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Satellite-Derived Bathymetry in Tropical Shallow Waters: Methods, Sensors, Accuracy, and Applications

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Abstract. Accurate bathymetry is fundamental to coastal navigation, habitat assessment, shoreline management, hydrodynamic modelling, and fisheries planning, yet conventional hydrographic surveys remain costly and difficult in remote or very shallow tropical waters. Satellite-derived bathymetry (SDB) provides a complementary approach by estimating water depth from optical reflectance, wave properties, or spaceborne laser altimetry. This review synthesizes methodological developments in SDB with emphasis on tropical shallow-water environments and studies published from 2018 to August 2026, while retaining foundational algorithms required to explain current practice. The literature was organized according to sensor, preprocessing, calibration data, retrieval model, validation metric, and environmental limitation. Sentinel-2 has become the principal freely available optical source because its 10-m visible bands, five-day revisit, and global coverage are well matched to reef flats, lagoons, and island coasts. Landsat remains important for historical reconstruction, whereas PlanetScope and very-high-resolution imagery improve representation of narrow channels and small geomorphic features. ICESat-2 has substantially changed SDB by supplying independent along-track depth observations that can calibrate empirical and machine-learning models where field soundings are unavailable. Band-ratio and log-linear approaches remain robust baselines, but Random Forest, Support Vector Regression, neural networks, and multi-temporal fusion increasingly improve performance in complex waters. Accuracy nevertheless depends more strongly on optical depth, turbidity, bottom heterogeneity, sun glint, tide, temporal mismatch, and reference-data quality than on algorithm complexity alone. For tropical archipelagic regions such as Indonesia, an operational workflow should combine aquatic atmospheric correction, glint and cloud screening, tidal normalization, spatially independent validation, and explicit uncertainty reporting. SDB should therefore be treated as a scalable complement to hydrographic surveying rather than an unrestricted replacement for echo sounding.
Keywords: satellite-derived bathymetry; Sentinel-2; ICESat-2; shallow water; coastal remote sensing

Abstrak. Data batimetri yang akurat merupakan dasar bagi navigasi pesisir, penilaian habitat, pengelolaan garis pantai, pemodelan hidrodinamika, dan perencanaan perikanan, namun survei hidrografi konvensional masih mahal dan sulit dilakukan pada perairan tropis yang terpencil atau sangat dangkal. Satellite-derived bathymetry (SDB) menyediakan pendekatan komplementer dengan mengestimasi kedalaman dari reflektansi optik, karakteristik gelombang, atau altimetri laser berbasis satelit. Artikel review ini mensintesis perkembangan metodologi SDB dengan penekanan pada perairan dangkal tropis dan publikasi periode 2018 sampai Agustus 2026, serta tetap memasukkan algoritma

dasar yang diperlukan untuk menjelaskan praktik modern. Literatur dikelompokkan berdasarkan sensor, prapengolahan, data kalibrasi, model estimasi, metrik validasi, dan keterbatasan lingkungan. Sentinel-2 menjadi sumber optik bebas akses utama karena band tampak beresolusi 10 m, revisit lima hari, dan cakupan global sesuai untuk reef flat, laguna, dan pesisir pulau. Landsat tetap penting untuk rekonstruksi historis, sedangkan PlanetScope dan citra resolusi sangat tinggi meningkatkan representasi saluran sempit dan fitur geomorfologi kecil. ICESat-2 mengubah perkembangan SDB secara signifikan karena menyediakan observasi kedalaman sepanjang lintasan yang dapat digunakan untuk mengalibrasi model empiris dan machine learning ketika data sounding lapangan tidak tersedia. Metode band-ratio dan log-linear masih menjadi baseline yang kuat, tetapi Random Forest, Support Vector Regression, neural network, dan fusi multitemporal semakin meningkatkan kinerja pada perairan kompleks. Meskipun demikian, akurasi lebih banyak ditentukan oleh kedalaman optik, kekeruhan, heterogenitas dasar, sun glint, pasang surut, perbedaan waktu data, dan kualitas referensi dibandingkan kompleksitas algoritma semata. Untuk wilayah kepulauan tropis seperti Indonesia, workflow operasional perlu menggabungkan koreksi atmosfer khusus perairan, penyaringan glint dan awan, normalisasi pasang, validasi spasial independen, serta pelaporan ketidakpastian secara eksplisit. SDB sebaiknya diposisikan sebagai pelengkap yang skalabel bagi survei hidrografi dan bukan pengganti tanpa batas bagi echosounding.
Kata kunci: batimetri satelit; Sentinel-2; ICESat-2; perairan dangkal; penginderaan jauh pesisir

1. Pendahuluan

Bathymetry controls the movement of waves and currents, sediment transport, navigational accessibility, habitat zonation, inundation pathways, and many engineering decisions in the coastal zone. The need is especially acute in tropical archipelagos, where reefs, lagoons, sand cays, shoals, seagrass beds, and mangrove-fringed channels form highly complex shallow-water landscapes. Many such areas are poorly surveyed because vessel-based echo sounding is expensive, operationally difficult in reefs or very shallow flats, and quickly becomes outdated in dynamic settings. Remote sensing cannot reproduce all capabilities of a hydrographic survey, but it can provide spatially continuous and repeatable information where conventional coverage is sparse.

Satellite-derived bathymetry usually refers to the estimation of depth from passive optical satellite imagery. In clear water, the amount and spectral composition of light returning from the seabed are progressively attenuated with depth. Empirical models exploit this relationship by connecting image reflectance to known depths, whereas physics-based approaches explicitly represent water-column optics and bottom reflectance. A third family derives depth indirectly from surface-wave characteristics. The emergence of ICESat-2 has added an active spaceborne source of bathymetric points that can be combined with passive optical imagery, reducing dependence on local boat soundings for model calibration (Parrish et al., 2019; Ma et al., 2020; Thomas et al., 2021).

The practical value of SDB has increased markedly with Sentinel-2. Its 10-m visible bands and frequent repeat coverage offer a useful balance between spatial detail, radiometric quality, and cost. Studies in coral reefs, Caribbean coasts, West Africa, island environments, and Indonesia have shown that Sentinel-2 can resolve important shallow-water geomorphology when optical conditions are suitable (Hedley et al., 2018; Caballero & Stumpf, 2020; Daly et al., 2022; Gasica & Pratomo, 2022). PlanetScope provides finer and more frequent imagery, while Landsat offers the longest archive. These differences mean that the best sensor depends on whether the purpose is navigation support, historical change, habitat modelling, or rapid coastal reconnaissance.

Algorithmic development has also accelerated. Classical log-linear and band-ratio methods remain widely used because they are transparent and computationally efficient, but machine-learning and deep-learning models can represent nonlinear relationships among spectral bands, bottom type, water quality, and depth. Recent work has fused Sentinel-2 with ICESat-2, time-series composites, Random Forest, Support Vector Regression, neural networks, and multi-scale deep networks (Xie et al., 2023; Le et al., 2024). Nevertheless, greater model complexity does not remove fundamental optical limits. Turbidity, bottom heterogeneity, glint, cloud, wave state, tide, and temporal mismatch can dominate the error budget.

This review evaluates the current methodological landscape of SDB with specific attention to tropical shallow waters. The objectives are to: (1) compare the roles of major satellite and airborne data sources; (2) synthesize empirical, physics-based, wave-based, and machine-learning approaches; (3) identify preprocessing and validation practices that most strongly affect accuracy; (4) assess the opportunities created by ICESat-2 and multi-temporal imagery; and (5) propose a reproducible workflow suitable for tropical and Indonesian applications.

2. Methods

A structured narrative review was conducted using peer-reviewed literature and authoritative technical sources related to satellite-derived and remotely sensed shallow-water bathymetry. Priority was given to publications from 2018 to August 2026 to capture Sentinel-2, ICESat-2, cloud computing, machine learning, and recent Indonesian applications. Foundational studies were retained where they define algorithms that remain central to current practice, particularly the log-linear family of Lyzenga and the band-ratio transform of Stumpf et al. (2003).

Search concepts included satellite-derived bathymetry, shallow-water bathymetry, Sentinel-2 bathymetry, ICESat-2 bathymetry, Landsat bathymetry, PlanetScope bathymetry, machine learning bathymetry, tropical coastal bathymetry, coral reef bathymetry, atmospheric correction, sun glint, turbidity, and Indonesia. Studies were screened for explicit depth retrieval, methodological comparison, uncertainty evaluation, or operational relevance. Papers dealing only with terrestrial elevation or deep-ocean bathymetry without a shallow-water remote-sensing component were excluded.

The retained literature was synthesized according to six dimensions: sensor characteristics; atmospheric and aquatic preprocessing; source of calibration/reference depth; retrieval model; validation metrics; and environmental limitations. Particular attention was given to independent RMSE/MAE or equivalent depth-error measures because correlation alone can be high even when absolute depths are biased. Findings from Indonesia were examined separately to assess transferability to turbid, reef-associated, and archipelagic conditions.

3. Results and Discussion

3.1 Optical and active sensors for shallow-water bathymetry

Table 1. Principal sensing platforms used for satellite-derived and remotely sensed bathymetry.

Platform	Characteristics	Best use	Main limitation
Landsat 5-9	30 m multispectral; long archive	Historical change, broad shallow banks, regional screening	Coarser pixels; mixed bottom types; limited narrow-channel detail
Sentinel-2 MSI	10 m visible bands; 5-day constellation revisit	Operational SDB, reefs, lagoons, island coasts	Cloud/glint/turbidity; depth limited by water clarity
PlanetScope / SuperDove	~3 m; near-daily commercial imagery	Small features, high-frequency composites, ultra-shallow water	Cost/licensing; cross-scene radiometric consistency
WorldView / similar VHR	Sub-5 m multispectral	Detailed reef and navigation-scale	Cost; narrow swath; atmospheric/glint

		geomorphology	sensitivity
ICESat-2 ATLAS	Photon-counting green lidar along tracks	Calibration/validation depth points; active-passive fusion	Track gaps; photon noise; refraction correction required
Airborne bathymetric LiDAR	Dense laser point cloud	High-quality reference and detailed coastal mapping	High cost; limited repeat coverage
UAV optical/hyperspectral	cm-scale imagery	Very local validation, ultra-shallow mapping, bottom detail	Small coverage; georeferencing and water-surface effects

Sentinel-2 currently provides the most practical open-access backbone for tropical SDB. Hedley et al. (2018) demonstrated its value for coral-reef bathymetry and benthic mapping and showed advantages relative to Landsat 8 in spatial resolution and reef coverage. Caballero and Stumpf (2020) further demonstrated routine shallow-water mapping under variable turbidity, emphasizing multi-date acquisition as a means of selecting or constructing scenes with improved water clarity. Because tropical coastal atmospheres frequently contain haze and thin cloud, repeated acquisitions are not merely convenient; they are part of the error-control strategy.

Landsat remains scientifically important because SDB can be reconstructed decades into the past where suitable clear-water scenes exist. Its 30-m pixels are less effective for narrow channels, steep reef slopes, or fragmented shallow habitats, but the archive is valuable for identifying persistent geomorphic change. Conversely, PlanetScope and very-high-resolution imagery resolve small-scale morphology more effectively. Recent PlanetScope studies show that added spatial and spectral detail can improve shallow-water estimation, but the benefit is not automatic: high-frequency commercial imagery still requires calibration, radiometric normalization, and careful evaluation of band behavior (Khakhim et al., 2024; Kulbacki et al., 2024).

ICESat-2 has altered the calibration problem. ATLAS was not launched primarily as a bathymetric mission, yet green-laser photons can penetrate sufficiently clear water and produce bottom returns after noise filtering and refraction correction. Parrish et al. (2019) validated this capability, and subsequent work used ICESat-2 points as reference data for Sentinel-2 SDB (Ma et al., 2020; Thomas et al., 2021). The resulting active-passive combination is especially attractive for remote islands where recent echo-sounder data are unavailable.

3.2 Preprocessing: the decisive stage before modelling

Table 2. Major preprocessing and environmental issues affecting SDB accuracy.

Issue	Why it matters	Recommended response
Atmospheric path radiance	Offsets blue/green reflectance and distorts band relationships	Aquatic atmospheric correction; scene comparison
Sun glint	Adds specular radiance unrelated to seabed depth	NIR-based correction; scene screening; multi-date compositing
Cloud/haze/shadow	Produces missing or biased pixels	Strict masks; use time series rather than one compromised scene
Turbidity/CDOM	Reduces bottom signal and maximum detectable depth	Water-quality screening; multi-temporal clean-water composite
Bottom type/albedo	Sand, coral, vegetation can mimic depth differences	Band ratio, stratified models, bottom-aware ML/physics models
Tide/water level	Changes absolute water depth between acquisition and reference survey	Reduce to common vertical datum using tide/water-level data
Waves/whitecaps	Increase noise; may also contain bathymetric information	Filtering or wave-based methods such as S2Shores
Temporal mismatch	Seabed morphology and water conditions differ between data dates	Use near-contemporaneous calibration/validation and report dates

Preprocessing frequently explains more variance in SDB performance than the choice between competing regression models. Atmospheric correction is critical because the depth signal is already a small fraction of the top-of-atmosphere radiance. Caballero and Stumpf (2020) showed that atmospheric correction strategies influence consistency across Sentinel-2 scenes, while their work in variable-turbidity environments demonstrated the value of multiple images rather than reliance on a single acquisition. A visually clear image can still contain residual atmospheric or adjacency effects that systematically bias shallow-water reflectance.

Sun glint is another major problem in tropical imagery. The specular component changes rapidly with wind, viewing geometry, and solar angle, and it does not contain information about the seabed. NIR-based glint correction is commonly used because water-leaving signal is weak in the NIR for clear deep water. However, this assumption becomes less reliable in extremely shallow water, turbid water, or over bright bottoms. Therefore, the correction should be evaluated rather than applied mechanically.

Turbidity is arguably the dominant environmental limit. Caballero and Stumpf's later coastal work demonstrated that multi-temporal Sentinel-2 compositing can identify cleaner-water conditions and improve operational bathymetry in areas where single-date SDB fails. Tropical estuaries, monsoon-affected coasts, and sediment-rich straits can have an optical depth far shallower than their physical depth. In such settings, no machine-learning method can retrieve a seabed signal that is absent from the measured radiance.

3.3 Empirical and semi-empirical models

Empirical SDB methods remain the most widely accessible. Lyzenga-type models transform multispectral radiance or reflectance to linearize the exponential attenuation of light with depth, then estimate coefficients from reference soundings. The method can incorporate several visible bands and has been repeatedly adapted to modern sensors. The principal strength is transparency: model coefficients and residuals can be directly inspected. The weakness is site dependence, because relationships between reflectance and depth change with water optical properties and bottom composition.

The Stumpf ratio transform uses the logarithmic ratio of two bands, typically blue and green. Stumpf et al. (2003) designed the approach to reduce sensitivity to varying bottom albedo and showed that it can remain stable over heterogeneous substrates. The model has consequently become a standard baseline for Sentinel-2 and high-resolution imagery. It should not be interpreted as universally superior; performance depends on the selected band pair, calibration-depth distribution, optical clarity, and the depth range used for fitting.

An important methodological principle is that calibration and validation points must be separated. Using the same soundings to fit and report model accuracy overstates predictive performance. Reference data should also span the full depth range. If calibration points are concentrated in 0-5 m water, a regression extrapolated to 15-20 m may appear spatially plausible while being poorly constrained. The vertical datum of soundings must also be harmonized with the tide at satellite acquisition.

3.4 Physics-based and wave-based approaches

Physics-based inversion models attempt to separate the contributions of water-column optical properties, bottom reflectance, and depth. Their conceptual advantage is greater transferability because the parameters have physical meaning. Hedley et al. (2018) demonstrated physics-based bathymetry over coral reefs using Sentinel-2. In practice, however, these approaches require sufficient spectral information and reliable parameterization of absorption and scattering. Tropical waters containing variable chlorophyll, suspended sediments, and colored dissolved organic matter make the inverse problem difficult, particularly with multispectral rather than hyperspectral data.

Wave-based methods infer depth through the dispersion relationship between wave frequency, wavelength, and water depth. This family is not limited by bottom visibility in the same manner as radiometric SDB, but it requires suitable wave fields and image characteristics. The S2Shores framework has demonstrated regional mapping and recent work qualified Sentinel-2 wave-correlation bathymetry against hydrographic standards. Daly et al. (2022) showed the possibility of regional-scale mapping along thousands of kilometres of West African coastline, illustrating that wave-based and radiometric methods are complementary rather than competing solutions.

For tropical reef environments, radiometric methods are usually strongest where water is clear and the seabed is optically visible, whereas wave-based approaches may extend utility in sandy open coasts with coherent wave propagation. A hybrid decision system that selects methods according to optical clarity and wave conditions may therefore be more operational than a single universal inversion algorithm.

3.5 ICESat-2 and the transition to fully spaceborne calibration

ICESat-2 provides discrete rather than continuous bathymetry, but its depth profiles can replace or supplement field soundings. Parrish et al. (2019) demonstrated the bathymetric mapping performance of ATLAS, while Ma et al. (2020) integrated corrected ICESat-2 depths with Sentinel-2 imagery to generate spatially continuous SDB. Thomas et al. (2021) extended this concept in a cloud-native workflow and compared Lyzenga, Stumpf, and Support Vector Regression models at sites including Florida, Crete, and Bermuda.

The approach is attractive for tropical islands because calibration data can be derived from space. Nevertheless, ICESat-2 processing is itself a modelling task. Photon clouds contain solar and atmospheric noise, the water surface must be identified, seabed photons must be classified, and refraction must be corrected. Errors in these steps propagate into the optical SDB model. In addition, ICESat-2 tracks may cross only part of the range of bottom types present in a scene. A model trained exclusively on sandy-bottom tracks may not transfer cleanly to seagrass or coral substrata.

The ICESat-2 bathymetry literature has matured rapidly, and the development of the ATL24 bathymetry product reflects movement toward standardized along-track processing. Yet even high-quality ICESat-2 depths do not eliminate spatial transfer uncertainty between the track and the surrounding Sentinel-2 pixels. Reporting the distance and environmental similarity between training tracks and prediction areas should become part of best practice.

3.6 Machine learning, deep learning, and time-series fusion

Machine-learning SDB treats the spectral and contextual variables as predictors of continuous depth. Random Forest and Support Vector Regression are popular because they capture nonlinearity while working with moderate training sets. Mudiyanselage et al. (2022) showed that Sentinel-2 image selection and machine learning can improve coastal bathymetry, while Xie et al. (2023) combined Sentinel-2 and ICESat-2 and reported machine-learning RMSE below approximately 1.5 m at one validation site. Neural networks and multi-scale deep-learning architectures further exploit spatial context rather than treating each pixel independently.

The strength of machine learning is also a risk. A flexible model can learn site-specific relationships produced by water quality, bottom albedo, acquisition geometry, or even preprocessing artifacts. Random pixel splits exaggerate generalization when neighbouring pixels share the same environmental conditions. Spatial block validation, independent islands, or separate survey transects are more credible tests. Model performance should also be stratified by depth, because an overall RMSE can hide strong degradation near the maximum optical penetration depth.

Multi-temporal approaches are increasingly important. Rather than selecting a single 'best' image, several acquisitions can be processed and combined so that cloud, glint, and transient turbidity are reduced statistically. Le et al. (2024) combined Sentinel-2 time series with ICESat-2 and reported high R^2 and sub- to approximately metre-scale RMSE in their test sites, while also producing reliability estimates. A 2024 clean-coastal-water composite study similarly evaluated time-series Sentinel-2 as an input to Random Forest bathymetry. These approaches are particularly relevant in monsoonal tropical regions where consistently clear individual scenes are rare.

3.7 Representative recent studies

Table 3. Representative studies illustrating recent developments in shallow-water SDB.

Study	Setting	Data	Method	Contribution
Hedley et al. (2018)	Coral reefs	Sentinel-2 / Landsat 8	Physics-based inversion	Demonstrated strong Sentinel-2 reef bathymetry capability
Parrish et al. (2019)	Multiple coastal sites	ICESat-2	Photon bathymetry validation	Established ATLAS shallow-water bathymetric capability
Caballero & Stumpf (2020)	Caribbean / U.S. coasts	Sentinel-2	Band-ratio, multi-date preprocessing	Operational mapping under variable turbidity
Ma et al. (2020)	Island/coastal test sites	ICESat-2 + Sentinel-2	Empirical active-passive fusion	Used only satellite data for calibration and mapping
Thomas et al. (2021)	Florida, Crete, Bermuda	ICESat-2 + Sentinel-2 + GEE	Lyzenga, Stumpf, SVR	Cloud-native fully spaceborne workflow
Mudiyanselage et al. (2022)	SW Florida	Sentinel-2	Machine learning + optimal imagery	Emphasized image selection and nonlinear models
Daly et al. (2022)	West Africa	Sentinel-2	Wave-based S2Shores	Regional coastal bathymetry over ~4000 km
Gasica & Pratomo (2022)	East Java / Bali Strait	Sentinel-2	Empirical SDB	Indonesian shallow-water application
Xie et al. (2023)	Islands / St. Thomas	ICESat-2 + Sentinel-2	RF/SVM/ML + AE-DBSCAN	ML active-passive SDB with satellite-only priors
Caballero et al. (2023)	Caribbean and U.S. coast	Sentinel-2 time series	Multi-temporal turbidity control	Targeted turbidity as dominant operational limitation
Khakhim et al. (2024)	Indonesian coast	Sentinel-2 + PlanetScope	Stumpf / GEE	Compared new PlanetScope bands with Sentinel-2
Antares et al. (2024)	Putri Island, Batam	Sentinel-2	Empirical bathymetry	Recent Indonesian island case study

Le et al. (2024)	Long Island / Qilianyu	Sentinel-2 time series + ICESat-2	Multi-model fusion + reliability	R^2 0.96-0.99; RMSE 0.42-1.18 m
Pujianiki et al. (2025)	Bali, Indonesia	Sentinel-2	Lyzenga	Recent Indonesian SDB assessment
Heng et al. (2025)	Coastal test area	Sentinel-2	Backpropagation neural network	Contemporary neural-network SDB
2026 multi-resolution study	Shallow coastal waters	PlanetScope SuperDove	Spectral-temporal averaging	Highlighted gains from spatial/spectral/temporal fusion

3.8 Accuracy assessment and hydrographic relevance

SDB accuracy should be expressed in physical depth units. RMSE, MAE, median absolute error, mean bias, and depth-stratified error are more informative than R^2 alone. Caballero and Stumpf's Sentinel-2 work demonstrated sub-metre median absolute errors in clear shallow sites, but such performance is not transferable to all environments. Turbid coasts, steep reef slopes, mixed pixels, and deeper optically shallow limits can produce errors of several metres. Studies should therefore avoid presenting a single accuracy value without the associated depth range and water conditions.

Hydrographic standards provide a useful benchmark, but an SDB product should not be described as navigation-ready solely because its global RMSE appears small. The International Hydrographic Organization framework considers uncertainty, feature detection, and survey purpose. Optical SDB may miss small hazards, rocks, or vertical structures smaller than the pixel size. It is more defensible to describe SDB as reconnaissance, update support, gap filling, or prioritization unless an application-specific hydrographic qualification has been completed.

Validation design also determines credibility. Reference data should be independent from calibration, corrected to a common vertical datum, distributed across the mapped depth range, and collected close enough in time to minimize morphological change. The number of points is less important than representative spatial and depth coverage. Thousands of neighbouring sonar points along a few lines do not necessarily provide stronger validation than fewer well-distributed independent transects.

3.9 Tropical-water challenges and implications for Indonesia

Tropical waters are simultaneously ideal and difficult for SDB. Clear oceanic lagoons and coral reefs can provide deep optical penetration, but monsoonal runoff, resuspended sediment, phytoplankton, and colored dissolved organic matter sharply reduce seabed visibility in many embayments and straits. Coral, sand, rubble, macroalgae, and seagrass create heterogeneous bottom albedo that can be confused with depth. Strong solar illumination also increases glint. These conditions demand scene selection and environmental stratification rather than direct transfer of one regression model across an archipelago.

Indonesia provides a particularly important use case because conventional hydrographic coverage is expensive across thousands of islands. Recent studies have applied Sentinel-2 SDB in the Bali Strait/eastern Java region, Batam, Bali, and other shallow coasts, and have compared Sentinel-2 with PlanetScope (Gasica & Pratomo, 2022; Khakhim et al., 2024; Antares et al., 2024; Pujianiki et al., 2025). These studies demonstrate feasibility but also underline the need for site-specific validation. Clear reef-fringed islands may support direct optical inversion, whereas sediment-rich northern Java and estuarine areas may require multi-temporal screening, wave-based approaches, or conventional surveys.

A national or regional workflow should therefore use SDB as a tiered monitoring system. Open Sentinel-2 data can identify areas where the seabed is optically detectable and produce first-order depth surfaces. ICESat-2 can supply calibration profiles when suitable tracks are available. PlanetScope or high-resolution data can be reserved for narrow channels and priority habitats, while echo sounder or LiDAR surveys remain necessary for safety-critical zones and rigorous validation. Such integration maximizes the value of both satellite and field data rather than framing them as substitutes.

3.10 Recommended workflow for tropical SDB

Table 4. Recommended workflow and minimum reporting standards for tropical satellite-derived bathymetry.

Stage	Recommended practice	Minimum information to report
1. Define purpose	Navigation screening, habitat modelling, geomorphology, change, or survey planning	Target depth range, resolution, required uncertainty

2. Select sensor	Match pixel size/revisit/spectral bands to coastal morphology	Sensor, product level, acquisition dates
3. Screen optical conditions	Cloud, haze, glint, turbidity, wave state, tide	Scene-selection criteria and rejected scenes
4. Correct imagery	Aquatic atmospheric correction, masks, optional glint correction	Processor/version, reflectance product, parameters
5. Harmonize water level	Reduce satellite and reference depths to common datum	Tide source, datum, time correction
6. Prepare reference data	Echo sounder/LiDAR/ICESat-2 with spatial-depth coverage	Instrument/product, accuracy, date, point distribution
7. Fit baseline models	Always test transparent band-ratio/log-linear methods	Band combination, coefficients, training set
8. Test advanced models	RF/SVR/NN/time-series only when data support complexity	Features, hyperparameters, spatial CV design
9. Independent validation	Use withheld spatially independent data	RMSE, MAE, bias, R^2, depth-binned errors
10. Map uncertainty	Flag optically deep/turbid zones and low-confidence predictions	Confidence/reliability layer and maximum valid depth
11. Report limitations	Avoid implying survey-grade navigation unless qualified	Pixel size, hazard-detection limits, transferability
12. Archive workflow	Preserve code, scene IDs, model and datum metadata	Reproducibility and update procedure

The workflow deliberately begins with application requirements rather than algorithm selection. Habitat suitability modelling may tolerate metre-scale vertical error, whereas port engineering and navigation require much stricter uncertainty and feature detection. Likewise, a 10-m Sentinel-2 pixel may be adequate for reef-flat morphology but inappropriate for a narrow navigational channel. The sensor and validation standard must therefore be chosen from the intended use.

A transparent empirical model should normally be retained as a benchmark even when machine learning is the final method. If a complex neural network improves RMSE only marginally over a Stumpf ratio model, the additional complexity may not be justified for operational updating. Conversely, substantial improvements under independent spatial validation can support the use of nonlinear approaches. This comparative design prevents accuracy gains from being confused with differences in training samples or scene selection.

Finally, every SDB map should contain a validity mask. Pixels beyond the maximum optical penetration depth, strongly turbid regions, cloud/glint contamination, and unsupported extrapolation zones should be coded as no-data or low confidence. Filling every water pixel with a numerical depth creates false completeness and is one of the most consequential ways SDB can be misused.

3.11 Research gaps and future directions

The first research need is transferable modelling. Many published SDB methods perform well at one or two clear-water sites but are not tested across contrasting bottom types, turbidity regimes, or seasons. Future studies should use multi-site validation, domain adaptation, or physically informed machine learning to separate general depth information from site-specific optical conditions.

Second, time-series SDB should be developed as an uncertainty-reduction framework rather than only an image-compositing technique. Multiple independent depth estimates can be used to quantify stability, identify transient turbidity, and flag pixels where bathymetry is inconsistent. The reliability framework demonstrated by Le et al. (2024) illustrates this direction.

Third, ICESat-2 integration will likely become more standardized as bathymetry-specific products mature. The key challenge will move from extracting individual bottom photons to determining how representative sparse tracks are for surrounding optical pixels. Combining ICESat-2 with Sentinel-2, commercial high-resolution imagery, and cloud computing creates a realistic pathway to regional SDB in remote tropical archipelagos.

Fourth, future SDB research should report uncertainty in a way compatible with coastal decisions. Users need to know not only the predicted depth but also whether the error is expected to be 0.5 m or 3 m at that location. Depth-stratified validation, probability intervals, ensemble dispersion, and environmental quality flags should become standard outputs.

4. Conclusion

Satellite-derived bathymetry has evolved from relatively simple radiometric regression into a multi-source coastal mapping framework that integrates open multispectral imagery, spaceborne lidar, cloud computing, machine learning, and time-series analysis. Sentinel-2 currently offers the most practical open-access platform for tropical shallow-water mapping, while Landsat provides historical continuity and PlanetScope or very-high-resolution imagery can resolve smaller features. ICESat-2 is particularly important because it can supply satellite-based calibration and validation depths for remote areas. Classical Lyzenga and Stumpf models remain essential benchmarks; machine-learning and deep-learning models can improve nonlinear prediction but cannot overcome absent seabed signal, strong turbidity, poor reference data, or temporal mismatch. In tropical waters, the main determinants of reliable SDB are appropriate scene selection, aquatic atmospheric and glint correction, tidal harmonization, representative calibration, independent validation, and explicit mapping of uncertainty. For Indonesia and other archipelagic regions, SDB is best deployed as a scalable complement to echo sounding and LiDAR: it can identify shallow morphology, fill information gaps, support habitat and fisheries studies, guide survey priorities, and enable repeat monitoring, while safety-critical hydrographic applications still require rigorous survey-grade verification.

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