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Assessing Incremental Coastal Inundation Under Sea Level Rise: A MIKE21-Based Analysis of Revetment and Mangrove Defence Performance at Pantai Punggur, Johor

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Abstract

Sea level rise (SLR) poses an escalating threat to low-lying coastal zones, particularly in sedimentary and intertidal environments such as the west coast of Johor, Malaysia. This study evaluates the incremental inundation response at Pantai Punggur, Johor, under projected SLR conditions for 2030, 2050, and 2100, using 2023 as the baseline. Eleven cross-shore transects representing two coastal defence settings, revetment-protected shores and mangrove-buffered zones, were analysed through hydrodynamic simulations conducted in MIKE21. Model inputs included high-resolution bathymetry and topography, ERA5 meteorological data, in-situ tidal and current measurements, and NAHRIM AR6-based SLR projections. Results show a progressive increase in inundation extent throughout the study period. During early-stage SLR (2023 – 2030), revetments demonstrated higher effectiveness in delaying inland water intrusion, with shorter inundation distances relative to most mangrove-fronted transects. However, beyond mid-century, the performance gap narrowed, and by 2100, revetment-protected transects recorded greater inundation distances (327%) than mangrove-buffered transects (189%), indicating a decline in structural effectiveness under prolonged sea-level pressure. In contrast, mangrove zones displayed more gradual and consistent inundation progression, reflecting adaptive buffering capacity influenced by vegetation health and continuity. The findings highlight that while revetments provide strong short-term flood protection, their effectiveness diminishes over long-term SLR scenarios, whereas mangrove ecosystems offer sustained, nature-based resilience. The study underscores the need for hybrid coastal protection strategies that integrate hard structures with mangrove conservation and restoration to strengthen long-term shoreline stability and climate adaptation in Pantai Punggur and similar vulnerable coastlines.

1. Introduction

Coastal zones represent some of the most dynamic and vulnerable environments, where natural processes and anthropogenic activities interact continuously. Rising sea levels, primarily driven by global climate change, have emerged as one of the most critical long-term threats to these environments [1]. The Intergovernmental Panel on Climate Change (IPCC) projects a global mean sea level rise (SLR) ranging between 0.26 m and 0.82 m by 2100, depending on future emission trajectories [2]. According to [3], such increases are expected to exacerbate tidal inundation, storm surges, coastal erosion, and saltwater intrusion, thereby posing substantial risks to human settlements, infrastructure, and ecosystems in low-lying coastal regions.

In Southeast Asia, these impacts are particularly pronounced due to the concentration of population and economic activities along coastal margins, coupled with extensive land reclamation, ecosystem degradation, and limited adaptive capacity. Malaysia, with an estimated 4,800 km of coastline, faces increasing exposure to SLR and related hydrodynamic forces [4]. According to [5], hydrodynamic forces are defined as the forces generated by the movement of water bodies, including waves, tides, and currents, which act upon coastal systems and significantly influence processes such as coastal inundation, erosion, and sediment transport. Among its vulnerable regions is the west coast of Johor, where the geomorphological characteristics of low-lying terrain, wide intertidal mudflats, and estuarine systems render the coast susceptible to inundation (see Fig. 1) [6]. Pantai Punggur, located in Batu Pahat District, exemplifies this condition, where both natural and engineered coastal defences coexist to mitigate the impacts of rising sea levels, as shown in Fig. 2.

Fig. 1 *Coastal inundation at the west coast of Johor, Pantai Punggur in October 2024*

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Fig. 2 *Natural and hard-engineered defences coexist at Pantai Punggur, Johor*

The principal coastal protection measures implemented along Malaysia's western coastline include revetment structures and mangrove buffers. Revetments, typically constructed from concrete armour units, rock armour, or Labuan block systems, serve as hard-engineering interventions designed to provide immediate physical resistance against wave attack, coastal flooding and erosion [7]. While these structures are effective in the short term, several studies have highlighted their limited adaptability to dynamic coastal processes. According to [8], over extended timescales, revetments may induce adverse consequences such as toe scouring, wave overtopping, and sediment imbalance, which can undermine their long-term stability and even accelerate localised erosion.

Conversely, a study by [9] highlights that mangrove ecosystems function as nature-based coastal defences, offering adaptive, self-sustaining protection through wave attenuation, sediment trapping, and shoreline stabilisation. The study further emphasises that the intricate root systems of mangroves dissipate hydrodynamic energy, promote vertical sediment accretion, and enhance coastal resilience under moderate SLR conditions. In addition to physical protection, mangroves provide multiple ecosystem services, including carbon sequestration, nutrient cycling, and biodiversity support. Nevertheless, [10] stated that the effectiveness of mangroves is spatially variable and highly dependent on forest health, species composition, and hydrological connectivity. Degraded or fragmented mangrove stands often exhibit reduced wave-damping capacity, rendering the adjacent coastline increasingly vulnerable to inundation [11].

Despite the widespread application of both hard-engineered and ecosystems-based coastal defences, comparative quantitative assessments of their long-term performance under projected SLR scenarios remain limited, particularly within the Malaysian context. Previous research has primarily focused on individual defence mechanisms, assessing either the hydrodynamic performance of engineered structures or the ecological function of mangrove ecosystems in isolation [12 & 13]. Few studies have examined how these systems perform concurrently under progressive SLR conditions, nor have they evaluated their temporal effectiveness in mitigating inland inundation across extended planning horizons [14].

Addressing this research gap, the present study investigates the incremental inundation response along 11 cross-shore transects at Pantai Punggur, Batu Pahat, Johor, under projected SLR conditions for the years 2023, 2030, 2050, and 2100. The year 2023 was selected as the baseline to represent current coastal conditions, while 2030, 2050, and 2100 were adopted as future projection horizons to capture short-, mid-, and long-term impacts of SLR, in accordance with the decadal projection intervals by the National Hydraulic Research Institute of Malaysia [15]. The transects encompass two principal coastal defence configurations, namely revetment-protected segments and mangrove-buffered zones, to enable a comparative assessment of their effectiveness. Hydrodynamic simulations were performed using the MIKE21 modelling system, [16] describes MIKE21 as a comprehensive numerical modelling platform that integrates a two-dimensional depth-averaged hydrodynamic framework based on the Reynolds-averaged Navier-Stokes equations. Within this study, the modelling approach simulates wave-current interactions and water level variations under projected SLR scenarios, thereby facilitating the quantification of inundation distances and the evaluation of the relative performance of the coastal defence configurations over time.

The findings of this study contribute to an improved understanding of the time-dependent effectiveness of coastal protection strategies under future SLR. Specifically, the analysis provides empirical evidence on the contrasting effects of engineered and natural defences, highlighting their respective strengths, limitations, and potential synergies. Insights from this research are expected to support the development of hybrid coastal management frameworks, integrating structural and ecosystem-based approaches to enhance long-term shoreline resilience and adaptability in the context of accelerating SLR.

2. Methodology

This study employed a combination of geospatial analysis and numerical hydrodynamic modelling to evaluate the incremental inundation response at Pantai Punggur, Johor, under projected SLR scenarios as shown in Fig.3. The methodological framework involved delineating 11 cross-shore transects (T1 – T11) across two distinct coastal defence settings, namely revetment-protected and mangrove-buffered zones, followed by the simulation of inundation extents using the MIKE21 Hydrodynamic (HD) module. The HD module is a two-dimensional, depth-averaged numerical modelling component that simulates water level variations and current dynamics through the solution of continuity and momentum equations derived from the Reynolds-averaged Navier-Stokes equations [16]. It is capable of representing key hydrodynamic processes, including tidal propagation, wave-current interactions, and wind-driven circulation, thereby enabling the analysis of spatial and temporal variations in water levels for coastal inundation assessment and the evaluation of coastal defence performance under projected SLR scenarios. The analysis was conducted for four temporal benchmarks, 2023 as the baseline year to represent current conditions, and 2030, 2050, and 2100 selected as projected year of SLR conditions. The resulting flood extents and inundation distances extracted along each transect were analysed to evaluate the long-term performance, resilience, and effectiveness of the two defence systems under evolving sea level conditions.

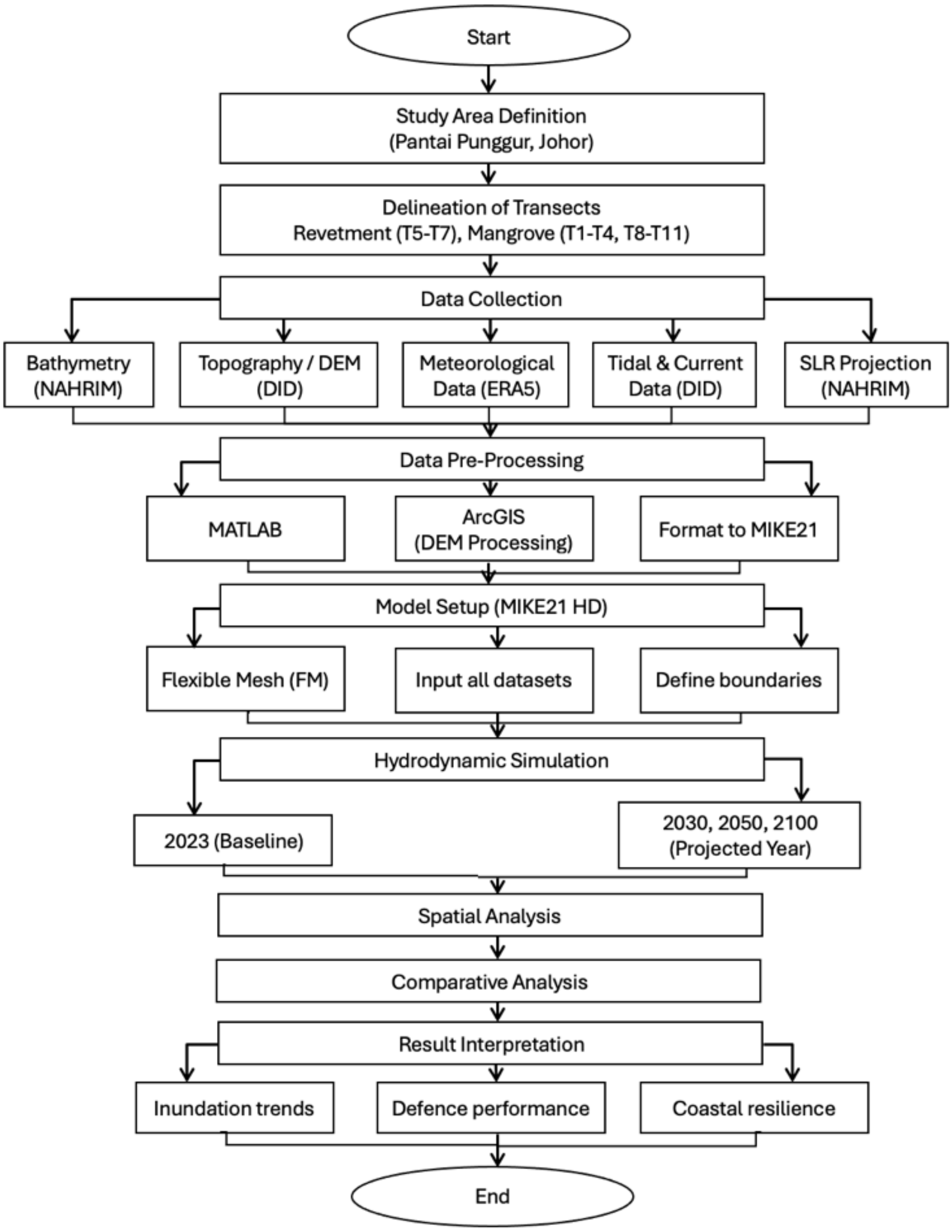

Fig. 3 *Methodology flowchart*

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2.1 Model Input

The model setup for this study required several key datasets to accurately represent the hydrodynamic and topographic characteristics of Pantai Punggur, Johor. The input parameters incorporated into the MIKE21 HD included bathymetric and topographic data, geomorphological data, SLR projections, and land use information to define surface roughness and boundary configurations.

2.1.1 Bathymetry and Topography Data

The bathymetric dataset utilised in this study was obtained from the National Hydraulic Research Institute of Malaysia (NAHRIM), providing high-resolution, site-specific information for the nearshore region of Pantai Punggur, Johor. The dataset comprised three-dimensional coordinates (x, y, z), representing longitude, latitude, and depth values, referenced to the WGS 1984 datum and UTM Zone 48N coordinate systems. These data were crucial for defining the seabed profile and nearshore gradients that influence hydrodynamic flow and wave propagation patterns across the 11 cross-shore transects.

Complementing the bathymetry, topographic data for the year 2023 were obtained from the Department of Irrigation and Drainage Malaysia (DID). The dataset, with a spatial accuracy of approximately 1 – 5m, captured the coastal elevation features and flood-prone lowlands of Pantai Punggur. The Digital Elevation Model (DEM) was processed and analysed using ArcGIS, where elevation points were extracted, interpolated, and converted into (x, y, z) coordinates for seamless integration into the MIKE21 HD modelling environment. Fig. 4 presents the bathymetry and topography of Pantai Punggur, Johor, for the year 2023.

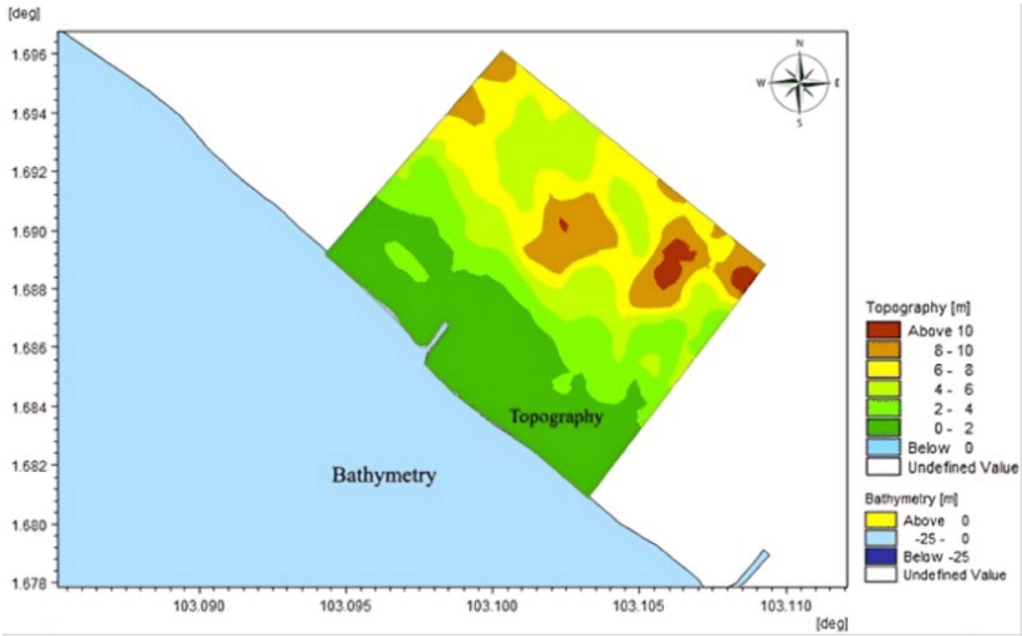

Fig.4 *Bathymetry and topography of Pantai Punggur, Johor, in 2023*

2.1.2 Meteorological Data

The wave and wind datasets utilised in this study were sourced from the United Kingdom Meteorological Office (UKMO) through the European Centre for Medium-Range Weather Forecasts (ECMWF). The ERA5 reanalysis product was selected due to its high spatial and temporal resolution, as well as its proven reliability in representing long-term atmospheric and oceanographic conditions. ERA5 provides hourly records extending from 1940 to the present, offering a comprehensive dataset suitable for coastal and hydrodynamic modelling applications. For this study, five key parameters were extracted, which are wind speed, wind direction, mean wave period, mean wave direction, and significant wave height, to support the simulation of wave propagation and inundation dynamics along the 11 cross-shore transects at Pantai Punggur, Johor. Data corresponding to the year 2023 were utilised as the baseline condition, with subsequent simulations incorporating projected SLR scenarios for 2030, 2050, and 2100 to assess temporal changes in inundation response.

Data pre-processing was performed using MATLAB, where hourly records were analysed, filtered, and formatted for integration into the MIKE21 modelling framework. The processed datasets were instrumental in defining boundary forcing and in characterising nearshore hydrodynamic behaviour under different SLR conditions. Preliminary analysis indicated that wind and wave patterns in the study area are predominantly influenced by the inter-monsoon period, which plays a significant role in modulating local wave energy and inundation potential. Fig. 5 illustrates a representative example of wind speed and direction recorded during October 2023, reflecting the transitional inter-monsoon conditions.

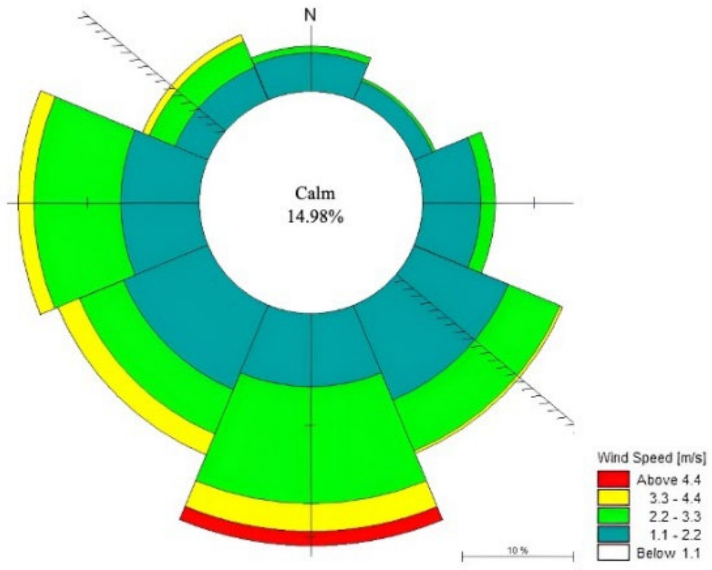

Fig. 5 *Wind speed and wind direction at Pantai Punggur, Johor, during the inter-moonsoon period (October 2023)*

2.1.3 Current and Tidal Data

Current and tidal data were acquired from the DID based on an in-situ monitoring conducted over 14 days, from 27 January to 9 February 2023. Measurements were recorded at 10-minute intervals to capture short-term fluctuations in current velocity and water level, ensuring sufficient temporal resolution for the hydrodynamic model developed. The Acoustic Doppler Current Profiler (ADCP) and tidal gauge (TG) stations were strategically positioned within the coastal zone of Pantai Punggur, Johor, to represent both nearshore and estuarine conditions relevant to the 11 cross-shore transects. The station locations are illustrated in Fig. 6.

Fig. 6 *Maps of ADCP and tidal gauge stations from Google Earth*

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2.2 Model Setup – Numerical Modelling

The study utilized the MIKE21 modelling system, incorporating the Hydrodynamic (HD) module to simulate inundation patterns along the selected transects. A Flexible Mesh (FM) approach was adopted to ensure high spatial resolution near the shoreline and numerical stability across complex coastal terrains. Model inputs included bathymetry, topography, tidal and current data, as well as wind and wave parameters, providing a comprehensive representation of the coastal environment. Simulations were conducted under projected SLR scenario to evaluate inundation extent and trends over time. Coastal defence features were explicitly represented within the model. Revetments were incorporated as input structures, directly influencing hydrodynamic interactions. On the other hand, mangrove zones were represented through modifications of topography and surface roughness to account for vegetation-induced flow resistance and wave energy dissipation. This approach enables a reliable assessment of the relative effectiveness of both defence types in mitigating coastal inundation.

2.2.1 MIKE21 Hydrodynamic (HD)

The MIKE21 HD model developed by [17] was applied to simulate two-dimensional free-surface flows, including tidal circulation, wave-current interaction, and inundation dynamics along the Pantai Punggur coastline. The model is based on the depth-integrated Reynolds-averaged Navier-Stokes equations, incorporating the Boussinesq approximation and assuming hydrostatic pressure conditions. Hydrodynamic processes are computed in both x and y directions using momentum equation and the principles of mass equation, as described in the governing equations (Eq. 1 and Eq. 2). These equations represent horizontal momentum balance and the continuity of flow, providing the basis for simulating surface elevation, current velocity, and depth variation under different SLR scenarios. The detailed configuration of the HD model parameters is presented in Table 1:

Momentum equation:

x-direction:

$$\frac{\partial p}{\delta t}+\frac{\partial}{\delta x}\left(\frac{p^2}{h}\right)+\frac{\partial}{\delta y}+\left(\frac{pq}{h}\right)+gh\frac{\delta\xi}{\delta x}+\frac{gp\sqrt{p^2+q^2}}{C^2.h^2}-\frac{1}{p_\omega}\left[\frac{\delta}{\delta x}\left(h\tau_{xy}\right)+\frac{\delta}{\delta x}\left(h\tau_{xy}\right)\right]-\Omega_q-fVV_x+\frac{h}{p_\omega}\frac{\partial}{\delta x}(p_a)=0 \quad (1)$$

y-direction:

$$\frac{\partial p}{\delta t}+\frac{\partial}{\delta y}\left(\frac{p^2}{h}\right)+\frac{\partial}{\delta x}+\left(\frac{pq}{h}\right)+gh\frac{\delta\xi}{\delta y}+\frac{gp\sqrt{p^2+q^2}}{C^2.h^2}-\frac{1}{p_\omega}\left[\frac{\delta}{\delta x}\left(h\tau_{yy}\right)+\frac{\delta}{\delta x}\left(h\tau_{xy}\right)\right]-\Omega_q-fVV_y+\frac{h}{p_\omega}\frac{\partial}{\delta y}(p_a)=0$$

Mass (continuity) equation: (2)

$$\frac{\partial\xi}{\delta t}+\frac{\delta p}{\delta x}+\frac{\delta q}{\delta y}=\frac{\delta d}{\delta t}$$

Where: x, y = directional components, t = time (s), $\xi(x,y,t)$ = water surface elevation (m), $h(x,y,t)$ = water depth (m), d = time-varying water depth (m), p = flux density in the x-direction, q = flux density in the y-direction, g = acceleration due to gravity (9.81m/s^2), p_a = atmospheric pressure (kg/m.s^2), p_ω = water density (kg/m^3), C = Chezy roughness coefficient (m$^{1/2}$/s), $\tau_{xx}, \tau_{yy,}\tau_{xy}$ = components of shear stress tensor (N/m^2), Ω = Coriolis parameter (s^{-1}), f = wind friction factor (dimensionless), V = wind velocity magnitude (m/s), and V_x, V_y = wind velocity components in x and y directions (m/s).

Table 1 *Parameter settings in the HD model for the study area*

Parameter	Type	Setting Value
Solution Technique	Low order, fast algorithm	CFL = 0.8
Flood and Dry	Drying depth	0.005 m
	Wetting depth	0.1 m
Density	Barotropic	Constant
Eddy Viscosity	Smagorinsky formulation	Constant
Bed Resistance	Manning	Constant = 32 $m^{(1/3)}/s$
Wind Forcing	Speed and direction	Varying in time, constant in domain
Structure	Dikes	Empirical formula
		Crest level = 3.2 m
Boundary	Water level	Global tide model

2.2.2 MIKE21 HD + SLR Scenarios for 2030, 2050, and 2100

The year 2023 was established as the baseline condition, representing the most up-to-date and comprehensive dataset available for tidal levels, current velocities, and meteorological parameters. This baseline serves as a reference to evaluating the progressive impacts of SLR across future timeframes. Future sea level projections were derived from the NAHRIM IPCC Sixth Assessment Report (AR6) [18], under the Shared Socioeconomic Pathway (SSP5-8.5) scenario, using data from the Kukup tidal station. This station was selected due to its geographical proximity to Pantai Punggur, its location within the same hydrodynamic system of the Straits of Malacca, and the availability of long-term, high-quality sea level observations. These factors make Kukup an ideal reference for representing regional sea level variability and enhancing the reliability of local inundation assessments.

The projected SLR increments for 2030, 2050, and 2100 were superimposed onto the baseline (2023) tidal levels within the MIKE21 HD model. This approach allowed the simulation to capture the progressive inland propagation of tidal water under elevated sea levels [19], thereby illustrating the incremental inundation response along the 11 cross-shore transects at Pantai Punggur. The integration of these projections enabled the assessment of potential shoreline retreat, landward inundation extent, and the future effectiveness of existing coastal protection structures under different SLR scenarios.

2.3 Data Analysis

The analytical framework involved two primary components: (i) evaluating the spatial extent and progression of coastal inundation, and (ii) assessing the temporal variation in shoreline displacement and inundation distance across different defence settings, namely revetment-protected and mangrove-buffered zones. The analysis aimed to identify critical thresholds of coastal exposure, evaluate the resilience of existing coastal protection measures, and provide a spatially explicit understanding of how rising sea levels may reshape coastal flood dynamics in the Pantai Punggur region.

The year 2023 was selected as the reference baseline, representing existing hydrodynamic and tidal conditions, while future SLR scenarios were derived from [18] at the Kukup station, as summarised in Table 2. The projected increments of SLR were applied to simulate the progressive influence of rising sea levels on coastal inundation dynamics. A series of perpendicular transects (T1 – T11), extending inland from the shoreline, was delineated in Global Mapper to systematically capture inundation variations across different coastal defence settings, revetment-protected and mangrove-buffered zones (Fig. 7). The simulated water level outputs from MIKE21 were spatially overlaid onto the coastal DEM to determine the extent of the inundation expansion for each projection year.

Table 2 *SLR projection [15]*

Year	Sea Level Rise Projection (Based on NAHRIM IPCC AR6)
	m
2030	0.10
2050	0.23
2100	0.81

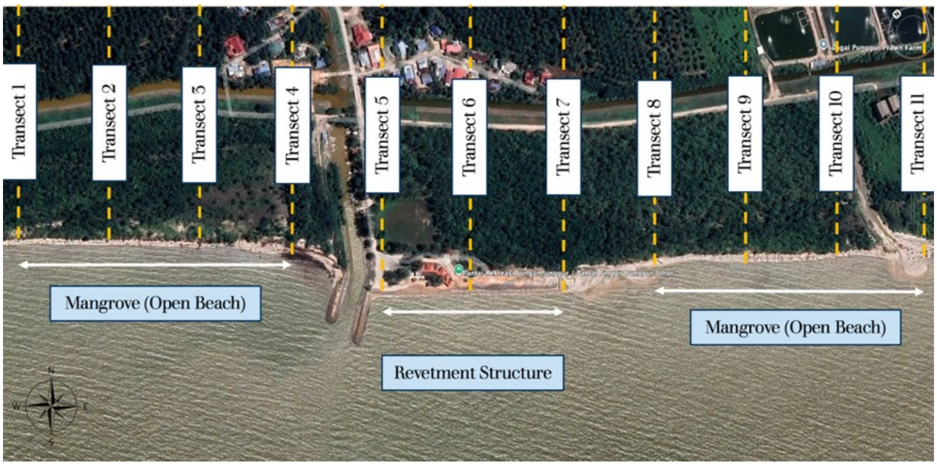

Fig. 7 *Transect-based method along the study area*

2.3.1 Analysis of Incremental Inundation Distance

To quantitatively assess the incremental inundation response under projected SLR conditions, this study conducted a transect-based spatial analysis. This approach enabled systematic evaluation of temporal changes in inundation extent and inland propagation across different coastal defence settings. Each inundation extent was overlaid with the transect network to measure the landward displacement of the inundation limit relative to the baseline shoreline position. The difference between projection years and the baseline (2023) was defined as the incremental inundation distance.

The resulting inundation distances were tabulated and compared between transects representing revetment structures (T5 – T7) and those within mangrove-buffered zones (T1 – T4, T8 – T11) to evaluate their relative effectiveness under progressive SLR scenarios. Furthermore, statistical summaries and graphical representations were produced to visualise average incremental inundation distances across SLR scenarios, thereby providing a clear comparison of inundation trends over time. These analyses offered valuable insights into the temporal degradation of revetment performance and the long-term buffering capacity of mangrove ecosystems, supporting a more comprehensive understanding of shoreline resilience under future sea level conditions.

3. Results and Discussions

This section presents the results of the evaluation incremental coastal inundation response along 11 cross-shore transects at Pantai Punggur, Johor. Outputs from the MIKE21 HD simulations were analysed to assess inundation patterns under projected SLR scenarios for 2023, 2030, 2050, and 2100. The discussion highlights how shoreline features, such as revetments and mangrove zones, influence inundation trends and coastal vulnerability. Overall, the findings provide insights into future inundation risks and the effectiveness of existing coastal protection under rising sea levels.

3.1 Analysis of Incremental Inundation Distances

The comparative assessment of incremental inundation distances, referring to Table 3 and Fig. 7, highlights distinct temporal and spatial variations in flood extent between revetment-protected (T5 – T7) and mangrove-buffered transects (T1 – T4, T8 – T11) at Pantai Punggur under projected SLR conditions for the years 2030, 2050, and 2100.

During the initial period (2023 – 2030), transects protected by revetment structures exhibit lower inundation distances (73.80 m – 90.36 m) compared to several mangrove-buffered transects, such as T4 (98.10 m), T9 (142.71 m), and T10 (127.74 m). This finding indicates that revetments effectively delay inland water intrusion in the early stages of SLR. In contrast, the mangrove-buffered transects demonstrate more variable responses, while T1 (73.08 m) and T2 (71.66 m) show minimal inundation increments; others, such as T9 and T10, record higher distances. These variations are likely influenced by differences in mangrove density, structure, and overall ecological condition, consistent with previous studies emphasising that mangrove effectiveness depends on vegetation health and continuity [20].

By 2050, the performance gap between revetment and mangrove defence begins to narrow. Although T5 (115.05 m) maintains a relatively low inundation level, transects such as T6 (183.97 m) and T7 (218.65 m) display inundation distances comparable to adjacent mangrove transects like T8 (215.11 m) and T9 (187.43 m). This convergence indicates that the efficiency of revetments diminishes under sustained SLR, likely due to increased overtopping, wave reflection, and structural degradation.

A notable reversal occurs by 2100, where revetment-protected transects record some of the greatest inundation distances, T5 (336.51 m), T6 (439.73 m), and T7 (427.16 m), surpassing most mangrove-protected transects, including T1 (359.67 m), T2 (352.28 m), and T8 (383.40 m). These results suggest that while revetments initially provide strong resistance, their long-term effectiveness declines as sea levels continue to rise. Structural fatigue, local scouring, and backwater accumulation may contribute to this decline, supporting earlier observations that rigid coastal defences are less adaptable to evolving hydrodynamic and morphological conditions [21 & 22].

Mangrove-buffered transects, although less capable of fully preventing inundation, display a more gradual and consistent increase in inundation distances across the projection periods. For instance, T3 (371.37 m) and T10 (417.17 m) experience progressive inundation growth, indicating that mangroves provide sustained, though limited, attenuation of flood impacts. Minor site-specific variations also emerge, for example, T11 shows a slightly lower inundation distance under the revetment condition (377.30 m) compared to its non-revetment scenario (382.71 m), reflecting the influence of local topography, vegetation health, and exposure.

The overall trend depicted in Fig. 8 confirms this temporal transition. Initially, revetment-protected transects exhibit lower average inundation distances; however, by 2100, they experience higher inundation than mangrove-buffered transects. This pattern indicates a shift in relative resilience, where static defences lose functionality over time, while nature-based systems maintain moderate but sustained protective capacity [23].

In summary, the results demonstrate that revetments offer effective short-term protection against coastal inundation but are less resilient under long-term SLR conditions. Conversely, mangrove ecosystems provide adaptive, longer-term buffering effects, although their performance depends on ecological conditions and site continuity. These findings underscore the necessity for hybrid coastal management strategies that integrate engineered and ecosystem-based approaches to enhance shoreline resilience and adaptability to future SLR

Table 3 *Incremental inundation distance for every transect*

Transect	Increment Inundation Distance (m)		
	2023 - 2030	2023 - 2050	2023 - 2100
T1	73.08	220.43	359.67
T2	71.66	168.86	352.28
T3	79.03	179.10	371.37
T4	98.10	183.66	377.89
T5	73.80	115.05	336.51
T6	90.36	183.97	439.73
T7	80.95	218.65	427.16
T8	88.72	215.11	383.40
T9	142.71	187.43	409.04
T10	127.74	187.81	417.17
T11	110.02	146.07	377.30

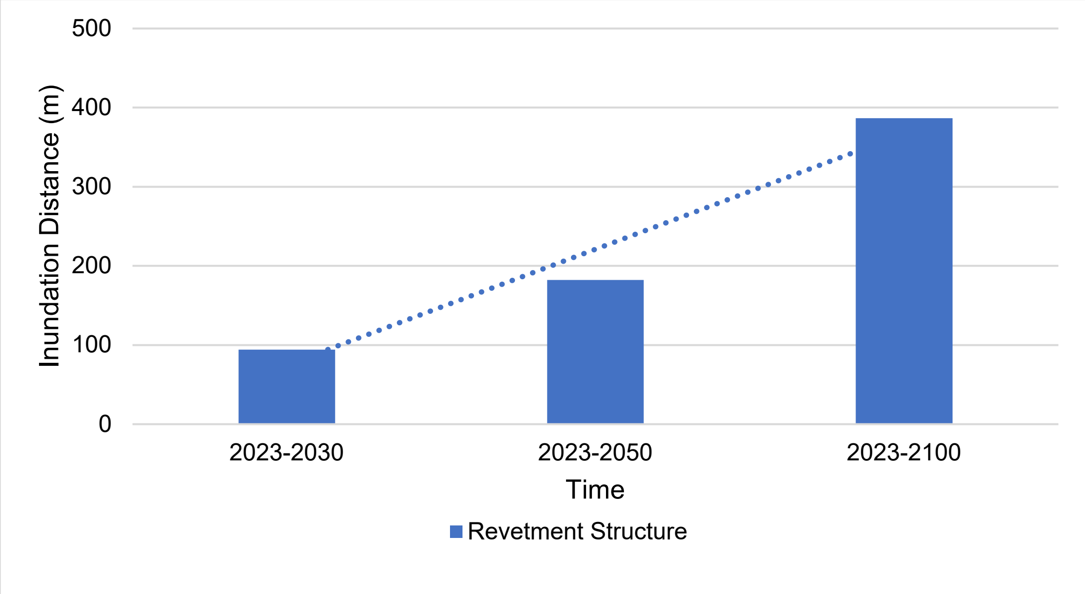

Fig. 8 *Average increment inundation distance, baseline and projected year*

4. Conclusion

This study examined incremental coastal inundation along 11 transects at Pantai Punggur under SLR projections for 2023, 2030, 2050, and 2100 using MIKE21 modelling. The results show that inundation increases progressively over time, with clear differences between areas protected by revetments and those fronted by mangroves. Revetments were more effective in the short term, limiting inland water movement between 2023 and 2030. However, their performance declined significantly by 2100, with several revetment transects experiencing greater inundation distances than mangrove areas. This indicates that hard structures may lose effectiveness under prolonged SLR and intensified coastal processes. Mangrove-buffered transects showed more gradual increases in inundation. Although mangroves did not completely prevent flooding, they provided steadier long-term buffering, highlighting their value as nature-based coastal protection. The results also show that mangrove condition and coverage play an important role in resilience. Finally, revetments offer strong short-term defence, but mangroves provide more consistent long-term benefits. A hybrid approach that combines engineered structures with mangrove conservation and restoration is recommended to enhance coastal resilience and support climate-adaptive planning in Pantai Punggur, Johor.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Ili Nadhirah Ibrahim, Mardiha Mokhtar;* ***contribution:*** *all authors mentioned. All authors reviewed the results and approved the final version of the manuscript.*

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