Study of Sediment Land Elevation Dynamics Using Airborne LiDAR in the Ajkwa Estuary, Mimika, Papua, Indonesia

Pratama S.A.P. [1,3*], Pramadarsah A.[2], Helmi M.[1] and A N Arifa.[1]

[1]Department of Oceanography, Faculty of Fisheries and Marine Sciences, Universitas Diponegoro, Indonesia

[2]Environmental Division, PT Freeport Indonesia, Mimika, Papua, Indonesia

[3]UKM-F REGISTER, Faculty of Fisheries and Marine Science, Universitas Diponegoro, Indonesia

*suryapratama344@gmail.com (*Corresponding author's email only)

Abstract *Estuarine environments are highly dynamic due to tidal activity and sediment input from rivers, often causing rapid elevation changes. The dynamic changes in the Ajkwa Estuary due to rapid sedimentation require a comprehensive and well-structured programme aimed at enhancing ecosystem services, which provide ecological benefits and support local livelihoods. This initiative seeks to establish a sustainable and harmonious estuarine environment through spatial planning, particularly by organising mangrove zones as integral elements of an ecologically, socially, and sustainably valuable landscape. This study examines elevation changes and the role of geo-tube and e-groin (bamboo structures) in enhancing sedimentation. Airborne LiDAR data from 2017, 2019, 2022, and 2024 were processed into digital elevation models (DEMs), and elevation change was analysed using the DEM of Difference (DoD) method within the Geomorphic Change Detection (GCD) tool. Although the DoD method has been used elsewhere with DEM data, its application in estuarine areas remains limited. This study enhances estuary monitoring by applying the method in a dynamic coastal system supported by LiDAR technology. Results show elevation loss between 2017 and 2019. From 2022 to 2024, after installing sediment management geo-tube and e-groin (bamboo structures), intervention areas recorded gains: 99.49% in Area A and 93.91% in Area B, while the non-structured area showed a more stable pattern. The findings confirm that sediments transported into the ModADA area can accumulate effectively with the aid of geo-tube and bamboo structures, making them suitable for mangrove planting and contributing to sustainable estuary management.*

Keywords: Ajkwa estuary, geomorphic change detection (GCD), digital elevation model (DEM), LiDAR, DoD

Introduction

Mangrove-dominated estuarine ecosystems play a critical role as blue carbon reservoirs and provide essential ecosystem services, including biodiversity support, sediment regulation, and coastal protection. The Ajkwa Estuary in Central Papua represents one such system that is highly dynamic due to rapid sediment deposition, requiring continuous monitoring of morphological changes to support sustainable management. Several coastal regions along the southern coast of Papua Island experience a high tidal range, such as Mimika Regency, where the tidal fluctuation ranges from 3.3 to 4.45 m (Aslan *et al*., 2018; Setyadi *et al*., 2021). A study conducted by Alifdini *et al*., (2018) using satellite altimetry data revealed that the maximum tide in Bintuni Bay reached 4.57 m, while in southeastern Papua near the Arafura Sea it reached 4.98 m, and in southern Papua near the Arafura Sea it reached 4.87 m. The wide tidal range is likely one of the main factors contributing to the extensive mangrove forests in southern Papua. Advances in geospatial technology, particularly Light Detection and Ranging (LiDAR), have enabled accurate monitoring of estuarine environments by producing high-resolution Digital Elevation Models (DEMs) with superior vertical accuracy compared to conventional photogrammetry or radar-based DEMs (DeWitt *et al*., 2015). LiDAR-derived DEMs are particularly advantageous in flat and vegetated environments, where they minimize shadow and occlusion effects commonly present in optical imagery (Prasvita *et al*., 2021). A widely adopted technique to analyze terrain change is the DEM of Difference (DoD), which involves subtracting DEMs from different survey periods to quantify elevation differences, erosion, and deposition (Azzoni *et al*., 2023). This method has been applied in diverse contexts, such as monitoring glacial retreat in the Italian Alps (Azzoni *et al*., 2023), detecting shoreline changes in volcanic coastal systems (Esposito *et al*., 2018), and evaluating sediment deposition following extreme storm events in Texas (Williams *et al*., 2024). These applications demonstrate the robustness of DoD in quantifying volumetric change and sediment dynamics across geomorphic settings.

To enhance DoD analyses, the Geomorphic Change Detection (GCD) software provides tools to account for uncertainty, measurement error, and minimum level of detection thresholds, thereby improving the reliability of change detection (Niculiță *et al*., 2020). The GCD framework has been increasingly applied in geomorphological studies, including river channel dynamics, hillslope erosion, and estuarine sedimentation. For example, Wolter *et al*., (2025) utilized GCD to analyze multi-temporal LiDAR DEMs in Iowa to quantify channel changes over an 11-year period, while Ahmad *et al*., (2024) applied GCD to UAV-based DEMs for landslide monitoring in the Himalayas. Furthermore, GCD allows spatially explicit mapping of sediment transport and morphological indices, supporting both scientific understanding and practical management of dynamic landscapes (Munasinghe *et al*., 2021).

In this study, LiDAR-derived DEMs of the Ajkwa Estuary are analyzed using the DoD method within the GCD framework to detect elevation changes caused by sediment deposition. The integration of these approaches provides an effective means to quantify geomorphic changes, supporting better ecosystem management and restoration planning in sediment-impacted estuarine systems.

Literature Review

Accurately detecting morphological change in riverine and estuarine systems requires robust methods for analyzing topographic data collected at different times. One of the most widely adopted approaches is the DEM of Difference (DoD) method, which subtracts one Digital Elevation Model (DEM) from another to quantify surface elevation changes over a specified period. This method has become a standard tool in fluvial and coastal geomorphology, providing spatially explicit measurements of erosion and deposition patterns (Wheaton *et al*., 2010; Azzoni *et al*., 2023). The DoD approach is particularly valuable for identifying sediment transport processes, evaluating restoration outcomes, and monitoring natural or anthropogenic changes in landscapes. The accuracy of DoD analyses is strongly dependent on the quality and resolution of the input DEMs. LiDAR-derived DEMs, for instance, offer high vertical accuracy and fine spatial resolution, making them especially suited for detecting subtle topographic variations (DeWitt *et al*., 2015). However, inherent survey errors, vegetation interference, and surface roughness can introduce uncertainties. For this reason, uncertainty estimation and error propagation are critical components of DoD-based studies (Wheaton *et al*., 2010). To address these challenges, the Geomorphic Change Detection (GCD) software was developed as a specialized tool for DEM differencing. GCD incorporates statistical techniques for error analysis, such as the application of minimum level of detection (minLoD) thresholds, which help distinguish genuine geomorphic change from noise (Niculiță *et al*., 2020). By integrating DEM differencing with uncertainty quantification, GCD provides researchers with reliable methods to calculate volumetric change, map geomorphic processes, and analyze sediment budgets.

Applications of GCD have demonstrated its utility in diverse settings. For example, Esposito *et al*., (2018) used DoD and GCD-based approaches to assess coastal cliff erosion in Southern Italy, while Wolter *et al*., (2025) applied GCD to long-term LiDAR data to evaluate river channel dynamics in Iowa. Similarly, Ahmad *et al*., (2024) employed UAV-derived DEMs within the GCD framework to monitor landslide deformation in the Himalayas. These examples underscore the versatility of DoD and GCD tools in geomorphological studies, ranging from mountainous to coastal and estuarine environments.

Within the Columbia Habitat Monitoring Program (CHaMP), the application of GCD has proven valuable in standardizing topographic survey data for geomorphic change assessment across multiple watersheds. The CHaMP framework emphasizes consistency in survey design, error estimation, and DEM processing to ensure that DoD outputs can be reliably compared across sites and time periods (CHaMP, 2011). By addressing sources of variability such as crew performance and instrument accuracy, CHaMP advances the practical implementation of DoD and GCD methods in large-scale monitoring programs.

The Geomorphic Change Detection (GCD) tools and the DEM of Difference (DoD) method represent highly significant and widely adopted approaches for quantifying topographic changes in geomorphological studies. The DoD method, frequently implemented through GCD software, serves as a fundamental technique for quantitatively estimating geomorphic changes. This involves subtracting an earlier terrain elevation model from a later one to identify areas of erosion (lowering) and deposition (raising), which is crucial for understanding the dynamics of landforms and their processes (Kociuba, 2023; Wheaton, 2008; Pasternack & Wyrick, 2017; Shahverdian *et al*., 2017; Hu *et al*., 2019). The utility of DoD/GCD extends across diverse geomorphic environments, including fluvial systems, glacial settings, landslide monitoring, and mining landscapes. In fluvial systems, the method is employed to assess changes in river channels and valley floors, quantifying erosion and deposition volumes, and shifts in topographic surfaces (Kociuba, 2023; Milan *et al*., 2007; Wheaton *et al*., 2010; Wheaton *et al*., 2013; Pasternack & Wyrick, 2017; Wolter *et al*., 2025). For glacial environments, DoD is applied to estimate geomorphic changes in glacier forelands and proglacial areas, reflecting the impact of glacier melt and associated fluvial processes (Kociuba, 2023; Kociuba *et al*., 2020). In landslide monitoring, the method is valuable for analyzing geomorphological changes before and after landslide events, quantifying erosion and deposition volumes, and assessing the impact of landslides on terrain (Hu *et al*., 2019). Furthermore, DoD is utilized to monitor geomorphic changes in open-pit mines, allowing for the estimation of detectable area, volumetric changes, and mined tonnage (Xiang *et al*., 2018; Haas *et al*., 2016; Esposito *et al*., 2016).

DoD/GCD also enables the assessment of changes resulting from single extreme hydro-meteorological events, such as floods, as well as changes occurring over several years (Kociuba, 2023; Kociuba, 2017). The success of DoD/GCD heavily relies on the availability of high-resolution Digital Elevation Models (DEMs) or Digital Terrain Models (DTMs) (Kociuba, 2023; Kociuba, 2017; Xiang *et al*., 2018). Raw data from LiDAR or SfM require meticulous processing, including ground point classification, to generate accurate DTMs. The Cloth Simulation Filter (CSF) algorithm is mentioned as an automatic method for ground point classification, although manual cleaning is also performed (Kociuba, 2023; Kociuba, 2020). A critical aspect of DoD analysis is accounting for uncertainty. Key sources of uncertainty include measurement errors, survey methodology, ground point classification and interpolation errors, and co-registration errors (Kociuba, 2023; Kociuba, 2020; Wheaton *et al*., 2010; Axelsson, 2000; Xiang *et al*., 2018; Westaway *et al*., 2000). To distinguish real geomorphic changes from noise, a minimum level of detection (min-LoD) is often applied, based on the uncertainty range of the measurements (Kociuba, 2023; Kociuba, 2020; Wheaton *et al*., 2010; Lane *et al*., 1994; Brasington *et al*., 2003). The concept of error propagation is used to determine the overall measurement uncertainty in DoD calculations (Kociuba, 2020; Brasington *et al*., 2003; Lane *et al*., 2003). Studies have indicated that ground point classification methods, such as the CSF algorithm, have a minimal impact on the overall uncertainty range for volumetric estimations of mineral resources in specific contexts (Kociuba, 2020). In summary, the DoD method, facilitated by GCD software, stands as a powerful and versatile tool for quantifying geomorphic changes across diverse landscapes. Its effectiveness is continually being refined through advancements in remote sensing technologies and a deeper understanding of associated uncertaintie

Methodology

Geographically, Mimika Regency is located between 134°31′0″ and 138°31′0″ East Longitude, and between 5°0′0″ and 5°18′0″ South Latitude. The study site is situated in the Otomona Watershed (DAS), specifically at the Ajkwa Estuary, Mimika, Central Papua, shown in Figure 1. The sedimentation rate in the mangrove forests of Mimika Regency was previously measured by Setyadi *et al*., (2021) using sediment stakes and sediment traps. The rate determined by the sediment stake method ranged from 8.4 to 12.3 mm per year, while the rate measured using the sediment trap method ranged from 18.5 to 25.4 mm per year, equivalent to 1.88–2.98 g/cm^2/year. The high sedimentation rate along the southern coast of Papua, particularly in Mimika Regency, enhances the capacity of mangrove forests to adapt to sea-level rise, which has been recorded at approximately 2.6 to 3.4 mm per year (Krauss *et al*., 2003; Saintilan *et al*., 2020). Therefore, the Ajkwa estuary area was selected for further analysis of sedimentation changes using LiDAR technology, supported by the GCD extension to determine the DEM of

Difference (DoD) values.

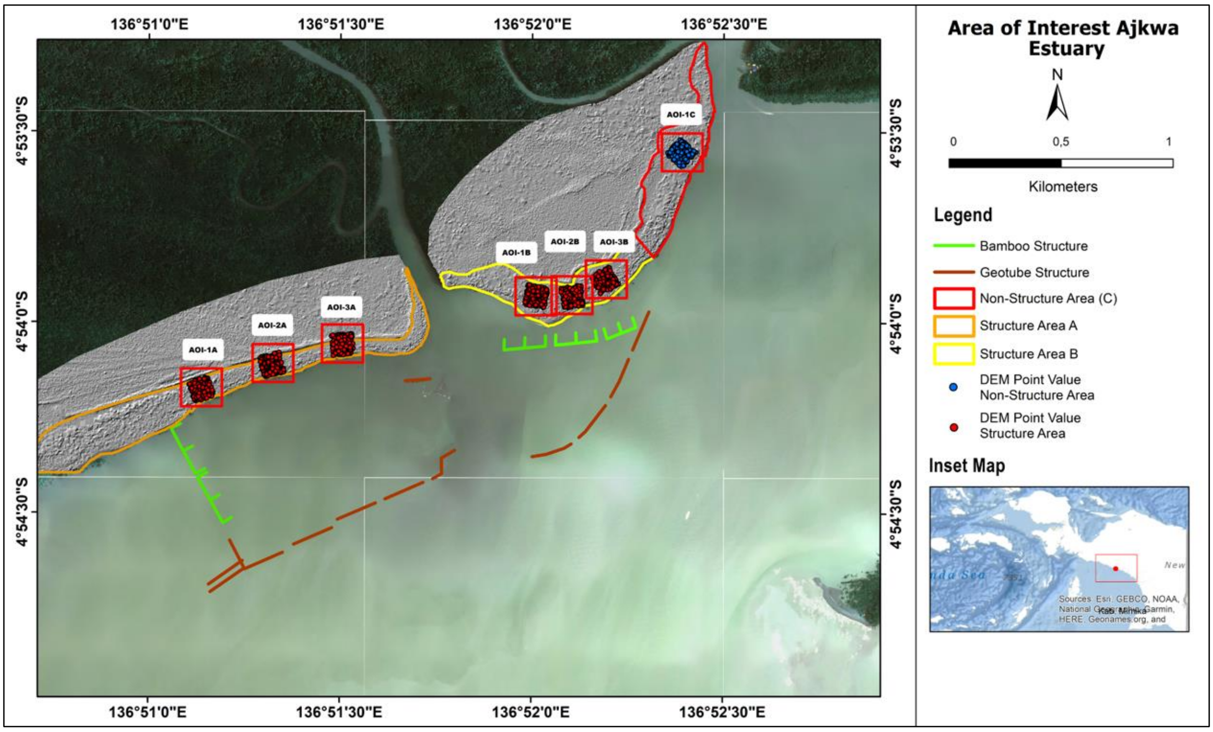
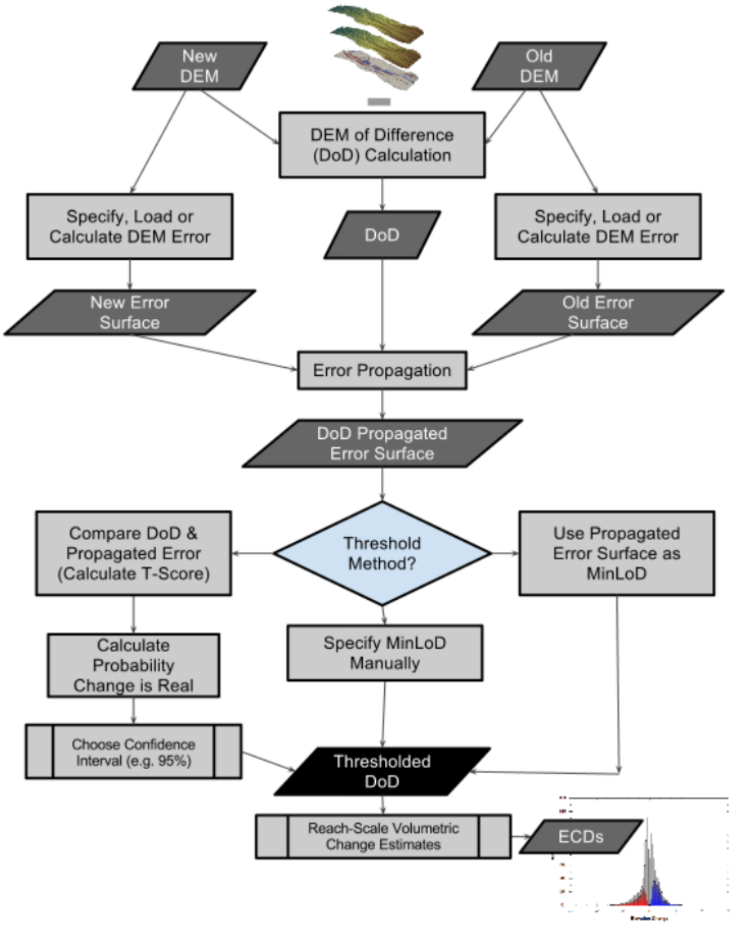


Figure 1: Location map of the study area in the Ajkwa Estuary, Papua, Indonesia.

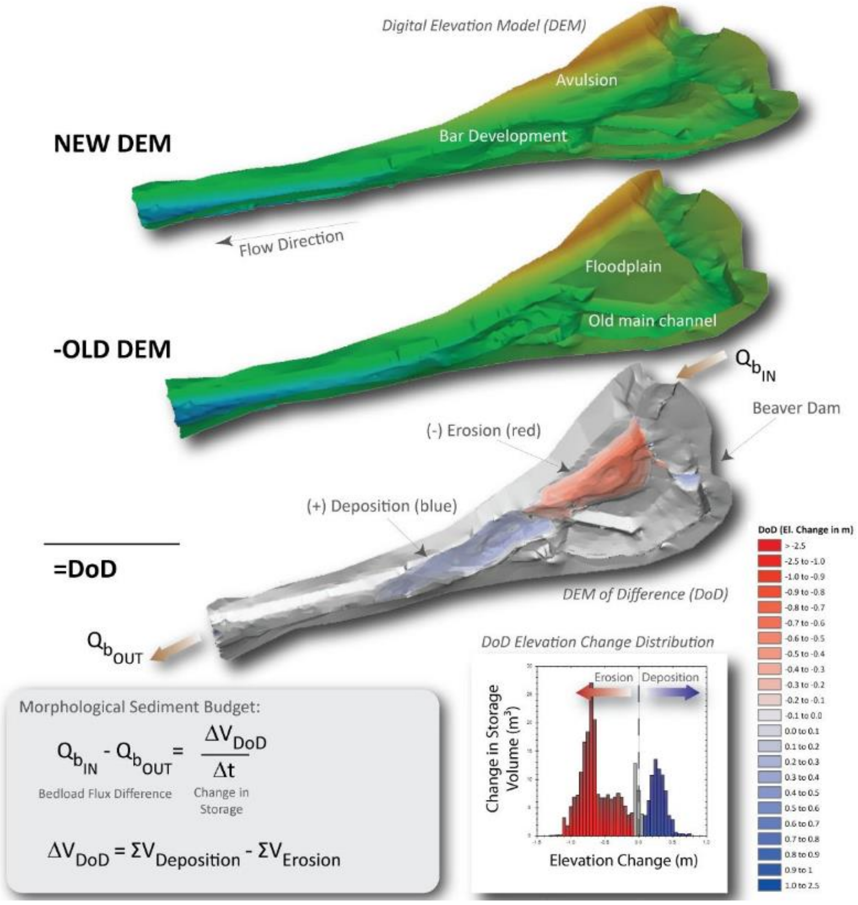
The materials used in this study consisted of both primary and secondary data. The primary data comprised airborne LiDAR imagery with a spatial resolution of 20 cm, which served as the main source for spatial analysis of the study area. Secondary data included the Indonesian Topographic Map (Rupabumi Indonesia/RBI) of Mimika Regency. The study employed a quantitative descriptive method, as the data analyzed were numerical and processed using statistical approaches, particularly to calculate changes in sediment surface elevation within the study area. This method was chosen to provide a clear depiction of sediment elevation dynamics in the Ajkwa Estuary. According to Waruwu *et al*., (2025), quantitative descriptive research is a type of study aimed at describing or characterizing a population or sample in measurable terms. A remote sensing approach using airborne LiDAR was applied. The sampling locations were determined using purposive sampling to ensure representation of environmental conditions at sites experiencing shoreline change, as identified through satellite imagery interpretation. Data processing focused on Digital Elevation Models (DEMs) of the Ajkwa Estuary to quantify changes in sediment elevation. LiDAR data with a resolution of 20 cm were processed into DEMs for the years 2017, 2019, 2022, and 2024.



Source: Wheaton, J.M. (2014). Invited Keynote Talk: Trends and Challenges in Geomorphic Change Detection.

Figure 2: A Standarized GCD Workflow

These DEMs were clipped using the administrative boundary shapefile of Mimika Regency obtained from RBI data, utilizing the "extract by mask" function in the Spatial Analyst tools of ArcGIS software. The extract by mask tool is commonly used to crop raster data, such as DEMs or erosion distribution maps, based on a predefined study area (Saeedi, 2023). Elevation values from each DEM were then extracted using the "extract values to points" function (Khan *et al*., 2022).. In this study, in addition to the analysis using the GCD extension to determine the DEM of Difference (DoD), DEM point data were also utilized. Sampling points were distributed across three study areas: Study Area A, Study Area B, and the Non-Structure Study Area (Area C). These points cover Study Areas A and B, which are coastal zones influenced by bamboo and geotube structures, and Area C, or the non-structure area, which is not directly affected by these structures. As shown in Figure 1, AOI-1A, AOI-2A, and AOI-3A represent locations within Study Area A, while AOI-1B, AOI-2B, and AOI-3B correspond to Study Area B. Meanwhile, Area C consists of a single DEM point, AOI-1C, which is situated in the non-structure study area. Study Areas A and B each contained three areas of interest (AOIs) with 200 elevation sampling points per AOI, while the Non-Structure Study Area contained one AOI with the same number of points. The extracted data were processed and visualized in the form of graphs using Microsoft Excel. This step aimed to provide a visual representation of eln cevatiohanges in each year, allowing for a quantitative and spatial assessment of surface morphology dynamics in the study sites.



Source: Bangen, S. & Wheaton, J.M. (2012). CHaMP Crew Variability: Influence on Topographic Surfaces & Derived Metrics.

Figure 3: Concept of DEM Differencing for Morphological Sediment Budgeting.

As CHaMP repeat monitoring continues, pairwise comparisons between more recent DEMs (New DEM) and previous DEMs (Old DEM) can be conducted through cell-by-cell subtraction of elevation values, resulting in negative (erosion) and positive (deposition) DoD values. These elevation changes can then be multiplied by the cell size and summed to estimate the total erosion and deposition volumes (Bangen & Wheaton, 2012). Subsequently, elevation change analysis was performed using ArcMap 10.8 software equipped with the Geomorphic Change Detection (GCD) extension (figure 2). DEMs from 2017, 2019, 2022, and 2024 were input into the GCD extension for spatial analysis. Comparisons were made between DEM pairs: 2017–2019, 2017–2022, and 2017–2024. The DEM of Difference (DoD) method was employed, which operates on the principle of subtracting a newer DEM from an older one to calculate elevation differences (Figure 3) (Azmoon *et al*., 2022).

An important application of DoD is its integration within GCD analysis, which enables quantitative measurement of geomorphic changes. GCD not only functions as a monitoring tool for surface morphology but also supports the calculation of sediment budgets and the assessment of uncertainty in topographic change modeling (Marić *et al*., 2021). This approach enhances the understanding of landform change patterns, whether driven by natural processes or human activities. By applying this method, elevation changes can be quantified through differences in DEM values across multiple time periods, thereby providing insights into surface accretion or degradation in the study area.

Results and Discussion

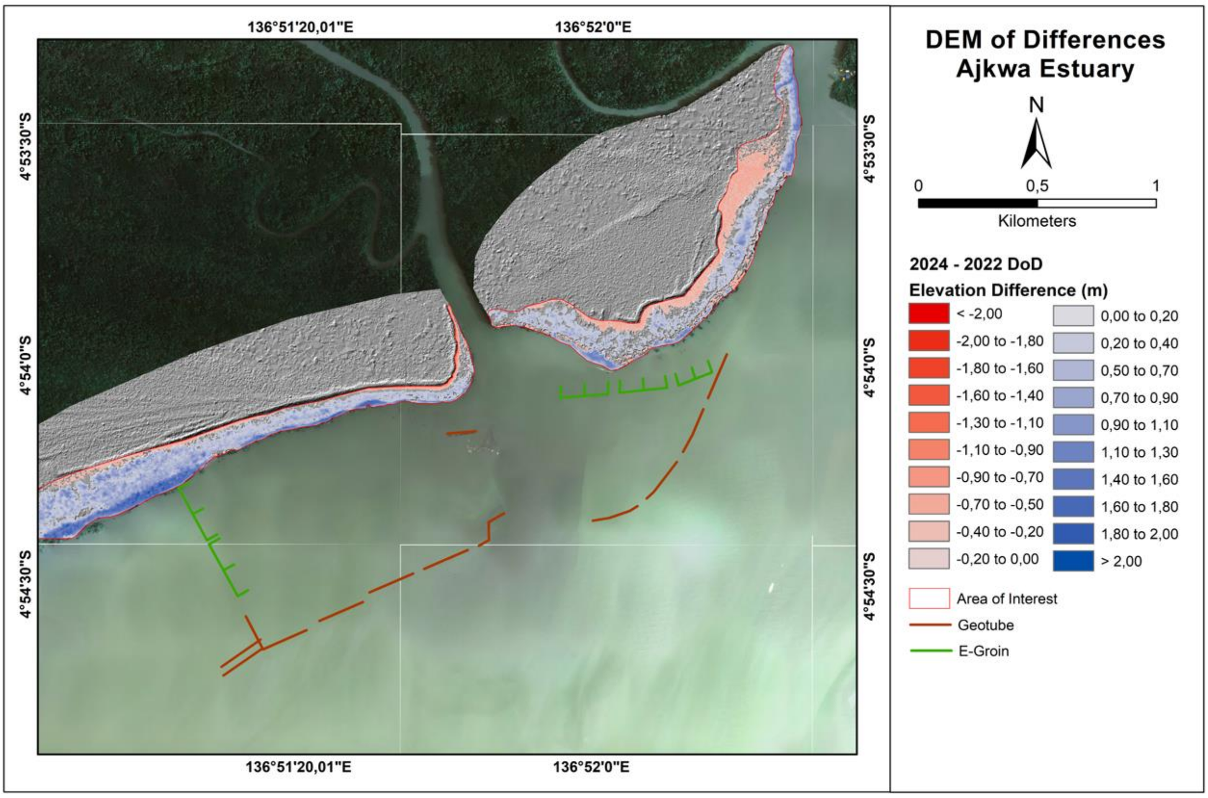


Figure 4: DoD 2024-2022 of Ajkwa Estuary

Based on Figure 4, the results of the DoD analysis for the 2024–2022 period are shown, with the masking area of interest applied to the entire study area. The DoD analysis between 2024 and 2022 in the Ajkwa Estuary revealed a complex pattern of topographic change. The total area experiencing surface lowering was recorded at 164,972.72 m² (16.50 ha), while the area undergoing surface elevation increase reached 415,916.44 m² (41.59 ha), out of a total study area of 580,889.16 m² (58.09 ha). The percentage of the area with detectable change reached 75.28%, indicating that the majority of the region underwent significant geomorphic transformation. In terms of volume, surface lowering amounted to 47,220.84 m³, while surface elevation gain was more dominant at 228,990.62 m³. The proportion of elevation change showed a considerable imbalance, with 17.10% of the area experiencing lowering and 82.90% showing an increase. This result aligns with Kim *et al.*, (2024), who reported that estuarine systems commonly exhibit a net depositional tendency due to tidal asymmetry and the residual transport of suspended sediments toward the inner estuary. Such hydrodynamic conditions can explain the greater proportion of surface elevation gain compared to lowering observed in this study. The ratio of net to total volume reached 65.81%, signifying that although sediment accumulation was still more dominant than erosion, sediment redistribution in this period was relatively greater compared to previous years. These changes are most likely influenced by river flow dynamics, sediment supply, or anthropogenic interventions within the estuarine zone, in line with Hidayah and Apriyanti (2020), who noted that estuarine change is largely driven by river dynamics, sediment input, and human activities.

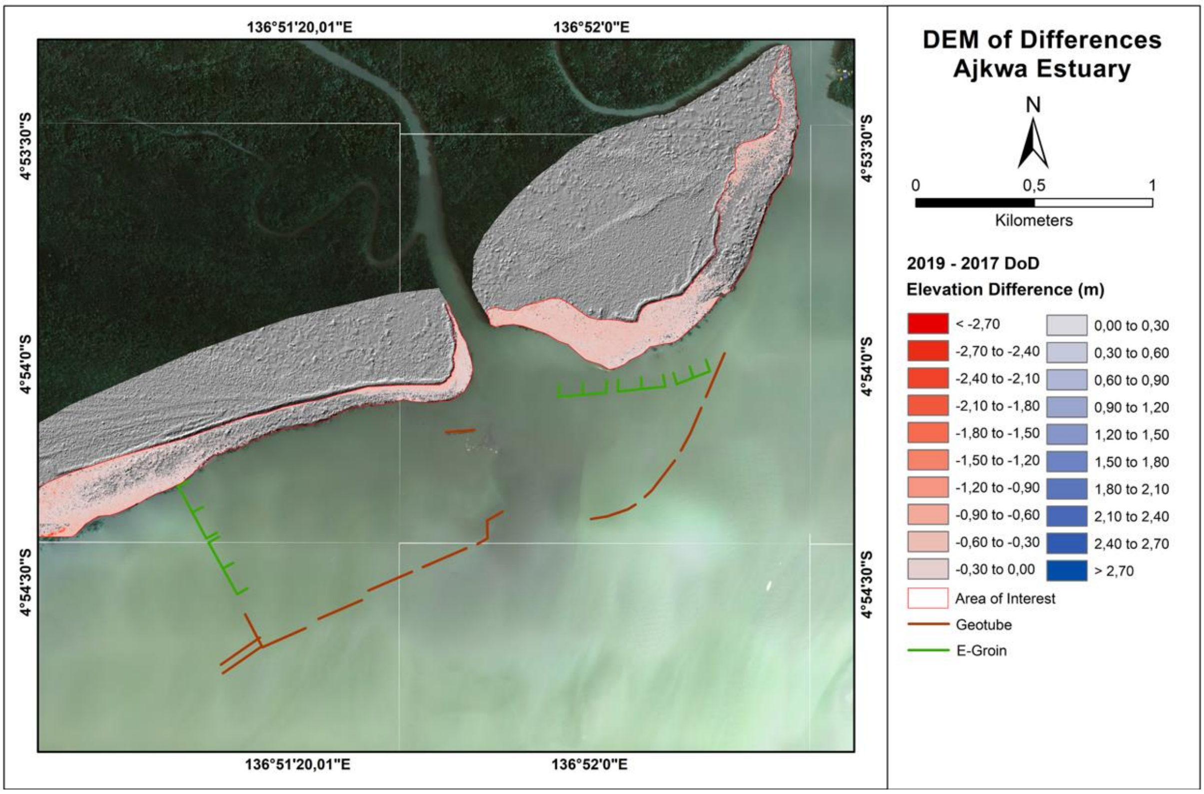


Figure 5: DoD 2019-2017 of Ajkwa Estuary

Based on Figure 5, showing the DoD results analysis between 2019 and 2017 in the Ajkwa Estuary indicated a strong dominance of erosion processes over sediment accumulation. The total area experiencing surface lowering was 554,792.64 m² (55.48 ha), substantially greater than the area of surface elevation increase, which was only 26,327.16 m² (2.63 ha), from a total study area of 581,119.80 m² (58.11 ha). The percentage of the area with detectable change was 58.29%, showing that more than half of the area experienced topographic transformation. In terms of volume, total surface lowering reached 134,765.53 m³, while the volume of surface elevation gain was only 1,433.52 m³, resulting in a large imbalance, with 98.95% of the area experiencing lowering and only 1.05% showing an increase. The imbalance percentage from equilibrium reached –48.95%, reflecting a strong tendency toward large-scale material loss. The negative net-to-total volume ratio (–97.89%) further confirmed that erosional processes were far more dominant than deposition, pointing to severe land degradation. This phenomenon is most likely triggered by accelerated river flow transporting material downstream without sufficient new sediment input to offset the loss, or by ecological disturbances and human activities within the estuary. This finding is consistent with Kurniadini and Putra (2024), who stated that coastal sedimentation is influenced by multiple factors, including river discharge, wave action, and sea level fluctuations, with rivers acting as the primary conveyor of sediment from upstream to downstream, where it is deposited in estuaries or deltas.

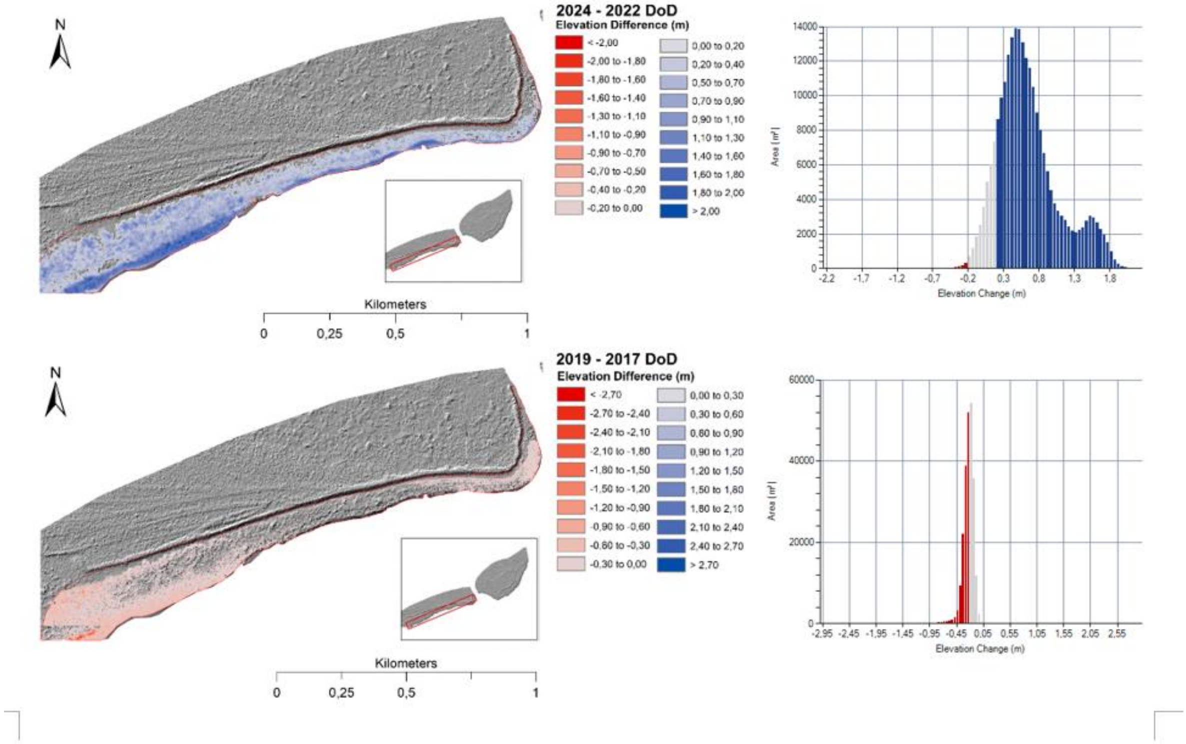


Figure 6: DoD 2024 – 2022 dan DoD 2019 – 2017 Area A of Ajkwa Estuary

The comparison of DoD results in Structure Area A of the Ajkwa Estuary between the periods 2019–2017 and 2024–2022 revealed highly contrasting geomorphological changes. During the

2019–2017 period, this area was dominated by extensive surface lowering processes, with a total lowered area of 235,483.64 m² (23.55 ha) and only 461.72 m² (0.05 ha) showing elevation gain. This resulted in an extreme imbalance, with 99.97% of the area experiencing lowering and a sharply negative net-to-total volume ratio of –99.95%. Such conditions reflect large-scale erosion leading to severe land degradation in the area. In contrast, during the 2024–2022 period, the situation was completely reversed, with surface elevation gain dominating across 228,869.80 m² (22.89 ha), while only 7,075.28 m² (0.71 ha) of the area experienced surface lowering. This morphological reversal is consistent with Gonçalves *et al*., (2025), who found that engineered coastal structures effectively trap finer sediments (silt and clay) and promote sediment accumulation within estuarine environments.

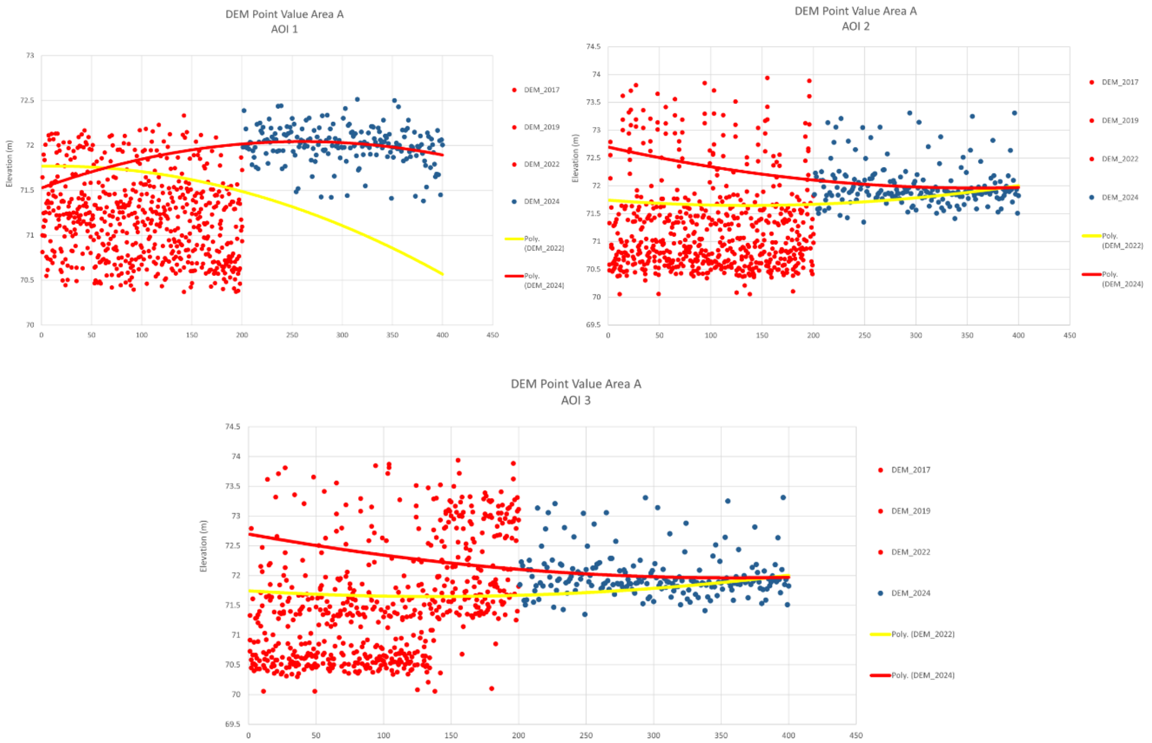


Figure 7: Elevation value graph for Area A in AOI-1A, AOI-2A, and AOI-3A

Based on the graphical results, elevation changes in Area A indicate that AOI 1 experienced a more pronounced increase in elevation compared to AOI 2 and AOI 3 following the installation of geotube and groin structures. Prior to the construction of these structures, the red data from the 2017–2022 period showed a consistent trend of surface lowering across all three AOIs, reflecting continuous erosion. However, after the structures were installed in 2023–2024, the blue data for AOI 1 demonstrated a clearer and more uniform elevation gain. This suggests that AOI 1 benefited from stronger protective effects, likely due to its more strategic position in dissipating flow energy and promoting sediment trapping and deposition. In contrast, AOI 2 appeared relatively stable without significant elevation gains, while AOI 3 showed partial recovery, although the increase was less substantial than that of AOI 1. These differences reflect the varying contribution of the structures across AOIs, depending on their positions and the hydrodynamic conditions in each sub-area. Consequently, AOI 1 can be considered the most positively impacted area by the structural interventions compared to the other two AOIs.

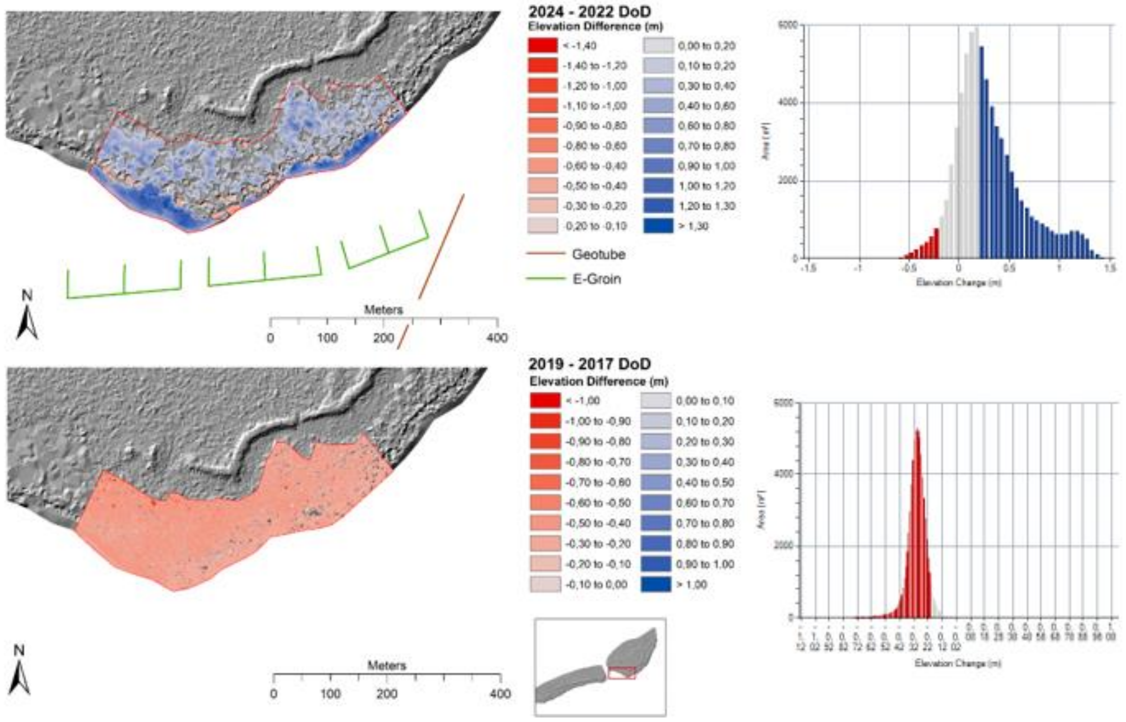


Figure 8: DoD 2024 – 2022 dan DoD 2019 – 2017 Area B of Ajkwa Estuary

The comparison of DoD results in Structure Area B of the Ajkwa Estuary between the periods 2019–2017 and 2024–2022 highlights a dramatic geomorphological transformation from erosion-dominated conditions toward recovery through sediment accumulation. During the 2019–2017 period, nearly the entire area experienced surface lowering, covering 71,354.72 m² (7.14 ha), with only 2.16 m² showing elevation gain an amount that is practically negligible. The total volume of surface lowering reached 21,203.87 m³, yielding a net-to-total volume ratio of –100%, which indicates a complete loss of material without compensatory sedimentation. By contrast, the situation reversed in the 2024–2022 period, when 60,360.52 m² (6.04 ha) of the area exhibited surface elevation gains with a total volume of 22,929.92 m³, while the area undergoing lowering was drastically reduced to 10,995.96 m² (1.10 ha). The elevation percentage also shifted significantly, from 100% lowering to 93.91% elevation gain. The imbalance, which was previously negative (–50%), reversed to a positive value of 43.91%, indicating the dominance of sediment deposition processes. The net-to-total volume ratio, which surged from –100% to 87.82%, further reinforces the evidence of recovery in this area, most likely driven by changes in river flow dynamics, increased sediment supply, or anthropogenic interventions that facilitated topographic restoration. These changes reflect a remarkable shift in geomorphological processes, from extreme degradation toward intensive landform regeneration.

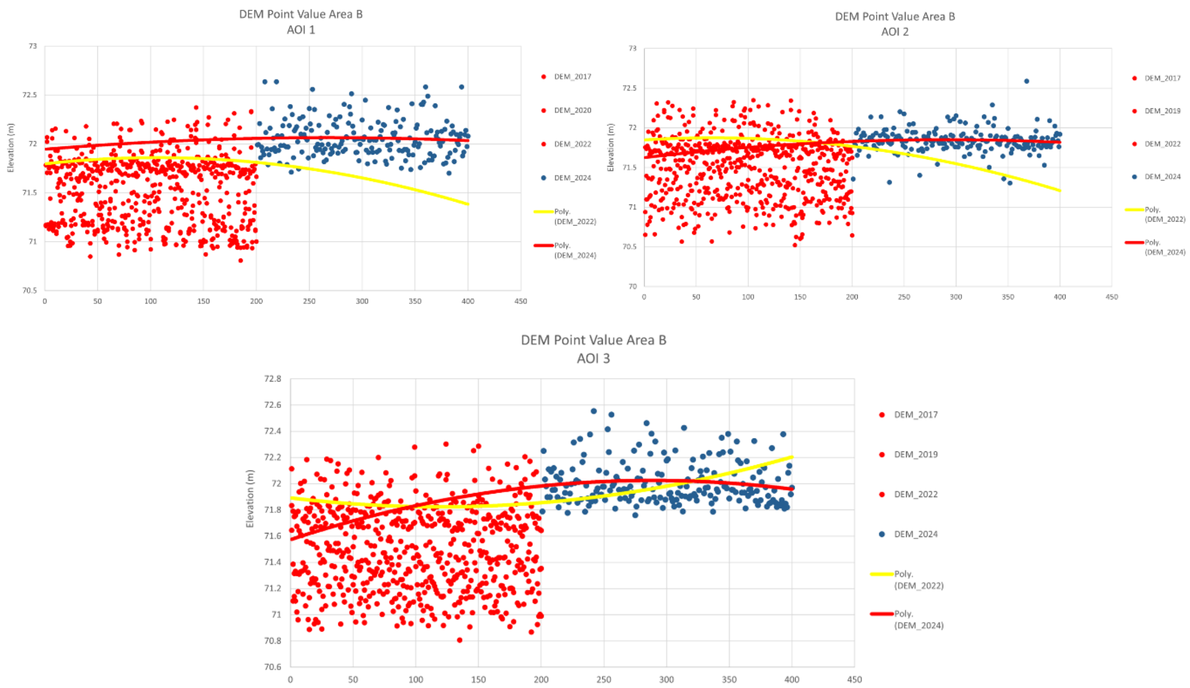


Figure 9: Elevation value graph for Area B in AOI-1B, AOI-2B, and AOI-3B

Based on the elevation graphs in Area B for AOI 1, AOI 2, and AOI 3, a clear difference can be observed between the periods before and after the installation of geotube and groin structures. In the 2017–2022 data, represented by red points, elevation generally declined or remained stagnant, indicating ongoing erosion and limited sediment accumulation. However, following the installation of structures in 2023–2024, represented by blue points, elevation trends became more stable, with some areas showing a marked positive increase. Area B is located near the e-groin structure, which was designed to slow water currents and retain sediments within the area. The influence of the e-groin appears to be particularly effective in AOI 3, where the blue elevation trend shows a more consistent increase compared to the other AOIs. The structure functions by trapping sediment transported by the current, creating depositional zones on the downstream side of the groin, thereby supporting surface elevation gains. In addition, the reduced flow velocity around the e-groin helps to minimize further erosion, providing long-term stability for Area B.

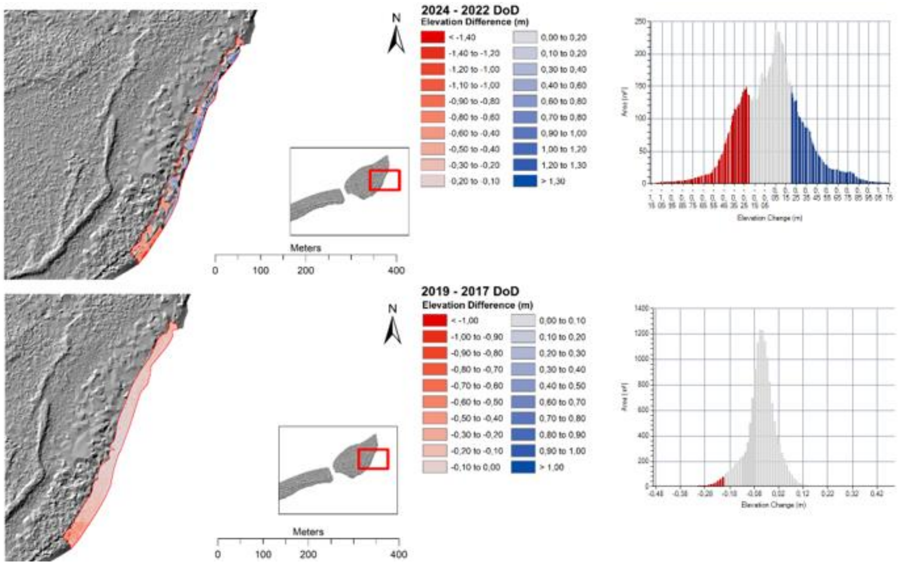


Figure 10: DoD 2024 – 2022 dan DoD 2019 – 2017 Area Non Structure (C) of Ajkwa Estuary

The comparison of DoD results in the non-structure area of the Ajkwa Estuary between the periods 2019–2017 and 2024–2022 reveals strikingly different dynamics, particularly when contrasted with the structured areas. During the 2019–2017 period, the non-structure area was dominated by surface lowering, covering 11,582.52 m² (1.16 ha) with a volume loss of 797.90 m³, while surface elevation gain occurred only across 2,295.64 m² (0.23 ha) with a minor volume of 78.70 m³. The dominance of surface lowering reached 91.02%, indicating stronger erosional processes in areas without structural protection. This stands in contrast to structured areas, which tended to be more stable due to the role of geotubes and groins in retaining sediments and buffering currents.

In the 2024–2022 period, however, the non-structure area demonstrated signs of recovery, with elevation gain covering 7,421.44 m² (0.74 ha), exceeding the surface lowering extent of 6,457.12 m² (0.65 ha). The gain in volume was also greater, reaching 1,749.38 m³ compared to the lowering volume of 1,546.62 m³, resulting in a relatively balanced imbalance ratio of only 3.08% and a positive net-to-total volume ratio of 6.15%. This indicates an increase in sediment deposition activity, although the area remains more vulnerable to change compared to areas with structural interventions. The absence of protective structures makes this area more susceptible to erosion during periods of high discharge, while also allowing it to more readily receive sediment during slower flows or when material is redistributed from upstream. This non-structure site was deliberately selected because it represents a zone not directly influenced by geotube and bamboo structures and is not located directly opposite the river mouth. As such, it serves as an important reference area for understanding natural patterns of erosion and deposition in the estuary.

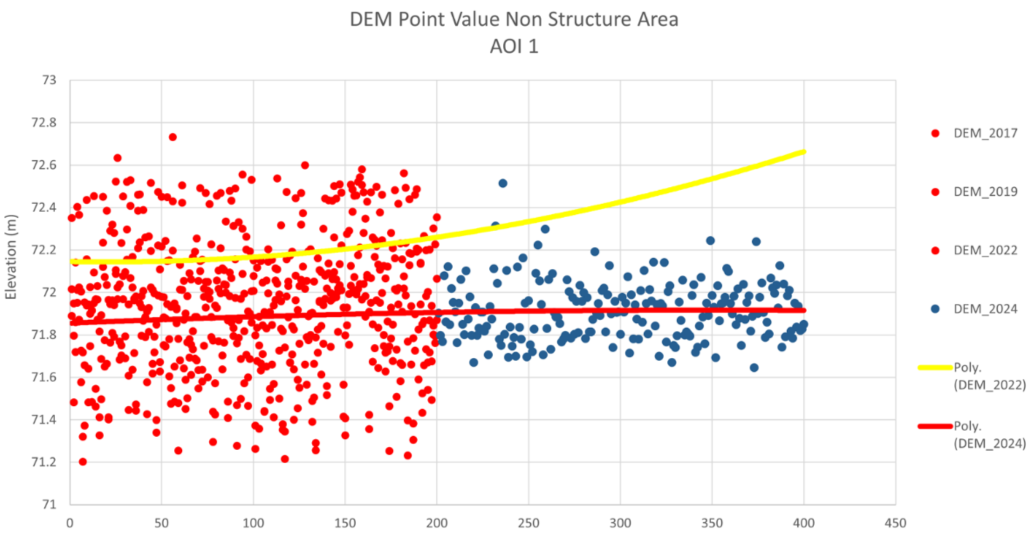


Figure 11: Elevation value graph for Area Non-Structure AOI-1C

In the non-structure area (AOI 1), the elevation graph displays a marked contrast compared to areas protected by geotube and e-groin structures. The 2017–2022 data (shown in red) reveal a relatively stable downward trend in elevation within the range of 71.6 to 72.2 meters. Although slight changes are evident in 2024 (shown in blue), the elevation generally remained flat without any significant increase. In contrast, structured areas exhibited clearer elevation gains in the blue data following the installation of geotube and e-groin structures. This indicates that, in the absence of physical barriers capable of retaining sediments, erosion processes tend to dominate, and the limited sedimentation occurring in the non-structure area is insufficient to produce substantial elevation recovery.

Conclusion and Recommendation

The DoD analyses in the Ajkwa Estuary demonstrate distinct geomorphological responses between structured and non-structured areas. In Area A, the results revealed a dramatic shift from extensive surface lowering in 2019–2017 to significant surface elevation gains in 2024–2022. This transformation indicates the effectiveness of geotube and groin installations, with AOI 1 showing the strongest recovery due to its strategic position in dissipating flow energy and promoting sediment deposition.

Similarly, Area B experienced a remarkable transition from complete material loss in 2019–

2017 to substantial sediment accumulation in 2024–2022. The presence of e-groin structures played a crucial role in stabilizing the area, particularly in AOI 3, where consistent elevation gains were recorded. These findings highlight the role of structural interventions in shifting the geomorphic balance from degradation toward regeneration.

In contrast, the Non-Structure Area exhibited greater vulnerability to erosion, with a dominance of surface lowering during 2019–2017. Although signs of recovery were observed in 2024–2022, the magnitude of sedimentation was limited and less consistent compared to structured areas. The absence of protective barriers made this area more prone to erosion during high flows, while deposition only occurred under favorable hydrological conditions. Overall, these results suggest that structural interventions such as geotubes and bamboo structures significantly enhance sediment retention and surface stability, whereas non-structured zones remain highly dynamic and susceptible to erosional processes.

Recommendations:

Despite the valuable insights provided by DoD and GCD analyses, the findings should be supported by ground checks or field validation to verify the accuracy of detected elevation changes. Field validation is essential to assess sediment composition, evaluate structural integrity, and confirm the spatial distribution of erosion and deposition. This integrated approach will improve confidence in remote sensing results and provide stronger foundations for designing adaptive management strategies in the Ajkwa Estuary.

Acknowledgements

The authors would like to express their sincere gratitude to the Environmental Division of PT Freeport Indonesia, particularly the Environmental Project Team, for their invaluable assistance in providing data facilities, supporting data processing, and facilitating field activities throughout this study. We also extend our appreciation to the World Class University (WCU) Program – Student Go International Scheme, Universitas Diponegoro, for their financial support that enabled participation in the Asian Conference on Remote Sensing (ACRS) 2025. Special thanks are also conveyed to the REGISTER (Remote Sensing, Geographic Information System, and Technology Research) Organization for providing a collaborative research platform that greatly contributed to the completion of this work.

References

Ahmad, N., Shafique, M., Hussain, M. L., Islam, F., Tariq, A., & Soufan, W. (2024). Characterization and geomorphic change detection of landslides using UAV multi-temporal imagery in the Himalayas, Pakistan. *Land, 13*(7), 904.

Alifdini, N., Putra, A., & Rachman, F. (2018). Analysis of ocean waves in three potential sites for renewable energy development in Indonesia. *Ocean Engineering, 165*, 34–42.

Aslan, A., Rahman, A. F., & Robeson, S. M. (2018). Investigating the use of ALOS PRISM data in detecting mangrove succession through canopy height estimation. *Ecological Indicators, 87*, 136–143.

Axelsson, P. (2000). DEM generation from laser scanner data using adaptive TIN models. *International Archives of Photogrammetry and Remote Sensing, 33*(4), 110–117.

Azmoon, B., Biniyaz, A., & Liu, Z. (2022). Use of high-resolution multi-temporal DEM data for landslide detection. *Geosciences, 12*(10), 378.

Azzoni, R. S., Pelfini, M., & Zerboni, A. (2023). Glacier and periglacial geomorphological changes detected using DoD analysis in the Italian Alps. *Remote Sensing, 15*(12), 3190.

Bangen, S., & Wheaton, J. M. (2012). *CHaMP Crew Variability: Influence on Topographic Surfaces & Derived Metrics.* Draft Report to Eco Logical Research, Inc. & Columbia Habitat and Monitoring Program: Logan, UT.

Brasington, J., Langham, J., & Rumsby, B. (2003). Methodological sensitivity of morphometric estimates of coarse fluvial sediment transport. *Geomorphology, 53*(3–4), 299–316.

Brasington, J., Rumsby, B. T., & McVey, R. A. (2000). Monitoring and modelling morphological change in a braided gravel-bed river using high-resolution GPS-based survey. *Earth Surface Processes and Landforms, 25*(9), 973–990.

DeWitt, J. D., Warner, T. A., & Conley, J. F. (2015). Comparison of DEMs derived from USGS DLG, SRTM, a statewide photogrammetry program, ASTER GDEM and LiDAR: Implications for change detection. *GIScience & Remote Sensing, 52*(2), 179–197.

Esposito, G., Mastrorocco, G., Salvini, R., Oliveti, M., & Starita, P. (2017). Application of UAV photogrammetry for the multi-temporal estimation of surface extent and volumetric excavation in the Sa Pigada Bianca open-pit mine, Sardinia, Italy. *Environmental Earth Sciences, 76*(3), 103.

Esposito, G., Salvini, R., Matano, F., Sacchi, M., & Troise, C. (2018). Evaluation of geomorphic changes and retreat rates of a coastal pyroclastic cliff in the Campi Flegrei volcanic district, southern Italy. *Journal of Coastal Conservation, 22*(5), 957–972.

Gonçalves, C., Verdelhos, T., Caçador, I., Oliveira, P. J. V., Marques, D., & Veríssimo, H. (2025). Effectiveness of eco-engineering structures to promote sediment particles retention in estuarine salt marshes. *Water, 17*(5).

Haas, F., Hilger, L., Neugirg, F., Umstädter, K., Breitung, C., Fischer, P., & Becht, M. (2016). Quantification and analysis of geomorphic processes on a recultivated iron ore mine on the Italian island of Elba using long-term ground-based lidar and photogrammetric SfM data by a UAV. *Natural Hazards and Earth System Sciences, 16*(5), 1269–1288.

Hidayah, Z., & Apriyanti, A. (2020). Deteksi perubahan garis pantai Teluk Jakarta bagian timur tahun 2003–2018. *Jurnal Kelautan: Indonesian Journal of Marine Science and Technology, 13*(2), 143–150.

Hu, S., Qiu, H., Pei, Y., Cui, Y., Wang, X., Zhang, Y., & He, Y. (2019). Digital terrain analysis of a landslide on the loess tableland using high-resolution topography data. *Landslides, 16*(3), 617–632.

Khan, Q., Liaqat, M. U., & Mohamed, M. M. (2022). A comparative assessment of modeling groundwater vulnerability using DRASTIC method from GIS and a novel classification method using machine learning classifiers. *Geocarto International, 37*(20), 5832–5850.

Kim, S. I., Seo, J. Y., Park, J. H., Kim, P. J., Kim, I. G., Kim, K. M., & Ha, H. K. (2024). Imbalance of sediment transport in a meso-tidal bay: effect of tidal pumping and residual circulation. *Frontiers in Marine Science, 11*, 1362583.

Kociuba, W. (2017). Assessment of sediment sources throughout the proglacial area of a small Arctic catchment based on high-resolution digital elevation models. *Geomorphology, 287*, 73–89.

Kociuba, W. (2020). Different paths for developing terrestrial LiDAR data for comparative analyses of topographic surface changes. *Applied Sciences, 10*(21), 7409.

Kociuba, W. (2023). Geomorphic changes of the Scott River alluvial fan in relation to a four-day flood event. *Water, 15*(7), 1368.

Krauss, K. W., Allen, J. A., & Cahoon, D. R. (2003). Differential rates of vertical accretion and elevation change among aerial root types in Micronesian mangrove forests. *Estuarine, Coastal and Shelf Science, 56*, 251–259.

Kurniadini, R. A., & Putra, A. K. (2024). *Selamatkan pesisir kita membangun kesadaran ekologis.* [In press].

Lane, S. N., Richards, K. S., & Chandler, J. H. (1994). Developments in monitoring and modelling small-scale river bed topography. *Earth Surface Processes and Landforms, 19*, 349–368.

Lane, S. N., Westaway, R. M., & Hicks, D. M. (2003). Estimation of erosion and deposition volumes in a large, gravel-bed, braided river using synoptic remote sensing. *Earth Surface Processes and Landforms, 28*, 249–271.

Marić, I., Šiljeg, A., Domazetović, F., & Cukrov, N. (2021). Application of geomorphic change detection (GCD) on tufa digital elevation models (DEMs) of submillimeter resolution – Case study National Park Krka, Croatia. *Zeitschrift für Geomorphologie, 63*(1), 81–93.

Milan, D. J., Heritage, G. L., & Hetherington, D. (2007). Application of a 3D laser scanner in the assessment of erosion and deposition volumes and channel change in a proglacial river. *Earth Surface Processes and Landforms, 32*(11), 1657–1674.

Munasinghe, D., Cohen, S., & Gadiraju, K. (2021). A review of satellite remote sensing techniques of river delta morphology change. *Remote Sensing in Earth Systems Sciences, 4*(1), 44–75.

Niculiță, M., Howard, A. J., & Chambers, J. (2020). Geomorphic change detection (GCD) and its role in landscape archaeology. *Remote Sensing, 12*(5), 889.

Pasternack, G. B., & Wyrick, J. R. (2017). Flood-driven topographic changes in a gravel-cobble river over segment, reach, and morphological unit scales. *Earth Surface Processes and Landforms, 42*(3), 487–502.

Prasvita, D. S., Santoni, M. M., Wirawan, R., & Trihastuti, N. (2021). Klasifikasi pohon kelapa sawit pada data fusi citra LiDAR dan foto udara menggunakan convolutional neural network. *JIPI (Jurnal Ilmiah Penelitian dan Pembelajaran Informatika), 6*(2), 406–415.

Saeedi, M. (2023). Desirability assessment with the aid of satellite imagery and chorographic data in the areas with agricultural land use in Esfahan; Geo-spatial analysis and fuzzy approach nexus. *Journal of Biotechnology and Bioprocessing, 4*(3), 2766–2314.

Saintilan, N., Khan, N. S., Ashe, E., Kelleway, J. J., Rogers, K., Woodroffe, C. D., & Horton, B. P. (2020). Thresholds of mangrove survival under rapid sea-level rise. *Science, 368*(6495), 1118–1121.

Setyadi, G., Sugianto, D. N., Wijayanti, D. P., Pribadi, R., & Supardy, E. (2021). Sediment accretion and total organic carbon accumulation among different mangrove vegetation communities in the Kamora Estuary of Mimika Regency, Papua, Indonesia. *Journal of Ecological Engineering, 22*(11).

Shahverdian, S. M., Macfarlane, W. W., Stevens, G., Meier, M., & Wheaton, J. M. (2017). *Geomorphic response to pilot river restoration on the San Rafael River, Utah: A pilot installation of beaver dam analogues.* Prepared for the Utah Bureau of Land Management & Utah Division of Wildlife Resources: Logan, UT.

Waruwu, M., Puat, S. N., Utami, P. R., Yanti, E., & Rusydiana, M. (2025). Metode penelitian kuantitatif: Konsep, jenis, tahapan dan kelebihan. *Jurnal Ilmiah Profesi Pendidikan, 10*(1), 917–932.

Westaway, R. M., Lane, S. N., & Hicks, D. M. (2000). The development of an automated correction procedure for digital photogrammetry for the study of wide, shallow, gravel-bed rivers. *Earth Surface Processes and Landforms, 25*(2), 209–226.

Wheaton, J. M. (2008). *Uncertainty in morphological sediment budgeting of rivers.* Doctoral dissertation, University of Southampton.

Wheaton, J. M., Brasington, J., Darby, S. E., & Sear, D. A. (2010). Accounting for uncertainty in DEMs from repeat topographic surveys: Improved sediment budgets. *Earth Surface Processes and Landforms, 35*, 136–156.

Wheaton, J. M., Brasington, J., Darby, S. E., Sear, D. A., & Kasprak, A. (2013). Morphodynamic signatures of braiding mechanisms as expressed through change in sediment storage in a gravel-bed river. *Journal of Geophysical Research: Earth Surface, 118*, 759–779.

Williams, H. F. L., Valastro, J., & Anderson, J. (2024). DEM of difference analysis of hurricane-induced sedimentation in Matagorda Peninsula, Texas. *Journal of Coastal Research, 40*(1), 12–25.

Wolter, C. F., Schilling, K. E., Streeter, M. T., & Anderson, E. S. (2025). Using LiDAR-based DEM elevation difference calculations to estimate net streambank erosion in an Iowa river, USA. *River Research and Applications.*

Xiang, J., Chen, J., Sofia, G., Tian, Y., & Tarolli, P. (2018). Open-pit mine geomorphic changes analysis using multi-temporal UAV survey. *Environmental Earth Sciences, 77*(6), 220.