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Sediment-Driven Expansion of Tropical Mangroves in the Bengawan Solo Delta Revealed by Multi-Decadal Google Earth Engine Analysis

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Abstract

Mangrove deforestation is a global problem, but sediment-dominated estuaries can resist it through their own morphodynamic processes. This study reconstructs the spatiotemporal trajectory of the Ujung Pangkah estuary (1995–2025) to weigh natural progradation against anthropogenic pressure. We mapped the estuary in Google Earth Engine using Landsat archives and a Random Forest classifier with four spectral indices (NDVI, mNDWI, EVI, and MVI) and then independently validated all four epochs (Overall Accuracy 92.25–95.00%; Kappa 0.845–0.900). Error-adjusted change-detection analysis shows a non-monotonic trajectory: mangrove extent grew from 898.88 ha (1995) to a 2410.44 ha peak in 2015 and then contracted to 1816.87 ha by 2025 (error-adjusted: 1261.11 to 2626.03 to 2213.71 ha). Across the 30-year record, this is a statistically significant net expansion ($z = 3.60$, $p < 0.001$). Spatial attribution shows the 2015–2025 contraction comes mostly from landward anthropogenic conversion (78.1%), not seaward erosion (21.9%). A lagged correlation between a suspended sediment proxy and decadal net change ($r = 0.92$) offers quantitative support for continued sediment-driven coastal progradation. Ujung Pangkah's resilience therefore coexists with a real, locatable anthropogenic pressure. Safeguarding this blue carbon ecosystem means targeting policy at the interior conversion zones already underway, alongside continued protection of the coastal frontier.

Keywords: mangrove dynamics; Google Earth Engine; coastal resilience; fluvial sediment flux; blue carbon; anthropogenic conversion; spatiotemporal analysis

1. Introduction

Mangrove forests represent one of the most biogeochemically active and ecologically important ecosystems in the biosphere. Situated at the dynamic interface between terrestrial and marine environments, these ecosystems provide critical services that underpin coastal resilience [1–3]. Their complex root architectures act as natural bio-shields, attenuating hydrodynamic energy, mitigating coastal erosion, and buffering vulnerable shorelines against storm surges and rising sea levels [4,5]. Furthermore, deltaic and estuarine mangroves are globally recognized as significant blue carbon sinks. Their capacity for long-term carbon sequestration within waterlogged estuarine sediments exceeds that of terrestrial tropical forests, making their conservation an imperative in the global climate change mitigation agenda [6,7].

Despite their ecological importance, these coastal ecosystems are currently undergoing a significant global decline. Over the past three decades, anthropogenic pressures primarily



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driven by coastal urbanization and the extensive conversion of intertidal zones into aquaculture ponds have resulted in substantial mangrove loss worldwide [8,9]. The widespread degradation of these biomes not only releases sequestered carbon back into the atmosphere but also compromises coastal resilience, leaving coastal communities highly susceptible to extreme hydrodynamic hazards [10,11]. Consequently, tracking and understanding the multidecadal spatiotemporal dynamics of these ecosystems has become a priority for global conservation frameworks [3].

Within this context, deltaic mangroves occupy a highly dynamic position. Deltas are actively changing geomorphological features, sustained by a balance between fluvial sediment supply, tidal hydrodynamics, and sea-level rise [12]. Indonesia presents a critical case: while it harbors the world's largest expanse of mangroves, it concurrently suffers from high attrition rates, predominantly due to shrimp farming expansion [3,13]. However, certain sediment-dominated estuarine systems exhibit distinct ecological trajectories. The Ujung Pangkah estuary, situated at the mouth of the Bengawan Solo River in East Java, Indonesia, presents a notable example. Rather than retreating under anthropogenic pressure, the mangrove frontiers in this region are experiencing seaward progradation, facilitated by continuous fluvial sediment fluxes [14]. The morphological evolution of the Bengawan Solo delta has been historically shaped by substantial sediment discharge [15], a process that demonstrably continues to drive recent estuarine growth [16].

Historically, understanding these complex, multidecadal morphodynamic shifts has been hindered by methodological limitations. Previous studies monitoring mangrove dynamics have often relied on temporally restricted field surveys or localized satellite imagery analyses that fail to capture long-term geomorphological transitions [17,18]. Furthermore, most global remote sensing literature has primarily focused on quantifying mangrove deforestation and loss [18,19]. There remains a critical research gap regarding the multidecadal mechanisms of natural, sediment-driven progradation in tropical deltaic systems. Few studies have successfully linked the long-term spatial expansion of intertidal vegetation directly to continuous estuarine sediment fluxes.

The application of cloud-based geospatial computing, specifically the Google Earth Engine (GEE) platform, has advanced large-scale environmental monitoring by providing efficient access to the historical archive of Landsat imagery [19–21]. By integrating robust machine learning algorithms, such as the Random Forest (RF) classifier, researchers can achieve accurate spatial modeling, effectively overcoming the complex spectral mixing inherent in dynamic intertidal zones [3,22].

Addressing these limitations, this study introduces an empirical approach linking multidecadal geospatial vegetation dynamics with hydrodynamic driver analysis (sediment flux). Specifically, this study aims to (1) reconstruct the 30-year spatiotemporal trajectory of the Ujung Pangkah mangrove ecosystem (1995–2025) using multitemporal Landsat imagery and Random Forest classification on the GEE platform; (2) quantify the long-term change dynamics (areal gain, loss, and stability) with design-based accuracy and uncertainty estimates; and (3) test whether fluvial sediment flux is quantitatively associated with the observed estuarine dynamics. This research offers a perspective for regional blue carbon management: sustaining mangrove resilience requires both preserving the natural hydro-sedimentary flows that drive seaward progradation and directly addressing the anthropogenic conversion pressure that this study finds is already emerging in the estuary's interior.

2. Materials and Methods

2.1. Study Area

The focal area of this multidecadal analysis is the Ujung Pangkah estuary, geographically positioned at the terminus of the Bengawan Solo River in East Java, Indonesia. Functioning as the primary discharge point for the longest river system on Java Island, this macro-tidal estuarine environment is influenced by dynamic monsoonal precipitation patterns. During the wet monsoon, the catchment area experiences intense terrestrial erosion, transporting suspended sediments into the Madura Strait. This continuous sedimentary process creates an active geomorphological setting suitable for studying naturally subsidized mangrove colonization (Figure 1).



Figure 1. Map of the Ujung Pangkah estuary study area.

2.2. Image Acquisition and Pre-Processing

To reconstruct the 30-year spatiotemporal trajectory (1995–2025), multispectral satellite imagery was acquired and processed within the Google Earth Engine (GEE) platform [3,23]. To overcome the limitations of tropical cloud cover, an annual median compositing technique was applied to all available scenes within each respective observation year (1 January to 31 December). This median reduction approach is effective in tropical regions, as it synthesizes cloud-free optical data and statistically normalizes tidal fluctuations, yielding a stable, mean-tide spectral representation of the estuarine landscape. Landsat 5 Thematic Mapper (TM) data were used for the 1995 epoch, Landsat 7 Enhanced Thematic Mapper Plus (ETM+) data were used for the 2005 epoch (Landsat 5 archive coverage was not available for this location and year), and Landsat 8 Operational Land Imager (OLI) data were used for the 2015 and 2025 epochs. All datasets were filtered to utilize Level-2 Surface Reflectance (SR) products, and pixel quality assessment (QA_PIXEL) bit masking was applied to mask out clouds and cloud shadows, ensuring atmospheric consistency. Because Landsat 7 has produced permanent scan-line gaps in every scene since the Scan

Line Corrector failure in May 2003, the annual median composite for 2005 may retain small residual data gaps despite this compositing approach.

Furthermore, to delineate the estuarine hydrological boundaries and the Bengawan Solo River network, a Digital Elevation Model (DEM) was processed. The Fill Sinks algorithm was applied to the raw DEM to eliminate artificial depressions (sinks) in the flat coastal topography, ensuring continuous and hydrologically correct flow routing across the deltaic landscape [24]. The satellite specifications and harmonized spectral bands are summarized in Table 1.

Table 1. Landsat image acquisition and spectral specifications (1995–2025).

Epoch	Satellite Sensor	Acquisition Window	WRS-2	Harmonized Bands (B, G, R, NIR, SWIR-1)
1995	Landsat 5 TM	Annual Median (Jan–Dec)	118/065	Band 1, Band 2, Band 3, Band 4, Band 5
2005	Landsat 5 TM	Annual Median (Jan–Dec)	118/065	Band 1, Band 2, Band 3, Band 4, Band 5
2015	Landsat 8 OLI	Annual Median (Jan–Dec)	118/065	Band 2, Band 3, Band 4, Band 5, Band 6
2025	Landsat 8 OLI	Annual Median (Jan–Dec)	118/065	Band 2, Band 3, Band 4, Band 5, Band 6

2.3. Feature Engineering and Classification Strategy

Intertidal estuarine environments exhibit highly complex spectral mixing between vegetation, tidal mudflats, and turbid water. To optimize the performance of the machine learning classifier, a robust feature engineering approach was implemented. Beyond the native multispectral bands, four advanced spectral indices were computed and integrated into the model as critical predictor variables:

Normalized Difference Vegetation Index (NDVI): Utilized to quantify mangrove canopy density and photosynthetic vigor based on the contrast between near-infrared (NIR) and red-band reflectance [25].

$$\text{NDVI} = \frac{\text{NIR} - \text{RED}}{\text{NIR} + \text{RED}}$$

Modified Normalized Difference Water Index (mNDWI): Integrated to separate saturated intertidal mudflats and water bodies from terrestrial features.

$$\text{mNDWI} = \frac{\text{Green} - \text{SWIR1}}{\text{Green} + \text{SWIR1}}$$

Enhanced Vegetation Index (EVI): Applied to minimize atmospheric scattering and soil background signals, providing sensitivity for densely vegetated mangrove canopies.

$$\text{EVI} = 2.5 \times \frac{\text{NIR} - \text{Red}}{\text{NIR} + 6 \times \text{Red} - 7.5 \times \text{Blue} + 1}$$

Mangrove Vegetation Index (MVI): Developed to distinguish mangrove ecosystems from terrestrial vegetation and water bodies, exploiting the spectral reflectance of mangrove canopies across the green, near-infrared, and shortwave-infrared spectrums.

$$\text{MVI} = \frac{\text{NIR} - \text{Green}}{\text{SWIR1} - \text{Green}}$$

Following feature engineering, a Random Forest (RF) machine learning algorithm was deployed for the binary landscape classification ('Mangrove' and 'Non-Mangrove'). The RF ensemble was parameterized with 50 decision trees. This hyperparameter was selected to balance computational efficiency with classification accuracy, preventing model overfitting while addressing the high-dimensional feature space. Furthermore, the variable importance

(Mean Decrease Gini) was extracted to mathematically evaluate the contribution of each spectral feature to the classification model.

2.4. Accuracy Assessment and Area Estimation

Due to the retrospective nature of this multidecadal analysis, direct in situ field validation for historical epochs was unfeasible. To address this limitation, ground truth reference data were generated via the visual interpretation of multitemporal, high-resolution satellite imagery (e.g., Maxar Technologies, CNES/Airbus) archived within Google Earth Pro, which serves as a globally accepted, high-fidelity proxy for field verification [26].

To avoid spatial autocorrelation and data leakage during model evaluation, a stratified random sampling technique was applied. An independent set of 400 validation points (200 per class) was generated across the study area for each of the four epochs, not for 2025 alone; the 2005 set retained 399 usable points after excluding one point coincident with a Landsat 7 scan-line-corrector gap (Section 2.2). Model performance was evaluated using a confusion matrix, reporting Overall Accuracy (OA), Producer's Accuracy (PA) for omission errors, User's Accuracy (UA) for commission errors, and the Kappa Coefficient.

Furthermore, to provide statistically rigorous spatial metrics, the error-adjusted area estimation method proposed by [27] was applied. This approach utilizes the confusion matrix data to calculate the adjusted mangrove extent and its associated confidence intervals at a 95% confidence level, mitigating the area estimation bias inherent in standard pixel-counting methods.

2.5. Post-Classification Change Dynamics and Statistical Analysis

Post-classification change detection was performed for each of the three consecutive decadal pairs (1995–2005, 2005–2015, 2015–2025) rather than as a single direct comparison between the baseline and final epochs, allowing the trajectory's temporal structure rather than only its net endpoint change to be resolved.

Because valid (cloud-free) data coverage differs substantially between epochs (Section 2.2), a direct pixel-wise comparison of the raw classified rasters would misattribute epoch-specific data gaps as confirmed land-cover change if those gaps were treated as Non-Mangrove. To avoid this, each decadal comparison was restricted to the intersection of pixels validly classified in both years of the pair:

$$V_{(t_1, t_2)} = M_{(t_1)} \cap M_{(t_2)}$$

where $M(t)$ denotes the valid-data mask of epoch t (i.e., pixels retained after cloud/QA masking, the elevation constraint, and the connected-pixel noise filter). Within this common valid extent, each pixel pair was assigned to one of three classes: Loss (Mangrove at t_1 , Non-Mangrove at t_2), Gain (Non-Mangrove at t_1 , Mangrove at t_2), or Stable (Mangrove at both dates). The area outside $V(t_1, t_2)$ invalid in at least one of the two epochs is reported alongside each comparison for transparency, rather than discarded silently. This substitution was validated by comparing the restricted-extent estimate against the naive (unrestricted) estimate for the 2015–2025 pair, the period with the largest data-gap disparity between epochs; the two methods differed by only 2.2% in the estimated Loss area, indicating that the correction has a modest effect on the point estimate itself, though it materially improves the transparency and defensibility of the comparison.

To attribute the drivers of the 2015–2025 net loss, Loss pixels were further classified by proximity to large, persistent water bodies as a proxy for distinguishing seaward (erosional) from landward (anthropogenic) loss. A naive water-occurrence mask (JRC Global Surface Water, occurrence >80%) does not distinguish the open sea and major tidal channels from small, persistently flooded aquaculture ponds, which would otherwise be miscounted as

“sea.” To isolate genuinely large water bodies, the water-occurrence mask was filtered by connected-component size:

$$\text{TrueSea} = \{p : \text{occurrence}(p) > 80\% \text{ AND } \text{ConnectedPixelCount}(p) \geq 1000\}$$

TrueSea = using an 8-connectivity neighborhood (GEE connectedPixelCount, capped at its maximum evaluable window of 1024 pixels). At the 30 m Landsat pixel scale, a threshold of 1000 connected pixels corresponds to approximately 90 ha of contiguous water, well above the typical 1–5 ha footprint of individual aquaculture ponds in the study area, while comfortably capturing the open sea, the Madura Strait, and the main channel of the Bengawan Solo. Euclidean distance from each Loss pixel to the nearest TrueSea pixel was then computed (5 km search radius), and Loss pixels were classified as near-sea (<200 m from TrueSea) or interior (≥ 200 m). Loss pixels beyond the 5 km search radius of any TrueSea pixel were left unclassified by this method and are reported as such.

Tidal-stage variability across epochs was additionally assessed to rule out systematic bias in the comparison. Acquisition metadata (scene count, date, and nominal local overpass time) were extracted for every Landsat scene contributing to each annual composite. A tidal-stage proxy (mNDWI) was computed at a fixed reference point on the tidal flat/channel margin for each individual scene prior to compositing to characterize the distribution of tidal conditions sampled within and across epochs.

To statistically quantify the significance and magnitude of the temporal trend, non-parametric tests were applied to the four-epoch mapped-area series. The Mann–Kendall test was used to assess the significance and direction of the overall (non-necessarily-monotonic) trajectory, and Sen’s slope estimator was applied to calculate the median rate of areal change (ha/year), providing a metric resistant to temporal outliers [28]. Because the exact Mann–Kendall test has limited power at $n = 4$, epoch-to-epoch significance was additionally assessed directly on the error-adjusted area estimates (Section 2.4) using independent two-sample z-tests, propagating each epoch’s own Olofsson-derived standard error:

$$z = \frac{\hat{A}_{t_2} - \hat{A}_{t_1}}{\sqrt{SE_{t_1}^2 + SE_{t_2}^2}}$$

This provides a design-based significance assessment for each transition that does not depend on the small- n limitations of the rank-based trend test alone.

2.6. Driver Analysis: Suspended Sediment Proxy

To investigate the hypothesis that estuarine progradation is associated with fluvial sediment flux, a hydrodynamic driver analysis was incorporated. Using the same annual composites applied for classification (Section 2.2), red-band surface reflectance (Band 3 for Landsat 5/7; Band 4 for Landsat 8) was extracted from open-water pixels in the adjacent coastal waters of the Madura Strait for each of the four epochs (1995, 2005, 2015, 2025). In estuarine remote sensing, the red band serves as an established proxy for total suspended solids (TSS) concentration. This four-epoch TSS proxy series was compared against the mangrove areal dynamics reported in Section 3.3 to assess the geomorphological processes associated with mangrove expansion and contraction (Section 3.5) [29–31].

3. Results

3.1. Classification Performance and Accuracy Assessment

The performance parameters of the Random Forest model and the integrated feature engineering approach (NDVI, mNDWI, EVI, and MVI) were evaluated across all four epochs to ensure the reliability of the spatial outputs. The contribution of each spectral

feature to the classification was assessed using the Mean Decrease Gini metric (Figure 2). The variable importance analysis indicates that NDVI (8.94) and EVI (7.17) are the primary discriminant parameters, followed by MVI (6.21), the near-infrared band SR_B5 (5.64), mNDWI (4.42), and the shortwave-infrared band SR_B6 (4.22); the remaining visible bands (SR_B3, SR_B2, and SR_B4) contributed the least (2.42, 1.93, and 1.51, respectively).

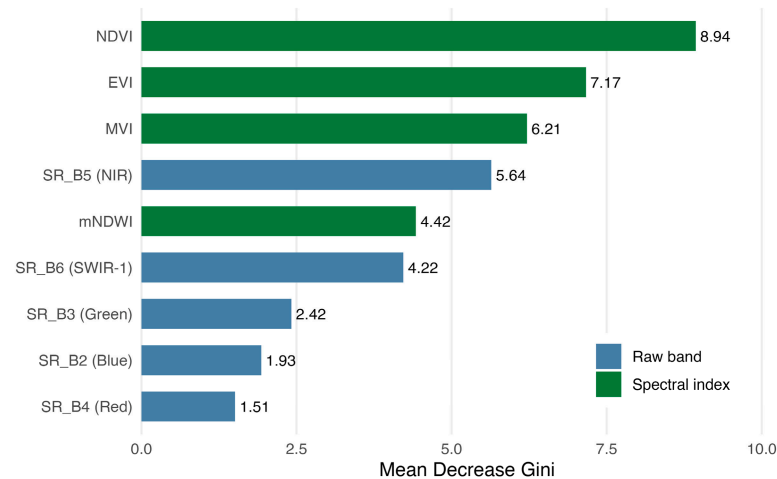


Figure 2. Random Forest feature importance (2025 model).

To test the necessity of these high-importance features, an ablation experiment compared the raw spectral bands alone against three- and four-index combinations, evaluated against the independent validation set. Excluding EVI produced no measurable accuracy loss relative to the full model (OA = 88.24%, κ = 0.763 vs. 88.24%, κ = 0.762) despite EVI's high Gini ranking, indicating that its contribution is largely redundant with NDVI. Excluding MVI, by contrast, reduced performance below even the band-only baseline (OA = 87.65%, κ = 0.751 vs. 88.00%, κ = 0.758 for bands alone) despite MVI's lower Gini ranking, indicating that MVI captures discriminative information, whereas the vegetation indices do not. The number of trees (50) was likewise selected via a sensitivity analysis (10–100 trees), which found accuracy peaked at 50 trees (OA = 88.24%, κ = 0.762) with no further gain at 80 or 100 trees.

For all four epochs, classification accuracy was independently assessed using stratified random samples of 400 points (200 per class; 2005: n = 399 after excluding one point coincident with a Landsat 7 scan-line-corrector data gap). Table 2 reports the resulting accuracy metrics.

Table 2. Confusion matrix and accuracy assessment of the 2025 mangrove classification using independent validation samples.

Epoch	n	OA	Kappa	UA Mangrove	PA Mangrove	UA Non-Mangrove	PA Non-Mangrove
1995	400	95.00%	0.900	92.50%	97.37%	97.50%	92.86%
2005	399	93.73%	0.875	92.46%	94.85%	95.00%	92.68%
2015	400	92.25%	0.845	88.50%	95.68%	96.00%	89.30%
2025	400	92.50%	0.850	90.00%	94.74%	95.00%	90.48%

All four epochs achieved Overall Accuracy above 92% and Kappa above 0.84, indicating consistently strong agreement between the classified maps and the reference data across the full observation period.

Following the good practice guidance of Olofsson et al. [27], the independent confusion matrix for each epoch was combined with the corresponding mapped class proportions

to produce error-adjusted area estimates with 95% confidence intervals (Table 3). In every epoch, Producer's Accuracy for the mangrove class is markedly lower than User's Accuracy (most pronounced in 2005: 51.96% vs. 92.46%), reflecting a consistent omission error: the mapped mangrove area underrepresents the true extent such that the error-adjusted area exceeds the naive mapped area by 9–78% in every epoch.

Table 3. Error-adjusted mangrove area estimation (2025).

Epoch	Mapped Area (ha)	Error-Adjusted Area (ha)	95% CI ($\pm$ ha)
1995	898.88	1261.11	374.24
2005	998.97	1777.52	518.42
2015	2410.44	2626.03	352.03
2025	1816.87	2213.71	358.46

3.2. Spatiotemporal Dynamics of Mangrove Extent

The geospatial extraction of intertidal vegetation revealed a substantially different spatiotemporal trajectory than previously reported. Rather than continuous expansion, the mapped extent shows a non-monotonic trajectory: a modest increase from 1995 to 2005, a pronounced expansion to a peak in 2015, and a subsequent contraction by 2025.

In 1995, the baseline mangrove extent was 898.88 ha (mapped) (1261.11 ± 374.24 ha error-adjusted). By 2005, the extent had increased modestly to 998.97 ha (1777.52 ± 518.42 ha adjusted). The most substantial expansion occurred between 2005 and 2015, reaching a peak of 2410.44 ha (2626.03 ± 352.03 ha adjusted), the maximum recorded extent across the observation period. Between 2015 and 2025, however, the mapped extent contracted to 1816.87 ha (2213.71 ± 358.46 ha adjusted), a net decline following the 2015 peak. Over the full 30-year record, the ecosystem nonetheless registered a substantial net gain, from 898.88 ha to 1816.87 ha mapped (or 1261.11 to 2213.71 ha error-adjusted), a statistically significant expansion (Section 3.4). This trajectory is visually represented in the multidecadal chart (Figure 3), and the spatial distribution of the most recent mangrove extent, alongside the independent validation points, is presented in Figure 4.

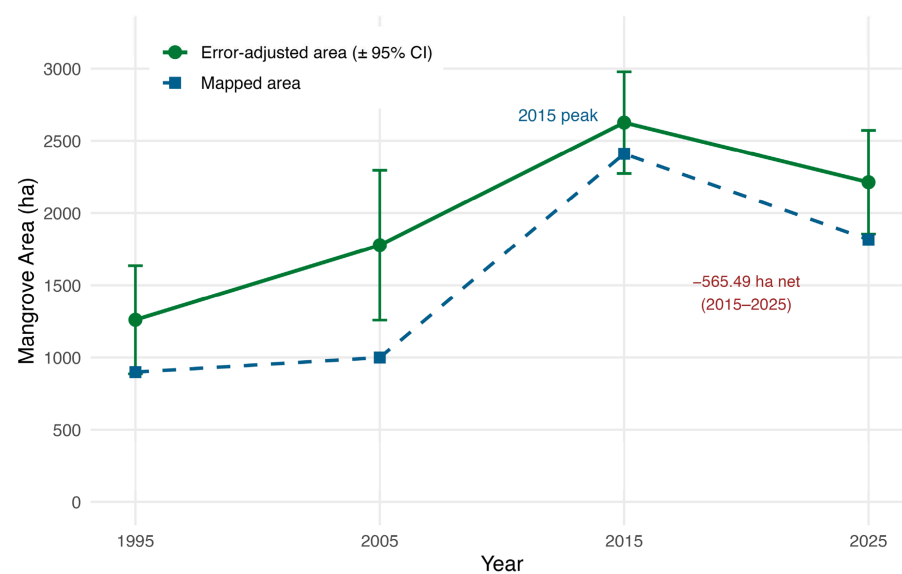


Figure 3. Decadal trajectory of mangrove areal dynamics (1995–2025).

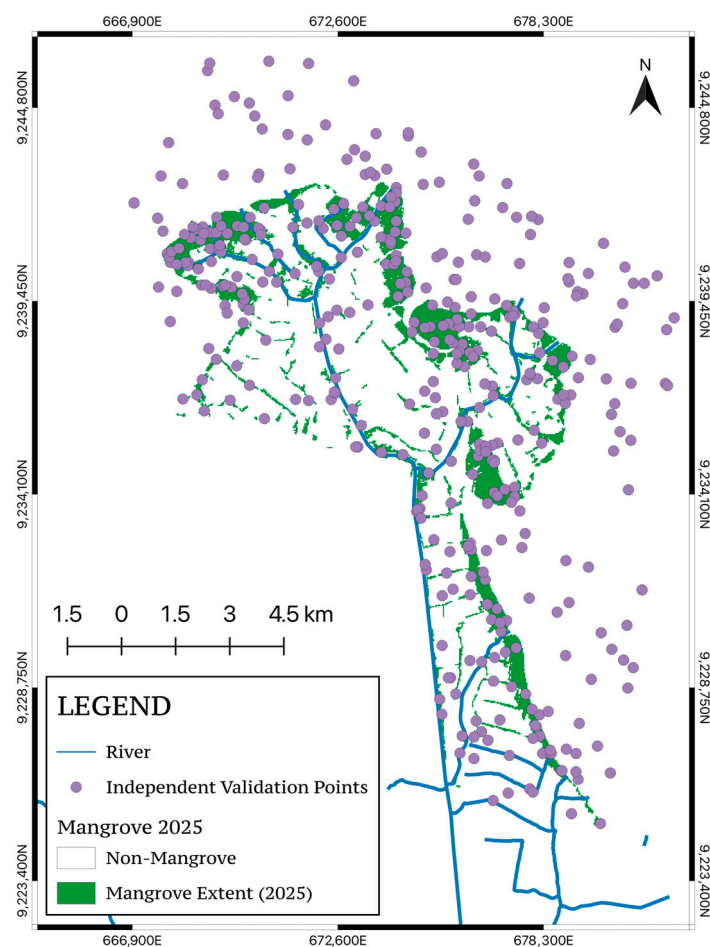


Figure 4. Mangrove extent and independent validation points (2025).

3.3. Post-Classification Change Trajectory (1995–2025)

To dissect the mechanisms underlying the net areal change, decadal post-classification change detection was performed for each consecutive epoch pair. Unlike the previous analysis, comparisons were restricted to pixels classified in both years of a given pair, avoiding the artificial inflation of apparent change from epoch-specific data gaps being treated as confirmed non-mangrove. The area excluded on these grounds is reported alongside each comparison for transparency (Table 4).

Table 4. Decadal mangrove areal dynamics (1995–2025).

Period	Loss (ha)	Gain (ha)	Stable (ha)	Net Change (ha)	Excluded (ha)
1995–2005	412.50	516.62	475.87	+104.12	57.89
2005–2015	132.36	1527.52	856.14	+1395.16	3412.85
2015–2025	1358.20	792.71	1021.14	−565.49	5060.42

The 2005–2015 period shows the largest net gain of the record, while 2015–2025 is the only period registering a net loss. To evaluate whether this loss reflects natural coastal erosion or landward anthropogenic conversion, loss pixels for 2015–2025 were classified by proximity to large, persistent water bodies—contiguous clusters ≥ 90 ha in the JRC Global Surface Water dataset, a threshold chosen to isolate the open sea and major channels from small-scale aquaculture ponds (typically 1–5 ha), which would otherwise be miscounted as “sea” under a naive water-occurrence mask. Of the loss area attributable to one of these two zones (782.84 ha, 57.6% of total loss; the remainder falls beyond the

5 km analysis radius), only 171.35 ha (21.9%) occurred within 200 m of a large water body, while 611.49 ha (78.1%) occurred farther inland. This indicates the 2015–2025 contraction is predominantly attributable to interior/landward conversion rather than seaward erosion, consistent with continued sediment-driven progradation at the coastal fringe being outpaced by anthropogenic attrition further inland (Figure 5).

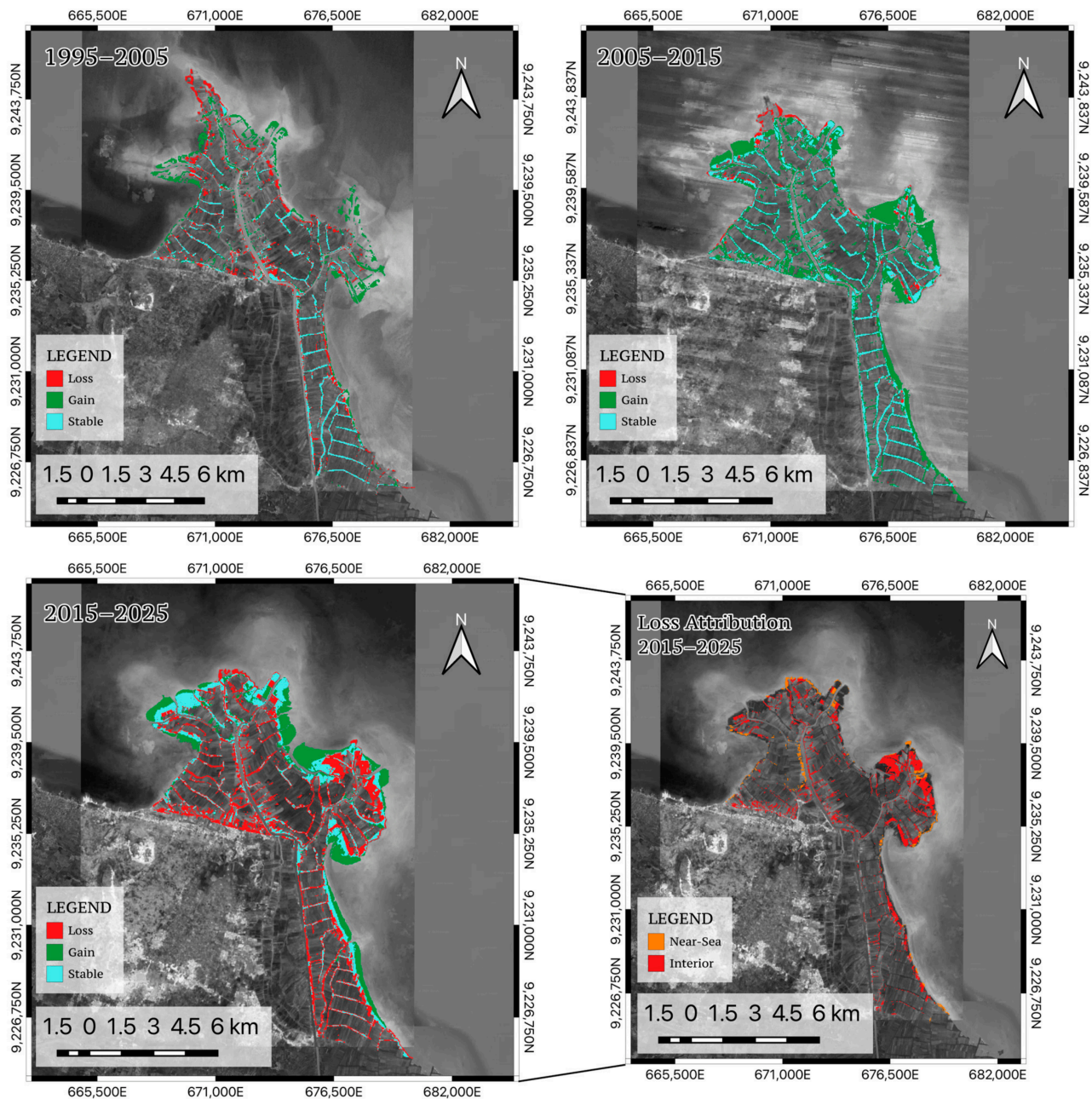


Figure 5. Spatiotemporal change map of the mangrove ecosystem: 4-panel decadal change (1995–2005, 2005–2015, 2015–2025) + loss attribution inset.

Spatiotemporal change in mangrove extent within the Ujung Pangkah estuary across three decades (1995–2025). To eliminate atmospheric data-gap artifacts, decadal change detection is strictly restricted to pixels validly classified in both years of each respective pair; areas lacking valid data in at least one epoch are excluded from the comparison (see Table 4 for the corresponding excluded area per period). The 2005–2015 panel visually captures the substantial phase of natural seaward expansion. Conversely, the 2015–2025 panel illustrates the subsequent contraction. Inset (bottom right): spatial attribution of

the 2015–2025 gross loss by proximity to large, persistent water bodies (≥ 90 ha connected clusters). The ‘Interior’ loss (red, ≥ 200 m inland) displays distinct rectangular, geometric grid patterns characteristic of artificial aquaculture ponds, visually consistent with the quantitative finding that anthropogenic landward conversion accounts for the majority of attributable loss, relative to physical ‘Near-Sea’ coastal abrasion (orange, < 200 m).

3.4. Magnitude and Statistical Significance of Areal Change

Non-parametric trend statistics were calculated on the four-epoch series. The Mann–Kendall test yields Kendall’s $\tau = 0.667$ ($S = 4$), where the single trend-discordant pair is now the 2015–2025 interval. With only four temporal observations, this test has inherently limited power. The exact two-sided p -value is 0.333, which does not reach conventional significance. Sen’s slope estimator gives a median rate of +35.75 ha/year across the record.

To assess statistical significance at the level of individual epoch-to-epoch transitions, independent z -tests were performed on the error-adjusted area estimates (Table 3), propagating each epoch’s own sampling uncertainty to assess transition significance (Table 5).

Table 5. Significance of epoch-to-epoch change in error-adjusted mangrove area.

Comparison	Δ Area (ha)	z	p	Significant ($\alpha = 0.05$)
1995 $\rightarrow$ 2005	+516.41	1.58	0.113	No
2005 $\rightarrow$ 2015	+848.51	2.65	0.008	Yes
2015 $\rightarrow$ 2025	−412.32	−1.61	0.108	No
1995 $\rightarrow$ 2025 (30-yr net)	+952.60	3.60	<0.001	Yes

The 2005–2015 expansion and the overall 30-year net gain are statistically robust. The apparent 1995–2005 increase and the 2015–2025 contraction, while directionally consistent with the point estimates and the spatial loss-attribution analysis above, do not reach statistical significance at the current validation sample size and should be interpreted with appropriate caution rather than presented as confirmed trend reversals.

3.5. Hydrodynamic Driver Trends

The time-series analysis of the total suspended solids (TSS) proxy, derived from red-band reflectance in open-water pixels within 3 km of the estuary mouth, yielded mean values of 0.0895 (1995), 0.0975 (2005), 0.0723 (2015), and 0.0601 (2025). To move beyond a purely descriptive treatment, these values were correlated with the mangrove areal dynamics reported in Section 3.3.

The contemporaneous correlation between TSS proxy and mapped mangrove area within the same epoch is weak and not statistically significant ($r = -0.77$, $p = 0.23$, $n = 4$). However, a lagged relationship TSS proxy at the start of each decade against the net areal change occurring during that decade shows a strong positive association ($r = 0.92$, $n = 3$): the elevated sediment proxy at the start of the 2005–2015 decade preceded the period’s large net gain (+1395.16 ha), while the comparatively reduced sediment proxy at the start of 2015–2025 preceded the only net loss recorded in the 30-year series (−565.49 ha). With only three decadal transitions available, this correlation cannot be considered statistically confirmatory ($p = 0.25$); it is presented as quantitative, if suggestive, support for a multi-year lag between fluvial sediment deposition and mangrove colonization, consistent with the mechanism proposed in Section 4.3, rather than as demonstrated causal evidence.

4. Discussion

4.1. Long-Term Progradation Overlaid by an Emergent Anthropogenic Contraction

The multidecadal spatiotemporal assessment of the Ujung Pangkah estuary reveals an ecological trajectory that both diverges from and partially converges with broader global trends. Over the full 30-year observation period (1995–2025), the ecosystem registered a statistically significant net areal gain, from 898.88 ha to 1816.87 ha mapped (1261.11 to 2213.71 ha error-adjusted; $z = 3.60$, $p < 0.001$; Section 3.4). This long-term expansion remains an anomaly relative to the prevailing global pattern of tropical mangrove decline driven by land-use conversion and coastal squeeze [32,33] and supports the broader claim that localized geomorphological processes can sustain mangrove resilience even as most tropical estuaries retreat [34,35].

However, this net expansion masks underlying temporal complexities. The decadal record shows the expansion was concentrated in 2005–2015 (a statistically significant +1395.16 ha net gain), while the most recent decade, 2015–2025, registered the only net loss of the study period (−565.49 ha, mapped extent declining from a 2015 peak of 2410.44 ha to 1816.87 ha by 2025). This decline does not reach conventional statistical significance at the current independent-validation sample size ($z = -1.61$, $p = 0.108$; Section 3.4) and should therefore be described as an emergent, directionally consistent pattern rather than a statistically confirmed reversal. Two independent checks support treating it as a genuine ecological signal rather than a data artifact: (i) restricting the change-detection comparison to pixels validly classified in both epochs—removing the possibility that epoch-specific cloud/data gaps were being misread as confirmed loss—changed the estimated loss by only 2.2% (Section 3.3), and (ii) a tidal-stage proxy shows 2025 was imaged at the lowest average tidal stage of all four epochs, which, if anything, would be expected to inflate rather than deflate the apparent 2025 extent, yet the mapped area still declined relative to 2015.

Ujung Pangkah therefore does not fit cleanly into either the “anomalous accreting delta” or “typical declining delta” category over its full record. It instead illustrates a spatially and temporally partitioned dynamic: sustained, sediment-driven seaward progradation operating alongside and, in the most recent decade, increasingly counteracted by landward anthropogenic conversion (Section 3.3). This dual character, rather than a single unidirectional trend, is the more accurate and more policy-relevant characterization of the system.

4.2. Comparative Deltaic Dynamics: Two Regimes Within One System

Placing Ujung Pangkah alongside other tropical deltaic systems is instructive precisely because its recent trajectory contains elements of both ends of the regional spectrum, rather than sitting cleanly at one extreme. In Southeast Asia and West Africa, prominent estuarine environments such as the Mekong Delta (Vietnam), Mahakam Delta (Indonesia), and the Niger Delta (Nigeria) have experienced sustained mangrove retreat over the last three decades [3,36,37], driven primarily by anthropogenic intervention [38,39]. In the Mekong Delta, upstream dam construction has reduced sediment loads, undermining the fluvial supply needed to maintain elevation against subsidence, compounded further by shrimp aquaculture expansion [40]. The Mahakam and Niger deltas have similarly fragmented under aquaculture pressure and fossil-fuel extraction infrastructure [41].

The seaward margin of Ujung Pangkah, by contrast, exhibits functional parallels with sediment-dominated systems such as the Amazon estuary and parts of the Sundarbans [42,43], where fluvial sediment supply continues to outpace erosive and subsidence pressures at the coastal fringe [44,45]. The quantitative loss-attribution analysis in Section 3.3 supports this parallel directly: of the 2015–2025 loss area attributable to

a defined zone, only 21.9% (171.35 ha) occurred within 200 m of the open sea or major channels, consistent with limited seaward erosion.

The interior of the system, however, increasingly resembles the anthropogenically driven deltas described above rather than the sediment-dominated ones. The majority of the 2015–2025 loss (78.1%; 611.49 ha) of the attributable total occurred farther inland, spatially consistent with conversion to aquaculture ponds and settlement expansion. This pattern is independently corroborated at the same site: an earlier, methodologically distinct GIS/remote sensing study of the Ujung Pangkah subdistrict found 101.70 ha of mangrove converted to fishponds between 2006 and 2016 alone [46], and a subsequent environmental-damage assessment of the Pangkah Kulon and Pangkah Wetan villages specifically attributed ongoing degradation to expanding pond aquaculture alongside coastal abrasion/accretion dynamics [47]. A governance case study of milkfish (bandeng) pond aquaculture in Pangkah Wetan further documents the socioeconomic conditions sustaining this expansion: limited farmer access to capital, dependence on patrons, and weak local institutions that make continued pond conversion the path of least resistance for coastal livelihoods in this specific area [48]. At the national scale, aquaculture conversion is likewise the single largest documented driver of Indonesian mangrove loss, accounting for over 80,000 ha of deforestation between 2009 and 2019 alone [49]. Together, this places Ujung Pangkah's interior fringe on a trajectory comparable to the anthropogenic pressures already well-documented at Mahakam and the Niger Delta [41], even as its seaward fringe continues to behave like a sediment-dominated, accreting system.

4.3. Fluvial Sediment Flux as a Contributing Driver of Seaward Progradation

The TSS proxy time series (Figure 6) is consistent with, though does not on its own confirm, a fluvial-sediment-driven mechanism for the seaward component of the observed expansion. The Bengawan Solo River is a continuous source of suspended particulate matter, with peak discharges corresponding to the regional wet monsoon; upon reaching the Madura Strait, deceleration of river flow combined with tidal mixing induces flocculation and deposition of these fluvial sediments [50]. This deposition can generate new intertidal mudflats, which, once reaching a critical elevation within the tidal frame, become viable substrates for colonization by pioneer species such as *Avicennia* and *Sonneratia* spp. [51–53].

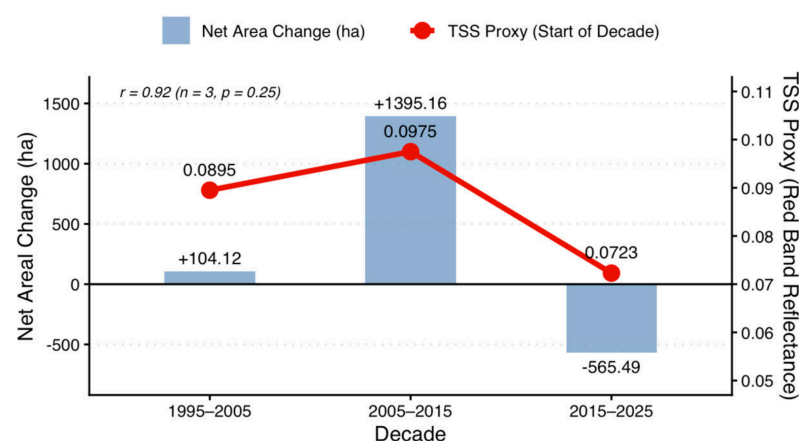


Figure 6. Lagged correlation between initial TSS and subsequent decadal change.

Quantitative support for this mechanism, developed in Section 3.5, comes from a lagged correlation between the TSS proxy at the start of each decade and the net areal change occurring during that decade ($r = 0.92$, $n = 3$): the elevated sediment proxy preceding the 2005–2015 decade coincided with that decade's large net gain, while the reduced sediment proxy preceding 2015–2025 coincided with the only net loss in the record. With

only three decadal transitions available, this correlation is not statistically confirmatory ($p = 0.25$) and should be read as quantitative, hypothesis-consistent evidence rather than demonstrated causation.

This mechanism must be properly contextualized: it offers a plausible explanation for the seaward gain component of the record, not for the interior loss documented in Sections 3.3 and 4.2, which is spatially and causally distinct (anthropogenic conversion, not sediment starvation). Unlike estuarine systems experiencing outright sediment starvation from extensive upstream damming, the Bengawan Solo continues to deliver sufficient particulate matter to sustain seaward advancement, but this seaward process operates independently of, and is currently being outweighed by, the landward conversion process.

We also note, as a study limitation, that red-band surface reflectance is an indirect optical proxy for suspended sediment concentration rather than a direct, field-calibrated measurement of fluvial sediment flux and can be influenced by other water column constituents (e.g., colored dissolved organic matter, chlorophyll-a, sun glint) that may co-vary with turbidity. Future work incorporating in situ turbidity/TSS measurements or validated satellite TSS retrieval algorithms would strengthen this causal inference.

4.4. Theoretical Contribution and Blue Carbon Implications

These findings clarify how sediment-mediated coastal resilience works in tropical estuaries and where it breaks down. Maintaining natural hydrological connectivity and fluvial sediment delivery is necessary, though evidently not sufficient on its own, for net mangrove persistence, since the same 30-year period that shows robust net gain also shows an emergent, spatially concentrated contraction operating in parallel. Estuarine stability in the Anthropocene depends on a morphodynamic balance between natural sediment accretion and human-induced land-use pressure, and at Ujung Pangkah, that balance has shifted measurably against the mangrove interior in the most recent decade, even as the seaward margin remains net-positive.

The policy implications follow directly from this partitioned pattern rather than from the expansion alone. The documented 30-year net gain does support the ecosystem's contribution to regional blue carbon sequestration capacity [54], as estuarine mangroves facilitate organic carbon burial within accreted mudflats. However, the 2015–2025 interior contraction indicates this contribution is not secure by default: rather than anticipating anthropogenic pressure solely as a future risk contingent on upstream hydrological modifications [55–57], the present data show landward conversion is already underway and already measurably counteracting a portion of the seaward gain. This reframes the relevant policy window from anticipatory (protecting against a hypothetical future disruption) to corrective (addressing an ongoing, spatially identifiable pattern of loss). Local and national spatial planning should accordingly prioritize gazettement and protection of the actively prograding seaward frontier, while directing enforcement attention toward the interior zones where aquaculture and settlement conversion are currently concentrated [58–62].

5. Conclusions

This study successfully reconstructed the 30-year spatiotemporal trajectory (1995–2025) of the Ujung Pangkah mangrove ecosystem using a cloud-computing framework in Google Earth Engine. By integrating a multi-index feature engineering approach (NDVI, mNDWI, EVI, and MVI) with the Olofsson error-adjusted area estimation, the Random Forest classification achieved an Overall Accuracy of 92.25–95.00% (Kappa 0.845–0.900) across all four independently validated epochs, providing statistically rigorous spatial metrics for the full observation period rather than a single snapshot year.

Contrary to the prevailing global trend of estuarine degradation, the Ujung Pangkah ecosystem demonstrated a statistically significant net expansion over the full 30-year record, from 898.88 ha (1995) to 1816.87 ha (2025) mapped extent (1261.11 to 2213.71 ha error-adjusted; $z = 3.60$, $p < 0.001$). This trajectory was not, however, monotonic: extent grew modestly through 2005, expanded substantially to a peak of 2410.44 ha in 2015, and then contracted by 565.49 ha (net) by 2025, the only decadal net loss recorded in the series. Non-parametric trend analysis (Sen's slope = +35.75 ha/year) is consistent with an overall positive regime, though it should be noted this rate is not uniform across the record, and the 2015–2025 contraction, while spatially and mechanistically plausible, does not independently reach statistical significance at the current validation sample size. This distinction—a robust long-term signal alongside a recent reversal—is a central finding of this revised analysis.

Spatial attribution of the 2015–2025 contraction indicates it is predominantly landward in origin: 78.1% of the attributable loss occurred in interior zones consistent with aquaculture pond and settlement conversion versus 21.9% near the open sea or major channels, consistent with limited seaward erosion. This pattern is corroborated by independent, methodologically distinct assessments of the same subdistrict and by documented socioeconomic drivers of continued pond expansion in the immediate study area. Concurrently, a lagged correlation between the sediment (TSS) proxy and decadal net change ($r = 0.92$, $n = 3$) offers quantitative, though not statistically confirmatory, support for the hypothesis that fluvial sediment delivery from the Bengawan Solo River continues to sustain seaward progradation. These two processes—sustained sediment-driven accretion at the coastal fringe and emergent anthropogenic attrition in the interior—operate concurrently rather than as a single unified regime, and their net balance, not either process alone, will determine the ecosystem's future trajectory and its contribution to regional blue carbon sequestration. Sustaining this ecological resilience accordingly requires coastal management policies that both protect newly accreted seaward frontiers and directly address the anthropogenic conversion already underway in the estuary's interior, making it a corrective policy priority rather than a purely anticipatory one.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/geographies6030085/s1>, GEE code of Ujung Pangkah.

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Abbreviations

The following abbreviations are used in this manuscript:

GEE	Google Earth Engine
RF	Random Forest
NDVI	Normalized Difference Vegetation Index
mNDWI	Modified Normalized Difference Water Index
EVI	Enhanced Vegetation Index
MVI	Mangrove Vegetation Index
TM	Thematic Mapper
OLI	Operational Land Imager
SR	Surface Reflectance
OA	Overall Accuracy
PA	Producer's Accuracy
UA	User's Accuracy
TSS	Total Suspended Solids
CC	Cloud Cover
LULC	Land Use/Land Cover
GIS	Geographic Information System
GCS	Geographic Coordinate System
WGS	World Geodetic System
USGS	United States Geological Survey

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