z., Yang, B., Yang, F., Wang, X.-H., & Li, S. (2020). Satellite-derived bathymetry using the ICESat-2 lidar and Sentinel-2 imagery datasets. *Remote Sensing of Environment*, 250, 112047. <https://doi.org/10.1016/j.rse.2020.112047>

- McFeeters, S. K. (1996). The use of the Normalized Difference Water Index (NDWI) in the delineation of open water features. *International Journal of Remote Sensing*, 17(7), 1425–1432. <https://doi.org/10.1080/01431169608948714>
- Prasetya, M. I., Siregar, V. P., & Agus, S. B. (2023). Comparison of satellite-derived bathymetry algorithm accuracy using Sentinel-2 multispectral satellite image. *Jurnal Kelautan Tropis*, 26(1), 113–125. <https://doi.org/10.14710/jkt.v26i1.16050>
- Rouse, J. W., Haas, R. H., Schell, J. A., & Deering, D. W. (1974). Monitoring vegetation systems in the Great Plains with ERTS. In *Proceedings of the Third Earth Resources Technology Satellite-1 Symposium* (NASA SP-351, pp. 309–317). NASA.
- Stumpf, R. P., Holderied, K., & Sinclair, M. (2003). Determination of water depth with high-resolution satellite imagery over variable bottom types. *Limnology and Oceanography*, 48(1, Part 2), 547–556. https://doi.org/10.4319/lo.2003.48.1_part_2.0547
- Vrdoljak, L., & Kilić Pamuković, J. (2022). Assessment of atmospheric correction processors and spectral bands for satellite-derived bathymetry using Sentinel-2 data in the Middle Adriatic. *Hydrology*, 9(12), 215. <https://doi.org/10.3390/hydrology9120215>