Journal of Marine Science and Engineering

MDPI

Article

Assessment of Tidal and Wave Energy Resource Potential in Malaysia with Sea Level Rise Effects

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Abstract: Ocean energy, e.g., waves, tidal current, and thermal and salinity gradient, can be used to produce electricity. These marine-based renewable energy technologies are at relatively early stages of development and potentially deployed at various sea conditions. In the past, numerous studies were undertaken to explore the feasibility of harvesting of the marine energy in Malaysia; however, those studies were limited to a specific location (i.e., the east coast of Peninsular Malaysia and East Malaysia) and the consideration of sea level rise effect was not studied. This study assessed the potential of tidal and wave energy resources in Malaysia's waters with the effect of projected sea level rise and was undertaken through numerical modeling using MIKE 21 software. The research outcomes were tidal and wave energy contours for Malaysia's waters with an inclusion of the sea level rise projection for 2060 and 2100, as well as a potential site determined for tidal and wave energy harvesting. The simulation results highlight the significant potential of tidal and wave energy in specific locations around Malaysia and its coastal regions, as well as in the South China Sea's offshore regions. By incorporating sea level rise projections into tidal and wave simulations, we revealed a notable increase in tidal and wave power.

Keywords: tides; waves; sea level rise; renewable energy; marine energy; numerical model

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Academic Editor: Decheng Wan

Received: 10 December 2024
Revised: 2 January 2025
Accepted: 4 January 2025
Published: 6 January 2025

Citation: Yaakop, Z.; Teh, H.-M.; Venugopal, V.; Ma, Z. Assessment of Tidal and Wave Energy Resource Potential in Malaysia with Sea Level Rise Effects. *J. Mar. Sci. Eng.* **2025**, *13*, 84. https://doi.org/10.3390/jmse13010084

1. Introduction

Energy poverty is undeniably a matter of great concern in many developing countries, including Malaysia. Despite being blessed with numerous energy resources, the electricity generation in Malaysia is still very dependent upon fossil fuels, even though its fuel reserve is getting depleted [1]. To combat its energy security problems, Malaysia's government launched the 5th fuel diversity policy in 2001. In order to ensure a diversity of fuel sources and a balanced fuel mix, the policy states to use renewable energy (RE) resources such as hydropower, solar photovoltaic (PV), biomass, biogas, and solid [2]. RE is needed by the government to support economic growth and industrialization, as well as to cater to a high energy demand rate of 8.1% annually [3]. At this time, Peninsular Malaysia has a total licensed RE capacity of 392 MW, which includes solar PV, biomass, mini-hydro plants, and biogas [4]. However, these major RE resources are not enough to meet the future energy demand in Malaysia. Hence, there is a need to utilize other RE resources such as wind, marine energy, biofuel/biodiesel, and geothermal [5]. RE will become the main electricity generation source soon [6]. Renewable energy is generally categorized as energy from resources that are naturally replenished on a human timescale, for example, wind, sunlight, rain, tides, waves, and geothermal heat. Malaysia's and Thailand's strategic locations in the tropical region have made countries with an abundance of renewable energy sources to venture into such as wind, solar, and wave energy. Most of the renewable energy resources are still being developed intensively to be used at a large scale and thus reduce the dependency on non-renewable energy.

The ocean, which covers around 70% of the earth's surface, is a vast reservoir of renewable energy sources. Ocean energy, sometimes referred to as marine energy, includes ocean current, wave energy, tidal energy, and ocean thermal energy [7]. Ocean energy, when being widely harnessed, is a promising renewable energy resource that can contribute greatly to the electrical energy supply of countries with coasts facing the sea. Malaysia is surrounded by the vast ocean and has high potential in harnessing this energy resource as a promising solution for enhancing the life quality of its people, particularly for those who reside on remote islands [8]. Accessibility to sustainable energy has been a long-standing goal and a challenge to off-grid rural islands, offshore facilities, and remote coastal areas. The access to sustainable and clean energy, as delineated in the Sustainable Development Goal 7: "Ensure Access to Affordable and Clean Energy for All", is an essential contribution for incessant economic growth and for improving the country's standard of living, including remote coastal and offshore areas, as well as facilities within the country [9]. These areas and facilities are located within the marine domain and thus subjected to various ocean renewable energies, e.g., tides, waves, current, ocean thermal and salinity gradient, etc. These marine RE resources are very eco-friendly and are easily reachable. However, these marine RE resources within the Malaysian waters have yet to be comprehensively explored.

Numerous marine RE technologies, including tidal range devices, tidal stream turbines, wave energy converters, ocean thermal energy conversion, and salinity gradient energy, have been developed, and some have been tested at sites and commercialized in the past. However, not all technologies are suitable to be adopted in Malaysia's waters due to limited energy content, environmental regulations and policies, and their sustainability over the long run. Hence, a detailed study is required to be conducted to determine the suitability of these technologies for different water regions in Malaysia.

In Peninsular Malaysia, the tidal range found in Pelabuhan Klang is 3 m in height, which is beyond the minimum requirement for tidal barrage implementation [10]. In another literature source, the highest tidal range of 5 m was found at Sabah and Sarawak based on the data of the Malaysia Metrology Department from 2007 until 2011 [11]. The Kuching Barrage, which is located in Sarawak, was constructed to mitigate floods in the city of Kuching. It has the potential to be developed into a tidal range power station. Another potential site for high potential extractable energy is Tanjung Manis in Sarawak measured between 50.7 kW and 39.2 kW [12]. In general, the tidal ranges in Malaysia are lower than those in other coastal countries. The average tidal range in Malaysia has not fulfilled the minimum requirement for a tidal barrage turbine. Therefore, advanced technology for increasing the tidal range is needed if the tidal potential energy is to be exploited. Despite these challenges, it remains valuable to study the tidal range energy in Malaysia, as several identified coastal locations demonstrate promising characteristics for effective tidal energy extraction [13]. There are sites that hardly meet the minimum requirement of the tidal range of 3 m, so a large tidal basin area is needed for the greatest output power generation to be generated [14].

Wave power generation is a key approach for tapping into wave energy resources and is one of the advanced technologies pursued by developed nations [15]. The global distribution of wave energy indicates that there are many countries that have a coastal wave climate favorable for the exploitation of this energy [16]. However, assessment of the viability of wave energy requires long-term measurements of waves, which can be very expensive and time-consuming. The worldwide estimated wave energy resources are more than 2 TW.

Malaysia is made up of two geographical regions country divided by the South China Sea: the Peninsular Malaysia (West Malaysia) located on the Malay Peninsula bordered by sea from both the east and west and the Malaysian Borneo (East Malaysia) located on the northern part of the Borneo Island facing the South China Sea to its north. This geographical location enriches its potential for wave and wind energy in the country. Ref. [17] studied the potentials of ocean energy sources around Malaysia in many forms such as tides, waves, ocean current, etc., and mentioned that the ocean is one of the most promising sources of energy that has only been exploited on a small scale, despite being a great alternative to fossil fuel energy. The study should be evaluated in the context of current technological and economic realities. In order to thoroughly and specifically assess the potential of ocean energy in Malaysia, an assessment should cover all the necessary factors that contribute to ocean energy exploitation, such as technological readiness, environmental impacts, costs, and infrastructure. In Malaysia, the east coast of Peninsular Malaysia in particular, due to its direct exposure to the South China Sea, holds significant potential for wave energy harvesting. The east coast of Peninsular Malaysia marks the western boundary of the southern South China Sea (SCS), allowing waves to travel from the northern areas. The influence of the strong northeast monsoon further contributes to high wave conditions, enhancing the potential wave energy to be harvested [16].

A great factor affecting the marine energy potential is global warming. Global warming is an aspect of climate change referring to rising of sea level. Anthropogenic sea-level rise results from atmospheric and oceanic warming, which causes ocean thermal expansion. Additionally, the melting of land-based ice contributes to sea level rise as water flows into the ocean [18]. According to McInnes et al. (2017) [19], the sea levels around Malaysia exhibit seasonal fluctuations driven by the reversal of wind patterns. During the summer monsoon, the southwesterly winds cause a drop in sea levels, while the northeasterly winds of the winter monsoon lead to higher sea levels. The study also highlights that sea levels around Malaysia are influenced on an interannual basis by the El Niño Southern Oscillation (ENSO), with El Niño (La Niña) events temporarily lowering (raising) sea levels. Additionally, variations in sea level are also affected by the Indian Ocean Dipole (IOD) and the Pacific Decadal Oscillation (PDO). The sea level trend derived from the gridded altimeter points nearest to the 21 tide gauges shows an average rate of 3.8 mm per year when using simple linear regression. In contrast, applying multiple linear regression, which considers factors like ENSO, IOD, PDO, and the trend itself, yielded a rate of 2.8 mm per year, which closely aligns with the global average rate of sea level rise during the same period. Sea level rise projections are created by considering future impacts from variations in ocean density and circulation, which are derived from existing climate models. These projections also account for additional contributions from the loss of mass in glaciers, surface mass balance changes, dynamic responses of the Greenland and Antarctic ice sheets, and alterations in land-water storage, as assessed in the IPCC AR5 report [20].

Numerous research studies on renewable energy have been conducted, but they lack precision and accuracy due to source availability. This research study is an update to previous studies using recent bathymetry information from the General Bathymetric Chart of the Ocean (GEBCO). Previous studies also demonstrated uncertainty in terms of future marine energy potentials with respect to climate change conditions, i.e., sea level rise. The South China Sea (SCS), which divides Peninsular Malaysia from East Malaysia, and the Strait of Malacca, separating the west coast of Peninsular Malaysia from Indonesia, play significant roles in driving regional sea level variability over seasonal to decadal timescales. Ref. [21] examined how strong prevailing winds from the north or northeast, occurring between December and early March (during the northeast (NE) monsoon), and the south to southeast winds from June to September (during the southwest (SW) monsoon) lead to significant seasonal fluctuation in sea level in the South China Sea (SCS). During the northeast (NE) monsoon from November to February, the sea levels in the southern South China Sea (SCS) rise by 30 cm or more, while during the southwest (SW) monsoon from June to August, they decrease by approximately 20 cm [21,22]. Increases in sea level rise are expected to increase the water level variation, which theoretically causes increases in energy potential. Therefore, this study aims to assess the potential of tidal and wave energy and investigate the climate effect on sea level rise with projections to 2060 and 2100 around the Malaysian territory using numerical modeling (Figure 1). By establishing an assessment that involves futuristic climate effects, this study could increase the certainty in the assessment of tidal and wave energy potentials for a long period, which could contribute to initiate an effective utilization of renewable energy around Malaysia. This assessment would also be beneficial to the marine energy harvesting sector to replace carbon-intensive energy sources and consequently reduce Malaysia's global warming emissions.

Figure 1. Study area.

2. Materials and Methods

2.1. Study Area and Model Domain

The research area is shown in Figure 1. A regional model coverage that extends from the South China Sea toward Java Sea and northern part of Malacca Strait was selected to assess the tidal and wave energy within Malaysian water.

2.2. Data Source

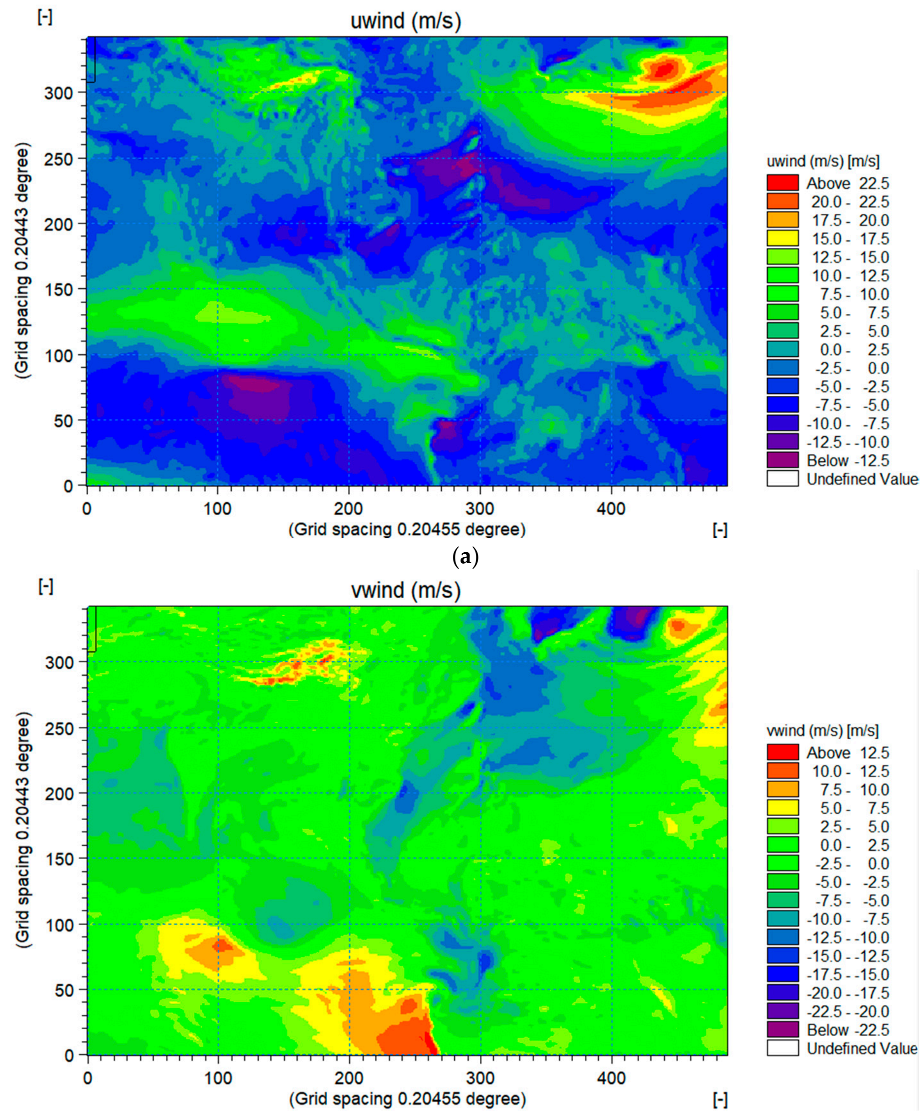
Met-ocean data that were acquired in this study are bathymetry, offshore wind, water levels, waves, and projected sea level rise in Malaysia, covering the east and west coasts of Peninsular Malaysia, as well as Sabah and Sarawak. These data were acquired or purchased from various sources and are listed as follows:

1. Bathymetry

The bathymetry data in year 2022 were sourced from General Bathymetric Chart of the Ocean (GEBCO), and electronic data were from MIKE C-Map and National Hydrographic Centre of Royal Malaysian Navy Department. The bathymetry data were important to develop the seabed profiles.

2. Offshore Wind

The offshore wind data were sourced from the Climate Forecast System Reanalysis (CFSR) wind field to drive the wave model [23]. The wind data have a spatial resolution of approximately 0.2° × 0.2° and temporal resolution of 6 h for year 2011. The wind field map was generated using MIKE 21 Toolbox, as shown in Figure 2.



(**a**) (**b**)

Figure 2. Wind field map: (**a**) u component; (**b**) v component.

3. Water Level

The validation of the tide model, using MIKE 21 Hydrodynamic (HD) module, involved comparison between the simulated water level and the measured water level. The measured water levels were purchased from Jabatan Ukur dan Pemetaan Malaysia (JUPEM). Nine (9) water level stations were used for this study (Figure 3). The stations are located at Langkawi, Penang, Lumut, Pelabuhan Kelang, Tg. Keling, Kukup, Tg. Sedili, Labuan, and Kota Kinabalu.

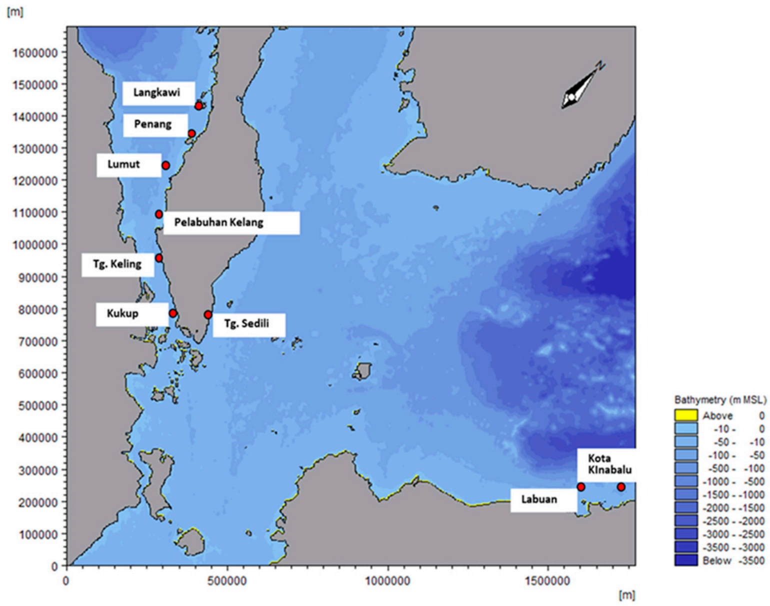


Figure 3. Location of measured water level.

4. Waves

The validation of the wave model, MIKE 21 Spectral Waves (SWs), was made by comparing the simulated wave height and wave period with the purchased hindcasted wave datasets from BMT ARGROSS and GROW. Eight (8) locations of wave data available were identified for this study (Figure 4). The wave data were recorded at Penang, Straits of Malacca, Terengganu, Pahang, Sarawak, Brunei Bay, Sabah, and Sandakan.

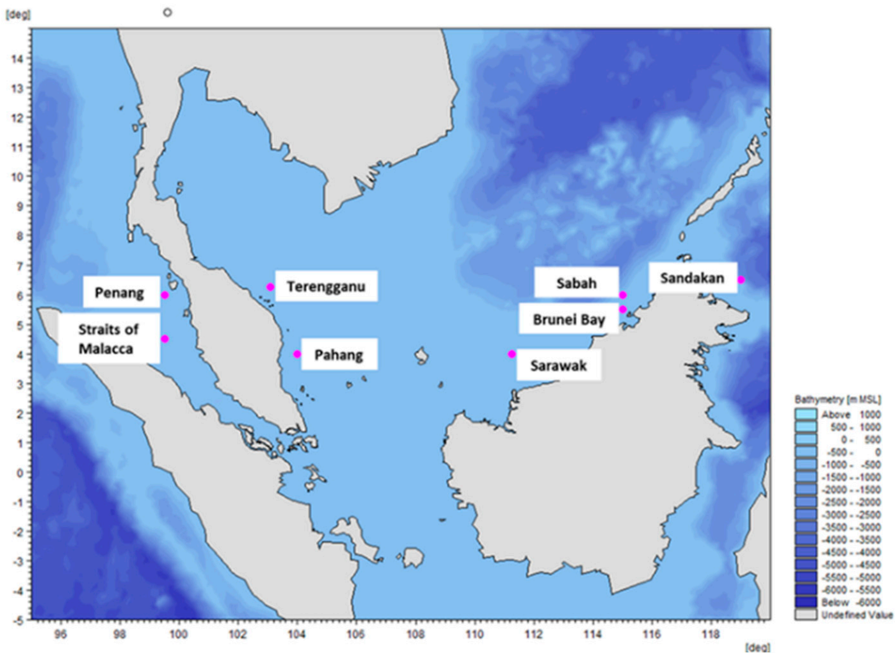


Figure 4. Location of hindcasted waves.

5. Projected Sea Level Rise

The future sea level rise projection by National Water Research Institute of Malaysia (NAHRIM) [19] was included in the model simulation to assess the effect of sea level rise on the tide model, MIKE 21 Hydrodynamic (HD) and wave model, and MIKE 21 Spectral Waves (SWs).

2.3. Numerical Model

2.3.1. Model Setting up for Hydrodynamic Model

Two-dimensional hydrodynamic modeling accounted for current flows and water level fluctuations. MIKE 21 Hydrodynamic (HD), the basic module within MIKE 21 modeling software used for this study, provided the hydrodynamic basis for computations performed in most of the other modules. The water levels and flows were resolved on a rectangular grid covering the area of interest when provided with bathymetry, bed resistance coefficients, and boundary conditions.

Model domains with a grid spacing of 3645 m were set up, as shown in Figure 5. The bathymetry was generated using gridded bathymetry data from General Bathymetric Chart of the Ocean (GEBCO). Model extends from the South China Sea toward Java Sea and northern part of Malacca Strait. Four boundary conditions (generated from MIKE 21 global tide toolbox) were set up along the open boundaries. The hydrodynamic model was simulated covering the areas of Peninsular Malaysia, Sarawak, and part of Sabah coastline. The northern part of Sabah was not included to ensure model stability due to the presence of many small islands.

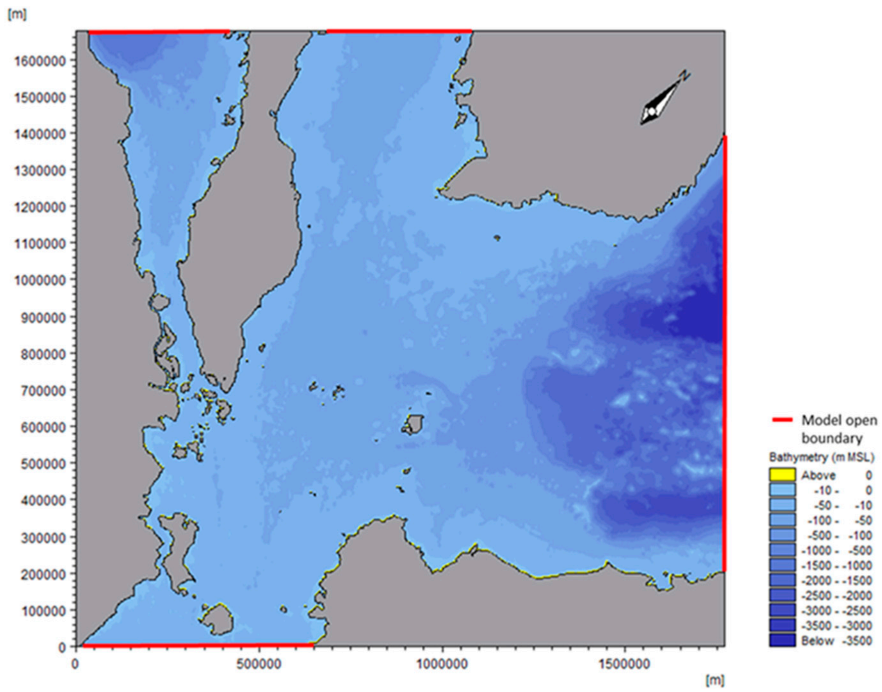


Figure 5. Model domain for hydrodynamic model.

Bed resistance was used to ensure that the model was capable of mimicking the real condition as much as possible. A map with varying values was specified as a function of depth on a point-by-point basis. Use of a resistance map comprising Manning Numbers was found to give a good model performance. A detailed resistance map with a basic depth relationship was developed (Table 1).

Table 1. Resistance map and depth relationship.

Depth (m)	Manning Number ($m^{1/3}/s$)
Less than 15	45
15 to 50	40
50 to 80	35
More than 80	32
Wetland	20

2.3.2. Model Setting up for Waves Model

A regional wave model was simulated using MIKE 21 Spectral Waves (SWs) module to transform offshore wave conditions to nearshore. MIKE 21 SWs is the wind–wave model that simulates the growth, decay, and transformation of wind-generated waves and swells in offshore and coastal areas based on unstructured meshes. The module is applicable for simultaneous wave prediction and analysis on regional and local scale. Two different formulations, directional decoupled formulation and fully spectral formulation, were used in MIKE 21 SWs module. An unstructured triangulated mesh was created with a spatial resolution that gradually increases from offshore boundaries toward the nearshore region (Figure 6). The wave model features a resolution of around 5 km at the offshore boundaries, which refines to approximately 1 km in the nearshore region. Bathymetric data for the model were sourced from the General Bathymetric Chart of the Oceans (GEBCO).

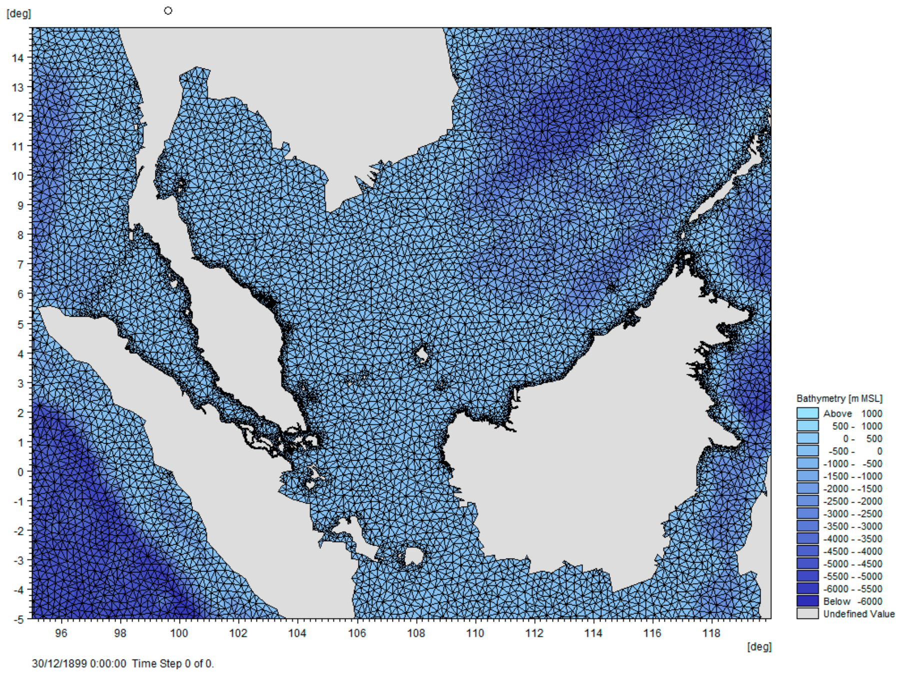


Figure 6. Generated mesh for wave model.

The offshore boundaries of the model were driven using wind fields from Climate Forecast System Reanalysis (CFSR). The wind data have a spatial resolution of approximately 0.2° × 0.2°. The temporal resolution of the wind data is 6 h. The model was simulated for one year event to cover all monsoonal conditions, with year 2011 selected for the study. The selected year was chosen based on the most completed one-year available dataset obtained from BMT ARGROSS (3 h interval) and GROW (1 h interval) for the purpose of model validation.

2.3.3. Model Validation for Hydrodynamic and Waves Model

Model validation was necessary to ensure the accuracy of the hydrodynamic and wave models used in this study. The simulated water level from hydrodynamic model was compared to the measured water level purchased from JUPEM, while for the wave model, the simulated wave height was compared to the hindcasted wave data from BMT ARGROSS and GROW. The selected time series values of water level and wave data were derived based on the measurement and hindcasted data available for the study. The water level data was used from January to December 2022. The wave data were used from January to December 2011.

The accuracy and reliability of the hydrodynamic and wave model were evaluated using two statistical measures: the root-mean-square error (RMSE) and Pearson Correlation Coefficient (r). The RMSE used in this study aligns with the criteria outlined in the Department of Irrigation and Drainage (DID) Guidelines for Coastal Hydraulic Study [24]. RMSE values approaching zero indicate good model performance, while a higher r indicates a better correlation between the datasets. The RMSE is calculated using Equation (1), and the r is shown in Equation (2) given below:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - y_i)^2} \quad (1)$$

where x_i is the measured value for the ith observation; y_i is the simulated value for the ith observation; and N is the number of observations.

$$r = \frac{\sum_{i=1}^{N}((x_i - \overline{x})(y_i - \overline{y}))}{\sqrt{\sum_{i=1}^{N}(x_i - \overline{x})^2\sum_{i=1}^{N}(y_i - \overline{y})^2}} \quad (2)$$

where n is the number of observations, x_i is the measured value for the ith observation; y_i is the simulated value for the ith observation; and $\overline{x}$ and $\overline{y}$ are the measured and simulated value means for X and Y, respectively.

Comparisons were made between the JUPEM water level datasets and the water level simulation results. The location of measured water level is shown in Figure 3. The selected locations were based on the stations with complete one-year datasets. The comparisons between JUPEM water level data and simulated results are shown in Figures 7 and 8. The time series values of measured and simulated water level were compared, and the error difference was calculated. The calculated RMSE and r used to assess the model's performance have been tabulated in Table 2 for water level.

Table 2. Calculated RMSE and r for water level.

Location	RMSE (m)	r
Langkawi	0.56	0.64
Penang	0.15	0.98
Lumut	0.46	0.74
Pelabuhan Kelang	0.49	0.91
Tg. Keling	0.31	0.87
Kukup	0.44	0.86
Tg. Sedili	0.19	0.94
Labuan	0.06	0.99
Kota Kinabalu	0.14	0.99

Comparisons were made between the BMT ARGROSS and GROW hindcasted wave datasets and the wave simulation results. The location of wave datasets is shown in Figure 4. The selected locations were based on the stations with complete one-year datasets. The comparisons made between BMT ARGROSS and GROW datasets and simulated results for wave height are shown in Figure 9. A comparison was made between the measured and simulated wave heights, and the resulting error difference was calculated. The calculated RMSE and *r* used to assess the model's performance have been tabulated in Table 3.

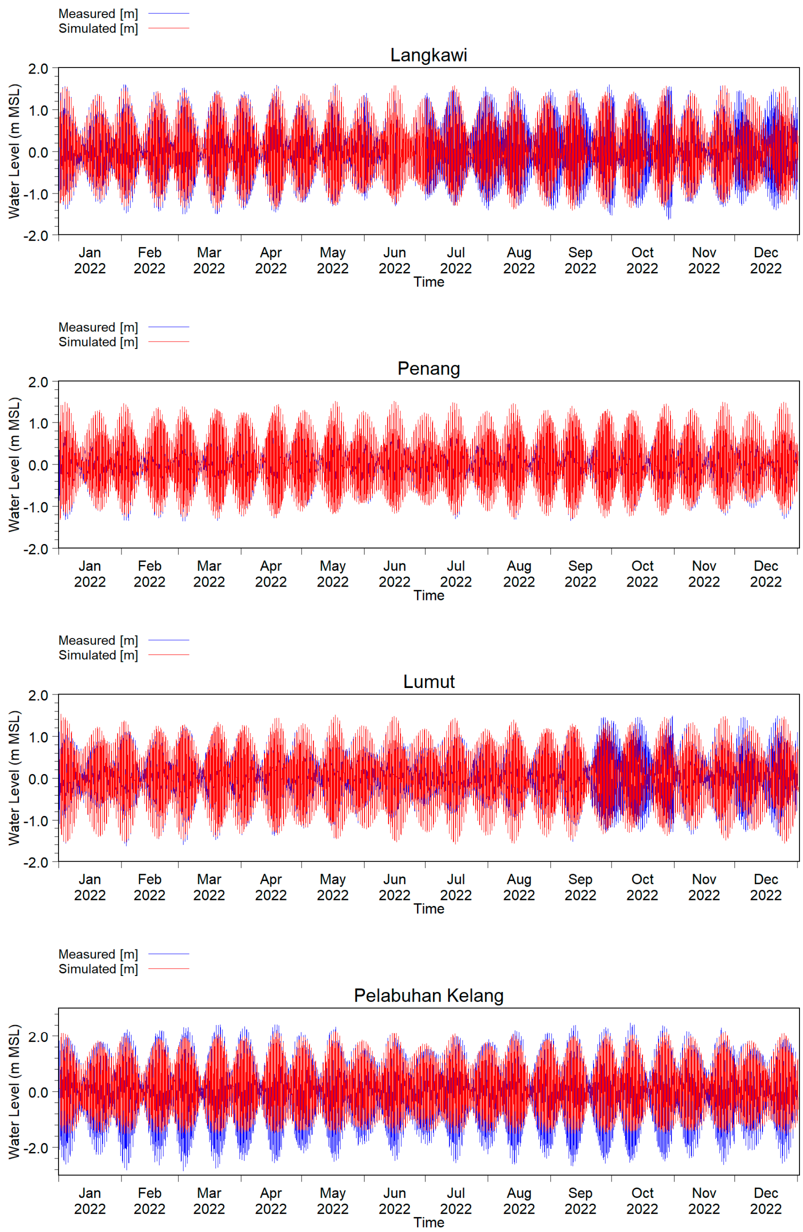


Figure 7. Comparison between measured and simulated water level at Langkawi, Penang, Lumut and Pelabuhan Kelang.

Table 3. Calculated RMSE and CC for wave height.

Location	RMSE (m)	*r*
Penang	0.27	0.82
Straits of Malacca	0.20	0.88
Terengganu	0.29	0.96
Pahang	0.31	0.97
Sarawak	0.39	0.96
Brunei Bay	0.18	0.92
Sabah	0.26	0.91
Sandakan	0.13	0.97

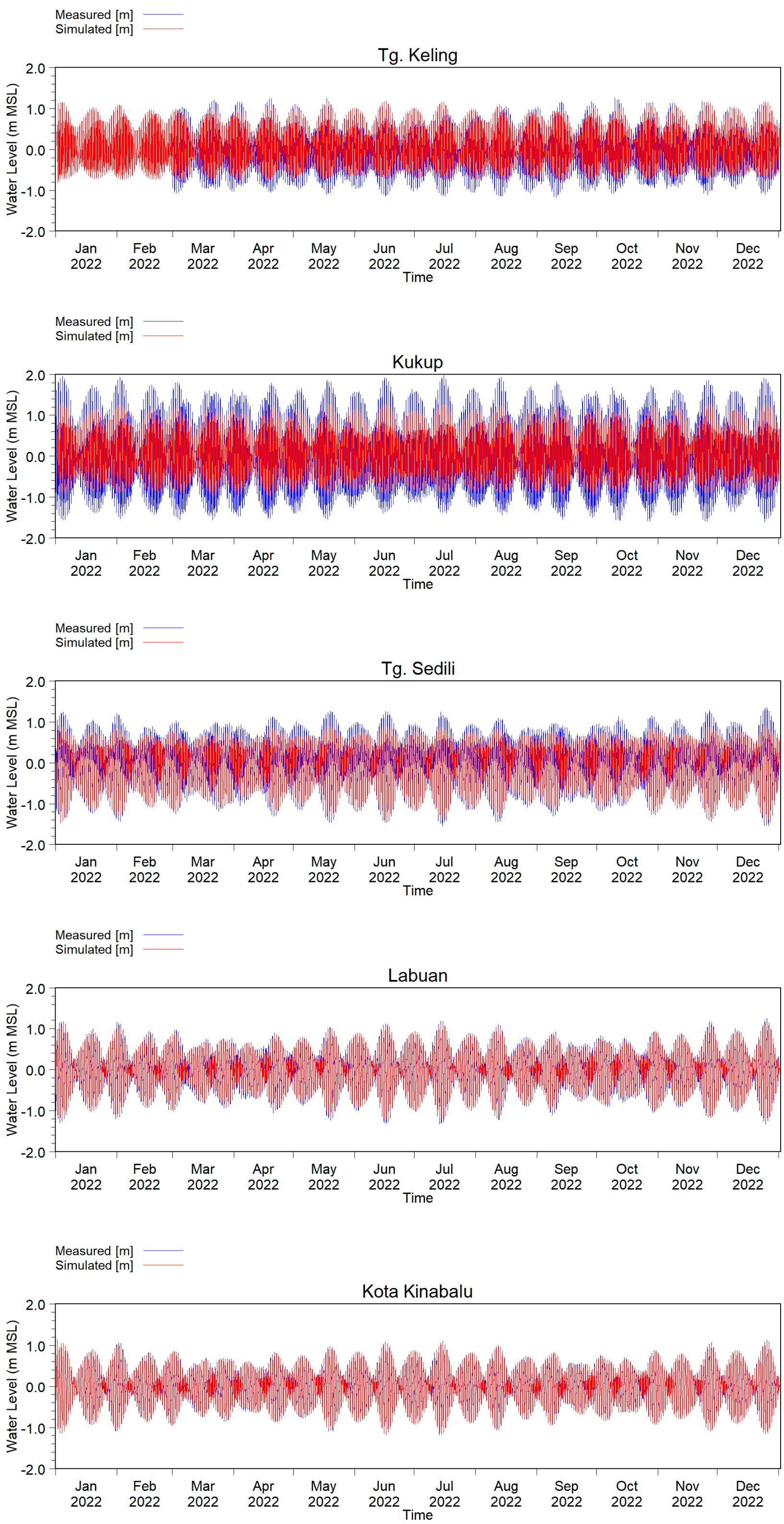


Figure 8. Comparison between measured and simulated water level at Tg. Keling, Kukup, Tg. Sedili, Labuan and Kota Kinabalu.

The RMSEs for tidal levels were generally below 0.6, i.e., between 0.06 and 0.56. The lowest value was observed at Labuan, while the highest value was detected at Langkawi. The correlation coefficient revealed that both the JUPEM measured data and simulated results compared well, with a r of 0.6 and above. The RMSE and r calculations at all locations showed good correlation between both data; the hydrodynamic model was concluded reliable for the purpose of this study. The RMSEs for wave height were generally below 0.4, i.e., between 0.13 and 0.39. The lowest value was observed at Sandakan, while the highest value was detected at Sarawak. The correlation coefficient revealed that both the BMT and GROW and simulated results compared well, with *r* values of 0.8 and above. Previous study applied a standard accuracy threshold of 0.3 m for RMSE [25] and 0.65 for r for good correlation [26]. The RMSE and *r* calculations at all locations showed good correlation between both data; the waves model was concluded reliable for the purpose of this study.

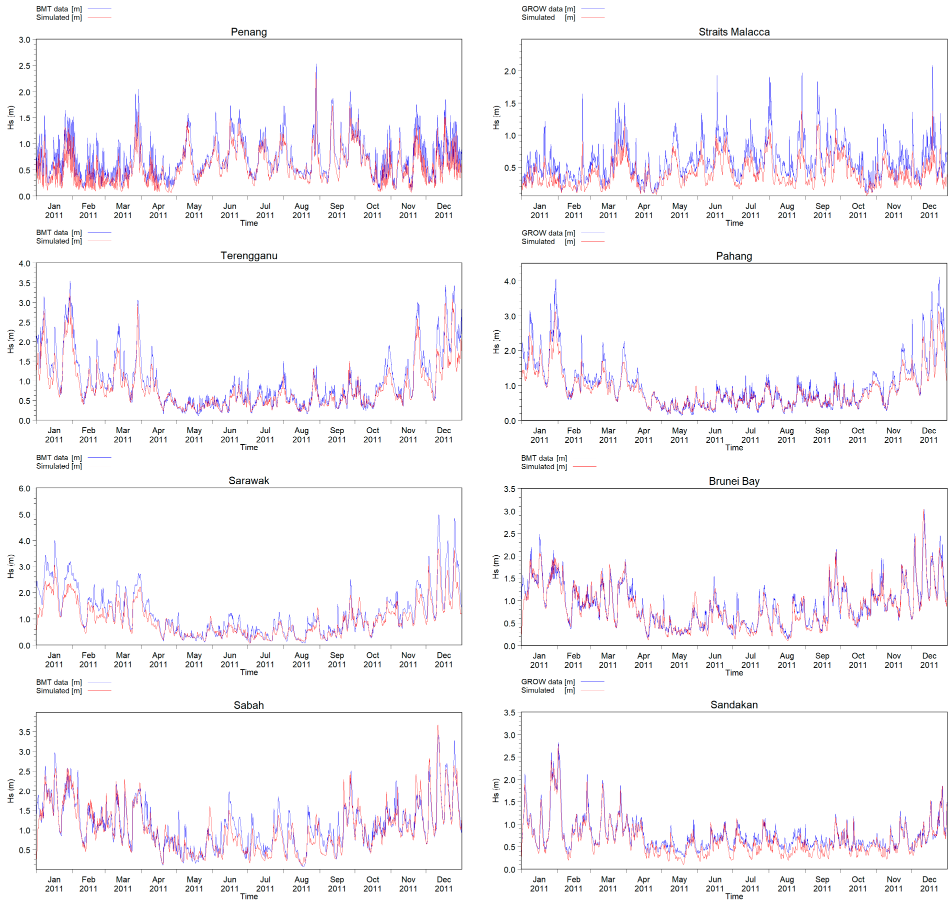


Figure 9. Comparison between hindcasted and simulated wave height.

2.3.4. Model Simulation Scenarios

In order for climate models to predict future earth system changes, including sea-level rise (SLR), they depend on scenarios of future anthropogenic greenhouse gas and aerosol emissions, which influence the resulting radiative forcing. These scenarios carry significant uncertainty, as they encompass factors such as population and economic growth, technological advancements, and potential political and social changes. For the IPCC's Fifth Assessment Report, the climate modeling community developed Representative Concentration Pathways (RCPs) to examine reliable future scenarios under Phase 5 of the Climate Model Intercomparison Project (CMIP5). RCP 8.5 represents a 'business-as-usual' scenario, leading to a radiative forcing of approximately 8.5 Wm. Under this scenario, sea-level rise is most distinct. Hence, SLR 2060 and SLR2100 for RCP 8.5 were selected to be included in the simulation of tidal and wave energy (Table 4). The modeling scenarios that were modeled are summarized in Table 5. Three (3) scenarios were setup for the purpose of tidal and wave potential energy assessment.

Table 4. Projected sea level rise: (a) year 2060; (b) year 2100 [19].

Locations	Projected Sea Level Rise	
	2060	**2100**
Pulau Langkawi	0.30	0.68
Pulau Pinang	0.29	0.68
Lumut	0.29	0.67
Pelabuhan Kelang	0.29	0.68
Tanjung Keling	0.30	0.69
Kukup	0.30	0.70
Johor Bahru	0.31	0.70
Tanjung Sedili	0.31	0.70
Pulau Tioman	0.31	0.71
Tanjung Gelang	0.31	0.71
Cendering	0.31	0.70
Getting	0.31	0.70
Miri	0.32	0.72
Bintulu	0.31	0.71
Sejingkat	0.31	0.72
Labuan	0.32	0.73
Kota Kinabalu	0.32	0.73
Kudat	0.33	0.74
Sandakan	0.33	0.73
Lahat Datu	0.32	0.73
Tawau	0.32	0.72

Table 5. Modeling scenarios.

Assessment	Scenario	Projected Sea Level Rise
Tidal energy	Present Baseline condition	-
	Future Scenario 1 condition	RCP8.5 (2060)
	Future Scenario 2 condition	RCP8.5 (2100)
Wave energy	Present Baseline condition	-
	Future Scenario 1 condition	RCP8.5 (2060)
	Future Scenario 2 condition	RCP8.5 (2100)

The tidal flow around Malaysian water was simulated to identify the potential location for tidal energy harvesting. The tidal potential energy (P_{energy}) was calculated for whole-model domain by using Equation (3). The unit of power is kW/m^2 [10].

$$P_{energy} = \rho g A h^2/2 \tag{3}$$

where ρ is the density of sea water, g is the acceleration due to gravity, A is the cross-sectional area, and h is the tidal range difference.

Wave energy around Malaysian waters was simulated to identify potential sites for wave energy harvesting. The wave power (P_{energy}) was computed for whole-model domain by using Equation (4). The unit of power is kW/m [27].

$$P_{energy} = \rho g c_g E \tag{4}$$

where ρ is the sea water density; g is the acceleration due to gravity; c_g is the group velocity—which is the wave propagation over varying depth and currents—and E is the energy density as function of the frequency and the wave direction, which was calculated from the wave generation from the wind forcing input in the model.

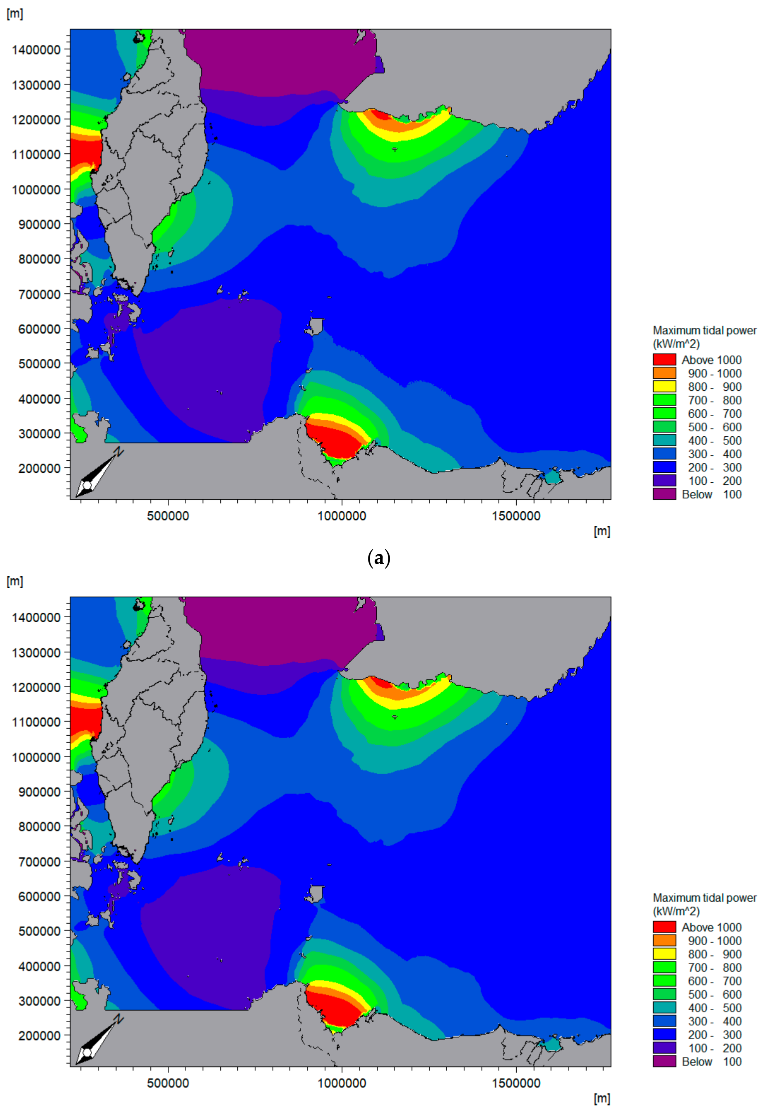
3. Results

This study aimed to evaluate the potential for tidal and wave energy around the Malaysian territory and to explore the impact of climate change on sea level rise projections for the years 2060 and 2100. Through the application of advanced numerical modeling techniques, the available energy resources were quantified, and their variability in response to projected climate scenarios was examined.

In this section, the findings from analyses will be presented beginning with the assessment of tidal and wave energy potential and followed by an exploration of how sea level rise is expected to evolve under different climate scenarios.

3.1. Tidal Energy

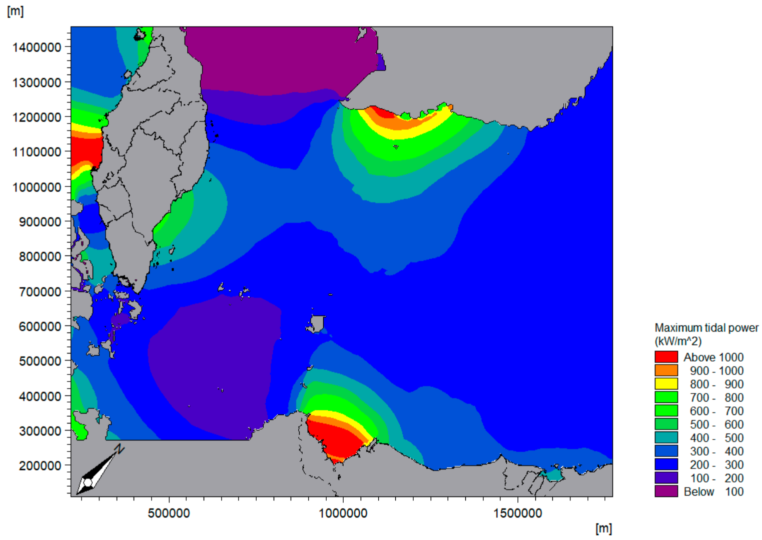
The results show that tidal power is predominantly influenced by the tidal range. Locations with a larger tidal range exhibited substantially higher tidal energy potential. This is evident in the data, where areas with significant tidal fluctuations were identified as having the highest energy potential (see Figure 10). The results have identified Selangor and Sarawak as the highest potential locations for tidal energy harvesting. Each location could generate a maximum tidal power of 600 to 1000 kW/m^2. Perlis, Kedah, Johor, Pahang and Sabah were observed to potentially generate maximum tidal powers from 400 to 700 kW/m^2.



(**a**)

(**b**)

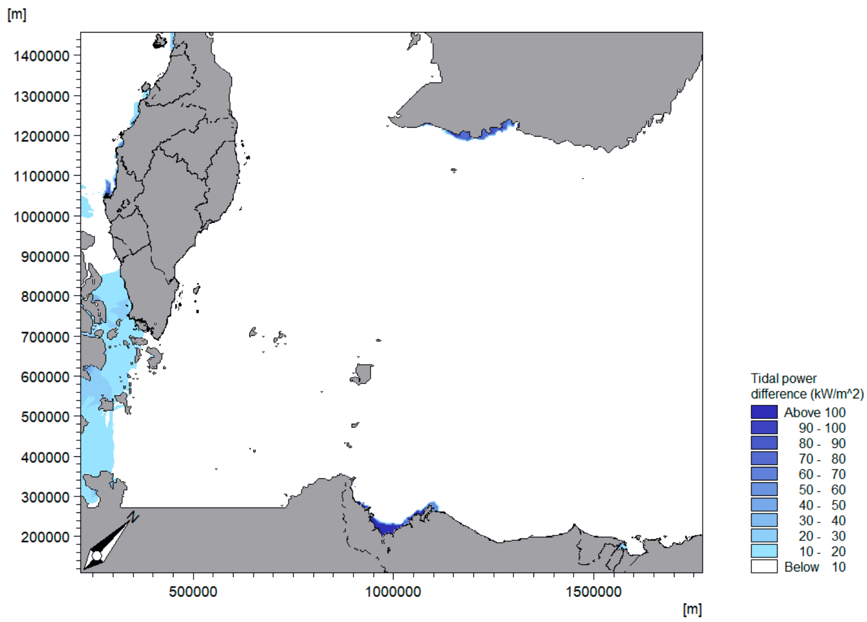
Figure 10. *Cont.*



(**c**)

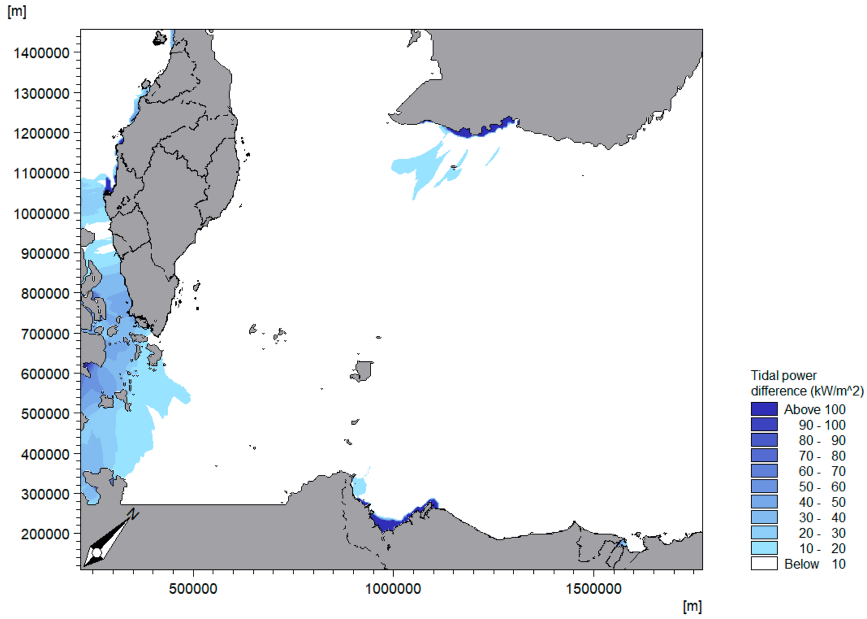
Figure 10. Potential location for tidal energy harvesting: (**a**) baseline condition; (**b**) scenario 1 condition; (**c**) scenario 2 condition.

When sea level rise projections were incorporated into the tidal flow simulations, a notable increase in tidal power was observed in nearshore bays and constricted straits. Specifically, the increase in sea level enhances the tidal range in these areas, leading to higher energy outputs. Figure 11 illustrates this trend, showing that regions with higher sea level rise projections experience a more pronounced increase in tidal power. The highest increase was found at Selangor and Sarawak, with a tidal power difference of up to 100 kW/m^2.



(**a**)

Figure 11. *Cont.*



(**b**)

Figure 11. Tidal power difference with the projected sea level rise: (**a**) scenario 1 vs. baseline condition; (**b**) scenario 2 vs. baseline condition.

3.2. Wave Energy

The wave energy potential is significantly influenced by both seasonal conditions and bathymetric features. According to Muzathik et al. [28], the intensity of the wave energy fluctuates seasonally in South China Sea, with the highest energy density occurring during the northeast monsoon season. Simulation results indicate that wave energy is higher in deeper offshore regions, where wave conditions are less affected by shallow waters. Conversely, the wave energy reduces as waves approach the shoreline due to decreasing water depth and the presence of smaller islands, which contribute to wave attenuation (see Figure 12). The wave power along the nearshore areas of the east coast of Peninsular Malaysia and the Malacca Strait is lower compared to the deeper waters of the South China Sea [29]. The maximum wave power was observed to be around 50 to 500 kW/m at offshore of South China Sea, while the maximum power at the nearshore area varied from 10 to 40 kW/m. Perak, Terengganu, Sarawak, and Sabah have been identified to be potential sites for wave energy harvesting.

When incorporating sea level rise projections into the wave energy simulations, it was observed that there was an increase in wave power along shoreline areas, especially at Sarawak and Sabah. Figure 13 illustrates that as sea levels rise, wave energy increases in coastal regions. This effect is attributed to the modification of wave dynamics caused by elevated sea levels, which enhances wave energy absorption and concentration at the shore. The simulations also indicate that higher projections of sea level rise resulted in more substantial increases in wave power along the Selangor, Perak, Pahang, Terengganu, Sarawak and Sabah coastline. The increase in wave power varied from 0.5 to 2 kW/m. This suggests that future sea level changes could further enhance the viability of wave energy harvesting in these regions.

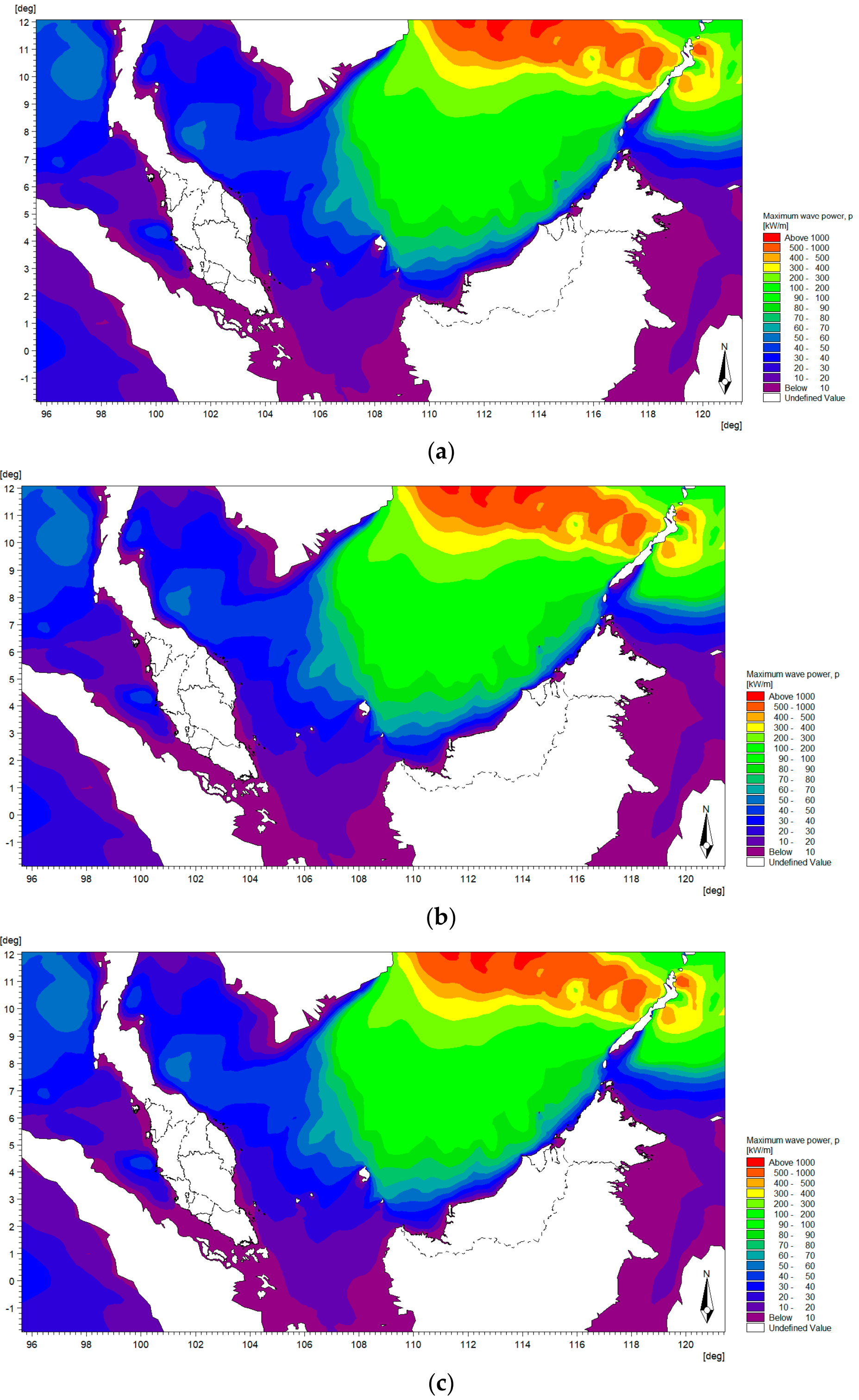
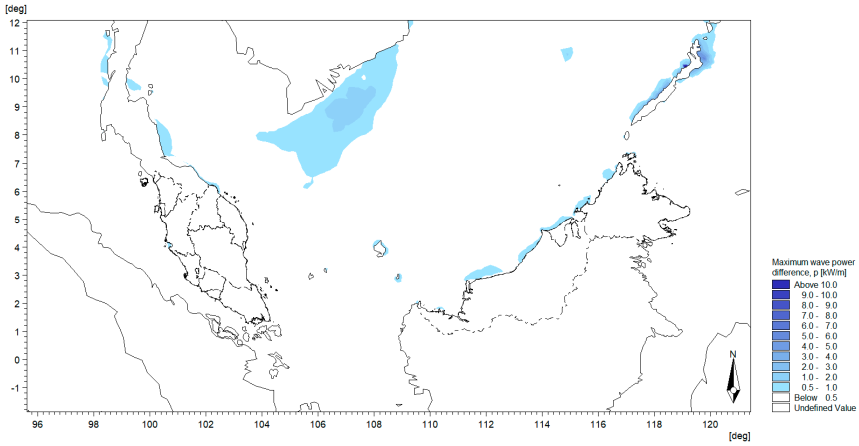
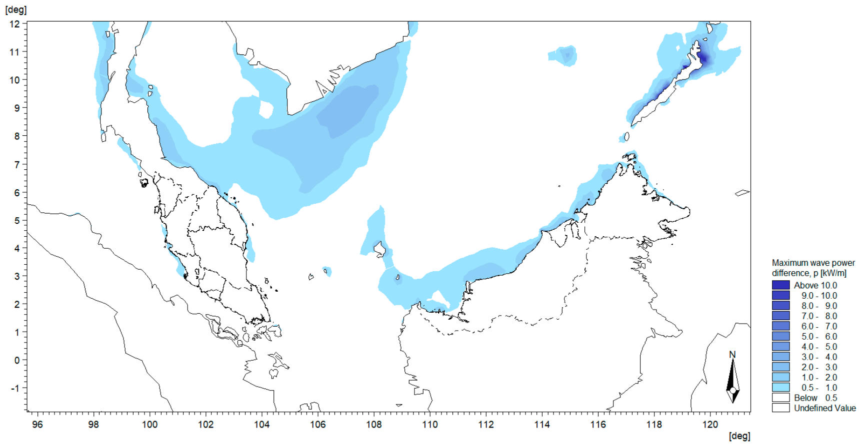


Figure 12. Potential location for wave energy harvesting: (**a**) baseline condition; (**b**) scenario 1 condition; (**c**) scenario 2 condition.



(**a**)



(**b**)

Figure 13. Wave power difference with the projected sea level rise: (**a**) scenario 1 vs. baseline condition; (**b**) scenario 2 vs. baseline condition.

4. Discussion

4.1. Tidal Energy

The simulations also highlight spatial variability in tidal energy potential. Areas characterized by extensive tidal ranges and strategic geographical features, such as narrow straits, exhibited greater tidal energy potential compared to more expansive, less constrained areas. The resulting findings align with those of Nazani et al., 2016 [10], who also reported higher tidal energy potential in regions with larger tidal ranges. Pelabuhan Klang and Sejingkat were identified to have highest tidal range of up to 3 m. However, this study's results extend the understanding by demonstrating a more pronounced increase in tidal power with sea level rise, particularly in constricted straits where no previous study was found to have been conducted to measure the sea level rise.

Overall, these results underscore the significant potential for tidal energy in specific locations around Malaysia, particularly where tidal range and sea level rise effects converge to enhance energy outputs. The findings suggest that in future research, targeted assessments of these high-potential areas could facilitate more effective harnessing of tidal energy resources.

4.2. Wave Energy

The spatial distribution of wave energy potential is notably variable, with pronounced differences between offshore and nearshore environments. Areas with favorable bathymetric and seasonal conditions have been identified as having higher wave energy potential, emphasizing the importance of localized assessments for optimizing wave energy extraction. The simulation results are consistent with A. Mirzaei et al., 2014 [29], who found that deeper offshore areas yield higher wave energy. However, this study reveals that the impact of sea level rise on wave power is more significant. In summary, the results highlight significant wave energy potential in deeper offshore areas and increasing opportunities along the shoreline with projected sea level rise. These findings suggest that coastal areas may become increasingly viable for wave energy projects, particularly as sea levels continue to rise in the future.

5. Conclusions

This study identified the potential location of tidal and wave energy harvesting around the Malaysian territory using numerical modeling. It investigated the climate effect on sea level rise with projections to 2060 and 2100. The RMSE and r calculations at all locations showed good correlation between the measured and simulated data; the hydrodynamic and waves model are considered reliable for the purpose of this study. Most of the stations showed RMSEs of less than 0.3 and r values of more than 0.65.

The results of tidal power highlight Selangor and Sarawak as the top locations for tidal energy harvesting, being capable of generating up to 1000 kW/m^3 of tidal power. Other notable areas such as Perlis, Kedah, Johor, Pahang, and Sabah also present significant potential, with their maximum tidal power outputs ranging from 400 to 700 kW/m^3. Incorporating sea level rise projections into tidal flow simulations revealed a notable increase in tidal power at Selangor and Sarawak, which could reach up to 100 kW/m^3 with higher sea level rise projections. The results of wave power indicate that the South China Sea's offshore regions show a maximum wave power output between 50 and 500 kW/m, while nearshore areas in Peninsular Malaysia and the Malacca Straits have lower wave power outputs, ranging from 10 to 40 kW/m. There was also significant enhancement in the wave power observed along the coastal regions, especially in Sarawak and Sabah, when sea level rise projection was incorporated into the wave simulation. Sensitivities with higher sea level rise projections resulted in increased wave power magnitudes. The observed increment in wave power ranged between 0.5 and 2 kW/m throughout various coastlines along Selangor, Perak, Pahang, Terengganu, Sarawak, and Sabah.

In summary, both tidal and wave energy resources in Malaysia show considerable potential for development, with specific areas offering enhanced opportunities due to their unique geographical and environmental conditions. Targeted evaluations and strategic investments in these high-potential regions could lead to more effective and sustainable energy solutions as sea levels continue to rise. In the next 10 years (2025–2035), initial small-scale demonstration projects might be tested in regions with promising wave and tidal energy potential, with sea level rise already being factored into the design. Commercial-scale installations could begin in regions with proven wave and tidal energy potential, especially as technology matures and sea level rise effects become more evident by years 2035–2045. By 2060, large-scale tidal and wave energy projects could be fully operational and become significant contributors to Malaysia's renewable energy mix.

Inaccuracies or uncertainties in climate predictions regarding the rate of sea level rise and changes in wave patterns can affect the reliability of the simulations for 2060 and 2100. There are also limited long-term real-world data in Malaysia as wave and tidal energy technologies are still developing. Hence, this study has been limited by the availability of such data, particularly with respect to Malaysia's specific coastal conditions and sea state variations.

Author Contributions: Z.Y.: Conceptualization, methodology, validation, analysis, writing—original draft preparation and editing; H.-M.T.: Supervision, Resources, Conceptualization, Project Administration and writing—review and editing; V.V.: Conceptualization and review Z.M.: Review. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Yayasan Universiti Teknologi PETRONAS Fundamental Research Grant (YUTP-FRG 1/2022), grant number 015LC0-453 (Assessment and characterization of the marine renewable energy resources potential in Malaysia).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data are contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest.

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