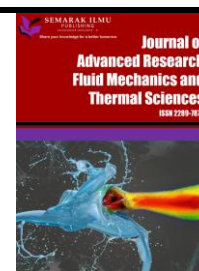




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Numerical Modelling of Wave Height using Wind-Tide Interactions in Coastal Flooding

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ABSTRACT

Pantai Punggur, Batu Pahat is a bustling town located on the Southwest Coast of Peninsular Malaysia, situated along the west coast of Malaysia. Despite its bustling nature, the area is prone to coastal flooding. In response, coastal defence structures have been constructed to protect the coastline. However, the issue lies that this structure cannot fully prevent coastline exposure to wave overtopping caused by strong waves or coastal inundation from high tidal fluctuations that exceed normal sea levels. Pantai Punggur has undergone the concerning issue, and it is worsening. Therefore, this study uses numerical modelling (MIKE21 Software) to investigate the wave scenario from the historical data of wind and tide in Pantai Punggur, Batu Pahat. The study location was digitised, and a new model MESH was developed in the MIKE21 Zero MESH Generator. The historical data from the ERA5-Reanalysis Dataset covering all 12 months (2022) at one-hour intervals was collected. To validate the new model MESH, the RMSE method was employed, which required achieving a result below the 10% threshold. Correlation analysis was conducted monthly throughout the year and revealed distinct relationships between significant wave height (SWH) and wind speed (indicating wave overtopping) and tidal levels (indicating coastal inundation). The correlation between tidal levels and SWH showed a stronger correlation than with wind speed, with the highest R-value reaching 0.5886 (34.64%). Hence, it can be seen that the stronger correlation between tidal level and SWH compared to wind speed and SWH, suggests that tidal fluctuations have a more substantial impact on wave heights and the potential fall on coastal inundation rather than wave overtopping resulting in coastal flooding. The current studies provide essential information relevant to conservation practices and future planning.

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1. Introduction

As a Southeast Asian country, Malaysia is located close to the equator and is divided into two (2) major regions: West Malaysia and East Malaysia. Surrounded by the sea, Malaysia has diverse environments with abundant biodiversity and natural resources. For instance, the west coast of Peninsular Malaysia is rich in various aquatic ecosystems, such as rivers, lakes, reservoirs, coral reefs, mangroves and estuaries [1]. On top of that, Batu Pahat known as a bustling town located on the Southwest Coast of Peninsular Malaysia in the state of Johor. It is one of the districts within Johor and known for its vibrant economy, cultural heritage and coastal attractions. The coastal areas located in Batu Pahat, one of which is known as Pantai Punggur and situated along the west coast of Malaysia, offer scenic beauty and recreational opportunities for residents along the Strait of Malacca [2]. Pantai Punggur faces the Strait of Malacca, known to be a strategic waterway that separates Peninsular Malaysia from the Indonesian Island of Sumatera. Nevertheless, due to its strategic location and economic significance as a trading hub and commercial centre, the area however faces vulnerabilities in the coastal zone [3].

A coastal zone is a region where the land meets the ocean or sea, encompassing both the terrestrial and marine environments that get to interact with each other [4]. It is known to be a complex and dynamic interface, playing a crucial role in ecological balance, human livelihoods and economic activities. However, Malaysia's coastline has been subjected to annual flooding due to seasonal monsoons and climate change, thus impacting critical infrastructure, ecosystems and communities near the coast. Coastal flooding can be defined as the inundation or submersion of land along the coast, usually caused by a combination of factors such as sea level rise (SLR), storm surge, tidal events and extreme weather events [5]. For example, the La Nina phenomenon is an SLR-related effect of climate change which causes flooding in Johor and the four (4) most affected areas were Segamat, Batu Pahat, Kluang and Muar [6]. Aside from that, as the country is located near the equatorial climate, the country experiences two (2) distinct monsoon seasons, which are the Southwest Monsoon (May to September) and the Northeast Monsoon (November to March). While the west coast region specifically was affected by floods the most along with thunderstorms during the inter-monsoon period, which was from September to November [7]. Seasonal monsoons can evolve into extreme monsoon events [8], which are characterized by unusually heavy rainfall and strong winds that can cause an abnormal rise in sea level above the predicted tide level, thus making the coastline vulnerable to tidal fluctuations and the low-lying coastal areas vulnerable to flooding.

Coastal zones are particularly exposed to threats from the ocean and the threats that can be considered a serious problem resulting in coastal flooding are wave overtopping and coastal inundation. Wave overtopping is a well-known phenomenon in extreme marine environments, where waves rise to the exposed surface on the seaward side of a structure, reach and cross its crest, causing water to flow (coastal overflow) [9]. Aside from that, it occurs when strong waves encounter coastal defence structures and are released over ridge structures into hinterland areas [10]. A study mentioned that extreme monsoon events causing storm surges associated with strong winds pushing the seawater onto the coast are increasing yearly, elevated storm surges that exceed the height of coastal structures may cause wave overtopping [11]. On the other hand, coastal inundation is a natural phenomenon characterized by rising local sea levels, where water levels exceed normal levels, leading to flooding in coastal regions [12]. It also refers to the flooding of coastal zones caused by increased river discharge, spring tides, severe storms or the generation of powerful waves due to tectonic activity, such as tsunamis [13]. Research has shown that the coastal area near Batu Pahat is particularly vulnerable to the effects of high tides, storm surges and heavy rainfall, which can raise water levels along the coast and result in the flooding of low-lying areas [14]. This indicates that as a

result of flood risk, wave overtopping and coastal inundation can have a direct impact on the population and damage to infrastructure. For this reason, many coastal countries have begun to build coastal defence structures, i.e., revetments to protect the coast from the damaging power of extreme waves and flooding.

The purpose of coastal defence structures is to reduce and mitigate the impact of flooding, erosion and other coastal risks [15]. The approaches of 'hard' engineering have been implemented as efficient coastal structures due to their ability to mitigate wave-induced energy [16]. Also, the coastal defence structures are capable of protecting coastal areas by storing and redistributing wave energy, almost 60% - 70% through absorption by the defence structure body and between 30% - 40% as a reflection in order to reduce the impact of flooding [17]. For these reasons, the construction of coastal structures is considered one of the ways in which coastal nourishment is achieved and its function is to generate more rehabilitation area at the side of the structure due to increasing trend in coastal flooding [18]. Even though coastal defence structures are being considered as plausibility, the existing structure today have been harmed and have caused flooding to the coastal area. Correspondingly, the issue at hand is the coastal structures today unable to fully protect the coastline exposure. Leaves in question, where it is due to wave overtopping caused by strong waves and winds that hit the structure repeatedly or coastal inundation from high tidal fluctuations that exceed normal sea levels, worsening potential flooding. The coastal regions on the west coast of Malaysia, particularly in Johor which includes Pantai Punggur have undergone the concerning issue where the coastal structure particularly revetment at the ponder area has been built, but the issue of coastal flooding is worsening despite the purpose of the structure are to mitigate. The existing revetment has failed to protect the coastal region due to the varies wave scenario along the coast that cause the areas to flood and impact the population, infrastructure and surrounding environment [19].

According to Mirzaei *et al.*, [20], the east coast of Peninsular Malaysia, particularly during the northeast monsoon season, experiences significant wind wave activity (wave overtopping). This region, which includes states like Kelantan, Terengganu and Pahang, where faces strong winds generated by monsoonal systems typically between November and March. These winds originating from the South China Sea, drive the formation of large overtopping waves that can reach considerable heights, particularly during severe weather events [21]. The study of Benson *et al.*, [21] focused on wave runup and overtopping caused by SLR due to the influence of monsoons, revealing that the east coast experiences a more significant impact from wind waves compared to the west coast. This finding suggests that the east coast is particularly vulnerable to overtopping waves, where the energy from wind waves leads to coastal flooding and infrastructure damage. However, since this study was conducted on the west coast, the uncertainties surrounding coastal flooding in that region, arising from different wave scenarios, thus further investigation are needed to effectively mitigate the risks to communities and industries.

Therefore, this study concentrated on investigating the wave scenario from the historical data of wind and tide in Pantai Punggur, Batu Pahat since the state of the coastal area is worsening potential flooding. In order to address this issue, the study aims to:

- i. Determine the model verification of the MESH study location to be compared with in-situ data
- ii. To simulate the wave patterns using Spectral-Wave (SW) module from numerical modelling (MIKE21 Software).
- iii. Intentionally to analyse the significant wave height (SWH) of the study location resulting from the SW numerical modelling related to wind speed and tidal level, in order to investigate whether the wave scenario due to wave overtopping forms or coastal inundation (tidal fluctuations).

The study location, Pantai Punggur was digitized and a new model MESH was developed using the MIKE Zero MESH Generator. Next, the study was conducted covering all historical data in 2022 for each month at one-hour intervals and historical data from the ERA5-Reanalysis Dataset, covering all 12 months was used for the simulation. The measured data in determining the model verification for MESH are provided to be compared with simulated data using the Root Mean Square Error (RMSE) method. Then, the data were analysed by using some statistical methods in order to see the wave scenario that influences the study location wave patterns resulting in coastal flooding either due to wave overtopping or coastal inundation (tidal fluctuations).

Wave overtopping occurs when waves surpass the height of coastal defences, while coastal inundation happens when high tides or storm surges elevate sea levels beyond normal limits, both leading to significant flooding in coastal regions. Understanding these processes is critical, as the damage they cause can be widespread, affecting infrastructure, ecosystems and the livelihoods of those living in coastal communities. By analysing wave patterns, tidal changes and their interactions with coastal defences, predictions can be made about when and where flooding is likely to occur. This predictive ability is vital for both immediate disaster response and long-term planning, helping to identify areas most at risk and guiding the design of more effective coastal protection measures.

A comprehensive understanding of wave overtopping, combined with insights into coastal inundation, enhances the ability to design defences like seawalls, dikes and levees that can better withstand projected wave heights and sea level rises, ultimately reducing flooding risks. Additionally, this knowledge leads to improvements in flood prediction models, making them more accurate and reliable. By incorporating real-time data on wave dynamics, sea level shifts and storm surges, these models can offer earlier and more precise warnings, giving coastal communities more time to prepare and, if necessary, evacuate.

This study aims to deepen our understanding of the relationship between wave overtopping and coastal inundation, thereby contributing to a clearer picture of coastal flooding dynamics. By examining how different wave conditions influence flooding, the research will provide valuable insights into the factors driving coastal flooding. These findings will not only support the development of more resilient and adaptive coastal defences but also inform flood mitigation and conservation strategies. Furthermore, the results of this research will have practical applications in improving coastal management, especially in areas vulnerable to rising sea levels and increasingly severe storms due to climate change. A better grasp of wave patterns will enhance early warning systems by integrating wave and tidal data into more precise predictive models, aiding in risk assessment and emergency preparedness. This proactive approach is essential for protecting coastal communities, minimizing flood damage and ensuring the long-term sustainability of coastal ecosystems. By addressing the objectives of this study, the research will provide crucial information for future planning, disaster readiness and the preservation of vulnerable coastal areas. Ultimately, the study will help strengthen the resilience of coastal regions, ensuring that both human populations and environmental systems are better equipped to handle the growing threats of coastal flooding and related hazards. Comparing, while many global and regional studies have explored coastal inundation due to SLR, specific investigations in Pantai Punggur, remain scarce. There is a need for localized assessments considering site-specific factors such as tidal influences, wave dynamics and sediment transport. Also, the long-term performance of existing coastal protection structures in Pantai Punggur under projected SLR conditions remain uncertain. More research is needed to evaluate whether these structures will continue to provide adequate protection or if adaptive measures are required.

2. Methodology

The methodology used for model preparation, data collection, model simulation, model verification and data analysis consist of several major steps. These steps include digitizing mapping of the study location, simulation of a new model for verification and validation by comparing measured data with simulated data using the RMSE method, simulation of the verified model using MIKE21 Software-SW module, data analysis and interpretation of analysed data using statistical method. The combination of these steps provides a comprehensive understanding of the wave scenario causing coastal flooding at the study location.

2.1 Digitizing Study Location

In this study area, Pantai Punggur, Batu Pahat have been selected and the location as shown in Figure 1. This coastal area was chosen due to its location related to the concerning issue which potential flooding that became increase yearly and the effectiveness of the coastal defence structure are varies.



Fig. 1. Study location

Figure 2 shows the location of the study area from 1.62°N, 102. 78°E to 1.87°N, 103.19°E.



Fig. 2. Location of Pantai Punggur, Batu Pahat, Johor

The area for digitizing is chosen from Muar to Mersing as shown in Figure 3 to ensure model verification point provided are included in the digitize map. On top of that, the Indonesian Island of Sumatera are also included in the simulated MESH just to ensure the wind and wave data from every perspective are considered.



Fig. 3. Digitized map on Google Earth

2.2 Model Preparation – MESH

Key steps in developing the model include digitizing the study location, generating a mesh with the MIKE Zero Mesh Generator and validating the model using in-situ Acoustic Doppler Current Profiler (ADCP) measurements to ensure accuracy. The bathymetry data, obtained from an open source know as General Bathymetric Chart of the Ocean (GEBCO) Gridded Bathymetry Data, is recognized for its reliability, particularly in deep-water environments, where it demonstrates strong correlation and low prediction errors, as indicated by the Pearson correlation coefficients and RMSE value in [22]. This makes GEBCO's data valuable for hydrodynamic modelling across various oceanographic applications, especially in regions with complex seafloor topographies. The mesh was

generated using MIKE21 software, with data processed through ArcGIS Pro, resulting in triangular mesh with varying spatial resolutions. Shallow, dynamic coastal waters were modelled with a finer solution of 1 km, while deeper, more stable waters were modelled with a course 5 km resolution as shown in Figure 4 and 5, optimizing computational efficiency without sacrificing accuracy.

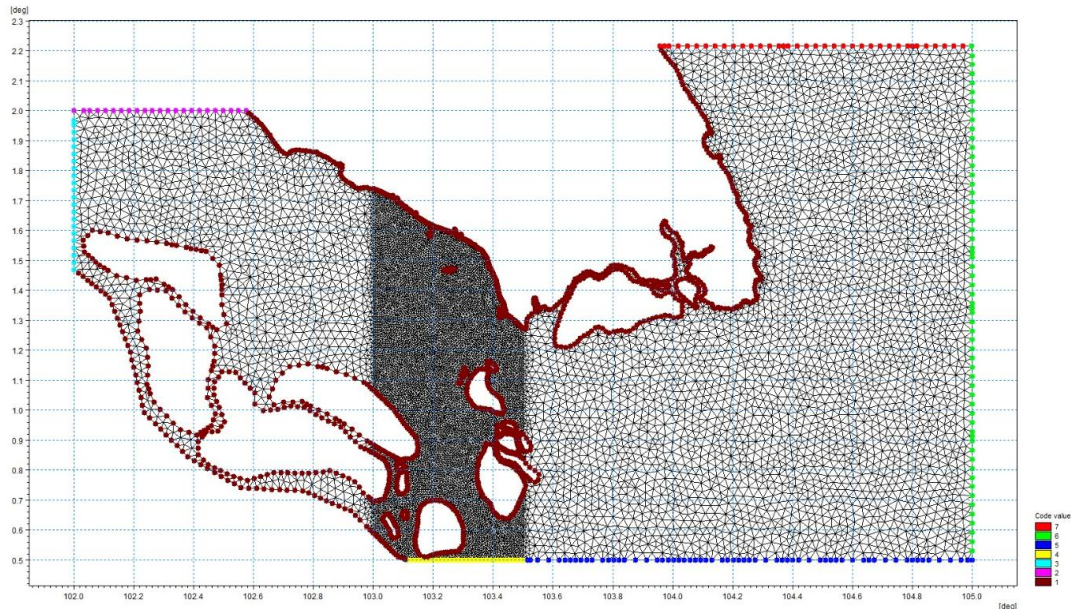


Fig. 4. Domain model

Validation of the model with ADCP data confirmed that the simulated conditions matched real-world observations, a critical step for ensuring the model's ability to accurately replicate complex hydrodynamic processes, including tidal flows and storm surges. The emphasis on finer spatial resolution in coastal waters reflects the need to capture rapid hydrodynamic changes driven by tides and wind, while the coarser resolution in deeper waters addresses the relatively stable hydrodynamic conditions in those regions. This balance between resolution and computational demand ensures the model's efficiency while enhancing its predictive capabilities, especially in capturing localized phenomena in the study area.

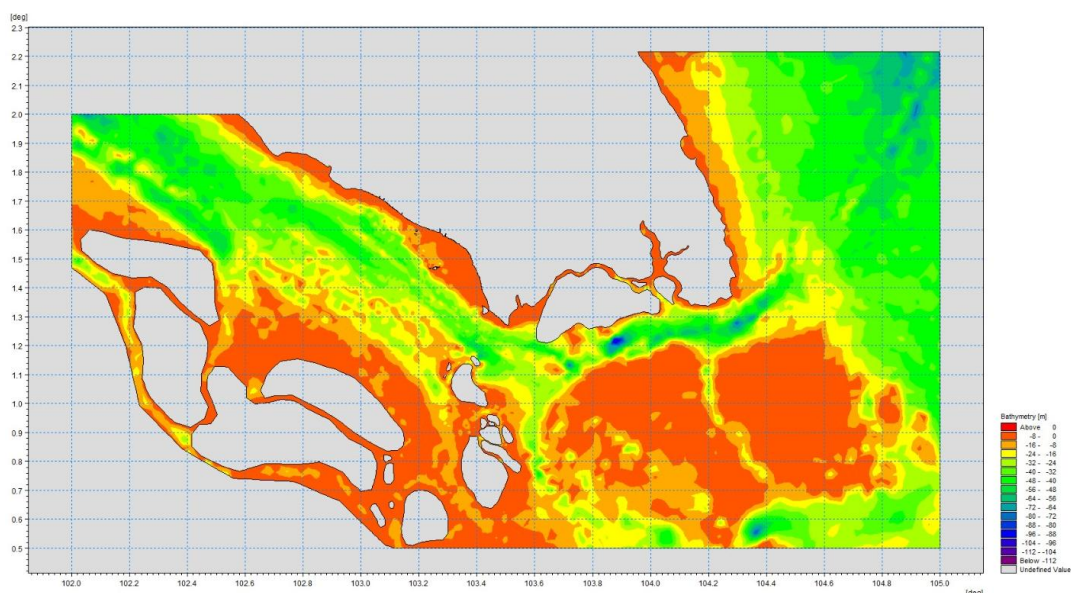


Fig. 5. Domain model with bathymetry

2.3 Data Collection

The secondary data was used for this study and has been collected from an open source known as ERA5-Reanalysis Dataset from the European Centre for Medium-range Weather Forecasts (ECWMF). The validation of using this open source can be seen in a recent study conducted. The study conducted in the coastal waters of India compared the significant wave height and mean wave direction from the ERA5 dataset with buoy-measured data at nearby locations [23]. The findings show that the correlation coefficients range from 0.82 to 0.99, with RMSE values between 0.15 and 0.31 m. Additionally, the ERA5 wave direction results significantly deviate from the buoy measurements, suggesting that the ERA5 dataset generally aligns well with the observed mean wave direction. Meanwhile, another study examining the accuracy of the ERA5 Wave Reanalysis against in-situ data from the Egyptian Mediterranean Coasts confirmed its validity across three main wave parameters [24]. This study found that the differences in mean significant wave height (SWH) for offshore buoys ranged from -0.17 to 0.14 m, with correlation values of 0.88, 0.96 and 0.96 and RMSE values for SWH ranging from 0.001 to 0.1126 m. Hence, these events showed the data collected ECWMF, ERA5-Reanalysis Dataset are considered valid as secondary data for this study.

2.3.1 Historical wind and wave data – ERA5 reanalysis

In this study, data was meticulously collected throughout the entire year of 2022, capturing measurements every day of each month (January to December) at one-hour intervals which includes several variables in order to obtain the data are required. Five (5) variables required such as wind speed (u_{10}), wind direction (v_{10}), mean wave direction (MWD), mean wave period (MWP) and significant height of combined wind waves and swell (SWH). This comprehensive approach ensured a detailed and continuous dataset, providing a robust foundation for analysing the wave patterns and trends across various time scales. Due to this, the aims of the study in order to investigate the wave scenario throughout the entire year can be seen thoroughly and the different wave patterns for every month can be easily classified from the data obtained. Maintaining consistent data collection at hourly intervals also helps the study to gather high-resolution information, allowing for a thorough examination of daily and seasonal variations, which is crucial for achieving accurate and reliable findings.

2.4 Data Extraction – MATLAB

After collecting data for the entire year of 2022 at one-hour intervals, the next step involved extracting and processing the data using MATLAB software. MATLAB, with its powerful computational and analytical capabilities, was used to import the raw data, perform necessary preprocessing steps and organize the information into a usable format for further analysis. One key advantage of using MATLAB for data extraction is its ability to handle large datasets efficiently, which is critical for processing year-long data at such frequent intervals. MATLAB's extensive toolbox allows for the extraction of relevant variables and application of various data processing techniques such as filtering, smoothing and interpolation, enabling more refined analysis. Such in the study of Mokhtar *et al.*, [25], the intricate mathematical model is converted into similarity equations through suitable transformations and the MATLAB function is utilized to numerically solve the equations with a detailed analysis, generating a comprehensive dataset.

Moreover, MATLAB offers a highly customizable environment for scripting and automation, which helps streamline the data extraction process. Effective coding practices in MATLAB ensure that

the script is robust, efficient and easy to understand, allowing for future modifications and extensions. The script used for this study was efficiently designed to extract data collected from the ECWMF ERA5-Reanalysis Dataset, focusing on five key variables. MATLAB's advanced matrix operations and built-in functions greatly enhance the accuracy and speed of extracting and processing such data. Additionally, MATLAB's visualization capabilities offer another advantage, enabling quick plotting and visual analysis of trends, helping researchers spot patterns early on. Thus, using MATLAB not only provided a robust framework for data extraction but also ensured that the data was well-prepared for subsequent analysis, with accurate, clean and structured datasets ready for detailed exploration of trends and patterns in the study.

2.5 Simulation – Numerical Modelling (MIKE21 Software – Spectral Wave Module)

Following the completion of data extraction, numerical modelling simulations were conducted to analyse and interpret the processed data. The SW module will be utilized for the numerical modelling in this study although MIKE21 Software provides various modules for wind and wave simulation. However, the SW module was identified as the most suitable for this study due to its inclusion of wave dissipation capabilities, which enhances the understanding of nearshore wave conditions, especially since the study area is located near the shore [26]. Utilizing this module allows for accurate simulation of wave scenarios and dynamics, helping to achieve the study's objectives. Additionally, the SW module is known for its precise calculations of wind-generated waves and swell sizes, making it a reliable and cost-effective option for offshore and nearshore wave-sensitive engineering projects [26]. The output integral wave parameters in the module are used referring to the Eq. (1) to Eq. (5) [26]:

Significant wave height, m

$$H_{m0} = 4\sqrt{m_0} \quad (1)$$

Maximum wave height, m

$$H_{max} = \min(H_{max}^1, H_{max}^2) \quad (2)$$

Mean wave direction, degree

$$MWD = 270 - \tan^{-1}(b/a) \quad (3)$$

Mean period, s

$$T_{01} = m_0/m_1 \quad (4)$$

Wind input

$$S_{in}(f, \theta) = \max(\alpha, \gamma E(f, \theta)) \quad (5)$$

The data extracted from the MATLAB will serve as the input for this model by providing essential information on wave characteristics such as SWH, MWP and MWD, which are crucial for accurate simulations. Moreover, water level is required as an input parameter which can be obtained from the MIKE Zero module in the tidal prediction by inserting nearby tidal gauge location which the study used are Tanjung Laboh (1.44°N, 102.59°E) referring to National Hydrographic Centre [27]. By inputting this comprehensive dataset into the SW module, the model can effectively replicate real-world conditions and predict wave patterns under various scenarios.

2.6 Model Verification & Validation

The model MESH was done completely in the MIKE Zero MESH Generator with a complete bathymetry and the modifications are allowed in this step to ensure that the bathymetry can expand, allowing model accuracy to be obtained as required as well as allowing the time for each simulation to be within the appropriate time. The model then simulated in MIKE21 Software and the output point required for the simulated data to be compared with was provided at the coordinate of 1.32208333°N, 104.4066111°E as shown in Figure 6.

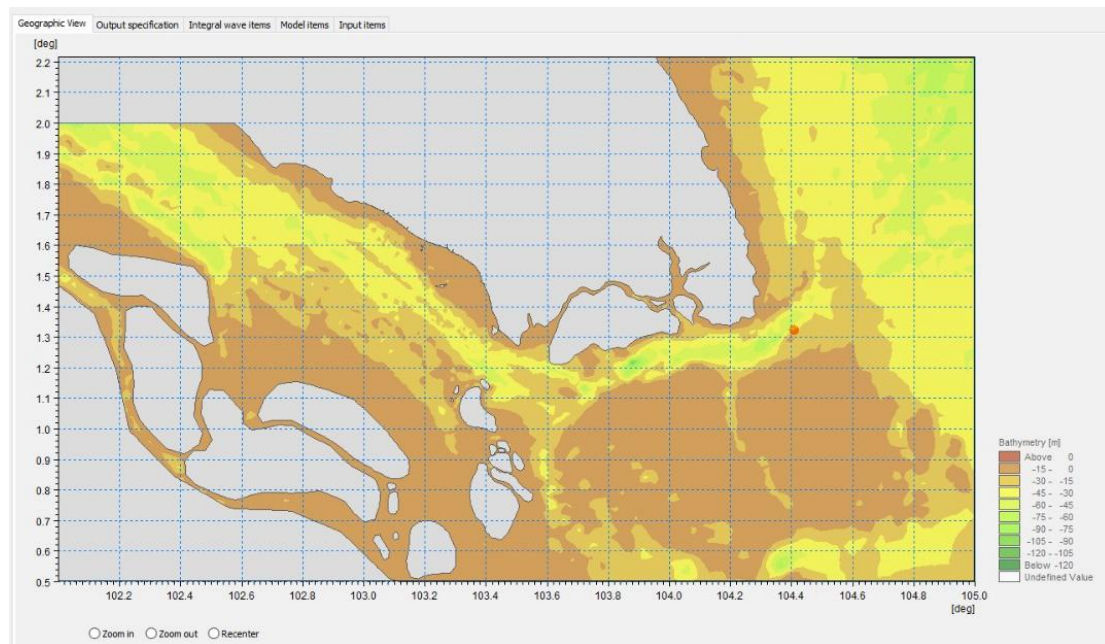


Fig. 6. Location of ADCP point

As for this study, the verification of the new model is carried out by comparing the maximum wave height (H_{max}) of the model data to measured values at one-hour intervals on October 2022 (7th until 22nd) referring to the measured ADCP value provided. The number of calibration points should be adequate relative to the size of the model or project area and the RMSE method employed. This will ensure the validation of calibration points can be effectively carried out using statistical tools in Microsoft Excel [28]. The RMSE method is a statistical technique used to assess a model's accuracy by measuring the difference between predicted values and actual observed values. A lower RMSE value signifies that the model's predictions are closer to the observed values, indicating greater accuracy [29]. According to Jabatan Pengairan dan Saliran Malaysia [28], the average differences in speed and direction shall not be more than 30% and 45° while, the average difference in water level and wave height shall not be more than 10%. The RMSE formula shown in Eq. (6) is used to calculate the standard deviation of the residuals (prediction errors) [28]:

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (p_i - a_i)^2}{n}} \quad (6)$$

2.7 Data Analysis

The core data analysis process involves extracting significant insights and patterns from raw data, including critical steps such as model verification, data validation, the analysis of wave simulation

patterns using MIKE21 software and performing a coefficient of determination (R^2) analysis. These processes are essential for transforming raw data into meaningful information that can inform key decisions. Statistical and analytical methods allow researchers to interpret complex datasets, enabling informed conclusions about environmental dynamics. In this study, data analysis was employed to explore and understand coastal dynamics at the Pantai Punggur, Batu Pahat shoreline region, contributing to a more comprehensive understanding of shoreline erosion, sediment transport and other coastal issues affecting the region.

Microsoft Excel 2019 was chosen as the primary tool for conducting the data analysis. Its flexibility and user-friendly interface make it well-suited for handling large datasets, running statistical tests and performing various calculations. Specific formulas and functions in Excel, such as regression analysis, were applied to calculate relevant statistical measures including the mean, standard deviation and correlation coefficients, which are essential for determining the accuracy and reliability of the data. Excel's capabilities for generating visualizations like graphs and charts also provided a convenient way to represent trends in the wave patterns and coastal data, helping to quickly identify anomalies or significant shifts over time.

Additionally, integrating Excel with more advanced analysis tools such as MIKE21 allowed the team to seamlessly compare simulation outputs with observed data. Excel's data management features ensured that the raw and processed data were easily accessible for further statistical analysis, while also simplifying the process of verifying and validating the simulation results. The coefficient of determination (R^2) analysis, for example, was crucial in assessing the goodness-of-fit between simulated wave patterns and real-world measurements, offering a quantitative measure of how well the model predicted actual conditions along the Batu Pahat shoreline.

By leveraging Excel's extensive functions and MIKE21's sophisticated wave simulation capabilities, the study was able to provide detailed insights into shoreline erosion processes, wave dynamics and other factors influencing coastal stability. This integrated approach not only enhanced the accuracy of the analysis but also contributed to more informed decision-making regarding coastal management and mitigation strategies for Pantai Punggur and the broader Batu Pahat region.

2.7.1 Correlation analysis

A thorough analytical analysis was developed to derive the data by using Microsoft Excel functions, charts. and statistical tools. Correlation analysis (R-values) was used in this study to analyse the SWH of the study location resulting from the SW numerical modelling to identify the correlation relationship between the wave patterns with wind speed and tidal resulting the ponder area to flooding. The results of this analysis will justify the wave scenario of the conducted study area flooded due to wave overtopping forms or coastal inundation (high tidal fluctuations). The statistical results obtained from the R-value have been interpreted according to the R-values classification as shown in Table 1 [29], to determine the strength and direction of the linear relationship between the variables (wave, wind and tidal).

Table 1
Classification of R-Values

R-Value	Interpretation
1	Perfect
0.7 – 0.9	Strong
0.4 – 0.6	Moderate
Less than 3	Weak

3. Results

This section discusses the results obtained from the simulation of MIKE21 Software in identifying the model verification and validation using the RMSE method. Other than that, the result obtained from the simulation in justifying the wave scenario is due to overtopping wave forms or coastal inundation (high tidal fluctuations) of the study location.

3.1 Simulation Analysis

Simulation wave analysis is a technique used to model and understand the behaviour of waves in marine and coastal environments. This analysis was implemented in MIKE21 Software, to simulate the dynamics of waves under various conditions, including different wind speeds, tidal patterns and water depths. In MIKE21 Software, vectors are used to visually represent wave movement, illustrating both the direction and magnitude of wave propagation in a marine and coastal environment as shown in Figure 7, displays the virtual simulation of wave movement in MIKE21 Software for this study. These vectors display provide a dynamic overview of how waves are moving across the water's surface, influenced by various factors such as wind speed and water levels. The length of each vector indicates the speed of the wave, while the direction of the vector shows the wave's propagation path. This visual representation is essential for understanding complex wave behaviours and patterns, allowing to analyse how waves interact with structures, shorelines and other environmental features.

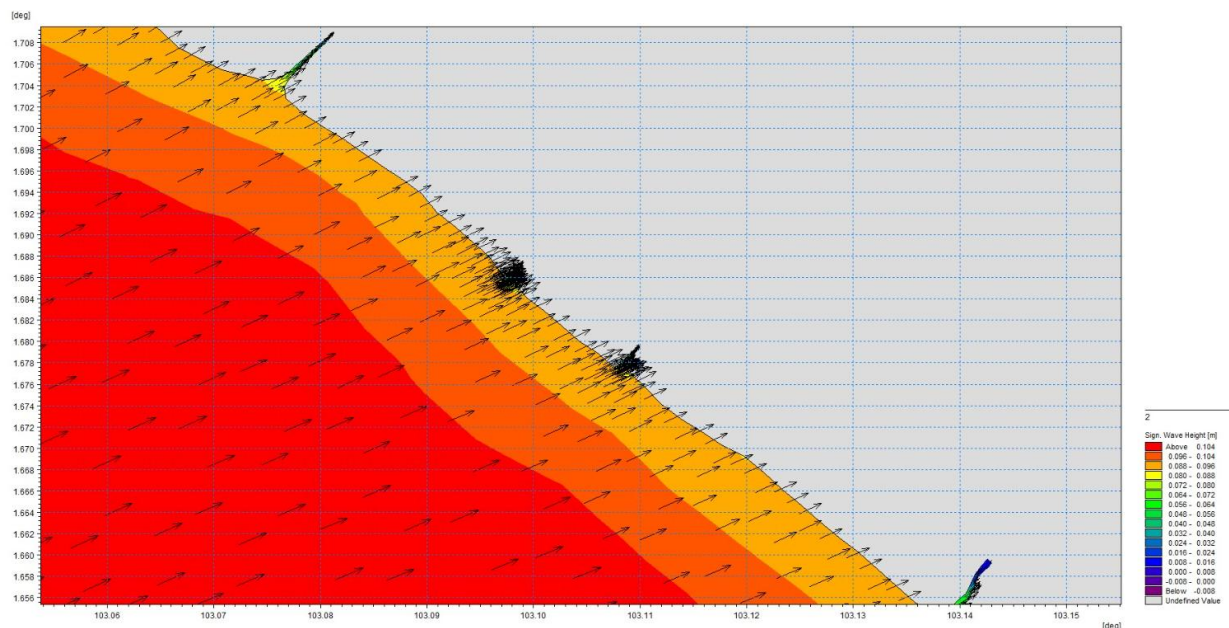


Fig. 7. The virtual simulation of model study location

3.2 Model Verification and Validation

The model verification is conducted by comparing the $H_{\max}$ value from the simulated model data with measured values at one-hour intervals from October 7th to October 22nd, 2022, based on the measured ADCP data provided. Figure 8 presents a graph comparing the measured and simulated $H_{\max}$ values, while Table 2 displays the calculated RMSE value between the measured and simulated $H_{\max}$. The mean average of the measured values, calculated at 0.64 m is slightly lower than the mean

average of the simulated values, 0.69 m. Aside from that, the RMSE results showed a value of 9.57%, which falls well within the acceptable threshold of 10% as referred to Jabatan Pengairan dan Saliran Malaysia [28]. Hence, the results indicate that the model's predictions are closely aligned with the observed data, demonstrating a high level of accuracy in the simulation. Achieving an RMSE below the requirement value ensures confidence in the model's outputs and justifies its use in making informed decisions based on the simulation results.

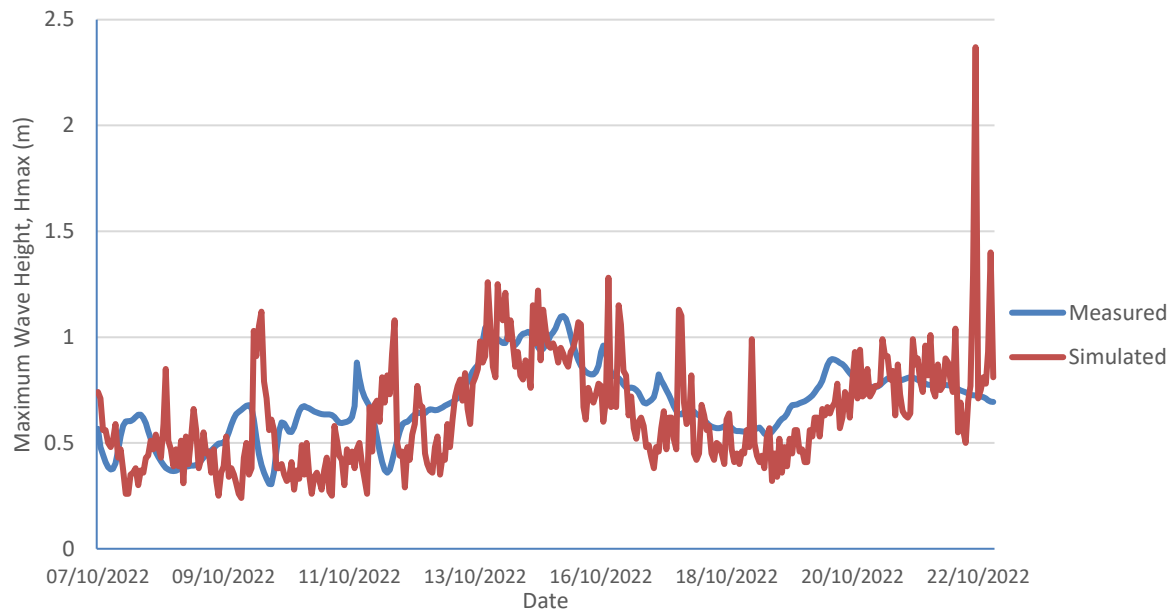


Fig. 8. The comparison between measured and simulated $H_{\max}$ values

Table 2

Statistical assessment between measured and simulated $H_{\max}$ values

Stations	Mean (m)	RMSE (%)	Requirement
Measured	0.64	9.57	< 10%
Simulated	0.69		

3.3 Correlation Analysis

Correlation analysis (R-values) was calculated to determine how variables such as SWH, wind speed and tidal levels are related to each other. The analysis was conducted on a monthly basis over the course of the entire year, covering all 12 months at one-hour intervals to ensure a comprehensive understanding of the data trends and patterns. The R-value has been summarised and tabulated as shown in Table 3. It reveals distinct relationships between SWH and wind speed (indicating wave overtopping) and tidal levels (indicating coastal inundation). The correlation coefficients (R) and the corresponding coefficients of determination (R^2) show varying degrees of correlation throughout the year. First, the relationship between SWH and wind speed, the R-values range from 0.02 in March to 0.425 in October, with R^2 values ranging from 0.0004 (0.04%) to 0.1807 (18.07%). This indicates a generally weak to lower moderate correlation. In contrast, the correlation between SWH and tidal levels presents a stronger and more consistent relationship throughout the year. The R-values for this relationship range from 0.165 in January to 0.589 in October, with corresponding R^2 ranging from 0.0272 (2.72%) to 0.3464 (34.64%). This indicates a generally weak to higher moderate correlation.

Table 3
Summary of correlation analysis for 2022

Month	Wind Speed vs SWH (Wave Overtopping)		Tidal Level vs SWH (Coastal Inundation)	
	R	R^2	R	R^2
January	0.0592	0.0035	0.1649	0.0272
February	0.0671	0.0045	0.1881	0.0354
March	0.0200	0.0004	0.1982	0.0393
April	0.1694	0.0287	0.3356	0.1126
May	0.1229	0.0151	0.3282	0.1077
June	0.2427	0.0589	0.3658	0.1338
July	0.3225	0.1040	0.4067	0.1654
August	0.2193	0.0481	0.4798	0.2302
September	0.2468	0.0609	0.4902	0.2403
October	0.4251	0.1807	0.5886	0.3464
November	0.4244	0.1801	0.5418	0.2936
December	0.1982	0.0393	0.2821	0.0796

The summary shows that August (0.4798) to November (0.5418), the tidal wave scenario had correlations close to or above 0.5. These higher correlations are likely due to the study being conducted in the west coast region, which influenced by the inter-monsoon period from September to November. As noted in previous studies, the west coast is particularly prone to flooding and thunderstorms during this period [7]. Seasonal monsoons can intensify into extreme events [8], making the coastline more vulnerable to tidal fluctuations and increasing the risk of flooding in low-lying coastal areas. Next, it can be concluded in October, the R-value between wind speed and SWH and between tidal level and SWH reveals notable differences in the strength of these relationship. October recorded the highest correlation for both wind speed and SWH and tidal level and SWH value. It can be seen from the scatter plot in Figure 9 shows for October at one-hour intervals, the R-value for the correlation between wind speed and SWH is 0.4251, with an R^2 value of 0.1807 (18.07%), this indicates a moderate positive correlation. The graph showed that as the SWH increases, there is a general trend of increasing wind speed. This relationship highlights the influence of wind speed on wave formation, as stronger winds typically generate higher waves. This event however indicates the potential for wave overtopping events, which can be proven by referring to a study where a combination of strong winds and elevated waves, associated with severe storms regulate wave overtopping and this event can be seen in Minsterworth, Maisemore, Elmore and Newnham in the Severn Estuary in 2014, causing flooding the roads and houses nearby [30].

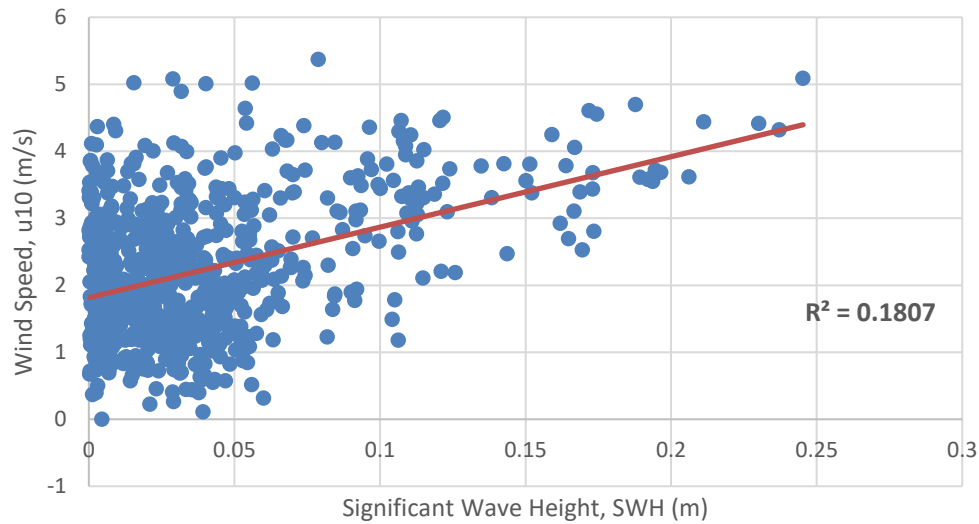


Fig. 9. The relationship between wind speed and SWH

Meanwhile, the scatter plot presented in Figure 10 shows the month of October at one-hour intervals, depicting the relationship between tidal levels and SWH. The correlation between tidal level and SWH in October is stronger compared to wind speed and SWH, with an R-value of 0.5886 and an R^2 value of 0.3464 (36.64%). This result indicates the positive correlation suggests that as the SWH increases, tidal levels tend to rise, which could have implications for coastal inundation, worsening potential coastal flooding. This can be seen in a study where the highest waves superimposed on high water levels can cause an instantaneous uprush of water at the coast and push large volumes of water over defence structures like seawalls or dikes in a short period causing inundation to the coastal area [30]. The stronger correlation between the tidal level and SWH compared to wind speed and SWH, suggests that tidal fluctuations have a more substantial impact on wave heights and the potential fall on coastal inundation rather than wave overtopping resulting in coastal flooding.

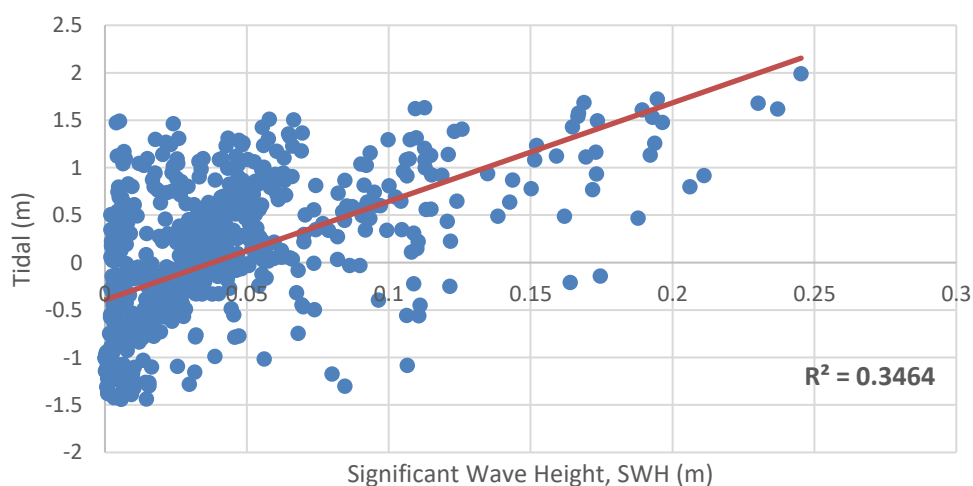


Fig. 10. The relationship between tidal level and SWH

4. Conclusions

Pantai Punggur is a coastal area on the west coast that provides scenic views and recreational activities along the Strait of Malacca. Despite its strategic location and economic importance as a trading hub and commercial centre, the area is vulnerable to coastal flooding. To protect against the destructive power of extreme waves and flooding, many coastal nations have constructed defence structures. However, the existing structures have been compromised, exacerbating the flooding issue. The main problem lies in the failure of the current coastal defences to protect the shoreline effectively. This failure has left questions about whether it is due to wave overtopping caused by strong waves repeatedly hitting the structures or by coastal inundation from high tidal fluctuations that exceed normal sea levels. Pantai Punggur has faced significant challenges where the revetment built to mitigate coastal flooding has not effectively prevented it. The existing revetment has not fully able to protect the coastal area due to the varies wave scenarios along the coast, leading to flooding that affects the population, infrastructure and environment. Given the worsening condition of the coastal area and its potential for flooding, this study focuses on analysing wave scenarios based on historical wind and tide data in Pantai Punggur, Batu Pahat, using numerical modelling with MIKE21 Software.

The results for the model MESH verification and validation show the RMSE was calculated to be 9.57%, which is well within the acceptable limit of 10%. These findings indicate that the model's predictions closely match the observed data, demonstrating a high degree of accuracy in the simulation. Following this, correlation analysis (R-values) was performed to assess the relationships between variables such as SWH, wind speed and tidal levels. This analysis was conducted monthly over the entire year, using one-hour interval data to ensure a thorough understanding of the trends and patterns. The hypotheses indicate distinct relationships: between SWH and wind speed (wave overtopping) and between SWH and tidal levels (coastal inundation). For the relationship between SWH and wind speed, the R-values range from 0.02 ($R^2 = 0.04\%$) in March to 0.425 ($R^2 = 18.07\%$) in October, indicating a generally weak to low-moderate correlation. In contrast, the relationship between SWH and tidal levels shows a stronger and more consistent correlation throughout the year, with R-values ranging from 0.165 ($R^2 = 2.72\%$) in January to 0.589 ($R^2 = 34.64\%$) in October, indicating a generally weak to moderately strong correlation.

Furthermore, In October, the R-values for the relationships between wind speed and SWH and between tidal level and SWH, show notable differences in their strengths. This month exhibited the highest correlation for both wind speed and SWH, as well as tidal level and SWH. The R-value for the correlation between wind speed and SWH was 0.4251 ($R^2 = 18.07\%$), indicating a moderate positive correlation. The graph illustrates that as SWH increases, there is a general trend of rising wind speeds, emphasizing the influence of wind speed on wave formation. Stronger winds typically generate higher waves, suggesting the potential for wave overtopping events. On the other hand, the correlation between tidal level and SWH in October is stronger than that between wind speed and SWH, with an R-value of 0.5886 ($R^2 = 34.64\%$). This positive correlation suggests that as SWH increases, tidal levels also tend to rise, which could contribute to coastal inundation and exacerbate potential coastal flooding.

Hence, the stronger correlation between tidal level and SWH compared to wind speed and SWH suggests that tidal fluctuations have a more significant impact on wave heights and the likelihood of coastal inundation rather than wave overtopping leading to coastal flooding. The finding revealed that the west coast experiences a more significant impact from tidal waves (coastal inundation) compared to the east coast. Consequently, the objectives of this study to investigate the wave scenarios using historical wind and tide data for Pantai Punggur, Batu Pahat through numerical

modelling with MIKE21 Software have been achieved. However, the study is limited by its focus on a single location and a one-year period. Therefore, it is recommended that future research extend to a 10-year period and include multiple study sites. In the end, it shows that understanding is crucial because it allows for a comprehensive assessment of the factors that contribute to coastal flooding, particularly wave overtopping and coastal inundation. Overall, this study has enhanced the understanding of wave scenarios that contribute to coastal flooding and provided valuable information for conservation efforts and future planning.

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