JOWRM

Journal of Water Resources Management
Journal homepage: https://journal.water.gov.my

e-ISSN: 2811-3578

Impact of Extreme River Discharge and Sea Level Rise on Estuarine Morphodynamics: A Numerical Modeling Approach

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Received 07 March 2025; Accepted 19 September 2025; Available online 27 December 2025

Abstract: Estuaries are dynamic and critical ecosystems governed by complex interactions between oceanic, fluvial, and atmospheric processes. Understanding the impact of extreme climate events on estuarine morphology is crucial for sustainable coastal management. This study integrates TELEMAC2D and SISYPHE numerical models to analyze hydrodynamic and sediment transport responses under three scenarios: (i) extreme river discharge, (ii) a 19 cm sea level rise (SLR), and (iii) a combination of both. Results indicate that extreme river discharge significantly enhances flow velocity, increasing by 125% to 184%, with peak velocity effects extending up to 4.71L_m times the estuary mouth width (L_m), leading to substantial morphodynamic changes. In contrast, the 19 cm SLR scenario reduces flow velocity by 8.30% to 26%, yet still influences estuarine morphology. The combined scenario demonstrates that extreme river discharge dominates over SLR in shaping estuarine bed morphology. These findings underscore the importance of integrating extreme climate scenarios into estuarine management strategies to mitigate long-term environmental risks. This study provides crucial insights for coastal engineers and policymakers in enhancing estuarine resilience amidst climate change.

Keywords: Estuarine morphology, Hydrodynamic modeling, Extreme river discharge, Sea level rise, Compound event.

1. Introduction

Estuaries are dynamic coastal environments where freshwater from rivers meets and mixes with saline ocean water (Zhen-Gang, 2017). These systems play a crucial role in maintaining ecological balance, supporting biodiversity, and providing critical ecosystem services such as flood protection, sediment trapping, and nutrient cycling. However, estuaries are highly sensitive to natural and anthropogenic influences, including hydrodynamic forces, sediment transport, and land-use changes (Zhu et al., 2017). Climate change further exacerbates these challenges, necessitating a deeper understanding of its effects on estuarine morphology.

The hydrological cycle is expected to intensify with global warming, potentially increasing the intensity of extreme rainfall events and flood risks (Tabari, 2020). Uncertainty remains regarding future rainfall patterns due to climate change, and high-flow events further exacerbate flooding (Pasquier et al., 2019). Additionally, a study by Lee (2018) indicates that river flow variations have a more direct impact on salinity fluctuations than sea level changes, which can disrupt estuarine ecosystems.

Future restoration efforts will become more complex due to climate change impacts, such as the projected increase in average temperature by 2–6°C and a 50–160% rise in CO_2 concentrations (Arnold et al., 2017) Climate change also leads to higher suspended sediment levels and water turbidity in river channels, degrading water quality. Reduced flow velocity and turbulence cause sediment deposition and accumulation at estuary inlets (Muttaleb, 2021).

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Furthermore, river water quality may deteriorate due to flooding. Therefore, river discharge characteristics are crucial in terms of geomorphology, hydraulics, flood control, navigation, stabilization, or expansion, depending on the intended use of water resources for aquatic organisms, domestic consumption, and other purposes (Kamarudin et al., 2017).

Extreme climate events, such as increased river discharge due to intensified rainfall and rising sea levels, significantly impact estuarine hydrodynamics and sediment transport processes. High river discharges can lead to excessive sediment transport and deposition, altering navigational channels and affecting water quality (Eidam et al., 2021; Gupta et al., 2023). Concurrently, sea level rise modifies tidal dynamics, influencing sediment redistribution patterns and potentially leading to erosion or accretion in different parts of the estuary. These changes can impact coastal infrastructure, ecosystem health, and economic activities dependent on estuarine stability.

Previous studies have explored estuarine responses to climate change; however, many have focused on either sea level rise or increased river discharge in isolation. The combined effects of these factors, known as compound events, remain relatively understudied. Understanding how estuaries respond to simultaneous changes in hydrodynamic conditions is crucial for predicting future morphological evolution and informing coastal management practices. Numerical modeling provides a powerful tool to simulate and analyze these interactions, offering insights into sediment dynamics under various climate scenarios.

Fig. 1 showed the research framework for this study. This framework consists of five main items which are background research into methodology, analysis, results, and conclusions. It incorporates numerical modeling using TELEMAC2D model which is widely used for hydrodynamic and sediment transport simulations due to its robust capabilities in capturing estuarine processes. The analysis examines morphological changes, tidal influences, and sediment transport responses, leading to key findings and recommendations.

The main objective of this study is to examine the combined effects of extreme river flow, particularly flood flows and sea level rise, on a mixed semidiurnal tidal estuary using a numerical computational model to analyze forecast data on hydrodynamic behavior and sediment transport.

To achieve this general objective, three specific objectives have been established:

i. Investigate the factors and mechanisms influencing hydrodynamic behavior, sediment transport, and estuarine changes.

ii. Analyze the impact of extreme river flow, sea level rise, and their combined effects on hydrodynamic behavior and sediment transport.

iii. Assess the potential impact of extreme river flow and sea level rise on estuarine morphological changes.

The findings from this research contribute to a deeper understanding of the processes and complex interactions that govern the hydrodynamics of mixed semidiurnal estuaries and sediment transport, as well as the impact of climate change on these complex systems. This is particularly important because semidiurnal estuaries are sensitive and vulnerable coastal ecosystems.

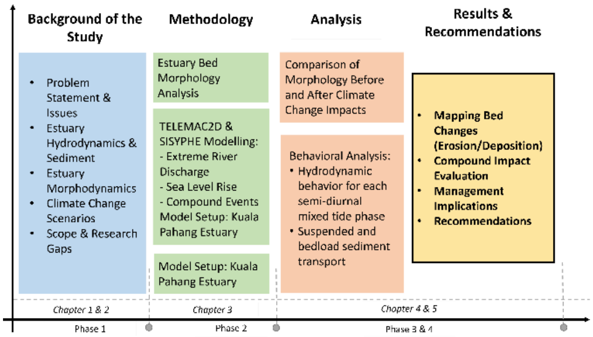

Fig. 1 - Research Framework for Estuarine Hydrodynamics and Sediment Transport Study.

2. Methodology

2.1 Study Area and Data Collection

The Kuala Pahang Estuary (Fig. 2), which connects the South China Sea to the Pahang River basin, is located on the eastern coast of Peninsular Malaysia. The Pahang River basin covers an area of 29,300 km², with the majority (27,000 km²) situated in the state of Pahang, while the remainder lies in Negeri Sembilan (Chang & Ab. Ghani, 2024; Nordin et al., 2023). The Pahang River is the longest river in Peninsular Malaysia, stretching approximately 435 km, and features numerous tributaries and small islands near its mouth. The interaction between the Pahang River's flow and the South China Sea creates complex hydrodynamic conditions, influenced by seasonal variations and tidal changes. The coastal plain surrounding the estuary consists of flatlands and swamps covering an area of 30 to 40 km. The Pahang River basin experiences annual rainfall ranging from 1,700 mm to 2,800 mm, with the northeast monsoon season contributing nearly 40% of the total yearly rainfall. Water level variations in the river correlate directly with rainfall patterns, where increased precipitation in upstream areas such as Chini and Pekan can lead to major floods in Pekan, with water levels rising between 8 to 9 meters. River flow dynamics during the monsoon season show velocities ranging from 0.308 to 0.582 m/s and discharge rates between 153.282 to 439.684 m³/s in January, with a slight decrease in February. Sedimentation processes in the Kuala Pahang Estuary are governed by the interaction between river discharge, tides, and wave action, with deposits primarily composed of sand, clay, and gravel. Studies indicate that suspended sediment transport is more dominant than bedload transport, with suspended sediment loads reaching up to 442.6 tons per day during the northeast monsoon season. Overall, the Pahang River contributes a significant amount of sediment to the South China Sea, with seasonal variations requiring continuous monitoring to assess its impact on the ecosystem and water resource management.

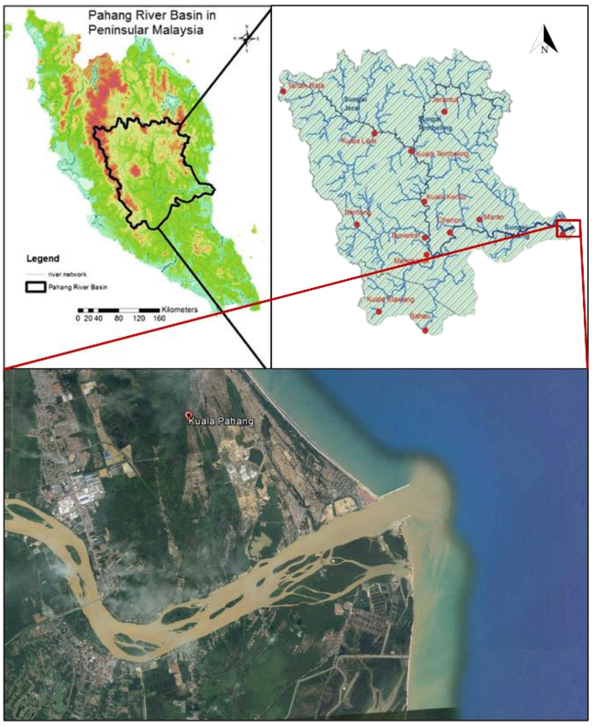

Fig. 2 - The Pahang River Basin, where the blue-marked area represents the catchment area, and the location of the Kuala Pahang estuary is indicated within the red box.

A field study was conducted at the Pahang River estuary to collect data on river currents, salinity, surface temperature, suspended sediment concentrations, and bed sediment samples to determine sediment grain size. The one-day survey was carried out on September 2, 2016, with a total of 20 samples collected from the Kuala Pahang estuary. The coordinates, depths, and observation points for each sampling location were recorded in Table 1.

Table 1 - Sampling Location with Latitude and Longitude Data for Current Speed, and Salinity on September 2, 2016

Sample Point, S	Latitude	Longitude	Current Speed (m/s)	Salinity (ppt)
1	3°31.705	103°28.494	0.66	28.97
2	3°31.523	103°28.448	0.52	28.33
3	3°31.495	103°28.627	0.08	31.53
4	3°32.148	103°28.446	0.11	31.57
5	3°31.742	103°27.909	0.23	31.77
6	3°31.540	103°27.810	0.27	31.30
7	3°31.391	103°27.898	0.17	30.73
8	3°31.296	103°27.364	0.19	31.17
9	3°31.180	103°27.003	0.18	31.43
10	3°30.942	103°26.402	0.27	31.00
11	3°31.071	103°26.460	0.29	31.77
12	3°30.590	103°25.966	0.05	20.90
13	3°30.429	103°25.592	0.28	30.13
14	3°30.633	103°25.731	0.26	30.90
15	3°30.835	103°26.073	0.35	28.97
16	3°31.271	103°26.690	0.38	31.13
17	3°31.394	103°26.963	0.25	31.10
18	3°31.606	103°27.280	0.46	31.30
19	3°31.724	103°27.670	0.23	31.57
20	3°31.775	103°27.783	0.20	30.03
Average	-	-	**0.27**	-

Sampling was conducted during high tide to ensure better access for the boat using the sampling equipment. According to Table 1, the average current velocity recorded was 0.27 m/s, with a maximum velocity of 0.66 m/s. Additionally, on-site salinity measurements (refer to Table 1) indicate that the estuary falls within the lower estuary category, with salinity levels ranging between 20 and 32 ppt.

2.2 **Numerical Model**

TELEMAC2D is a part of the TELEMAC-MASCARET modeling system and is integrated into this system. TELEMAC2D is a two-dimensional (2D) numerical model used to simulate hydrodynamics in rivers, estuaries, and coastal areas. The TELEMAC2D code solves the depth-averaged free surface flow equations using the finite element method (FEM), allowing for a more flexible and accurate representation of complex and dynamic estuarine geometries. The "Barre de Saint-Venant Equations", also known as the shallow water equations, are fundamental in maritime and fluvial hydraulics. These equations form a set of partial differential equations that describe shallow water flow. They are derived under the assumption that vertical fluid motion is negligible compared to horizontal motion, achieved by integrating the laws of mass conservation and momentum (Cao et al., 2017; Filippini et al., 2018). The hydrodynamic module in the TELEMAC2D model solves the Saint-Venant shallow water equations through the 2D depth-averaged Navier-Stokes equations (Ji et al., 2020) as referenced in Equations 2.1-2.4.

$$\frac{\partial h}{\partial t} + u \cdot \nabla(h) + h\,\mathrm{div}(u) = S_h \tag{2.1}$$

$$\frac{\partial U}{\partial t} + u \cdot \nabla(u) = -g\frac{\partial Z}{\partial x} + S_x + \frac{1}{h}\mathrm{div}(hv_t\nabla u) \tag{2.2}$$

$$\frac{\partial V}{\partial t} + u \cdot \nabla(v) = -g\frac{\partial Z}{\partial y} + S_y + \frac{1}{h}\mathrm{div}(hv_t\nabla u) \tag{2.3}$$

$$\frac{\partial T}{\partial t} + u \cdot \nabla(T) = S_T + \frac{1}{h}\mathrm{div}(hv_t\nabla T) \tag{2.4}$$

TELEMAC2D demonstrates significant potential in simulating estuaries compared to other available modeling packages. The process-based model is structured using the TELEMAC2D morphodynamic modeling system, which integrates hydrodynamic and small-scale sediment transport process descriptions. The key components of the morphodynamic model include the flow module, sediment transport module, and bed evolution module.

TELEMAC2D was initially developed by the National Laboratory for Hydraulics and Environment (Laboratoire National d'Hydraulique et Environnement, LNHE) under the Research and Development Directorate of Électricité de France (EDF-R&D). The model solves the full Saint-Venant equations on an unstructured mesh. The depth-averaged two-dimensional model, based on the Saint-Venant equations, has been widely used in studies of estuarine hydrodynamics and sediment transport (Haverson et al., 2018; Helaire et al., 2019; Lanzoni, 2002; Mańko, 2018; Sainte-Marie, 2010).

In this context, predictive modeling becomes crucial, as uncertainties regarding future events can be reduced through detailed investigations and impact analysis of climate change. Numerical modeling techniques have been widely adopted and applied in many countries worldwide (e.g., Ijaz et al. 2019; Mariani, Lessa & Marta-Almeida 2022; Mondal et al. 2018;; Xie et al. 2022; Zhao et al. 2019). Several studies have conducted in-depth investigations into erosion models, including those by Pham & Bui, (2023), Azhikodan & Yokoyama, (2021) and Merz et al., (2014). Morphodynamic models employ advanced flow simulations to precisely estimate particle detachment, transport, and deposition, based on velocity fields or flow energy. These models have been developed by researchers such as Vetsch et al. (2020) and Zhou et al. (2023), as well as in Malaysia (e.g., Gasim, Khalid & Muhamad 2015; Lee et al. 2015; Mohd Salleh et al. 2018; Soo, Ling & Nyanti 2018). However, the application of numerical modeling mechanisms in Malaysia remains limited in assessing estuarine systems.

2.3 Model Setting

Fig. 3 showed the methodological framework for this study follows a systematic approach to assess estuarine hydrodynamics and sediment transport under extreme climate change scenarios, utilizing TELEMAC2D with Blue Kenue as the pre- and post-processor. The process begins with problem identification and objective setting, focusing on the impact of climate change-induced factors such as sea level rise and extreme river discharge on estuarine morphology. The data collection phase gathers essential input parameters, including projected sea level rise of 19 cm by 2050 and 52 cm by 2100, as well as historical extreme discharge events, particularly the 2021 flood, and compound impacts that combine both factors. In the model setup stage, Blue Kenue is used to generate and refine an unstructured triangular mesh, ensuring high-resolution representation in critical estuarine areas for accurate hydrodynamic simulation. The calibration and validation process follows, where the model output is compared against observed data to ensure accuracy; if discrepancies arise, parameter adjustments are made until validation criteria are met. Once validated, the model is applied to TELEMAC2D simulations incorporating the defined climate change scenarios, allowing for a comprehensive analysis of hydrodynamic variations, sediment transport behavior, and estuarine morphological responses. The results are then interpreted to assess the system's resilience to changing conditions, followed by the conclusion and application phase, where findings contribute to the scientific understanding of estuarine processes and inform sustainable management strategies for climate adaptation. The framework concludes with a structured summary of insights that can aid policymakers and environmental managers in developing effective mitigation measures for estuarine sustainability in the face of climate change.

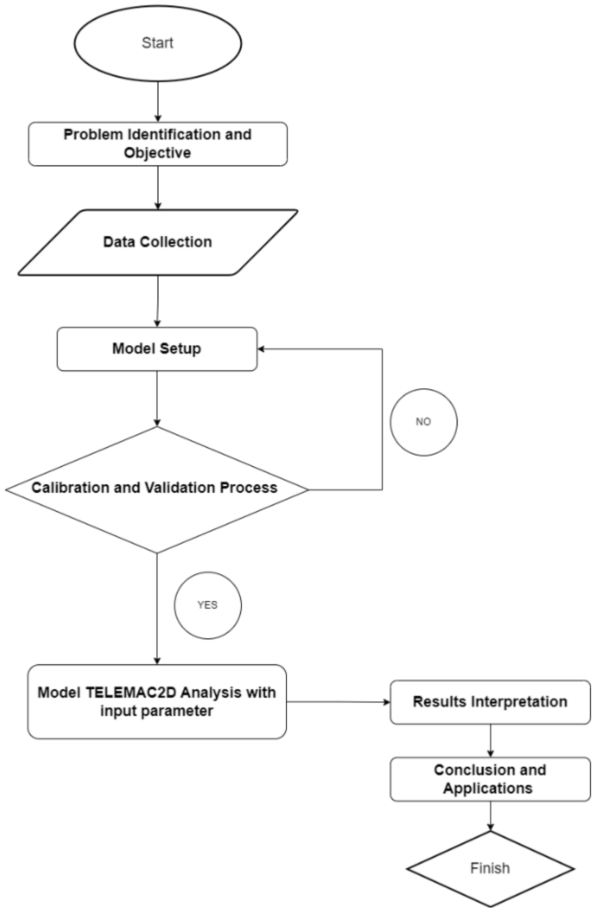

Fig. 3 - Flowchart of the methodological framework for estuarine hydrodynamic and sediment transport modeling under extreme climate change scenarios using TELEMAC2D, with Blue Kenue as the pre- and post-processor.

The Blue Kenue software was developed by the National Research Council Canada as a hydraulic modeling tool to prepare, visualize, and analyze study areas. The BLUE KENUE modeling system provides both quadrilateral grids and triangular meshes. The input data for the grid generator can include points, lines, or other regular and triangular grids. The triangular mesh generator allows users to define "hard points" and "break lines" that are preserved during the creation of nodes and elements. The node density is calculated by interpolating from a user-supplied density map, which can be in the form of a rectangular grid, triangular mesh, or polygonal data.

The workspace in Blue Kenue provides an organizational structure for data files and the active view window within EnSim. On the left side of the screen, the workspace is displayed as a tree structure, consisting of a hierarchical display of categories (organizational titles for objects) and objects (data objects or views), similar to the hierarchical file structure of Windows Explorer, which

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represents relationships between objects and between objects and views (Fig. 4).

This model utilizes an unstructured triangular mesh, where hard lines and break lines are preserved during the construction of nodes and elements. The mesh generation process begins by tracing the coastline and river boundaries using Google Earth Pro software, which is then saved in KML format. Next, using GIS software, the format is converted to ASCII format to enable its use in Blue Kenue for the mesh generation process.

Fig. 4 also showed the model domain extends between 3° 38.480' N and 3° 21.907' N, and 103° 28.803' E and 103° 29.755' E, as shown in Figure 3.25, covering 14 km upstream of the river mouth and 15 km downstream. Meanwhile, the open boundary at the upstream extends 14 km. The TELEMAC2D model, formed using an unstructured triangular mesh, consists of 605,252 nodes and 1,196,776 elements. The minimum mesh size in the estuary area, from upstream to 4 km towards the coast, ranges from 3 m to 5 m node-to-node. The mesh size gradually increases towards the open sea, starting from 10 m to 100 m node-to-node. All islands within the study area are included and designated as soft boundaries.

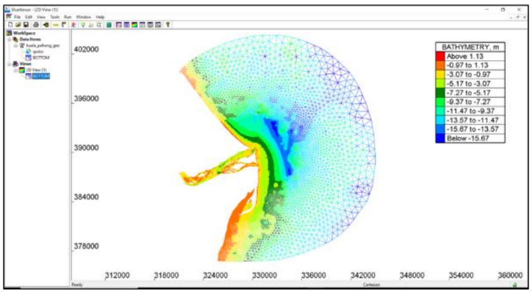


Fig. 4 - The organizational structure for data files and the active view window in EnSim BLUE KENUE, as well as the location and unstructured triangulation grid of the study area in BLUE KENUE, with the applied bathymetry.

2.4 Model Calibration and Validation

Table 2 presents the Root Mean Square Error (RMSE) and Relative Mean Absolute Error (RMAE) values for both calibration and validation analyses of a hydrodynamic model, focusing on water level and current speed. During calibration, the RMSE for water level was 0.18, with an RMAE of 0.137, indicating a slight deviation between simulated and observed values. The current speed showed a lower RMSE of 0.11 and an RMAE of 0.075, suggesting a relatively more accurate prediction. In the validation phase, the model exhibited improved accuracy, with the RMSE and RMAE for water level decreasing to 0.17 and 0.156, respectively. Similarly, the RMSE for current speed was further reduced to 0.07, with an RMAE of 0.057, demonstrating enhanced model performance. These results provide a basis for assessing the model's accuracy and reliability in predicting estuarine hydrodynamics. According to the calibration thresholds set by the Department of Irrigation and Drainage Malaysia (DID), water level errors should not exceed 10%, while current velocity errors must remain within 20% (Mohd, 2019). Additionally, Williams & Esteves (2017) suggest that for estuary models, water level deviations should be within ±0.10 m at the estuary mouth and ±0.30 m at the estuary head, while current velocity RMSE should remain within ±0.20 m/s (or within 10–20% of measured velocity). Model performance can also be evaluated based on predicted maximum velocity errors, with <0.05 m/s classified as excellent, <0.1 m/s as good, <0.2 m/s as moderate, and >0.2 m/s as poor. Based on these criteria, the validation results indicate that the developed model performs within acceptable thresholds, ensuring reasonable accuracy in simulating estuarine hydrodynamics.

Table 2 - Root Mean Square Error (RMSE), and Relative Mean Absolute Error (RMAE), were calculated for calibration and validation analysis.

		RMSE	RMAE
Calibration	Water level	0.18	0.137
	Current speed	0.11	0.075
Validation	Water level	0.17	0.156
	Current speed	0.07	0.057

Fig. 5 showed the validation assessment of the hydrodynamic model by comparing simulated and observed data for water level and current speed. Fig. 5(a) illustrates the comparison of generated tidal data with real site data, where the black line represents the model simulation, and the red dotted line denotes observed water levels. The close alignment between the two lines suggests that the model accurately captures tidal fluctuations over time. Fig. 5(b) displays a similar comparison for current speed, showing variations in simulated and observed values. While there are some discrepancies in peak values, the model follows the overall trend of measured current speed, indicating reasonable performance in replicating hydrodynamic conditions. These validation results demonstrate that the model effectively simulates estuarine water level and current speed within acceptable error thresholds.

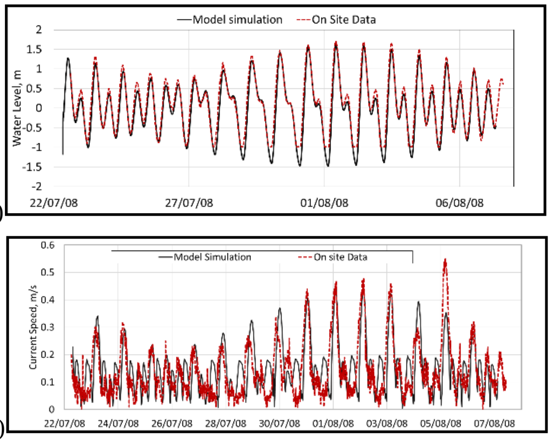
(a)
(b)


Fig. 5 - Assessment of validity in (a), a comparison is conducted between generated tidal data and real site data; in (b), an analysis of current speed is shown. The red dotted line

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represents the site data observed, while the black line illustrates the results of the model simulation.

3. Results and Discussion

3.1 Effects of 19 cm Sea Level Rise

The analysis of current speed under normal conditions and sea level rise impact had shown in Fiq. 6. Under normal conditions, the findings indicate that river flow dominates the estuary mouth, with current velocity ranging between 0.75 m/s and 1.3 m/s during the tidal cycle from Lowest High Water (LHW) to Lowest Low Water (LLW) during a spring tide. The maximum velocity exceeds 0.9 m/s, occurring as the tidal current approaches LLW. The results also reveal that high-velocity currents primarily correspond to the outflow of river water into the ocean during the ebb tide, driven by the transition from LHW to LLW.

During the flood tide, as the water level rises to 73% of the tidal range from Lowest Low Water (LLW) to Highest High Water (HHW), the current velocity experiences a significant 86% reduction, reaching a minimum of 0.07 m/s. With a 19 cm sea level rise, notable variations in current velocity distribution are observed. Specifically, there is a 7.07% to 8.16% decrease in maximum velocity during the transition from HHW to High Low Water (HLW), along with a 2.38% to 3.08% reduction from LHW to LLW. In contrast, during the LLW to HHW phase, current velocity increases by 11.76% to 14.58%. These changes indicate that sea level rise alters the hydrodynamic regime, affecting the magnitude and distribution of tidal currents within the estuarine system.

These findings suggest that rising sea levels alter estuarine hydrodynamics, affecting both the tidal flow regime and current velocity distribution. Fig. 6 illustrates the distribution pattern of average current velocity at the Kuala Pahang estuary for sea level rise scenarios of 19 cm, along with the extent of areas where current velocity exceeds 0.33 m/s and the dispersion distance from the estuary mouth width (L_m) for current velocities up to 0.25 m/s. The arrows indicate the direction of flow. Based on the simulation results, the distribution of average current velocity exhibits a similar pattern for both sea level rise scenarios. However, the 19 cm sea level rise presents a distinct Y-shaped flow pattern, with the outgoing current extending 2.79 L_m for the 19 cm scenario.

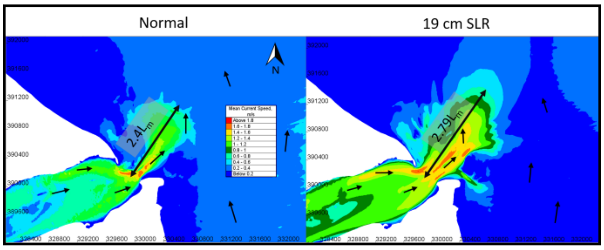

Fig. 6 - Comparison of the distribution pattern of average current velocity at the Kuala Pahang estuary under normal conditions, as well as for sea level rise scenarios of 19 cm along with the dispersion distance from the estuary mouth width (L_m) for current velocities up to 0.25 m/s. The arrows indicate the direction of the current flow.

3.2 Impact of Extreme River Discharge and Compound Event Responses

An increase in extreme river discharge leads to a corresponding rise in current velocity. This indicates that the additional kinetic energy from extreme river flow enhances the current's capacity to transport sediment, resulting in greater erosion at the estuary bed and riverbanks. Under extreme conditions, stronger currents have the potential to transport larger amounts of sediment, increasing the risk of estuarine instability due to uneven sediment transport and deposition.

As highlighted by Mathew & Winterwerp (2020), extreme events cause significant changes in sediment dynamics, leading to irregular deposition and erosion throughout the estuary, which can affect its long-term stability and morphology. Moreover, during extreme flood events, (Liu et al., 2023) reported an increase in sediment resuspension, contributing to both localized erosion and deposition, thereby significantly impacting the estuarine sediment balance.

Overall, extreme river discharge profoundly influences estuarine hydrodynamics, including substantial changes in tidal water levels and increased current velocity. These changes may negatively affect estuarine ecosystem stability and alter long-term sedimentation patterns. Continuous monitoring is essential to better understand and manage estuarine systems affected by extreme climate variability. Results in Fig. 8 shows a comparison of maximum current velocity under normal conditions on December 21, 2021, at 6:26 AM during Peak Spring Tide (PSP) with extreme river discharge, 19 cm sea level rise as well as the combined effect of sea level rise scenarios of 19 cm with extreme river discharge at the same date and time. Based on the velocity distribution in Fig. 8, the extreme flow conditions exhibit a distribution pattern resembling clusters similar to broccoli cross-sections. However, the concentration of distribution for extreme river discharge is noticeably higher compared to the combined scenario. Meanwhile the pattern of current speed distribution with increasing 19 cm sea level, the pattern showed same pattern with normal conditions. Additionally, the velocity distribution pattern exceeding 2.4 m/s in the extreme river discharge scenario is primarily concentrated on the right side of the estuary. When combined with a 19 cm sea level rise, the concentration of the distribution decreases.

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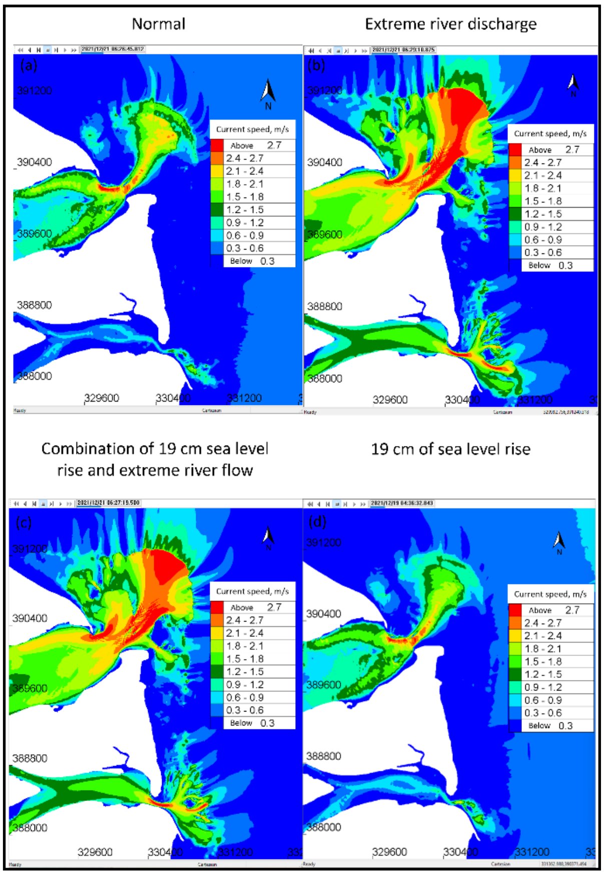

Fig. 7 - Comparison of the maximum current velocity distribution patterns during normal conditions (a) on December 21, 2021, at 6:26 AM during spring tide (PSP) with extreme river flow (b), the combined effect of a 19 cm sea level rise with extreme river discharge (c), and a 19 cm sea level rise (d).

The estuary bed is typically in a state of dynamic equilibrium, where there is a balance between erosion and sedimentation. However, when this stability is disrupted by factors such as extreme river discharge, flooding, or sudden tidal changes, morphological changes to the estuary bed can occur. Disturbances to the estuary bed stability often led to changes in depth and shape, which can impact the stability of the surrounding ecosystem and infrastructure.

3.3 Implications to Estuary Bed Morphology

Table 3 evaluates the potential impact of extreme river discharge and combined sea level rise scenarios (19 cm) on sediment transport and estuarine morphology. The results indicate that extreme river flow significantly increases both bedload and suspended sediment transport, with bedload transport reaching a maximum of 2.5 × 10^{-3} m^2/s (6.63 kg/m/s). When combined with a 19 cm sea level rise, bedload transport remains high. This suggests that extreme river discharge is the dominant force driving sediment transport, while sea level rise acts as a secondary factor that modifies transport patterns rather than exceeding the effects of river flow alone. Similarly, suspended sediment transport increases with extreme river flow, reaching a maximum of 0.015 m^2/s, and when combined with sea level rise, it achieves an average maximum of 4.05 × 10^{-3} m^2/s. meanwhile the potential impact of 19 cm sea level rise is low. The analysis was conducted over a short temporal scale to assess the overall impact of sea level rise. However, based on the findings, sea level rise can influence sediment transport behavior and estuary morphology, but not significantly.

Table 3 - Assessment of the Potential Impact of Extreme River Flow and Combined Sea Level Rise of 19 cm and 52 cm Along with Extreme River Flow on Bedload Transport, Suspended Sediment Transport, and Estuary Bed Morphology

Scenario	**Bedload Transport, Suspended Sediment Transport, and Impact on Estuary Bed Morphology**		
	Low	Moderate	High
Impact of 19 cm Sea Level Rise	✓ (bedload)	✓ (suspended sediment)	
Impact of Extreme River Flow			✓
Impact of Combined 19 cm Sea Level Rise and Extreme River Flow			✓
Description	Sediment transport behavior and morphological change is low for 19 cm sea level rise scenario because higher velocity and energy are required for suspended sediment and bed sediment transport to occur. Extreme conditions increase bedload transport to a maximum of 2.5 × 10^{-3} m^2/s, equivalent to 6.63 kg/m/s. In contrast, the combined impact increases bedload transport to a maximum of 2.0 × 10^{-3} m^2/s, equivalent to 5.3 kg/m/s. Suspended sediment transport increases to a maximum of 0.015 m^2/s due to extreme river flow. Meanwhile, the combined impact reaches an average maximum of 4.05 × 10^{-3} m^2/s. Morphological changes are high for extreme river discharge and combining 19 cm sea level rise and extreme river flow impacts. Extreme river flow, which dominates flow velocity, leads to significant bed changes in the estuary.		

Morphological changes in the estuarine bed are significant across all scenarios, as strong river currents reshape the bed through increased transport capacity. The combination of extreme river flow and sea level rise intensifies these changes, likely due to greater tidal penetration and altered flow dynamics. These findings highlight the vulnerability of estuaries to extreme hydrodynamic conditions, with potential consequences for habitat stability, water quality, and navigational channels. Increased sediment transport can lead to channel siltation, shifts in estuarine ecosystems, and challenges for coastal infrastructure. Therefore, sustainable estuarine management strategies must be implemented to address these combined impacts, incorporating sediment monitoring, floodplain management, and infrastructure adaptation to mitigate long-term morphological and ecological changes.

3.4 Implications for Coastal Management

The interaction between extreme river discharge and sea level rise with the natural semi-diurnal tidal dynamics of an estuary creates highly dynamic and complex hydrodynamic conditions. These changes influence sediment transport, water quality, and ecosystem dynamics, making it essential to consider these factors in estuary management, climate change adaptation strategies, and conservation efforts. Understanding the impact of extreme events on hydrodynamic processes is crucial for predicting and mitigating potential risks to coastal communities, infrastructure, and the environment.

This study significantly contributes to the sustainability of estuarine systems and their surroundings by providing a scientific foundation for more effective management and control of climate change impacts. Through hydrodynamic and sediment transport modeling, it identifies critical areas for cost-effective monitoring and control. The study supports SDG 13.1 by enhancing the resilience and adaptive capacity of coastal communities and policymakers to the effects of sea level rise and extreme river discharge. Additionally, it aligns with SDG 14.5 by providing in-depth scientific assessments to guide conservation strategies for estuarine habitats and water quality.

4. Conclusion

Extreme climatic conditions significantly influence estuary morphology, highlighting the need for proactive adaptation measures. The results assist policymakers and coastal engineers in developing robust estuary management strategies. The projected sea level rise of 19 cm and 52 cm for the years 2050 and 2100 has led to a 30.69% reduction in current velocity during ebb tide and a 47.06% reduction during flood tide for the scenario with a 52 cm sea level rise. Simultaneously, the maximum velocity decreased by 7.07% to 8.16% due to the 19 cm rise in sea level. The tidal range increased from 13.53% to 20.88% due to the 19 cm rise in sea level. In reaction to the 52 cm increase in sea level, the tidal range increased by 34.22% to 35.96%, leading to a 5% reduction in suspended sediment movement to 26%. In contrast, the dominance of river outflow was produced by an increase in current velocity ranging from 125% to 184% and a decrease in tidal range between 46% and 66% due to severe river discharge. The distribution area of bedload sediment transport expanded by 39.68%, leading to a downstream extension of 4.71 km. The distribution of suspended sediment transport was 4.5 km at ebb tide and 3.74 km during flood tide. The current speed and tidal range reacted similarly to the highest river flow when the effects of 19 cm and 52 cm of sea level rise and the highest river flow were added together. Nonetheless, the cumulative effect of severe occurrences, coupled with a 52 cm sea level increase, led to a 16.6% to 43% drop in current velocity, while the combined effect with a 19 cm sea level rise produced an 8.30% to 26% decrease in velocity relative to extreme river discharge alone. The assessment indicates that the potential effects of catastrophic climate change on sediment movement will significantly influence estuarine ecosystems and water quality.

Acknowledgement

The authors extend their gratitude to Jabatan Pengairan dan Saliran Malaysia for their support in providing hydrodynamic and sediment transport data, which were crucial for this research.

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