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Current challenges in coastal erosion management for southern Asian regions: examples from Thailand, Malaysia, and Sri Lanka

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Abstract

Different countries practice various approaches to coastal erosion management, which have characteristics strengths and weaknesses. Protection of the land from coastal erosion is a complex task, and it depends on many socio-economic and environmental factors. Asian countries have unique cultural, social, environmental, and political behaviors. Therefore, the objectives of this study are to analyze the current status of coastal management in Thailand, Malaysia, and Sri Lanka, and to synthesize a common coastal management framework for those countries. In this study, we analyzed the situation of coastal erosion, and the existing responsible government department and their legal authorities in Thailand, Malaysia, and Sri Lanka. After that, we evaluated specific challenges and common issues in the management of coastal erosion. The main challenges can be summarized as rapid urbanization and the construction of infrastructure along the coasts, rising sea levels as a consequence of climate change, inadequate coastal zone planning and management framework, a deficit of sediment supply compared to erosion rates, and face constraints in terms of financial and technical resources for coastal erosion management. A multi-faceted approach is required to address these challenges, and it combines both structural and non-structural measures. For example, this approach involves (i) sustainable coastal zone planning, (ii) the implementation of nature-based solutions, (iii) restoration of natural coastal features, (iv) regulation of coastal development activities, and (v) the integration of climate change considerations into coastal management practices. Finally, collaborative efforts among government agencies, researchers, local communities, and international organizations are crucial for successful coastal erosion management in Thailand, Malaysia, Sri Lanka, and potentially other Asian regions.

Keywords Anthropocene coasts, Coastal protection, Coastal governance, Institutional complexity

1 Introduction

Recently, coastal erosion and management have been a focal point in coastal research. Coastal erosion is controlled by various factors such as changing global climate (e.g., sea-level rise), reduced amounts of riverine sediment due to mainly sand mining and dam constructions, land use conversion (especially mangrove being transformed into aquaculture), interrupting alongshore sediment transportation due to coastal engineering structures (e.g., jetties and breakwaters), natural high waves during monsoons, and other anthropogenic activities that disturb sediment equilibrium (Rangel-Buitrago et al. 2015; Ariffin et al. 2019; Palamakumbure et al.

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2020; Bombino et al. 2022; Saengsupavanich et al. 2022; Ritphring et al. 2022). The changes in sediment supply are responsible for short- and long-term coastal erosion. For example, sand trapping by the Burdekin Falls dam in Australia starved the sandy Cape Bowling Green peninsula, and generated coastal erosion (Wolanski and Hopper 2022). Gas exploitation and groundwater pumping deteriorate coastal erosion in Italy, especially in the Emilia-Romagna coastal plain (Calabrese et al. 2021). Flor-Blanco et al. (2021) reported that the increased frequency of unusually strong storm waves destroyed numerous ports and seafront promenades along the dune-fringed coastlines of Asturias (northwest Spain). Similarly, coastal erosion is very severe and complex in Asian countries due to its extensive coastline and diverse geographical features (Uda 2022; Setyawan 2022; Dhanil Dev et al. 2023). Therefore, coastal erosion processes are highly site-specific in a particular coastline and unsolved problems in most sea-connected nations. The understanding of geology and geomorphology, wave and current patterns, sediment supply and transport, human activities, and climate change provides valuable insights into erosion rates, vulnerable areas, and potential mitigation strategies tailored to the specific site.

Managing coastal erosion is not an easy task since it involves numerous factors, including physical, environmental, social, financial, cultural, and legal aspects. Each country copes with problems occurring in its coastal area differently, based on their domestic contexts (Hossen et al. 2019). Although few articles are published to show how an individual country addresses erosion, such studies provide guidelines for management on a regional scale with valuable experiences and lessons learned (Alves et al. 2020). Nations in the same continent are more or less similar in terms of their settings, thus applying regional knowledge is a wise and effective approach to protecting the coastlines. This article focuses on current coastal erosion management in three Asian nations, Thailand, Malaysia, and Sri Lanka. In this article, we discussed the current status of coastal erosion in each country, responsible governmental departments with their supporting or conflicting legal authorities, how each country deals with coastal erosion during the last 5 years, and current challenges in erosion management. We also developed a coastal management framework to mitigate coastal erosion in three countries. Consequently, coastal managers from throughout the world can practice the shared knowledge of this study.

1.1 Management of coastal erosion in Thailand

1.1.1 Situation of coastal erosion

Thailand is a tropical country with diverse coastal resources. It has 23 shore-connected provinces, and

approximately 3,150 km length of shoreline. Thailand consists of sandy (1,631 km), rocky (326 km), and muddy (1,020 km) coasts, and the rest area is composed of coastal features such as inlets and estuaries (Department of Marine and Coastal Resources 2017). Coastal erosion has been threatening the country, destroying infrastructures as well as deteriorating coastal communities' livelihoods. The main causes of coastal erosion in Thailand include monsoon waves, man-made engineering structures that intercept alongshore sediment transport (Saengsupavanich 2019, 2020a), mangrove destruction, land subsidence, and groundwater withdrawal (Bidorn et al. 2021). The severity of coastal erosion in Thailand is visualized by using three cases in Nakhon Si Thammarat, Chonburi, and Samutprakarn Provinces.

Coastal erosion has severely devoured the lands in Tasala District of Nakhon Si Thammarat Province (Fig. 1), due to natural and anthropogenic activities, such as the construction of coastal structures and aquaculture ponds, and seasonal waves (Yun et al. 2023). The shoreline along Tasala District is rather straight and exposed to northeast monsoons. Storm waves from the east occur from November to February with a wave height greater than 3 m. The authors estimated that the 50-year significant wave height is 4.76 m with a spectral peak wave period of 11.46 s. The installed ripraps by the local government were already disintegrated. Many groins and jetties existing in this area disrupted alongshore sediment transport, and worsened the erosion.

Muang District (Chonburi Province) is a dense coastal town with diverse coastal utilizations. Land use change, dense urbanization, and disruption of alongshore sediment transport are major causes of coastal erosion. Land-based sediment that used to recharge the littoral zone has been drastically reduced due to urban developments. In addition, seasonal southwest monsoons occurring from April to July have attacked the coast. The authors estimated that the 50-year significant wave height is 3.74 m with a spectral peak wave period of 10.35 s. Since houses, roads, and hotels have been constructed on coastal dunes, the local inhabitants attempted to protect their properties from severe waves. Several vertical seawalls can be seen in this area (Fig. 1), inducing strong wave reflection, and steepening the front beach berm. When the front beach is scoured, the vertical seawalls collapse. Therefore, coastal erosion is continued due to unsuccessfully designed coastal protection structures.

Muddy coastline along Muang District in Samutprakarn Province is a good example of the impact of mangrove destruction and aquaculture pond conversion on coastal erosion. Wave climate along the upper Gulf of Thailand is milder than that of the southern part of the country. The authors estimated that the 50-year

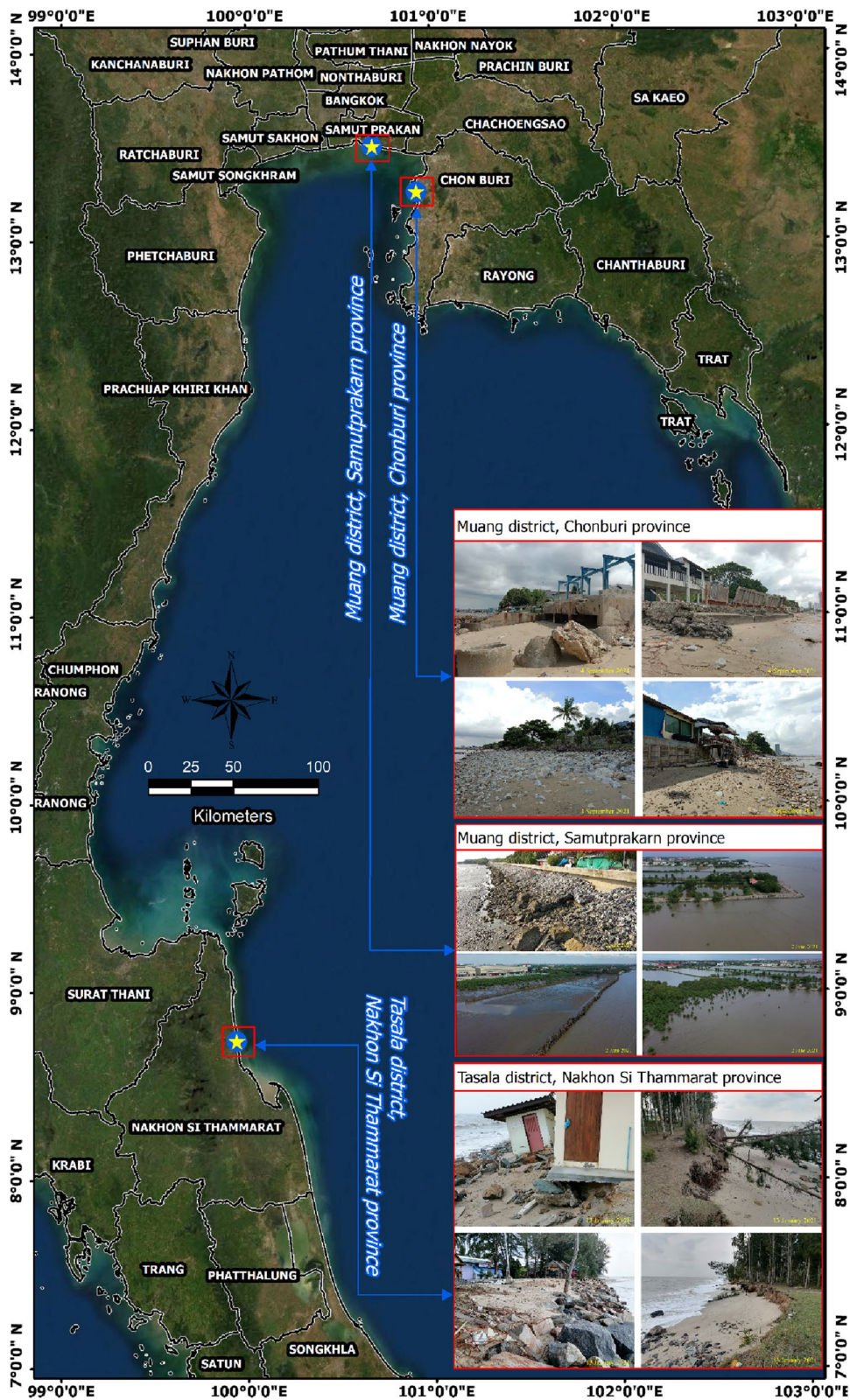


Fig. 1 Examples of coastal erosion situation in Thailand

significant wave height is 3.71 m with a spectral peak wave period of 10.3 s. Although gabion revetments, low-crested rock revetments, and bamboo fences were installed (Fig. 1), many parts of the shoreline along Samutprakarn Province are still being eroded. Saengsupavanich (2012) reported that large heavy coastal protection structures on a nearby muddy coastline experienced large settlements. The bamboo fences broke and continued coastal erosion (Pranchai et al. 2019).

1.2 Existing responsible government departments and their legal authorities

In 2022, three governmental departments in Thailand are responsible for coastal protection: (a) the Department of Public Works and Town and Country Planning (DPT), (b) the Department of Marine and Coastal Resources (DMCR), and (c) the Marine Department (MD). During the last 5 years, the DPT has been very enthusiastic in defending the eroding coasts with revetments, having armored more than 45.7 km of the eroded shoreline. Being under the Ministry of Interior, the DPT is responsible for public works such as building design and construction control, town and rural development, formulating and supervising land use policies, and national infrastructures. Assigned by the cabinet, the DPT has to ensure the well-being of coastal communities. It realized that the revetments can induce many environmental impacts (such as downdrift erosion, beach inaccessibility, and shortened front beach berm (Griggs and Patsch 2019)). The DPT has carefully designed its revetment to minimize such negative shortcomings (Saengsupavanich 2022; Sanitwong-Na-Ayutthya et al. 2022). Table 1 shows the list of relevant government institutes related to coastal protection in Thailand.

The DMCR has been established in 2002 to manage coastal resources. The DMCR has attempted to balance coastal development and conservation, according to the granted legal power from the Marine and Coastal Resources Management Promotion Act 2015. The DMCR systematized coastal erosion status in Thailand by establishing coastal littoral cells throughout the country. All coastal protection projects need to be approved by a committee established by the DMCR, and thus experienced disagreement in opinions usually. Since the DMCR focuses on protecting natural coastal resources while the DPT emphasizes defending the eroding area, some eroding coastal communities do not receive approval from the DMCR. The DMCR tries to promote soft coastal protection options such as bamboo fences. However, most bamboo fences can be easily damaged (Fig. 2), and are ineffective in dissipating storm waves (Pranchai et al. 2019; Quang and Trong 2020; Sathyanarayana et al. 2021).

In Thailand, the Marine Department (MD) has the legal power to permit any construction of coastal protection structures in the ocean. Having its legitimate authority, the MD has also implemented various types of coastal structures such as piers, revetments, offshore breakwaters, jetties, as well as beach nourishments. Therefore, three governmental departments in Thailand have been attempting to protect the national coastlines.

In summary, the current processes in Thailand can be summarized as (i) the DPT or the MD finishes the design of a coastal protection structure with inputs from public meetings and preparation of environmental mitigation measures as well as conformations with other related regulations, (ii) the DMCR convenes a meeting to approve/disapprove the proposed coastal protection projects undertaken by either the DPT or the MD, and

Table 1 Relevant government institutes related to coastal protection in Thailand

Institution	Act	Remarks
1. Department of Public Works and Town & Country Planning (DPT) https://www.dpt.go.th	• City Planning Act, 2019 • Buildings Control Act, 1979	The DPT is responsible for public works such as building design and construction control to ensure the well-being of coastal communities
2. Department of Marine and Coastal Resources (DMCR) https://www.dmcrc.go.th	• Marine and Coastal Resources Management Promotion Act, 2015	The DMCR has the authority to manage marine and coastal resources including coastal erosion
3. Marine Department (MD) https://www.md.go.th	• Navigation in Thai Waters Act, 2017	The MD owns the legal power to permit any construction of coastal protection structures in the ocean
4. Department of National Parks, Wildlife and Plant Conservation (DNP) https://www.dnp.go.th	• National Parks Act, 2019	If an eroding coastline is within the national park's boundary, the design and construction of coastal defense structures must be approved by the DNP
5. Provincial Administrative Organization		The local government takes care of coastal erosion at a provincial level
6. Subdistrict Administration Organization		The smallest local government unit that takes care of a group of villages



Fig. 2 Bamboo fences in Thailand

(iii) the MD considers allowing/disallowing the construction. However, having many departments to manage coastal erosion at the same time may not be the most effective approach because it can retard the process and create more managerial obstacles (Uda 2022). Although a power balance between development and conservation can be acquired, the intertwined wrestling of legal power often happens. For example, the DPT finished the design process, but could not proceed with the construction without getting approval. Accordingly, the ineffective institutional arrangement can promote land erosion and loss of properties of local people living in coastal areas.

1.3 Challenges in the management of coastal erosion

Managing coastal erosion in Thailand has not been easy due to many obstacles. Social, environmental, economic, and political settings have retarded effective coastal erosion management. The following 4 types of complications and challenges are currently demoting coastal protection in Thailand.

First, Thailand needs a variety of field data such as physical, environmental, and socio-economic conditions to undertake coastal projection projects (Sanitwong-Na-Ayutthya et al. 2022). However, severely eroded a few southern provinces such as Pattani and Narathiwat Provinces are unprotected due to regional violence originating from historical conflicts between Malay-Muslims (who are the predominant ethnic group in Pattani Province) and Thailand's central government (Sathian and Derin 2020). Although the DPT and MD want to undertake projects in these provinces, no field officers are willing to take a risk in collecting data. Therefore, the coastal protection projects automatically ceased in the unrest sites.

The second factor is the impediment and constraint of government departments (Saengsupavanich et al. 2012). Although these departments have the same goal, they have their strategic plans. Accordingly, it often creates conflicts of interest among government departments.

The DPT emphasizes engineering structures, especially revetments as effective structures. On the other hand, the DMCR adheres to soft approaches such as bamboo and wooden fences. Therefore, several disagreements are taken place during the decision-making.

The third difficulty in coastal erosion protection in Thailand is the prioritization of eroding areas due to limited budget allocation (Saengsupavanich 2020b). According to the DMCR estimation in 2017, Thailand had 145.73 km of unprotected eroding coastline. The DPT and the MD can only defend the coastline about 5 km/yr. Therefore, it will take 30 years to protect the remaining eroded coasts. However, coastal erosion can accelerate after 30 years than today, following climatic changes/sea-level rising, dropping land-based sediment supply, and expiring the existing coastal defense structures. However, the Thailand government cannot increase the budget currently, due to other urgent commitments in the country.

The last issue is the management of environmental impacts originating from coastal defense structures. No legal requirement is required yet to undertake an Initial Environmental Examination (IEE) or the Environmental Impact Assessment (EIA) in Thailand (Saengsupavanich 2011). Although the DPT has collected environmental parameters and set up environmental mitigation measures in every project, people were still raising questions on social media about downdrift erosion, narrower front beach, and moss on the revetment surface. However, future revetment projects will need EIA approval, implying that the related environmental impacts of revetments can be managed in advance.

1.4 Management of coastal erosion in Malaysia

1.4.1 Situation of coastal erosion

Malaysia consists of two regions separated by the South China Sea with West Malaysia as Peninsular Malaysia, and East Malaysia occupies the north and west region of Borneo with a total of coast 4,809 km long. National

Coastal Erosion Study in 1985 was considered the national scale document for coastal erosion (Department of Irrigation and Drainage 1985). This study derived the erosion index based on the rate of erosion and the threat to existing shore-based facilities of substantial economic value. The categories were defined as follows:

Category 1 (critical): Shorelines currently in a state of erosion and where shore-based facilities or infrastructure are in immediate danger of collapse or damage.

Category 2 (significant): Shorelines eroding at a rate whereby public property and agricultural land of value will become threatened within 5 to 10 years unless remedial action is taken.

Category 3 (not critical): Undeveloped shorelines experiencing erosion but with no or minor consequent economic loss if left unchecked.

On the west coast of Peninsular Malaysia, about 25% of erosion shorelines represent Category 1 and Category 2 due to urbanization along this coastline (Saw 2000). According to Mohamad et al. (2014), waves along the west coast of Peninsular Malaysia are not so high compared to the east of Malaysia which blocking by Sumatra and Indonesia, and are frequent influence by the tidal wave. Furthermore, the east of Peninsular Malaysia and east of Malaysia are directly influenced by wind waves from the South China Sea (Mirzaei et al. 2013; Ismail et al. 2020; Shariful et al. 2020). The highest seasonal wind waves were recorded during the northeast monsoon, from the end of October to March (Ariffin et al. 2019). The Department of Irrigation and Drainage (DID) is the authority to mitigate coastal erosion in Malaysia. The DID implemented several adaptations and mitigation plans to protect the coastal area. However, rapid urbanization and climate change enhance the wave topping on the buffer zone, and thus increase the coastal erosion. The National Coastal Erosion Study from 1985 (DID 1985) was updated in 2015 (DID 2015) with revising erosion index as follows:

Category 1 (critical erosion): Fast retreating coastline at the rate of more than 4 m/yr with generally fairly dense human settlement, with some commercial/industrial activities being served by significant public infrastructure and facilities.

Category 2 (significant erosion): Retreating coastline at the rate of between more than 1 m/yr but less than 4 m/year with a generally sparsely-populated area, with some agricultural activities being served by relatively minor public infrastructure and facilities.

Category 3 (acceptable erosion): Slowly retreating coastline of less than 1 m/yr with generally no human settlement and minimal agricultural activities, and not served by public infrastructure and facilities.

Results of upgrading the erosion index in the National Coastal Erosion Study (NCES) 2015 reveal that Category 1 (the number of areas: $n=44$) and Category 2 ($n=3029$) increased by 32% in the whole of Malaysia (Fig. 3). Therefore, Malaysian government takes several actions to protect the coastline.

1.5 Existing responsible government departments and their legal authorities

The NCES was commissioned by the Economic Planning Unit (EPU) Prime Minister's Department in 1985 to address coastal erosion issues countrywide and to examine their impacts on coastal communities, agriculture, transportation, and recreation with the institutions whoes involve in coastal management plan at Malaysia as example in Table 2. Government entrusts the DID by establishing National Coastal Erosion Control Council (NCECC) and Coastal Engineering Technical Centre (CETC) in 1987. The DID was given a key role in the evaluation of all coastal developments proposal, whereas NCECC and CETC were established as consultative bodies in coastal erosion programs. There mainly provided operational leadership and recommendations for the program, budget and implementation coordination among Federal, State Governments and together with private sectors which are headed by the Director-General of the Implementation Coordination Unit (ICU) in the Prime Minister's Department.

The CETC was later known as the Coastal Division of DID, which carry out technical studies and give advisory services on coastal engineering. The NCECC member was EPU, the Ministry of Finance, the Ministry of Science and Technology, the Ministry of Agriculture, the Department of Irrigation and Drainage (DID), the Department of Town and Country Planning (DTCP), the Department of Forestry (DOF), the Department of Public Works (PWD), State Governments, professional institutions, universities, and private sectors. Several non-government organizations also play a major role in shoreline management.

The EPU was the principal government agency responsible for the preparation of development plans for the nation. In addition, the NCES report addresses national coastal erosion and examines its impact. The DID was the central agency in shoreline management, which was charged with providing coastal protection works, river mouth improvement works, flood mitigation works, and the conservation of river systems. It also serves as

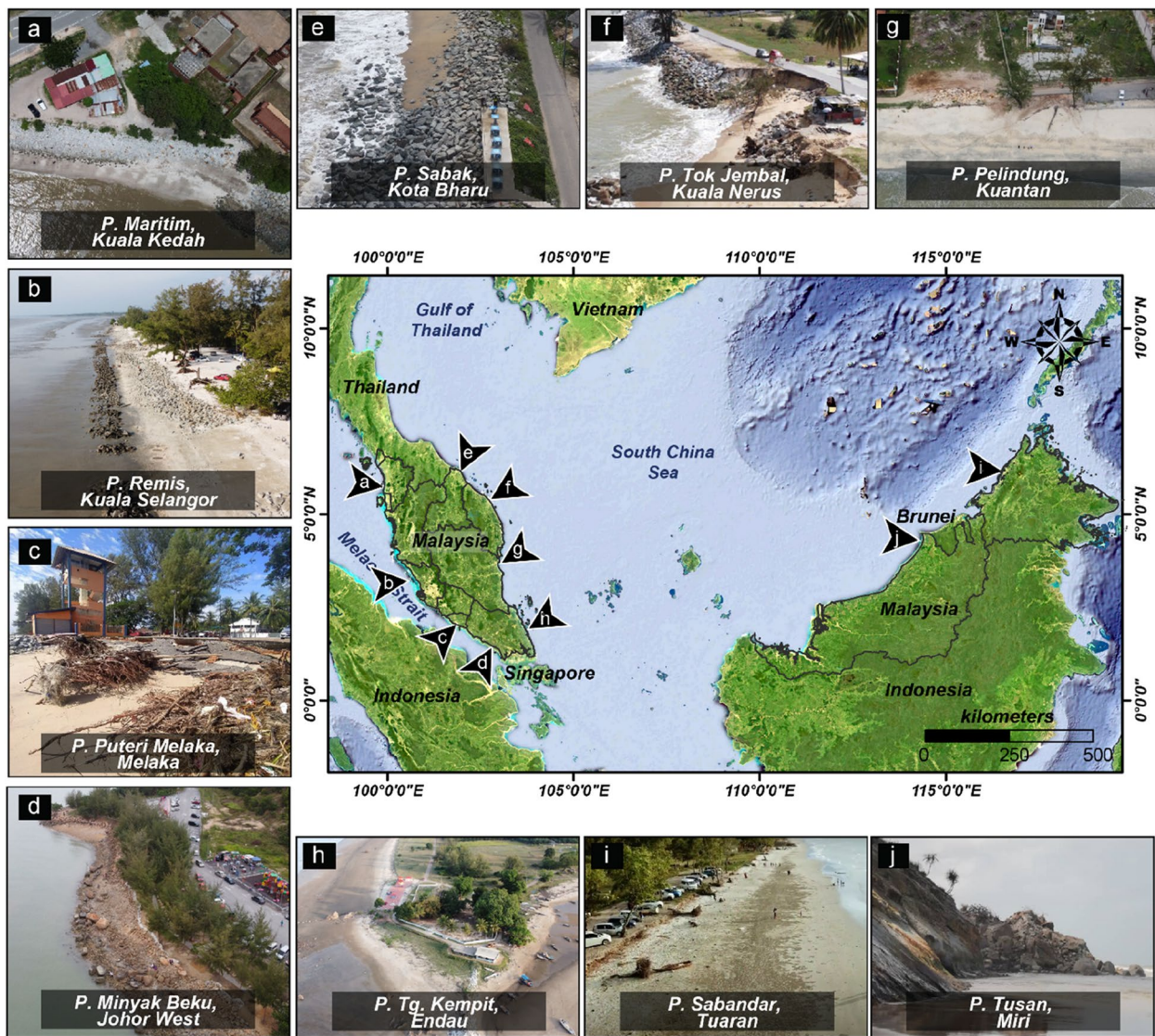


Fig. 3 Examples of coastal erosion situation in Malaysia

Secretariat to NCECC which formulates coastal erosion control strategies at the federal level. The DTCP was the advisor of the State on town planning matters and secretariat to the State Planning Committee as well.

Since it was responsible for overseeing and assisting local authorities in advising on the program and contents of development plans under the guardian of the Town and Country Planning Act 1967, its decision have a direct impact on shoreline management and coastal development. It also published comprehensive documents addressing require standards for development in a zone covering recreational coastal forests, mangrove forests, turtle sanctuaries, river and river mouths, recreation at the river, shoreline and open coast, eco-tourism, housing, industrial, aquaculture, sandy beach, muddy beach, and rocky beach.

The Department of Environment (DOE) carries administration to enhance the quality of the environment, by assessing EIA, and advising on environmental issues. Guidelines were regulated for the development of coastal resorts, fishing harbors, land-based aquaculture, tourist and recreational facilities, coastal and land reclamation and sand mining. The Department of Land and Mines (DLM) is responsible to receive and processing applications for conversion and subdivision of land-use change. The State Director of Lands and Mines gives jurisdiction to District Land Offices on land administration. Further, they have the full power on the sand resource management (i.e., beyond 3 nautical miles from the mean low water line from shore) and protection of coral reef areas outside Marine Parks.

Table 2 Relevant governmental departments and their authority related to coastal erosion and conservation acts

Institution	Act
1 Economic Planning Unit https://www.epu.gov.my/en	• Ministerial Functions Act 1969
2 Department of Irrigation and Drainage (DID) https://www.water.gov.my	• Irrigation Areas Ordinance, 1953. (Revised) 1989 • Town and Country Planning Act 1976 • Environmental Quality Act 1974: (1985) • Environmental Quality Order 1987 (Environmental Impact Assessment—Prescribed Activities) • Mining Enactment 1936 (F.M.S. Cap 147) • Fisheries Act 1963 (1985) / Inland Fisheries Act
3 Department of Town and Country Planning (DTCP) https://www.planmalaysia.gov.my	• Town and Country Planning Act 1976
4 Department of Environment (DOE) https://www.doe.gov.my/	• Environmental Quality Act 1974: (1985)
5 Department of Lands & Mines (DLM) https://www.jkptg.gov.my/en/	• National Land Code 1965, Act 625 • National Land Code (Validation) Act 2003 • Land Conservation Act 1960 • Continental Shelf Act 1972—Act 83 • Mineral Development Act, 1994
6 State Executive Committee (EXCO)	• Local Government Act 1976—Act 171
7 State Planning Committee (SPC)	
8 State Economic Planning Unit (SEPU)	• Municipal and Town Boards (Amendment) Act, 1975 • Town Boards (Amendment) Act, 1961 • Town Boards Enactment of the Federated Malay States, 1952
9 Public Works Department (PWD) https://www.jkr.gov.my/	• Road Transport Act, 1987 • Malaysian Highway Authority Act, 1980 • Road Traffic Ordinance, 1958
10 Marine Department (MD)/Jabatan Laut https://www.marine.gov.my/	• The Merchant Shipping Ordinance 1952- Act 70 • Federation Port Rules 1953 • Port Authorities Act 1963—Act 488 • Port Privatisation Act 1990—Act 422 • Merchant Shipping (Oil Pollution) Act, 1994 • Petroleum Mining Act, 1966, (Revised) 1972
11 Department of Forestry / Jabatan Perhutanan https://www.forestry.gov.my/my/	• National Forestry Act 1984—Act 313
12 Department of Mineral and Geoscience (DMG) / Jabatan Mineral and Geosains https://www.jmg.gov.my/	• Geological Survey Act 1974

State agencies also play roles in shoreline management. State Executive Committee (EXCO) is the highest executive authority of the state and functions as giving approval to land conversion and subdivision and ratifying the development plans. In addition, State Planning Committee (SPC) supervises the preparation of development plans and provides approval of structure plans. State Economic Planning Unit (SEPU) is responsible for formulating policies, strategies, and programs for the economic development of the shoreline. However, the PWD involves any preparation and planning issues on road collapsing.

1.6 Challenges in the management of coastal erosion

Planning is a continuous process that repeats several steps cyclically over time. Data collection and analysis are essential for long-term planning. Planners and subject-matter specialists are seldom satisfied with the available information. Plans include activities throughout the

given time that can fill the gaps and build a knowledge base. Therefore, long-term research is required to generate satisfactory data set for a future planning cycle. The traditional planning approach starts by identifying problems and then formulating goals aimed at solving these problems. The goals are defined concerning the problems. A different mindset is now required. Problems, challenges, constraints, and hindrances are factors that slow down progress toward those long-term goals. Some problems such as coastal erosion need immediate actions to achieve long-term goals.

The DID needs budgetary approval from the Malaysia Ministry of Finance before proceeding to carry out erosion mitigation works (Ariffin et al. 2018). The areas concerned with budgetary requirements were further eroded during approval procedures. Therefore, the initial approved budget for coastal defense works can be exceeded to complete the latest levels of erosion. Once these breakwaters and beach nourishment systems are implemented by the DID, the stakeholders (mainly public

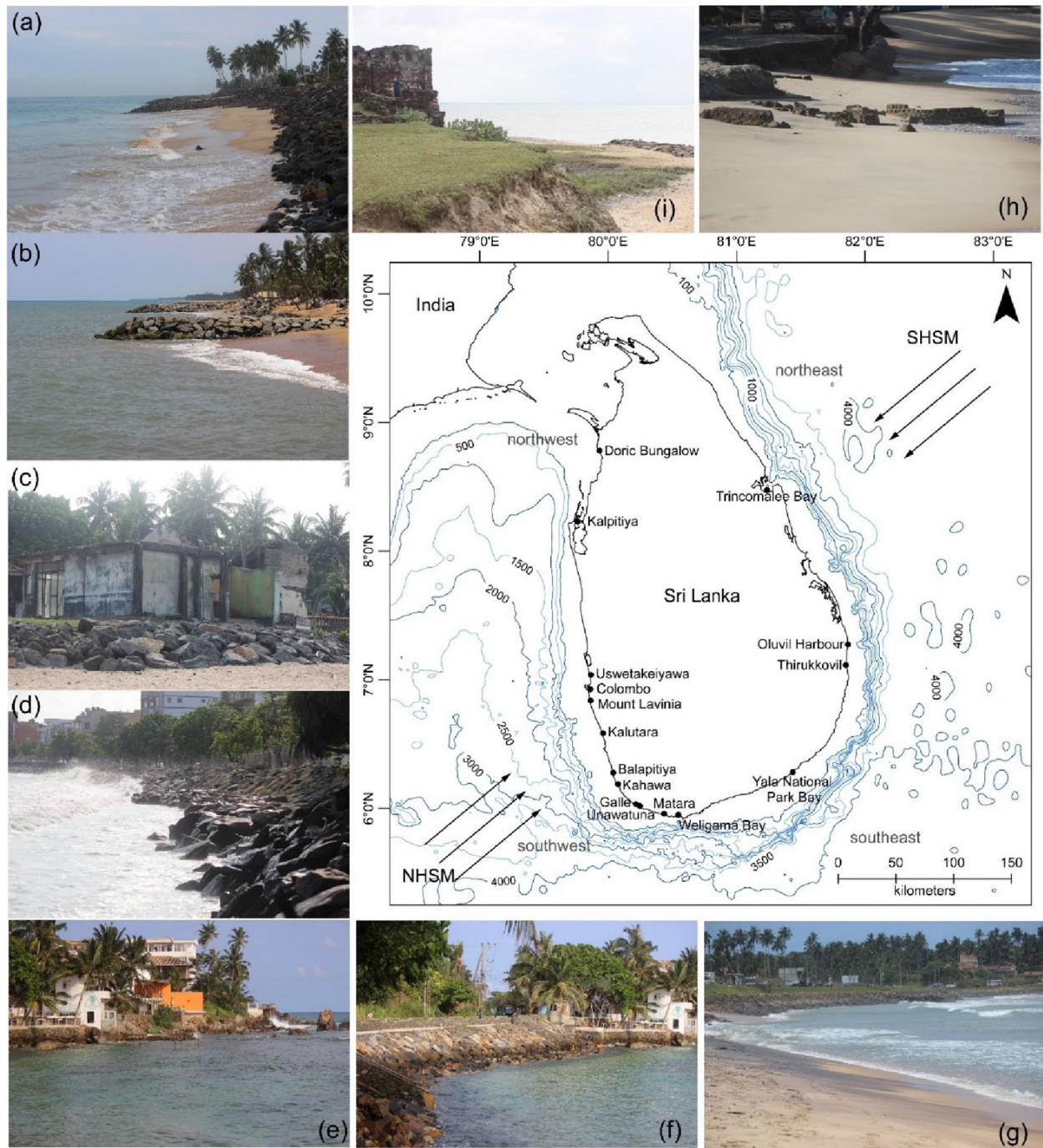


Fig. 4 General Sri Lanka map shows prominent areas for coastal erosion

communities) are very keen to see the completion of the proposed solutions for a more sustainable coastline. In addition, many authorities with different job scopes work in the same area during the coastal disaster that happens along the coastline. For example, the PWD repaired the collapsed road and residents due to beach erosion. At the

same time, State Executive Committee (EXCO) involves in helping the coastal community, considering coastal erosion as a natural disaster. Ariffin et al. (2018) provided a strategy for communication between all authorities and coastal communities which set up the Focus Group Discussion (FGD) to have final decisions.

1.7 Management of coastal erosion in Sri Lanka

1.7.1 Situation of coastal erosion

Sri Lanka is an island in the Indian Ocean with a coastline of approximately 1600 km in length, and the coastal zone contributes 40% of the national gross domestic product (GDP) of the country. Coastal erosion issues were identified during the construction of fortresses at Galle, Colombo, and Matara dating back to the seventeenth and eighteenth centuries (Weerakkody 1997 and references therein). Coastal erosion has gradually increased after urbanization and industrialization, and this has been recognized as one of the main hazards in the coastal areas, especially on densely populated southwest coasts (Fig. 4). For example, Coast Conservation Department (CCD) estimated that about 175,000 to 285,000 m² of coastal lands are eroded along the west and southwest coast (length 685 km from Kalpitiya to Yala National Park Bay). Several key drivers control spatial and temporal coastal erosion in Sri Lanka. The continental shelf of Sri Lanka is between 8 and 24 km. The northeast shelf in Sri Lanka is broad and its southwest coast is narrow (Fig. 4). Accordingly, wave energies are relatively low and high on the northeast and southwest shelves, respectively. Coastal erosion is thus high along the southwest coast, but it is also observed in other areas (Fig. 4). Therefore, coastal erosions are highly site-specific, and several hundreds of infrastructures (e.g., roads, houses, tourist hotels) have been washed away during the last few decades around Sri Lanka (Fig. 4). Accordingly, the energy of waves, beach orientation, and wave obliquity play a key role in beach erosion.

In general, beaches are eroded during its prominent monsoon season (i.e., west coast for southwest monsoon and east coast for northeast monsoon). The eroded beach sediments are deposited in nearshore areas and partially transported by longshore currents. These eroded beach sediments are redeposited during inter-monsoon periods, and eroded again during the next monsoon (Amalan et al. 2018). On the other hand, several engineering projects such as harbors and outfalls are constructed without adequate feasibility studies for estimating seasonal trends of sediment transport rates and measuring shoreline changes. Furthermore, several examples indicate that the construction of artificial barriers directly altered the sediment budget on the shorelines. Therefore, hard structures are not always effective for coastal management. This leads to disappointing results and wastes taxpayers' money due to significant alteration of the natural sediment budget. For example, the southern and northern parts of the Olivil Harbor are subjected to sediment accretion and erosion, respectively (Weerasingha and Ratnayake 2022). Consequently, the entrance of the harbor is completely blocked by longshore drift sediments, and it can be identified as a dead harbor now.

Coastal vegetation such as mangroves in sheltered environments contributes to defending coasts against erosion, and destruction by storms and tsunamis. The intertidal forests are green belts for coastal erosion, especially on the southern coast of Sri Lanka. However, deforestation enhances coastal erosion by reducing the stability of soils. Coastal erosion has created many environmental problems such as salinity intrusion into rivers and estuaries. Water supply to coastal cities depends completely on rivers and reservoirs, and water availability for drinking and industrial purposes is governed by river discharge. Since coastal erosion has caused seawater intrusion into upstream during the dry season, the supply of water quality has been reduced in metropolitan areas such as Kaluthara town (Ratnayake et al. 2013). Moreover, seawater intrusion into wetlands is severely affected the coastal ecosystems (Ratnayake et al. 2018). The disappearance of sand spits at river mouths (e.g., Kalu Ganga outlet) due to rapid erosion also creates huge socioeconomic impacts on the coastal system (Gunasinghe et al. 2021). In contrast, the coastal sediment budget is drastically reduced at present due to sand mining of river beds and being trapped by dam-constructed reservoirs. Therefore, coastal erosion is increasing followed by the loss of a certain amount of sediments before reaching the beaches.

Geological and geomorphological characteristics are also important to control long-term coastal erosion and landform changes in Sri Lanka. About 90% of the land area consists of high-grade Precambrian metamorphic rocks. The hard rock outcrops along the shore and on beaches resist coastal erosion, whereas lithologically weak rocks are subjected to coastal erosion and create different landforms such as bays (e.g., Trincomalee Bay, Weligama Bay).

1.8 Existing responsible government departments and their legal authorities

The initial coastal stabilization was conducted by the PWD, but a lack of success in terms of coastal erosion. The establishment of the Division of Coast Protection Works of the Colombo Port Commission was the first step toward proper management of the coastal zone of Sri Lanka. This led to the establishment of a CCD and lastly developed a separate government department known as the CCD of Sri Lanka. The initial legal power was obtained along with the Parliamentary Act, No. 57 of the Coast Conservation in 1981. The CCD was established under the provisions of the act to implement national-level policies and plans for coastal zone management. Several conservation activities have been introduced in the master plan for coastal erosion management in 1986 and the coastal zone management plan in 1990

such as including brushwood mattresses, fences or log walls made of coconut trunks, and constructed seawalls using granite and cement mainly along the coasts from Colombo to Galle (Weerakkody 1997). However, the beaches in front of seawalls are disappeared now. Later stage, the construction of groins and breakwaters was introduced and widespread up to the present (Fig. 4). In general, hard structures constructed to protect against coastal erosion had enhanced downdrift erosion on some beaches. Recently, several beach nourishments have been carried out in Sri Lanka, and identified as failed projects such as Uswetakeiyawa and Mount Lavinia projects (Ratnayake et al. 2019; Gunasinghe et al. 2022). Furthermore, the CCD introduced the following principal provisions (i) use cost-effective and environmentally acceptable erosion control techniques, (ii) establish new development away from eroded shores, (iii) allocate sufficient distance between new construction and the shore, (iv) control human activities such as coral and sand mining, and (v) protect inhabit natural features, etc.

1.9 Challenges in the management of coastal erosion

According to the CCD, the annual coastal erosion along the coasts from Kalpitiya to Yala is about 175,000–285,000 m² in 1990. Some coastal areas are stable and resistant to erosion, whereas other areas are not stable and resistant. It is highly site-specific, and regional scale modeling or interpretation is limited in Sri Lanka. At present, a database for coastal erosion research is very poor. Public education on coastal management, and budgetary allocations are also limited in Sri Lanka. Therefore, the lack of up-to-date quantitative data, and simulations on coastal erosion and nearshore wave data are one of the major challenges to estimating coastal erosion, interpreting landform changes, and preparing policy documents. Accordingly, a nationwide program is required to compile data and research outcomes for estimating coastal erosion, management, and decision-making. The CCD should be carried out such surveys and research in cooperation with relevant government institutes, research institutes, and universities.

Few attempts have been made to examine potential land loss from beach erosion and inundation caused by accelerated sea-level rise, and it is required to implement adaptation policies for coastal zone erosion. For example, specific attention should be focused on the identification of potentially vulnerable areas for ongoing sea-level rise. These variances should be considered for formulating policies and implementing adaptation strategies. Therefore, site-specific variations can also be identified as a challenge in the management of coastal erosion in Sri Lanka.

Efforts in emerging alternative coastal protection strategies (e.g., the establishment of effective green belts such as mangrove forests) are still at the initial stage, and it is a challenge due to rapid urbanization and socio-economic conflicts in coastal areas. Different stakeholders introduce different strategies depending on their interests. For example, the Coastal Conservation and Coastal Resource Management Department initially introduced hard engineering structures such as breakwaters, revetments, submerged, and groins for protecting against coastal erosion. Sand nourishment (without hard structures) has later introduced considering the stakeholders' interests. The application of a variety of coastal structures without proper scientific justifications and environmental impact assessments can be linked with socio-economic conflicts.

Several government institutions are involved in coastal resource management with certain powers (Table 3). For example, the entire coastal zone in Sri Lanka has been gazetted as an Urban Development Area (UDA) under the Urban Development Authority Act, No. 41 of 1978. Next, Geological Survey and Mines Bureau (GSMB) has the authority to issue permits for mining activities in coastal areas. The Board of Investment can bypass the authority of the CCD. Such provisions in overlapping policies can cause conflict in coastal zone management. Therefore, CCD should have the authority to coordinate all activities in the coastal areas. The lack of coordination is one of the major challenges in controlling coastal erosion in Sri Lanka.

Monitoring and measuring impacts, improving links to conflict-prone communities, integrating disaster risk concerns in coastal management and development (i.e., assessment of coastal hazards, vulnerability and risk, criteria for design and construction of buildings and other structures in the coastal environment, assessment of socio-economic impacts on set-back standards), and less awareness for future vulnerabilities can also be identified as challenges in erosion management in Sri Lanka.

1.10 Improvement in coastal management framework

In this study, we considered a series of challenges and problems in existing governance and coastal management frameworks. It is important to provide successful coastal planning on preparation, investigation, implementation, mitigation, and adaptation. This coastal planning needs to have coastal protection in favor of the practice. However, it is quite difficult in many countries due to the complex and chaotic mix of institutional arrangements (Văidianu et al. 2020). In addition, the design process is more straightforward with the established procedure, engineering calculation, and field survey techniques and data. Furthermore, it is important to understand the social, and environmental impacts of coastal protection projects.

Table 3 Relevant governmental departments and their authority related to coastal erosion and conservation

Institution	Act
1 Department of Wildlife Conservation (DWC) http://www.dwc.gov.lk/	• Fauna and Flora Protection Ordinance No 2, 1937 (as amended)
2 Department of Fisheries and Aquatic Resources (DFAR) https://www.fisheriesdept.gov.lk/	• Fisheries and Aquatic Resources Act No. 2, 1996 and the Regulations under this Act
3 Coast Conservation and Coastal Resource Management Department http://www.coastal.gov.lk/	• Coast Conservation Act No. 57, 1981 (as amended)
4 Marine Environment Protection Authority (MEPA) http://www.mepa.gov.lk/	• Marine Pollution Prevention Act 35, 2008 and Regulations under this Act
5 Central Environmental Authority http://www.cea.lk	• National Environment Act No. 47, 1980 (as amended)
6 The Sri Lanka Land Reclamation & Development Corporation (SLLRDC) http://www.landreclamation.lk/	• Land Reclamation and Development Corporation Act No. 15, 1968 (as amended)
7 National Aquatic Resources Research and Development Agency (NARA) http://www.nara.ac.lk/	• National Aquatic Resources Research and Development Agency Act (No. 54, 1981)
8 The National Aquaculture Development Authority (NAQDA) http://www.naqda.gov.lk/	• National Aquaculture Development Authority of Sri Lanka Act No. 53, 1998 (as amended)
9 Department of Coast Guard (DCG) http://www.coastguard.gov.lk/	• Department of Coast Guard Act No. 41, 2009
10 Sri Lanka Tourism Development Authority (SLTDA) https://www.sltda.gov.lk/	• Tourism Act No. 38, 2005
11 Water Resources Board http://www.wrb.gov.lk/	• Water Resources Board Act No. 29, 1964
12 Municipal Councils	• Municipal Councils Ordinance No. 29, 1947
13 Urban Council	• Urban Councils Ordinance No. 61, 1939 (as amended)
14 Pradeshiya Saba	• Pradeshiya Saba Act No 15, 1987 (as amended)
15 Urban Development Authority (UDA) http://www.uda.gov.lk/	• Urban Development Authority Law No. 37, 1978 (as amended)
16 Geological Survey and Mines Bureau (GSMB) http://www.gsmb.gov.lk/	• Mines and Minerals Act No.33 of 1992
17 Forest Department http://www.forestdept.gov.lk/	• Forest Ordinance No. 16, 1907 (as amended)
18 Soil Conservation Act No. 25, 1951 (as amended) and the Regulations under this Act	
19 Maritime Zones Law No. 22, 1976	

Ngoran et al. (2016) mentioned that the most difficult set of frameworks is bringing together and harmonizing the perspectives of competing different levels of government agencies (each with their interests, mandates, and perspectives), and different disciplines (each with their language, outlooks, and methodologies). Similarly, there are different departments involved in the current coastal management in Thailand, Malaysia, and Sri Lanka. Therefore, this conflict of power management can sometimes make it difficult to problem-solving. Besides Asian countries, similar conflicts also appeared in Europe countries as resulting from a lack of institutional arrangements for management and fragmented decision-making (Stepanova and Brukmeier 2013). Questions such as “which agency is fully in charge?”, “who will coordinate?”, “who is listening?”, and “who will render judgment?” are not always answered in the current coastal management in Thailand, Malaysia, and Sri Lanka.

For example, geographical region of Taiwan, the Legislative Yuan passed and adopted the Coastal Management Law in 2015. In 2018, the Ocean Affairs Council was founded as the single entity responsible for coordinating numerous affairs and enacting related laws, retaining command and supervision authority over the coastal areas (Lan and Hsu 2021). Their local specialized agencies are also linked with the management of a variety of specific affairs and law enforcement. However, the current coastal management system in Thailand, Malaysia, and Sri Lanka still poses inconsistent operation of national policy, and uncertainty in the permit process. In addition, inadequate budget allocation can occasionally stop or postpone coastal development projects, based on the annual budget allocation. In most cases, the target coastline can be protected without downdrift erosion by spending the entire budget at once. As a common feature, national funding is limited for coastal erosion projects in Thailand, Malaysia, and Sri Lanka. Accordingly, only

a limited section can protect from the available funds. It might also result in the loss of ecological value of coastal resources by creating impacts on neighboring shorelines or generating exorbitant expenditures for both private investors and the public. Consequently, inadequate budgeting can prevent the full implementation of environmental mitigation and monitoring activities (Biber 2011), and intermittent budgets also making impossible in long-term monitoring.

Analysis of the literature evidence suggests that the sophistication of coastal protection is increased through public involvement. The coasts are used by many stakeholders, and it is hard to meet all of their requirements. For instance, small-scale fishermen prefer bare beaches to tow their boats on the shoreline, whereas landowners want to secure their property with coastal structures. In addition, governments across the world often separate the engineering and the environmental departments. The engineers want to protect the coast, while the environmentalists prefer to leave things in the same manner. The primary premise is “coastal protection is not solely about the engineering”, but the financial, societal, and environmental factors are also involved in pondering.

To ensure the sustainability of coastal resources while providing management flexibility for the future, a coastal

erosion mitigation framework is suggested for these three countries to reduce the current coastal degradations at the national levels (Fig. 5). To improve the present national and local planning capability for the coastal zone, this framework covers holistic, site-specific, and protect-based multiple approaches. Through the idea and strategy of improving the framework, coastal communities might be able to thrive and be resilient while continuing to live and work on a healthy coast, including enhancement of proper planning at the local level, and national level.

Many coastal development projects are approved in Thailand, Malaysia, and Sri Lanka. However, the pluralistic regulatory review system in place presently has come under fire for its potential to prolong conflicts and raise coordination needs among federal, state, and local agencies that evaluate development proposals. Before proposing a coastal plan for determining appropriate prevention measures within the coastal zone plan at the local or national level, these three countries must understand the evolution trends of the coastline as the first step. Long-term coastal evolution analysis can be carried out using digital processing of satellite images and calculations of spatial change (e.g., Weerasingha and Ratnayake 2022).

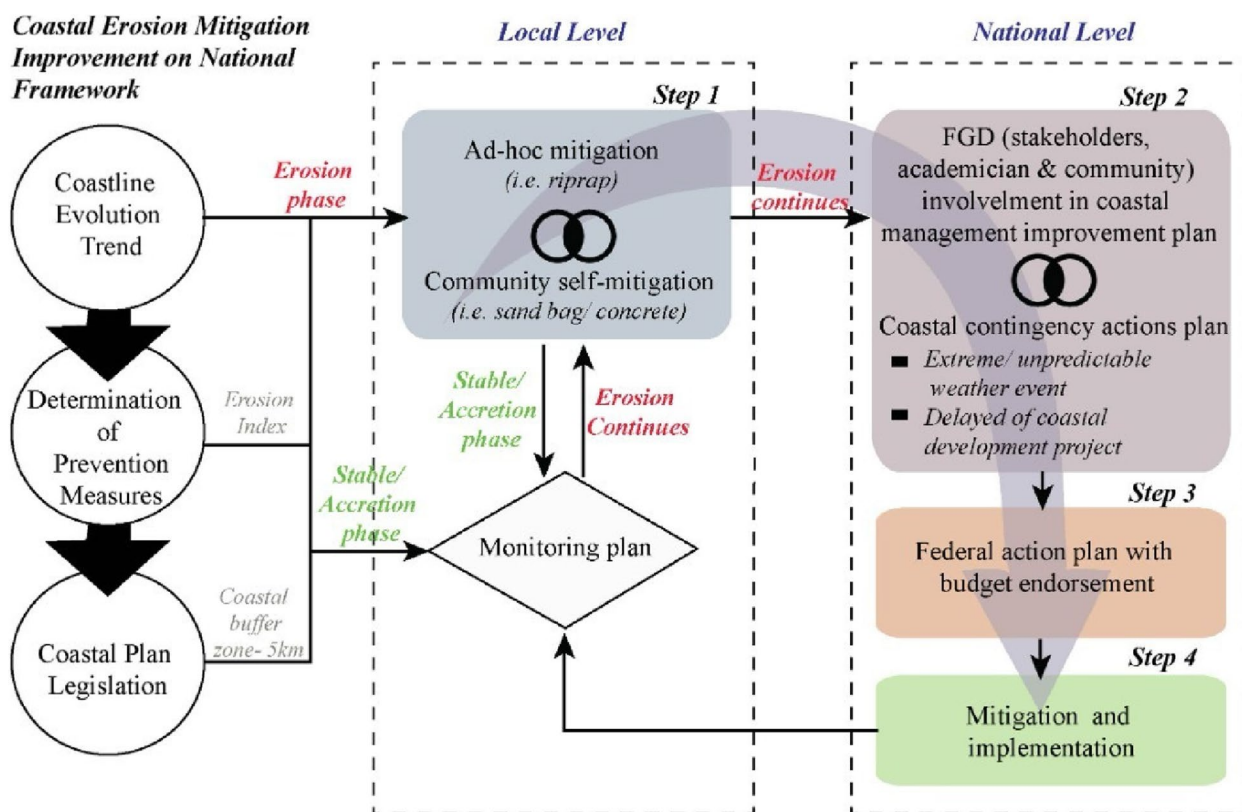


Fig. 5 The concept of how to improve the current coastal erosion mitigation framework

Based on previous research on coastline evolution trends in other regions, several practical assessments were implemented to aid planning and management (Duck and da Silva 2012; Pranzini et al. 2020; Rangel-Buitrago et al. 2020). Understanding how coastlines change should be investigated thoroughly before designing management strategies. Therefore, the establishment of coastal plan legislation is required in these three countries. This legislation should cover at least a 5 km coastal buffer zone from the project boundary, considering coastal development, protection, and ecological conservation. Such legislation is already developed in China (Wei et al. 2021), and is useful in avoiding improper coastal use by disaggregating populations into enumerations areas and buffer zones.

There are four main connected steps comprised and suggested in this study for Thailand, Malaysia, and Sri Lanka (Fig. 5). First, if the coast identifies in an erosion phase through a coastal evolution analysis, a coastal plan from the local level should be applied in an ad-hoc manner by using coastal structures measures (e.g., riprap) and community self-mitigation (e.g., sandbag) to secure infrastructures and properties. Second, if the coast continues facing erosion, a national coastal plan should be necessitated by involving focus group discussions from similar coastal backgrounds or experiences (e.g., stakeholders, academician, and community) and preparing a coastal contingency actions plan in the cases of the extreme weather event and delayed coastal development project.

The complete awareness and involvement of all parties would help establish and assign proper corresponding responsibilities and formulate reliable and standard norms (Costanza et al. 1998). Third, a federal action plan with budget endorsement should be implemented to help states and localities develop coastal zone management plans. The state programs can sometimes fail before the reaching of its all objectives. Accordingly, federal funding is not maintained, and there is a risk in the continuation of the project. Fourth, mitigation and implementation are suggested as the final step required for humans to secure both the environment and their lives. For instance, one of the mitigating options for coastal erosion involves bypassing the sediment from accumulated updrift to eroding downdrift (Anfuso et al. 2011; Saengsupavanich et al. 2022). The ability of mitigation approaches to accommodate dramatic coastal shifts would provide a more robust framework for managing coastal environmental changes (Chang et al. 2018). However, the last step needs to continue monitoring the plan with the identification of accretion/stable and/or erosion indicators. If the erosion continues, it needs to be returned to the first step, especially on the local level.

2 Conclusion

We analyzed the current situation of coastal erosion in Thailand, Malaysia, and Sri Lanka. In addition, this study discussed the current limitation and challenges in coastal zone management. Monsoon waves, disruption of alongshore sediment transportation due to man-made engineering structures, mangrove destruction, and other anthropogenic activities are the main causes of coastal erosion. Managerial obstacles among different departments, inconsistent interpretation of national policy, highly site-specific coastal erosion, extreme weather events along with monsoon waves, and social, environmental, economic and political complexities are the major challenges to protecting coastal erosion in these three countries. In summary, mitigation strategies can divide into several categories such as (i) assuming and accepting risk, (ii) avoidance of risk, (iii) controlling risk, (iv) transferring risk, and (v) watching and monitoring risk. Consequently, several actions such as artificial beach nourishment, protective structures (e.g., seawalls, revetments), structures to trap sediment movement, vegetation planting, maintenance, land use regulation, coastal zone management planning, and enhancement of natural buffers can be recommended as mitigation strategies.

Abbreviations

CCD	Coast Conservation Department
DID	Department of Irrigation and Drainage
DMCR	Department of Marine and Coastal Resources
PWD	Department of Public Works
DPT	Department of Public Works and Town
DTCP	Department of Town and Country Planning
EPU	Economic Planning Unit
EIA	Environmental Impact Assessment
IEE	Initial Environmental Examination
MD	Marine Department
NCECC	National Coastal Erosion Control Council
NCES	National Coastal Erosion Study

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Authors' contributions

Cherdvong Saengsupavanich: conceptualization, writing-original draft preparation, methodology, investigation, resources, reviewing, writing-review & editing, visualization, supervision, project administration, Amila Sandaruwan Ratnayake: conceptualization, writing-original draft preparation, methodology, investigation, resources, reviewing, investigation, writing-review & editing, visualization, supervision, project administration, Lee Shin Yun: writing-review & editing, Effi Helmy Ariffin: conceptualization, writing-original draft preparation, methodology, investigation, resources, reviewing, investigation, writing-review & editing, visualization, supervision, project administration.

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Availability of data and materials

The dataset supporting the conclusions of this article can be found in the main text. Further inquiries can be directed to the corresponding author.

Declarations

Competing interests

The authors declare that they have no conflict of interest.

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