SLJoAS Sri Lankan Journal of Applied Sciences

Research Article

Vulnerability Assessment of the Coastal Zone of Sri Lanka to Sea-Level Rise Scenario: a GIS Based Study

M. Rajapaksha[a1], S.K. Madarasinghe[a1]*, N.P. Dissanayaka[a], K.A.S. Kodikara[a]
[a]Department of Botany, Faculty of Science, University of Ruhuna, Matara. 81000
[1] Co-first authors

*** Corresponding author**: sandunikm89@gmail.com

(Received 1st June 2023; Accepted 26th August 2023)

Abstract:

Coastal areas are facing the consequences of climate change related disasters at both country and global level. Sea-level rise (SLR) is identified as a major consequence of climate change and the level of vulnerability of Sri Lanka to SLR has not been studied to a greater extent. This study therefore aimed to identify and assess the current (2020) coastal vulnerability of Sri Lanka to SLR scenario. Highly vulnerable coastal areas along the Sri Lankan coastal zone for SLR were identified using Google earth pro and ArcMap 10.3 software, taking coastal geomorphological slope and prevailing coastal ecosystems into consideration. Coastal areas with less slope and less barrier-effective coastal ecosystems were identified as highly vulnerable areas. The results revealed that 81% of the Sri Lankan coast is vulnerable as of 2020 to SLR when only the coastal geomorphological slope is considered. Although the barrier effect of coastal ecosystems has considerably reduced the coastal vulnerability, 34% of the Sri Lankan coast still remains highly vulnerable to SLR. The results further exposed that most of the Sri Lankan beaches, some lagoons, estuaries, coastal cities and industrial regions are highly vulnerable for the SLR scenario. Therefore, restoration and conservation of mangroves and sand dunes which serve as effective barriers against SLR in suitable areas of the coastal zone and establishing hard structural barriers are important to minimize the risk.

Keywords: Vulnerability assessment, sea-level rise, climate change, barrier effect, coastal ecosystems

1. Introduction

Sri Lanka's coastal zone is defined by the coastal conservation act NO.57 of 1981 [1] as "the area lying within a limit of three hundred meters (300 m) landwards of the Mean High Water line (MSL) and a limit of two kilometres (2 km) seawards of the Mean Low Water line and in the case of rivers, streams, lagoons, or any other body of water connected to the sea either permanently or periodically, the landward boundary shall extend to a limit of two kilometres measured perpendicular to the straight baseline drawn between the natural entrance points thereof and shall include the waters of such rivers, streams, and lagoons or any other body of water so connected to the "sea" while shoreline is defined as the physical interface of land and water [2]. Sri Lankan coastal area consists of various types of coastal ecosystems such as estuaries and lagoons, mangroves, seagrass beds, salt marshes, coral reefs and large extents of beaches including barrier beaches, spits and dunes which are rich in biodiversity [3] and play a vital role in terms of ecological services and economic benefits that include flood control, pollution control, shoreline stabilization, erosion control, carbon sequestration, providing breeding and nursery habitats, providing substrate for high species and genetic diversity along with provisioning various food and fuel wood for the dwellers [4-6]. Moreover, coastal ecosystems are important in shoreline protection against extreme events such as storms and hurricanes, storing and cycling nutrients and carbon sequestration [6-9]. With all these ecological services, coastal areas moreover provide excessive involvement in the Sri Lankan economy. Approximately 25% of the country's total cropland areas are situated in the coast while 33% of Sri Lankan population resides in the coastal zone of the country [10].

Despite the importance of the coastal area and associated ecosystems, coastal ecosystems of many countries are threatened at an unprecedented rate mainly because of anthropogenic activities [5,11-14] and natural disasters [15,16]. Among these disastrous scenarios, temperature variations in the ocean which are influenced by climate, causing thermal expansion of seawater, melting glaciers and ice sheets, and shifting ocean currents and change in mean sea-level has received much attention [17]. According to IPCC (2019) [18] global mean sea-levels (GMSL) will most likely rise between 0.95 feet (0.29 m) and 3.61 feet (1.1 m) by the end of this century. Rising sea-level gives a higher risk for coastal states with a high percentage of the tidal area and small islands with low-lying land areas [19]. As an example, since 80 % of 'Maldives' islands are less than 1meter above sea-level, it is considered as the most vulnerable country in the world to sea-level rise scenario

[20]. In the Sri Lankan context, it is more vulnerable to climate change impacts since the country is a small island with a tropical climate [21]. In Sri Lanka, low-lying land areas without green barriers were severely affected by the Indian Ocean tsunami [7,22] drawing attention to the importance of green barriers against natural calamities.

Based on coastal features such as coastal geomorphology and slope and the variability of waves and tides along the coast, the effects of rising sea-levels may differ [23] and several impacts of sea-level rise (SLR) can be expected on the coastal zone. As a result of SLR, seawater intrusion may result in loss of agricultural land and destroy ground water supply in the low coastal regions or adjacent to the deltas [24]. In addition, coastal flooding, erosion of sandy beaches and destruction of other commercial constructions could be identified as major physical impacts of SLR [25,26].

Many researches have addressed the problem of the SLR scenario with climatic change at global level. Nicholls & Cazenave [27] has reported that by the year 2100 SLR will reach 30 cm-180 cm. It further stated that the climate change-induced SLR scenarios would affect several regions worldwide with low elevation including many tropical islands. Moreover, IPCC [28] has revealed that “Due to projected sea-level rise, a million or so people along the coasts of South and Southeast Asia will likely be at risk from”. Since Sri Lanka is a South Asian country, it draws our attention to the SLR scenario with coastal vulnerability. Similarly, Ahmed & Suphachalasai [29] has reported that the impact of 1 m SLR would cover 0.72% of drylands and 0.75% of wetlands in the South Asian countries and it would increase to 3.17% with the extreme storm surges. Further, they have mentioned Sri Lankan coastal zone is vulnerable to SLR and increased frequency of storm surges when future trends of climate change are considered.

The identification of coastal vulnerability is challenging due to the highly dynamic nature and the lack of updated data on the geomorphological features of the Sri Lankan coastal zone [4]. In that perspective, it is highly required to update the vulnerability status of the Sri Lankan coastal zone for natural hazards. However, few studies have been carried out to investigate the vulnerability of the Sri Lankan coast to the climate change and particularly to SLR scenario. Bakker & Bakker [30] have reported SLR induced coastal recession and beach loss along the Sri Lankan coastal zone focusing on the consequences of SLR on the width of Sri Lankan beaches. According to the findings, 196 beaches along the Sri Lankan coast will be lost due to long term SLR induced climatic changes. However, due to the limitations in their methodology, vulnerable areas along the entire Sri Lankan coastline to SLR have not been identified by the aforementioned study. Furthermore, Frykman & Seiron [31] have investigated the effects of climate induced SLR on the coastal areas in the Hambantota District, Sri Lanka, applying Digital Elevation Model (DEM) and the Bruun Rule and has revealed the potential impact on the coastal areas of the Hambantota district due to SLR. Although there are few studies conducted on the vulnerability of Sri Lankan coast to SLR, they have been conducted focusing on only one part of the country. Therefore, it is essential to conduct research on the whole Sri Lankan coast to assess the vulnerability to SLR as well as other coastal hazards. Satyanarayana et al. [4] has discussed the coastal vulnerability of Sri Lanka, taking land-use/cover and elevation data into account and has identified Trincomalee, Yala and Puttalam as ‘less vulnerable’ areas and Kaluvanchikudy-Komari and Jaffna as ‘vulnerable areas’. However, the aforementioned study has been conducted from the data from year 2008 and thus there is a need to check the current situation and assess the coastal vulnerability for the whole Sri Lankan coast that will help in country’s decision making and policy enforcements towards coastal protection. Therefore, the present study aimed at identifying and assessing the current (2020) coastal vulnerability of Sri Lanka for SLR scenario. Further, suitable barrier models are proposed to minimize the effect of SLR scenario in highly vulnerable areas of the Sri Lankan coast.

2. Methods:

A GIS based study, followed by field verification was carried out to assess the vulnerability of the Sri Lankan coastal zone for SLR scenario. Vulnerability was assessed taking physical factors i.e. (i) geomorphological slope and (ii) prevailing coastal ecosystems into consideration.

2.1 Study area

The whole Sri Lankan coast which lies between 50° 55’- 90° 51’ N latitudes and 079° 41’- 081° 54’ E longitudes was taken into consideration in the present study. Sri Lanka has an area of about 65610 km^2 with a coastline of around 1738 km [32]. The total area of the coast that include up to 4 m elevation was studied in the present study to assess the vulnerability of the coastal zone of Sri Lanka to SLR scenario.

2.2 Shoreline and contour mapping

Latest available high resolution Google earth pro satellite images were used to map the current shoreline of Sri Lanka and contour lines for elevation. Fourteen satellite images were required to map the shoreline and contour lines of the whole Sri Lankan coast at 750 m eye altitude. This eye altitude level was selected to maintain the best image interpretability after several trial-and-error efforts and the same eye altitude level was maintained in mapping on all fourteen satellite images to reduce the digitizing error due to the zoom level. Any tilt of satellite images was removed before mapping the shoreline and contour lines to minimize the geometric distortions. The land-water boundary was considered as the shoreline through visual interpretation in this study and mapped on the above-mentioned images.

Contour lines of 0 m, 2 m, and 4 m elevations were mapped on the same Google earth satellite images with the use of Google earth elevation data. In this case, contour lines were mapped connecting the locations with the same elevation along the coastline. Mapped shoreline and contour lines were then then converted from .kml (keyhole markup language) format to layer format on ArcMap 10.3 interface for further processing.

2.3 *Identification of highly vulnerable areas for sea-level rise scenario*

Highly vulnerable areas for the sea-level rise were identified based on two factors; (1) coastal geomorphological slope and (2) coastal ecosystem types present.

Vulnerable areas for the SLR were first identified according to the geomorphological slope in the coast that were calculated using 706 randomly selected points on 0 m contour line. Straight lines were marked at 90 degree angle to the 0 m contour until 4 m contour at each point. The calculation was done using the straight distance on the ground (e.g. distance from 0 m line to 4 m line) and respective height in between the considered two contours (e.g. 4m in above mentioned example) at a particular line drawn (see Eq 1 and Fig. 1). Subsequently, coastal geomorphological slopes at all 706 points were calculated using ArcMap *v*.10.3 and Microsoft excel software.

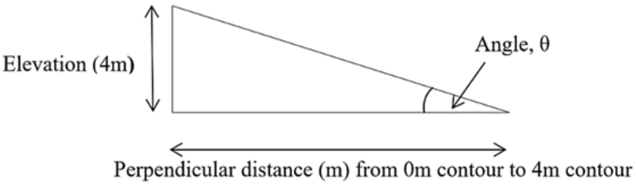

Fig. 1. Trigonometrical calculation of slope.

Tan θ = H / D…………………………………..Eq 1

Where,

H = Elevation of the considered contour line in meters
D = Perpendicular distance in meters from 0m line to 4m line
θ = Slope angle in degrees

Vulnerability of each area was then identified, based on calculated geomorphological slopes. Calculated geomorphological slope values were assigned into three vulnerable categories [33] based on the slope angle in degrees. Places with less than 5^0 slope angle (less steepness in general) were assigned as highly vulnerable places whereas 5^0 - 10^0 slope angles were assigned as moderately vulnerable places (moderate steepness). Places where the slope angle was higher than 10^0 were assigned as less vulnerable places. The theory behind this logic is if the geomorphological slope is lower (less steepness) then water inundation area is higher becoming the area highly vulnerable. If the geomorphological slope is higher water inundation area is lower becoming the area less vulnerable (see Fig. 2).

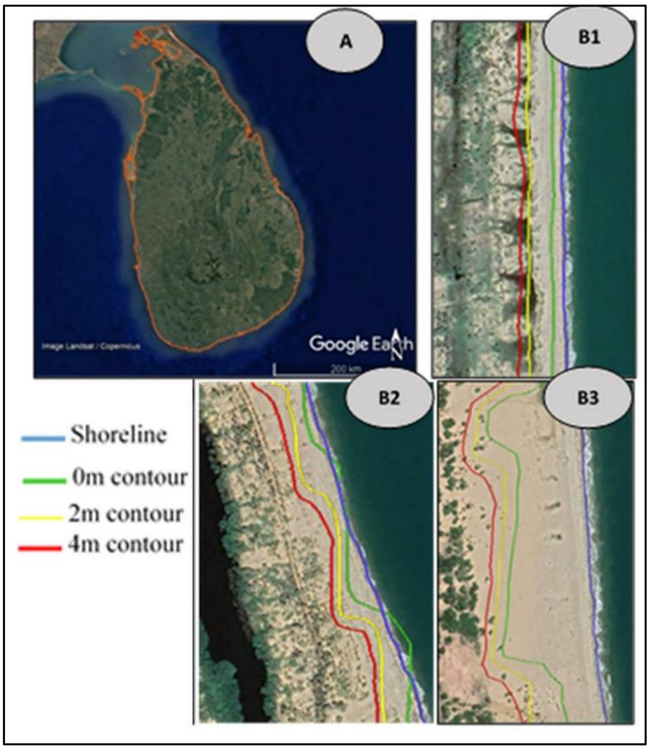

Fig. 2. (A) Mapped shoreline of Sri Lanka (brown colour line) using Google Earth satellite imagery. (B) Mapped contour lines on Google earth imagery at 750m eye altitude. Each coloured line is showing contour lines and marked shore line. (B1) Contour lines in high steep area (B2) Contour lines in moderate steep area (B3) Contour lines in less steep area.

2.4 *Identification of vulnerable areas for sea-level rise scenario based on the coastal ecosystems present*

Satyanarayana et al. [4] has categorized the ecosystems along the Sri Lankan coast into sixteen classes; i.e. sand dunes, mangroves, *Casuarina*, bare soil, dense urban bare soil, sparse vegetation, dense urban spares vegetation, semi dense urban spares vegetation, dense vegetation, Semi dense urban dense vegetation, coconut, semi dense urban coconut, water and others. Vulnerability categorization was determined based on coastal ecosystem types. Each aforementioned coastal ecosystem was categorized into three vulnerable categories based on their barrier effect (see Table 1). Vulnerability levels of the coastal ecosystems were marked using ArcMap, on the georeferenced land-use/cover map obtained from Satyanarayana et al. [4] (see Fig. 3).

2.5 *Identification of highly vulnerable areas based on both criteria (slope and ecosystems) and field verification*

Final places of highly vulnerable areas along the Sri Lankan coast were identified by overlapping the two vulnerability maps prepared based on (1) coastal geomorphological slope and (2) coastal ecosystems. Accordingly, slope based highly vulnerable places which were lying within highly vulnerable ecosystem areas were considered as "highly vulnerable areas". After overlapping, 196 places along the Sri Lankan coast were identified as highly vulnerable areas. Above areas were then viewed on Google earth pro satellite images for cross check. Highly vulnerable places and their locality in the coastal zone, district and city were further identified. Field verification was carried out from Kalutara to Hambantota in August 2020 to determine the accuracy of the criteria used for determination of coastal vulnerability. Field observations and community interviews were carried out in the selected highly vulnerable areas in August 2020.

Table 1. Vulnerability of coastal ecosystems to sea-level rise (source: [4]).

Vulnerable category	Coastal ecosystem types
Less vulnerable	Sand dune, Mangrove
Moderately vulnerable	*Casuarina*, Coconut plantations, Dense vegetation, Paddy, Semi dense urban coconuts, Semi dense urban dense vegetation, Semi dense urban spares vegetation, Spares vegetation
Highly vulnerable	Bare soil, Dense urban bare soil, Dense urban spares vegetation, Water

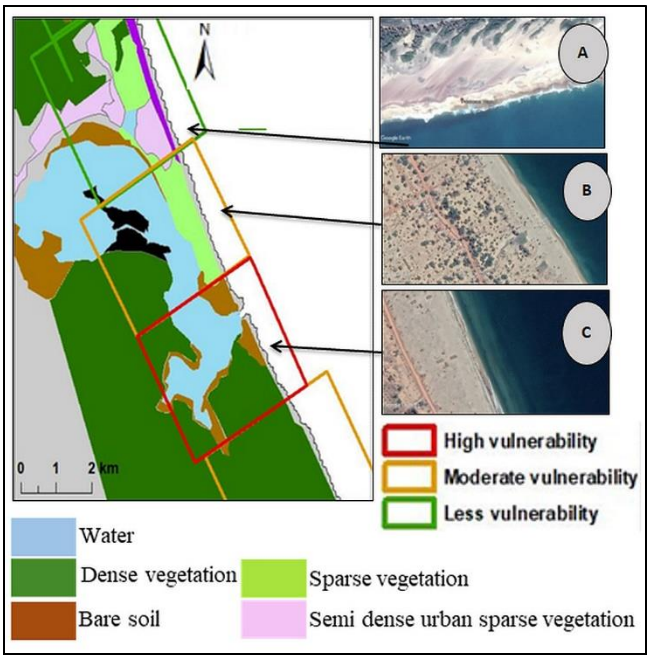

Fig. 3. Vulnerability of each coastal ecosystem to sea-level rise, based on the ecosystems present in the coast. Images A, B, C show Google earth satellite images of (A) Sand dune – Less vulnerable (B) Sparse vegetation – Moderately vulnerable (C) Bare soil – Highly vulnerable.

Barrier models were proposed for the visited highly vulnerable areas in the western and southern coasts of Sri Lanka. This was carried out based on the identified geomorphological features and information from the coastal conservation department (CCD) and the community in the highly vulnerable areas during the field verifications.

3. Results:

High resolution satellite images were required for the study because of the dynamic nature of the coastline due to natural forces [34] and the complexity of geomorphology. Thus Google earth pro was selected as the suitable image source in obtaining high resolution satellite images free of charge.

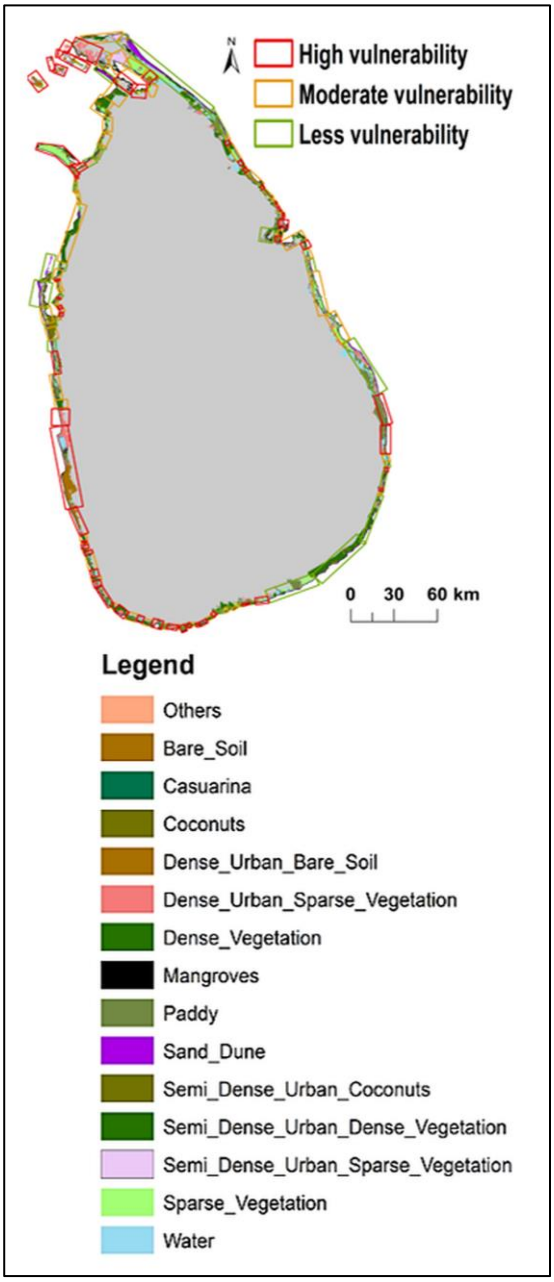

Fig. 4. Classification of the Sri Lankan cost into vulnerability categories based on the ecosystems present.

According to the map of vulnerability in terms of coastal geomorphological slope, only 12 places (2%) were identified as less vulnerable whereas 119 places (17%) were moderately vulnerable and 575 places were highly vulnerable. These numbers imply that 81% of the coastal areas in Sri Lanka are highly vulnerable to SLR when geomorphological slope is considered. Fig. 4 represents the obtained vulnerability categories in each coastal area based on the coastal ecosystems present. The northern coastal zone has larger stripes of sand dunes while large stripes of dense vegetation could be seen in north-western and northern coastal zones. The results demonstrate that the western coastal zone is highly vulnerable in terms of their coastal ecosystems. Following the distances of each vulnerability stripes, 40% of the coastal area is highly vulnerable whereas 39% is moderately vulnerable and 21% is less vulnerable for SLR scenario in terms of their prevailing coastal ecosystems.

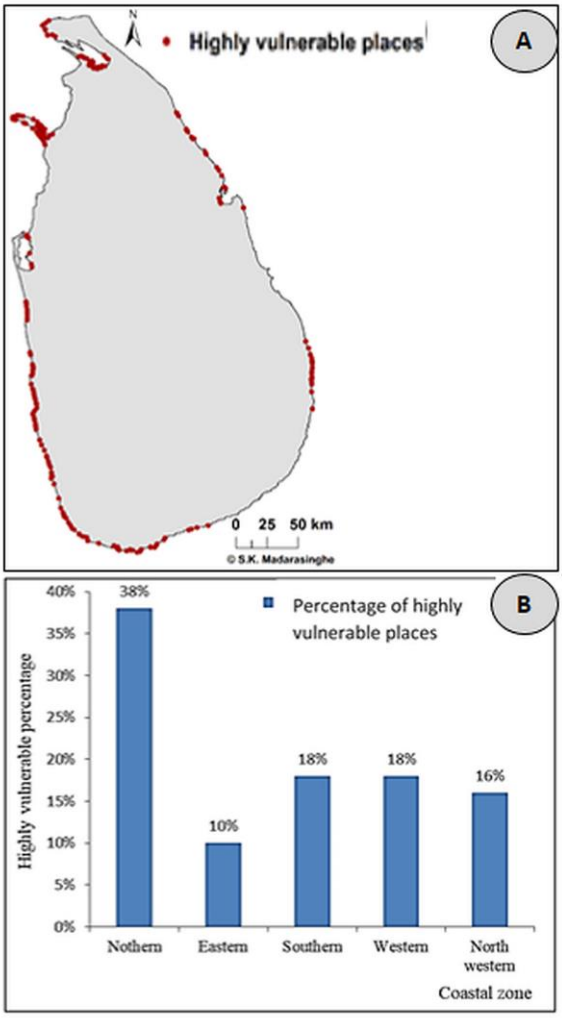

Fig. 5. (A) Highly vulnerable places along the Sri Lankan coast to sea-level rise when geomorphological slope and prevailing ecosystems are considered, (B) percentages of highly vulnerable places in each coastal zone of Sri Lanka.

When both criteria (geomorphological slope and ecosystems) are taken into consideration by overlapping the two maps of the vulnerable areas, only 196 places were identified as highly vulnerable areas along the Sri Lankan coast (Fig. 5). This implies that 34% of Sri Lankan coast is highly vulnerable to SLR when both criteria are taken into consideration. Fig. 5(B) indicates the percentage of highly vulnerable places in each coastal zone of Sri Lanka. According to the results of the present study, the highly vulnerable areas along the Sri Lankan coast to SLR scenario include various land-use/cover types including beaches, some lagoons and estuaries, bays, river delta, urban settlements, roads, fishery harbours, industrial regions and ports. Highly vulnerable beaches could be identified in Ambalangoda, Devinuwara (Dondra), Dikwella, Kalmunai, Kalutara, Katukurunda, Koggala, Madiha, Mahamodara, Nilaveli, Nintavur, Palamunai, Tangalle, Waskaduwa and Weligama. Kokkilai, Puttalam, Mannar, Nayaru and Vankalai lagoons were identified as highly vulnerable lagoons while Deduru oya, Kalu river, Gal oya estuaries were identified as highly vulnerable estuarine areas for SLR. Highly vulnerable coastal cities include Bentota, Colombo, Mannar, Negombo and Thalai Mannar while industrial regions in Puttalam, Mannar, Paranthan were also identified as highly vulnerable for the SLR scenario. Colombo, Galle and Hambantota ports along with Beruwala, Chilaw, Hikkaduwa, Mathagal and Negombo fishery harbours were also identified as highly vulnerable. Colombo port city, which is a newly constructed commercial city is also identified as a highly vulnerable area for SLR.

Field verifications suggested that the criteria used in determining the coastal vulnerability in the present study is correct as the results obtained through mapping, well agreed with the ground observations (some examples are given in Fig. 6). Interviews with the coastal community in Kalutara revealed that the beach area was protected from *Pandanus* sp. plantation layer twenty years ago. However, illegal constructions in the beach area have caused to remove the *Pandanus* and coconut plantation layers. Moreover, people claimed that tourist attraction to the beach has reduced due to the loss of natural beauty in Kalutara beach. Community interviews with the dwellers of Calido beach, Kalutara further revealed that two decades ago, the Calido beach area extended more than sixty feet further from the present place. However, due to the coastal erosion and tidal effects, the beach area has greatly reduced. The field observations further revealed that the Coastal Conservation Department (CCD) has already taken steps to reduce the coastal erosion at Calido beach by constructing an artificial sea wall and a stone layer (Fig. 6). In addition, sand pumping to the area has been done by CCD to minimize flooding in the area. However, the coastal community claimed that there was a sand pumping project executed in this area which was not successful. According to the field observations, a cascade stone layer was observed in Katukurunda beach area. Further, interviews with the public revealed that sand mining is a huge problem in this area. Wash out of sand from the Kalutara-Southern sand nourishment project in 2020 has caused a closure at the Katukurunda lagoon mouth with a sand barrier that resulted in minimizing the water circulation in the lagoon. This has negatively affected the lagoon fisheries as well. Furthermore, there is a high risk to Katukurunda railway road from coastal erosion in near future. In addition, field observations verified that the Beruwala fishery harbour is a less steep area with less vegetation. Artificially constructed stone jetties were observed in both Beruwala and Hikkaduwa fishery harbours to minimize the coastal erosion.

The field observations further verified that Devinuwara (Dondra) beach which was identified as a highly vulnerable area is not protected from a vegetation layer and is having a low geomorphological slope. According to the information gathered through community interviews and field observations, coastal zone at Mahamodara has previously been identified as a highly vulnerable area for SLR and coastal erosion. However, the existing artificial sea wall in Mahamodara area that was constructed to minimize the effects was not effective for seawater related impacts and an effective coastal vegetation layer was not observed as well. Less coastal geomorphological slope was observed in Weligama beach area with *Calophyllum innophylum* plant layers along the coast. Highly vulnerable area in Madiha beach consisted of *Pandanus* sp. and *Thespesia populnea* plant layers while large hotel buildings could be observed around five meters away from the Madiha beach.

Fig. 6. Images showing some highly vulnerable areas of Sri Lankan coast for sea-level rise; (A) Calido beach, (B) sand dumping at Kalutara beach, (C) sand migration to the road at Mahamodara, (D) Devinuwara (Dondra) beach and (E) Beruwala beach. (Photo © Rajapaksha M. and Madarasinghe S.K.)

4. Discussion:

In the present study, "vulnerable areas for SLR" include the coastal lands lying under the 4m contour line of Sri Lanka. According to Weerakkody [35] geologic and geomorphologic characters are the main factors that determine the vulnerability to SLR. In that sense, coastal geomorphological slope and coastal ecosystems were taken into consideration to identify and assess the vulnerable areas in the present study. The present study considered areas with both less geomorphological slope (less steep) and less barrier-effective coastal ecosystems, as highly vulnerable areas for SLR scenario. Coastal ecosystems play a vital role as a buffer for natural coastal hazards. Sand dunes and mangroves are at the top in terms of their barrier effect than any other coastal ecosystem against coastal hazards [4]. Architecture of the mangrove plants enable them to reduce the force of the water currents and moderate the effect while sand dunes serve as a direct wall.

According to the results of the present study, many of the Sri Lankan beaches, coastal cities, roads, fishery harbours, industrial regions and ports are highly vulnerable to the SLR scenario which indicates that the SLR scenario will considerably affect the Sri Lankan coastal economy in future. Loss of land, loss of physical infrastructure and increment of the coastal protection expenditure due to SLR may give high impact in economic context of a country [36]. On the other hand, it will affect coastal ecosystems in various means. For an example, SLR can reduce the carbon sink function of the mangrove ecosystems [37] due to flushing off of the major sources of carbon in the system. Furthermore, degradation of coastal agricultural lands due to salinization is another major problem in Sri Lanka [37,38] that can increase with SLR. Gopalakrishnan et al. (2020) [39] reports that about 90% of the Sri Lankan coastline is vulnerable to any kind of sea water related impacts whereas low lying coastal areas are highly sensitive. However, the present study revealed that vulnerability to SLR scenario is 34% when geomorphological slope and coastal ecosystems are taken into account.

According to the findings of this study, majority of the western coast of Sri Lanka is categorized under less vulnerability status in terms of geomorphological slope. However, it is interesting to note that the western coast shows high vulnerability due to less coastal barrier ecosystems. It implies most of the barrier-effective coastal ecosystems in the western coast have already been degraded and removed. Coastal urbanization and increase in coastal population play major roles in the degradation of coastal ecosystems and increasing the anthropogenic pressure on them [40]. Therefore, it is clear that introducing suitable green barriers for these areas could reduce the impact of SLR to the western coast. However, in recent past, sand nourishment projects have been executed in some places within the western coastal zone; such as at Calido beach which is recorded as a highly vulnerable place from the present study. The community interviews at Calido beach revealed that the sand nourishment project has failed to protect the beach and instead it caused to block down the estuary of Kalu river. Such instances emphasise that the coastal protection projects should be launched scientifically with the involvement of experts. On the other hand, eastern coast is less vulnerable in terms of coastal ecosystems while highly vulnerable according to the slope data. Therefore, destruction of the coastal ecosystems in the eastern coast can lead to increase its vulnerability to SLR. This highlights the importance of conserving the existing barrier-effective ecosystems in the eastern coast while implementing restoration programmes to increase the cover of such ecosystems in order to minimize coastal erosion and other impacts of SLR in the area.

Most of the Sri Lankan lagoons are protected from coastal hazards due to the distribution of mangrove ecosystems [41] [42]. However, according to the obtained results, Puttalam lagoon is highly vulnerable to SLR. The major reason is the establishment of aquaculture farms in Puttalam lagoon and as a result, more than 50% of the mangroves in Puttalam lagoon have been removed [43]. This indicates the massive impacts on coastal ecosystems from anthropogenic activities. Most of the beaches in Sri Lanka are tourist destinations. However, results from this study reveal that most of them are highly vulnerable to SLR that hints about a threat of losing the attractive beaches and thereby affecting the tourism industry in Sri Lanka in a negative manner. The condition might be worsened in future due to the weak regulation of tourism activities within the coastal zone.

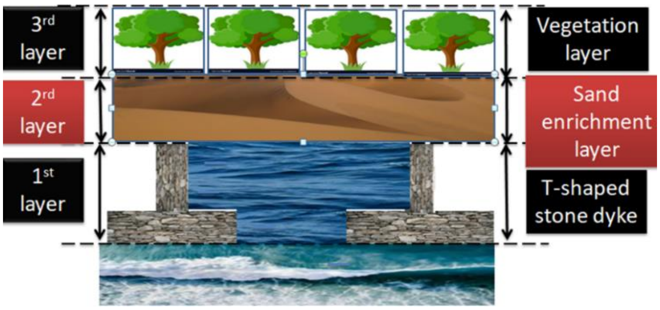

Fig. 7. Mixed barrier model for highly vulnerable sites for sea-level rise.

A mixed barrier model (Fig. 7) can be proposed for the identified highly vulnerable areas to minimize the effects of SLR to coastal zones. A hard barrier can be proposed as the first layer that could be constructed towards the seaward direction at the high-risk areas. For an example, a T- shaped stone dyke can be implemented as a hard barrier. This type of barriers have already been established along the Kaluthara coast as a SLR mitigation strategy. A soft barrier can be proposed as the second layer that will include sand enrichment layers. A vegetation layer can be proposed as the third layer in the model [44]. First layer should be implemented towards the seaward direction whereas second and third layers should be implemented towards the landward direction. Nevertheless, priority should be given for the highly vulnerable areas in following adaptation measures and conservation strategies. Developing “Green Barrier Models” for highly vulnerable areas is a pragmatic solution for countries like Sri Lanka [22]. However, developing a natural vegetation barrier needs expert knowledge and continuous monitoring and should make sure to secure the environmental and economic stability of the country when applying the proposed barrier models. For instance, Weligama beach area is confined into a narrow stripe and therefore is not easy to develop a green barrier in the limited space. Thus, the best option is to construct a stone dyke towards the ocean to reduce the risk of SLR in the area. When the land-use architecture in Unawatuna beach is considered, it consists of many settlements including hotels and other tourism-related constructions. Therefore, green barrier concept cannot be applied as a solution to SLR in Unawatuna. Under such condition, construction of an artificial seawall could be a practical solution in mitigating the effects of SLR in Unawatuna area. On the other hand, ports in a country are considered as major economic accelerators. Sri Lanka has seven economically important ports in Trincomalee, Oluvil, Hambantota, Galle, Colombo, Point Pedro and Kankasanthurai. According to the obtained results Hambantota, Galle and Colombo ports were recorded as highly vulnerable places for SLR. Therefore, the Sri Lankan port authority should pay attention to this matter and take necessary actions to protect these economically important ports from the impacts of SLR.

Table 2. Proposed green barrier for selected highly vulnerable areas.

Highly vulnerable place	Suitable plants for the green barrier/sand enrichment
Estuary of Kalu river (near to Calido beach)	*Pandanus* sp., *Terminalia catappa*
Katukurunda beach	*Scavola taccada*, *Ipomea pes-caprae*, *Pandanus* sp.
Ambalangoda beach	*Pandanus* sp.
Koggala beach	*Pandanus* sp.
Weligama beach	*Calophyllum inophylum*
Madiha beach	*Pandanus* sp., *Thespesia populnea*
Dickwella beach	*Calotropis gigantea*
Tangalle beach	*Terminalia catappa*

In addition to coastal geomorphological slope and prevailing ecosystems, coastal vulnerability to SLR depends on several other factors such as tidal variations, monsoonal effects, bathymetry, water current and wind current [45]. Therefore, further research is recommended to determine the coastal vulnerability to SLR with consideration of more factors that decide the coastal vulnerability status.

5. Conclusions

According to the findings of the present study, 81% of the Sri Lankan coast is vulnerable to SLR when only the coastal geomorphological slope is concerned. The barrier effect of coastal ecosystems reduces the vulnerability of Sri Lankan coast to SLR to 34%. Furthermore, many of the Sri Lankan beaches (e.g. Ambalangoda, Calido, Dikwella, Kalmunai, Kalutara, Katukurunda, Koggala, Madiha, Mahamodara, Nilaveli, Nintavur, Palamunai, Tangalle, Waskaduwa, Weligama), some lagoons (Kokkilai, Nayaru, Negombo) and estuaries (Deduru oya, Kalu river, Gal oya), coastal cities (Bentota, Colombo, Mannar, Negombo, Thalai Mannar), fishery harbours (Beruwala, Chilaw, Hikkaduwa, Mathagal, Negombo), industrial regions (Puttalam, Mannar, Paranthan) and ports (Colombo, Galle, Hambantota) are highly vulnerable for the SLR scenario. Therefore, restoration and conservation of mangroves and sand dunes in suitable areas of the coastal zone are essential to minimize the risk. Further, it is highly recommended to introduce mixed model concept to those places where high vulnerability to SLR exists.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

Acknowledgments

Financial assistance from the FSPI-SEDRIC Project, French cooperation under the umbrella of the French embassy at Colombo, Sri Lanka is gratefully acknowledged.

References

[1] Coast Conservation Act, No.57, 1981. Published as a supplement to Part II of the Gazette of the Democratic Socialist Republic of Sri Lanka of September 11, 1981. Department of government printing, Sri Lanka.

[2] Dolan R, Hayden B P, Rea C and Heywood J 1979 Shoreline erosion rates along the middle Atlantic coast of the United States. Geology 7, p.602–606.

[3] Joseph L 2003 National report of sri lanka, Bay of Bengal Large Marine Ecosystem Programme [Preprint].

[4] Satyanarayana B, Van der Stocken T, Rans G, Kodikara K A S, Ronsmans G, Jayatissa L P, ... and Dahdouh-Guebas F 2017 Island-wide coastal vulnerability assessment of Sri Lanka reveals that sand dunes, planted trees and natural vegetation may play a role as potential barriers against ocean surges. Global Ecology and Conservation, 12, 144-157. Available: https://doi.org/10.1016/j.gecco.2017.10.001.

[5] Madarasinghe S K, Yapa K K, Satyanarayana B, Udayakantha P M P, Kodikara S, and Jayatissa L P 2020a Inland irrigation project causes disappearance of coastal lagoon: the trajectory of Kalametiya lagoon, Sri Lanka from 1956 to 2016. Coastal Management, 48(3), p.188-209. Available: https://doi.org/10.1080/08920753.2020.1747914

[6] Cooray P L I G M, Kodikara K A S, Kumara M P, Jayasinghe U I, Madarasinghe S K, Dahdouh-Guebas F, ... and Jayatissa L P 2021 Climate and intertidal zonation drive variability in the carbon stocks of Sri Lankan mangrove forests. Geoderma, 389, 114929. Available: https://doi.org/10.1016/j.geoderma.2021.114929

[7] Dahdouh-Guebas F, Jayatissa L P, Di Nitto D, Bosire J O, Seen D L, and Koedam N 2005 How effective were mangroves as a defence against the recent tsunami?. *Current biology*, *15*(12), R443-R447. Available: https://doi.org/10.1016/j.cub.2005.06.008

[8] Martínez M L, Intralawan A, Vázquez G, Pérez-Maqueo O, Sutton P, and Landgrave R 2007 The coasts of our world: Ecological, economic and social importance. *Ecological economics*, *63*(2-3), 254-272. Available: https://doi.org/10.1016/j.ecolecon.2006.10.022.

[9] Gunathilaka D U V, Wijesundara W M I C, Abeysinghe N K, Ranawaka D P D, De Silva P M C S, Madarasinghe S K, ... and Kodikara K A S 2022 Blue Carbon Stocks; Distribution, Threats, and Conservation in Sri Lanka; Insight towards climate change mitigation. Rajarata University Journal, p.62-73. Available: http://repository.rjt.ac.lk/handle/123456789/4730

[10] Bank A D 2010 'Sri Lanka : Coastal Resource Management Project', (December).

[11] Lewis M, Pryor R and Wilking L 2011 Fate and effects of anthropogenic chemicals in mangrove ecosystems: a review. Environmental pollution, 159(10), 2328-2346. Available: https://doi.org/10.1016/j.envpol.2011.04.027

[12] Madarasinghe S K, Amarasinghe Y W P, Liyanage C H, Gunathilake H M S A T, Jayasingha J A I K, Jayasingha M, ... and Jayatissa L P 2020b Retrospective study on changes in Dondra lagoon (2006–2017) resulting from tsunami impact and post-tsunami development. Journal of Coastal Conservation, 24, p.1-11. Available: https://link.springer.com/article/10.1007/s11852-020-00777-1

[13] Wang Y S and Gu J D 2021 Ecological responses, adaptation and mechanisms of mangrove wetland ecosystem to global climate change and anthropogenic activities. International Biodeterioration & Biodegradation, 162, 105248. Available: https://doi.org/10.1016/j.ibiod.2021.105248

[14] Ofori S A, Kodikara S K, Jayatissa L P, Madarasinghe S K, Nijamdeen T M and Dahdouh-Guebas F 2023 What is the ecological footprint of aquaculture after 5 decades of competition between mangrove conservation and shrimp farm development?. Aquatic Conservation: Marine and Freshwater Ecosystems, 33(1), p.15-28. Available: https://doi.org/10.1002/aqc.3897

[15] Islam S D U and Bhuiyan M A H 2018 Sundarbans mangrove forest of Bangladesh: causes of degradation and sustainable management options. Environmental Sustainability, 1(2), p.113-131.

[16] Ruan L, Yan M, Zhang L, Fan X and Yang H 2022 Spatial-temporal NDVI pattern of global mangroves: A growing trend during 2000–2018. Science of The Total Environment, 844, 157075. Available: https://doi.org/10.1016/j.scitotenv.2022.157075

[17] IPCC 2013 CLIMATE CHANGE 2013. Edited by G.-K.P. Stocker, Thomas F., Dahe Qin.

[18] IPCC 2019 Sea Level Rise Is a Present and Future Danger | NRDC. Available: https://www.nrdc.org/experts/rob-moore/new-IPCC-report-sea-level-rise-challenges-are-growing (Accessed: 25 February 2023)

[19] Yang X 2014 Coastal ecosystems, Encyclopedia of Earth Sciences Series. Available: https://doi.org/10.1007/978-0-387-36699-9_19

[20] Stojanov R and Němec D 2017 Slow Onset Climate Change Impacts in Maldives and Population Movement from Islanders ' Perspective Brain', (April).

[21] Kottawa-Arachchi J D and Wijeratne M A 2017 Climate change impacts on biodiversity and ecosystems in sri lanka: A review. Nature Conservation Research, 2(3), p. 2–22. Available at: https://doi.org/10.24189/ncr.2017.042

[22] De Silva D A M and Yamao M 2007 Effects of the tsunami on fisheries and coastal livelihood: a case study of tsunami-ravaged southern Sri Lanka. *Disasters*, *31*(4), p.386-404.

[23] Kakani N R, Ajai and Rajawat A S 2010 Vulnerability of the Indian coast to sea-level rise. (February).

[24] Kibria G 2016 Sea-level rise and its impact on wetlands, water, agriculture , fisheries , aquaculture , public health , displacement , infrastructure and adaptation. (October 2014). Available: https://doi.org/10.13140/RG.2.1.1267.2487

[25] Kont A, Jaagus J and Aunap R 2003 Climate change scenarios and the effect of sea-level rise for Estonia. Global and Planetary Change, 36(1–2), p. 1–15. Available: https://doi.org/10.1016/S0921-8181(02)00149-2

[26] Boateng I 2012 An assessment of the physical impacts of sea-level rise and coastal adaptation: A case study of the eastern coast of Ghana. Climatic Change, 114(2), p. 273–293. Available: https://doi.org/10.1007/s10584-011-0394-0

[27] Nicholls R J and Cazenave A 2018 Sea-Level Rise and Its Impact on Coastal Zones. (January). Available: https://doi.org/10.1126/science.1185782

[28] IPCC 2014 SROCC_PressRelease_EN. IPCC Ar5 [Preprint], (September).

[29] Ahmed M and Suphachalasai S 2014 Assessing the Costs of Climate Change and Adaptation in South Asia. Available: http://hdl.handle.net/11540/46. License: CC BY 3.0 IGO

[30] Bakker P J J 2018 future coastline recession and beach loss in sri lanka Future Coastline Recession and Beach Loss in Sri Lanka. M.Sc. Thesis (University of Twente). Available: chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/http://essay.utwente.nl/76140/1/Bakker%2C%20P.J.J.%201390198%20_openbaar.pdf

[31] Frykman H and Seiron P 2009 The Effects of Climate Induced Sea Level Rise on the Coastal Areas in the Hambantota District, Sri Lanka. M.Sc. Thesis (Lund University, Sweden) p.173. Available: chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://lup.lub.lu.se/luur/download?fileOId=1857862&func=downloadFile&recordOId=1857835

[32] Ranasinghe T S 2012 Mangrove restoration efforts in Sri Lanka. *In Sharing Lessons on Mangrove Restoration*, *Mamallapuram, India*. p.75-81.

[33] Eberli G P and Ginsburg R N 1989 Cenozoic progradation of northwestern Great Bahama Bank, a record of lateral platform growth and sea-level fluctuations. Controls on carbonate platform and basin development, (February), pp. 339–351. Available: https://doi.org/10.2110/pec.89.44.0339

[34] Gunatilake J and Pussella P 2015 Coastline Changes : Vulnerability and Predictions - A Case Study of the Northwestern Coastal Belt of Sri Lanka. (February 2017).

[35] Weerakkody U 1997 Potential Impact of Accelerated Sea-Level Rise on Beaches in Sri Lanka. Journal of Coastal Research, (24), p. 225–242. Available: https://www.jstor.org/stable/25736096

[36] Hallegatte S 2012 A framework to investigate the economic growth impact of sea level rise. Environmental Research Letters, 7(1). Available: https://doi.org/10.1088/1748-9326/7/1/015604

[37] Perera K A R S, De Silva K H W L and Amarasinghe M D 2018 Potential impact of predicted sea level rise on carbon sink function of mangrove ecosystems with special reference to Negombo estuary, Sri Lanka. Global and Planetary Change, 161(December), p. 162–171. Available: https://doi.org/10.1016/j.gloplacha.2017.12.016

[38] Chamika N V K, Athapatthu A R P E, Arachchi G T G, Ranawaka D P D, Wijeratne G G N K, Gunathilaka D U V, ... and Kodikara K A S 2022 Level of Salinization in the Walawe River and Its Impacts on Associated Agricultural Lands. Proceedings of the 19th Academic sessions, University of Ruhuna. p.92. Available: http://ir.lib.ruh.ac.lk/xmlui/handle/iruor/5803

[39] Gopalakrishnan T, Kumar L and Hasan M K 2020 Coastal settlement patterns and exposure to sea-level rise in the Jaffna Peninsula, Sri Lanka. Population and Environment [Preprint]. Available: https://doi.org/10.1007/s11111-020-00350-w

[40] Sekhar N U 2005 Integrated coastal zone management in Vietnam: Present potentials and future challenges. Ocean and Coastal Management, 48(9–10), p. 813–827. Available: https://doi.org/10.1016/j.ocecoaman.2005.07.003

[41] Katupotha K N J 2016 Mangroves in Lagoon Ecosystems : a Neglected Habitat in Sri Lanka. Wildlanka, 4(3), p. 79–105. Available: http://dr.lib.sjp.ac.lk/handle/123456789/3731

[42] Kodikara K A S, Mukherjee N, Jayatissa L P, Dahdouh-Guebas F and Koedam N 2017 Have mangrove restoration projects worked? An in-depth study in Sri Lanka. Restoration Ecology, 25(5), p.705-716. Available: https://doi.org/10.1111/rec.12492

[43] Harkes I H T, Drengstig A, Kumara M P, Jayasinghe J M P K and Huxham M 2015 Shrimp aquaculture as a vehicle for climate compatible development in Sri Lanka. The case of Puttalam

Lagoon. Marine Policy, 61, p.273-283. Available: https://doi.org/10.1016/j.marpol.2015.08.003

[44] Wijesundara W M I C, Kodikara K A S, Madarasinghe S K, Rajapaksha M and Jayatissa L P 2021 Mixed Model Approach. Proceedings of 18th Academic sessions, University of Ruhuna, Sri Lanka, p. 46. Available: http://ir.lib.ruh.ac.lk/xmlui/handle/iruor/3428

[45] Parthasarathy A and Natesan 2015 'Coastal vulnerability assessment: a case study on erosion and coastal change along Tuticorin, Gulf of Mannar', Natural Hazards, 75(2), p. 1713–1729. Available: https://doi.org/10.1007/s11069-014-1394-y