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Monitoring Shallow Bathymetry and Suspended Particulate Matter Concentration Using Only Satellite-Based Measurements

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ABSTRACT

This study investigates the impact of the Mandalika International Circuit construction on coastal sediment dynamics and water quality in Kuta Beach, Lombok, by analyzing changes in shallow bathymetry and the Concentration of Suspended Particulate Matter (Cspm) from 2019 to 2024. Using only satellite-based data, including Sentinel-2 imagery and ICESat-2-derived depth points, this study applies Satellite-Derived Bathymetry (SDB) and empirical models to monitor environmental changes associated with large-scale coastal development. The results show a significant increase in Cspm concentrations over the six-year period, particularly near the shoreline after the completion of construction in 2022. Bathymetric analysis reveals initial sediment accretion in the western nearshore area during the construction phase (2019-2022), followed by notable erosion between 2022 and 2024. These patterns highlight the lasting influence of construction on sediment transport and seabed morphology. Beyond assessing environmental impacts, this research also demonstrates the effectiveness of remote sensing as a practical and scalable method for monitoring dynamic coastal systems. The findings support the integration of satellite-based observation into long-term coastal management strategies, especially in data-scarce or rapidly developing regions.

1. Introduction.

Bathymetric changes are changes in the topography of the seabed that can occur due to natural processes such as sedimentation transport, tectonic activity, and storms, or due to human activities such as coastal reclamation and development (Caballero and Stumpf, 2020; Chen et al., 2023; Sakhaee and Khalili, 2021). Bathymetric changes need to be measured because they can pose a hazard to sailing and are needed for disaster mitigation purposes in coastal areas (Susa, 2022; Salameh et al., 2019).

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Bathymetric changes are generally measured using survey vessels with echo sounders or using airborne LiDAR (Wu et al., 2016; Yang et al., 2022). However, measurements using echo sounders and airborne LiDAR require large costs and time, and measurements using echo sounders are also risky in shallow areas (Liu et al., 2024). The Satellite Derived Bathymetry (SDB) method is an alternative for measuring bathymetric changes because it is cheaper, faster, and can be used in shallow areas.

Satellite-Derived Bathymetry (SDB) is a method for modeling underwater topography using data from satellite sensors. While satellite data offers broad coverage, it has a lower spatial resolution compared to traditional survey methods, which results in less detailed bathymetric models (Cao et al., 2024). However, the advantage of SDB lies in its high temporal resolution, allowing frequent updates of bathymetric changes in the same location. This makes it possible to track underwater topography shifts over short time periods (Caballero and Stumpf, 2021).

Bathymetric changes closely linked to sediment transport processes, which govern the movement, deposition, and resuspension of sediments in aquatic environments (Winterwerp and van Kesteren, 2004). When sediment-laden water experiences reduced turbulence, fine particles suspended in the water column settle onto the seabed, leading to sediment deposition - (Wright and Nichols, 2018). Over time, continuous deposition can cause sediment accumulation, raising the seabed and reducing water depth. This process is particularly prominent in estuaries, deltas, and coastal zones where river discharge, tidal currents, and wave action transport large amounts of suspended sediments (Gao, 2009). Human activities such as deforestation, land reclamation, and dredging can further increase sediment input, accelerating bathymetric changes by enhancing deposition rates (Syvitski and Kettner, 2011).

Concentration of Suspended Particulate Matter (Cspm) are used to quantify suspended particles in a body of water. These particles can originate from natural processes such as river discharge, coastal erosion, and wave-induced resuspension, as well as human activities like dredging, land reclamation, and deforestation (Wang et al., 2019). Cspm plays a crucial role in aquatic ecosystems, influencing water quality, light penetration, and sediment transport dynamics. High concentrations of Cspm can lead to increased sediment deposition, affecting bathymetric changes by contributing to seabed accumulation and potential shallowing of water bodies (Neukermans et al., 2012). Monitoring Cspm variations is essential for understanding sediment dynamics, coastal morphodynamics, and environmental changes, and satellite remote sensing provides an effective means of large-scale and frequent observation. Through the information of changes in Cspm and shallow bathymetry in an area, more complete insight in the process of morphological process can be understood even only using satellite data.

2. Data and Methods.

2.1. Study Regions in Kuta Beach, Lombok.

The study regions, Kuta Beach, are an active tourist destination in the Lombok Islands. In 2018 to 2022, there is a development of international circuit for motorcycle race right next to the beach. This development brings an impact to the quality of water and the underwater topography in Kuta Beach through the increase of sediment discharge that are caused by the development.

As shown in Figure 1, the Mandalika Circuit is located directly adjacent to Kuta Beach, with a visible stream flowing from the inland area beside the circuit into the coastal waters. This proximity raises concerns about the potential for sediment transport from the construction site into the beach environment. Large-scale developments such as this F1 Race circuit can increase surface runoff, especially during rainfall, carrying loose soil and construction-related particles into nearby waterways. Over time, this stream may act as a conduit for sediment deposition into the nearshore zone, which could alter water clarity and affect coastal dynamics.

Figure 1: Satellite image of Kuta Beach and Mandalika International Circuit.

Source: Sentinel-2 imagery acquired from Copernicus Data Space Ecosystem on May 1, 2025. Processed by ESA.

2.2. LiDAR ICESat-2 Data.

ATL03 data from the ICESat-2 mission are used to train model for SDB. The LiDAR data area downloaded from NASA's OpenAltimetry website. Before used as training data, the LiDAR data are corrected for the refraction that happen as the signal penetrate water surface. The refraction correction are done using model developed by Parrish et. al. In 2019.

Figure 2: The position of depth point derived from ATL03 Icesat-2.

Source: Sentinel-2 imagery acquired from Copernicus Data Space Ecosystem on May 1, 2025. Processed by ESA. ATL03 data acquired from OpenAltimetry (Khalsa et al. 2020).

Figure 2 illustrates the distribution of depth points derived from ICESat-2 ATL03 photon data, specifically from the data ATL03_20230808074608_07502008_006_02, which was recorded on August 8, 2023. These points have undergone refraction correction to account for the transition of the laser signal from air to water, ensuring more accurate depth estimations in the nearshore environment. Although multiple ATL03 datasets from 2020 to 2024 were evaluated, this data was the only one that met the spatial and quality requirements for reliable bathymetric extraction. The limitations in usable data were primarily due to unfavorable satellite pass alignment, insufficient photon return over shallow water, or cloud contamination. The retained dataset, however, provided high-quality measurements across the key areas of interest adjacent to the Mandalika shoreline, offering valuable ground-truth reference points for validating the satellite-derived bathymetry models developed from Sentinel-2 imagery.

2.3. Satellite Derived Bathymetry (SDB).

SDB is a method of determining water depth using remote sensing data that utilizes the characteristics of electromagnetic wave penetration in the water column. This paper uses the SDB algorithm developed by Stumpf et al. In 2003.

This model applies the basic principle that each band has a different level of water column absorption. These different absorption levels will conceptually produce a ratio between bands and this ratio will consistently change together when the depth change. The Stumpf algorithm uses the equation:

$$Z = m_1 \left[\frac{\ln(nR_w(\lambda_i))}{\ln\left(nR_w(\lambda_j)\right)} \right] - m_0 \quad (1)$$

where:
Z : Depth (positive value)
m_1, m_0 : Regression coefficients
nR_w : water surface reflectance
λ_i, λ_j : wavelength of different bands

2.4. Concentration of Suspended Particulate Matter (Cspm) Modelling.

Concentration of suspended particulate matter are derived from model developed by Liu et. al. In 2017. This model describe the concentration of suspended sediment using band 7 of sentinel 2 imagery (B7). The output of this model are the quantity of concentration in unit of ml/liter.

$$C_{\text{spm}} = 2950 * B7^{1.357} \quad (2)$$

where:
C_{spm} : Consentration of Suspended Particulate Matter, in miligram/litre
$B7$: Band 7 of Sentinel-2 Imagery

Both bathymetry and Cspm modelling utilizes Sentinel-2 imagery acquired annually every August from 2019 to 2024 to model both bathymetry and Cspm in the study area.

The consistent selection of August scenes was intended to ensure temporal uniformity and minimize the influence of seasonal variability, particularly in atmospheric and hydrodynamic conditions. By focusing on a single month, the study reduces the impact of fluctuating factors such as water turbidity due to monsoonal shifts, changes in chlorophyll concentration, and sea surface roughness. Moreover, this temporal consistency helps mitigate errors related to the satellite–Earth–Sun geometry, which can vary significantly throughout the year and affect reflectance values due to changes in solar zenith angle and atmospheric path length. Standardizing the acquisition time to August ensures that the observed changes in Cspm and bathymetry are more likely attributed to anthropogenic and geomorphological processes, rather than seasonal environmental noise.

Table 1: Sentinel-2 imagery used for Cspm and SDB modelling.

Year	Sentinel-2 file name	Satellite sensing time
2019	S2B_MSIL2A_20190816T021609	2019-08-16 02:16:09 (UTC)
2020	S2B_MSIL2A_20200810T021609	2020-08-10 02:16:09 (UTC)
2021	S2B_MSIL2A_20210805T021609	2021-08-05 02:16:09 (UTC)
2022	S2A_MSIL2A_20220815T021541	2022-08-15 02:15:41 (UTC)
2023	S2A_MSIL2A_20230810T021541	2023-08-10 02:15:41 (UTC)
2024	S2A_MSIL2A_20240814T021601	2024-08-14 02:16:01 (UTC)

Source: Sentinel-2 imagery acquired from Copernicus Data Space Ecosystem on May 1, 2025. Processed by ESA.

3. Development.

3.1. Results.

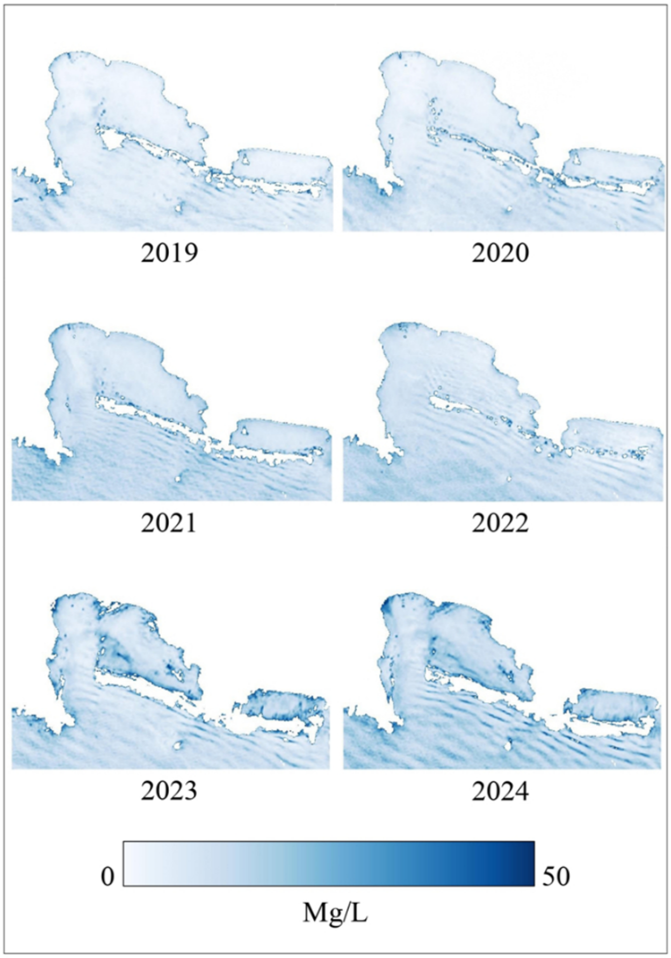
The results of this study are presented in two main components: changes in the Cspm and changes in shallow bathymetry in Kuta Beach from 2019 to 2024. The findings highlight spatial and temporal patterns that reflect both natural coastal processes and the influence of large-scale coastal development. Each section below describes the observed trends and spatial distributions, as well as how they relate to the construction timeline of the Mandalika International Circuit.

3.1.1. Concentration of Suspended Particulate Matter (Cspm).

Figure 3 illustrates the temporal changes in Cspm along the coastal waters of Kuta Beach from 2019 to 2024. The data reveals a consistent and gradual increase in Cspm beginning in 2018, with concentrations steadily rising each year. By 2024, certain nearshore areas exhibit concentrations reaching up to 50 mg/L, indicating a significant increase of particulate matter over the six-year period.

Figure 4 presents the changes in Cspm in Kuta Beach across three periods: 2019–2022, 2022–2024, and the overall change from 2019–2024. In the 2019–2022 period, which coincides with the active phase of circuit construction, there is a noticeable decrease in Cspm (represented in red) along the immediate coastline, while increases are observed in deeper offshore areas. This suggests that the construction activities may have caused sediment displacement toward deeper waters rather than increased turbidity nearshore. In contrast, the 2022–2024 period, following the completion of the construction, shows a more widespread increase in Cspm, particularly concentrated

Figure 3: Cspm in Kuta Beach from 2019 to 2024.



Source: Authors.

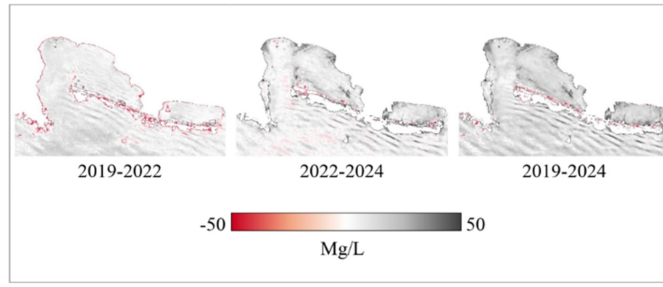
near the shoreline. This pattern may indicate resuspension or accumulation of particles in shallower areas once construction activity ceased. The overall change from 2019 to 2024 confirms a significant increase in Cspm throughout the Kuta Beach coastal zone, especially along the nearshore region, highlighting long-term changes in sediment dynamics and water quality over the study period.

3.1.2. Satellite Derived Bathymetry.

Figure 5 displays the annual changes in shallow bathymetry along the coastal area of Kuta Beach from 2019 to 2024. In the left section of each panel, a consistent pattern of bathymetric change is evident. From 2019 to 2022, there is a noticeable shallowing of the seabed, as indicated by decreasing depth values. This trend suggests a gradual accumulation or elevation of the seabed over the three-year period. However, starting in 2022 and continuing through 2023 and 2024, the depth in this same region begins to increase again, indicating a reversal of the earlier trend. By 2024, the seabed in the left portion of the area appears significantly deeper compared to its shallowest state in 2022.

Figure 6 illustrates the bathymetric changes in Kuta Beach

Figure 4: Cspm changes from 2019 to 2022 (left), 2022 to 2024 (center), and 2019 to 2024 (right). Red color shows decrease in Cspm, while black color shows increase.



Source: Authors.

for the periods 2019-2022, 2022-2024, and the overall span from 2019-2024. During the 2019-2022 period, which coincided with the circuit construction phase, the western section of the study area experienced significant seabed elevation, with some areas showing increases in bed level of up to 2 meters. This suggests notable sediment accretion likely due to localized sediment deposition. In contrast, the 2022–2024 period, following the completion of construction, shows a shift toward erosional processes, with the same region undergoing seabed lowering or scouring of up to 2 meters. This change indicates a possible redistribution or removal of previously deposited sediments. Over the full period from 2019 to 2024, however, only a limited area exhibits substantial bed level change. The majority of the seabed across the study area shows relatively stable conditions, with changes in depth generally remaining within ±1 meter.

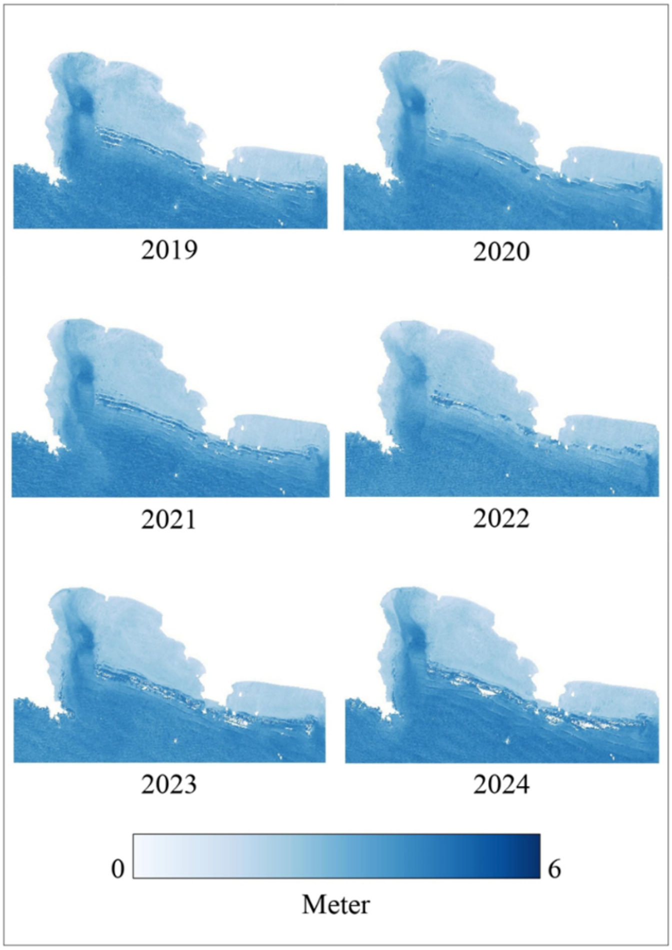
3.1.3. Validation of SDB.

To evaluate the accuracy of the Satellite-Derived Bathymetry (SDB) models, three statistical parameters are used: Root Mean Square Error (RMSE), Mean Absolute Error (MAE), and the coefficient of determination (R^2). RMSE measures the average magnitude of the prediction errors, providing insight into the overall accuracy of the depth estimates. MAE reflects the average absolute difference between predicted and reference values, indicating how close the predictions are to actual measurements regardless of direction. R^2 assesses the strength of the linear relationship between the predicted and reference depths, showing how well the model captures spatial variability. Together, these metrics provide a comprehensive evaluation of model performance across all years.

Table 2 summarizes the annual accuracy metrics of the depth models derived using SDB when compared against ICESat-2 reference data. RMSE and MAE values remain consistently low throughout the six-year period, with RMSE decreasing from 0.988 meters in 2019 to 0.718 meters in 2024, and MAE from 0.556 meters to 0.397 meters. These low error values indicate that the SDB-derived depths closely align with the actual depth values measured by ICESat-2, suggesting a high level of accuracy in absolute depth estimation.

However, the coefficient of determination, which measures

Figure 5: Shallow depth in Kuta Beach from 2019 to 2024.



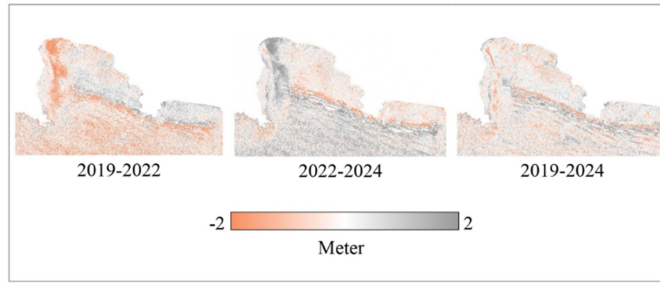
Source: Authors.

the strength of the linear relationship between the predicted and reference data, shows relatively lower values, particularly in earlier years. For example, R^2 is only 0.501 in 2019 and improves to 0.744 by 2024. This implies that although the depth values predicted by the model are numerically close to the reference, the model is less effective at capturing the spatial variability or pattern of depth changes over time. In other words, while the absolute differences are small, the model does not always predict depth changes in a manner that closely mirrors the structure or trends in the ICESat-2 data, especially in earlier years.

3.2. Discussion.

The results of this study reveal a consistent increase in Suspended Particulate Matter (SPM) concentrations from 2019 to 2024, despite the completion of the Mandalika Circuit construction in 2022. This persistent rise in SPM suggests that the factors driving sediment resuspension and transport extend beyond the immediate impacts of the construction activities. While the construction phase (2019–2022) likely contributed significantly to the initial increase in SPM through land disturbance, dredging, and coastal modifications, the continued rise post-

Figure 6: Changes in shallow water depth from 2019 to 2022 (left), 2022 to 2024 (center), and 2019 to 2024 (right). Orange color show accretion, while grey color show erosion.



Source: Authors.

2022 indicates that other mechanisms are at play. These may include natural processes such as seasonal wave action, tidal currents, and riverine sediment input, as well as potential long-term changes in coastal hydrodynamics induced by the construction.

The observed bathymetric changes in the western part of Kuta Beach provide further insight into the relationship between human activities and coastal dynamics. From 2019 to 2022, the shallowing of the seafloor in this region aligns closely with the timeline of the Mandalika Circuit construction. During this period, sediment mobilization from construction activities, such as land clearing, dredging, and infrastructure development, likely contributed to increased sediment deposition in the adjacent coastal waters. This deposition resulted in a net shallowing of the seabed. However, the subsequent deepening observed from 2022 to 2024 suggests a shift in sediment dynamics following the completion of the construction. This deepening could be attributed to the redistribution of previously deposited sediments by natural hydrodynamic forces, such as waves and currents, which may have eroded and transported the sediments away from the area.

The correlation between the construction timeline and the observed bathymetric changes highlights the significant impact of human activities on coastal sediment transport and morphology. However, the continued increase in SPM concentrations after 2022 underscores the complexity of coastal systems, where human-induced changes can trigger long-term alterations in sediment dynamics. For instance, the construction may have modified local hydrodynamic patterns, creating new pathways for sediment transport or enhancing erosion in certain areas. Additionally, the increased SPM levels could be influenced by secondary factors such as land-use changes in the surrounding watershed, which may have increased sediment runoff into the coastal zone.

These findings have important implications for coastal management and environmental monitoring. The persistent rise in SPM concentrations, even after the cessation of construction activities, suggests that the impacts of large-scale coastal development can extend well beyond the project timeline. This underscores the need for long-term monitoring and adaptive management strategies to mitigate the environmental impacts of such projects. Furthermore, the observed bathymetric changes high-

Table 2: Statistics parameter for each shallow bathymetry model.

Year	RMSE	MAE	R^2
2019	0.988	0.556	0.501
2020	0.856	0.428	0.588
2021	0.832	0.417	0.687
2022	0.854	0.519	0.542
2023	0.736	0.392	0.782
2024	0.718	0.397	0.744

Source: Authors.

light the importance of considering both short-term and long-term sediment dynamics in coastal planning. Understanding these processes is critical for predicting the potential impacts of future development projects and for designing measures to minimize their environmental footprint.

In addition to the environmental findings, this study also highlights the potential of using satellite-based remote sensing as a practical tool for coastal monitoring. The successful application of Satellite-Derived Bathymetry (SDB) and satellite-based models of Suspended Particulate Matter (Cspm) demonstrates that meaningful insights into underwater topography and water quality can be achieved without relying on expensive or logistically intensive field surveys. While traditional methods still offer higher precision and are necessary for specific applications, satellite data provide the advantage of regular temporal coverage, wide spatial extent, and cost-effectiveness. This approach allows for continuous observation of coastal areas impacted by human activity and natural processes, enabling better-informed coastal management decisions in data - scarce or budget - constrained regions.

4. Conclusions.

This study demonstrates the significant environmental impact of the Mandalika Circuit construction on coastal sediment dynamics in Kuta Beach, Lombok. The observed increase in Concentration of Suspended Particulate Matter (Cspm) and the alternating patterns of seabed accretion and erosion align closely with the construction timeline, highlighting how large - scale coastal development can alter sediment transport processes and seabed morphology. Notably, the increase in Cspm persisted even after construction activities ended, suggesting that such developments can lead to lasting changes in coastal water quality and sediment dynamics.

In addition to these environmental findings, this study underscores the value of satellite-based remote sensing as a tool for monitoring coastal change. The application of Satellite-Derived Bathymetry (SDB) and optical models for estimating Cspm using Sentinel-2 imagery proved effective in capturing both spatial and temporal variations in the study area. These methods offer an efficient and scalable alternative to traditional survey techniques, especially for long-term monitoring or in regions where in-situ data collection is limited. The ability to track changes over time using freely available satellite data highlights the potential of remote sensing to support sustainable coastal management and environmental impact assessment in the context of rapid development.

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Data Availability Statement

- Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

Bathymetry data derived from SDB.

Cspm data derived from modelling.

Some or all data, models, or code generated or used during the study are available in a repository or online in accordance with funder data retention policies.

Sentinel-2 Imagery can be downloaded from Copernicus Data Space Ecosystem. Copernicus Sentinel data 2018-2024. Retrieved from Copernicus Data Space Ecosystem [May 1, 20-25], processed by ESA. https://dataspace.copernicus.eu/.

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Declaration of Interest Statement

The author declares that there are no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

AI Use Declaration

During the preparation of this manuscript, OpenAI's ChatGPT (version GPT-4, accessed via ChatGPT as of April 2025) and Google Gemini was employed in the final writing and editing stages across the text. The tool was used exclusively for language refinement, including grammar correction, phrasing, vocabulary enhancement, and overall stylistic improvement. AI was not used for the research methodology, data processing, literature synthesis, reasoning, analysis, interpretation, or the formulation of conclusions. All research findings and interpretations are the original work of the authors, who take full responsibility for the scientific integrity, originality, and accuracy of this manuscript.

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