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Review article

The impact of climate change on coastal erosion in Southeast Asia and the compelling need to establish robust adaptation strategies

Wan Shiao Dong[a], Aminah Ismailluddin[a], Lee Shin Yun[a], Effi Helmy Ariffin[a,b,*], Cherdvong Saengsupavanich[c], Khairul Nizam Abdul Maulud[d,e], Muhammad Zahir Ramli[f], Mohd Fuad Miskon[f], Muhammad Hafeez Jeofry[a], Juliana Mohamed[g], Fazly Amri Mohd[h], Saiful Bahri Hamzah[i], Kamaruzzaman Yunus[g]

[a] *Faculty of Science and Marine Environment, Universiti Malaysia Terengganu, 21030, Kuala Nerus, Terengganu, Malaysia*
[b] *Institute of Oceanography and Environment, Universiti Malaysia Terengganu, 21030, Kuala Nerus, Terengganu, Malaysia*
[c] *Faculty of International Maritime Studies, Kasetsart University, Sri Racha Campus, 199 Moo 6 Sukhumvit Rd., Tungsukla, Sri Racha, Chonburi, 20230, Thailand*
[d] *Department of Civil Engineering, Faculty of Engineering & Built Environment, Universiti Kebangsaan Malaysia, 43600, UKM, Bangi, Selangor, Malaysia*
[e] *Earth Observation Centre, Institute of Climate Change, Universiti Kebangsaan Malaysia, 43600, UKM, Bangi, Selangor, Malaysia*
[f] *Institute of Oceanography & Maritime Studies, Kulliyyah of Science, International Islamic University Malaysia, 25200, Kuantan, Malaysia*
[g] *Kulliyyah of Science, International Islamic University Malaysia, Kuantan Campus, Kuantan, Pahang, Malaysia*
[h] *Centre of Studies for Surveying Science & Geomatics, Faculty of Architecture, Planning & Surveying, Universiti Teknologi MARA, Perlis, 02600, Arau, Perlis, Malaysia*
[i] *National Water Research Institute of Malaysia, Ministry of Energy Transition and Water Transformation, 43300, Seri Kembangan, Selangor, Malaysia*

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ABSTRACT

Climate change alters the climate condition and ocean environment, leading to accelerated coastal erosion and a shift in the coastline shape. From previous studies, Southeast Asia's coastal region is suffering from severe coastal erosion. It is most sensitive and vulnerable to climate change, has broad and densely populated coastlines, and is under ecological pressure. Efforts to systematically review these studies are still insufficient despite many studies on the climate change linked to coastal erosion, the correlation between coastal erosion and coastal communities, and the adaptative measures to address these issues and their effectiveness in Southeast Asia. Therefore, by analyzing the existing literature, the purpose of this review was to bridge the knowledge gap and identify the link between climate change and coastal erosion in Southeast Asia in terms of sea-level rise, storm surge, and monsoon patterns. The RepOrting standards for Systematic Evidence Syntheses (ROSES) guided the study protocol, including articles from the Scopus and Dimension databases. There were five main themes considered: 1) climate change impact, 2) contributing factors to coastal erosion, 3) coastal erosion impact on coastal communities, 4) adaptation measure and 5) effectiveness of adaptation measure using thematical analysis. Subsequently, nine sub-themes were produced from the themes. Generally, in Southeast Asia, coastal erosion was reflected by the rising sea level. Throughout reviewing past literature,

* Corresponding author. Faculty of Science and Marine Environment, Universiti Malaysia Terengganu, 21030, Kuala Nerus, Terengganu, Malaysia.
E-mail address: effihelmy@umt.edu.my (E.H. Ariffin).

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an interesting result was explored. Storm surges also had the potential to affect coastal erosion due to alterations of the atmospheric system and seasonal monsoon as the result of climate change. Meanwhile, an assessment of current erosion control strategies in relation to the relative hydrodynamic trend was required to avoid the failure of defence structures and the resulting danger to coastal communities. Systematically reviewing the existing literature was critical, hence it could significantly contribute to the body of knowledge. It provides valuable information for interested parties, such as authorities, the public, researchers, and environmentalists, while comprehending existing adaptation practices. This kind of review could strategize adaptation and natural resource management in line with coastal communities' needs, abilities, and capabilities in response to environmental and other change forms.

1. Introduction

Since the mid-20th-century, climate change has been a threat to the global environment. As it threatens every part of the planet, developing countries will hit the worst, the fastest, and the least ability to adapt. Southeast Asia is known as one of the most sensitive and vulnerable to the effects of climate change than other regions of the world due to its expansive and densely populated coasts and ecological strain [1]. It has tropical monsoon climates, dry and wet monsoon climates, and tropical rainforest climates with high temperatures and ample rainfall. Southeast Asia is also known as one of the world's most dynamic locations, with enormous potential and a wealth of natural and human resources [1]. According to Eckstein et al. [2], Myanmar, the Philippines, Vietnam, and Thailand were among the ten most-affected countries on the long-term Global Climate Risk Index (CRI) list (Fig. 1) from 1999 to 2018. CRI is an index list that quantifies the effects of catastrophic weather occurrences in mortality and economic damage.

The leading cause of climate change in this region was induced by human activities, releasing enormous amounts of greenhouse gases (GHG) such as carbon dioxide (CO_2) and methane. The continuous emission of GHG day after day and year after year has accelerated the atmospheric GHG concentration, the main contributor to global warming. The ocean is the primary storage sink for the ~93% additional thermal energy caused by global warming, which has resulted in warming of the upper and deeper oceans [3,4]. Since 1900, global sea surface temperatures have risen by an average of 0.7 °C [5,6]. The warmer water temperature causes a domino effect on ocean circulation, currents, regional wind patterns, local climate, and sea level [4].

Warmer sea surface temperature creates a more significant gradient between continental thermal low pressure and high oceanic pressure, which strengthens upwelling winds in the Eastern Boundary Current Systems (EBCSs) and might overcome the countervailing effects of upper-ocean warming and stratification to cause regional cooling. Other than the Gulf Stream, all western boundary currents are likely to intensify due to tropical atmospheric changes and shifts in wind patterns due to identified ocean surface warming [6]. Furthermore, the uneven distribution of thermal energy on the waterbody modifies thermohaline circulation and has intensified climatic phenomena such as the El-Nino/La-Nina-Southern Oscillation (ENSO) and the North Atlantic Oscillation [6–9]. Changes in ocean circulation and oscillation can intensify coastal storm systems [4,6].

Coastal storm systems such as tropical cyclones, hurricanes, typhoons, and storms were affected by the latent heat of water vapor condensation over tropical hot ocean basins. The frequency and intensity of tropical storms had increased due to warmer oceans and altered atmospheric circulation [6]. There has also been an increase in the number and proportion of hurricanes reaching higher intensity categories [6]. Furthermore, the increasing global warming phenomenon has resulted in a rise in sea level. The combined effect of ocean thermal expansion and the declining volume of the polar ice, where the thick and multiyear ice was replaced by thin and

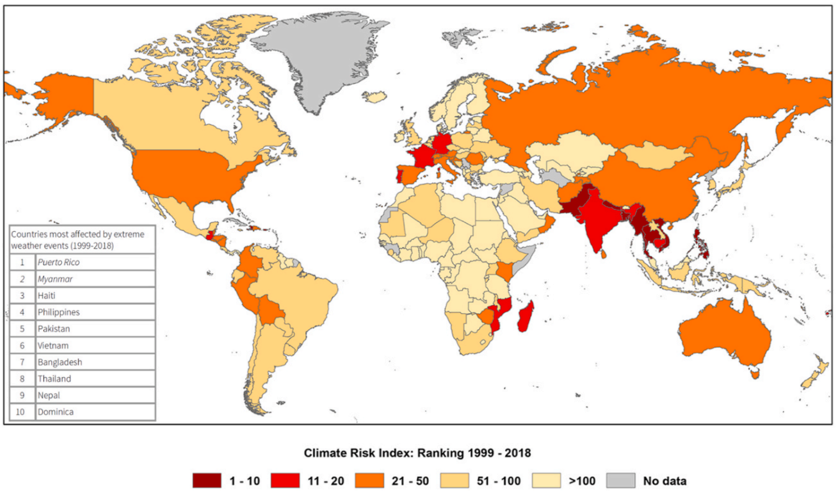

Fig. 1. The world map of the Global Climate Risk Index 1999–2018 (Eckstein et al., 2019).

first-year ice, also contributed to the rising sea level [10].

Between 1901 and 2010, the global sea level rose by 0.19 m. By 2040, the average global sea level is expected to rise by 0.2 m with 2 °C warmings, with 90% of the coastal region will experience a more remarkable rise [6,10]. By 2100, the projected mean global sea level estimated that the global mean sea level would rise between 0.29 m and 0.59 m under Representative Concentration Pathway (RCP) 2.6 and between 0.61 m and 1.1 m under RCP 8.5 [4]. Sea-level rise and other climate-related ocean changes will almost certainly force millions of people worldwide to flee their homes, with the poorest households bearing the brunt of the consequences [8]. Sea-level rise is challenging for low-lying island nations, affecting their entire economies and populations [4,11]. Therefore, coastal areas in South, Southeast, and East Asia with dense populations and low-lying elevations are particularly vulnerable to sea-level rise [12].

Rising sea levels, combined with increasing storm frequency and intensity, are likely to have severe consequences for ocean and coastal economic infrastructure [8,13,14]. These effects are anticipated to be the most disruptive of all the climate-related ocean changes to the coastal environment due to its unique geographical location [10]. The coastal region is the interface between land and sea; it is home to approximately 60% of the world's population and is one of the world's most densely populated areas [3]. It is also one of the most critical parts of the world ocean and the most vulnerable environment under climate change impact [10]. Due to coastal region geographical location, a coastal region also acts as a buffer zone between land and the ocean, filtering pollutants and other

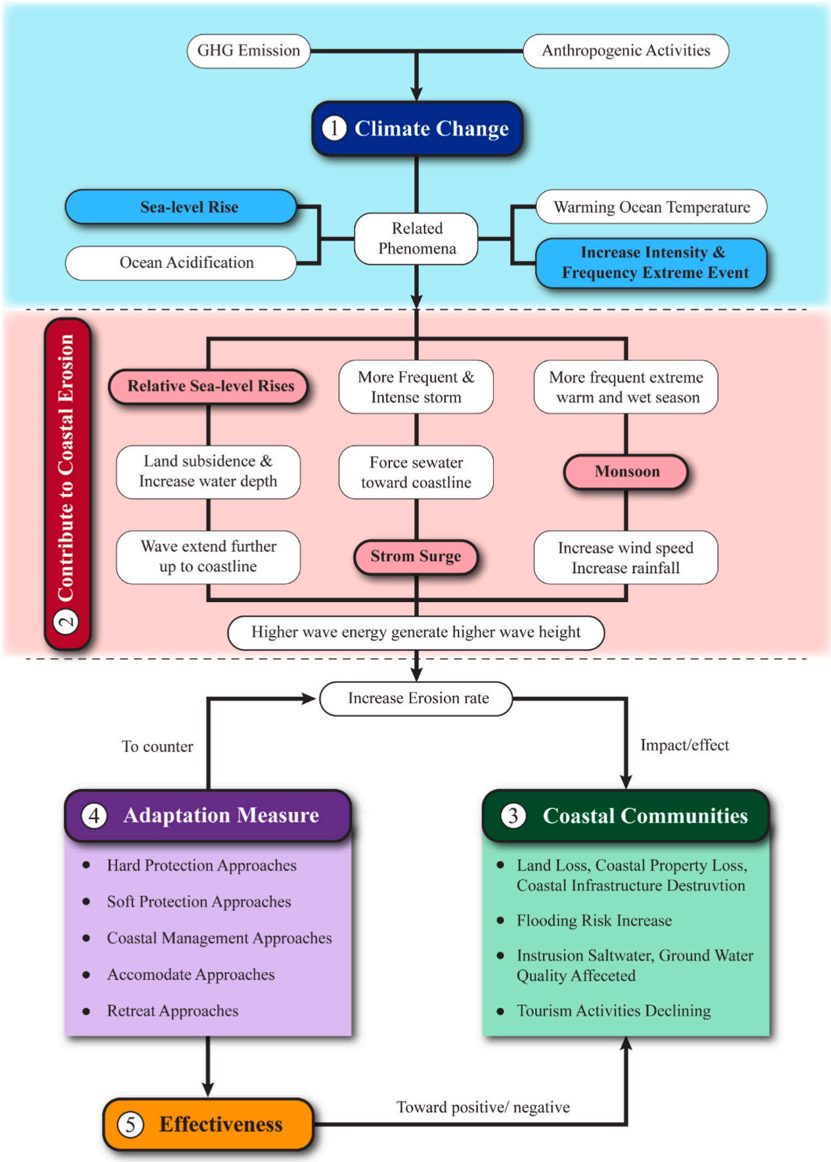

Fig. 2. The conceptual framework on the relationship between climate change toward coastal erosion issues, its further impact on the coastal community, the adaptation strategies and their effectiveness where impact to the coastal community.

land-derived contaminants before they reach the ocean and protecting uplands from storms and flooding [10]. Coastal erosion is a natural phenomenon that occurs on the coastline, and it is the landward displacement caused by the effects of waves and currents [3, 15]. However, due to the alteration of various climate variations, atmospheric disturbances, and constant changes in water bodies, coastal erosion has become a global issue that affects practically every country on the planet with a coastline [3,13].

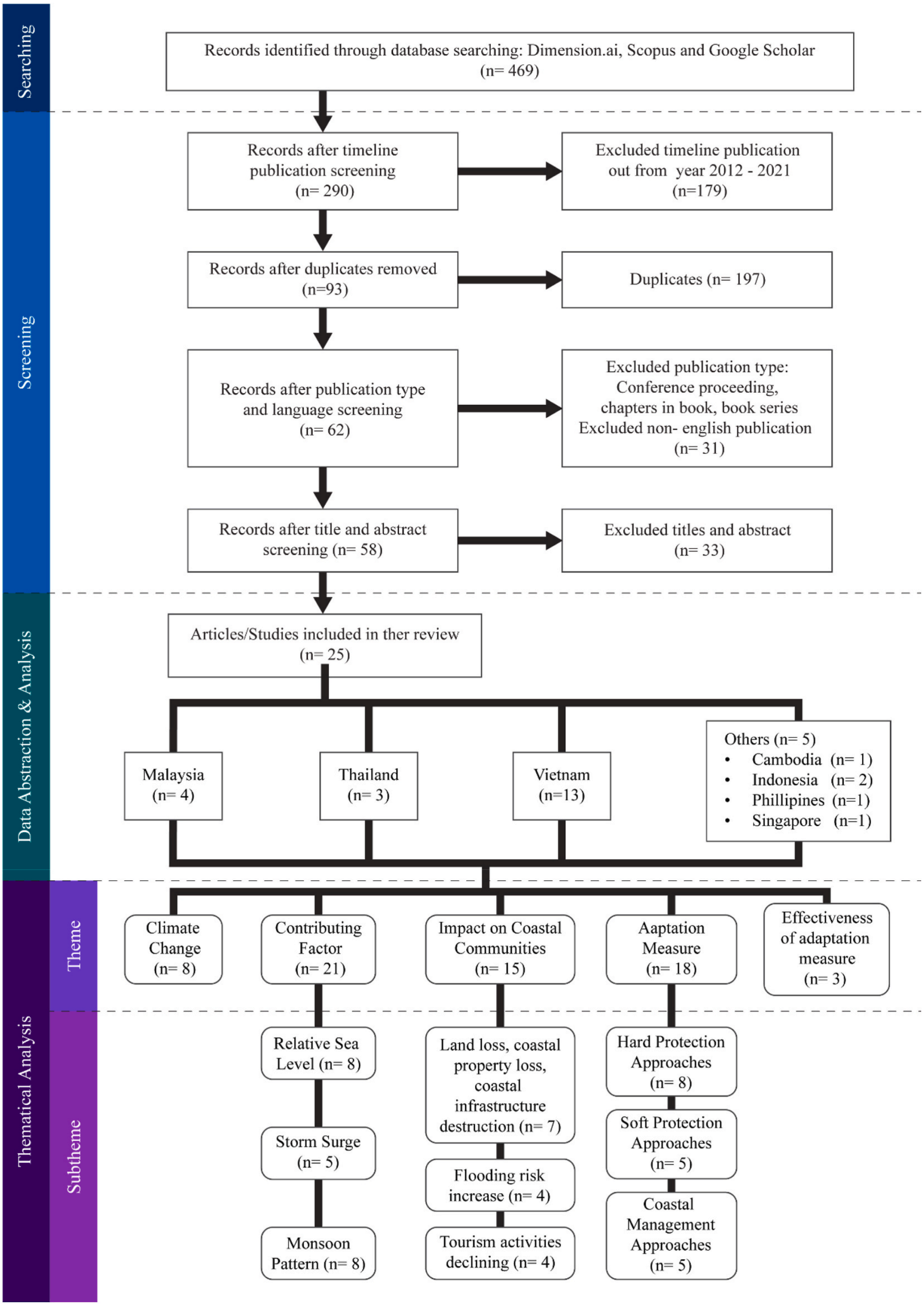

Fig. 3. The flow diagram guide by ROSES protocol and Thematical Analysis.

The consequences of climate change that impact coastal erosion are storm surge, monsoon pattern, wind-wave climate, and relative sea-level rise, which will lead to increased erosion rates, coastal squeeze, and more frequent and extreme storm events [16]. Sandy beaches are one of the most vulnerable regions due to coastal erosion [13,17]. Approximately 70% of the world's sandy beaches are being eroded. Only 10% of the sandy beaches have experienced accretion, while the remaining 20% are in a stable state [17]. Increased erosion rates will have a direct or indirect impact on coastal communities, such as coastal property loss, increased flooding risk, saltwater intrusion, and declining tourism activities, to name a few. Therefore, the government, authorities, and communities have implemented various adaptation measures to combat coastal erosion [18,19]. However, the effectiveness of climate change adaptation measures will determine whether communities are relieved of the effects of coastal erosion or vice versa (Fig. 2).

Previous studies have shown that climate change contributed to the recent coastal erosion phenomenon [2,20,21]. Some claimed that global warming had a direct influence on rising global and relative sea levels. The increased frequency and intensity of storm events drove the accelerated coastal erosion rate and shift in coastline shape. According to Malaysia's Third National Communication and.

Second Biennial Update Report, around 1349.3 km of Malaysia's coastline is continuously eroding due to coastal development and sea-level rise. There are 44 places in the Critical Erosion category with a total length of approximately 55.4 km, 309 sites in the Significant Erosion category with a total length of around 376.1 km, and 2344 areas in the Acceptable Erosion category with a total length of ≈916.5 km.

Kuala Nerus, Terengganu, as severe erosion regions in the East Coast of Peninsular Malaysia, experienced maximum shoreline retreat between - 11 m/year and - 150 m in 2004–2016 [15,22]. Another study conducted by Tagaki et al. [20] reported Vietnam as one of the most vulnerable coastal disasters and climate change. The Vietnam coastlines, such as Nam Dinh, Quang Ninh, Quang Binh, Quang Nam, Tien Giang Ca Mau Provinces, and Phan Thiet and Hai Phong cities, are experiencing severe coastal erosion [23,24].

Long-term monitoring of coastal erosion in three Thailand provinces - Koh Kho Khao, Ban Nam Khem, and Phang Nga, was made following the December 2004 tsunami. From 2012 to 2016, one location with a 0.02 ha region experienced a low degree of erosion. Five locations covering a 1.54 ha region were subjected to moderate erosion, while one location with 4.27 ha experienced severe erosion. A total of 5.83 ha of coastline has been eroded [25].

Efforts to systematically literature review these studies are still insufficient even though there are many studies on the climate change linkage to coastal erosion, the correlation between coastal erosion and coastal communities, and the adaptative measures to address these issues and their effectiveness in Southeast Asia. Therefore, by analyzing existing literature, the purpose of this review was to bridge the knowledge gap and identify the link between climate change and coastal erosion in Southeast Asia. Reviewing current and past literature systematically would contribute valuable knowledge, comprehension, and information on related issues. It is vital for all parties involved, including local authorities, government authorities, the public, developers, researchers, and environmentalists. Moreover, understanding the presently implemented adaptation approaches aided in involving parties and strategizing adaptation approaches and natural resource management that meet coastal communities needs, abilities, and capabilities in response to environmental and other forms of change [22].

2. Methodology

2.1. The review protocol – ROSES

Several kinds of systematic review protocols can be used to guide and conduct a systematic literature review paper. Haddaway et al. [26] reported that ROSES is a systematic review protocol designed explicitly for transparent reporting of systematic reviews and maps in environmental management and conservation. It provided a comprehensive set of reporting standards tailored to the conservation and environmental management research synthesis community. Thus, in this study, a systematic literature review was guided by the ROSES review protocol (Fig. 3). Appropriate research questions for this systematic literature review (SLR) as the first stage based on the ROSES review protocol were developed. The second stage explained the searching strategies, including the keyword used, the journal database, and the article selection criteria of the study utilized in the review. Subsequently, a strategy for appraising the quality of the selected article and the method of data abstraction and analysis was reported.

2.2. Formulation of research questions

As a research inquiry, the systematic literature review should be guided by research questions. The overall review processes, such as study selection, data extraction and analysis, and reporting, are driven by research questions. These processes are required to fulfill the research questions. This systematic literature review generated five research questions.

1. What causes climate change?
2. What are the contributing factors of climate change on coastal erosion?
3. What are the effects of coastal erosion on coastal communities?
4. What is the adaptation measure for coastal erosion as a result of climate change?
5. How is the effectiveness of adaptation to the coastal communities measured?

2.3. Systematic searching strategies

2.3.1. Selection of studies

The main keyword for the study was defined for the search processes. Synonyms, related terms, and variations with the main keyword were also determined to get more related reviews from the database [27]. Six main keywords were selected: sea-level rise, storm surge, monsoon, Vietnam, Thailand, and Malaysia. In the database searching process, search string functions such as boolean operator, phrase searching, truncation, wild card, and field code were applied with synonyms and related terms of main keywords such as climate change impact, coastal community, and adaptation measure. The two main databases of this study were Dimensions and Scopus. Gusenbauser and Haddaway [28] reported that Scopus could provide a high-quality article with a multidisciplinary focus, while Haddaway et al. [29] suggested that Google Scholar could be utilized for the additional database.

In the first phase searching stage had retrieved 1487 article. The searches of these three databases with six main keywords had generated then. Out of the ten Southeast Asian countries, only the articles from Indonesia, Malaysia, the Philippines, Singapore, Thailand, and Vietnam were acquired during the search process (Figs. 4 and 5). However, only Vietnam, Thailand, and Malaysia were proposed in this systematic review due their landform and threated by south china sea. The screening process on the selected articles with inclusion and exclusion criteria was also performed in this study. The article inclusion criteria were timeline publication (from 2012 to 2021, a 10-year range), determining keywords, a focus on studies related to coastal erosion in Southeast Asian countries, and articles with English publications. Contrarily, the article exclusion criteria were the same article. The following process, post screening process had excluded 68 articles and only 58 procced to next phase.

2.3.2. Appraisal of the quality

The best evidence synthesis method was used to appraise the quality of this systematic literature review. According to Littlewood et al. [30], the best evidence synthesis is a process whereby the systematic review team evaluates the previously assigned inclusion criteria of the review based on a pre-defined guideline. The selected studies will be deemed scientifically acceptable or not. Next, the author chose to use the four inclusion selection criteria, as mentioned earlier. Any selected articles that met these criteria were included in the systematic literature review.

2.3.3. Data abstraction and analysis

This systematic literature review's data abstraction and analysis were applied with quantitative and qualitative techniques and thematic analysis. The data abstraction process depended on the five research questions. Any data reviewed from the selected article that is capable or relevant to the research question was abstracted and placed in a table or pooled in a group (see Table 1) [27].

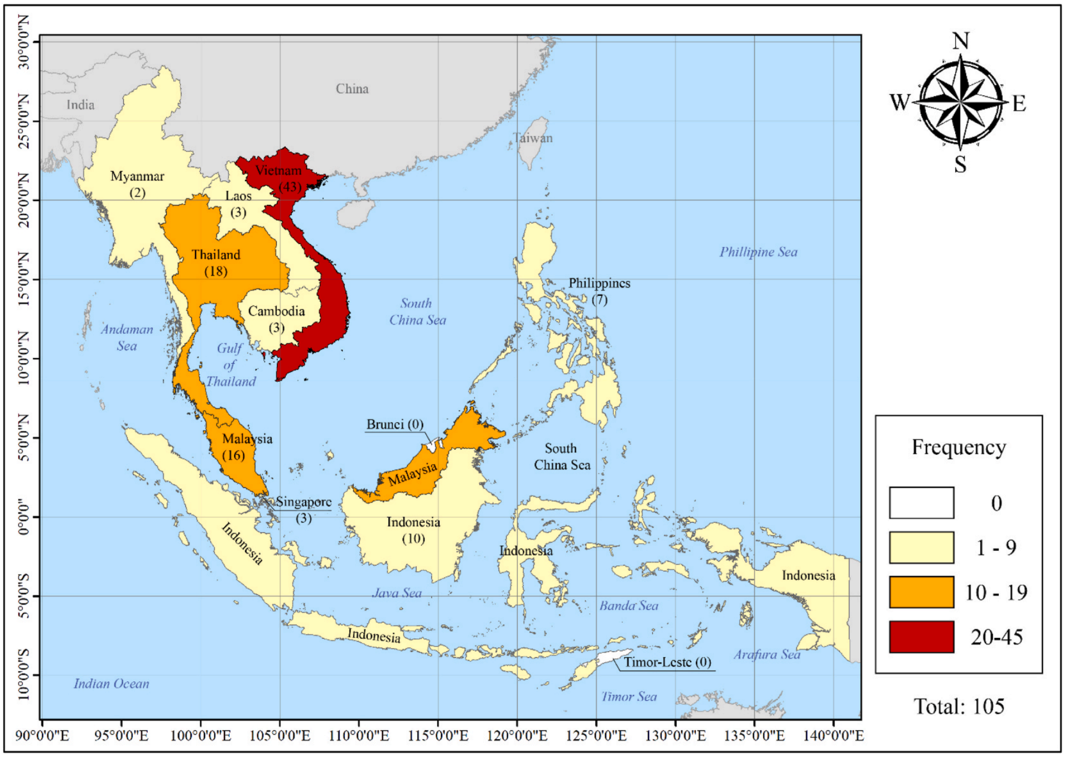

Fig. 4. Frequency of contribution from each Southeast Asia country (2012–2021) with total 105 articles.

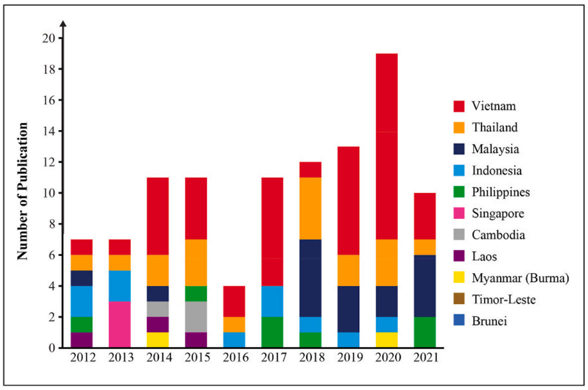

Fig. 5. Annual number of publications by each Southeast Asia country (2012–2021) with total 105 articles.

Meanwhile, thematic analysis is a descriptive method that reduces the data mount in the flexible model when combined with other data analysis techniques [31]. The technique applied to determine the pattern of reviewed studies depends on the similarity and relationship with the abstracted data. The themes and sub-themes were then developed from this.

3. Results

3.1. Background of the selected articles

There were 25 selected articles acquired for current study. Five themes and sub-themes were generated based on the thematic analysis: climate change, contributing factors on coastal erosion, coastal erosion impact on coastal communities, adaptation measure of coastal erosion, and utility of adaptation measure. Nine sub-themes were analyzed further from those five themes. 13 selected articles studies were conducted in Vietnam, 3 articles in Thailand, 4 articles in Malaysia, 5 articles for others countries such as Cambodia, Indonesia, Philippines and Singapore, with two, was published in 2012, one in 2013, one in 2015, two in 2016, five in 2017, two in 2018, three in 2019, three in 2020, and the rest in 2021 (Table 2).

3.2. The themes and the sub-themes

3.2.1. Climate change

Climate change is a well-known threat that has a global impact on the economy, society, and environment [32]. GHG emissions and other related human activities contribute significantly to the accumulation of anthropogenic GHG in the earth's atmosphere, leading to anthropogenic global warming. It continues to cause global climate change, such as temperature rises, precipitation pattern changes, melting of the ice sheet and glaciers, thermal expansion of water, and other effects [33–35]. As Southeast Asia also identified regional impacts of climate change, such as warming trends and sea level rise having similar trends to the global projected value, increasing annual rainfall, frequency of extreme warm and wet seasons and decrease in extreme dry season frequency [35].

Coastal territories were suffering from degraded and unsustainable conditions due to human-induced pollution, resource over-exploitation, and land use. Meanwhile, degraded coastal conditions had become more severe due to the combined effect of climate change-related phenomena such as sea-level rise, warming of ocean temperatures, increasing acidity of the ocean, and increased occurrence and intensity of extreme events [32,34,36].

Panpeng and Ahmad [32] also reported that the global average temperature rose by 0.85 °C from 1880 to 2012, and the global mean sea level rose by 3.2 mm per year from 1993 to 2010. Temperature and sea level have increased in magnitude and frequency, putting coastal areas and small islands at risk from climate change-related phenomena. Moreover, the sea-level rise was linked to rising sea temperatures. This is a severe climate change-related phenomenon with far-reaching impacts between climate change and coastal areas. The coastal infrastructure, natural resources, and coastal systems will threaten and exacerbate the coastal community's livelihood, especially in coastal developing countries and small islands [32]. Additionally, the climate change impact on Southeast Asia was more intense and occurred faster than in other parts of the world [37].

3.2.2. Contributing factor on coastal erosion

Coastal processes are contributed by three factors: internal, external, and human interferences. Internal factors include various processes such as nearshore currents, wave energy, tidal inundations, changes in sediment budget, and others. Contrarily, external factors are natural disasters such as storm surge, tsunami, flooding, and heavy rainfall. Meanwhile, anthropogenic factors include deforestation, urbanization, infrastructural development, dredging, and coastal minerals exploitations. Climate change has driven the variations in atmospheric circulation and resulted modification of regional wave climate and sediment transport rates. These factors complicated the coastline, resulting in severe social and environmental outgrowths, particularly coastal erosion [38,39].

Table 1
Overview of the reviewed studies.

No.	Study ID	Country	Title	Aim
1	Van Cuong, C., Russell, M., Brown, S., Dart, P. (2015)	Cambodia	Using Shoreline Video Assessment for coastal planning and restoration in the context of climate change in Kien Giang, Vietnam	Describe how Shoreline Video Assessment Method (SVAM) was applied and compares the results to identify changes and proposes a management and restoration program to enable adaptation to climate change and sea level rise
2	Marfai M.A. (2012)	Indonesia	Preliminary assessment of coastal erosion and local community adaptation in sayung coastal area, central java -indonesia	To understand the determinants of autonomous adaptation of households in coastal communities in three countries (Indonesia, the Philippines, and Vietnam) as regards climate change.
3	Winterwerp J.C.; Albers T.; Anthony E.J.; Friess D.A.; Mancheño A.G.; Moseley K.; Muhari A.; Naipal S.; Noordermeer J.; Oost A.; Saengsupavanich C.; Tas S.A.J.; Tonneijck F.H.; Wilms T.; Van Bijsterveldt C.; Van Eijk P.; Van Lavieren E.; Van Wesenbeeck B.K. (2020)	Indonesia	Managing erosion of mangrove-mud coasts with permeable dams – lessons learned	To present and discuss more than a decade of experience with the design, construction, maintenance and success of permeable dams along tropical mangrove-mud coasts.
4	Yaacob, R., Shaari, H., Sapon, N., Ahmad, M. F., Arifin, E. H., Zakariya, R., & Hussain, M. L. (2018).	Malaysia	Annual changes of beach profile and nearshore sediment distribution off Dungun-Kemaman, Terengganu, Malaysia	To determine the trend of morphological changes along the beach from Dungun to Kemaman and investigate the distribution of sediment characteristics.
6	Bagheri, M., Ibrahim, Z. Z., Mansor, S. B., Abd Manaf, L., Badarulzaman, N., & Vaghefi, N., (2019)	Malaysia	Shoreline change analysis and erosion prediction using historical data of Kuala Terengganu, Malaysia	To assess the rate of shoreline change and to predict the erosion based on sea-level changes from 2015 to 2020 on the Kuala Terengganu coast.
5	Ehsan, S., Begum, R. A., Md Nor, N. G., & Abdul Maulud, K. N., (2019)	Malaysia	Current and potential impacts of sea level rise in the coastal areas of Malaysia	To highlight the current and potential impacts of sea level rise in several high risk coastal areas of Malaysia
7	Mohamed Rashidi, A. H., Jamal, M. H., Hassan, M. Z., Mohd Sendek, S. S., Mohd Sopie, S. L., & Abd Hamid, M. R. (2021).	Malaysia	Coastal structures as beach erosion control and sea level rise adaptation in malaysia: A review	To assess the current state of coastal erosion and sea-level rise scenarios in the country.
8	Combest-Friedman, C., Christie, P., Miles, E. (2012)	Philippines	Household perceptions of coastal hazards and climate change in the Central Philippines	Examines local meteorological information and explores household perceptions of climate change and coastal hazard risk. F
9	Bhullar, L.(2013)	Singapore	Climate change adaptation and water policy: Lessons from singapore	To evaluates the contribution of Singapore's water policies and practices to climate change adaptation, and examines whether they can support the development of adaptation strategies in the water sector for other similarly situated cities in vulnerable countries
10	Saengsupavanich, C. (2017)	Thailand	Coastal revetment design process in Thailand	To present the current procedure that Thailand is undertaking to design a coastal revetment.
11	Panpeng, J.& Ahmad, M. (2018)	Thailand	Awareness of coastal fishing communities on climate change and its impacts: A case study of coastal erosion and seawater inundation in Chanthaburi Province, Thailand	To understand the current awareness of coastal people on climate change and its impact, particularly the severity of coastal erosion and seawater inundation and simulating potential sea-level rise and quantifying land loss and affected people due to coastal erosion and seawater inundation.
12	Thepsiriamnuay, H., & Pumijumnong, N. (2019)	Thailand	Modelling Assessment of Sandy Beaches Erosion in Thailand	Quantifies the contribution and relevance of sea-level rise (SLR) to sandy beach erosion compared to other factors, including ad-hoc short-term impacts from stochastic storminess.
13	Dastgheib, A., Reyns, J., Thammasittirong, S., Weesakul, S., Thatcher, M., & Ranasinghe, R. (2016)	Vietnam	Variations in the Wave Climate and Sediment Transport Due to Climate Change along the Coast of Vietnam	Quantifies the climate change (CC)-driven variations in wave characteristics and the resulting variations in potential longshore sediment transport rate along mainland coast of Vietnam.
14	Yasuhara, K., Tamura, M., Van, T. C., & Duc, D. M. (2016)	Vietnam	Geotechnical Adaptation to the Vietnamese Coastal and Riverine Erosion in the Context of Climate Change	Explains the possibility of smart adaptation combining soft and hard adaptation to reduce severe coastal and riverine erosion in the Vietnamese deltas.

(*continued on next page*)

Table 1 (*continued*)

No.	Study ID	Country	Title	Aim
15	Do, M. D. & Hieu, N. M. (2017)	Vietnam	Analysis of Sea-Level Rise Impacts on Sea Dike Stability in Hai Hau Coast, Vietnam	To assess quantitative impacts of SLR on sea dike stability.
16	Duc, D.M., Yasuhara, K., Hieu, N.M.& Lan, N. C. (2017)	Vietnam	Climate change impacts on a large-scale erosion coast of Hai Hau district, Vietnam and the adaptation	Assesses climate change impacts on coastal erosion, especially in two projected SLR scenarios of RCP2.6 and RCP8.5.
17	Karlsrud, K., Vangelsten, B. V., & Frauenfelder, R. (2017)	Vietnam	Subsidence and shoreline retreat in the Ca Mau Province - Vietnam causes, consequences and mitigation options	Main cause of the land-loss is subsidence of the ground surface as a result of ongoing groundwater pumping.
18	Nguyen, T. A., Vu, D. A., Van Vu, P., Nguyen, T. N., Pham, T. M., Nguyen, H. T. T., Le, H. T., Nguyen, T. V., Hoang, L. K., Vu, T. D., Nguyen, T. S., Luong, T. T., Trinh, N. P. & Hens, L. (2017).	Vietnam	Human ecological effects of tropical storms in the coastal area of Ky Anh (Ha Tinh, Vietnam)	To inventories the perception of local people, assesses and values main aspects of the livelihood damage caused by the tropical storms of the period 2008–2013
19	Hens, L., Thinh, N. A., Hanh, T. H., Cuong, N. S., Lan, T. D., Van Thanh, N., & Le, D. T. (2018)	Vietnam	Sea-level rise and resilience in Vietnam and the Asia-Pacific: A synthesis	A summary of the current state of knowledge of sea level-rise and its effects on both human and natural ecosystems.
20	Dang, A. H., & Nguyen, T. D. (2019)	Vietnam	Coastal Erosion in Cua Dai Beach: Future Influence of Climate Change and Sea Level Rise on Coastal Protection.	To describe the current erosion situation that has been observed and learned at Cua Dai Beach. To estimate how coastlines suffer from erosion and other disasters.
21	Hung, N. T., Duc, D. M., Quynh, D. T., & Cuong, V. D. (2020)	Vietnam	Nearshore Topographical Changes and Coastal Stability in Nam Dinh Province, Vietnam	Investigation of nearshore topography shows the recent changes to the coast.
22	Van Liem, N., Van Bao, D., Bac, D. K., Cuong, N. C., Nga, P. T. P., Burkhard, B., & Chi, G. T. K. (2020)	Vietnam	Assessment of shoreline changes for setback zone establishment from Son Tra (Da Nang city) to Cua Dai (Hoi An city), Vietnam	Presents the latest results of shoreline changes using different open-source remote sensing resources and the most modern methods available in calcuating shoreline changes.
23	Dang, A. T., Kumar, L., Reid, M., & Nguyen, H. (2021)	Vietnam	Remote sensing approach for monitoring coastal wetland in the Mekong Delta, Vietnam: Change trends and their driving forces.	To determine the long-term dynamics of wetlands using remote sensing approaches, and analyse the potential factors driving these dynamics.
24	Lin, T. Y., Van Onselen, V. M., & Vo, L. P. (2021)	Vietnam	Coastal erosion in Vietnam: Case studies and implication for integrated coastal zone management in the Vietnamese south-central coastline	To review and identify the most serious threats to coastal areas and summarize the suggested and implemented solutions, assessing their effectiveness so far
25	Veettil, B. K., Ward, R. D., Dung, N. T. K., Van, D. D., Quang, N. X., Hoai, P. N., & Hoang, N. D. (2021).	Vietnam	The use of bioshields for coastal protection in Vietnam: Current status and potential.	Investigated the possibilities, advantages and limitations of using bioshields for coastal protection in Vietnam

3.2.2.1. Relative sea level. Relative sea-level rise is a well-known climate change-related phenomenon. It was contributed by various factors, including global sea-level rise, local factors, and vertical land movement. Global sea level rose due to unexpectedly rapid melting of glaciers, ice caps, and sheets and increased temperature mediated seawater surface thermal expansion. Next, the local factors are contributed by monsoonal winds and freshwater inflow. Meanwhile, vertical land movement includes glacial isostatic adjustment (GIA), specific-area vertical land movement, and human-induced vertical land movement [17,39]. The relative sea-level change impacted the ecosystems and local community activities in the low coastal plains, both directly and indirectly. The direct impact was related to extreme weather events, floods, salinization of the ground table, and salt intrusion [35]. Meanwhile, the indirect impact included coastal erosion, mangrove loss, loss of wetland, and other fragile coastal ecosystems [37,40]. It also adversely affected the social and economic community, not only in maritime cities [37]. According to the reporting from Intergovernmental Panel on Climate Change (IPCC), the global sea levels rose 1.70.5 mm year-1in 20th century while in the SEA was projected rise 2.5 mm year-1, approximately 40 cm by 2100 [36].

Panpeng and Ahmad [32] reported that rising relative sea-level toward coastal erosion is the most crucial driver that caused Laemsing District, Chanthaburi Province in Thailand vulnerable to climate change and its impact. Rising sea levels of 11.22 mm/year are expected to be confronted during the first 30 years of the century, from 2000 to 2030. The rising-rate will reach 12.05/mm year in the first 60 years and 12.99 mm/year in the first 90 years. Shoreline retreat was associated with the potential rise in relative sea level, which was predicted to increase the retreat distance continuously. By 2060, the shoreline at Paknamlaemsing and Bangkachai is estimated to retreat by 64 m and 59 m, respectively. Coastal erosion and tidal flooding resulting from rising relative sea levels have threatened community livelihoods and physically degraded the region's ecosystems.

Thepsiriamnuay and Pumijumnong [17] also predicted that the relative sea-level change of Thailand's 18 provinces from 1995 to 2100 has an increased tendency of around 17.50–147.90 cm. Moreover, the predicted shoreline retreat is consistent with the relative sea-level change, which retreats from 41.64 to 517.09 m over the same period. Based on the case study by Karlsrud et al. [41], Vietnam was one of the most severely affected countries by the accelerating sea-level rise, with the East Coast of Vietnam experiencing a 3 mm/year sea-level rise between 1993 and 2008 and a 20 cm rise over the last 50 years. The shoreline of the Ca Mau's coastal area was retreating due to sea-level rise and observed subsidence. The case study by Dang et al. [42] also reported that the observed rising sea

Table 2
Distribution of themes and sub-themes of review articles.

No.	Study ID	Country	Climate Change	Contributing Factor			Impact on Coastal Communities			Adaptation Measure			Utility of adaptation measure
				RSL	SS	MP	LL	FR	TA	HPA	SPA	CMA	
1	Van Cuong et al., 2015	Cambodia			✔			✔					
2	Marfai, 2012	Indonesia					✔					✔	
3	Winterwerp et al., 2020	Indonesia									✔		✔
4	Yaacob et al., 2018	Malaysia				✔							
5	Bagheri et al., 2019	Malaysia				✔			✔				
6	Ehsan et al., 2019	Malaysia	✔				✔	✔		✔		✔	
7	Mohamed Rashidi et al., 2021	Malaysia		✔		✔				✔		✔	✔
8	Combest-Friedman et al., 2012	Philippines	✔	✔									
9	Bhullar, 2013	Singapore	✔	✔	✔			✔		✔			
10	Saengsupavanich, 2017	Thailand								✔			
11	Panpeng & Ahmad, 2018	Thailand	✔	✔		✔		✔					
12	Thepsiriamnuay & Pumijumnong, 2019	Thailand		✔					✔				
13	Dastgheib et al., 2016	Vietnam	✔										
14	Yasuhara et al., 2016	Vietnam			✔		✔						
15	Do & Hieu, 2017	Vietnam					✔			✔	✔		
16	Duc et al., 2017	Vietnam								✔	✔		
17	Karlsrud et al., 2017	Vietnam		✔	✔	✔							
18	Nguyen et al., 2017	Vietnam										✔	
19	Hens et al., 2018	Vietnam	✔	✔	✔	✔	✔		✔				
20	Dang & Nguyen, 2019	Vietnam	✔			✔	✔						
21	Hung et al., 2020	Vietnam				✔							
22	Van Liem et al., 2020	Vietnam	✔										
23	Dang et al., 2021	Vietnam		✔									
24	Lin et al., 2021	Vietnam							✔	✔	✔	✔	✔
25	Veettil et al., 2021	Vietnam					✔			✔	✔		

Contributing Factor
RSL = Relative Sea Level
SS = Storm Surge
MP = Monsoon Pattern

Impact on Coastal Communities
LL = Land loss, coastal property loss, coastal infrastructure destruction
FR = Flooding risk increase
TA = Tourism activities declining

Adaptation Measure
HPA = Hard Protection Approaches
SPA = Soft Protection Approaches
CMA = Coastal Management Approaches

level of 14 cm from 1995 to 2019 strongly correlates with the expansion of water bodies and the shoreline retreat rate.

3.2.2.2. Storm surge. Storm surge levels have been recognized as a contributing factor to the coastal erosion problem caused by climate change. Storm surge levels are mainly contributed by extreme weather conditions such as tropical cyclones, hurricanes, and typhoons. They put additional pressure on the coastal environment and cause higher-than-usual waves [37]. In addition, typhoon events will eventually cause nearshore coastline regions to erode, and sediment loss will result in a steeper offshore profile [43]. The force of wind swirling around the storm also pushed seawater toward shore [35]. Therefore, it eventually allows the wave energy to greater and future penetration onshore [37,43]. However, even though extreme events such as typhoons and tropical cyclones occur only occasionally, the combined effect of climate change leads to very high surges, which cause severe damage to the coastal system, social and economic coastal communities, and erosion once they occur [37,41].

According to Hens et al. [37], Vietnam is one of the most seriously affected countries by climate change. Tropical cyclones are a usual climate event in northern Vietnam known as typhoon season. During the typhoon, the Nghe An-Ha Tinh coast experienced the highest surges, 4 m above the average high-water level. The lowest extreme surges were also measured at 1.5 m in the coastal areas near Da Nang, Phu Yen, and Binh Thuan. In 1999, a typhoon event on Nghia Phuc caused an approximately 100-m erosion rate on the Hai Hau coast. The historical wave height at Hai Hau tide station during the typhoon was 3.2–4.25 m. When the wave height is 4.25 m, the erosion rate at Hai Hau can reach 7.1 m in 2.4 h [44].

Hens et al. [37] and Bhullar [35] stated that the frequency, intensity, timing, and distribution of tropical cyclones are associated with climate change-related phenomena, especially sea temperature rise, sea-level rise, increase in extreme rainfall and winds, as they form in warm water regions in the tropics and rotate counterclockwise in the northern hemisphere. As evidenced by the case study mentioned above, climate change-driven tropical cyclones are becoming more intense and frequent [44].

3.2.2.3. Monsoon Pattern. The monsoon pattern dominated the wave characteristics and rainfall pattern during the monsoon season. Seasonal constant monsoon winds and changing direction of storm surge have a continuous influence on coastal erosion [41]. The monsoon may cause coastline erosion as it alternates surges, waves, and currents. It also has an impact on sea states. Irrigation and flood discharge in canals reduce sediment supply in some regions and increase coastal erosion rates [41].

According to Panpeng and Ahmad [32], the monsoon had influenced the rainfall pattern in Laemsing District, Thailand. Heavy rainfall is most common during the southwest monsoon (June–September) but rarely during the northeast monsoon (November–February). Based on the research, the total amount of rainfall was high and rising from 1983 until 2012, with heavy rainfall amounts and days averaging around 13 mm/year, a day every five years, and over 50.80 mm/day. Rainfall slightly decreased from 32 mm/year between 1984 and 1993 to 48 mm/year between 2003 and 2012. Moreover, the number of days with heavy rainfall increased from 1.5 to 3 days per five years.

Malaysia is geographically located in the equatorial region. Thus, the wave climate hydrological regime was strongly influenced by the monsoons. Malaysia coastline will be affected by the Southwest monsoon from May to September while the Northeast monsoon from October to March. The Northeast monsoon brings heavy rainfall and storm waves to the east coast, especially Terengganu [40,45]. Onshore strong winds fetch and speed generated a significant wave, which eroded the large scale of beach sediment when combined with rising offshore bottom currents and conveying sediment offshore [40,46]. Consequently, the east coast region is dominated by coarser and relatively steeper sands and beach slopes [45,46].

In southern Vietnam, the Southwest and the Northeast monsoon are the two monsoon seasons. The Southwest monsoon is the wet season, which affects the West coast of Ca Mau with the north-bound current, while the Northeast monsoon is the dry season, which influences the East coast of Ca Mau. The wave height during the Southwest monsoon reaches 1 m, but the Northeast monsoon could reach 2 m. As a result of sea-level rise, storm surges are expected to increase by more than 1 m and cause overtopping dikes [41]. It has been reported that the monsoon pattern also influences the Nha Trang Bay in Vietnam. During the Northeast monsoon period, the tropical monsoon winds appear in higher and calmer waves than in the non-monsoon period.

3.2.3. *Coastal erosion impact on coastal communities*

Coastal erosion is eroding large segments of the beach and moving it landward. Consequently, the erosion will threaten local infrastructure, house destruction, and coastal communities' socio-economic well-being [34,37,44]. A coastal defense structure, such as a sea dike, is built to prevent lateral beach erosion. However, the coastal defense structure discourages longshore sediment transport. It further causes beach sediment erosion, lower beach topography, and local souring along the Hai Hau coast [47]. Meanwhile, the erosion even cause damaged and collapse of the coastal infrastructure such as sea dyke and road [34,48].

3.2.3.1. Land loss, coastal property loss, coastal infrastructure destruction. When the erosion process was dominant at Cua Dai beach, a sand loss in front of resorts was also occurred, which took 85 ha [33]. However, the accretion process on the right side was only about 10 ha. The erosion was faster than the accretion process. As a result, the abandoned resorts near the water finally collapsed and were destroyed due to coastal erosion [33]. Hence, the negative influences on promoting sediment transport and beach lowering were strengthened by the hydrodynamic variables caused by the climate-related phenomenon of sea-level rise [49].

Sea-level rise caused by climate change could also reduce the size of the low-lying coastal area and its infrastructure and exacerbate erosion and other coastal hazards. The coastal event or hazards could affect the coastal region in both direct and indirect ways. Coastal hazards such as typhoons, storm surges, tropical storms, strong waves, and the rise of sea levels have not only had a direct impact on the coastline but have also had unfavorable consequences such as floods or saline intrusion, which have influenced infrastructure, deteriorated coastal or tourist facilities and livelihoods, and caused problems further inland and in agricultural zones [47,48,50].

3.2.3.2. Flooding risk increase. Coastal flooding is a constant threat to low-lying coastal areas caused by high tides colliding with high water and damaging the coastline. This problem is intensified by heavy and regular rainfall from the seasonal monsoon and inadequate drainage systems to curb excessive rainfall [34,35]. Flooding can affect some parts of roads, health stations, infrastructure, and aquaculture farms, increasing the coastal community's livelihood and socio-economic difficulties [32,34]. According to Ehsan et al. [34], the coastal flood in Johor, Malaysia, in 2006 and 2007, destructed and affected over 100,000 victims, resulting in an estimated RM 0.35 billion (USD 75.1 million) in infrastructure damage and RM 2.4 billion (USD 0.51 billion) economic losses. Moreover, RM 84 million (USD 18 million) in agricultural production was estimated to be lost, with approximately 7000 farmers were affected. It was estimated that repairing the transport infrastructure and hydraulic structure would cost RM 147 million (USD 31.5 million) and RM 260 billion (USD 55.9 billion).

In the case of the Kien Giang coast [43], the mangrove fringe was less than 100 m wide, and this thin fringe was not able to combat strong waves penetrating during monsoon season. Therefore, this weak shoreline and even the sea dyke experience erode. Those earthen and mud dyke will be exposed and overtop by significant waves, which cause the agriculture, aquaculture, infrastructure, and local properties and property destroyed and inundated.

3.2.3.3. Tourism activities declining. Long stretches of beach are always a tourist attraction. However, this type of beach has been prone to erosion, resulting in severe significant shoreline retreat [51]. Some beaches in the Southern Vietnamese city of Vung Tau have eroded hundreds of meters, if not kilometers, over the past decades. Since resorts and other related businesses are located in unstable areas, local authorities have spent much money to reduce beach erosion [51]. The coastal erosion process and reduced sand deposition caused beach regressions in the southern-central province of Binh Thuan, Vietnam. The loss of these beaches impacted the attraction for recreation and the large amount of money invested by local authorities in tourism infrastructure [37].

In Malaysia, Kuala Terengganu is an essential source of socio-economic development for the coastal community, particularly tourism activities, as Malaysia's beaches are tourist destinations [46]. Sea level rise and coastal erosion threaten the coastal region, affecting the state's overall economic income. The Kuala Terengganu Airport, prone to erosion and flooding, could threaten the tourism industry, as it handles more than 500,000 passengers annually [46]. It is also worth noting that Thailand has several renowned and attractive beaches such as Sai Keaw, Patong, Pattaya, Sai Ree, Railay, Khanom, and Chao Mai. If coastal erosion ruins and damages these valuable beaches, Thailand's tourism and the economy will be affected [17].

3.2.4. Adaptation measure of coastal erosion

Adaptation approaches are recognized as critical approaches to diminishing the unfavorable impact of global climate change. It brings wide-ranging benefits in reducing the vulnerability of the society to coastal hazards and minimizing the detrimental impacts on the coastal community by preventing or reducing potential negative outgrowths while benefiting from possible positive outgrowths [34]. The adaptation strategy can be divided into three categories: protection, accommodation, and retreat approaches. Protection approaches are used to construct structures and others to protect vulnerable areas from coastal hazards [52]. Accommodation approaches utilize the vulnerable area and endure a greater degree of flooding by altering land use, construction methods, and advancing preparedness. Meanwhile, retreat approaches resettle residents from the abandoned currently developed region by managing realignment or coastal setbacks [34,40].

3.2.4.1. Hard protection approaches. Protection was the most implemented approach in the erosion control strategy in Thailand, Vietnam, and Malaysia coastline [40,48]. As coastal protection at Di Duong Beach, Vietnam, they constructed a low soft seawall by pumping sand into a tube and using geotextile [51]. The structure has been observed and investigated, and it has proven to be highly effective in preventing shoreline movement landward. Since the time of the field investigation in 2017, no signs of erosion have been observed. Since 1980, sea dikes have been installed along the Vietnam coast. Wave attacks and typhoons have repeatedly breached it. To adapt the SLR impact, Vietnam government had planting mangrove forest, upgrade and develop sea dike system along road side and construct sluice system to strengthening, upgrading and rehabilitating sea dikes system along Quang Ninh to Quang Nam and Quang Ngai to Kien Giang [48]. In Thailand, rock and concrete stepped revetments have been implemented and proven successful in many beaches. The implementation of the stepped concrete revetment at Pra-Ae beach, Thailand, could solve coastal erosion while promoting coastal tourism. They concluded that, when properly designed, the revetment can not only protect the coastline but can also promote natural vegetation as well as increase beach beauty. It can even promote tourism activities and become a resting place for both local people and visitors.

Traditional solutions such as revetment, T-groins, tripods, and mangrove forest reinforcement have been used to reinforce the dikes to protect the Hai Hau coast over the past decade. The concrete groins, reinforced with concrete tubes, were 10 cm thick and 1 m in diameter. The tubes are continuously placed at 0.5 m depth beneath the tidal flat, with 80 m between links and 1.5 m height sandbags inside [46,53]. The sea dike system has been intensively reinforced by extending the height to 4.5–5.5 m, placing the foot at a depth of 4.5 m, and covering seaside slopes with a polygonal precast concrete revetment of 100 kg mass tripod lines [47,48,53]. The standby block of limestone near the soil dyke segments was disposed of for emergency rehabilitation during bad weather conditions [47,53]. In Singapore, 70–80 percent of the coastline was implement hard wall, stone embankments, revetment and others coastal defence systems to protect the coastal areas from erosion [35].

3.2.4.2. Soft protection approaches. Soft structure protection such as permeable bamboo fences, breakwaters made from geotube sandbags, bamboo and wooden piles were found to be implemented at the Mekong Delta coastline as a low-cost solution and for area wave height below 0.9 m [48]. In Bogorame, a small village at Demak, Central Java of Indonesia, a permeable dam was constructed in November 2013 to restore the mangrove forest under threats of erosion and flooding [54] The permeable dams reduced wave energy to enhance sedimentation rate by trapping sediment in the basins. It was also noted as a nature-based adaptive approach as the dams were temporary, relatively cost-effective and low-tech construction, which local communities could also build and maintain through basic training.

In Thailand, low-crested rock revetment, sediment-filled geotextiles ("sand sausages") and bamboo fences have been installed along the upper Gulf of Thailand's coastline to address the coastal erosion issues and restore the mangrove area [54]. Bamboo fences were assembled of dense spaces of bamboo poles in vertically single rows positions and have a similar function as permeable dams, slowing down wave energy and enhancing sedimentation.

3.2.4.3. Coastal management approaches. The coastal infrastructures such as roads, railways and drainage were also upgraded and reinforced to adapt to the climate change impacts as they were the essential economic drivers. According to Mohamed Rashidi et al. [40], the Malaysian government was concerned with rail development to minimize traffic congestion problems at Klang valley. Meanwhile, it was an essential connection between Port Klang and further inland. In Vietnam, hazard prevention was encouraged to be integrated into transportation plans to overcome the storm impact by constructing military roads along coasts, reinforcing physical barriers and increasing the elevation to be resilient to sea level rise scenarios [55].

Aside from the construct structure, vegetating the defense structure's inner slope also seems effective in controlling the erosion rate. Vetiver grass was applied to protect the inner slope of the coastal sea dike system slope on the Hai Hau coast due to insufficient investment and the current coastal dikes suffering from a wave overtopping. The vetiver hedgerows at the inner slope successfully reduce slope soil loss by 62–86% compared to those without hedgerows [47]. The inner slope of the construct structure was also vegetated in Hai Trieu, Vietnam, one of the coastal regions that are constantly eroding. The inner slope was just bare soil without the vertical concrete wall. Consequently, erosion rates of up to 50 cm/h were predicted. The vegetated inner slope significantly reduces overtopping water flows velocities and erosion [53].

To counteract the suggestion of upgrading dike systems and constructing good jetties, Lin et al. [51] recommended the particular industry avoid building too close to the beach and remove the human-made structure located along the shoreline. They also suggested using natural approaches to create a buffer zone with more dynamic environments near the shore. Natural management approaches, such as dunes rebuilding or maintaining inner land, would better protect coastal erosion from extreme weather events. The dune could naturally recover after a typhoon or other extreme event. Hence, the natural and social systems' resilience capacity will be improved. Before construction, the impact assessment was also recommended to minimize the risk of coastal hazards, such as downsized and smaller-scale implementation of changing from cultivation industries and aquatic farming activities to reduce land use.

Based on report of Marfai [50], local government of Tambaksari-Sayung, Indonesia implements few adaptation strategies to coastal communities. Some local communities decide to relocated household, some who choose to stay had provide fund to built stage house to reduce risk from coastal inundation.

3.2.5. Effectiveness of adaptation measure

The structural measure aims to reduce wave and coastal erosion to aid in sediment accumulation and beach restructure [49]. Since this solution aimed to stabilize the coast, the current situation, building appearance, and structure should be considered to confirm that each coastal region's sustainability and suitability are harmoniously connected with existing coastal infrastructure. Small waves reduction works, such as breakwaters or coastal protection embankments, will be a practical approach to decreasing the wave height, as they are stable and convenient for construction, maintenance, and management [40,49].

Meanwhile, the river mouth of the Ca Ty River estuary at the Duc Long site had constructed a groin in 1995. However, the "groin-effect" had developed over time and resulted in stiff downdrift erosion on the southern beach of Duc Long Ward, causing hundreds of houses to collapse and relocating residents in the Tien Duc Area. In 2017, local authorities decided to build a sea dike for other development purposes. Nevertheless, the constructed seawall was relatively low, facing high flooding risk and constantly being washed over by waves. The implemented tetrapod was also no longer effective as it was constructed with an incorrect cement-to-non-cement ratio and showed signs of erosion [51].

Along the Hai Hau coast, the troughs of dikes are protected by concrete tubes installed 1.5 m above the beach surface. However, due to the influence of sea-level rise, the sediment supplies of the adjacent area of the dike were diminishing, the beach lowering rate increased, and the tubes could fail in the next six to ten years. Beaches in Vietnam were then covered into concrete structures and massive sandbag walls made of non-durable materials as a short-term solution to prevent erosion. Nevertheless, this had developed a side effect of causing water flow in and erosion at the other region along the coast or spreading further inland in the unprotected area [51].

According to Hung et al. [49], the lowering bathymetry in 2019 caused a threefold increase in wave height compared to 2009. Higher waves will give additional pressure on the sea embankment slope. Thus, the maximum pressure from high waves under bathymetry in 2019 was approximately three times higher than in 2009. Therefore, despite intensive coastal protection measures, nearshore topographical changes and coastal erosion continue to be severe issues in Nam Dinh province.

According to Winterwerp et al. [54], permeable dams work as a nature-based solution as an alternative to hard infrastructure sea defence to halt erosion in the mangrove coastline in Indonesia. The permeable dams target mangrove rehabilitation through the re-establishment of fine sediment dynamics. The first observation of sedimentation behind the dams at first, but longer-term sedimentation rates decline considerably. The less effective result was due to the subsidence, where the subsidence rate of coasts is 0.05 m per year or higher, from initially emerging above the MHW level and disappearing below MSL. The dams require more effort and cost maintenance to keep them effective.

The combination of hard and soft protection approaches implemented at the Gulf of Thailand coastline successfully addresses coastal erosion. In the early stage, only soft protection approaches, such as sand sausages and bamboo fences, were installed along the coastline. However, the result was unsatisfactory after implementation by the local Sub-district Administration Organization (SAO) and the governmental department. It was due to the severity of the problem, limited budget, sand sauges sinking into the soil, durability of bamboo fences, the decomposed bamboo fences causing obstructing navigation, damage to sand sauges and mangrove stems and threat to local fishermen. The placing of low-crested rock revetment later made the whole system successful. And this combination of approaches was subsequently implemented at the coastline of Bangkok Metropolitan, Samutsongkhram Provinces, Samut Sakhon Provinces and the west coast of Thailand, Banklang Klong Prasong. Especially the Ban Klong Prasong coastline, experience erosion and storm damage plenty of years ago, with the failure of the erection of a concrete seawall in 2003, which not solved the flooding problem but enlarged the problem by waterlogging.

4. Discussion and recommendation

There were five themes and nine subthemes developed throughout the thematic analyses. This section expands on the previously developed themes. It was clear throughout the review that climate change impacted the coastal erosion process, both directly and indirectly, by changing relative sea level, storm surge, wave climate, and monsoon pattern. The climate pattern, ocean circulation, and geographical location of Vietnam, Thailand, and Malaysia were distinguished as the major contributing factors to their respective coastal erosion.

4.1. Significance of contribution factor to Southeast Asia erosion issue

4.1.1. Sea level rise – indirectly, long-term erosion

Sea-level rise appears to be a significant factor in coastal erosion in Vietnam, Thailand, Malaysia, Singapore, Cambodia, Indonesia, and the Philippines. The impacts of sea level rise were slow, repetitive, and cumulative, acting as a leading driving force in long-term erosion [56]. The magnitude and type of impacts of rising sea levels are determined by the environment's geological setting and physical and ecological processes such as low-lying geographies, mangrove and coral habitats, local circulation pattern, and land subsidence [3]. The low-lying characteristics of coastal geographies like Vietnam, Malaysia, and Singapore make various regions extremely vulnerable to rising sea level. Based on the study [57], most of Malaysia's coastal regions were low-lying regions less than 0.5 m above the highest tide or within 100 m of the high watermark inland. In the case of Singapore, 30% of the islands was lowland region less than 5 m above the Singapore Height Datum, and most of the land was less than 15 m above sea level and 180 km of relatively flat coastline [35,58]. Moreover, several essential infrastructure facilities, such as airports, ports, commercial and residential buildings, and roads, were located at the reclaimed land elevated less than 2 m above sea level [35], making the coastline especially vulnerable to land loss and coastal erosion from rising sea levels.

The natural and anthropogenic land subsidence somehow accelerates the rising sea level, as in Vietnam, the sea level rising rate was comparable to the global rate due to the anthropogenic subsidence from groundwater extraction or natural subsidence [2,20]. The same issues were also discovered in Thailand, the extreme spatial variations of relative sea level between regions were shown in the studies by Saramul and Ezer (2014). The land subsidence caused by ground extraction in the upper Gulf of Thailand resulted in the highest sea-level rise [59,60]. Furthermore, the entire region has significantly increased regional sea-level rise since the 2004 Sumatra–Andaman Earthquake and Indian Ocean tsunami. Many parts of Thailand are sinking based on the measured data [59].

The climate change-induced rise in sea level caused the coastline to be in danger of erosion disasters and wiped off mangrove habitats and coral reefs due to altered ocean currents by rising sea levels [61,62]. In particular, countries like Indonesia have the largest archipelagic country and the largest covered mangrove plant globally with high diversity, and the Philippines has a coastline of 27000 km^2 coral reefs and 120000ha of mangrove remains, respectively [62]. In addition, local circulation patterns, thermostatic, local climate and topographical conditions also magnitude the impact of rising sea levels [2,40,57].

4.1.2. *Storm surge – directly, short-term erosion*

Storm surge was another major factor contributing to coastal erosion in Southeast Asia. In particular, countries such as Vietnam, the Philippines and Thailand are geographically located under the path of cyclones.

Vietnam is highly susceptible to tropical cyclones as it lies within the tropical cyclone occurrence region, between 10° and 30° latitude in both hemispheres [24]. Since tropical cyclones have become a one-of-a-kind weather phenomenon in Vietnam, the annual typhoon season lasts from June to November, with July to October being the most impacted [63]. In Vietnam, 72 typhoons have been recorded over the last three decades. Therefore, its wave regime is influenced not only by monsoons but also by typhoons (i.e., Typhoon Molave 2020, Typhoon Vamco 2020, Typhoon Goni 2020). The passing typhoon causes high water levels, large waves, and strong winds, resulting in wave overtopping and dike and dune erosion [24].

Regarding coastal storms in Thailand, the Thailand Meteorological Department has recorded 12 tropical cyclones and one typhoon over the last three decades [64]. Among them were significant storms such as Typhoon Gay (1989), Tropical Storm Linda (1997), and Tropical Storm Pabuk (2019). Thailand was shielded from Vietnam, Laos, and Cambodia when the storm from the Pacific and the east-to-west trajectory typhoons from the South China Sea entering the Gulf of Thailand impacted the eastern coast of the Thai Peninsula. However, due to insufficient historical shoreline data in Thailand, there is no report on shoreline recession caused by coastal storms [64].

The Philippines' geographical location makes it frequently face weather-related catastrophes, ranking fourth in the Global Climate Risk Index for 1999–2018 [2]. Located in the most cyclone-prone regions, the coastline was highly vulnerable to storm surges that induced coastal erosion [65,66].

4.1.3. *Monsoon pattern – another factor to wind-wave climate*

Monsoon Pattern was a minor factor contributing to coastal erosion, which cannot be disregarded in the process of coastal erosion. The monsoon system was a seasonal-driven wind that contributed to the regional wind-wave climate, influencing wave and coastal processes. Climate change also impacts the monsoon system's strength, the magnitude of precipitation, and wind strength [67].

Malaysia's climate is tropical and humid, heavily dependent on mountainous topography and complex land-sea interaction. Despite this, Malaysia is considered a climate-related disaster-free zone [57]. The wave climate of Malaysia is dominated by the monsoon all over the year, with the highest average wind speed and erosion cases documented during the wet season, the northeast monsoon [57,68–70]. In Malaysia, the seasonal monsoon wind catalyzes coastal erosion [68–70].

4.2. *The erosion management by countries*

4.2.1. *Vietnam*

Vietnam established management agencies and legislation on dikes at several levels in 1946 to protect the Vietnam coast from severe erosion and the combined effects of climate change, such as the Central Committee on Dike Protection (Ordinance No. 70-SL on May 22, 1946) and the Committee on Dyke Protection (Ordinance No. 194-SL on May 28, 1948) [23]. Before 1990, Vietnam had no long-term plan to address the coastal erosion problem passively. Numerous policies only deal with part of the actual requirements to solve coastal erosion problems due to the shortness of the economy and facilities. After 1990, various specialized organizations and legislation were founded to direct and guide the implementation of disaster-prevention measures [23]. New policies were founded for coastal dikes and embankment renovation and construction, mangrove restoration, dike and land laws violation penalties, and other ordinances as coastal erosion prevention measures. However, no specific legislation or institutional office in Vietnam deals with coastal erosion management and countermeasures [23].

Nevertheless, coastal erosion issues are still addressed solely through standard provisions in the Natural Disasters Management Program. The disaster management structure in Vietnam includes ministries, boards, and sectors such as the Central Committee for Flood and Storm Control [23]. It was clear that Vietnam lacked coastal erosion mitigation strategies. Priority was always given to the business and industrial sector development along the coast. Integrated planning and coordination between different levels were lacking without an appropriate legal framework and monitoring [23,51]. Therefore, establishing a policy system that suits Vietnam's natural and economic development requirements is necessary for coastal erosion management [23].

4.2.2. Thailand

The erosion management in Thailand was collaborated by multiple agencies to participate in building the structures to protect the coast from erosion and have jurisdiction in the coastal zone, such as the Marine Department, Department of Public Work and Tow and Country Planning, Department of Highway, Department of Mineral Resources, Royal Irrigation Department, Fisheries Department, provincial administrative organizations, local administrative organizations, and private companies [71,72]. Government agencies have established various committees and sub-committees to coordinate coastal and marine governance [73]. The Department of Marine and Coastal Resources (DMCR) was the central authority on coastal resource management, but decision-making authority was shared with other agencies. For instance, the National Environment Board (NEB) established sub-committees for the national strategic plan for coastal resources, marine environmental protection, and coastal erosion management to promote participation, integration, and coordination among sectors [73].

Strategies, policies, and work plans for climate change in coastal erosion were established by responsible government agencies in Thailand to reduce the impact of climate change and erosion on the coastline. The DMCR proclaimed coastal management policy in the "Action Plan for Integrated Coastal erosion Prevention and Mitigation Management 2008," with additional the Promotion of Marine and Coastal Resources Management Act, 2015 which included five principles such as i) *create database*; ii) *promotion of public participation*; iii) *formulation of integrated coastal zone management*; iv) *securing hinterland and implementation of measures against coastal erosion* and; v) *to establish a system to manage, supervise, evaluate coastal management projects* [74].

4.2.3. Malaysia

The National Coastal Erosion Control Council (NCECC) and Coastal Engineering Technical Center (CETC) were established in 1987 by the Malaysian government to manage coastal erosion issues [75]. The NCECC is composed of various agencies, including the Ministry of Finance, the Ministry of Science, Technology, and Environment, the Department of Drainage and Irrigation, the Public Works Department, the Governors of Sabah, Sarawak, and two other states on a rotating basis, as well as professionals from various institutions and universities involved in erosion protection. NCECC is responsible for designing a coastal program, which CEC will recommend and approve before processing. CEC is also responsible for coastal erosion control performance, engineering work for critical erosion areas, and providing technical support to NCECC. Meanwhile, the data will be collected by other government agencies. The Malaysian government has adopted a two-pronged strategy to address coastal erosion in Malaysia: short-term and long-term. The short-term strategy was implementing structural, or engineering works to protect the coastal region, classified as Category 1 (critical erosion), to reduce or prevent further economic loss [69]. In comparison, the long-term strategy was to introduce institutional changes and formulate administrative guidelines to manage future development [75,76].

4.2.4. Singapore

Singapore's National Water Agency, a statutory board under the Ministry of Sustainability and the Environment, was responsible for coastal management in Singapore. According to the report from scientists from Singapore's Centre for Climate Research, the mean sea level around Singapore is projected to rise to 1 m by 2100, which is higher than the highest emission scenario SSP5-8.5 global mean sea level (0.45–1.02 m) [77]. Therefore, the National Climate Change Strategy 2008 (Strategy or NCCS) was established as a national climate change mitigation and adaptation policy. It aims to identify the potential impact of climate change on the water sector, such as increased flooding, coastal land loss and water resource scarcity [35,78]. However, although strategies included several initiatives but actual aims are missing. For coastal erosion and land loss, the government adopt the reactive approach, like protecting the foreshore and coastal areas to adapt to sea level rise when needed. It is partially because only a few options allow for the reasonable estimation of the costs and benefits of adaption measures. Knowledge gaps and inexistence or unreliable data are also part of the cause.

With the National Climate Change Strategy (2012), the Building and Construction Authority (BCA) 's Coastal Adaptation Study CAS commissioned a Risk Map Study in 2013. The CAS scope is to assess the potential impact of coastal inundation and to study possible long-term adaptation measures. As reported by NCCS [79], they had efforts to protect the coastline from erosion by constructing concrete seawalls and stone embankments over 70% of Singapore's coastline. The rest of the natural areas were beaches and mangroves. Meanwhile, they raised the minimum land reclamation level from 3 to 4 m over Singapore Height Datum in 2011 to adapt to the long-term sea level rise impact [80].

4.2.5. Cambodia

The coastline of Cambodia usually suffers from floods, windstorms and seawater intrusion due to the high precipitation, typhoon and coastal lowland region with rising sea levels, respectively. Implementing coastal management was guided by National Strategic Development Plan (NSDP), 2006–2010 [81,82]. The key ministries involved were the Ministry of Agriculture, Forestry and Fisheries, the Ministry of Industry, Mines and Energy, the Ministry of Tourism, Rural Development, and the Ministry of Environment. A few state bodies also get involved, such as National Committee for Land Management Urbanization and Construction, The National Coastal

Steering Committee (NCSC), The Coastal Coordination Unit and Commission on Monitoring and Assessing for Suppressing Encroachment into Mangrove Land and Coastal Reclamation to regulate construction activities, management and protection of the environment and natural resources through the sustainable use and development, coordinating coastal activities, reporting and making recommendations and preventing the encroachment on the mangroves [82].

Cambodia's National Assembly 1996 approved the Environmental Protection and National Resources Management to address environmental planning, protected area management, environmental impact assessment, environment monitoring, pollution control and inspection, and public participation under the Ministry of Environment. The King of Cambodia also enacted the Law on Fisheries in 2006, addressing fisheries management, increasing the protection and sustainable use of fishery resources, and managing the mangrove area and flood forests. Relatively short Cambodia's coastline and major GDP were contributed by rice, making its economic development focus on inland and freshwater. Meanwhile, coastal management still paid little attention because almost 75% of aquatic protein is produced by Tonle Sap and Mahkong Rivers. However, it might affect by the increasing harm to mangrove areas. Thus, the Cambodian Environment Ministry and the Organization for Industrial, Spiritual, and Cultural Advancement (OISCA) collaborated in establishing the Mangrove Forest Rehabilitation Programme to reforest the mangrove area. In addition, Cambodia also focuses on climate change impact and preparing the National Adaptation Programme of Action to Climate Change. Few national adaptation programs were implemented to adapt to climate change, like rehabilitation of coastal protection infrastructure, community and household water supply in coastal provinces and rehabilitation of multiple-use canals [83].

4.2.6. Indonesia

Indonesia was the largest archipelagic country and the largest covered mangrove plant globally with high diversity. The climate change-induced sea level rise caused the coastline at danger of erosion disasters and wiped off mangrove habitats due alters ocean currents by rising sea levels [61]. From the aspect of governance, it is essential to be clear and regulate the institution responsible in erosion control and especially their management. Coordinating Ministry for Maritime and Investment Affairs (CMMIA) as a coordinator to collaborate on infrastructure construction between the Ministry of Public Works and Public (MPWP) Housing and the Ministry of Marine Affairs and Fisheries (MMAF). Moreover, enhancement of coordination between the central government such as MMAF, Ministry of Land and Spatial Planning/National Land Agency (MLSP/NLA), Ministry of Environment and Forestry (MEF), and local government on environmental impact assessments and permissions for building or construction in coastal zones [84].

4.2.7. Philipines

The Philippines has 823 out of 1541 coastal municipalities (54%), including all major cities with 62% of the population. Its coastline was rich with coral reef and mangrove habitat and exposure to storm surge, rising sea levels, and coastal erosion threats. The

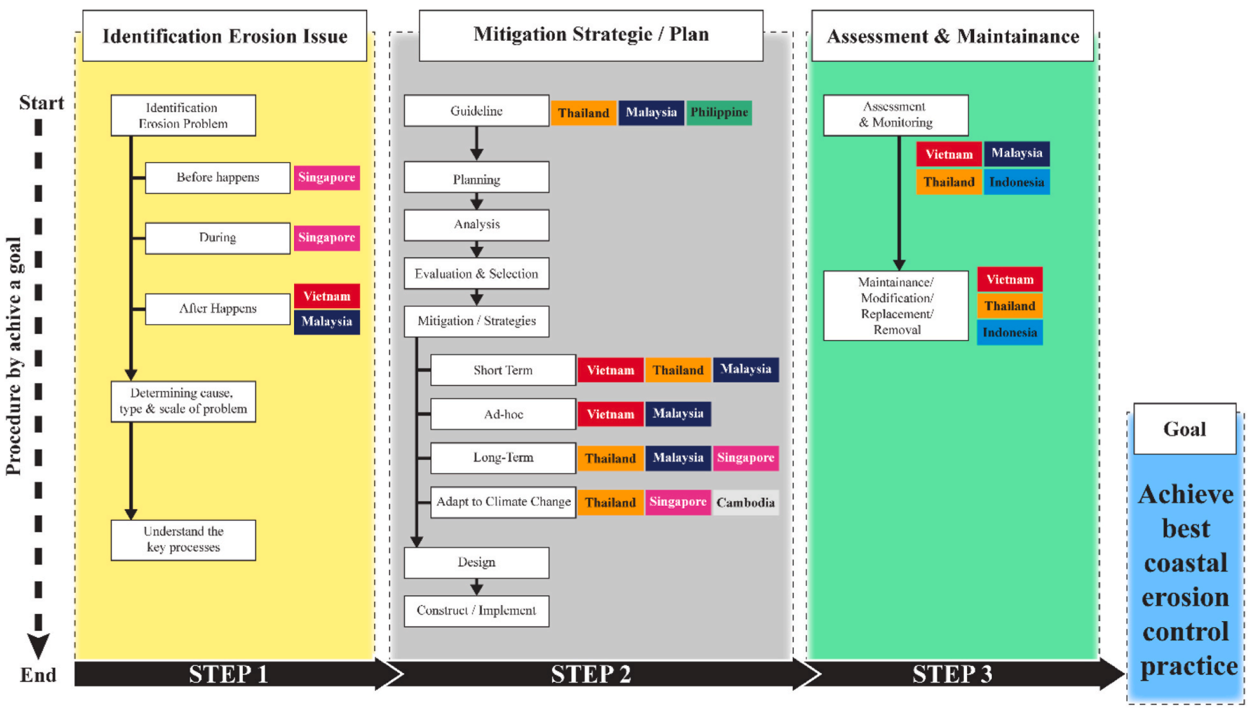

Fig. 6. An improved coastal erosion management framework is suggested based on the studies from Refs. [85–87]. A best coastal erosion control practice should include three steps: identifying erosion issues, a comprehensive mitigation plan, and assessing and maintaining the implemented mitigation in the post-development stage. The countries' names are placed at some of the procedure parts, representing each country's current state of coastal erosion management.

coastal management of the Philippines includes local government units (LGUs): Municipality and City units, provincial units, barangay units; national government agencies (NGAs): Department of Environment and Natural Resources(DENR), Bureau of Fisheries and Aquatic Resources (BFAR), Department of Interior and Local government (DILG), Department of Science and Technology (DST), Department of Transportation and Communication (DTC), Philippine Council for Aquatic and Marine Research and Development; Nongovernment organizations, and other assisting organizations like academic institutions and donors, community stakeholder and people's organization to have a conservation and sustainable use of coastal resources [62].

Coastal management was a basic function delivered by LGUs; NGAs will assist and train local government and other sectors. In the meantime, coastal communities and LGUs are supported and facilitated to implement coastal management efforts by NGOs and other assisting organizations. Lastly, the private sector and other stakeholders contribute by participating. A series of guidebooks was created to promote the practical application of the planning and management process and explain the lessons discovered via local and global experience. Additionally, the Philippine Disaster Risk Reduction and Management Act of 2010 (DRRM Act) changed and helped the nation's strategy from only responding to catastrophes to a more proactive one [65].

Coastal erosion management was always a topic, not only the mitigation and the strategies implemented but also the management and the authorities. Meanwhile, the mitigation plan must consider various limitations, such as financial problems, resources, materials, and environmental policies. In order to improve and have effective coastal erosion management, involvement and cooperation between all the authorities and stakeholders was very important, whether government agencies, NGOs, institutes, academicians, consultancies, or communities. Coastal erosion management is towards balancing environmental, economic, social, and cultural factors over the long term to have a sustainable and effective strategy. Guidelines, policies and frameworks (for example, Fig. 6) would be powerful tools to help stakeholders manage better.

5. Conclusion

The impact of climate change on coastal erosion was systematically reviewed. This study revealed that climate change is the main contributing factor in coastal erosion in Southeast Asia. Coastal erosion is driven by natural and anthropogenic factors such as sea-level history, relative sea-level change, geology, sediment, waves, tides, storm surges, longshore sediment transport, and human activities. However, climate change is likely to exacerbate coastal erosion, and coastal response is also vulnerable to wave climate change.

Among those climate change impacts, the rising sea level was the major contributor to increasing coastal erosion cases in Vietnam, Thailand, Malaysia, Indonesia, Philippines, Singapore and Cambodia, affecting countries worldwide. The impact of sea level rise was indirect and contributed to long-term erosion, where it won't be observed significantly in a short time, like a chronic poison, slowly eroding. The increased water depth caused changes in tidal hydrodynamics, currents, and wind-wave climate, allowing waves to penetrate further inland. On the other hand, storm surges from typhoons or storms have a direct impact on coastal erosion, leading to short-term erosion, and could reshape the coastline within hours. Climate change has made natural disasters more frequent and intense, resulting in higher storm surges and increased wind speed year by year. Other than typhoons or storms, the monsoon pattern is also another factor in wind-wave climate, it alternates wave characteristics, rainfall patterns, storm surge direction, and wind speed. Therefore, this review offered how each factor influences the coastal erosion rate in Vietnam, Thailand, Malaysia and other countries differently. The findings revealed that increasing coastal erosion significantly impacted coastal communities.

Moreover, the study also provides an overview of the coastal erosion management in Vietnam, Thailand, Malaysia, Indonesia, the Philipines, Singapore and Cambodia. In most countries, short-term or ad-hoc strategies were widely used, which implemented hard structures to address the emergence erosion problem. The implemented adaptive measure for erosion issues still needs to the assessed for its effectiveness and impact not just short-term or emergence but long-term as well as any natural or man-made structure that will disturb and impact coastal hydrodynamics. The review also provides some proof that inappropriate adaptive measures usually worsen the erosion situation. Moreover, since the sea level rise has heavily impacted all countries, it should also be given idea or taken into consideration by government or authorities to have mitigation strategies toward climate change adaptation like Thailand, Singapore and Cambodia does. Learning from the successful case could also help in the best coastal erosion control practice like in Thailand and Indonesia.

It is important to understand past and present events, predict future trends, eliminate the influence factor of severe erosion, and implement an adaptive measure that suits the situation, circumstances, and environment to countermeasures against coastal erosion. In addition, the government should encourage and include erosion issues on the national agenda in the short and long term. Collaboration among government, institutions, and local agencies, along with the appropriate legal framework, policy, and strategic plans, can lead to sustainable coastal erosion management.

This study has limitations where the review of coastal erosion management of each country just provided general information and overview based on assessable online resources. Furthermore, this study solely focuses on Southeast Asia, which restricts the generalizability to other coastal areas worldwide, as different regions experience different climate change impacts and adaptation challenges. Further research or review suggests conducting a complete and more comprehensive coastal erosion management, strategies and plans to produce a better management framework and learn from the best practices and mistakes in Southeast Asia.

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CRediT authorship contribution statement

Wan Shiao Dong: Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Aminah Ismailluddin:** Writing – review & editing. **Lee Shin Yun:** Writing – review & editing. **Effi Helmy Ariffin:** Writing – review & editing, Supervision, Conceptualization. **Cherdvong Saengsupavanich:** Writing – review & editing. **Khairul Nizam Abdul Maulud:** Writing – review & editing. **Muhammad Zahir Ramli:** Writing – review & editing. **Mohd Fuad Miskon:** Writing – review & editing. **Muhammad Hafeez Jeofry:** Writing – review & editing. **Juliana Mohamed:** Writing – review & editing. **Fazly Amri Mohd:** Writing – review & editing. **Ts Saiful Bahri Hamzah:** Writing – review & editing. **Kamaruzzaman Yunus:** Writing – review & editing, Funding acquisition.

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References

[1] Y. Zhang, X. Hou, Characteristics of coastline changes on southeast Asia Islands from 2000 to 2015, Rem. Sens. 12 (3) (2020) 519, https://doi.org/10.3390/rs12030519.
[2] D. Eckstein, V. Kunzel, L. Schafer, M. Winges, Global Climate Risk Index 2020, Germanwatch, Bonn, Germany, 2019.
[3] D.H. Prasad, N.D. Kumar, Coastal erosion studies—a review, Int. J. Geosci. 5 (3) (2014) 341–345, https://doi.org/10.4236/ijg.2014.53033, 2014.
[4] S. Gaines, R. Cabral, C. Free, Y. Golbuu, R. Arnason, W. Battista, D. Bradley, W. Cheung, K. Fabricius, O. Hoegh-Guldberg, M.A. Juinio-Menez, J.G. Molinos, E. Ojea, E. O'Reilly, C. Turley, The Expected Impacts of Climate Change on the Ocean Economy, World Resources Institute, 2019.
[5] L. Jewett, A. Romanou, Ocean acidification and other ocean changes, in: D.J. Wuebbles, D.W. Fahey, K.A. Hibbard, D.J. Dokken, B.C. Stewart, T.K. Maycock (Eds.), Climate Science Special Report: Fourth National Climate Assessment, U.S. Global Change Research Program, Washington, DC, USA, 2017, pp. 364–392, https://doi.org/10.1073/pnas.1605312113.
[6] M. Barange, T. Bahri, M.C. Beveridge, K.L. Cochrane, S. Funge-Smith, F. Poulain, Impacts of Climate Change on Fisheries and Aquaculture: Synthesis of Current Knowledge, Adaptation and Mitigation Options, United Nations' Food and Agriculture Organization, 2018. ISSN: 2070-7010.
[7] W. Cai, A. Santoso, G. Wang, S.W. Yeh, S.I. An, K. Cobb, ENSO and global warming, Natural Climate Change 5 (2015) 849–859, https://doi.org/10.1038/nclimate2743.
[8] IPCC, IPCC special report on the ocean and cryosphere in a changing climate (SROCC), in: H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weye (Eds.), Geneva: Intergovernmental Panel on Climate Change, 2019. In press.
[9] G. Wang, W. Cai, B. Gan, L. Wu, A. Santoso, X. Lin, Z. Chen, M.J. McPhaden, Continued increase of extreme El Niño frequency long after 1.5 C warming stabilization, Nat. Clim. Change 7 (8) (2017) 568–572, https://doi.org/10.1038/nclimate3351.
[10] Y. Lu, J. Yuan, X. Lu, C. Su, Y. Zhang, C. Wang, X. Cao, Q. Li, J. Su, V. Lttekkot, R.A. Garbutt, S. Bush, S. Fletcher, T. Wagey, A. Kachur, N. Sweijd, Major threats of pollution and climate change to global coastal ecosystems and enhanced management for sustainability, Environ. Pollut. 239 (2018) 670–680, https://doi.org/10.1016/j.envpol.2018.04.016.
[11] S. Ehsan, R.A. Begum, K.N.A. Maulud, Z.M. Yaseen, Households' perceptions and socio-economic determinants of climate change awareness: evidence from Selangor Coast Malaysia, J. Environ. Manag. 316 (2022) 115261, https://doi.org/10.1016/j.jenvman.2022.115261.
[12] T. Spencer, M. Schuerch, R.J. Nicholls, J. Hinkel, D. Lincke, A.T. Vafeidis, R. Reef, L. McFadden, S. Brown, Global coastal wetland change under sea-level rise and related stresses: the DIVA Wetland Change Model, Global Planet. Change 139 (2016) 15–30, https://doi.org/10.1016/j.gloplacha.2015.12.018.
[13] F. Shariful, M. Sedrati, E.H. Ariffin, S.M. Shubri, M.F. Akhir, Impact of 2019 tropical storm (Pabuk) on beach morphology, Terengganu coast (Malaysia), J. Coast Res. 95 (SI) (2020) 346–350, https://doi.org/10.2112/SI95-067.1.
[14] S. Ehsan, R.A. Begum, K.N.A. Maulud, M.S. Mia, Assessing household perception, autonomous adaptation and economic value of adaptation benefits: evidence from West Coast of Peninsular Malaysia, Adv. Clim. Change Res. 13 (5) (2022) 738–758, https://doi.org/10.1016/j.accre.2022.06.002.
[15] M.S.Z. Zulfakar, E.H. Ariffin, M.F. Akhir, N.A. Awang, Variation of seasonal monsoon wave-driven circulation pattern in the lee of groyne in Kuala Nerus beach, in: IOP Conference Series: Earth and Environmental Science, vol. 698, IOP Publishing, 2021, March 012042, https://doi.org/10.1088/1755-1315/698/1/012042. No. 1.
[16] C. Saengsupavanich, Elevated water level from wind along the Gulf of Thailand, Thalassas 33 (2) (2017) 179–185, https://doi.org/10.1007/s41208-017-0035-0.
[17] H. Thepsiriamnuay, N. Pumijumnong, Modelling assessment of sandy beaches erosion in Thailand, Environment and Natural Resources Journal 17 (2) (2019) 71–86, https://doi.org/10.32526/ennrj.17.2.2019.14.
[18] C. Saengsupavanich, Which eroding site is more urgent for the government?: a reflection from coastal communities, J. Coast Conserv. 24 (1) (2020) 9, https://doi.org/10.1007/s11852-020-00729-9.
[19] W.B. Setyawan, Adaptation strategy to coastal erosion by rural communities: lessons learned from Ujunggebang village, Indramayu, West Java, Indonesia, Maritime Technology and Research 4 (2) (2022) 252846, https://doi.org/10.33175/mtr.2022.252846.
[20] H. Takagi, N.D. Thao, L.T. Anh, Sea-level rise and land subsidence: impacts on flood projections for the Mekong Delta's largest city, Sustainability 8 (9) (2016) 959, https://doi.org/10.3390/su8090959.
[21] K.N. Abdul Maulud, S.N. Selamat, F.A. Mohd, N. Md Noor, W.S. Wan Mohd Jaafar, M.K.A. Kamarudin, E.H. Ariffin, N.A. Adnan, A. Ahmad, Assessment of shoreline changes for the selangor coast, Malaysia, using the digital shoreline analysis system technique, Urban Science 6 (4) (2022) 71, https://doi.org/10.3390/urbansci6040071.
[22] M.S.Z. Zulfakar, M.F. Akhir, E.H. Ariffin, N.A. Awang, M.A.M. Yaacob, W.S. Chong, A.M. Muslim, The effect of coastal protections on the shoreline evolution at Kuala Nerus, Terengganu (Malaysia), J. of Sustainability Science and Management 15 (3) (2020) 71–85. SSN: 2672-7226.
[23] L.V. Cong, N.V. Cu, T. Shibayama, Assessment of Vietnam coastal erosion and relevant laws and policies, in: Coastal Disasters and Climate Change in Vietnam, Elsevier, 2014, pp. 81–106, https://doi.org/10.1016/B978-0-12-800007-6.00004-6.
[24] M. Larson, N.M. Hung, H. Hanson, A. Sundström, E. Södervall, Impacts of typhoons on the Vietnamese coastline: a case study of Hai Hau beach and ly hoa beach, in: Coastal Disasters and Climate Change in Vietnam, Elsevier, 2014, pp. 17–42, https://doi.org/10.1016/B978-0-12-800007-6.00002-2.

[25] W. Pantanahiran, Using remote sensing data for calculating the coastal erosion in southern Thailand, Int. Arch. Photogram. Rem. Sens. Spatial Inf. Sci. (2019), https://doi.org/10.5194/isprs-archives-XLII-3-W7-51-2019.

[26] N.R. Haddaway, B. Macura, P. Whaley, A.S. Pullin, ROSES RepOrting standards for Systematic Evidence Syntheses: pro forma, flow-diagram and descriptive summary of the plan and conduct of environmental systematic reviews and systematic maps, Environ. Evid. 7 (1) (2018) 1–8, https://doi.org/10.1186/s13750-018-0121-7.

[27] H.A. Mohamed Shaffril, N. Ahmad, M.E. Hamdan, A.A. Samah, S.F. Samsuddin, Systematic literature review on adaptation towards climate change impacts among indigenous people in the Asia pacific regions, J. Clean. Prod. (2020) 120595, https://doi.org/10.1016/j.jclepro.2020.120595.

[28] M. Gusenbauser, N.R. Haddaway, Which academic search systems are suitable for systematic reviews or meta-analyses? Evaluating retrieval qualities of Google Scholar, PubMed, and 26 other resources, Res. Synth. Methods 11 (2) (2020) 181–217, https://doi.org/10.1002/jrsm.1378.

[29] N.R. Haddaway, A.M. Collins, D. Coughlin, S. Kirk, The role of Google Scholar in evidence reviews and its applicability to grey literature searching, PLoS One 10 (9) (2015) e0138237, https://doi.org/10.1371/journal.pone.0138237.

[30] C. Littlewood, K. Chance-Larsen, S.M. McLean, Quality appraisal as a part of the systematic review: a review of current methods, Int. J. Physiother Rehabil. 1 (1) (2010) 53–58. ISSN: 2349-5987.

[31] M. Vaismoradi, H. Turunen, T. Bondas, Content analysis and thematic analysis: implications for conducting a qualitative descriptive study, Nurs. Health Sci. 15 (3) (2013) 398–405, https://doi.org/10.1111/nhs.12048.

[32] J. Panpeng, M.M. Ahmad, Awareness of coastal fishing communities on climate change and its impacts: a case study of coastal erosion and seawater inundation in Chanthaburi Province, Thailand, Int. J. Agric. Resour. Govern. Ecol. 14 (2) (2018) 138–164, https://doi.org/10.1504/ijarge.2018.093992.

[33] A.H. Dang, T.D. Nguyen, Coastal erosion in Cua Dai beach: future influence of climate change and sea level rise on coastal protection, in: International Conference on Asian and Pacific Coasts, Springer, Singapore, 2019, pp. 521x–528x, https://doi.org/10.1007/978-981-15-0291-0_72.

[34] S. Ehsan, R.A. Begum, N.G.M. Nor, K.N.A. Maulud, Current and potential impacts of sea level rise in the coastal areas of Malaysia, in: IOP Conference Series: Earth and Environmental Science, vol. 228, IOP Publishing, 2019 012023, https://doi.org/10.1088/1755-1315/228/1/012023.

[35] L. Bhullar, Climate change adaptation and water policy: lessons from Singapore, Sustain. Dev. 21 (3) (2013) 152–159, https://doi.org/10.1002/sd.1546.

[36] C. Combest-Friedman, P. Christie, E. Miles, Household perceptions of coastal hazards and climate change in the Central Philippines, J. Environ. Manag. 112 (2012) 137–148.

[37] L. Hens, N.A. Thinh, T.H. Hanh, N.S. Cuong, T.D. Lan, N. Van Thanh, D.T. Le, Sea-level rise and resilience in Vietnam and the Asia-Pacific: a synthesis, Vietnam Journal (2018).

[38] A. Dastgheib, J. Reyns, S. Thammasittirong, S. Weesakul, M. Thatcher, R. Ranasinghe, Variations in the wave climate and sediment transport due to climate change along the coast of Vietnam, J. Mar. Sci. Eng. 4 (4) (2016) 86, https://doi.org/10.3390/jmse4040086.

[39] N. Van Liem, D. Van Bao, D.K. Bac, N.C. Cuong, P.T.P. Nga, B. Burkhard, G.T.K. Chi, Assessment of shoreline changes for setback zone establishment from son tra (da Nang city) to Cua Dai (hoi an city), Vietnam, Vietnam Journal of Earth Sciences 42 (4) (2020) 363–383, https://doi.org/10.15625/0866-7187/0/15410.

[40] A.H. Mohamed Rashidi, M.H. Jamal, M.Z. Hassan, S.S. Mohd Sendek, S.L. Mohd Sopie, M.R. Abd Hamid, Coastal structures as beach erosion control and sea level rise adaptation in Malaysia: a review, Water 13 (13) (2021) 1741, https://doi.org/10.3390/w13131741.

[41] K. Karlsrud, B.V. Vangelsten, R. Frauenfelder, Subsidence and shoreline retreat in the Ca Mau Province–Vietnam. Causes, consequences and mitigation options, Geotechnical Journal of the SEAGS & AGSSEA 48 (1) (2017) 26–32. ISSN: 0046-5828.

[42] A.T. Dang, L. Kumar, M. Reid, H. Nguyen, Remote sensing approach for monitoring coastal wetland in the Mekong Delta, Vietnam: change trends and their driving forces, Rem. Sens. 13 (17) (2021) 3359, https://doi.org/10.3390/rs13173359.

[43] C. Van Cuong, M. Russell, S. Brown, P. Dart, Using shoreline video assessment for coastal planning and restoration in the context of climate change in kien Giang, Vietnam, Ocean Sci. J. 50 (2015) 413–432.

[44] K. Yasuhara, M. Tamura, T.C. Van, D.M. Duc, Geotechnical adaptation to the Vietnamese coastal and riverine erosion in the context of climate change, Geotech. Eng. 47 (1) (2016) 7–14. ISSN: 0046-5828.

[45] R. Yaacob, H. Shaari, N. Sapon, M.F. Ahmad, E.H. Arifin, R. Zakariya, M.L. Hussain, Annual changes of beach profile and nearshore sediment distribution off Dungun-Kemaman, Terengganu, Malaysia, Jurnal Teknologi 80 (5) (2018).

[46] M. Bagheri, Z.Z. Ibrahim, S.B. Mansor, L. Abd Manaf, N. Badarulzaman, N. Vaghefi, Shoreline change analysis and erosion prediction using historical data of Kuala Terengganu, Malaysia, Environ. Earth Sci. 78 (15) (2019) 1–21, https://doi.org/10.1007/s12665-019-8459-x.

[47] M.D. Do, N.M. Hieu, Analysis of sea-level rise impacts on sea dike stability in Hai Hau Coast, Vietnam, Int. J. Civ. Eng. 15 (3) (2017) 377–389, https://doi.org/10.1007/s40999-017-0191-x.

[48] B.K. Veettil, R.D. Ward, N.T.K. Dung, D.D. Van, N.X. Quang, P.N. Hoai, N.D. Hoang, The use of bioshields for coastal protection in Vietnam: current status and potential, Regional Studies in Marine Science 47 (2021) 101945, https://doi.org/10.1016/j.rsma.2021.101945.

[49] N.T. Hung, D.M. Duc, D.T. Quynh, V.D. Cuong, Nearshore topographical changes and coastal stability in Nam Dinh province, Vietnam, J. Mar. Sci. Eng. 8 (10) (2020) 755, https://doi.org/10.3390/jmse8100755.

[50] M.A. Marfai, Preliminary assessment of coastal erosion and local community adaptation in Sayung Coastal Area, Central Java–Indonesia, Quaest. Geogr. 31 (3) (2012) 47–55.

[51] T.Y. Lin, V.M. Van Onselen, L.P. Vo, Coastal erosion in Vietnam: case studies and implication for integrated coastal zone management in the Vietnamese south-central coastline, in: IOP Conference Series: Earth and Environmental Science, vol. 652, IOP Publishing, 2021 012009, https://doi.org/10.1088/1755-1315/652/1/012009. No. 1.

[52] C. Saengsupavanich, Coastal revetment design process in Thailand, WIT Trans. Built Environ. 170 (2017) 33–44, https://doi.org/10.2495/CC170041.

[53] D.M. Duc, K. Yasuhara, N.M. Hieu, N.C. Lan, Climate change impacts on a large-scale erosion coast of Hai Hau district, Vietnam and the adaptation, J. Coast Conserv. 21 (1) (2017) 47–62, https://doi.org/10.1007/s11852-016-0471-7.

[54] J.C. Winterwerp, T. Albers, E.J. Anthony, D.A. Friess, A.G. Mancheño, K. Moseley, B.K. Van Wesenbeeck, Managing erosion of mangrove-mud coasts with permeable dams–lessons learned, Ecol. Eng. 158 (2020) 106078.

[55] T.A. Nguyen, D.A. Vu, P. Van Vu, T.N. Nguyen, T.M. Pham, H.T.T. Nguyen, H.T. Le, T.V. Nguyen, L.K. Hoang, T.D. Vu, T.S. Nguyen, T.T. Luong, N.P. Trinh, L. Hens, Human ecological effects of tropical storms in the coastal area of Ky Anh (Ha Tinh, Vietnam), Environ. Dev. Sustain. 19 (2017) 745–767, https://doi.org/10.1007/s10668-016-9761-3.

[56] D.L. Passeri, S.C. Hagen, S.C. Medeiros, M.V. Bilskie, K. Alizad, D. Wang, The dynamic effects of sea level rise on low-gradient coastal landscapes: a review, Earth's Future 3 (6) (2015) 159–181, https://doi.org/10.1002/2015ef000298, doi: 10.1002/2015EF000298.

[57] H.A. Rahman, Climate change scenarios in Malaysia: engaging the public, Int. J. Micro Nano Syst. 1 (2) (2018) 55–77. ISSN: 2620-9578.

[58] C. Marzin, R. Rahmat, D. Bernie, L. Bricheno, E. Buonomo, D. Calvert, H. Cannaby, S. Chan, M. Chattopadhyay, W. Cheong, M.E. Hassim, L. Gohar, N. Golding, C. Gordon, J. Gregory, D. Hein, A. Hines, T. Howard, T. Janes, R. Jones, E. Kendon, T. Krijnen, S. Lee, S. Lim, C.F. Lo, J. Lowe, G. Martin, C. Marzin, K. McBeath, K. McInnes, C. Mc Sweeney, M. Mizielinski, J. Murphy, C. O'Neill, M. Palmer, G. Redmood, C. Roberts, S. Shany, M. Sanderson, C. Scannel, D. Sexton, F. Shaw, J. Slingo, X. Sun, J. Tinker, S. Tucker, C. Wang, S. Webster, S. Wilson, R. Wood, S. Zhang, Singapore's Second National Climate Change Study – Phase 1, 2015. http://ccrs.weather.gov.sg/publications-second-National-Climate-Change-Study-Science-Reports.

[59] S. Saramul, T. Ezer, Spatial variations of sea level along the coast of Thailand: impacts of extreme land subsidence, earthquakes and the seasonal monsoon, Global Planet. Change 122 (2014) 70–81, https://doi.org/10.1016/j.gloplacha.2014.08.012.

[60] B. Bidorn, K. Sok, K. Bidorn, W.C. Burnett, An analysis of the factors responsible for the shoreline retreat of the Chao Phraya Delta (Thailand), Sci. Total Environ. 769 (2021) 145253, https://doi.org/10.1016/j.scitotenv.2021.145253.

[61] D.N. Sugianto, A. Ambariyanto, E.P. Handayani, Coastal protection and rehabilitation technology as climate mitigation and adaptation strategies, in: Food Sustainability, Environmental Awareness, and Adaptation and Mitigation Strategies for Developing Countries, IGI Global, 2023, pp. 225–235.

[62] Department of Environment and Natural Resources, Bureau of Fisheries and Aquatic Resources of the Department of Agriculture, and Department of the Interior and Local Government, Phillippine Coastal Management Guidebook No.1: Coastal Management Orientation and Overview, Coastal Resource Management Project of the Department of Environment and Natural Resources, Cebu City, Philippines, 2001, p. 58p.

[63] PEMSEA, Viet Nam Administration for Seas and Islands (VASI) & Ministry of Environment and Natural Resources (MONRE), *National State Of Oceans and Coasts 2018: Blue Economy Growth of Viet Nam.* Partnerships in Environmental Management for the Seas of East Asia (PEMSEA), Quezon City, Philippines, 2020, p. 232. Retrieved on December 2020, from, http://pemsea.org/sites/default/files/NSOC_Viet_Nam_2018_20210330.pdf.

[64] M. Kiguchi, K. Takata, N. Hanasaki, B. Archevarahuprok, A. Champathong, E. Ikoma, C. Jaikaeo, S. Kaewrueng, S. Kanae, S. Kazama, K. Kuraji, K. Matsumoto, S. Najamura, D. Nguyen-Le, K. Noda, N. Piamsa-Nga, M. Raksapatcharawong, P. Pangsiwanichpong, S. Ritphring, H. Shirakawa, C. Somphong, M. Srisutham, D. Suanburi, W. Suanpaga, T. Tebakari, Y. Trisurat, K. Udo, S. Wongsa, T. Yamada, K. Yoshida, T. Kiatiwat, T. Oki, A review of climate-change impact and adaptation studies for the water sector in Thailand, Environ. Res. Lett. (2020), https://doi.org/10.1088/1748-9326/abce80.

[65] S. Tye, J. Waslander, M. Chaudhury, Building Coastal Resilience in Bangladesh, the Philippines, and Colombia: Country Experiences with Mainstreaming Climate Adaptation, 2020.

[66] E.H. Peñalba, A.P.J. David, M.J.D. Mabanta, C.R.C. Samaniego, S.D. Ellamil, Climate change adaptation: the case of coastal communities in the Philippines, Journal of the Geographical Institute" Jovan Cvijic", SASA 71 (2) (2021) 115–133.

[67] Y.Y. Loo, L. Billa, A. Singh, Effect of climate change on seasonal monsoon in Asia and its impact on the variability of monsoon rainfall in Southeast Asia, Geosci. Front. 6 (6) (2015) 817–823.

[68] E.H. Ariffin, M. Sedrati, N.R. Daud, M.J. Mathew, M.F. Akhir, N.A. Awang, R. Yaacob, N.A. Siddiqui, M.L. Husain, Shoreline evolution under the influence of oceanographic and monsoon dynamics: the case of Terengganu, Malaysia, in: Coastal Zone Management, Elsevier, 2019, pp. 113–130.

[69] E.H. Ariffin, M.S.Z. Zulfakar, N.S. Redzuan, M.J. Mathew, M.F. Akhir, N.B. Baharim, N.A. Awang, N.A. Mokhtar, Evaluating the effects of beach nourishment on littoral morphodynamics at Kuala Nerus, Terengganu (Malaysia), J. Sustainability Science and Management 15 (5) (2020) 29–42, https://doi.org/10.46754/jssm.2020.07.005.

[70] N.I. Ismail, E.H. Ariffin, M.L. Rosnan Yaacob, The impact of seasonal monsoons on the morphology of beaches protected by barrier islands in setiu, Terengganu, Malaysia, Journal Of Sustainability Science And Management 15 (4) (2020) 120–129, https://doi.org/10.46754/jssm.2020.06.012.

[71] C. Saengsupavanich, E. Pranzini, The 2021-procedure for coastal protection by revetments in Thailand, Journal of Applied Water Engineering and Research 2022 (2022), https://doi.org/10.1080/23249676.2022.2110529.

[72] S. Sanitwong-Na-Ayutthaya, C. Saengsupavanich, E.H. Ariffin, S. Buayam, L. Wiramitchai, K. Kayunha, Y. Charuseiam, Coastal protection by a stepped revetment in Thailand, Journal of Sustainability and Management 17 (7) (2022) 28–45, https://doi.org/10.46754/jssm.2022.07.003.

[73] S. Satumanatpan, P. Moore, A. Lentisco, H. Kirkman, An assessment of governance of marine and coastal resources on Koh Tao, Thailand, Ocean Coast Manag. 148 (2017) 143–157, https://doi.org/10.1016/j.ocecoaman.2017.08.001.

[74] Japan International Cooperation Agency (Jica), Office of natural resources and environmental policy and planning the kingdom of Thailand (ONEP), The JICA Sector Study on Climate Change Program Loan in Thailand: Final Report (2010). Retrieved on October 2010, from, https://openjicareport.jica.go.jp/pdf/12015442_03.pdf.

[75] N.H.M. Ghazali, Coastal erosion and reclamation in Malaysia, Aquat. Ecosys. Health Manag. 9 (2) (2006) 237–247, https://doi.org/10.1080/14634980600721474.

[76] M.L. Hamzah, A.A. Amir, K.N.A. Maulud, S. Sharma, F.A. Mohd, S.N. Selamat, O. Karim, E.H. Ariffin, R.A. Begum, Assessment of the Mangrove forest changes along the Pahang coast using remote sensing and GIS technology, Journal of Sustainability Science and Management 15 (5) (2020) 43–58, https://doi.org/10.46754/jssm.2020.07.006.

[77] S. Cooley, D. Schoeman, L. Bopp, P. Boyd, S. Donner, D.Y. Ghebrehiwet, S.-I. Ito, W. Kiessling, P. Martinetto, E. Ojea, M.-F. Racault, B. Rost, M. Skern-Mauritzen, Oceans and coastal ecosystems and their services, in: H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (Eds.), *Climate Change 2022: Impacts, Adaptation and Vulnerability.* Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York, NY, USA, 2022, pp. 379–550, https://doi.org/10.1017/9781009325844.005.

[78] MEWR (Ministry of the Environment and Water Resources)., Singapore's National Climate Change Strategy 2008, 2008, March. Retrieved from, http://www.elaw.org/system/files/Singapore_Full_Version.pdf.

[79] National Climate Change Secretariat, Climate Change & Singapore: Challenges, Opportunities, Partnerships. National Climate Change Strategy 2012, 2012. Retrieved from, http://app.nccs.gov.sg/data/resources/docs/Documents/NCCS-2012.pdf.

[80] National Environment Agency, Singapore's Second National Communication, under the United Nations Framework Convention on Climate Change, 2010, November. Retrieved from, http://app.nccs.gov.sg/data/resources/docs/SINGAPORE%27S%20SECOND%20NATIONAL%20COMMUNICATIONS%20NOV%202010.pdf.

[81] Royal Government of Cambodia, National Strategic Development Plan 2006–2010, 2006.

[82] N. Nasuchon, Coastal Management and Community Management in Malaysia, Vietnam, Cambodia and Thailand, with a Case Study of Thai Fisheries Management. Divison for Ocean Affairs and the Law of the Sea Office of Legal Affairs, the United Nations, New York, 2009.

[83] C. Change, NATIONAL ADAPTATION PROGRAMME OF ACTION TO CLIMATE CHANGE (NAPA), 2006.

[84] T. Solihuddin, S. Husrin, H.L. Salim, T.L. Kepel, E. Mustikasari, A. Heriati, B. Berliana, Coastal erosion on the north coast of Java: adaptation strategies and coastal management, in: IOP Conference Series: Earth and Environmental Science, vol. 777, IOP Publishing, 2021, May 012035. No. 1.

[85] U.S. Army Corps of Engineers (USACE), Coastal Engineering Manual: Chapter I-4 the Coastal Engineering Manual, U.S: U.S. Army Corps of Engineers, 2002.

[86] D.I.D. Malaysia, DID Manual, Volume 3-Coastal Management, Department of Irrigation and Drainage, Malaysia, 2009.

[87] N. Rangel-Buitrago, W.J. Neal, Coastal erosion management, in: Encyclopedia of Earth Sciences, 2018, https://doi.org/10.1007/978-3-319-48657-4_409-1.