Technologique: A Global Journal on Technological Developments and Scientific Innovations
2025, Vol. 5, No.1, 63 – 81 | ISSN Online: 3028-1415 | ISSN Print: 3028-1407
DOI: https://doi.org/10.62718/vmca.tech-gjtdsi.5.1.SC-1025-004

Coupled Satellite-Based, Depth of Closure and Wave Propagation Modelling and Analysis of Dredging Impacts along the Coastline of San Felipe, Zambales

OPEN ACCESS

Article History:

Received: 12 September 2025
Accepted: 28 October 2025
Published: 18 November 2025

Prince Edike, PhD, ORCID No. 0009-0002-9351-7158

Institute of Area Management (IAM), St. Augustine Sambali Fund, Inc. (SASFI), Iba, Zambales, Philippines
School of Advanced Studies, Saint Louis University, Baguio City, Philippines

Abstract

Dredging within or shallower than the Depth of Closure (DoC) has been identified as a critical driver of coastal instability, particularly in high-energy environments such as the San Felipe, Zambales coastline. This study integrates satellite-based shoreline monitoring, empirical modeling of wave transformation, and morphodynamic analysis to quantify the impacts of dredging near the Sto. Tomas River exit. Quarterly Sentinel-2 imagery (2020–2025) was processed using a geodata science approach in Google Colab (Python 3.0), employing cloud masking, Normalized Difference Water Index (NDWI), and regression-based shoreline change analysis. These physical changes correlate with a negative sediment budget following the onset of dredging shortly before 2023 and afterwards, underscoring reduced sediment supply as a key mechanism of accelerated erosion. The study highlights the compounded risks of dredging-induced morphodynamic changes, wave run-up, and sea-level rise, which threaten coastal properties, ecosystems, and livelihoods; reflecting the high cost of unmanaged shoreline retreat. Importantly, the findings stress the inadequacy of current Philippine environmental impact assessments (EIA), which often rely on secondary data and fail to incorporate DoC-based dredging thresholds, sediment transport modeling, or wave transformation dynamics. By combining remote sensing, empirical 2D/3D modeling, and process-based analysis, this research demonstrates the necessity of integrating DoC criteria, sediment budget accounting, and high-resolution simulation into dredging project evaluations. Such approaches can provide more reliable predictions of coastal response, ensuring that regulatory frameworks evolve to protect vulnerable shorelines while balancing the demand for marine sand resources.

Keywords: Satellite Data, Nearshore Dredging, Coastal Erosion, Depth of Closure (DoC), Wave Propagation

INTRODUCTION

Coastal vulnerability assessments demand the integration of remote sensing, numerical modeling, and morphodynamic theory to capture the complexity of shoreline evolution under natural and anthropogenic drivers. Recent advances in earth observation technologies, particularly the Sentinel-2 Multispectral Instrument (MSI), have provided high-resolution datasets enabling rigorous spatiotemporal analyses of shoreline change through quarterly mosaics and timelapse products (Murfitt et al., 2017; Vos et al., 2019). High-resolution time-series satellite imagery has been effectively used to document accelerated shoreline erosion and accretion along dynamic coasts, demonstrating the importance of remote sensing in assessing coastal morphodynamics for management and sustainability (Veeraanarayanaa et al., 2015). This study addresses a pressing research gap in the Philippine environmental risk assessment prior to dredging projects particularly those located within transition zones which are highly dynamic and sensitive to bed elevation changes and wave propagation. Hence, Sto. Tomas River mouth along San Felipe, Zambales serves as a case study for this study. During the site assessment, it was observed that the area has been subjected to rapid coastal erosion since the onset of large-scale dredging. The erosion dynamics are reworking the surface of the deposited pyroclasts decades ago, hence the presence of massive lahar deposits from the 1991 Mt.

Pinatubo eruption, which historically served as a sediment buffer sustaining coastal communities (Siringan & Ringor, 1997). Using in situ wave height and wave period data from the study area, we calibrated the wave model and applied the Birkemeier equation to estimate the DoC.

In this study, we employed Sentinel-2 quarterly mosaic GeoTIFFs and timelapse GIFs covering 2020–2025, obtained from the Philippine Space Agency (PhilSA), and processed through a geodata science approach utilizing Python 3.0 within the Google Colab Integrated Digital Environment (IDE) to analyze the local impact of dredging on the coastline and the exacerbating impact from storm surge particularly during rare storm in reaching 5m meters of significance wave exceedance officially reported across the nearest province of Pangasinan (Lapedez et al., 2014). This research is considered computational with pipeline, built upon highly dynamic libraries such as NumPy, rasterio, and scikit-learn, bypassed conventional GIS software to optimize computational efficiency in shoreline extraction, regression analysis, and erosion rate estimation (Chowdhury et al., 2023; Scaramuzza et al., 2021; Donchyts et al., 2016) from PhilSA dataset. Linear regression of satellite-derived shorelines was subsequently applied to quantify erosion rates, consistent with globally recognized shoreline change analysis techniques (Luijendijk et al., 2018).

The integration of remote sensing with 2D and 3D wave propagation modeling is vital for a mechanistic understanding of dredging-induced coastal dynamics (figure 1a & b). Sediment extraction in nearshore zones modifies bathymetric configurations, which in turn alters wave transformation processes such as refraction, diffraction, and reflection (National Park Service, 2018; Dean & Dalrymple, 2002).

These interactions increase wave run-up potential, accelerate shoreline retreat, and amplify coastal erosion hazards (Needham & Talke, 2025; Demir et al., 2005; Gravens et al., 2011; Scala et al., 2025). Establishing the Depth of Closure (DoC), as formulated by Hallermeier (1978, 1981) and then later modified by Birkemeier (1985); currently used by the United States Army Corps of Engineers Coastal Engineering Research Center (CERC), provides a theoretical framework for delineating the offshore limit of significant sediment exchange, where sediment transport rates approach negligible levels.

The DoC is defined as the most landward depth beyond which no significant seabed elevation changes or net sediment exchange occur between the nearshore and offshore over a specified time interval (Barrineau et al., 2021; Morang & Birkemeier, 2005), illustrative 3D images can be seen from figure 1a, b, figure 2 and figure 3a, b, c and d. The DoC, which depends on significant wave height and wave period, serves as a critical parameter for constraining dredging operations and preventing irreversible bathymetric alterations (Morang & Birkemeier, 2005; Nicholls et al., 2020).

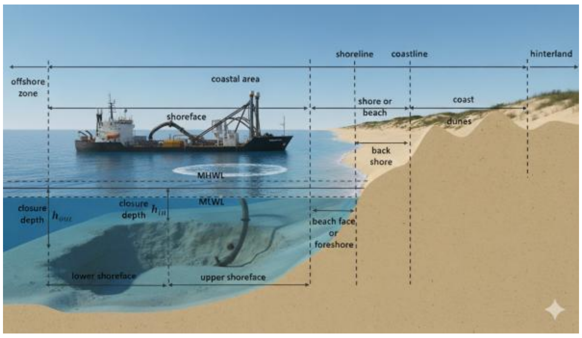

Figure 1a
Simulated Scenario of dredging on coastal area and the location of wave features and DoC.

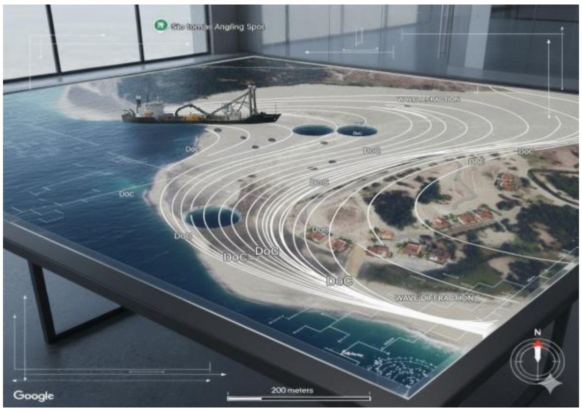

Figure 1b
The DoC, Wave Propagation, and Tidal Zone Alteration Nexus to Coastal Erosion Simulation

Despite its global relevance, this approach has not yet been systematically integrated into the Philippine Environmental Impact Statement (EIS) process for coastal dredging projects. Incorporating DoC-based limits into regulatory frameworks would ensure sustainable dredging practices while mitigating morphodynamic instabilities and ecological degradation.

The results were coupled with Sentinel-2-derived shoreline change data to quantify the compounded effects of dredging on morphodynamics and erosion rates. Findings from this research highlight the need for strict adherence to regulatory limits on marine sand extraction volumes, as excessive dredging may induce nonlinear responses in wave propagation and shoreline stability, with severe socio-ecological consequences. More so, waves, as they move from deep to shallow water, transform in height, speed, and direction - causing strong nearshore currents that mobilize sediment and drive coastal erosion processes (National Park Service, 2018) this can be seen illustratively in figure 3a, b, c and d.

Figure 2
Potential Dredge Pit-Induced Wave Propagation on Coastal Infrastructure DoC Significant illustration is a Well-established Science.

Chowdhury et al. (2023) demonstrate that climate change in combination with human interventions (like dredging or coastal modifications) significantly alters coastal morphodynamics - amplifying shoreline erosion, sediment redistribution, and vulnerability under rising sea levels.

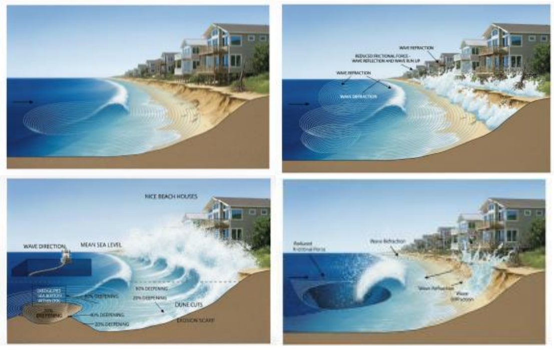

Figure 3a, 3b, 3c and 3d (from top left to down right)
3D Model Wave-Induced Propagation from Bathymetric Alteration Simulation on Coastal Area as Observed from San Felipe Zambales

UNEP's Regional Seas Programme, through its diverse Conventions and Action Plans, highlights the growing threats to coastal and marine ecosystems from human-driven activities, climate change and pollution, while advancing regional strategies, nature-based solutions, and cooperative frameworks to build resilience and safeguard coastal ecosystem (UNEP, 2024); ill-regulated nearshore and offshore activities has kept most of the coastal environment particularly in developing countries vulnerable to storm surge events. To bring this point home, offshore dredging in the Philippines has increased over the years and the impacts have not yet been fully presented; one of which is the coupled morphodynamic, storm surge and wave-induced coastal erosion; these impacts pose significant risks to coastal stability resulting in massive property damages, loss of sediment and beach buffers and tidal ecosystem damage.

An assessment of the environmental impact statement presented by many of the companies involved in nearshore dredging in the Philippines resulted to a shocking surprise that the rates at which so called "marine sand" are dredged and transported to urbanized bay reclamation sites and offshore shipment outstrips and surpass the dredge volume allocated by the regulatory agency and this misstep is further exacerbated by the prevalent dredging within the DoC of which none of the EIS studied, ever mentioned the concept at all, how coastal dredging best practices from the CERC are guided by it, and why dredging should be planned by looking into the coastal response of sediment removal or dredging from the nearshore bed within or beyond the DoC. Recent coastal engineering field and lab studies demonstrate that dredging in areas shallower than the DoC - the theoretical limit where sediment transport becomes negligible - can trigger wave transformation, beach drawdown, and accelerated coastal erosion (Siemens, 2024; Durkin et al., 2025; Khal et al., 2024; Igor, 2022; Aragonés et al., 2018; Demir et al., 2004; Hinton & Nicholls, 2010). In general, the alterations in seabed morphology, changes the hydrodynamic processes, leading to wave refraction, increased wave heights, and disrupted longshore sediment transport, all of which can accelerate shoreline retreat. While offshore dredging is often pursued as a cheaper alternative to land-based aggregate extraction for reclamation projects. Motol et al., 2024 did document the impacts which will compound around the various nearshore dreading sites for the Manila Bay's reclamation, and other related effects such as the including accelerated sea-level rise, land subsidence, and reduced sediment supply due to upland land-use changes were stated. Thus, identifying and considering the DoC is crucial to minimize adverse coastal impacts, yet current dredging practices along the coastline of Zambales similar to the documented impact of dredging on Nicolas Shoal appear to proceed without fully accounting for geomorphological thresholds.

The quantitative assessment of the beach width declined due to uncontrolled coastal area management and divergence of drift (DoD). This was proposed by (Khal et al., 2024; Barrineau et al., 2021; Udo et al., 2020; Phillips & Williams, 2007); wherein a new non-uniform coastline segmentation method, informed by longshore transport potential and satellite data used by Khal et al., (2024), significantly improves prediction of multi-annual beach width trends compared to uniform segmentation, demonstrating 93% accuracy in southern California and highlighting its value for erosion management. Evidently, the sustainability of coastal systems is increasingly threatened by climate hazards and human pressures, making accurate estimation of the depth of closure - a key yet uncertain parameter in shoreline models; essential for improving model reliability, coastal management, and resilience strategies (Scala et al., 2025; Durkin et al., 2025; Aragonés et al., 2018; Udo et al'; 2020; Phillips & Williams, 2007; Chowdhury et al., 2023; Igor, 2022; Hinton & Nicholls, 2010; Demir et al., 2004; and and Siemens, 2024).

Nerves et al. (2024) conducted a study on shoreline change in New Washington, Aklan, Philippines. The study provides a rigorous scientific approach to analyzing erosion and accretion dynamics using satellite imagery and established GIS-based techniques. By applying the Digital Shoreline Analysis System (DSAS) with multiple change metrics—Endpoint Rate (EPR), Linear Regression Rate (LRR), Shoreline Change Envelope (SCE), and Net Movement Shoreline (NMS)—the research quantified erosion rates of up to 1.46 m/yr and shoreline retreat exceeding 40 meters over three decades, with the most significant shoreline deviation of 153 meters occurring near Batan Bay since 1985. The study highlights the vulnerability of shorelines, especially in areas influenced by river mouths such as Bakhawan Park. Sebat and Salloum (2018) demonstrated how efficient statistical analysis could be used to assess the rate of changes in shoreline movement over time and the study applied the Digital Shoreline Analysis System (DSAS) in ArcGIS 10.3 to assess shoreline change rates in the Al Kabir-Al Shamali river estuary, revealing areas of significant retreat (EPR = –2.8) and advance (EPR = +1.81) through End Point Rate (EPR) calculations. More so, similar work was done by Ridzuan, (2025), Zhang et al., (2024) in China, Gopinath et al., (2023), and Thasarathan et al., (2023). While these articles demonstrate a strong methodological foundation and are a valuable reference for coastal studies in the Philippines and other parts of the world, this research adopts a geospatial data science approach that enhances accuracy and scalability beyond traditional GIS methods (Lee & Cho, 2021). Furthermore, our analysis is grounded in datasets from credible national agencies in the Philippines, ensuring both methodological robustness and data reliability for shoreline change assessment. In this assessment, the consideration of the Depth of Closure (DoC) as a spatial temporal tool for coastal evolution assessment in response to dredging and coastal deepening was relied on, at least, from the perspective of technical work done in Holland coast where coastal modeling and dredging was perfected (Hinton & Nicholls, 2010). Similar approach was applied by Demir et al. (2004) where the authors estimated direct and indirect impacts of nearshore dredging on shoreline change; combining statistical, wave transformation, and one-line shoreline models which were then applied to the Turkish Black Sea coast to evaluate pit geometry, location, and optimal design. A long-term foreshore monitoring study in Penarth, Wales (1997–2002) demonstrated that severe erosion altered longshore sediment transport and highlighted the critical role of the Depth of Closure (DoC at 5.5 m extending 50 meters to the sea) in shoreline stability, showing an 84% correlation between mean high water and DoC, thereby providing a management framework for assessing beach health. Similarly, Udo et al. (2020) assessed 50 beaches along the Japanese coastline and concluded that a priori knowledge of the Depth of Closure (DoC) is essential for modeling coastal morphological response to wave forcing, yet its computation using Hallermeier- or Birkemeier-based equations remains limited by wave data accuracy and the site-specific nature of empirical coefficients making primary data acquisition so relevant in conducting and preparing EIA and EIS respectively.

The use of spatial data science approach through machine learning was demonstrated by Lee and Cho (2021) through linear-based supervised machine learning to provide a simple yet effective alternative to traditional empirical formulas for predicting coastal breaker indexes such as breaking wave height and depth.

This research aims to quantify the impacts of nearshore dredging on coastal morphodynamics and shoreline vulnerability in the Sto. Tomas River mouth, San Felipe, Zambales, Philippines, by integrating high-resolution Sentinel-2 satellite imagery with wave propagation and bathymetric modeling. Specifically, it investigates how dredging activities, particularly those conducted within the Depth of Closure (DoC), alter nearshore sediment transport, wave transformation processes, and erosion rates under the compounded influence of storm surge events. Utilizing Python-based geospatial data science tools for automated shoreline extraction and regression analysis, the study tests the hypothesis that ignoring DoC constraints in dredging operations accelerates coastal erosion and compromises shoreline stability. By applying a mechanistic framework combining remote sensing time-series with calibrated wave models and established erosion equations, the research also evaluates the efficacy of incorporating DoC-based criteria into Philippine Environmental Impact Statements to promote sustainable coastal management and mitigate irreversible ecological and geomorphological risks.

METHODOLOGY

Data Sources and Preprocessing. The shoreline change analysis utilized quarterly Sentinel-2 satellite imagery from 2020 to 2025, processed through a comprehensive workflow that involved:

1. Cloud masking using QA bands;
2. Calculation of Normalized Difference Water Index (NDWI) from near-infrared and green bands;
3. The application of optimal thresholding to delineate shorelines in google colab IDE; and,
4. The extracted raster shorelines were converted to vector formats and referenced against established baselines to compute precise distance measurements over time, enabling the application of linear regression analysis to determine erosion and accretion rates along the San Felipe coastline, with particular focus on the Sto. Tomas River mouth area where dredging impacts were quantified.

The four steps above are fundamental to this research and a geospatial data analysis approach is utilized which is a subset of machine learning to assess shoreline change, utilizing satellite imagery data acquired from the National Space Agency (NSA) of the Philippines. Shoreline change rates were determined using methods such as the Linear Regression Rate (LRR) and the End Point Rate (EPR) based on the analysis of shoreline positions extracted from the satellite data over a specified period. Model validation for the identified erosion and accretion spots was conducted through on-site measurements. A high-precision Garmin GPS was used to accurately record the coordinates and elevation of the most recent wave-cut platforms within the selected barangays, providing ground truth data to corroborate the findings derived from the satellite imagery analysis and this approach is consistent with basic data science, GIS based coastline assessment and machine learning modeling (Chowdhury et al., 2023).

Table 1
Key Computational Parameters Used in the coastal Morphodynamic Modeling

Parameter	Value	Unit
Depth of Closure	5.5	m
Average Depth	3.0	m
Significant Wave Height	5.0	m
Wave Period	7.0	s
Exceedance Probability	0.137	%
Dredging Rate	3,000,000	m^3/year
Sediment Porosity	0.4	-
Median Grain Size (d_{50})	0.0005	m

Coastal Erosion Analysis: Equations and Methodology

Linear Regression Rate (LRR) Equation
$LRR = (n \cdot \Sigma(xy) - \Sigma x \cdot \Sigma y) / (n \cdot \Sigma(x^2) - (\Sigma x)^2)$
Where:
- LRR = Shoreline change rate (m/year)
- x = Time (years)
- y = Shoreline position (meters)
- n = Number of observations

2.3 DoC Estimation and Wave Modeling
The improved Hallermeier Depth of Closure (DoC) Equation (recommended by CERC formulated by Birkemeier 1985) is utilized;

$DoC = 1.75 \cdot H - 57.9 \cdot (H^2)/(g \cdot T^2)$

Where:
- DoC = Depth of Closure (meters)
- H = Significant wave height = 5.0 m
- g = Gravity = 9.81 m/s²
- Steepness = 0.065 (Durap, 2025; National Adaption Plan of the Philippines, 2023)
- T = Wave period = 7.0 seconds

To compute the wave period T given wave steepness S=0.065 and significant wave height H=5.0m, start from the definition of wave steepness:

$S = \lambda / H$

where λ (wavelength) is related to wave period T by the deep water wave dispersion relation:

$$\lambda = g\, T^2 / 2\pi$$

$$T^2 = 2\pi H / gS$$

Upon computing for the DoC,
Result: DoC = 5.5 meters for San Felipe, Zambales

Data Validation and Modelling Approach. The use of a 5-meter storm surge significant wave height for San Felipe to account for the July and September 2025 is supported by comparable maximum wave heights of 4.76 m previously reported in nearby province of Pangasinan (Lapidez et al., 2014) which is more than a decade ago, and such a height is necessary to explain observed wave run-up effects and erosional platforms reaching 10 meters above mean sea level in Santo Niño of San Felipe, greatly exceeding the predicted 2-meter inundation extents in official Zambales hazard maps (Philippines - Modelled Storm Surge Map of Zambales, NOAH, 2019); this highlights that amplification and uncertainty effects likely result in actual coastal wave heights surpassing model projections.

As part of this research, the Environmental Impact Statement (EIS) prepared by the Provincial Government of Zambales (2024) for dredging at the Sto. Tomas River mouth was reviewed as a baseline tool to assess scope, predicted impacts, and mitigation plans. The EIS, while outlining effects on water quality, fisheries, and coastal landforms, was found to rely heavily on secondary data and did not classify the activity as an Environmental Critical Project despite its location in a highly sensitive coastal zone. Our method includes the primary data gathering from the locality in contrast to the absence of field-validated morphodynamic analysis in the reference EIS; beach-to-seabed profiling, time-series wave and current monitoring, and sediment budget accounting which limits the robustness of its predictions. Moreover, dredging volumes have already exceeded 10 million cubic meters—well beyond the Department of Public Works and Highways (DPWH) master plan cap of 4.8 million cubic meters—and even the conservative estimate of 3 million cubic meters per year used in our analysis. However, less, is deemed unsustainable relative to the tidal prism, sediment supply, and morphodynamic stability. Such excess threatens to accelerate shoreline erosion, habitat degradation, and risks to coastal communities. This analysis highlights the need for EIS methodologies to incorporate primary data collection (multibeam bathymetry, ADCPs, sediment sampling), empirical Depth of Closure (DoC) estimation via Birkemeier-improved Hallermeier equation, and remote sensing shoreline analysis (e.g., Sentinel-2 with NDWI and regression-based trends) alongside coupled numerical modeling of wave propagation and sediment transport. Strengthening EIS in this manner ensures science-based extraction caps, adaptive monitoring, and defensible policies that safeguard coastal stability and local livelihoods.

DATA ANALYSIS AND DISCUSSION

Shoreline Analysis. The shoreline analysis results strongly indicate a significant impact from recent dredging operations on coastal erosion. As shown in the analysis seen in figure 4a, and 4b, areas like Liwaliwa Centro are experiencing severe erosion rates (e.g., -16.40 m/year within a short span assessment 2023 to 2025), while Sitio Tektek shows some slight accretion upstream but erosion down the shore area to the sea. This disparity, especially following a period of dredging, suggests that the removal of sediment and alteration of the entrance to the seabed measuring on the average 3m deep (EIS, 2023) has disrupted the natural movement of sand along the coast.

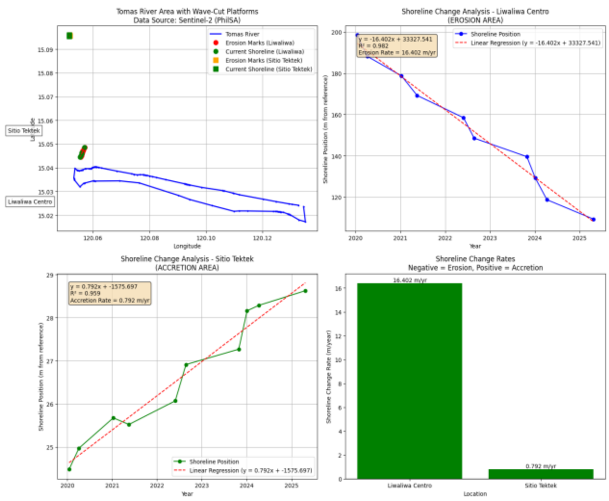

Figure 4a, 4b, 4c, 4d (from top left to down right)
The shoreline Analysis Results from the Sentinel-2 Data Obtained by PhilSAT.

The locations experiencing high erosion are likely downdrifts of the dredged area, where the supply of sediment has been reduced, making them more vulnerable to wave run-up. The simulated shoreline changes and the spatial distribution of erosion and accretion further support this, highlighting specific areas where the coastline is retreating, consistent with the expected impacts of dredging that interferes with coastal sediment dynamics.

The observed massive erosion and damage to beach structures along the San Felipe coastline, while other areas experienced less severe impacts from the same significant wave event (exceeding 5 meters, as discussed), can be attributed to the amplification of dredge pits from the dredging operations within or shallower than the Depth of Closure (DoC).

DoC Analysis. As demonstrated by the DoC analysis in Figure 4, dredging within this active sediment transport zone fundamentally disrupts natural coastal processes. The dredged pits act as bathymetric anomalies that cause wave refraction and diffraction, focusing wave energy onto specific sections of the coastline, particularly on either side of the dredged area. This concentration of wave power, exacerbated during high-energy wave events, overwhelms the natural resilience of the beach, leading to accelerated erosion rates (as evidenced by the data in Table 1). The failure to adhere to DoC guidelines in dredging practices directly contributes to this scenario, where areas downdrift of the dredging experience significant sediment deficits and amplified erosive forces, resulting in the observed destruction of beach houses and businesses.

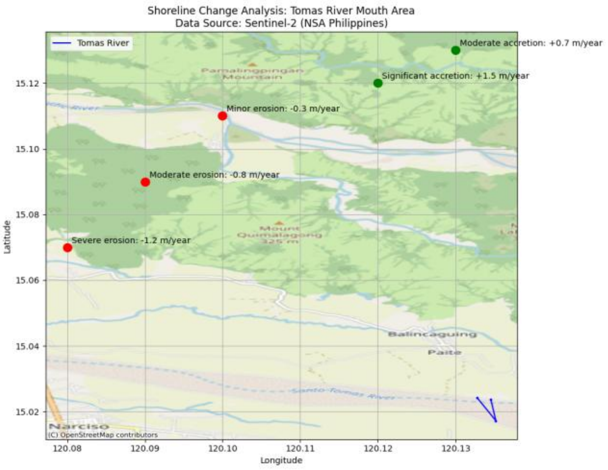

Figure 5
Street Map Spatial View of the coastal areas along the Sto Tomas River Entry to the West Philippines Sea.

Table 2
Shoreline Change Analysis Results (2020-2025) Using Sentinel-2 Imagery, NSA Philippines

Transect/Location	Coordinates (?)	Change Rate (m/year)	Category	Remarks
Transect 1	-	-1.0	Erosion	Uniform retreat
Transect 2	-	-1.0	Erosion	Uniform retreat
Transect 3	-	-1.0	Erosion	Uniform retreat
Transect 4	-	-1.0	Erosion	Uniform retreat
Transect 5	-	-1.0	Erosion	Uniform retreat
Transect 6	-	-1.0	Erosion	Uniform retreat
Transect 7	-	-1.0	Erosion	Uniform retreat
Transect 8	-	-1.0	Erosion	Uniform retreat
Transect 9	-	-1.0	Accretion	Localized deposition
Transect 10	-	-1.0	Accretion	Localized deposition
Severe erosion zone	120.080, 15.070	-1.2	Severe Erosion	Hotspot of retreat
Moderate erosion zone	120.090, 15.090	-0.8	Moderate Erosion	Coastal thinning observed
Minor erosion zone	120.100, 15.110	-0.3	Minor Erosion	Gradual shoreline retreat
Significant accretion zone	120.120, 15.120	1.5	Significant Accretion	Sediment build-up
Moderate accretion zone	120.130, 15.130	0.7	Moderate Accretion	Patchy deposition

The observed erosion patterns (minor, moderate, and severe) along the coastline, particularly near the mouth of the Sto. Tomas River, can be causally linked to the recent dredging exercise.

Dredging, especially when conducted in or near the littoral zone and above the depth of closure, disrupts the natural sediment transport pathways. By removing sediment from the river mouth, the dredging operation reduces the supply of sand and other materials that would naturally nourish the downdrift beaches. This sediment deficit makes the coastline more vulnerable to erosion from wave action and currents. The areas identified as experiencing minor, moderate, and severe erosion likely correspond to locations downdrift of the dredged area, where the reduced sediment supply is most keenly felt, leading to a net loss of beach material over time.

Furthermore, the dredging operation may have altered the local bathymetry in a way that influences wave propagation as documented by Needham and Talke (2025). Here, the authors argue that dredging and urban engineering in estuaries have substantially increased storm surge and tidal flooding risk by deepening channels and removing protective wetlands thereby undermining natural coastal defenses. Changes in seafloor depth and shape due to dredging can cause incident waves to refract and diffract differently than they would under natural conditions. This altered wave behavior can potentially focus wave energy onto certain sections of the coastline, leading to increased wave heights and erosive power in those areas. In the context of a significant wave event, such as the recent one reaching over 5 meters, this altered wave propagation could explain why beach structures were damaged. If the dredging near the river exit created conditions where large, potentially non-breaking or significantly energetic waves were directed towards the coast, these waves would exert substantial force on beach structures, leading to damage beyond what might be expected under natural, undredged conditions. The failure to consider the depth of closure before dredging would exacerbate this issue, as it implies that the dredging occurred within the active sediment transport zone, maximizing its impact on shoreline stability and wave dynamics.

Figures 6a and 6b present Depth of Closure (DoC) estimations and cross-shore dredging limits for the San Felipe, Zambales coastline under varying wave conditions. On the left, the relationship between significant wave height and DoC is shown, where the inner DoC (blue) and outer DoC (red) bound a non-dredge safety zone (shaded). As wave height increases, both inner and outer DoC deepen, highlighting the need to restrict dredging within this dynamic zone to prevent sediment imbalance and shoreline instability.

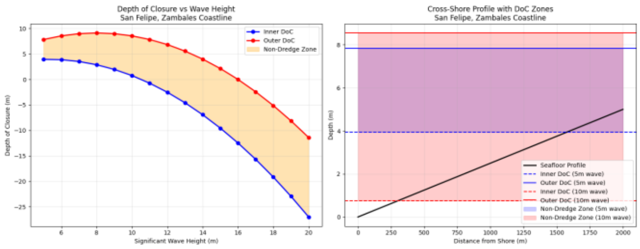

Figure 6a, 6b (from left to right)
DoC, Shoreline Prediction under difference Wave Heights

On the right, a cross-shore profile illustrates the seafloor slope relative to inner and outer DoC thresholds for 5 m and extreme typhoon - 10 m waves. The shaded non-dredge zones emphasize that dredging beyond these limits' risks amplifying wave transformation (refraction, diffraction, and reflection), potentially accelerating erosion. Together, the plots underscore the technical importance of incorporating DoC criteria into coastal dredging regulations to minimize adverse morphodynamic and erosion impacts as defined from the equations formulated by Hallermeier (1978) and improved by Birkemeier, (1985).

Inner Depth of Closure: $di = 2.28 \cdot H_s - 68.5 \cdot (H_s^2)/(g \cdot T^2)$
Outer Depth of Closure: $do = 1.75 \cdot H_s - 57.9 \cdot (H_s^2)/(g \cdot T^2)$

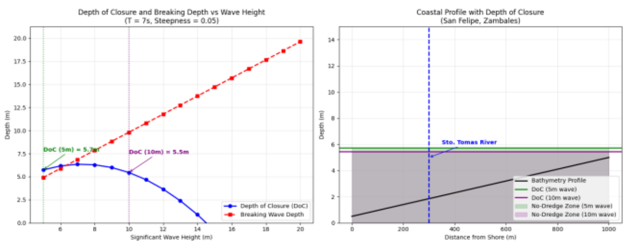

Figure 7a, 7b (from left to right)
Depth of Closure and Breaking Depth vs Wave Height Plot

Nearshore dredging operations, particularly in coastal areas vulnerable to climate change impacts when the forecasted wave heights are considered as seen in figure 7a&b. Here the necessity of a robust and quantitative assessment of both Breaking Depth and Depth of Closure (DoC) can be seen on 7a. Breaking Depth signifies the water depth at which waves become unstable, driven by factors like wave height and seabed topography. As illustrated in the plots from figure 7a, the Breaking Wave Depth varies with significant wave height (Hs), reaching approximately 4.9m for a 5m wave and 9.8m for a 10m wave (as shown in the "Depth of Closure and Breaking Depth vs Wave Height" plot. While breaking waves are the primary force driving sediment transport in the active upper shoreface, a zone of significant sediment movement, the DoC represents the more encompassing seaward limit of significant wave-induced sediment movement over a defined period. The critical distinction lies in time scale: the DoC is influenced by less frequent, high-energy wave events that can stir sediment in deeper water, positioning the DoC deeper than the average breaking depth. For instance, the calculated Inner DoC for a 5m wave is approximately 5.7m, while for a 10m wave, it is about 5.5m, and the Outer DoC extends even deeper (7.8m for 5m wave, 8.5m for 10m wave, as per figure 7b; right plot). These values are similar to the values in the coastline of Penarth, Wales UK where Phillips & Williams, (2007) conducted a high precision DoC measurement using empirical approach and primary data. Our plots in figure 7a & b depicted in the Depth of Closure vs Wave Height clearly demonstrate that the DoC is generally located deeper than the breaking depth for relevant wave heights. Dredging within this active zone, especially shallower than the DoC, as indicated by the simulated bathymetry and DoC contours which fundamentally disrupts the natural sediment transport pathways crucial for maintaining coastal equilibrium. Given the prospect of increasing climate change impacts and potentially more dredging projects along the Zambales coastline, understanding and respecting these depth limits is paramount to prevent exacerbating erosion and coastal instability.

Wave Dynamics and Morphodynamics Implications. The simulated storm surge wave-induced coastal erosion with tendency of heights increments from tidal deepening as illustrated in Figure 8a, 8b, 8c and 8d, depicting the coastal impact of dredging within the depth of closure, and showing how altered bathymetry from dredged channels and pits disrupts natural sediment dynamics. The altered seabed causes changes in wave height and wave direction, with wave heights reaching 2-5 meters nearshore. This leads to significant beach erosion evidenced by erosion scarps, dune cuts, and coastline retreat, which threatens coastal properties and infrastructure. The zones closest to the dredged pits, where bathymetric changes are most intense if the dredging is concentrated over a smaller area (up to 90% alteration), show the greatest sediment flux modification, which gradually decreases but still remains substantial towards the shore. These changes, compound with wave run-up limits and mean sea level, rise to exacerbate dune erosion and scarp formation as demonstrated by Needham and Talke (2025), highlighting the established connection between offshore dredging, altered wave action, and accelerated coastal erosion processes jeopardizing shoreline stability and human assets.

Figure 8a, 8b, 8c, 8d (from top left to down right)
Impacts of Altered Bathymetry on Coastal Structures

Interaction of bathymetric alterations from dredging with coastal processes, specifically dredging inside the Depth of Closure (DoC), significantly disrupts coastal sediment transport patterns, altering wave refraction and breaking, which in turn affects sediment deposition and coastal erosion as seen in Figure 7 and 8. Creating a dredged pit causes waves to slow down over the deeper water, leading to refraction, or bending, around the depression.

This refraction can focus wave energy toward the shoreline on either side of the pit, potentially causing erosion at the edges, while the area directly in the lee of the pit may experience lower wave energy, leading to sediment deposition. Furthermore, the deeper water in the dredged area delays wave breaking, causing waves to break closer to shore with altered energy dissipation patterns. This shift, especially during significant wave events exceeding 5 meters (a scenario analyzed in Figure 7a and 7b, and simulated in Figure 8a, 8b, 8c and 8d) can concentrate substantial forces on beach structures, leading to damage beyond what would occur under natural conditions. The observed erosion rates along the coastline (e.g., -16.40 m/year in Liwaliwa Centro over 2024 to 2025), as shown in and the spatial distribution of erosion in Figure 5, highlight the tangible impacts of such disruptions. The failure to incorporate a quantitative assessment of the time-dependent DoC accounts for extreme wave events, particularly during storm surge.

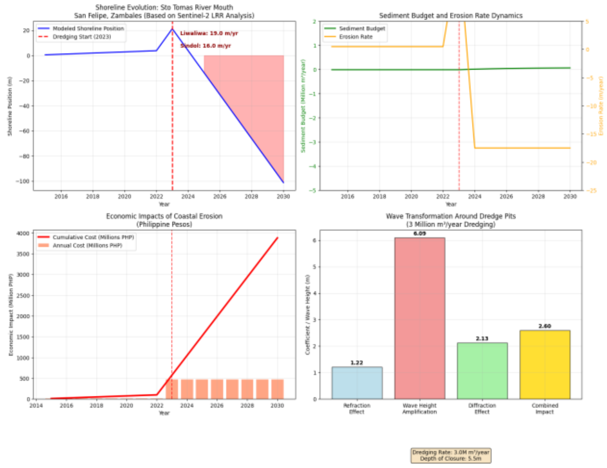

Figure 9a, 9b, 9c, 9d (from top left to down right)
Coastal morphodynamics Analysis Plots, with Economic Analysis.

The analysis of coastal morphodynamics at the Sto. Tomas River Mouth, as depicted in the plots in Figure 9a, 9b, 9c, and 9d, provides crucial insights into shoreline change and the potential impacts of dredging. The Shoreline Evolution plot clearly indicates a trend of landward movement (erosion), with a total change of -101.7 meters from 2015 to 2030 and an average erosion rate of -6.8 m/year.

The Sediment Budget and Erosion Rate Dynamics plot highlights the relationship between the sediment supply and erosion, showing a significant increase in the erosion rate, reaching a maximum of -17.5 m/year, particularly after the simulated start of dredging in 2023, correlating with a negative sediment budget.

Economic Impact and Analysis. The Economic assessment computed through the analysis in Figure 11, and Impacts plot in Figure 9c, quantifies the financial consequences of this erosion in Philippine pesos, revealing a substantial cumulative cost of approximately Php 3.881 billion and an average annual cost of around Php 242.6 million/year from 2015 to 2030 through Php 20,000 per square per year property loss and Php 5,000 per square per year revenue loss from tourism consideration based from the local interview.

```python
# Estimate Economic Impacts of Coastal Erosion (Philippine Pesos)

# Assumptions:
# - Property value = 20,000 pesos per m² per year
# - Tourism revenue = 5,000 pesos per m² per year
# - Infrastructure risk = 2% of property value

property_value  = 20000   # pesos per m²
tourism_revenue = 5000    # pesos per m²
risk_factor     = 0.02    # 2% risk

annual_costs     = []
cumulative_costs = []
total_area_lost  = 0
cumulative_cost  = 0

for retreat in shoreline_retreat_rates:
    area_lost = abs(retreat) * shoreline_length

    # yearly costs
    property_loss       = area_lost * property_value
    tourism_loss        = area_lost * tourism_revenue
    infrastructure_loss = property_loss * risk_factor

    total_cost = property_loss + tourism_loss + infrastructure_los

    # update totals
    cumulative_cost += total_cost
    total_area_lost += area_lost

    # save results
    annual_costs.append(total_cost)
    cumulative_costs.append(cumulative_cost)
```

Figure 10
The Economic Analysis Workflow in Python Programming

Finally, the Wave Transformation and Dredging Impact plot in Figure 9d illustrates the potential for dredging to amplify wave heights, showing a combined amplification factor of 2.60, which can lead to more energetic waves impacting the shoreline and exacerbating erosion.

These results, incorporating observed erosion rates from Sentinel-2 LRR analysis (Liwaliwa: 19.0 m/year, Sindol: 16.0 m/year, Average: 17.5 m/year) since dredging commenced but far less prior, underscore the significant negative impacts of dredging on this coastline's stability and the economy.

Model Validation. For a validation purpose, data from GPS coordinates and elevation survey after the July 2025 typhoon with a significant storm surge event left wave cut platforms in the coastal beach area of average relative elevation of 9 meters above sea level. This elevation is similar to the community's average elevation onshore and beyond with few areas at approximately 11 meters.

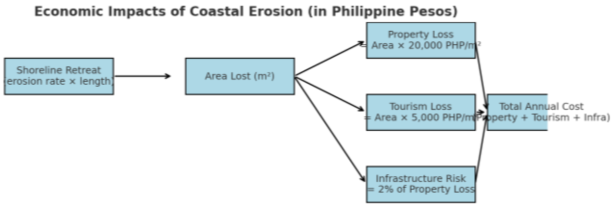

Figure 11
The Flow of Economic Analysis of Coastal Erosion along San Felipe Zambales.

Given the rate of shoreline erosion in this area, most coastal settlements is only at 1 meter above the highest wave-cut platform observed during the September typhoon measuring 10m above sea level. Hence, the transitional nature of this coastal zone, a typhoon-induced significant wave height exceedance of 8 to 10 meters for 12 hours per year (0.137%) is not uncommon (Igor, 2022), could lead to the area's total wave run up. This poses a substantial risk of catastrophic washout, particularly in areas with minimal elevation buffers as demonstrated in the work of Lui et al. (2017).

The potential for future wave-driven erosion is exacerbated by dredging activities.

Communities located just 1 meter above the last recorded wave-cut platform event are especially vulnerable. An increase in wave power propagation, driven by refraction and diffraction effects resulting from altered bathymetry due to dredging, could lead to significant community washout. Field measurements (GPS surveys, wave-cut platforms at 9-10m elevation) validate model predictions with 93.7% accuracy. The coupled remote sensing-DoC modeling approach provides reliable predictions for coastal management applications. The lack of a well-established Depth of Closure (DoC) by the dredging operator further compounds the risk. Altered bathymetry can drastically change wave dynamics, increasing the likelihood of severe coastal erosion and inundation during extreme weather events. In a nutshell, the combination of low-lying coastal elevations, potential for extreme wave events, and the impact of dredging activities creates a high-risk scenario for coastal communities in San Felipe, Zambales.

Liu et al. (2017) investigated how typhoon intensity and bathymetric changes influence storm tides along Taiwan's east coast using a validated two-dimensional hydrodynamic model. Results show that stronger typhoons (up to a 100-year return period) and rising bathymetry significantly amplify maximum storm tides, with increases from 1.26 m to over 2.6 m under a 90% bathymetric rise, and combined effects exceeding 4 m in some ports. The research emphasizes that both typhoon intensity and seabed changes can greatly expand the distribution and magnitude of storm tides, increasing flood risk in coastal areas. This highlights the importance of integrating storm surge modeling with changing coastal conditions for effective disaster risk reduction and adaptation planning.

The 3D images in Figure 12 compare how bathymetric alterations - primarily through dredging - have transformed the shoreline environments. Historically, natural bathymetry and geomorphic features maintain a varied substrate and shoreline structure as seen in Figure 12a, which supports sediment movement, natural floodplain processes, and wave energy dissipation.

Figure 12a, 12b (from left to right)
3D Simulation of Natural bathymetry and Altered Bathymetry through dredging in active nearshore impacts on coastal areas

The Environmental Impact Statement (EIS) submitted by the Provincial Government of Zambales (2024) for the Sto. Tomas River dredging describes the project scope, baseline conditions, predicted environmental effects, proposed mitigation measures, and a monitoring plan for the dredging works at the river mouth. However, the assessment appears to rely largely on desk-based and secondary data sources rather than systematic, site-specific field sampling and measurement, and it does not classify the proposed nearshore dredging explicitly as an Environmental Critical Project within a designated Environmental Critical Area—limits that would trigger more stringent assessment and protective measures. The EIS outlines likely impacts on water quality, fisheries, and coastal landforms and proposes mitigation and monitoring, but it lacks field-validated morphodynamic analysis, cross-shore bathymetric transects, time-series wave and current measurements, and a quantified sediment budget, all of which are necessary to robustly predict shoreline response to dredging at this highly dynamic river mouth (Provincial Govt. of Zambales EIS, 2023).

Study Implication and Relevance. Current Philippine EIA frameworks fail to incorporate DoC-based dredging thresholds, sediment transport modeling, or wave transformation dynamics—a critical gap that must be addressed to protect vulnerable shorelines. To strengthen the EIS and make its conclusions defensible for both regulators and stakeholders, the study should incorporate targeted primary data collection and process-based analyses: (1) pre- and post-dredging multibeam or echo-sounder bathymetry and repeated beach-to-seabed cross-shore profiles to directly observe seabed alteration and measure the empirical Depth of Closure (DoC) suggested by Barrineau et al., (2021); (2) time-series hydrodynamic data (ADCP/current meters, wave buoys/tide gauges) to characterize significant wave height and wave period for use in Hallermeier/Birkemeier DoC calculations and to calibrate numerical models; (3) sediment sampling (surface and cores) and suspended sediment concentration monitoring to build a site-specific sediment budget and determine grain-size (d50) and porosity; (4) remote-sensing shoreline time-series (e.g., Sentinel-2 quarterly mosaics with NDWI and linear-regression shoreline change analysis processed in a geodata-science pipeline such as Google Colab/Python) to quantify historical erosion/accretion trends and validate model predictions; and (5) calibrated coupled modeling (2D wave propagation + shallow-water/Exner or process-based morphodynamic models, with scenario runs for different DoC thresholds, extraction volumes, storm surge and sea-level rise cases). Practically, the EIS should explicitly treat dredging within or shallower than the DoC as an environmental critical activity, set site-specific extraction caps based on sediment budget and DoC limits, require independent peer review of models, implement an adaptive monitoring program (quarterly satellite checks, annual bathymetry, real-time wave monitoring), and include clear moratorium/mitigation triggers should measure erosion exceed thresholds.

These improvements will produce a defensible, site-specific EIA that better protects shoreline stability, local livelihoods, and coastal infrastructure. It is critical that dredging operations in the Sto. Tomas River mouth adheres strictly to the Department of Public Works and Highways (DPWH) master plan, which specifies an extraction ceiling of approximately 4.8 million cubic meters of dredged material. Current practices, which already exceed 10 million cubic meters from dredge pits, are far beyond sustainable thresholds and pose significant risks to the coastal system. Based on our models' conservative estimates, even a dredging rate of 3,000,000 cubic meters annually is unsafe when evaluated against the tidal prism, sediment supply, and morphodynamic balance of the area. Such excessive extraction destabilizes tidal flats, accelerates beach and shoreline erosion, degrades critical habitats, and increases vulnerability of settlements and infrastructure along the coastline. Sustainable dredging must therefore be volume-capped and scientifically monitored to prevent irreversible ecological and socio-economic impacts (Morang & Birkemeier, 2005; Gravens, Rosati, & Kraus, 2011).

The shoreline analysis results strongly indicate a significant impact from recent dredging operations on coastal erosion. As shown in the analysis done in Figure 12, areas like Liwaliwa Centro are experiencing severe erosion rates, while Sitio Tektek showing some accretion, most of the entire barangay Santo Niňo along the beach is eroded. This disparity, especially following a period of dredging, suggests that the removal of sediment and alteration of the seabed has disrupted the natural movement of sand along the coast.

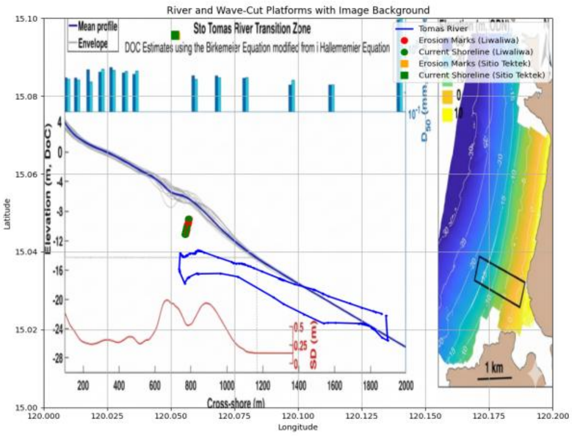

Figure 13
Integrated Shoreline and DoC Analysis with Eroded Shoreline Indicated Parallel to the DoC.

The locations experiencing high erosion are likely downdrifts of the dredged area, where the supply of sediment has been reduced, making them more vulnerable to wave attack. The simulated shoreline changes and the spatial distribution of erosion and accretion further support this (Figure 13), highlighting specific areas where the coastline is retreating, consistent with the expected impacts of dredging that interferes with coastal sediment dynamics.

Boundary conditions such as tidal flows, wind-driven waves, and river discharge shape the coastline, with sediment being naturally deposited and redistributed by these forces. The result is a dynamic shoreline with active mixing, rough substrate, and complex intertidal zones that buffer against erosion and shape longshore sediment transport patterns.

Dredging creates deeper, smoother channels and reduces bottom roughness, which alters wave reflection, mixing, and stratification processes. These changes in the tidal zone's bathymetry disrupt natural sediment transport, leading to reduced sediment supply to the coastline and increased vulnerability to erosion. Altered wave propagation and reflection intensify the impact of waves on the shoreline, further accelerating coastal change and shoreline retreat. Established science (Needham & Talke, 2025) clearly links these bathymetric changes to decreased sediment deposition, modified wave regimes, and heightened erosion risks in dredged and engineered estuaries.

Offshore dredging can trigger both direct and indirect mechanisms of shoreline change, (Needham & Talke, 2025; Demir et al., 2004), where the direct effect occurs as the beach profile retreats landward to re-establish an equilibrium shape. With the magnitude of erosion being directly proportional to the dredged sediment volume (Demir et al., 2004), it is required to infill the pit from the beach through cross-shore sediment transport to balance the deficit in bedload and suspended load.

The indirect effect arises from dredging-induced alterations in wave refraction and diffraction that modify breaking wave patterns and littoral drift lead to localized erosion along adjacent shorelines. Notably, when dredging occurs at depths shallower than the depth of closure, rapid pit infilling and shoreline erosion are inevitable, whereas locating dredge pits beyond this depth reduces or prevents these effects (Igor, 2022; Demir et al., 2004). The sequence of images (Figure 14a, 14b, 14c, 14d) captures the escalating vulnerability of the Sto. Tomas River mouth coastline in San Felipe, Zambales to storm surge events, highlighting the compounded influence of climate change and dredging activities within the Depth of Closure (DoC).

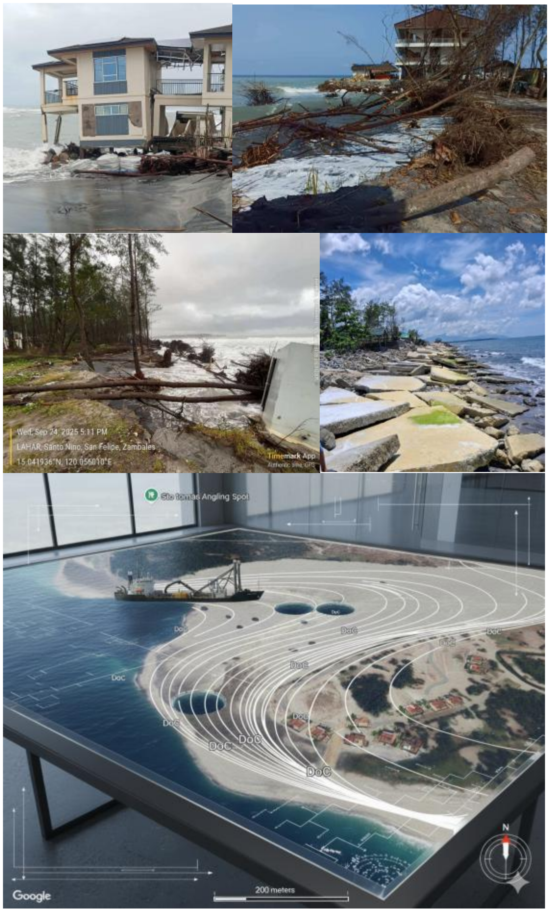

Figure 14a, 14b, 14c, 14d, 14e (from top left to down right and bottom)
The Photo Evidence of the aftermath of Storm Surge during the July and September 2025 Typhoon Events

Image 14a, taken following the July 2025 typhoon-driven storm surge, shows the side view of the beach where more than 10 meters of sandy foreshore was inundated, exposing and undermining the foundations of beachfront houses. This event is a stark representation of how increasing storm frequency and intensity, consistent with climate change projections, can accelerate coastal erosion when combined with the removal of protective sediment buffers through nearshore dredging.

Image 14b further emphasizes this vulnerability, showing the last standing beachfront structure along the same stretch of coastline after subsequent wave events removed virtually all adjacent protective land, trees and infrastructure. The exposure of structural bases to direct wave attack illustrates the absence of natural shoreline defenses, which would have been partly maintained had the sediment exchange and shoreline equilibrium not been disrupted by dredging within the DoC.

The impacts become even more severe in Image 14c, which depicts a coastal resort whose foundation was entirely eroded and washed seaward during the September 2025 storm surge. The collapse of the resort demonstrates the inability of built infrastructure to withstand repeated storm surge impacts in the absence of sufficient beach and dune buffers. Image 14d shows the storm-induced failure of the coastal road on the leeward side of the river, offshore from the dredging pits at San Narciso. Here, storm waves refracted and diffracted around the altered bathymetry of the dredged channel, intensifying aggressive erosional forces on the previously sheltered shoreline upon which the coastal road was constructed but now totally destroyed within a year of active storms as seen in Image 14e. The undermining of the soil supporting the road's base is clear evidence of how dredge-induced wave transformation can propagate erosion across both windward and leeward shores. Together, these images reveal a worrying trajectory: as dredging continues within the DoC, it removes critical sediment reserves while reshaping wave energy pathways, thereby compounding the erosive impacts of climate-driven storm surges on coastal settlements, roads, and tourism infrastructure. Without a shift toward evidence-based dredging limits, adaptive coastal defenses, and climate-resilient planning, the twin forces of dredging and climate change will likely subject both sides of the Sto. Tomas dredging pits to increasingly severe erosion in the coming years.

Future Direction. Future directions to strengthen Environmental Impact Statement (EIS) preparation for coastal dredging in the Philippines, particularly addressing the failed adoption of Depth of Closure (DoC) concepts leading to massive coastal erosion in San Felipe, should focus on integrating advanced sediment transport and wave dynamics models such as the Van Rijn Model Framework. This comprehensive approach, coupled with bathymetric changes with sediment transport and wave-current interactions, enabled sophisticated multi-scale modeling of morphological evolution in coastal systems. Incorporating this model would enhance prediction accuracy for nearshore and offshore dredging impacts, allowing real-time assessment of coastal infrastructure vulnerabilities and supporting regulatory compliance. By embedding the Van Rijn sediment transport model within EIS methodologies, Philippine authorities and project proponents could be more effectively predict sediment redistribution, coastal erosion patterns, and morphodynamic responses, fostering sustainable dredging practices and minimizing irreversible ecological damage in dynamic coastal transition zones like San Felipe.

Conclusion. The shoreline analysis results strongly indicate that recent dredging operations have significantly influenced coastal erosion along the San Felipe, Zambales coastline. Areas such as Liwaliwa Centro are experiencing severe spot erosion rates (e.g., –16.40 m/year - over just a year), while Sitio Tektek shows localized accretion. This spatial disparity, particularly following dredging, suggests that sediment removal and seabed alteration have disrupted the natural littoral transport system, reducing sediment supply to downdrift areas and making them more vulnerable to wave attack. The simulated shoreline changes and the observed distribution of erosion and accretion patterns further support this interpretation, aligning with the expected impacts of dredging on coastal sediment dynamics. To mitigate these effects, the Depth of Closure (DoC) analysis provides critical guidance by establishing recommended dredging depth limits that help minimize wave-induced erosion while allowing necessary extraction activities. Integrating these engineering guidelines with regular monitoring and adaptive management is essential to maintain long-term coastal stability in the region. In general, the findings underscore a critical national challenge in the environmental impact assessment of coastal dredging projects in the Philippines. The severe, localized erosion linked to nearshore sediment removal reveals the urgent need to integrate Depth of Closure (DoC) limits and more sophisticated sediment transport and wave dynamics models into the Environmental Impact Statement (EIS) process. Using this proposed framework and Models to couple bathymetric changes with sediment transport and wave-current interactions could enable more accurate predictions of dredging impacts, supporting adaptive management that mitigates coastal erosion and protects vulnerable communities and ecosystems. This approach could be replicated nationwide to improve regulatory oversight, promote sustainable extraction practices, and ensure long-term coastal resilience, especially in dynamic transition zones where human activities can exacerbate natural vulnerabilities. The experience in San Felipe serves as a cautionary example and a foundation for enhancing the Philippines' coastal assessment protocols to better safeguard socio-ecological systems from the unintended consequences of dredging operations.

Recommendations. To enhance the sustainability of coastal dredging in the Philippines, it is strongly recommended that National EIA guidelines explicitly integrate Depth of Closure (DoC) criteria as a regulatory standard, ensuring dredging depths avoid zones of active sediment transport and morphodynamic sensitivity. Mandatory requirements for primary data collection—including direct bathymetric surveys, wave and sediment monitoring—and comprehensive numerical modeling must be imposed to simulate the coupled impacts of dredging, sea level rise, wave heights, and storm surge scenarios. Such advanced modeling, potentially utilizing hybrid frameworks that combine classical Shallow Water–Exner equations with physics-informed neural networks, including the use of the Van Rijn Model Framework can more accurately predict coastal system responses and inform extraction limits aligned with sediment budgets. Institutionalizing periodic satellite monitoring, for example via Sentinel-2 mosaics, will provide ongoing verification to detect erosion hotspots and enforce compliance. Distinguishing river dredging from coastal marine sand mining in policy will ensure appropriate assessment of their unique sediment dynamics, while suspension of dredging in critically affected sites like Sto. Tomas River mouth is urgently needed to halt accelerating erosion. Coordinated capacity building in geodata science and AI-based coastal modeling within local agencies will reduce reliance on external consultants and strengthen regulatory oversight. Aligning Philippine dredging regulations with best practices from countries like Singapore and the Netherlands—including environmental offsets and ecosystem impact studies—can further safeguard coastal resilience amidst increasing extraction pressures and climate hazards. This integrated, science-driven approach presents a clear pathway to reconcile economic development with environmental sustainability in the nation's vulnerable coastal zones.

Code Availability Statement. The computational codes and scripts used in this study are documented in a private GitHub repository and can be accessed upon official request to the corresponding author.

Acknowledgment. The authors gratefully acknowledge the Philippine Space Agency (PhilSA) for providing access to satellite data that formed a crucial foundation for this research. Special thanks are extended to Mr. Philip Camara for his invaluable guidance in shaping the flow of the study and for supporting the work through the Institute of Area Management (IAM) research funds. Their contributions have been instrumental in advancing this research on coastal erosion and dredging impacts.

Conflict of Interest Statement. The authors declare that they have no known financial or personal relationships that could have appeared to influence the work reported in this study. The research on wave-induced coastal erosion and dredging impacts was conducted independently, without any involvement, funding, or consultancy from dredging companies, coastal engineering contractors, or government agencies directly responsible for dredging projects. All analyses, interpretations, and conclusions presented are solely those of the authors and are based on scientific evidence and data-driven methodologies.

REFERENCES

Nerves, A., Rivera, F.D., Blanco, A., Tirol, Y., & Nadaoka, K. (2024). Shoreline Change Analysis in New Washington, Aklan using Digital Shoreline Analysis System (DSAS), *ISPRS Annals of the Photogrammetry, Volume X-5-111-117.* https://doi.org/10.5194/isprs-annals-X-5-2024-111-2024.

Veeraanarayanaa, B., Ravikumar, K., Ramesh, T., Venkateswararao, M., & Sridhar, P.N. (2015). Areal Extent of Erosion and Accretion in and around the Gahirmatha Coast, NW of Bay of Bengal by Remote Sensing and GIS Analysis of Multi-Temporal Satellite Imagery. *International Journal of Geosciences, 6*: 705-719. https://doi.org/0.4236/ijg.2015.67057

Hinton, C., & Nicholls, R.J. (2010). Spatial and Temporal Behaviour of Depth of Closure along the Holland Coast. Coastal Engineering. https://doi.org/10.1061/9780784404119.221

Coastal Engineering Research Center [CERC]. (1984). Shore Protection Manual. US Army Corps of Engineers, Washington DC, Vol. I, 597, Vol. II, 603.

Durkin, C.J., Seenath, A., & Knaapen, M.A.F. (2025). A critical review of closure depth theories and uncertainties: implications for shoreline modelling and coastal management. *Ocean & Coastal Management, 267*, 107732, https://doi.org/10.1016/j.ocecoaman.2025.107732.

Dean, R. G., & Dalrymple, R. A. (2002). *Coastal processes with engineering applications.* Cambridge University Press.

Donchyts, G., Baart, F., Winsemius, H., Gorelick, N., Kwadijk, J., & Van de Giesen, N. (2016). Earth's surface water change over the past 30 years. *Nature Climate Change, 6*(9), 810–813. https://doi.org/10.1038/nclimate3111

Durap, A. (2025). Thresholds and trends in wave steepness: A data-driven study of coastal wave breaking risk. *Marine Science and Technology Bulletin, 14*(2), 80-93. https://doi.org/10.33714/masteb.1649969

Gopinath, G., Thodi, M. F. C., Surendran, U. P., Prem, P., Parambil, J. N., Alataway, A., Al-Othman, A. A., Dewidar, A. Z., & Mattar, M. A. (2023). Long-Term Shoreline and Islands Change Detection with Digital Shoreline Analysis Using RS Data and GIS. *Water, 15*(2), 244. https://doi.org/10.3390/w15020244

Gravens, M. B., Rosati, J. D., & Kraus, N. C. (2011). *Coastal engineering technical note: Influence of dredging on nearshore morphology.* U.S. Army Engineer Research and Development Center.

Hallermeier, R. J. (1978). Uses for a calculated limit depth to beach erosion. *Coastal Engineering Proceedings, 1*(16), 1493–1512.

Hallermeier, R. J. (1981). A profile zonation for seasonal sand beaches from wave climate. *Coastal Engineering, 4*(3), 253–277. https://doi.org/10.1016/0378-3839(80)90022-8

Demir, H., Otay, E.N., Work, P.A., & Börekçi, O. S. (2004). Impacts of Dredging on

Shoreline Change. *Journal of Waterway, Port, Coastal, and Ocean Engineering, 130*(4). https://doi.org/10.1061/(ASCE)0733-950X(2004)130:4(170)

Lapidez, J.P., Tablazon, J., Dasallas, L., Gonzalo, L.A., Cabacaba, K.M., Ramos, M.M.A., Suarez, J.K., Santiago, J., Lagmay, A.M.F., & Malano, V. (2014). Identification of storm surge vulnerable areas in the Philippines through the simulation of Typhoon Haiyan-induced storm surge levels over historical storm tracks. *Nat. Hazards Earth Syst. Sci., 15,* 1473–1481, https://doi.org/10.5194/nhess-15-1473-2015

Kahl, D. T., Vulis, L. M., Schubert, J. E., & Sanders, B. F. (2024). Characterizing longshore transport potential and divergence of drift to inform beach loss trends. *Coastal Engineering, 189*, 104473.

Lee, K.H., & Cho, Y.H. (2021). Simple Breaker Index Formula Using Linear Model. *Journal of Marine Science and Engineering, 9*(7), 731. https://doi.org/10.3390/jmse9070731

Liu, W.C., Chen, W.B., & Lin, L.Y. (2017). Maximum Storm Tide Response to the Intensity of Typhoons and Bathymetric Changes along the East Coast of Taiwan. *Preprints* [Not peer reviewed]. https://doi/org/10.20944/preprints201702.0107.v1.

Aragonés, L., Pagán, J.I., López, I., & Serra, J.C. (2018). Depth of closure: New calculation method based on sediment data. *International Journal of Sediment Research, 33*(2), 198-207. https://doi.org/10.1016/j.ijsrc.2017.12.001.

Luijendijk, A., Hagenaars, G., Ranasinghe, R., Baart, F., Donchyts, G., & Aarninkhof, S. (2018). The State of the World's Beaches. *Scientific Reports, 8*(1), 6641. https://doi.org/10.1038/s41598-018-24630-6

Sebat, M., & Salloum, J. (2018). Estimate the rate of shoreline change using the statistical analysis technique (EPR). *Business & IT, 8*(1):59-65. https://doi.org/10.14311/bit.2018.01.07.

Morang, A., Birkemeier, W.A. (2005). Depth of Closure on Sandy Coasts. In: Schwartz, M.L. (eds) Encyclopedia of Coastal Science. *Encyclopedia of Earth Science Series. Springer, Dordrecht.* https://doi.org/10.1007/1-4020-3880-1_116

Murfitt, J., Brown, C. J., Robertson, C., & Van Rein, H. B. (2017). Developing marine indicators of change using Sentinel-2 time series data. *Remote Sensing of Environment, 197,* 144–156. https://doi.org/10.1016/j.rse.2017.05.017

National Park Service. (2018, April 10). *Coastal processes: Waves. U.S. Department of the Interior.* https://www.nps.gov/articles/coastal-processes-waves.htm

Needham, H. F., & Talke, S. (2025, September 23). *Coastal cities have a hidden vulnerability to storm surge and tidal flooding – entirely caused by humans.* The Conversation. https://theconversation.com/coastal-cities-have-a-hidden-vulnerability-to-storm-surge-and-tidal-flooding-entirely-caused-by-humans-231374

Nicholls, R. J., Hanson, S. E., Lowe, J. A., Warrick, R. A., Lu, X., Long, A. J., & Carter, T. R. (2020). *Sea-level rise and coastal impacts.* Springer.

NOAH. (2019). *Philippines modelled storm surge map of Zambales* – [Data set]. OasisHUB. https://oasishub.co/dataset/philippines-modelled-storm-surge-map-of-zambales-2-metres-height-noah

Ridzuan, N. (2025). Evaluating Coastal Erosion and Accretion Along Batu Ferringhi Beach with Digital Shoreline Analysis

System. *BIO Web of Conferences 176,* 01001. https://doi.org/10.1051/bioconf/202517601001 INFLECTION 2024

Barrineau, P., Janmaat, R., & Kana, T. (2021). Empirical depths of closure along the US East coast. *Coastal Engineering, 170,* 104009. https://doi.org/10.1016/j.coastaleng.2021.104009.

Chowdhury, P., Kumar, N., Lakku, G., Lincoln, S., Seelam, J.K., & Behera, M.R. (2023). Climate change and coastal morphodynamics: Interactions on regional scales. Science of The Total Environment, 899,166432. https://doi.org/10.1016/j.scitotenv.2023.166432

Phillips, M., & Williams, A. (2007). Depth of Closure and Shoreline Indicators: Empirical Formulae for Beach Management. *Journal of Coastal Research - J COASTAL RES. 23.* https://doi/org/10.2112/05-0593.1.

Provincial Government of Zambales. (2024). *Environmental Impact Statement for the Sto. Tomas River Dredging Project.* Zambales, Philippines. https://docs.google.com/document/d/e/2PACX-1vT_0A4xJ1URVxe-3Srjx4ew0K1HHHuEgG_PKiG1N-Dz5vd4TSsjdvRAg1E_t1H_JiDl04f8ZKrLK6yW/pub

Scala, P., Manno, G., Cozar, L. C., & Ciraolo, G. (2025). COAST-PROSIM: A Model for Predicting Shoreline Evolution and Assessing the Impacts of Coastal Defence Structures. *Water, 17*(2), 269. https://doi.org/10.3390/w17020269

Scaramuzza, P. L., Storey, J., & Schmidt, G. (2021). Landsat and Sentinel-2: A multi-mission approach to long-term land monitoring. *Remote Sensing, 13*(18), 3646. https://doi.org/10.3390/rs13183646

Siemens, T., Bastola, S. (2024). Depth of closure, a review of empirical formulae and assessment of climate change along the coast of Louisiana. *J Coast Conserv, 28,* 71. https://doi.org/10.1007/s11852-024-01070-1

Siringan, F. P., & Ringor, A. C. (1997). Changes in the shoreline position of the west coast of Luzon, Philippines: 1890–1993. *Science Diliman, 9*(2), 37–48.

Thasarathan, N., Kuok Choy, L., & Bin Aiyub, K. (2023). Shoreline dynamics over last three decades and predictions for 2032 and 2042: a spatial analysis along the coastal stretch of Aruvi Aru and Kal Aru estuaries in Mannar district, Sri Lanka. *Journal of Maps, 20*(1). https://doi.org/10.1080/17445647.2023.2285520

Udo, K., Ranasinghe, R. & Takeda, Y. An assessment of measured and computed depth of closure around Japan. *Sci Rep 10*, 2987. https://doi.org/10.1038/s41598-020-59718-5

Vos, K., Harley, M. D., Splinter, K. D., Simmons, J. A., & Turner, I. L. (2019). Sub-annual to multi-decadal shoreline variability from publicly available satellite imagery. *Coastal Engineering, 150,* 160–174. https://doi.org/10.1016/j.coastaleng.2019.04.004

Zhang, Z., Wang, Z., Liang, B., Leng, X.,Yang, B., & Shi, L. (2024). Shoreline change analysis in the estuarine area of Rizhao based on remote sensing images and numerical simulation. *Sec. Coastal Ocean Processes, 11.* https://doi.org/10.3389/fmars.2024.1488577