Evaluation of coastal protection strategy and proposing multiple lines of defense under climate change of the Mekong Delta for sustainable shoreline protection

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Abstract

Coastal protection measures and management play an important role in coping with climate-induced sea-level rise in Vietnam, a country with a long coastline which is vulnerable to coastal flooding and erosion. In this study that follow the success and failure of specific coastal protection structures that include: revetments, geotubes, t-shaped bamboo fences, Pile-rock breakwaters, Busadco's breakwaters, Semi-Circular breakwaters, and Hollow triangle breakwaters is reported over the study period from a field observation over 10-15 years is reported. This paper briefly reviews current situation of coastline erosion and accretion, and illustrates the extraordinary severity of the current erosion rate that threatens the safety of coastal communities. Then, we focus on the evaluation of the advantages and disadvantages of various coastal management approaches applied in the Mekong Delta to classify different types of possible measures for coastal management to find a holistic measure for planning, construction investment, and integrated coastal management on a regional scale. Finally, the multiple lines defense (MLD) solution is proposed to comprehensively protect the coastal Vietnamese Mekong Delta towards as a green infrastructure solution under climate change condition to improve biodiversity, mangrove forest restoration, and sustainable livelihoods for local communities.

Keywords: Multiple lines defense, Nature-based solutions, Coastal management, Climate change and Sea level rise, Vietnamese Mekong Delta.

1. Introduction

The Vietnamese Mekong Delta (VMD) is under multiple economic and climatic stressors with a dense population (995 people/km^2), high capital investment, and rapid development (Buschmann et al., 2008). Unfortunately, the environmental condition of the VMD is detiorating with tremendous coastal hazard impacts from an arrays of coastal and inland forces including cross-boundary factors from upstream sediment deposition in the Mekong River Basin, sea-level rise, coastal erosion, and salinity intrusion (Van Brakel et al., 2010; Kondolf et al., 2018; Anthony et al., 2015; Minderhoud et al., 2019; Kulp and Strauss, 2019). Furthermore, the anthropogenic activities and climate change effects in coastal zones have resulted in cumulative substantial environmental impacts that have adversely affected the socio-economic condition of coastal communities as Mekong (Nicholls et al., 2007; Schmidt, 2015; Chávez et al., 2021). These call for sustainable coastal protection measures under climate change that can ensure ecosystem restoration, mangrove forest protection, reduce shoreline erosion, and protect the large agricultural yield of VMD.

There are a number of climate change adaptation portfolios are adopted to mitigate and response to adverse consequences of coastal hazards related to coastal hazards in coastal Mekong Delta including but not limited to construction and upgrade of sea dyke and saline-prevented sluice, shift to new crop varieties with saline-tolerant, land use change planning, livelihood diversification, protection of mangrove forest, conversion to aquacultural farming, and strengthen adaptive capacity and improving governance (Adger et al, 2005; Hoa et al., 2007; Howden et al., 2007; Birkmann et al., 2010, 2012; Birkmann, 2011; Smajgl et al., 2015; Triet et al., 2017; Le et al., 2018; Tran et al., 2019; Poelma et al., 2021). These solutions have achieved certain success to adapt to climate change and ameliorate the livelihood for local coastal communities. However, coastal protection and reduction of erosion are still challenging due to the complexity of coastal morpho-hydrodynamic processes and human intervention.

Many engineering solutions have been proposed to protect the VMD coastline. The most widely applied and prioritized solutions have been hard infrastructure but these solutions have shown certain shortcomings when considered from a multi-purpose coastal management and long-term protection perspective. Moving from these traditional hard infrastructure solutions to green infrastructure solutions shows promise as a path that achieves the dual outcomes of improved human well-being and nature preservation (Day et al., 2007; Romero et al., 2012; Silva et al., 2017). On a worldwide scale, "Nature-based solutions" have become a mainstream concept for water-related infrastructure that includes restoring coastal and marine ecosystems (Waterman, 1995; 2008; 2010; De Vriend et al., 2015).

The Multiple Lines of Defence (MLD) solution has been proposed as an alternative method that can harnesses both the coastal benefits of hard solutions while simultaneously achieving the benefits of green solutions ensuring the sustainability of the the natural and human habitat and coastal ecosystems. The MLD concept was first introduced by the Pontchartrain Conservancy after the devastation of Hurricane Katrina and Hurricane Rita in the United States of America in 2005 (Lopez et al., 2009) and was a crucial tool to inform design of flood control and wetland restoration infrastructure for coastal areas of Louisiana. In addition, MLD methods have been coupled with the design of coastal green infrastructure (IUCN, 2021; Chávez et al. 2021), which is widely applied in coastal areas worldwide including the United States of America and the Netherlands. This coupling of methods is expected to result in greater economic development and ecosystem rehabilitation (Narayan et al., 2016; Ellison et al., 2020). MLD have also been shown to promote sustainable livelihoods for local communities as described in the Integrated Coastal Zone Management guidebook (Moksness et al., 2009), and are compatible with the principles of Green Infrastructure and Building with Nature (Benedict & McMahon, 2002; De Vriend et al., 2015).

MLD solutions have a number of benefits over traditional hard solutions. Firstly, unlike single hard engineering structures that require large capital investments and are prone to catastrophic failure, MLD utilises multiple defense strategies that require lower capital investment while providing increased resilience to strong high waves (Sutton-Grier et al., 2015). Secondly, single hard engineering structures generally require higher additional investment related to upgrading and optimizing the structural design for adverse weather, such as strong wind and complex wave conditions (Vousdoukas et al., 2020). Finally, frequent tidal hydrodynamics, stresses from waves and storm surges, and coastal flooding impose a greater level of stress on single hard engineering protective structures leading to an increased risk of severe damage, and reduced longevity of the coastal construction (Idier et al., 2017; Kirezci et al., 202). Therefore, compared to traditional hard solutions, the MLD provides a holistic solution that simultaneously protects coastal areas while maintaining the green belt, restoring habitats, and enhancing biodiversity.

There is significant potential for MLD solutions to have a significant positive impact on natural and human habitat and coastal ecosystems in the VMD region. The VMD has a coastal line of 744 km stretching in seven provinces, including Tien Giang, Ben Tre, Tra Vinh, Soc Trang, Bac Lieu, Ca Mau, and Kien Giang. This coastline is rich in ecological diversity, and plays a vital role in

Vietnam's socio-economic development and national security (Guong and Hoa, 2012; Ziv et al., 2012; Campbell, 2012). The region has favorable conditions for socio-economic growth from industries including tourism, agriculture, aquaculture, and fishing. However, for these industries to grow coastal erosion needs to be urgently addressed as it has historically lead to massive land loss, degradation of ecosystems, narrowing of mangrove forests, and has threatened the livelihoods of local communities (Anthony et al., 2015; Li et., 2017; Phan et al., 2015). Moreover, Mekong Delta communities are located in one of the most globally vulnerable deltas, exposed to the combined effects of rising sea levels, salinity intrusion and coastal erosion (Smajgl et al., 2015; Minderhoud et al., 2019; Nicholls et al., 2021;).

Many structural and non-structural solutions have been proposed and applied in several locations along the VMD coastline but these methods have had limited success in protecting the VMD coastline because they are generally not long-term and sustainable solutions. Furtheremore, if efforts are focuses solely on upgrading the current sea dike and revetments infrastructure, the cost of the system will be significant and there will still be uncertainties and high risks associated with extreme weather conditions and severe sea states. Moreover, construction of high sea dykes will lead to the separation of the seaside and coast side and prevent environment exchange. The resulting massive land and loss of coastal landscape will affect the environment and surrounding areas.

Meanwhile, taking advantage of existing mangroves or preserving and expanding mangroves has the effect of reducing waves, protecting the sea-dyke, and enhancing biodiversity, maintaining habitat for flora and fauna, sea birds, and creating a clean ecological environment for marine tourism. Besides, mangroves are a perfect biosphere reserve for carbon sequestration and exchange (Kauffman et al. 2011; Alongi & Mukhopadhyay, 2015), as well as acting as a wastewater filter system for groundwater recharge (Robertson & Phillips, 1995; Wong et al. 1997; Ouyang & Guo, 2016). Finally, mangrove forests in the VMD coast are a precious resource, a long-standing home, and a place to provide food for residents of the western provinces for generations (Phung, 2012). Hence, based on their benefits over existing hard solutions, once implemented sustainable shoreline protection measures will provide a comprehensive solution to cope with the current situation of increasing chronic risks such as coastal erosion, flooding, and storm surges due to sea-level rise in the VMD.

The main objective of this paper is to evaluate the potential benefits of sustainable shoreline protection solutions over traditional solutions for coastal protection in the VMD. To achieve this objective this paper will: (i) evaluate the advantages and disadvantages of different coastal management approaches applied in the Mekong Delta to classify the existing measures for coastal management to find a holistic measure for planning and integrated coastal management on a regional scale. (ii) propose the sustainable shoreline protection solution to comprehensively protect the coastal VMD towards green infrastructure solution to improve biodiversity, mangrove forest restoration, sustainable livelihoods for local communities.

2. Material and Method

This study applied three main components of research activities including document review, field observation campainges and obtaining data from annual measurement projects (see Figure 1). Accordingly, we have selected to review three important projects recently implemented in Mekong Delta consisting of Integrated Coastal Management Programme (ICMP/GIZ); the Vietnam Mekong Delta Integrated Climate Resilience and Sustainable Livelihood Project (GEF-ICRSL) and Research on Reasonable Solutions and appropriate Technologies to reduce the erosion and stabilize the coastline and estuaries of the Mekong River, from Tien Giang to Soc Trang (RSTESMR). The detail information of these project can be found in Table 1A in the Appendix.

For document review, we have focused on the lesson-learned from the pratical implication, the design specifications, the success and failures obtained from the documented projects implemented within the period of 10 years (2011 – 2021). The technical notes to check the calculation of stability of construction; wave, wind conditions and the selection of set of wave parameters are also reviewed.

For the purpose of field observation, many in site field visits in the breakwater construction site and mangrove forest were done in Mekong Delta coast during 2011-2021 to gain insight of the construction progress and implementation condition and the performance during storm surge, monsoon seasons is observed. The pictures and video is captured by camera and flycam have taken to analyze the working states and broken or collapse of constructions. The consultant and interview with local authorities and local people, fishermen were also took place during the visit.

For the gathering the data from annual measurement projects, the Southern Institute of Water Resources Research (SIWRR) measured all hydrological and hydrodynamic data, sediment concentration, satellite images and other variables for many years from the Basic investigation project financed by MARD. We analyzed the data measurement to evaluate the coastal accretion and erosion, shoreline changes and hydrodynamic condition related to the sediment transport and coastal erosion in short- and long-term.

Using the three components as discussed above, we have drawn the advantage and disadvantage of each type of construction with the consultancy from high-skill experience experts in national and international organizations. We have classified four different types of coastal protections and proposed the multiple line defense solution to practice effective coastal management in VMD (see Figure 1).

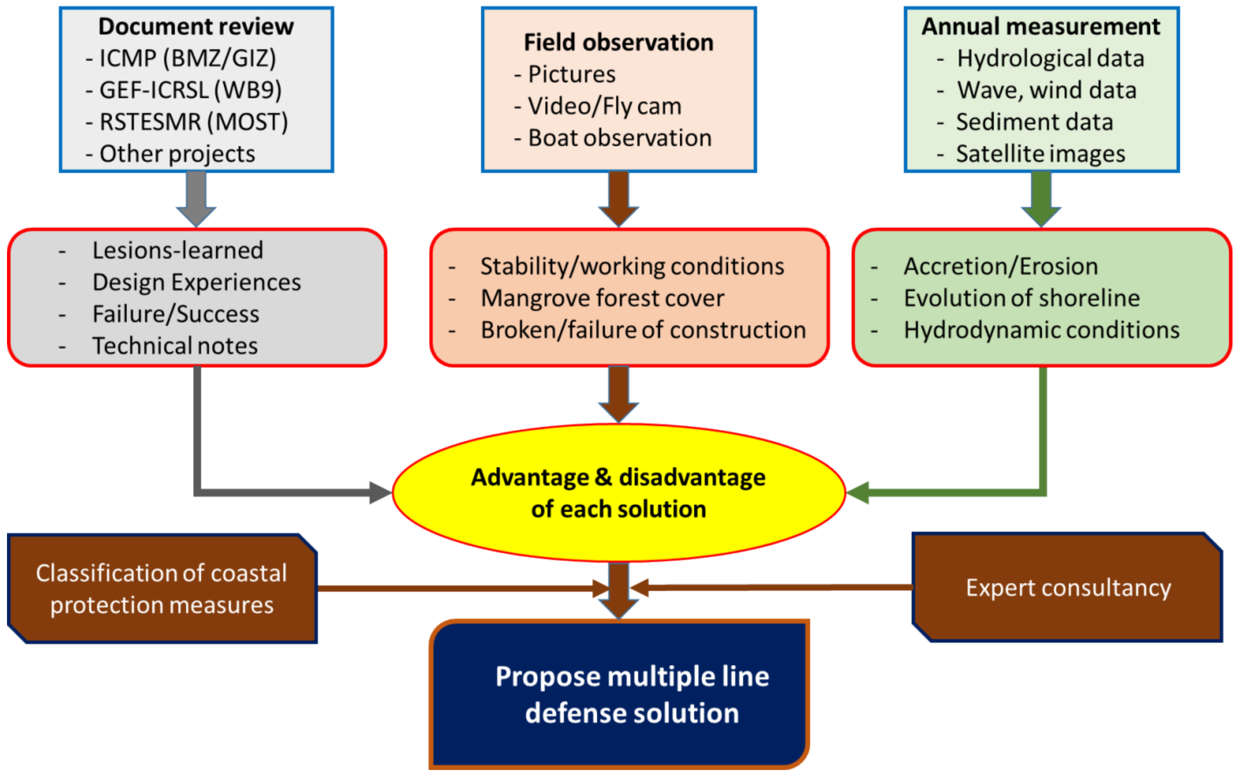


Figure 1. Flow chart of research methodology

3. History of coastal accretion and erosion in the coastal VMD

In the last 15 years, coastal erosion has occurred frequently in the VMD coastline, causing massive land loss, severe damage to coastal infrastructure, and degradation of mangrove forests (Figure 2 and Figure 3). The extent of coastal erosion is approximately 275 km of the 744 km total shoreline with an average horizontal erosion rate of 15 m to 50 m/year (Southern Institute of Water Resources Research, (SIWRR, 2018), with 168 km of the VMD shoreline under severe erosion. Moreover, Li et al. (2017) showed that 66% of the total shoreline of the VMD is in an eroding state, which has been increasing due to significant decreases in sediment supply caused by upstream dam construction. The results of satellite image analysis in the period 1990-2015 show the location of erosion and accretion along the coast of the Mekong Delta (Figure 4 and Figure 5). Coastal erosion can be classified into erosion caused by natural processes and erosion caused by anthropogenic activities (Erban et al., 2014; Nguyen et al., 2016; Minderhoud et al., 2017; Parker, 2020). Studies indicate that deficit of sediment transported to the VMD from the upper Mekong River basin significantly contributes to erosion along the VMD coast (Tamura et al., 2020; Anthony et al., 2015).

Figure 6 shows several examples of shoreline changes of some erosion/accretion areas in the Coastal of VMD during the 1990-2018 period.

Coastlines from Tien Giang to Ca Mau Cape that have numerous areas with siginifcant erosion impacts include: the Tan Thanh area, the Go Cong Dong district, the Tien Giang province (with an average erosion rate of 30 m/year); the southern Ham Luong estuary in Thanh Hai Commune, the Thanh Phu District, the Ben Tre Province (37 m/year); the Vinh Hai, Lai Hoa, and Vinh Tan areas - Vinh Chau town, Soc Trang province (30 m/year); the Nha Mat, Ganh Hao - Bac Lieu (25m/year) areas. The area around the Bo De estuary, the Ho Gui estuary in Tam Giang Dong and the Khai Long communes of Ca Mau have strong erosion rates of more than 40 m/year. The coastal area from the Cua Tieu estuary to the East Cape of Ca Mau not only has strong erosion, but also has strong accretion. Finally, the Cu Lao Dung area, Soc Trang province, Dat Mui - Ca Mau province has an average accretion rate of 30-50 m/year.

The Western coast from Ca Mau to Kien Giang alternates with areas of accretion and erosion. The strongest erosion is at the coast of Tran Van Thoi and U Minh - Ca Mau with a rate of 20-40 m/year, in An Minh, An Bien district - Kien Giang with a erosion rate of 15-25 m/year. There is a strong accretion area around the mouth of the Bay Hap river and the Cua Lon river and on the west coast near Ca Mau cape, the accretion rate is 15-40 m/year.

Figure 2. Coastal erosion in Mekong Delta (a) Tan Thanh – Tien Giang, (b) Duyen Hai – Tra Vinh and Vinh Chau - Soc Trang (c, d) (Note: photo c, d from Albers et al. 2013)

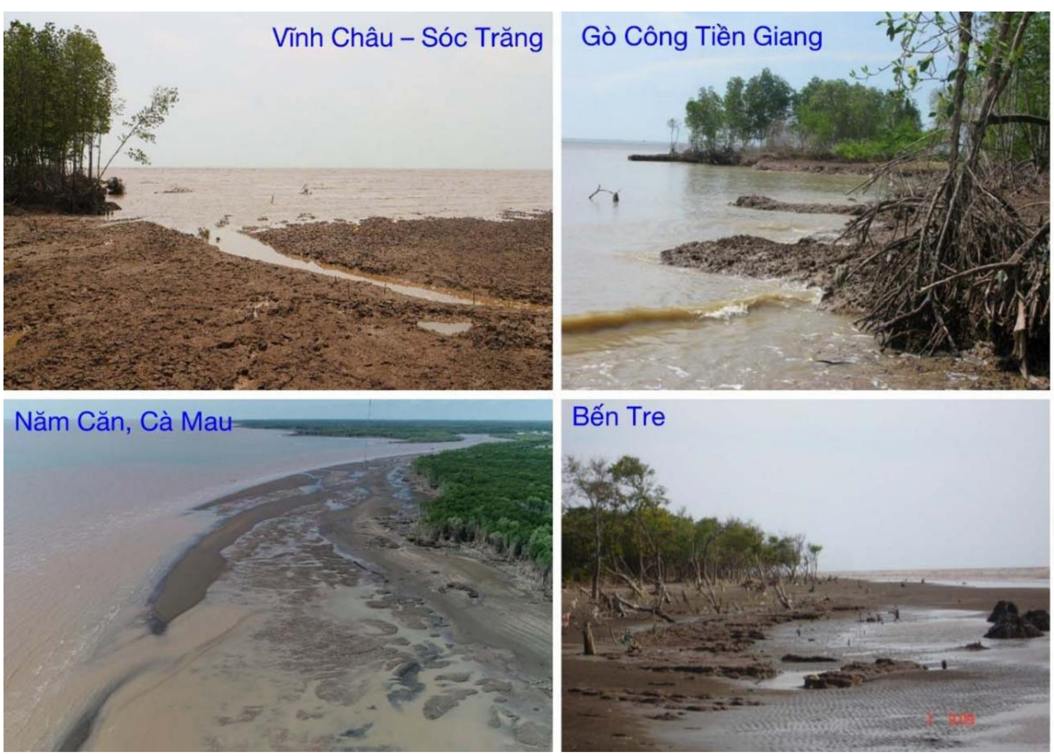


Figure 3. Coastal erosion in Soc Trang, Tien Giang, Ben Tre, Ca Mau in coastal VMD (Source: SIWRR, 2020)

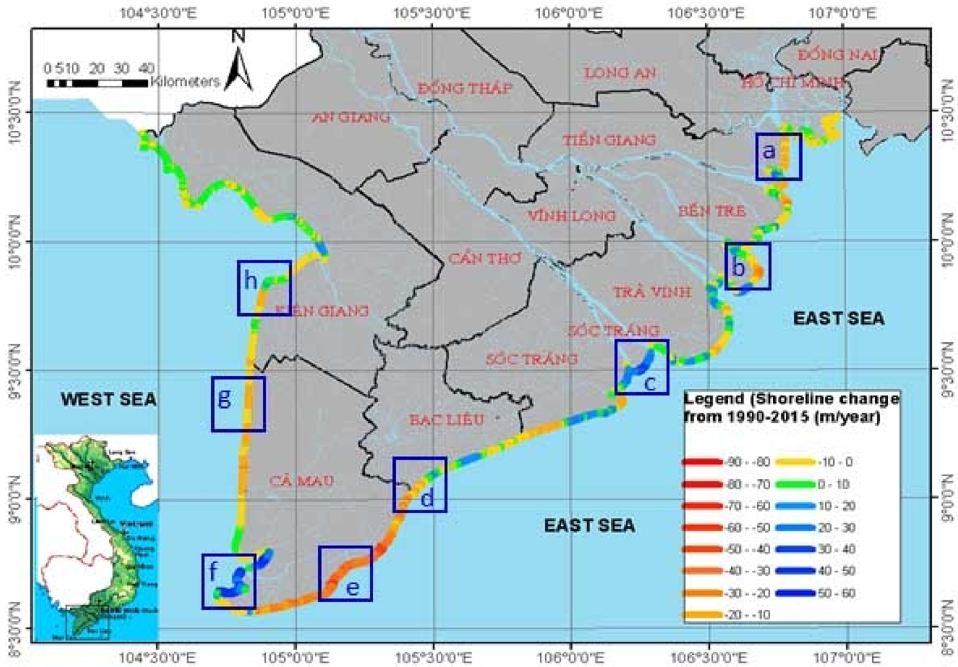


Figure 4. Shoreline erosion from 1990 to 2015 in the VMD (Source: SIWWR, 2020)

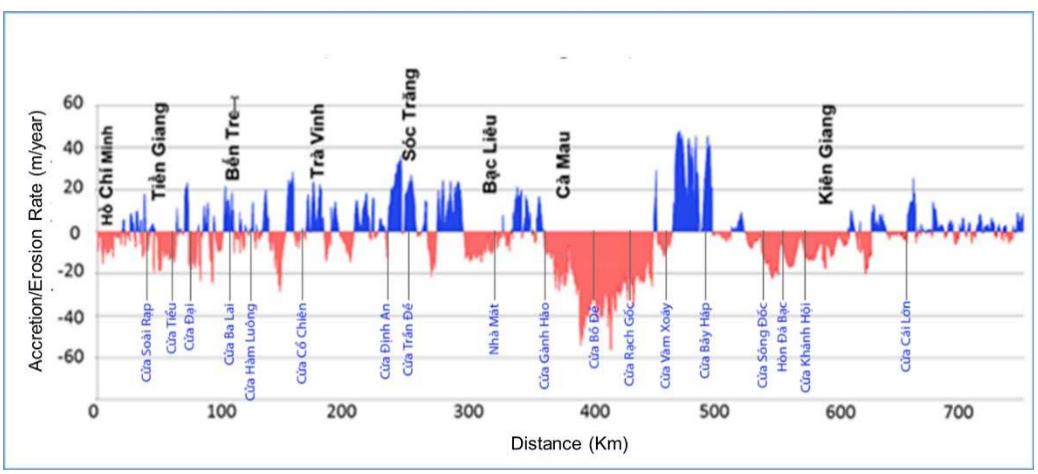


Figure 5. Average erosion/accretion rates of the VMD coastline for the period 1990-2015 (Source: SIWWR, 2020)

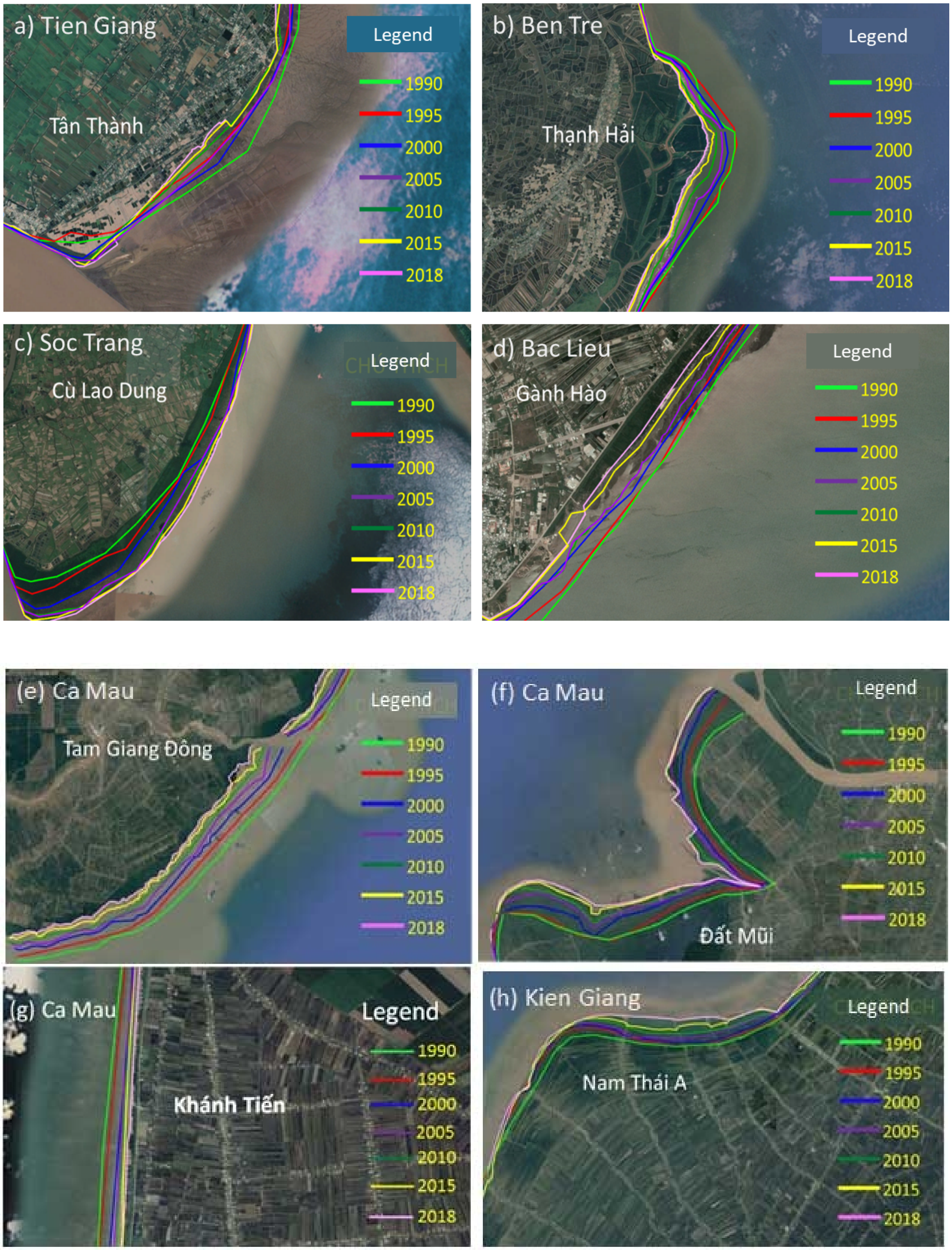


Figure 6. Shoreline developments of some erosion/accretion areas in the Coastal of VMD during 1990-2018 (Source: SIWRR, 2020)

4. Evaluation of current measures for coastal protection in VMD

Numerous measures are being adopted to protect the VMD coast and restore the mangrove forests. These measures include direct and indirect shoreline protection and offshore wave reduction techniques (Frank Thorenz, 2016; Le Xuan et al. 2020). These alternatives generally work effectively initially in terms of wave reduction and sediment trapping, but they reveal several shortcomings over the longer-term use. Over time, severe structural damage may occur and these measures degrade the breakwater performance. In the sections that follow the advantages and disadvantages of specific coastal protection structures that include: revetments, geotubes, t-shaped bamboo fences, Pile-rock breakwaters, Busadco's breakwaters, Semi-Circular breakwaters, and Hollow triangle breakwaters is reported over the study period.

4.1. Revetments

Revetments (Figure 7) are sloping structures located on banks or cliffs and are designed to absorb the incident wave energy. This structure protects the coastline directly by application of precast concrete blocks installed in the riverbank slope. This type of construction is suitable for low and weak incident waves for protecting coastal urban areas or tourist spots. Revetments have been recently constructed in Go Cong, Tan Thanh, Tien Giang, Tra Vinh, Soc Trang and Ca Mau (Figure 7). Several benefits while engagaing the revetments have noticed such as erosion reduces under the waves and currents action, no complexity in construction, and high stability is observed. Despite these benefits revetments are not appropriate to restore the mangroves forests. This construction is not found as eco-friendly, hardening the shoreface, preventing expansion of the hinterland. Additional disadvantages of revetments include unstable to trap sediment in stabilize the shoreface and require a high capital investment for construction.

Figure 7. The revetments constructed in Go Cong, Tien Giang and Long Hoa, Tra Vinh, VMD (Source: SIWRR, 2020)

4.2. Geotube breakwaters

Geotube breakwaters are constructed from large sand filled bags and positioned at offshore to reduce incident wave energy (Albers et al., 2013). For instance, a Geotube breakwater was constructed along the VMD coast in 2019 with a total length of 6.7 km and the Tien Giang; Hiep Thanh, Tra Vinh, Nha Mat, and Bac Lieu coasts (Figure 8). The key advantage of Geotube breakwaters is that they are relatively simple to construct as they can be filled with local sand materials. This types of constructions need less investment. However, the disadvantages of this breakwater are its short lifetime due to damage to the outer lining from incident waves, human impacts from water transport anchoring , and punctures from drifting objects (wooden trunks, sharp garbage). Leaked bags spills sand that can also reduce the crest elevation and decrease the ability to obstruct the incident waves. Moreover, the geotube has a low capacity to promote the sedimentation and water exchange for facilitating aquatic species due to its nature of impermeability. These problems is reported in Nha Mat and Bac Lieu, Hiep Thanh – Tra Vinh, Go Cong- Tien Giang. This reduced sediment flow is in the hinterlands cannot create favorable conditions for mangroves restoration. Lastly, the maintenance cost is also high due to frequent geotube lining failure and occasional structural failure. Once the structure becomes unfunctional, the remaining of these breakwaters create garbage on the coast that takes a long time to decompose, polluting the coastal landscape. Due to these disadvantages, this breakwater structure can only be applied in areas where severe coastal erosion requires urgent short-term (3 – 5 years) and medium-term (10 – 15 years) control.

Figure 8 demonstates the geotube project built in Nha Mat in 2013 and Tien Giang in 2017. After 2 years of operation, the sand bag was found in significant damage leading to lower crest elevation, reducing the wave energy dissipation efficiency of the breakwater. The sedimentation zone in the hinterland was formed with an increased sediment layer of 30-50 cm, but the mangrove forest was not reproduced due to high waves crossing through the Geotube breakwater. When the dyke breaks, the waves and currents carry the sediment and sediment elsewhere eliminating the settlement of mangrove forests.

Figure 8. The Geotube breakwater constructed in Nha Mat- Bac Lieu (top panel) and Go Cong Dong and Tien Giang (bottom panel) (Source: SIWRR, 2020)

4.3. T-shaped bamboo fence

Another coastal protection measures available in VMD are T-shaped bamboo fences. T-shaped bamboo fences are a permeable dam with a double row of bamboo fences. The first row is filled with soft brushwood bundles and the second row is filled with stiff brushwood bundles (Schmitt & Albers, 2014; Albers & Schmitt, 2015; Winterwerp et al., 2020, Tuan and Luan, 2020). A T-shaped bamboo fence of about 800 meters long was constructed by Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) organization in a pilot project in 2014 in Vinh Tan commune, Vinh Chau town, Soc Trang (Schmitt et al., 2013) (Figure 9 – top panel). The project aimed to restore mangrove forests and protect Vinh Chau sea dikes. However, after a couple of monsoon seasons, the fence was breached due to the severe environmental conditions (i.e. alternating dry and wet conditions leading to rotting of the bamboo trunks) and the submerged part of the bamboo poles were severely broken down by the barnacles (Figure 10). This physical damages leads to deflection of the structure and loosening of the structural joints. As soon as the fences were constructed, sediment accumulated, mangrove species naturally regenerated with high density and tree height. Therefore, the role of bamboo fences is to trap the sediment in the short term, and the project was considered relatively successful. The T-shaped bamboo fence is successful for sediment trapping however these breakwaters can be easily washed away with severe storm surge. In several location adopting the T-shaped bamboo fence is found unsuccessful. For instance, with almost the same boundary and natural conditions as in Vinh Tan, the T-shaped bamboo fence near the wind power plant in Bac Lieu province completely failed to support the restoration of mangroves forests after only a few northeast monsoon seasons. The bamboo fences with different structures (1 layer, 2-3 layers) were broken by waves, coastal currents, and the harsh natural marine environment. Some mangrove seedlings were uprooted due to the effects of incident waves and deficit of sediments, which created unfavorable conditions for their growth. The resaon is promarily attributed to high wave actions. There have been several reasons proposed as to why the bamboo fence was efficient in Vinh Tan and inefficient near the Bac Lieu wind power plant. Previous research suggested that in Vinh Tan the mudflats are mainly formed with fine sand and mud that are transported from the adjacent mudflats and retained in the mangrove planting areas. In contrast on the front/offshore beaches in the Bac Lieu coast there are no mudflats are present rather sandy coast.

Soft wall solutions (i.e., bamboo fences with one layer or 2-3 layers) have been continuously advocated by the Institute of Ecological and Work Protection (Tuan and Luan, 2020). The soft walls are constructed using local materials, including bamboo piles, branches, horizontal and vertical splints, plastic-coated zinc wires, and plastic wires. The soft wall measures were constructed and tested in Hon Da Bac, Ca Mau province, but this type of breakwater was also destroyed quickly after a few southwest monsoon seasons (Figure 9 – bottom panel).

The T-shaped bamboo fence has the advantage of wave attenuation of both high- and low-frequency waves. The differences in the fence porosity effects on the transmission coefficient (Tuan and Luan, 2020). The T shaped bamboo fence promotes the mangrove restoration and accumulation of fine-grained sediment in some areas with low-cost local materials. However, some of its disadvantages are, its unstablity with relatively high waves and strong currents, steep slope of the coast, and short construction life. This type of construction is only applicable in flat areas with low wave height, low erosion rate, and or wave has a tendency to accretion. These bamboo fences are effective in recovering mudflats and facilitating the mangroves restoration in the short term.

Figure 9. The T-shaped bamboo fence damage after three years in Vinh Tan, Vinh Chau (top panel), and Hon Da Bac - Ca Mau (bottom panel) (left-bottom picture courtesy R. Sorgenfrei, 2016)

Figure 10. The T-shaped bamboo fence destruction after four years in Nha Mat, Bac Lieu (March 2022) due to harsh environmental conditions and severely corroded by the barnacles (Source: SIWRR, 2022).

4.4. Pile-rock breakwaters

The structure of Pile-rock breakwaters consists of two rows of round concrete piles linked with a beam frame system at the top of the pile, filled with granite rocks (Frank Thorenz, 2016; Le Xuan et al., 2020; Luom et al. 2021). Examples of this structure include a stretch of coast of more than 50 km long, mainly on the west coast of Ca Mau, more than 5 km in the East Sea, and 2.5 km located in Vinh Chau-Soc Trang; Nha Mat, Ganh Hao, Bac Lieu; Rach Goc, Rach Mui, Ca Mau (Figure 11).

Laboratory experimental results of Pile-rock breakwaters show that this type of breakwater has a significant wave energy dissipation ability from 60% to 80% (Le Xuan et al., 2020). Moreover, field measurements in multiple locations (i.e. Ca Mau, Bac Lieu) indicate that the wave reduction efficiency of this breakwater was relatively high, approximately between 50% to 80%. These results concretely confirm the efficiency and stability of Pile-rock breakwater.

The main advantage of pile-rock breakwaters is their high sediment accumulation potential due to their porous structure allowing fine-grained sediment to penetrate through the structure that creates accretion in the hinterland. This breakwater has also been shown to be stable on soft foundation in the mud coast of the VMD. However, there are several disadvantages of this structure. The reflected wave of this structure was found to be high (over 50% in Le Xuan et al., 2020). The possibility of foreshore erosion is very high, according to the monitoring data in Ganh Hao, toe erosion reached -0.40 m/year. As these breakwaters are permanently fixed on certain coastal locations they also cannot be reused or the post construction maintenance are not easy. Furthermore the concrete beams connecting the top of the piles is difficult to setup in construction which may affect the overall quality of the breakwater structure. The continuous construction without gaps disrupts the process of sediment exchange and the environment affecting the sedimentation capacity and the restoration of mangroves. Therefore, it is necessary to adjust the spatial arrangement (distance between dike sections, distance from dyke to shore) to make the breakwaters work more efficient.

Figure 11. The pile-rock breakwater constructed in Soc Trang, Bac Lieu, and Ca Mau (Source: SIWRR, 2020)

4.5. Non-metallic reinforced hollow breakwater

The non-metallic reinforced hollow breakwater example is hollow breakwater in the west sea of Ca Mau province constructed in 2018 by the Busadco company. The structures were built from Vam Da Bac to Vam Kenh Moi with a length of 1.2km, and at the East sea in Rach Goc estuary, Ngoc Hien, Ca Mau with a length of 2.0 km (Figure 12). These constructions were seriously damaged in the 2018 monsoon season. The structures was later fixed by adjusting the diameter of the holes from 25cm to 12cm and increased the thickness of the rock layer from 1m to 1.2m in the breakwater toe in a short time. This rapid installation and repair works indicates an advantage of the reinforced hollow breakwater as all materials are already manufactured with high quality and accurate dimensions. However, the disadvantages of the breakwater are presented are: 1) The weight of the components is insufficient to ensure self-stability for construction, 2) High waves transmitted behind the construction create shoreline erosion due to large pores size (> 32%).

Figure 12. The Busadco's hollow breakwater was constructed in the West (left-top panel) and East Seas, Ca Mau coast (Source: SIWRR, 2020)

4.6. Semi-Circular Breakwater

The semi-circular breakwater is a 2.6 m high, half-hollow prefabricated cylinder, with both sides perforated using casting reinforced grade 50 MPa. This structure was built in 2016 having a total length of 180 m in the areas between Vam Da Bac and Vam Kinh Moi, Khanh Binh Tay, Ca Mau (Figure 13- top left). When the installation was completed, the breakwater was moved during the monsoon season and required additional loads of rocks to maintain stability. This breakwater produced positive initial impacts on sediment accumulation in the West Sea. An updated version of this breakwater was developed and built over a 500 m stretch of coastline in Tran Van Thoi in 2018 and another 200 m in Nha Mat, Bac Lieu in 2020 (Figure 13). This updated structure was 3.04 m in height and 16 tons in weight that can effectively attenuate the energy of incident waves and increase the stability in the strong influence of morpho-dynamic conditions. One of the advantages of this breakwater is its ability to capture sediment in the hinterland due to the perforation on both sides. The drawback of this breakwater is that the structure was placed directly on a soft foundation leading to considerable subsidence. There were no interlock between the components causing instability of the construction over time.

Figure 13. Semi-Circular breakwater was constructed in Nha Mat, Bac Lieu, and Ca Mau. The uneven subsidence of this structure is shown in April 2020 (Source: SIWRR, 2020)

4.7. Hollow triangle breakwater

The Hollow triangle breakwater (TC1) was developed by the Southern Institute of Water Resources Research (SIWRR) in 2017 (Appendix A). An example structure constructed in Con Cong, Tan Thanh, Tien Giang, in the VMD is provided in Figure 14. These breakwaters have a trianglular prism shape with perforations on both the coast and ocean side. The structure varies between 2.5m and 3 m in height and between 9.0 and 12.0 tons in weight. Le Xuan et al. (2022) tested a physical model of a hollow triangle breakwater with different percentages of porosity and incident wave conditions with wave reduction efficiency at in laboratory in SIWRR. Moreover, the field measurement results also showed that the efficiency of wave reduction of this breakwater was approximately 60-75%. At present, these constructions have achieved the goal of reducing erosion and has increased hinterland sedimentation by about 60cm to 80cm, leading the mangrove seedlings to start growing markedly on Con Cong – Tien Giang (Figure 15).

This structure has advantages that overcome several shortcomings of previous breakwaters such as the need to increase the weight of the breakwater components; longer and more stable interlocking between components; optimization of porosity (diameter and number of holes), more stable structural shape, an foundation reinforcement by the introduction of melaleuca pile rafts to avoid deflection and subsidence (Le Xuan et al., 2022). So far, there is no evidence of any failure or deficiency with this type of breakwater. This breakwater works as a filter for most short-breaking waves (waves generated by the wind) but allows partially long waves to pass and carry sediment through the breakwater to allow exchange of marine species and sediment. Due to the advantages of this breakwater, it has recently been applied in Con Cong in 2019 under the pilot project with total length of 1.6 km, and further extend to construct in Tan Thanh coast -Tien Giang in 2020 and 2021 with a total length of 3.2 km.

Figure 14. The Hollow Triangle Breakwater constructed in Con Cong, Tan Thanh, Tien Giang, in the VMD (Source: SIWRR, 2021)

Figure 15. The sedimentation and the restoration of mangrove apple (*Sonneratia caseolaris*) behind the dyke (right) at Con Cong coast – Tien Giang (Source: SIWRR, 2021)

4.8. Critical summary of lessons learned about current measures

The lessons learned from the previous coastal erosion projects are summarized as follows:

- Coastal erosion in the VMD coast has been a critical problem for several years, with an increasing sea-level rise at both temporal and spatial scales. Unfortunately, there has been no comprehensive planning for the entire region. Consequently, there is no effective shoreline protection strategy, while many structural efforts have caused adverse effects that have contributed to erosion in neighboring areas;

- Coastal erosion occurs on a large scale with different levels of severity, requiring significant capital investment to implement protection solutions throughout the region. However, the local investment is minimal, and local governments can only focus on immediate issues. With limited funding, provinces end up carrying out coastal protection work in small disconnected fragments and do not invest adequately in science and technology to research appropriate protection solutions for each area. The solutions are mainly for local and single treatment, not yet applicable to a whole system with many different coastal protection components.

- The Geotube breakwater has been applied on numerous coastline locations in the VMD but some of these structures have almost failed such as in Nha Mat, Bac Lieu in 2013, Con Nhan, Tra Vinh in 2015; Go Cong, Con Ngang – Tieng Giang in 2016. This indicates that this structure should not further applied in the VMD without significant technical improvements to the quality of sand bags used in the construction.

- The T-shaped bamboo fence has been shown to effectively reduce wave energy and has facilitated sedimentation in some areas (i.e., Vinh Chau, Soc Trang) but was has not been operationally effectively in other locations with strong wave and forceful currents (i.e., Bac Lieu and Soc Trang). Furthermore, this structure has a short lifetime and requires regular structural maintenance to allow for long-term protection of the coastline.

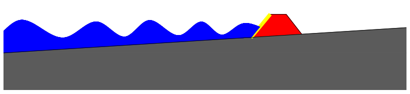
- The coast of Ca Mau province has experienced the worst erosion rates and the most significant mangrove degradation over the past two decades due to the decline of sediment accretion, increased subsidence and sea level rise along with the process of deforestation to converst large areas into shrimp ponds and farm land. Many types of breakwaters were applied along this coastline, but no monitoring and evaluation system has been implemented to evaluate the effectiveness of the various shore protection measures. So far, there is not enough scientific evidence to: i) confirm the effectiveness of coastal protection technology; ii) provide guidance on optimal layout of the structures; or iii) determine which type of breakwater offers the most effective protection under specific conditions when submerged or emerged state.

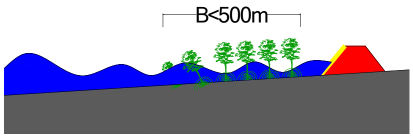
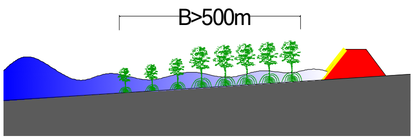
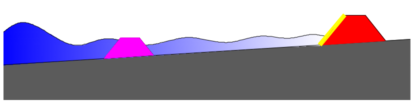
- The perforated breakwaters such as Semi-Circular, and Hollow triangle breakwaters have many advantages. These include high quality construction, effective wave reduction, and smaller reflected waves than those structures that employ vertical walls. The level of stability of these breakwaters is generally higher, there is a more efficient exchange environment between seaside and shoreside, and they can be constructed relatively quickly and re-deployed to other locations along the coastline. Due to these advantages porous breakwaters show the most promise for widespread application in the VMD. However, several of these porous breakwaters including Semi-cicular breakwaters and Non-metallic reinforced hollow breakwaters require further investigation to improve their spatial layout, overall structural strength, optimal perforation percentage, hole size, and appropriate reinforcement of foundations.

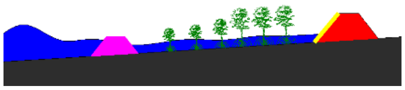
5. Classification of possible sustainable measures for coastal management of VMD

It is hard to achieve sustainable coastal protection without consideration of the technical, social-economic, and environmental aspects of the multiple solutions. Therefore, we classify the coastal system into four types and a brief evaluations for each type is presented in Table 1. To classify the current coastal protection system applied in the VMD coast, we considered two main functions of the system: preventing erosion and flooding for the coastal strip and no further assessment of environmental and ecosystem functions. Different components protect the VMD coast. Each component has its own function. For example, sea dykes only prevent water from overflowing into the hinterland and do not serve an erosion resistive function. Also, revetments function as an armor that protects the shoreline to reduce erosion, but these structures prevent sedimentation from occuring. The offshore breakwaters have the function of reducing incident waves and also enabling sedimentation. However, they are not able to prevent over topping. Mangroves can block and reduce the amplitude of incoming waves, augment sediment trapping, and maintain and improve ecosystem resilience to climate-induced sea-level rise.

Table 1. Classification and evaluation of the current coastal protection system

Coastal System Classification	Description	Evaluation
Type 1: Sea dike/embankment without additional measures 	The areas of cultivated land or only earth dykes, sea embankments contiguous face to the sea, directly affected by waves, storm surge.	This system is at high risk of damage and over topping water without revetments on the seaside. Erosion of sea dyke foot frequently occurs when tremendous tides and storm winds attack.
Type 2a*: *Sea dyke/embankment + mangrove forest (B<500m)	Mangrove belts in front of sea dyke with a thickness of < 500m. Coastal erosion can occur if the thickness of mangroves is not enough	This system is at high risk of damage due to the degradation of protective mangroves forest. Protection capacity under

	to protect the sea dyke. In these conditions the mangrove forest can rapidly narrow.	tremendous tide and storm surge are low. If there is no protection and restoration solution, over time the mangroves disappear and this becomes Type 1.
Type 2b: Sea dyke/embankment + mangrove forest (B>500m) 	Mangrove belts in front of sea dyke with the thickness > 500m. The protection of mangroves is sufficient for the sea dyke behind.	This system works effectively with enough thickness of mangroves forest. The protection capacity of this type under tremendous tides and stormwind attacks is very efficient.
Type 3: Sea dyke/embankment + offshore breakwater 	Sea dyke with revetments and an offshore breakwater.	This system only ensures the safety of the sea dyke in the case of monsoon winds, and allows sediment accumulation. Reduction of water overtopping inside under tremendous storm surge. The protection capacity is low.
Type 4: Sea dyke/embankment + mangrove forest + offshore breakwater	Sea dyke with revetments, a central mangrove forest, and an offshore breakwater.	This system is complete with multi-layer protection. High tide and storm surges are reduced

	significantly by the breakwater. The remaining energy is dissipated by the mangroves to protect the sea dyke.

The VMD coast is highly vulnerable due to coastal erosion and sea level rise and land subsidence, but the current coastal protection system is not complete due to limited regional capital investment. Mangrove belts along the coast of 601.7 km are mainly natural forests that are combined with planted forests. At the same time, other shoreline protection solutions such as revetments, embankments, and breakwaters are built very limitedly, accounting for only 10% of the coastline (82.35 km). Most importantly, the current shoreline protection solutions are still both single and discrete; there is no practice of applying a combination of solutions to achieve higher effectiveness. Therefore, it is essential to continue upgrading coastal protection in an integrated approach by applying multiple solutions with appropriate functions to achieve optimal benefits.

6. Outlook and strategy for coastal management

6.1. Multiple Lines of Defense Strategy for sustainable shoreline

"*The Multiple Lines of Defense Strategy (MLDS) identifies a system to reduce flooding for coastal communities through natural landscape features found in a healthy estuary and engineered structural features such as levees and floodgates*" (https://www.crcl.org/mlods). Initially, the new *MLDS* concept was applied to the lowland coast to combine many components for shoreline protection and ecosystem restoration in the USA, such as Louisiana in 2006, and the North Atlantic region in 2015. This strategy is based on the principle of "Building with nature" or "Green

Infrastructure” as previously introduced. The general approach is to restore the natural coastal protection system by utilising various complementary protection measures.

The multiple lines of defense proposed for Louisiana, the United States, including hard and soft solutions that included construction of a barrier island, a new highway, a flood gate and levee as well as other hard engineering structures such as a marshland bridge, natural ridge, higher building regulations, and an evacuation route as a soft solution (Lopez, 2009). To protect the coast from erosion and restore America's coastal ecosystems, the "Living shoreline" project was proposed (New Jersey Resilient Coastlines Initiative, 2016). Due to the demonstrated coastal protection and environmental benefits, there are many countries with coastal lowlands that have applied multiple lines of defense solutions such as the Netherlands, Germany, Louisiana (USA), Java (Indonesia), or Samut Sakhon (Thailand) in recent years (Lopez, 2009; Naohiro et al., 2012; Winterwerp et al., 2020).

6.2. Multiple lines of defense in the coastal VMD

Integrated Coastal Zone Management (ICZM) has developed a coastal protection plan in the direction of coastal protection by combining natural and artificial solutions to maintain coastal ecosystems while allowing for further socio-economic development. The strategy is to reserve space for the beach, and we propose a new term "Room for the Coast" to potentially apply for the VMD region.

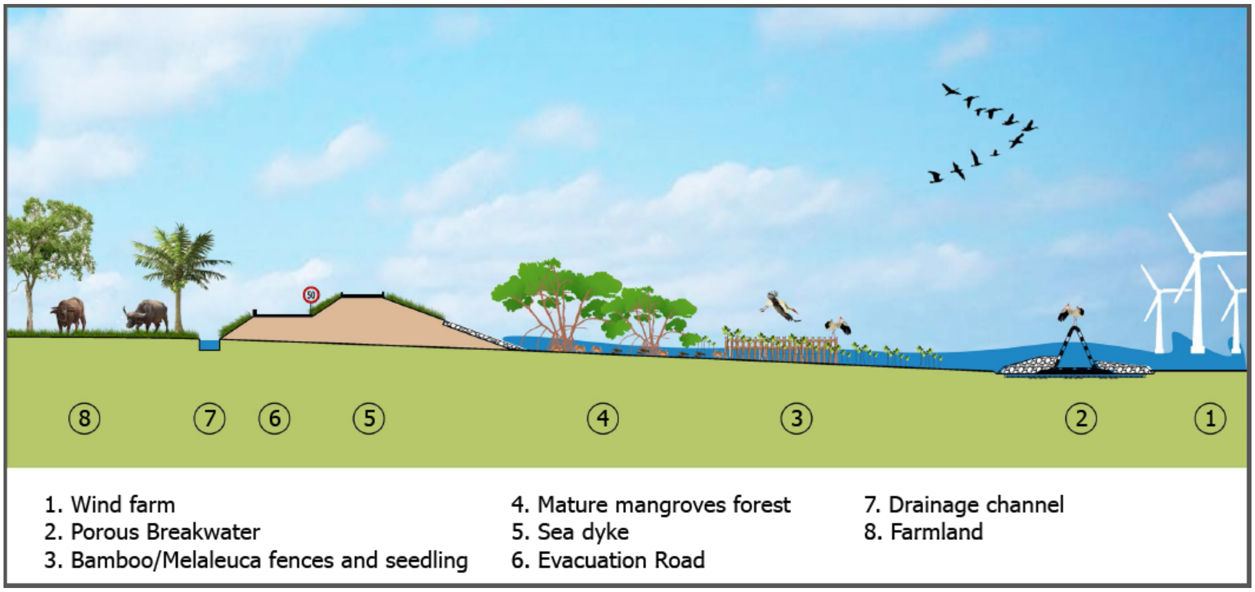


Figure 16. Proposed multiple lines of defense for the VMD coast

Figure 16 illustrates the complete system of multiple lines of defense solution for the coastal VMD, including main components such as offshore porous breakwater/groins, bamboo/coconut or melaleuca fences, a mangrove forest, and a sea dyke. Porous breakwaters are the main barrier to reduce the strong incoming waves and to allow sediment to pass through. Bamboo/melaleuca T fences work as permeable breakwater to rapidly trap the sediment, reduce the horizontal velocity significantly for vertical settling fine sediment, and help mangroves seedlings take root into the soil under a calm water environment. Moreover, seed pods germinate while on the mangrove tree, so they are ready to take root when they drop under calm water conditions and settle in a suitable substrate within the sedimentation basin. Mature mangroves are an effective defense line to dissipate completely remaining wave energy to protect the sea dyke behind. Besides, mangroves also bring enormous benefits in terms of economics and environment, such as habitat for flora and fauna, biosphere reserve for carbon sequestration and exchange, wastewater filter system for aquifers, and a clean ecological environment. The sea dyke is the last defense line to prevent the saltwater from overflowing into the villages' farmlands, assets, and houses.

The construction of multiple lines of defense solution in the Mekong Delta has been established at numerous locations such as the coast of Phu Tan, U Minh- Ca Mau; the coast of Go Cong Dong, Tan Phu Dong -Tien Giang; Ganh Hao coast - Bac Lieu; Hiep Thanh beach, Dong Hai - Tra Vinh, Ngoc Hien, U Minh - Ca Mau, and Vinh Chau - Soc Trang. Currently, this solution has been deployed to promote its function in preventing coastal erosion and restoring mangroves. Moreover, the accretion rate of sedimentation basin is around 40 – 50 cm/year based on the result of the measurement by SIWRR. Increasing in elevation of sedimentation basin behind offshore breakwater is positive signal to adapt to sea level rise by climate change.

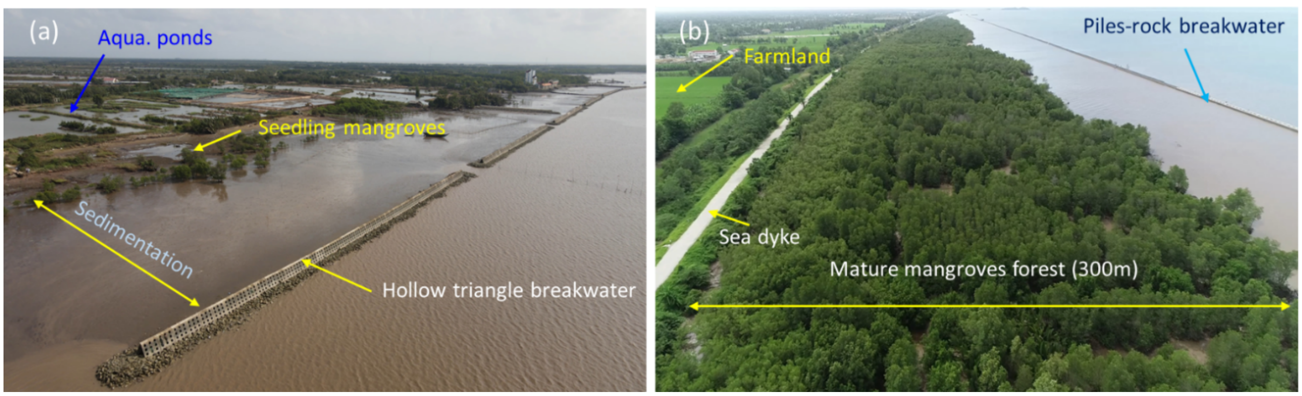


Figure 17. (a) The MLD solution deployed in Con Cong-Tien Giang (the Hollow triangle breakwater was constructed in 2019), (b) the MLD in U Minh-Ca Mau (the Pile-rock breakwater was constructed in 2013).

Figure 17a shows the initial formation of a MLD solution in Go Cong, Tien Giang, with positive first steps towards reducing incoming waves and allowing for sedimentation behind the breakwater. Specifically, mangroves seedlings have started to grow due to the recovery of the sedimentation basin resulted from constructing the Hollow triangle breakwater in 2019. Bamboo or melaleuca fences may be built behind this breakwater to stimulate sediment accumulation to ensure more rapid mangrove restoration. Meanwhile, the full function of the MLD solution in Phu Tan, U Minh - Ca Mau demonstrates significant effectiveness of this solution. Eight years after the breakwater was constructed, the reduced incoming waves increased sedimentation and restored a 300m wide mangrove belt. As well as the benefits from the restoration of the ecosystem, the restoration of the mangrove forest between the breakwater and the innermost sea dyke serves as a protection measure to prevent sea water from overtopping the sea dyke (Figure 17b).

Based on many studies and lessons learned from field investigations in the VMD, we classify coastal protection situations into five types, and propose a solution for each type as described in Table 2. With five types of coastal protection systems existing along the coastal strip of the VMD, there is a clear need to develop a hybrid solution to eliminate the adverse impacts of sea-level rise.

Table 2. Situation and proposed solutions for different types of coastal VMD.

Type	**Situation**	**Proposed solutions**
Type 1	The coastal strip is eroded without protection by mangroves forest, and without wave reduction structures.	Urgently reinforce the revetments/sea dykes, then construct additional sea dykes to prevent water from overflowing into the fields, followed by building offshore breakwaters to reduce waves causing accretion, bamboo or melaleuca fences to trap sediment and to restore mangrove forests;
Type 2	The coastal strip is eroded, no mangrove forests, no breakwater structure, and non-suitable conditions for restoration of mangroves due to slow sedimentation.	Construct revetments and sea dykes, and create sand dunes/beaches. Mud nourishment should be applied to enrich the land reclamation before planting mangroves.

Type 3	Mangroves forests have protected the coastal strip, but the mangrove forest is being eroded and degraded.	Quickly construct offshore breakwaters, then build bamboo or coconut trunks fences to prevent the ongoing degradation of mangroves, then restore mangroves in the lost areas and, if possible, expand mangroves.
Type 4	Mangroves forests no longer protect the coastal strip. The breakwaters have been built for sedimentation but sedimentation rate is slow (Figure 17a).	Evaluate the effectiveness of the sedimentation and wave reduction ability of different breakwaters, especially to evaluate the adverse impact of the breakwaters on neighboring areas to find suitable solutions. Simultaneously, need to restore mangroves' forests. Mud nourishment should be applied to stimulate sediment accumulation rapidly.
Type 5	The coastal strip is stable without erosion, with effective protection of mangroves forest, and a stable sea dyke (Figure 17b)	No additional work is required. Moving forward pay attention to the management and protection to avoid harmful activities that cause damage to the shoreline and mangroves forests.

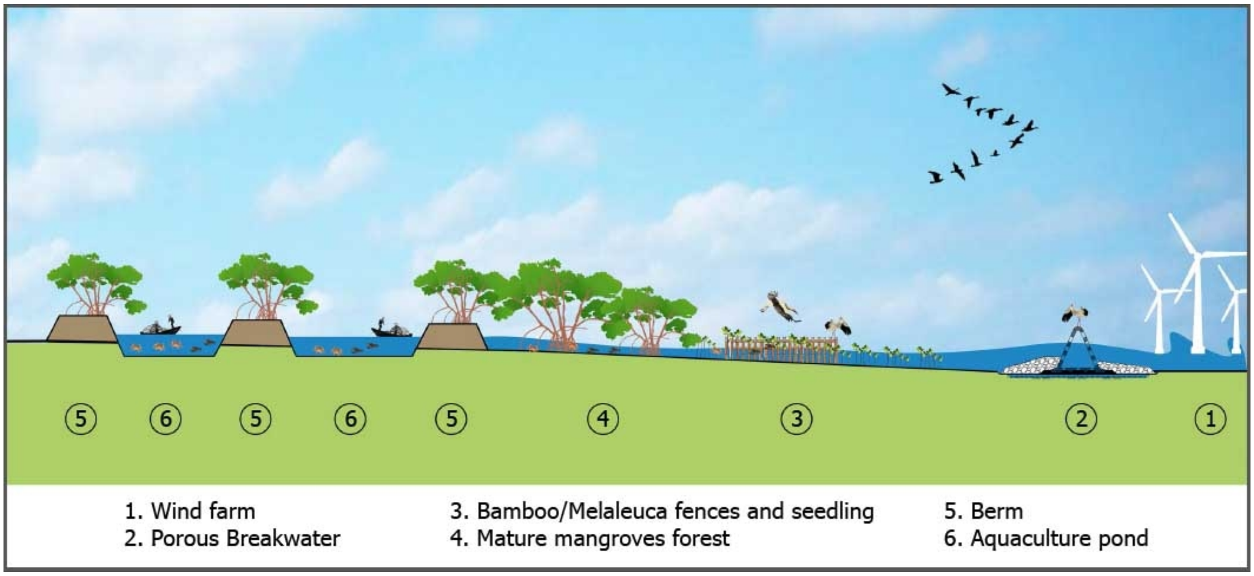


Figure 18. The MLD and Integrated Mangrove Forest – Aquaculture Systems in coastal VMD

The MLD system can also be integrated with aquaculture ponds for shrimp and crab farming. A numbers of aquaculture ponds can be constructed behind the MLD solution for the purpose of brackish water shrimp farming. This model promotes socio-economic efficiency in creating livelihoods for local people in coastal areas such as combining the model of afforestation with natural aquaculture so-called Integrated Mangrove Forest – Aquaculture Systems (Figure 18). Integrated mangrove−shrimp farming increases forest protection compliance on State land and increases forest cover on private land. Furthermore, the economic analysis based solely on the economic returns from shrimp culture showed that the farming systems with a mangrove coverage of 30-50% of the pond area gave the highest annual economic returns. These results demonstrate a better economic return to farmers who maintain mangroves in their farming systems (Binh et al., 1997).

6.3. Potential application for global deltas

There are large number of the world's coastline are eroding at rates exceeding 0.5 m/yr and 52% of the world's sandy beaches are unstable (Luijendijk et al., 2018). In which, large river deltas such as Mekong Delta and coastal zone in SouthEast Asia are significantly impacted by coastal erosion. The coast of the Mekong Delta has similar conditions in topography, sediment and mangrove characteristics with the coastal strips in Guyana, Indonesia, Suriname, Thailand, Bangladesh (Joffre and Schmitt, 2019; Winterwerp et al., 2020). These deltas have low-lying topography and are mainly mudflat, creating favorable conditions for mangroves to develop (Anthony and Gratiot, 2012). However, the coastal strips in these delta are also being seriously eroded (Anthony et al., 2010; Saengsupavanich, 2013; Hendra and Muhari, 2018) consequence of massive loss of mangrove forest and therefore the permeable dams (bamboo fences, brushwood) were constructed on these coasts to restore mangrove belt as a low-tech structures based on best-engineering practice but a little of scientific background (Winterwerp et al., 2013; 2020). Single solution such as permeable dams promote positive results in a short time during first three years after constructing. However, after long time of operation without maintenance, these dams are severely damaged by wave and environmental factors such as harsh weather and marine species attack. Moreover, only permeable alone can not withstand the forceful incident wave conditions, strong winds and large water level fluctuations in moonson reasons. The single defense like offshore breakwater or bamboo fense lack sufficient resiliency against future storms and wave surges associated with sea level rise by climate change (Winterwerp et al., 2020). Therefore, the multiple lines defense is an effective solution for these detlas to rehabilitate mangrove-mud coasts. The potential application of multiple lines defense at mudflat coastal areas grobally as above-mentioned is promising as a Nature-based Solutions to create living shoreline to adapt to climate change and sea level rise.

7. Conclusion

The VMD coast is standing at a crossroads. For many years, scientists and managers have struggled with finding suitable solutions for VMD coastal management. These threats affect coastal infrastructures and crops, posing a continuing risk to coastal livelihoods and ecosystems. Hence, it is essential to explore a comprehensive solution that considers multiple aspects of integrated coastal management to achieve sustainable development. From hard to soft solutions, from simple to sophisticated measures, there is no single solution that solves this complex and multi-objective problem. Moreover, there are emerging approaches such as "Nature-based Solutions" to create a "living shoreline" solution in the future, which are friendly and in harmony with the environment and represent a new trend for coastal protection in the way of a green solution. In that context, multiple lines of defense (MLD) strategies that combine hard and soft structures show significant potential for lowland areas like the VMD coast.

In this study we briefly reviewed and highlighted coastal erosion and accretion situations to draw out the need to propose appropriate comprehensive solutions for protecting the coastal environment in the VMD. Based on many years of research, design, and monitoring coastal constructions, we evaluated the advantages and disadvantages of different breakwaters that have been applied on the VMD coast. Since then, many valuable lessons have been learned from practice to serve as a basis for designers and managers to consider future projects. Furthermore, a classification of different ongoing coastal protection systems was introduced to provide area-specific measures for the integrated coastal zone management at a regional scale. Finally, we propose the MLD solution to comprehensively protect the VMD coastal areas in the direction of green infrastructure solutions and make “Room for the Coast" as land reclamation process to mitigate coastal squeeze and improve biodiversity and restore mangroves. This solution can be widely applied in global mangrove-mud coasts with same condition of topography and sediment characteristics with Mekong Delta to better adapt to climate change and sea level rise. Lastly, the MLD solution will need to be further evaluated, adjusted and adapted to individual regions applying the learning by doing method to develop a complete solution that can be applied other coastal areas.

Disclosure statement

The authors reported no potential competing interest.

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Appendix A

Table 1A: Description of implemented coastal protection projects in VMD

No.	Name of projects	Lead executing agency/Implementing organizations	Objectives/Scope of study	The main outputs	Implemented Duration
1	Integrated Coastal Management Programme (BMZ)[i]	MARD/GIZ	The strengthened coastal zone around the Mekong Delta is better able to cope with a changing environment, thereby establishing a basis for sustainable growth	The better protection of 720 km of the Mekong Delta's coastline; more than 3.5 million people in coastal districts safer from the impacts of climate change and successfully introduced T-shaped breakwaters.	2011-2018
2	Annual basic investigation of water resource in Mekong Delta	MARD/SIWWR	i) provide the basic data of wind, wave, sediment and hydrological data for researches. ii) extend and fill out the lack and missing of the basic data. iii) measure the specified data for certain researches.	Data available of all components of hydrological, hydrodynamic conditions, sediment, sea states in Mekong Delta.	2016-2022
3	The Vietnam Mekong Delta Integrated Climate Resilience and Sustainable Livelihood Project (GEF-ICRSL, WB9)[ii]	MARD/CPO	i) strengthen planning tools/plans for climate change adaptation for each region in the Mekong Delta. ii) improve resilience to climate change for land and water resource management activities. iii) create stable livelihoods for people and establish a database system to monitor, operate and support decision making.	• Delta-wide institutional coordination mechanism put in place, with a mandate for integrated planning and decision-making across sectors and provinces in the Mekong Delta; • Number of provinces where planning authorities are using the Decision Support System developed through the project, to inform planning/ selection of low-regret investments;	2016-2022

				• Land area and assets protected/ enhanced by project-financed priority investments to address (i) seasonal flooding, and (ii) saline intrusion, and coastal erosion; • Number of farmer households adopting climate resilient agricultural and aquacultural practices, disaggregated by gender and income	
4	Research on Reasonable Solutions and appropriate Technologies to prevent Erosion and Stabilize the coastline and estuaries of the Mekong River, from Tien Giang to Soc Trang (RSTESMR) (ĐTĐL.CN-07/17)[iii]	MOST/SIWWR	(i) Assess the current situation, causes and mechanisms of erosion and accretion in the coastal strip; (ii) Proposing solutions and technologies for coastal protection being environmentally friendly, suitable to the socio-economic conditions; (iii) Developing a process for calculating, designing and constructing coastal protection solutions; (iv) Apply technology to build experimental models to prevent erosion and stabilize the coastline in reality.	• Experimental construction of pilot project in Tien Giang coast, Mekong delta; • Database of hydrology, sediments, basic set of parameters on waves for research. Map of coastline and mangrove changes • Analysis reports, manuals, design drawings on the situation of alluvial erosion, causes and mechanisms of erosion; • International publications	2017-2021

3

[i] Project website: https://www.giz.de/en/worldwide/18661.html

[ii] Project website: https://projects.worldbank.org/en/projects-operations/project-detail/P153544

[iii] Project website: http://www.siwrr.org.vn/?id=539&cid=876&page=2&lang=