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Potential Use of Mangroves for Coastal Protection: A Case Study from Sri Lanka

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Mainstreaming coastal biodiversity certainly brings nature-based solutions for the conservation of offshore and onshore resources. Being an island, the long-term shoreline change of Sri Lanka is particularly important for management of the island's coastal resources. This study was carried out at the southwestern and southern coasts of Sri Lanka to investigate the protective capacity of mangroves against coastal erosion, and coastal inundation hazards due to the climate associated sea-level rise. Structural diversity of mangrove stands was assessed in terms of alpha-diversity, plant species richness, basal area, tree height, density, and structural complexity index. Analysis of aerial photographs and the ASTER Global Digital Elevation Model was used to identify shoreline changes along the southwestern and the southern coasts of Sri Lanka. Results revealed that by and large, the southwestern coast is highly vulnerable to coastal erosion and inundation hazards whereas the southern coast manifests a tendency to retreat. The average annual rate of shoreline change however varies within the two coastal areas, as there were accreting as well as eroding segments on both southern and southwestern coasts, nevertheless, all retreating beach segments were the sites of improper maritime developments. Segments with lower rates of shoreline erosion and coastal inundation hazards were found to be located close to the mangrove and other coastal vegetation with varying structural complexity and diversity. Reforestation and restoration of vegetation in coastal lagoons and estuarine habitats are evidently effective strategies not only to protect the low-lying coastal hinterlands but also to preserve coastal biodiversity.

(***Key words:*** *Aerial photographs, ASTER global digital elevation model, Coastal erosion, Mangroves, Sri Lanka)*

Sri Lanka being an island state in the Indian Ocean, protection of its coastline is considered a national priority for the well-being of her coastal inhabitants and the natural resource base that they depend on. Coastal areas around Sri Lanka are also affected by, cyclones and inundation due to tidal waves associated with climate-induced sea-level rise as well as a variety of anthropogenic activities such as fishing, coral and sand mining, mangrove destruction, sewage disposal, urban expansion, and tourism (Balasuriya, 2018; Lowry and Wickremeratne, 1989), that contributes to coastal erosion. The low-lying coastal area of Sri Lanka is very dynamic where erosion and deposition constantly change the shoreline (Narayana, 2016), some of which are seasonal while others are more permanent (Joseph, 2007). Sri Lanka's coastal areas are densely populated than the inland areas (Weerakkody, 1996; Berg *et al*., 1998; Gopalakrishnan *et al*., 2020) and among them, the southwestern coastal zone is the most populous (Elizabeth and Turner, 2005). A significant extent of the southwestern coastal resource base is under heavy utilization, and there are even signs of over-exploitation in several areas (Gerritsen and Amarasinghe, 1977; Senevirathna *et al*., 2018). Besides, this coast is impacted by the island's annual sea-level rise of 1.98 mm (Indika *et al*., 2017). Escalating investments in economic development activities, coupled with the population increase in the coastal areas of Sri Lanka, particularly on the western and southwestern coasts have drawn considerable interest over protecting its shoreline.

Observations lead to the belief that mangroves and other coastal forests are of great service to the coastal communities as protectors of the coast by dissipating the energy of waves and checking erosion, dampening winds and storms, and also reducing tidal/saltwater intrusion to the hinterland (Amarasinghe, 1997a, 1988; Jayakody *et al*., 2008; Zhang *et al*., 2012; Krauss and Osland, 2020). The capacity of mangrove ecosystems to resist tidal currents and waves depends on its vegetation characteristics such as density, height, species composition, width of the forest, diameter of mangrove roots and stems, as well as the topography

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of mangrove habitats, that create drag force, resulting attenuation of energy in waves, preventing coastal erosion (Menashe, 1993; Barbier, 2006; De Silva, 2011; Zhang *et al*., 2012). Mangroves are also reckoned for their contribution to coastal fisheries by serving as nursery grounds for most aquatic organisms that contribute to coastal fisheries (Islam and Haque, 2004; Bosire *et al*., 2008; Hutchison *et al*., 2014). The physical structure of mangroves provides a shelter for growth and survival for juveniles. Mangroves also provide nursery grounds for off-shore species, including reef fish (Lowry and Wickremeratne, 1989; Mumby *et al*., 2004; Zhang *et al*., 2012; Silva *et al*., 2013). A coral reef fish species, *Lutjanus fulviflamma* spends its juvenile stage in mangroves (Kimirei *et al*., 2013). Mumby *et al*. (2004) revealed that some fish species such as *Scarus guacamaia*, which is the largest herbivore species in the Atlantic suffered extinction due to the degradation of mangrove habitats, suggesting that the survival of some fishes strongly depend on mangrove habitats. Mangroves are a highly productive ecosystem and their productivity is not proportional to the global coverage of mangroves (Amarasinghe and Balasubramaniam, 1992; Jayakody *et al*., 2008). Mangroves have been estimated to produce 11% of marine organic matter (Faunce and Serafy, 2006) which may contribute to marine food webs (Amarasinghe, 1997b; Hutchison *et al*., 2014) and hence to fish production.

Climate change and subsequent sea-level rise evidently impact coastal ecosystems, coastal inhabitants and their livelihoods that are primarily based on small-scale fisheries. The presence of mangroves has also been shown to contribute to reducing the rate of coastal erosion (Mazda *et al*., 2002; Thampanya *et al*., 2006; Naohiro *et al*., 2012). Mangroves have also been reckoned to have a high capacity in carbon sequestration (Perera and Amarasinghe, 2019; Jakovac *et al*., 2020), in comparison to terrestrial forests (Donato *et al*., 2011). Hence, mangroves potentially play a key role in mitigating climate-related sea-level rise by reducing atmospheric carbon dioxide (Duarte *et al*., 2013) and impeding the inundation of low-lying coastal areas.

Remote sensing technology and geographic information systems (GIS) are useful tools to investigate the dynamics of coastal ecosystems. The shoreline changes can be investigated through a time-series comparison of satellite imagery and aerial photography. Characterization of coasts with respect to the erosive forces in action and the potential influence of the presence of coastal vegetation on erosion rates provide important insights into adopting plant-based protective measures for coastal protection, which are more economical than the hard engineering solutions (Lowry and Wickremeratne, 1989). The present study was an attempt to understand the potential of mangrove vegetation in checking coastal erosion that can be utilized to design green belts for coastal protection.

MATERIALS AND METHODS

Study area

Our study sites are located on the southern and south western coasts that extend over wet (2400 - 2600 mm annual rainfall) and dry (1000 - 1250 mm annual rainfall) climatic zones of Sri Lanka (Fig. 1). These coasts are characterized by sandy beaches, rocky cliff coasts, sandstone reefs, coralline reefs, and vast areas of tidal flats and mangroves. A larger human population inhabits the southwestern coast and its' shoreline is subjected to considerable change as a result of natural and anthropogenic disturbances. Sites to carry out detailed studies were selected depending on the nature of the coast with respect to erosion and accretion characteristics (Fig. 1 and Table 1).

Mangrove study sites

The mangrove study sites, Rekawa, Kalametiya, and Kirinda are situated in the Hambanthota District on the southern coastal stretch of Sri Lanka (Fig. 1). Mangroves at Kirinda (6° 13′ 48.4896″ N, 81° 20′ 24.4248″ E) occur about 30 m away from the sea. The study area extends about 50 m from sea-ward to land-ward. Kalametiya lagoon is located in south eastern Kalametiya (6° 5′ 20.1876″ N, 80° 56′ 56.1228″ E). This lagoon is 23 km^2 in extent and it is surrounded by Lunama-Kalametiya sanctuary which consists of sand dunes, salt marshes, mangroves, lagoon, scrublands, and grasslands. Mangrove areas of Rakawa (6° 2′ 59.784″ N and 80° 50′ 30.2244″ E) border the Rekawa lagoon. Coastal wetlands in the area include the Rekawa lagoon (256 ha in extent). Rekawa has a well-developed mangrove stand which is situated about 70 m away from the sea (Table 1).

Vegetation structure

Belt transects of 10 m width laid perpendicular to

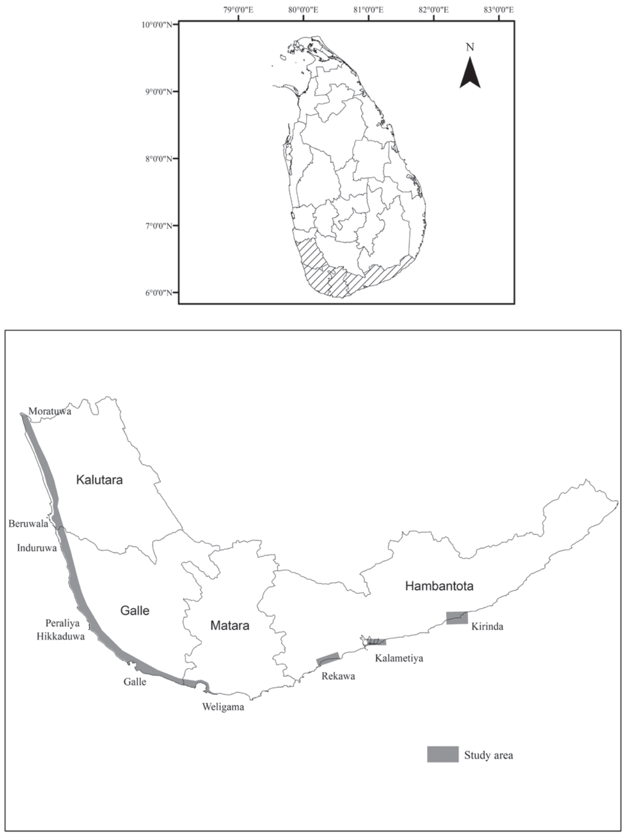

Fig. 1. *Study area of the coastal districts, Kalutara, Galle, Matara, and Hambanthota on southwestern and southern coastal zones of Sri Lanka*

the shoreline (of the lagoon/ creek/open waters) along the sea-land gradient were used to collect data on mangrove vegetation structure. Each belt of 30-40 m long was laid perpendicular to the lagoon/creek shoreline and divided into 10 m x 10 m sub-plots and data were collected from each sub-plot. All the plants encountered in transects with diameters above 2.5 cm were identified in the field and enumerated. Other structural parameters in terms of tree height, species composition, and basal area were measured. All plants encountered with trees > 2.5 cm in diameter were counted and the density was calculated. Tree heights were measured in meters using a graduated pole. The girth of trees with a diameter equal to or more than 2.5 cm was measured at a level, 1.3 m above ground (dbh) (Cintrón and Novelli, 1984).

Characterization of south-west and south coasts with respect to coastal erosion and accretion

To measure shoreline decline or progress over the 38 years, we used aerial photographs available for 1956 (scale 1: 40,000) and 1994, (scale 1: 20,000). Scanned aerial photographs (black and white) in TIFF format were georeferenced and converted to Sri Lankan projection, *i.e*., the Universal Transverse Mercator (UTM) projection (UTM zone 44N), along with the World Geodetic System 1984 (WGS 1984) datum. The spatially-referenced aerial photographs were then used

Table 1: *The study sites/ segments of coast selected for study and the reasons for their choice.*

Coastal zone	Study site	Reason/s for selection
Southwest	Moratuwa to Galle	-Beachfront is relatively wide in certain places of this coastal stretch, e.g., Induruwa, Kosgoda (30-60 m in width), Thiranagama, (20-30 m in width), Beaches at Moratuwa, Angulana, Beruwela, Payagala, and Hikkaduwa, are narrow (0-10 m in width). With a belt of sparse vegetation consisting, strand plants and *Pandanus sp*. The ocean-front zone supports herbaceous plant species, *Vigna marina, Desmodium triflorum, Phyla nodiflora, Ipomoea pescaprae, Spinifex littoreus, Cyperus bubosus, Launaea sarmentosa, Emilia baldwinii, Pedalium murex,* and *Hydrophylax maritime*. These beaches provide recreational opportunities and aesthetic amenities.
South	Galle to Welligama	-Ahangama, Unawatuna, and Mirissa south beaches are narrow (0-10 m in width) with sparse vegetation composed of herbaceous plant species such as *Ipomoea pescaprae, Launaea sarmentosa, Vigna marina, Desmodium triflorum, Gomphrena celosioides*, and *Phyllanthus rotundifolius.*
	Rekawa	-Rekawa lagoon supports a 10 – 80 m belt of mangroves. Presence of mangroves have protected the hinterland from tsunami waves in 2004.
	Kalametiya	-An estuary separated from the sea by a sand spit and the estuarine shoreline is covered with mangroves. Presence of mangroves has reduced tsunami damage in the hinterland.
	Kirinda	-Mangrove area at Kirinda is associated with a creek that drains straight into the sea.

to detect shoreline changes between 1956 and 1994. In this study, the High Water Line (HWL) was taken as shorelines of 1956 and 1994, as HWL is demonstrated to be the best indicator of the land-water interface for historical shoreline comparison studies. The shorelines of spatially-referenced aerial photographs were identified and were digitally traced (outlined) by hand using a line-drawing tool in ArcGIS to evaluate shoreline change for the period of 1956 and 1994. Various zoom levels were used to make accurate delineations of the shoreline. Digitization captured all linear vector themes of the shoreline within the study area for both 1956 and 1994 used to calculate the annual rate of shoreline change.

Determination of annual rate of shoreline change

A baseline that follows the trend of the historical shoreline of 1994 was drawn. Transects that intersect the shorelines were constructed perpendicular to this baseline. Transect spacing was 100 m (Fig. 2). The difference in shoreline position was measured at 100 meters spacing along the entire shoreline for 38 years to determine the extent of erosion or accretion associated with the shoreline and its' rate of change (distance/time).

Coastal inundation risk assessment of the study area with ASTER GDEM

Coastal flood inundation assessment associated with Sea-Level Rise (SLR) was performed to investigate how sea-level rise affects the shoreline under the present study. Digital Elevation Model (DEM) was used to model predictions of SLR scenarios and thus to assess

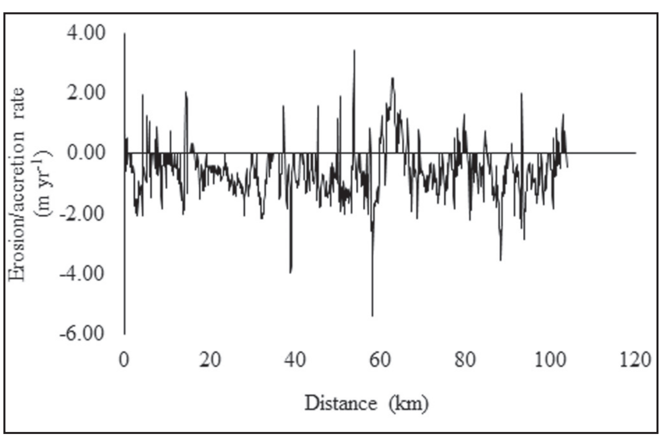

Fig. 2. *Shoreline change from Moratuwa to Mirrissa along southwestern and southern coasts of Sri Lanka*

coastal flood inundation risk. Open source ASTER Global Digital Elevation Model (ASTER GDEM) combined with spatial analysis techniques in GIS were used to develop inundation models (NASA/METI/AIST/Japan Space Systems and U.S./Japan ASTER Science Team, 2019). ASTER GDEM data of the study area with 30 m pixel size were used to generate topographic contour lines maps using topo to raster map interpolation method. The potential coastal area loss due to sea-level rise/ inundation was determined using sea-level rise scenarios of 1m and 2m (Horton *et al*., 2020).

Data analysis

Mangrove vegetation structure was analyzed and presented as Complexity index (CI) and Shannon-Weiner diversity index (Amarasinghe and Balasubramaniam, 1992). Statistical analysis was performed with R software 3.6.1 (R Development Core Team, 2019). Alpha-diversity at each study site was calculated with the R package vegan (Oksanen, 2019) and one-way ANOVA to determine whether the difference between plots is statistically significant.

RESULTS AND DISCUSSION

Mangrove vegetation structure and floristic composition

The presence of vegetation in the coastal zone is one of the factors that contribute to protecting coasts against erosion, destruction by storms and tsunamis. The structure of the coastal vegetation, including intertidal forests such as mangroves, has a considerable bearing on coastal protection, as the vegetation structure provides resistance to destructive forces and also stabilizes the soils. Structural data gathered from the mangrove stands of the study sites on the southern coast of Sri Lanka revealed considerable variation that exists among them.

Rekawa mangroves were the most diverse and it was dominated by *Ceriops tagal*, while the other two areas were dominated by *Avicennia marina. Lumnitzera racemose and Excoecaria agallocha* were the other species in all the sites and *Rhizophora mucronata* and *Bruguiera gymnorhiza* were present only at Rekawa. Although the diversity was greater at Rekawa, the mangrove vegetation was of lower stature than the other two mangroves. Mangroves of Rekawa were also the most complex in vegetation structure (Table 2). Furthermore, the distribution of mangrove species on southwestern and southern coasts has been listed in Table 3.

Table 2: *Stand structure of mangrove sites. Complexity index of stands was estimated with complexity index (CI=Number of species ×stand density×stand basal area×stand height×10^{-5}) and diversity of the stands was calculated with Shannon-Wiener index.*

Family	Mangrove species	Coastal zone
Arecaceae	*Nypa fruticans* (Thunb.) Wurmb	SW and S
Avicenniaceae	*Avicennia marina* (Forsk.) Vierh	SW and S
	Avicennia officinalis L.	S
Combretaceae	*Lumnitzera racemosa* Willd.	SW and S
	Lumnitzera littorea (Jack) Voigt	SW
Euphorbiaceae	*Excoecaria agallocha* L.	SW and S
Rhizophoraceae	*Ceriops tagal* (Perr.) C.B. Robinson	S
	Bruguira gymnorrhiza (L.) Lamk	SW and S
	Bruguiera sexangula (Lour.) Poir.	SW and S
	Rhyzophora apiculata BL.	SW and S
	Rhizophra mucronata Lamk.	SW and S
Myrsinaceae	*Aegiceras corniculatum* (L.) Blanco	SW and S
Sonneratiaceae	*Sonneratia caseolaris* (L.) Engler	S
Sterculiaceae	*Heritiera littoralis* D	SW and S

Table 3: *Distribution of mangrove species on south western (SW) and southern (S) coastal zones in Sri Lanka (De Silva, 2011; Amarasinghe and Perera, 2017)*

Sites	Species	Relative basal area (%)	Density (Trees ha^{-1})	Complexity Index (CI)	Diversity
Kirinda	*Avicennia marina* (Forsk.) Vierh	70.26	473.33	0.16	0.26
	Lumnitzera littorea (Jack) Voigt	27.04			
	Excoecaria agallocha L.	2.69			
Kalametiya	*Avicennia marina* (Forsk.)	72.76	184.33	0.06	0.30
	Lumnitzera littorea (Jack)	1.57			
	Excoecaria agallocha L	25.67			
Rekawa	*Lumnitzera littorea* (Jack)	13.95	806.4	0.2	0.61
	Excoecaria agallocha L	25.53			
	Ceriops tagal (Perr.) C.B. Robinson	53.32			
	Rhizophra mucronata Lamk.	6.32			
	B. gymnorhiza (L.) Lamk	0.88			

Characterization of south-west and south coasts with respect to coastal erosion and accretion

Analyses of aerial photographs of 1956 and 1994 and satellite images revealed that the overall southwestern coastal is more recessive than advancing. However, there is micro-scale variability in the annual rate of shoreline change and inundation within the shoreline (Table 4, Fig. 4). The coastal stretch from Balapitiya up to Gintota consists of more recessive coastline segments than advancing / accreting segments. The areas that experience erosion severely on the southwestern coast include, Beruwela, Thotagamuwa, Seenigama, and Paraliya (Fig. 2). Having critical shoreline erosion at Beruwala, Hikkaduwa and its suburbs/ or coastal hamlets, this coastal segment is the most vulnerable for shoreline change on the southwestern coast (5.55 m yr^{-1} for Hikkaduwa, 3.95 m yr^{-1} for Beruwala, and 4.37 m yr^{-1} for Benthota). Shoreline accretionary trends

Table 4: *The summary of shoreline changes calculated for study sites. Minus signs (-) show the erosion and plus sign (+) show the accretion of the study sites*

Sector	District	Length of coast line (km)	Erosion rate (m yr^{-1})	Accretion rate (m yr^{-1})	Net shoreline change rate (m yr^{-1})
South West	Kalutara	36.5	-0.76	+0.03	-0.73
	Galle	96.8	-0.83	+0.09	-0.74
South	Matara	25.4	-0.81	+0.08	-0.73
	Hambantota				
	- Kalametiya	6	-0.15	+0.09	-0.06
	- Rekawa	9	-0.14	+0.27	+0.13
	- Kirinda	6	-1.31	+0.06	-1.25

were observed at some localities in this coast from Bentota, Induruwa, Moratuwa, and Kaluthara (Fig. 2). Southern coastal stretch too shows predominantly a shoreline retreating tendency. The coastline closer to Rekawa mangrove areas however is the least eroded or most stable on the southern coastal reach (Fig. 3). The shoreline close to Kalametiya mangrove area was found to be eroded faster (0.15 m yr^{-1}) than accreted (0.09 m yr^{-1}). Shoreline at Kirinda too is recessive and shows sea-level rise driven inundation hazards (Fig. 4).

Potential of mangrove ecosystems in shoreline protection

Structural properties may render the mangrove communities varying capacities to withstand erosive and destructive forces, including inundation by seawater that the coastal lands are commonly subjected to. In Kalametiya, sand dunes with strand vegetation and sporadic *Pandanus* plants that extends parallel to the shoreline between the sea and Kalametiya lagoon where mangroves occur, supplement coastal protection against erosion. Nevertheless, large scale removal of seashells from beaches of Kalametiya shoreline has been reported as a contributing factor enhancing erosion of this stretch of coast (Madduma Bandara, 1989). Rekawa coast too has an elevated sandy beach. Besides the presence of mangroves, this sandy beach with *Pandanus* plants protects against erosion. Our results revealed that Rekawa has a high species diversity, and *R. mucronata* dominates the waterfront areas. Mangrove roots' architecture improves slope stability by consolidating sediment along the shore, and thus it protects the shoreline from erosion (Prasetya, 2007).

According to the orientation of the southern coast, it is directly impacted by southern swell generated in the mid and southern part of the Indian Ocean causing coastal erosion and inundation hazards in the southern coastal zone. Dayananda (1992) stated that the action of the southern currents in this area results in an eroding coast at Kirinda. Our results corroborate that observation as Kirinda coastline is retreating at an average rate of 1.25 m yr^{-1}, suggesting Kirinda undergoes a combination of high coastal erosion and high inundation hazards. Our analyses also revealed that some localities on the southern coast manifest signs of low erosion rates and inundation hazards compared to that of the southwestern coast (Figs. 2, 3 and 4).

The presence of vegetation, especially the mangroves serve as barriers to destructive forces that affect coastal areas and their inhabitants. Mangroves of Rekawa have been reckoned as the primary reason for the resulting lowest number of casualties in the hinterland villagers at Rekawa during the Indian Ocean tsunami in 2004 (Ranasinghe and Kallesoe, 2006). Our results suggest that beach forest species with stilt/ prop roots and dense foliage which exhibit the resistance to sea-level rise driven inundation hazards, especially within the lower strata.

Coastal vegetation improves slope stability and consolidates sediment along the shore, and hence it contributes to protect the shoreline from erosion. Although numerous hard engineering measures have been taken to check coastal erosion thus far, the rates remain the same in certain areas of the southwestern and southern coasts (Satyanarayana *et al*., 2017). Lagoons, estuaries, backwater systems, mudflats, and river outfalls which are sheltered coastal environment, can be used for mangrove afforestation and reforestation, that can reinforce the natural capacity of coasts to resist

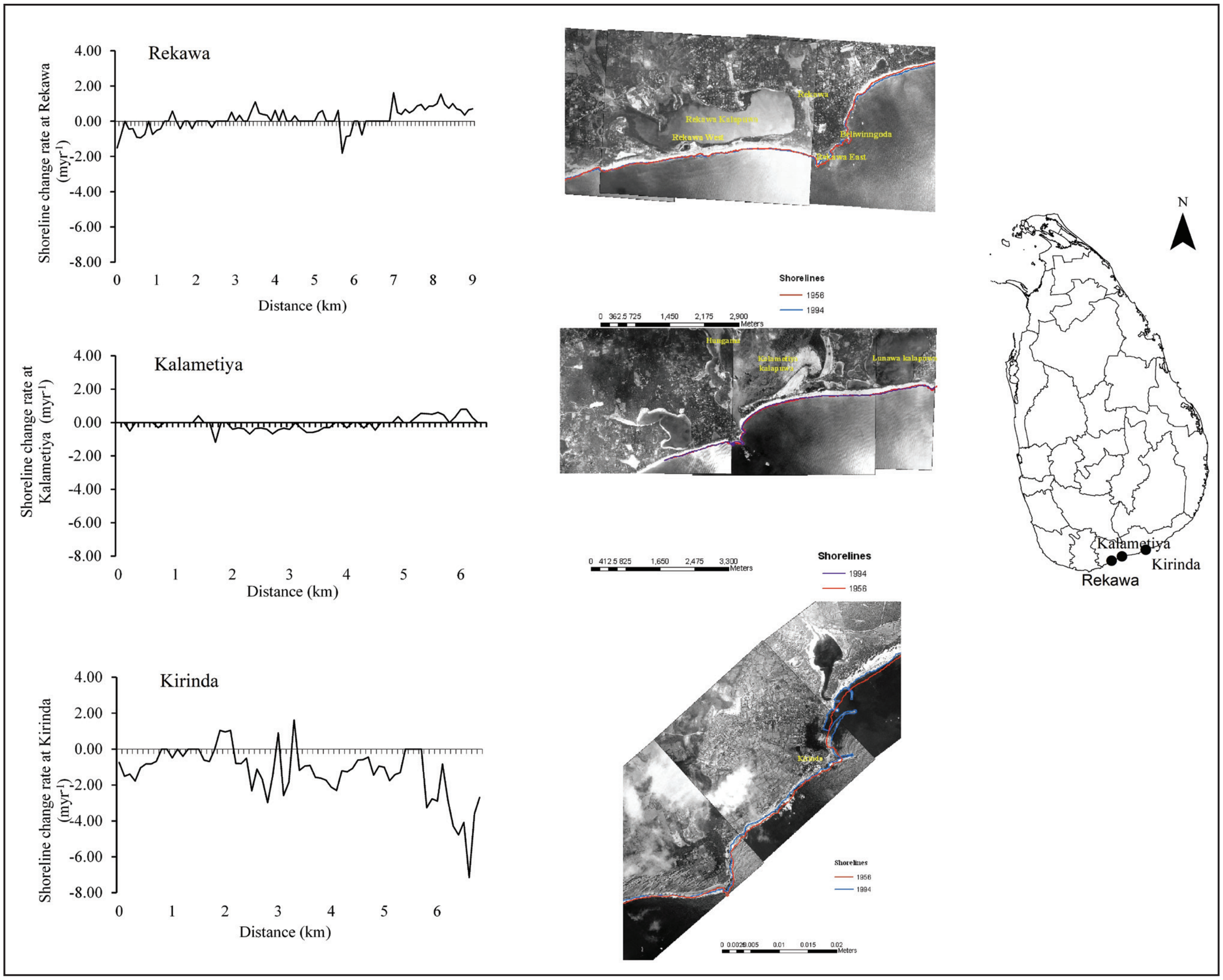

Fig. 3. *Coastal erosion rates of coastal reaches where mangrove areas located in Hambanthota district in Sri Lanka. Aerial photographs depict historical shorelines of 1994 and 1956 for measuring relative shoreline change (displayed on recent aerial photograph on 1994). Datum: D_WGS84; Projection: UTM Zone 44N*

the destructive forces that can potentially change the shorelines, especially in the current context of climate change. Mangrove afforestation interventions can be carried out by constructing shallow canals parallel to the shoreline and linking them to a nearby creek, distributaries, or the main river. Mangrove species such as *A. marina, R. mucronata, R. apiculata, C. tagal, E. agallocha,* and *B. gymnorrhiza* are suitable for mangrove afforestation on southwestern and southern coasts (De Silva, 2011), as they are the most abundant species that naturally occur in the wet climatic zone. *A. marina* with its extensive pneumatophores and spreading prop roots of *Rhizophora spp*. can attenuate wave energy effectively (Koch *et al*., 2009; De Silva, 2011).

The Indian Ocean tsunami in 2004 also revealed the inferiority of hard engineering solutions in coastal protection and provided sound evidence over the potential of coastal vegetation, particularly mangroves and seashore plants such as *Pandanus odoratissimus* in protecting the coast against erosion and occasional natural calamities like tsunamis (Kathiresan and Rajendran, 2005; De Silva, 2011; Nandasena *et al*., 2012). Determination of the magnitude of coastal erosion, identification of suitable localities, plant species and vegetation structure is of utmost importance to establish effective green belts for coastal protection. Efforts in developing alternative coastal protection strategies are still a need of the hour in Sri Lanka.

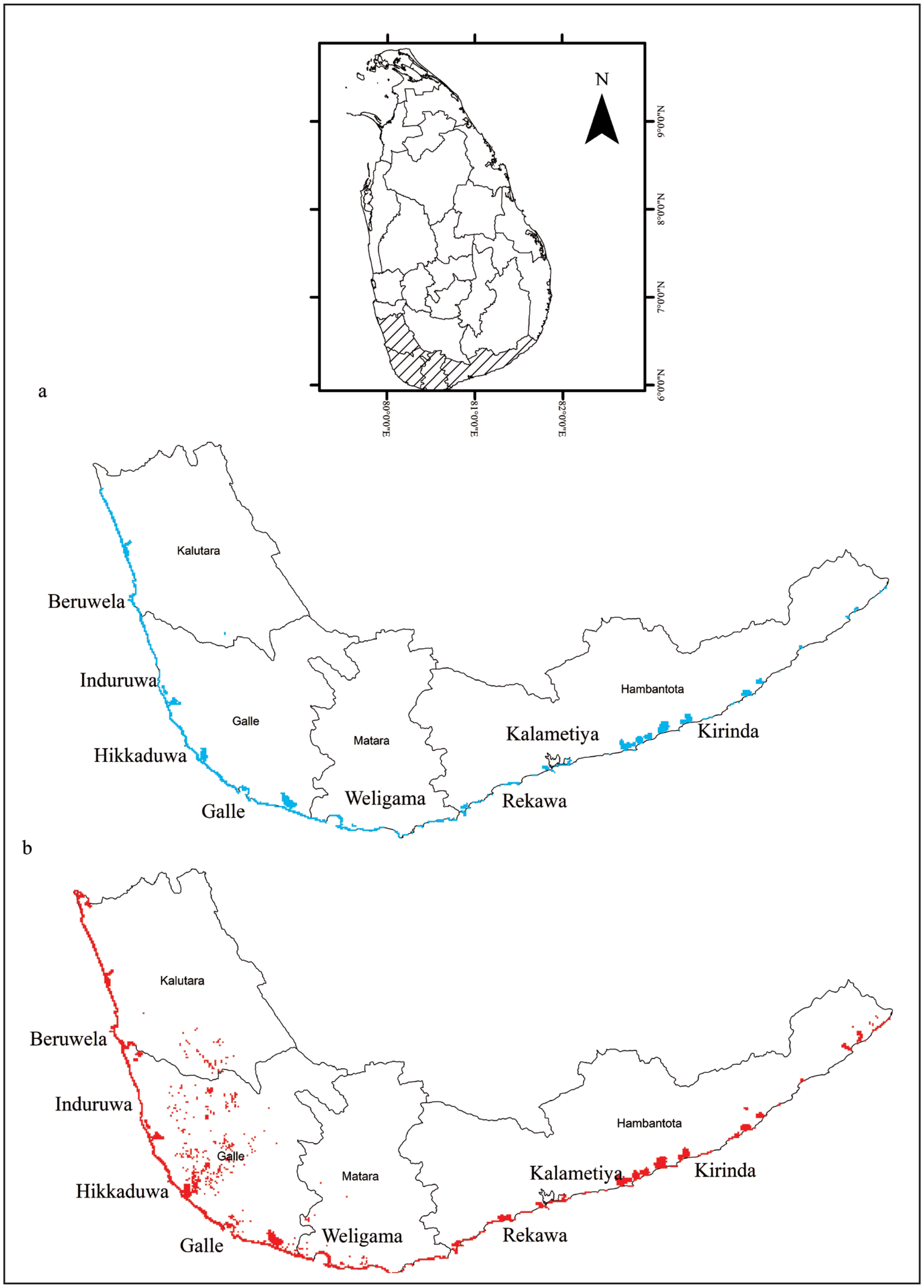

Fig. 4. *Area loss showing in blue color due to the sea-level rise scenario 1m (a) and, area loss showing in red color due to the sea-level rise scenario 2m (b)*

This study shows how remote sensing and GIS technology help in identifying long term shoreline changes. Knowledge generated with the present study, therefore, is useful to deepen the insight into erosive and sedimentary forces in action at present in various segments of the shoreline on the southwestern and southern coasts of Sri Lanka. The southern and southwestern coasts of Sri Lanka are vulnerable to coastal erosion and inundation due to sea-level rise. Erosion rates of Rekawa are generally lower than the other areas on this southern coast. The presence of mangroves may potentially reduce coastal erosion and protect the coast and its inhabitants. The establishment of mangrove green belts at appropriate coastal localities appears an effective alternative measure for coastal protection in Sri Lanka.

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CONFLICTS OF INTEREST

No potential conflict of interest was reported by the authors.

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