INSIGHT INTO KEDAH STATE'S COASTAL PERILS: TSUNAMIS AND SEA LEVEL INCREASE

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Coastal hazards refer to various natural processes and events occurring at coastlines and are driven by a combination of geological, meteorological, and oceanographic factors, posing risks to human activities, infrastructure, and the environment. Efforts to mitigate the consequences of these hazards are essential to minimise the potential risks and ensure the sustainability of the nearshore communities. Such efforts are developing early warning systems, constructing protective structures, proper land-use planning, and sustainable coastal management practices. In the last decade, coastal hazards become more severe due to the climate change consequences, which directly contribute to sea level rise, storm intensification, and flooding. Therefore, investigating the coastal hazards in a specific region is of utmost importance to understand the degree of danger and prepare effective mitigation strategies. This study specifically examines coastal hazards along the mainland Kedah and Langkawi Island shorelines. It involves a comprehensive analysis of historical incidents and the prognosis of future scenarios. The study focuses on the primary natural hazards, including tsunamis and rising sea levels. Particularly, it scrutinises significant past occurrences, notably the devastating tsunami of 2004. Additionally, projections regarding sea level increments for 2030, 2050, and 2100 are presented and deliberated upon. The paper concludes by suggesting recommendations for appropriate coastal management practices and effective mitigation strategies.

Keywords: Coastal Flooding, Coastal Hazards, Malaysia, Sea Level Rise, Tsunami

1.0 INTRODUCTION

Coastal hazards refer to a range of natural events and processes occurring in coastal areas that pose risks to human life, infrastructure, and the environment. These hazards include tsunamis, flooding, storm surges, sea-level rise, and coastal erosion. Understanding and mitigating these hazards is essential for effective coastal management and resilience-building efforts (Ewing, 2008; Mukhopadhyay *et al.,* 2012). Coastal areas worldwide face many risks, and the Kedah State coastal region stands as no exception, contending with the challenges posed by tsunamis, flooding, and the escalating threat of rising sea levels. The Kedah State coast is situated northwest of Peninsular Malaysia and encompasses a diverse landscape, vibrant ecosystems, and thriving human settlements. However, this picturesque stretch is not immune to nature's forces, which could significantly impact its environmental sustainability (Ghazali *et al.,* 2018).

Tsunamis are super-powerful waves that can be really dangerous for places near the sea (Geist *et al.,* 2006; Ghaderi *et al.,* 2014). The potential for seismic activity in the adjacent regions, notably the Andaman Sea and the broader Indian Ocean, presents a constant concern for the coastal communities. The historical footprint of tsunamis, both globally and within the region, underscores the pressing need for preparedness, early warning systems, and resilient infrastructure along the Kedah coastline (Satake, 2014). Flooding, on the other hand, keeps happening often, especially when heavy rains come during the monsoon seasons (Shah *et al.,* 2023). Kedah's layout, with its low areas and rivers, makes it easy for water to cover the land (Mohd *et al.,* 2011). The intricate balance between human development, agricultural practices, and the natural hydrological system highlights the complexity of managing flood risks in this coastal expanse. Meeting these challenges requires a comprehensive strategy combining urban planning, land-use control, and sustainable infrastructure development (Rosmadi *et al.,* 2023).

Kedah's coastal communities face a growing threat from rising sea levels due to global warming. The melting of polar ice caps and the thermal expansion of seawater are contributing to this alarming trend, amplifying the risk of inundation. It's not merely about having more water around; it has far-reaching impacts. It affects crucial aspects such as the availability of drinking water, the viability of farming, and the well-being of plants and animals along the coast. To tackle this growing challenge, it's essential to adopt adaptive strategies. These strategies could include building more robust defenses along the coast, implementing sustainable rules for how land is used, and actively involving the local community in these initiatives. Doing so is crucial to reduce the effects of this increasingly threatening situation (Ehsan *et al.,* 2019).

Navigating these multifaceted challenges demands a comprehensive understanding of the interconnectedness between natural processes, human activities, and environmental sustainability. Bird *et al.,* (2007) conducted a study investigating the physical attributes of the Indian Ocean Tsunami in Langkawi, Malaysia. Their research included examining the maximum elevation, reaching 4.29 meters, along with a maximum flow depth of 2.0 meters and the extent of inland inundation and penetration. The study noted that buildings within 50-150 meters from the shoreline experienced structural damage, with 10% completely destroyed and 60-70% significantly affected. Areas lacking engineered coastal protection faced more severe damage. The wave energy concentrated on offshore breakwaters constructed to safeguard the Langkawi port and airport heavily impacted the coastline in the study area. While the emergency response post-tsunami was prompt and practical, the study suggested that improvements could have been made by disseminating informal advance warnings more widely. Efforts by the people of Langkawi to decrease vulnerability to future tsunamis were evident, including developing emergency action plans and installing a siren warning system (Bird *et al.,* 2007).

Ahmadun *et al.,* (2020) conducted a study to evaluate and review the diverse impacts of the 2004 Indian Ocean tsunami disaster on Malaysia. A tsunami wave runup heights map was presented for the affected areas along the peninsular coastline, as shown in Figure 1. Five records were obtained in mainland Kedah, where the wave runup height ranged from 1 to 3 m. On the other hand, Langkawi Island experienced higher wave runup heights, which exceeded 4.0 m near Kuala Teriang and Kampung Kok. Ahmadun *et al.,* (2020) also discussed the impacts of the 2004 Indian Ocean tsunami from different aspects, including human casualties, injuries, and displacement; physical/structural damages; environmental impacts; and socioeconomic and psychosocial consequences.

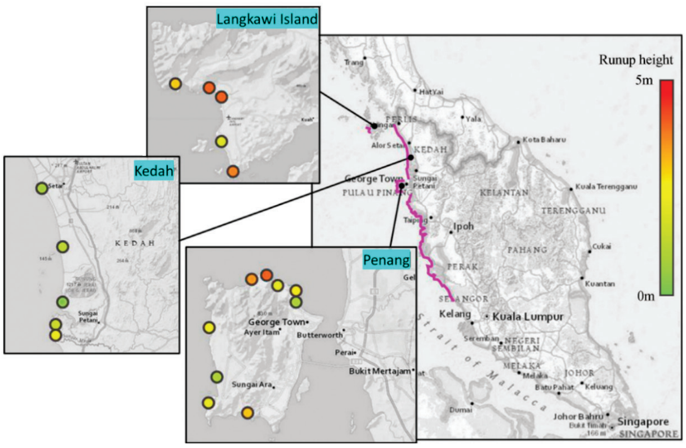

Figure 1: Affected areas along Peninsular Malaysia's coastal area during the 2004 tsunami, the pink color line represents the affected shoreline, and locations represent the recorded tsunami wave runup heights (Ahmadun et al., 2020)

Another study on the impacts of the Indian Ocean 2004 tsunami was performed by Moon *et al.,* (2022), focusing on its effects on Peninsular Malaysia, where post-event observations regarding tsunami characteristics were presented in the form of maps. Building damage, including damage modes of wall failure, total collapse, debris impact, and structure tilting, was also reported. According to Moon *et al.,* (2022), Kuala Muda in mainland Kedah, Langkawi Island, and Penang Islands were the most affected places along the entire northern coastal areas of the peninsular. Firstly, the tsunami waves reached Langkawi Island slightly more than three hours after the earthquake, with an average speed of 240 km/h and nearshore positive amplitudes ranging from 2.5 m to 3.0 m (Bird *et al.,* 2007). In terms of damaged buildings, Kedah state, particularly the Kuala Muda region, was deemed one of the most severely affected areas among the affected states of Malaysia, where 900 houses were damaged compared with 615 buildings in Penang Island and 20 buildings in Perak (Moon *et al.,* 2022).

Herein, an effort has been made to explore the historical context, present challenges, and future projections that will unravel the intricacies of these threats, particularly to Kedah's coastal zone. Delving into the socioeconomic, environmental, and infrastructural implications will provide a holistic perspective on the vulnerabilities and opportunities inherent in this dynamic coastal landscape. Furthermore, this study aims to illuminate pathways toward resilience, emphasizing the importance of proactive measures, community engagement, and sustainable practices in safeguarding the coastal areas of Kedah against the perils of tsunamis and rising sea levels.

2.0 STUDY AREA

The present study investigated the coastal perils, including tsunamis and rising sea levels along the Kedah state coastal area. Geographically, Kedah state is situated in the northwestern region of Peninsular Malaysia, boasting a vast expanse covering more than 9,000 square kilometers. This state comprises both the mainland, characterized by a predominantly flat terrain, and the enchanting Langkawi islands, which form an archipelago featuring numerous islands, the majority of which remain uninhabited, adding to the natural allure of the area. To the north, Kedah shares its borders with Perlis, and it establishes an international boundary with the Songkhla and Yala provinces of Thailand. To the south, Kedah is bordered by the state of Perak, while Penang lies to its southwest, as shown in Figure 2. Kedah State boasts an extensive coastline, stretching over approximately 440 kilometers. This includes 109 kilometers along the mainland of Kedah and an additional 331 kilometers along the enchanting

Figure 2: Study area (source: Google Earth Pro)

Langkawi archipelago. The diverse shoreline of Kedah state not only adds to the scenic beauty of the region but also plays a vital role in shaping its economic activities, including fisheries, tourism, and trade. Therefore, the presence of coastal hazards in this region poses a substantial risk to human safety, the environment, and critical infrastructure. Effective mitigation strategies and regular monitoring are imperative to address and manage these potential dangers.

3.0 KEDAH STATE COASTAL PERILS

3.1 Tsunami

Basically, a tsunami can be defined as a series of ocean waves with extremely long wavelengths and high energy, often caused by a large and sudden disturbance beneath or near the ocean floor. These disturbances can include underwater earthquakes, volcanic eruptions, landslides, or, less commonly, meteorite impacts. The 2004 Indian Ocean tsunami caused 12 deaths in Kedah. The Department of Irrigation and Drainage (DID) conducted a study in 2004 after the tsunami's occurrence to evaluate the severity and impact of the disaster. The study covered the shorelines of Perlis, Kedah, Penang, and Perak. The study concluded that mainland Kedah's entire shoreline was affected by the tsunami, as shown in Figure 3. On the other hand, for Langkawi Island, only the western coast including the Kuala Sungai Muda area was severely affected, as shown in Figure 4. The coastal bunds in the Yan and Kota Setar districts remained relatively intact, where the tsunami wave did not overtop the bund with a height of 2.5 m LSD northward of Kuala Ibus. Also, it was reported that the shore south of Tanjung Dawai generally experienced the main tsunami wave (Abdullah *et al.,* 2005).

The shoreline from Kuala Sungai Teriang to Kuala Sungai Melaka, including Pantai Cenang was the area that was mainly affected in Langkawi. The waves originated from the northwest diffracting towards and inundating Kuala Sungai Melaka as evidenced by photo and video footage. The maximum landward inundation was about 0.58 km as measured by DID. Areas affected by the tsunami were primarily constricted areas such as river mouths and marinas. The funneling phenomenon occurred as the small space forced the water level to drastically increase. Kuala Sungai Teriang was submerged almost up to the rooftop of a single-story house. The rise in water level enabled the tsunami wave to penetrate into Sungai Melaka resulting in flooding of paddy fields upstream. Despite this, only one death was reported in Langkawi. The dramatic rise and fall in water level within a short time caused a drawdown effect resulting in river bank collapse at various locations. The overtopping also caused small damage to rock bunds at stretches where there was less interlocking of rocks.

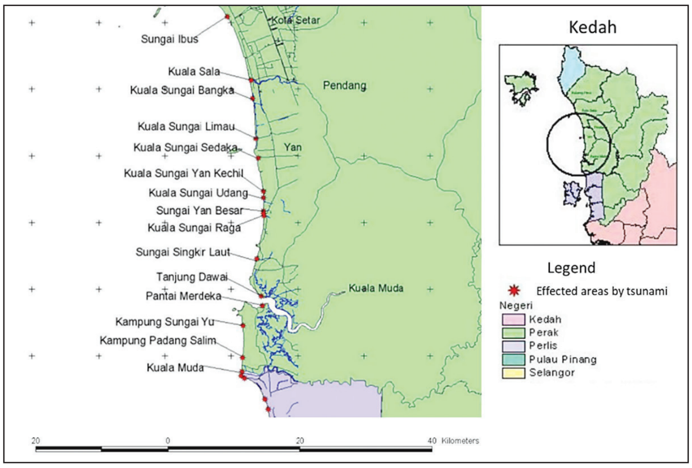

Figure 3: Affected locations by the 2004 tsunami along mainland Kedah's coastal area (Abdullah et al., 2005)

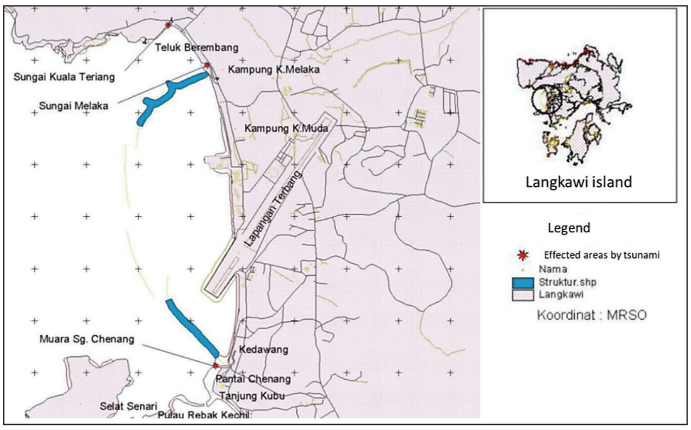

Figure 4: Affected locations by the 2004 tsunami along the Langkawi Island coastal area (Abdullah et al., 2005)

Figure 5: 2004 tsunami at Kuala Muda district (a) Tsunami level at Kuala Muda, (b) Houses located closest to the open waters (30 m) at Kg. Kepala Jalan was destroyed, (c) Rock revetment at Kuala Sungai Muda (Kg. Tepi Sungai) was not affected by the tsunami, and (d) Tsunami wave inundated the road at Kg. Padang Salim (DID, 2020)

Figure 6: Locations badly affected by the 2004 tsunami at Kuala Muda district (a) Kg Tepi Sungai, (b) Kg Haji Kudong, (c) Kg. Kepala Jalan, and (d) Kg. Padang Salim (DID, 2020)

Kuala Sungai Muda was the most impacted location along mainland Kedah's shoreline (see Figure 5). The affected villages included Kg. Kuala Sungai Muda, Kg. Kepala Tengah, Kg. Sungai Meriam, Kg. Padang Salim, Kg. Tepi Sungai, Kg. Sungai Yu dan Kg. Hj. Kudong (see Figure 6). A revetment constructed at Pantai Kampung Kuala in 1994 mitigated the tsunami impact at this location. Kuala Sungai Muda received almost the full brunt of the tsunami as its shoreline was exposed to waves from the northwestern to the northern sector. Two waves were experienced at 1:15 pm and 1:45 pm. The maximum inland inundation was 0.4 km along the shoreline. 11 deaths occurred on mainland Kedah. Most of them were senior citizens and children. Most of the victims were at their homes situated along unprotected shorelines devoid of mangroves or revetment when the tsunami struck. The revetment's crest level at Kg. Tepi Sungai was 3.2 m LSD. However, traces of mud on coconut trees and walls of houses indicated that the water level during the tsunami was at least 4.7 m LSD. Table 1 summarizes the affected districts along the mainland Kedah and Langkawi Island shoreline during the 2004 tsunami.

Damage at Pantai Merdeka was in the form of fallen trees. No erosion occurred, but much mud was brought on land by the waves. The revetment in the south reduced the wave energy of the tsunami waves. The unprotected area to the north was badly affected. This caused more damage to houses sited further inland than those located at the river mouth. About 4 km of the coastal bund was overtopped at Padang Salim, situated north of Kuala Muda. All houses sited in front of the bund were damaged. Inundation reached further inland at locations where mangroves are thin compared with areas where mangrove vegetation is relatively denser. Ahmadun *et al.*, 2020 summarise the damages that were reported along the Kedah state coastal areas in terms of human casualties, injuries, and displacement; physical/structural damages; environmental impacts; and socioeconomic and psychosocial consequences as listed in Table 2.

A study commissioned by DID aimed to devise strategies for minimising the impact of potential tsunami disasters (DID, 2009). Using GIS-based analysis, a classification map was developed to pinpoint vulnerable areas along Peninsular Malaysia's northwest coast. This involved assessing physical vulnerability parameters, such as determining the Physical Vulnerability Index (PVI) for the coastal regions and establishing the Structural Vulnerability Index (SVI) for evaluating the vulnerability levels of structures and buildings susceptible to tsunami floods. The study produced Tsunami Vulnerability Index (TVI) maps in various scales, including a macro-scale map outlining tsunami impacts, a local-scale PVI map detailing the physical vulnerability in highly impacted areas identified from the macro-scale map, and a macro-scale SVI map depicting the vulnerability of built structures within the high-risk PVI areas identified earlier. The SVI maps aimed to qualitatively and quantitatively capture physical and economic resources within tsunami inundation zones. Factors determining vulnerability, such as geomorphology, geologic materials, and coastal slope, were identified by assessing physical parameters. The PVI was computed using the USGS methodology, ranking geophysical variables on a scale from 1 (very low) to 5 (very high). Figure 7 illustrates the ranking of physical variables in the Kuala Muda and Langkawi districts (DID, 2009).

Table 1: Summary of 2004 tsunami consequences along mainland Kedah and Langkawi Island shoreline (DID, 2020)

District	Location	Maximum Inundated Distance (measured from 0 m MSL) (m)	Maximum Overtopping (m LSD)	Remark
Kuala Muda	Sungai Yu	n.a.	n.a.	n.a
	Tanjung Dawai	n.a.	n.a.	Footbridge damaged
	Kuala Muda	400	2.0	n.a
	Padang Salim	n.a.	n.a.	n.a
Yan	Sungai Udang	n.a.	n.a.	n.a
	Sungai Yan Besar	n.a.	n.a.	n.a
	Sungai Sala	20	n.a.	River bank overflowed
	Sungai Singkir Laut	20	n.a.	River bank overflowed
	Kg. Sungai Keriang	n.a.	n.a.	Slight damage to the bund
	Kuala Sungai Sedaka	n.a.	n.a.	Slight damage to the bund
	Kuala Sungai Raga, Pantai Murni	n.a.	n.a.	Slight damage to the bund
Pantai Murni"	Sungai Ibus	10	n.a	Bund overtopped
Kota Setar	Sg. Cenang Kedawang	n.a.	n.a.	The tidal bore reached up to 350 m upstream
Langkawi	Sg. Melaka	583	2.0	The tidal bore reached up to 350 m upstream and overflowed into paddy fields
	Kuala Sg. Teriang	230	3	The tidal bore reached up to 350 m upstream

n.a. = not available

Table 2: Indian Ocean 2004 tsunami impacts in the Kedah coastal area (Ahmadun et al., 2020)

Dimensions	Impact
Humans	• 74 persons lost their lives overall in the country, with 12 deaths in Kedah. • 694 injury cases were reported, mainly in Langkawi Island.
Physical/ Structural	• Timber and single-brick wall houses along Kuala Muda, Kampung Masjid, and Kampung Tepi Sungai's coastline in Kedah were destroyed by the tsunami. • Damage to structures occurred on houses located within 150 m from the coastline at Kuala Teriang, Langkawi Island. 250 houses were damaged/destroyed, with the majority of them suffering significant structural damage. • Reinforced concrete houses withstood the waves, though their exterior walls were scoured due to the wave action.
Environmental	• Sparsely vegetated mangrove trees in Kedah were flattened, while areas with denser vegetation suffered low damage as assessed using the Tsunami FAO-AG Field Damage Criterion. • Coastal erosion was observed along the Kuala Muda intertidal zone in Kedah, with bottom-layer clay being visible. • Up to 27% decrease in pelagic fish populations was recorded in Kedah, including absence for certain species.
Socioeconomic	• Up to 7721 fishermen were affected by the tsunami in Kedah, Penang, Perak, Perlis, and Selangor due to damaged boats and fishing gears.
Psychosocial	• Some fishermen developed an intense fear of the ocean, leading to a change in economic activities towards farming and construction.

The susceptibility of buildings to tsunami impact is determined by various factors: (i) the nature of buildings or structures exposed to the tsunami flood, (ii) the presence of offshore barriers, (iii) distance from the shoreline, and (iv) flood depth. An exposure database was established, encompassing details about physical and structural elements in the region, including coastal structures, key infrastructure, and significant buildings. This database aimed to evaluate and anticipate the area's vulnerability to future tsunamis. Upon delineating inundated areas using the inundation model, a Structural Vulnerability Index was computed for each building within these inundation zones, employing the NOAA Methodology (Papathoma Tsunami Vulnerability Assessment Model). Each parameter was assigned a ranking scale ranging from -1 (indicating the least vulnerability) to 1 (representing the highest vulnerability).

Besides tsunamis, coastal areas are projected to flood events which are commonly due to intense river discharge during storms originating from inland or extreme fluctuations in the overall water level within open waters (Idier *et al*., 2019). Figure 8 summarizes the factors contributing to the overall water level near the shore, influencing the possibility of coastal flooding.

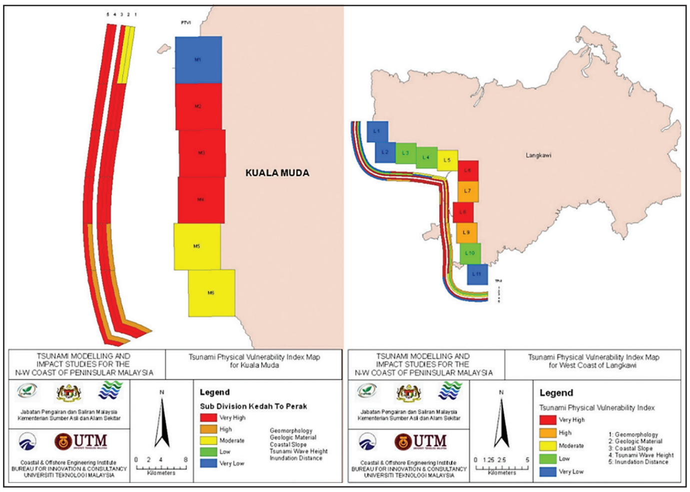

Figure 7: Tsunami physical vulnerability index (PVI) map for Kuala Muda district and the west coast of Langkawi (DID, 2009)

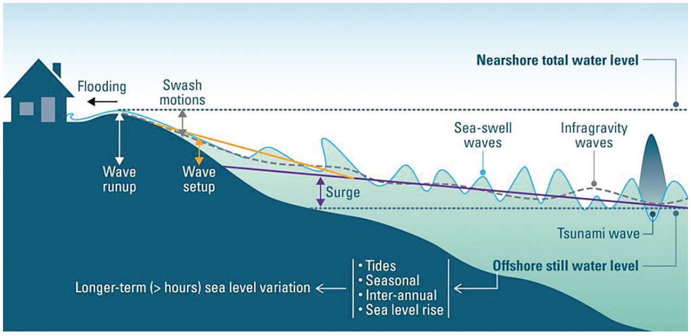

Figure 8: Factors contributing to the overall water level near the shore, influencing the possibility of coastal flooding (Morris et al., 2021)

In the Kedah coastal area, coastal flooding events in varying degrees have been reported to occur during high tide events and high wave activity by the various DID district offices. Almost the entire stretch of Kuala Muda district is projected to be inundated due to coastal flooding. The affected villages include Kg. Paya, Sungai Meriam, Kg. Sg. Yu, Kg. Kepala Jalan, Kg. Padang Salim, Kg. Huma, Kg. Nelayan, Tanjung Dawai and Kg. Sg. Pial. The shorelines at Dulang, Ruat, Pantai Murni, and Singkir are susceptible to coastal flooding (refer to Figure 9) (DID, 2020). Water brought in by waves overtops the coastal bund and

Figure 9: Coastal flooding in Kubang Pasu and Langkawi districts (a) In the vicinity of Kg. Jeruju, Kubang Pasu district, (b) Pantai Teluk Yu, Langkaw (DID, 2020)

flows into the borrow pits located landward of the bund. About 2 km of the shoreline between Kuala Kuar and Kuala Jerlun in Kubang Pasu district experiences coastal flooding issues. The affected areas are Kampung Jeruju and Kampung Kuala Jerlun. About 0.3 km of Pantai Teluk Yu's shoreline in Langkawi district experiences coastal flooding. The affected areas are Kampung Teluk Yu and Taman Awam Teluk Yu (DID, 2020).

3.2 Sea Level Rise

The gradual elevation of mean sea levels holds a growing sway over prolonged periods. The Intergovernmental Panel on Climate Change (IPCC) foresees a global average rise in sea levels by 2100, estimated between 0.29 to 0.59 meters for the low emissions scenario and 0.61 to 1.1 meters for the high emissions scenario in comparison to the period between 1986 and 2005 (Pörtner *et al.,* 2019).

Sea level rise has been identified as one of the significant climate change effects that impact Malaysia (Tang, 2019). Other elements like storms, erosion, and deposition collaborate with sea level alterations, influencing the structure and dimensions of Malaysia's coastlines, wetlands, and rivers. The escalating pace of sea level rise might progressively become the predominant force steering coastal transformations. This affects approximately 8,600 kilometers of the nation's shoreline, where 70% of its 30 million inhabitants' dwells. It directly results in the immediate submergence of a portion of intertidal land as sea levels ascend.

Table 3: Vulnerability and capacity factors for a shoreline subjected to sea level rise

Factor	Index Parameter
Physical Vulnerability	
Dominant land use	Regions dominated by the built environment will be at higher risk of sea level rise.
Shoreline	Regions with closer proximity to the sea or open water bodies have higher vulnerability.
Critical facilities	Regions that have more critical facilities in terms of importance and scale of services have higher vulnerability.
Social Vulnerability	
Projected population density	Higher population density leads to higher vulnerability.
Education level	Population with lower education levels leads to higher flood vulnerability.
Poverty level	Regions with a higher ratio of population below the poverty line have higher vulnerability.
Vulnerable group	Infants/toddlers, the elderly, and the disabled population are more vulnerable.
Economic Vulnerability	
Land value/ price	Higher-priced land has a higher vulnerability.
Program continuity	The existence of any intervention programs increases the capacity level.
Community involvement	Community involvement in intervention programs increases the capacity level.
Program success	Programs that show evidence of lowering hazard or vulnerability increase the capacity level.

The accelerated upward surge in sea levels could potentially submerge low-lying areas, trigger intrusion of saltwater into groundwater and watercourses, and intensify the scale and impact of coastal inundation (Bosserelle *et al.,* 2022). Sea level rise results in the deepening of the sea thereby increasing tidal inundation, propagation of storm surges, and magnitude of waves and currents; these factors are the driving forces of erosion and sedimentation (Yin *et al.,* 2017).

Persistent sea level rise doesn't recede, unlike transient flooding events. Areas at lower elevations that aren't elevated face continual inundation. Evaluating a shoreline's susceptibility to rising sea levels involves assessing three key facets: physical, social, and economic vulnerability. Summary data on vulnerability and capacity factors to be considered is outlined in Table 3.

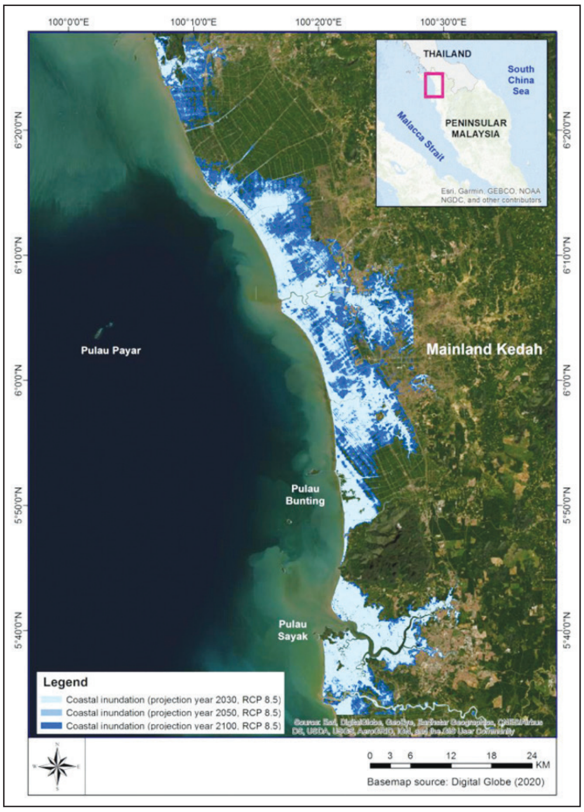

Figure 10: Coastal inundation map for mainland Kedah due to rising sea levels (NAHRIM, 2019)

Inundation due to sea level rise has been developed by the National Hydraulic Research Institute of Malaysia (NAHRIM) using the 'bath-tub fill' method (NAHRIM, 2019). The 2008 Digital Elevation Model (DEM) was procured from the Department of Surveying and Mapping Malaysia (JUPEM) together with the 2010 sea level rise projections for the study porpoises. The analysis enabled the identification of areas with inundation potential. The inundation maps for the mainland Kedah and Langkawi archipelago are shown in Figures 10 and 11, respectively. The results showed that the average sea level rise ranged from 0.07 to 0.14 m in 2050, while for the 2100 scenario, the average sea level rise is projected to be about 0.25 to 0.52 m. Maximum values are predicted to occur in low-lying areas. However, it is worth highlighting that the presence and height of the coastal bunds and other coastal protection measures along the shoreline might not have been adequately represented in the DEM data. The results showed that the majority of the mainland Kedah coastal area is projected to the sea level rise where Kota Setar and Kuala Muda districts are the most affected areas. On the other hand, the sea level rise projections along the Langkawi Island shoreline are not significant.

Malaysia's government has built several coastal protection structures along Kedah's shoreline to mitigate coastal hazards, most of which are rock revetment or riprap. However, there is a need for further investigation to upgrade these structures in the future to account for sea level rise, storm surge, and increased wave activity. Furthermore, during the design stage of any new coastal structures, it is recommended to consider the parameters related to sea level rise, as presented in Figure 12. Apart from conventional structures, natural ecosystems play a role in lessening coastal hazards by engaging in ecosystem functions like enhancing bed friction, creating local shallows, depositing sediments, and fostering vertical biomass growth. These activities prompt changes in shore profile and elevation concerning sea level, along with reducing wave impact, thus mitigating coastal risks. Being living systems, nature-based approaches adapt to changing climates and can self-recover post-storm events. This stands in contrast to conventional rigid structures that lose effectiveness over their lifespan and require continuous upgrades or replacements due to climate changes. Solidifying shorelines disrupt the link between land and shallow marine environments, leading to a significant decline in biodiversity as natural habitats are supplanted.

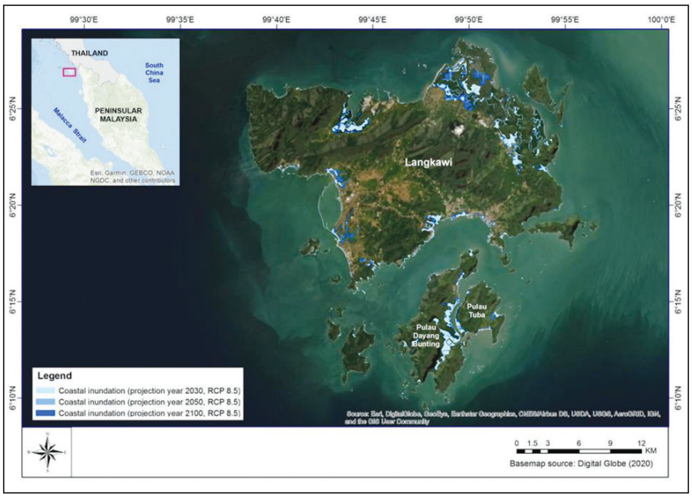

Figure 11: Coastal inundation map for Langkawi Island due to rising sea levels (NAHRIM, 2019)

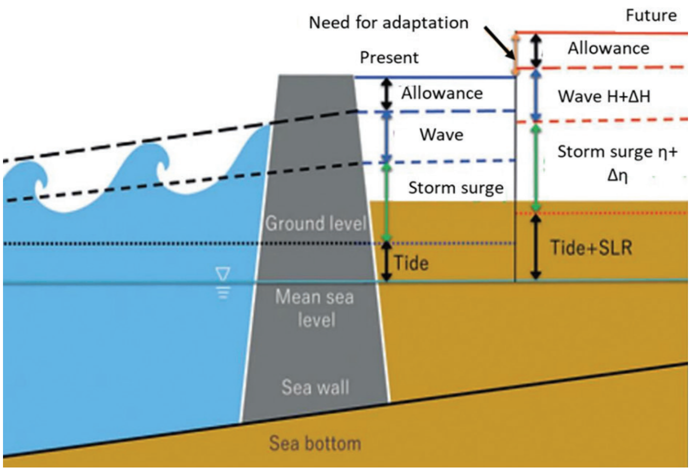

Figure 12: Design of new coastal structures needs to incorporate adaptation (Mori and Shimura, 2020)

4.0 REGIONAL CLIMATE MODELS IMPACT ON COASTAL VULNERABILITY

Coastal areas are already facing various risks due to increasing climate-related hazards that are likely to amplify with the changing climate and make the households living in these areas even more vulnerable in terms of livelihoods and living conditions (Ehsan *et al.,* 2022). Generally, the Intergovernmental Panel on Climate Change (IPCC) has provided evidence indicating that the global climate is undergoing unprecedented changes in human history. These changes are affecting geophysical, biological, and socioeconomic systems. Malaysia has a noticeable upward trend in annual mean surface temperature, mean sea level, and extreme weather events (Tang, 2019). Coastal areas, constituting 1,349.3 km of the total 8,840 km of coastline in Malaysia, are particularly vulnerable to climate-related hazards, with continuous erosion reported (Ehsan *et al.,* 2019).

The adverse impacts of climate change on coastal areas' natural resources are evident, including reduced fish density, a 1.67% decrease in yearly marine fish production in 2014, instances of mass coral reef bleaching, and reduced agricultural productivity and profitability (Alam *et al.,* 2014). Projections for the 21st century anticipate further increases in temperature, sea level rise, spatially variable rainfall, and more frequent extreme weather events in Malaysia (Ehsan *et al.,* 2019). The anticipated impacts of climate change in coastal areas encompass shoreline erosion, flooding, saltwater intrusion, and inundation, posing

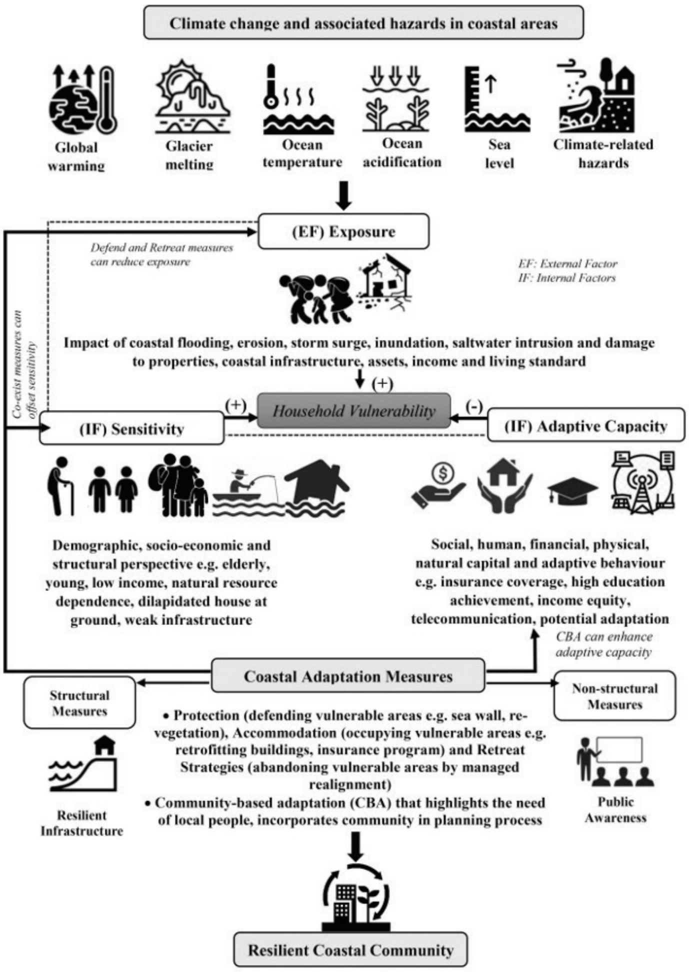

Figure 13: Elements of household vulnerability to climate change in coastal areas (Ehsan et al., 2022)

risks to low-lying coastal areas and impacting coastal property, critical infrastructure, mangrove functions, aquaculture, cultural resources, livelihoods, and public health and safety (Bove *et al.,* 2020). These challenges exacerbate the vulnerability, risk, and hazard potential for developing sustainable coastal townships. Figure 13 highlights the linkage between climate change and the elements of exposure, sensitivity, and adaptive capacity that are likely to influence household vulnerability and associates the role of community-based adaptation to reduce vulnerability and build resilience.

Therefore, coastal adaptation strategies can mitigate potential impacts, such as building resilient infrastructure (reducing sensitivity), implementing early warning systems (reducing exposure), and adopting a community-based adaptation (CBA) approach tailored to local needs. Community participation plays a crucial role in nurturing household adaptive capacity by mobilizing essential assets and translating latent adaptation into actual adaptation.

5.0 CONCLUSIONS

Coastal areas are inherently vulnerable to a spectrum of natural events and processes that endanger human life, infrastructure, and the environment. The multifaceted coastal hazards including tsunamis, flooding, storm surges, sea level rise, and erosion underscore the critical need for understanding, mitigating, and managing these risks. Kedah State, situated northwest of Peninsular Malaysia, grapples with a dynamic coastal landscape, hosting diverse ecosystems and thriving settlements. Nevertheless, this scenic area is confronted by coastal hazards, underscoring the urgency for strategic planning and the implementation of resilience-building measures. This paper provided a comprehensive overview of these hazards along the Kedah state coastal area, and the following conclusions were drawn:

- The mainland Kedah coastal area was found to be vulnerable to tsunami hazards, especially in the Kuala Muda district, which was classified as very high risk under the physical vulnerability index.
- The west coast of Langkawi Island starting from Pantai Cenang in the southwest to Kampung Teluk Burau in the northwest was also reported to be vulnerable to tsunami hazards. The high-risk physical vulnerability index was indicated at Kuala Teriang and Kampung Kedawang.
- The Indian Ocean 2004 tsunami extremely affected the whole coastal area of mainland Kedah and Langkawi Island. The highest wave runup height surpassed 4 m at Kuala Teriang in Langkawi Island and 3 m at Kuala Muda in mainland Kedah.
- During the 2004 tsunami event, Kedah state was deemed one of the most severely affected areas among the affected states of Malaysia in terms of building damage. A total of 900 houses were damaged compared with 615 buildings on Penang Island and 20 buildings in Perak. This indicates the necessity of evaluating the durability and integrity of the houses along the northwest of the peninsular.
- In the Kedah coastal area, coastal flooding events in varying degrees have been reported to occur during high tide events and high wave activity. Almost the entire stretch of Kuala Muda district is projected to be inundated due to coastal flooding. Also, about 2 km of the shoreline between Kuala Kuar and Kuala Jerlun in the Kubang Pasu district experience coastal flooding issues.
- In terms of sea level rise, the NAHRIM 2019 study indicated that the average sea level rise will range from 0.07 to 0.14 m in 2050. While, for the 2100 scenario, the average sea level rise is projected to be about 0.25 to 0.52 m. The maximum values are predicted to occur in low-lying areas along the coastline.
- Regional climate models play a crucial role in assessing and understanding the implications of climate change on coastal vulnerability which helps in predicting sea level rise at a finer spatial scale. This is vital for coastal vulnerability assessments as it helps to identify areas at risk of inundation and coastal erosion.

The authors believe that the present study gives an in-depth overview of the coastal perils along the Kedah state coastal area and indicates the importance of developing proper mitigation strategies to prevent future events impacts. Therefore, it is recommended that the new coastal protection measures must evolve to account for sea-level rise, storm surges, and increased wave activity. Natural ecosystems are also recommended to be established as they play a pivotal role in mitigating hazards and providing adaptive solutions compared to traditional hard structures.

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