Vidyodaya Journal of Humanities and Social Sciences

VJHSS (2024), Vol. 09 (02)

Changes in Coastal Landforms from the Poonaryn Peninsula to the Malwathu Oya (Aruvi Aru) Estuary, Northwestern Coastal Zone (NWCZ) of Sri Lanka

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Article Info

Article History:
Received 12 Feb 2024
Accepted 20 June 2024
Issue Published Online
01 July 2024

Key Words:
Coastal Landforms
Poonaryn Peninsula
Vedithalatiu
Coastal Habitats
Enticing

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https://orcid.org/ 0009-0008-1659-5412

Journal homepage:
http://journals.sjp.ac.lk/index.php/vjhss

http://doi.org/10.31357/fhss/vjhss.v09i02.02

VJHSS (2024), Vol. 09 (02), pp. 21-42

ISSN 1391-1937/ISSN 2651-0367 (Online)

ABSTRACT

Changing coastal landforms are constantly occurring due to wind, waves, sea currents, tidal fluctuations, and human interference. This paper makes a special effort to ensure the correct usage, management and utilization of these landforms, which will benefit society through economic growth. A variety of peculiar coastal landforms have formed between the Poonaryn Peninsula (9°36'10.23"N, 80°03'16.74"E) and Malwathu Oya (Aruvi Aru) estuary (8°46'30.22"N and 79°56'12.85"E), which are approximately 120 km long coastal stretch. The Poonaryn Peninsula extends from Pallikuda Beach to Kalladi Yutha Kovil (9°35'53"N, 80°3'10"E). The peninsula stretches northwest to southeast, covering dunes with a maximum elevation of 17 meters. The selected study location is favourable for the coastal environment, and the coastal environment can be defined as the area lying at the interface between land and Mannar Bay, Palk Bay and a part of the Jaffna Lagoon. This area includes non-barrier delta estuaries with seasonal rivers and bar-built perennial delta estuaries. The zone of shallow water within which waves can move sediment and the area landward of this zone, including beaches, low coastal dunes and vegetation cover, are affected to some degree by the direct or indirect effects of waves, tides, winds and currents. The coastal environment itself may extend inland for many meters or kilometers. These processes make it possible to identify several coastal habitats, such as mangroves, salt marshes, covered and covered dunes, beaches, barrier beaches and spits. Lagoons, riverine estuaries, brackish water bodies, water holes, and marshes. When considering biodiversity, local and migratory avifauna, beach mangroves, seagrass beds, tidal creek system are very important for tourist attraction. Additionally, fishery harbours, boat landing sites, traditional fisheries (beach seines, koodo fishing), etc., and tourism were established in the northwestern coastal stretch owing to enticing coastal processes and landforms in the area for correct usage, management and utilization for enormous benefits of the fishing society, the environment and the economy.

1. Introduction

The Sri Lankan coastal zone (coastal lowlands), which has an elevation above mean sea level (MSL), is characterized by a series of attractive sandy beaches, barrier beaches, sand dunes, spits, and buried and emerged coral reef patches. Similarly, lagoons and salt-water pools, beach rock shoals, which are mostly related to the Holocene Epoch (Katupotha 1988), beach mangroves, mangrove forests and fringes, river estuaries and tidal creaks, marshes, are other important coastal habitats that contribute considerably to coastal livelihoods and ecotourism in north western coastal zone (NWCZ). Most surficial deposits are composed of poorly consolidated clay, silt, sand, or gravel-sized particles that are produced chiefly by erosion and are transported by and finally deposited by water and wind, but are also partly produced by the in-situ weathering of bedrock. These geologically recent unconsolidated sediments may include stream channel and floodplain deposits and beach sands in tropical areas.

Superficial deposits in the area are the youngest deposits formed during the most recent period, and geologically unconsolidated sediments may include stream channels, beach sands, floodplain deposits and gravel beds in palaeo river systems. Hence, a special focus on the correct usage, management, and utilization can have enormous benefits for the fishing community, the environment, and the economy, particularly for the ecotourism sector in the NWCZ of Sri Lanka.

2. Materials and Methods

Geomorphological shape of selected estuaries was identified using satellite images, including Google images from 2005 to 2023. Much information was collected from available feasibility reports, articles and available maps from Survey Department and Geological Survey and Mines Bureau. Climatological information, data on land use, sea wave, and climate were collected from relevant government departments related to the study area. Figure 1 depicts the process followed to prepare the land use maps in the present study.

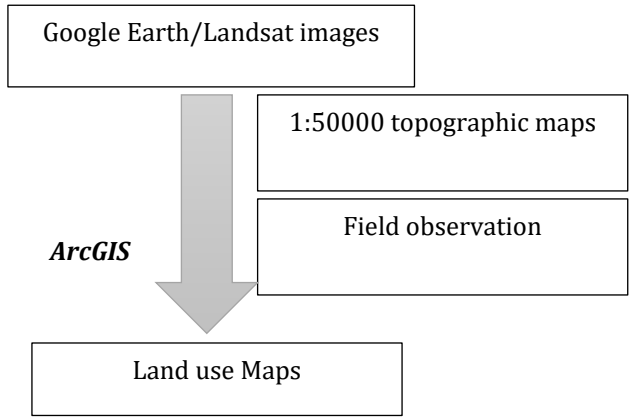
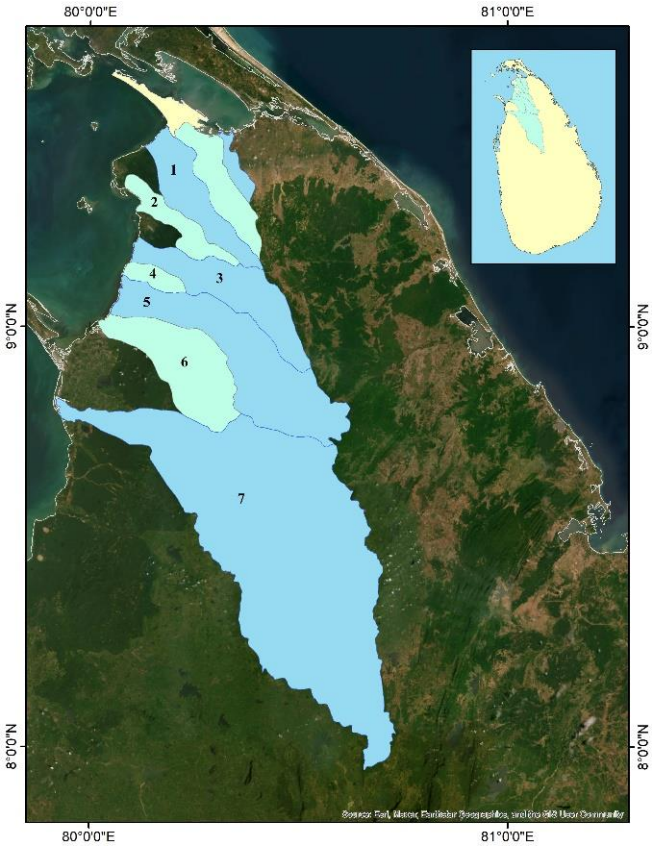


Figure 1. ArcGIS flow chart for land use map preparation

2.2 Study Area

The Poonaryn Peninsula (9°36'10.23"N, 80°03'16.74"E) and Malwathu Oya (Aruviaru) estuary (8°46'30.22"N, 79°56'12.85"E), is an approximately 120 km long coastal stretch. It can be designated as the northwestern coastal zone (NWCZ) of Sri Lanka (Figure 2). Poonaryn is a noteworthy village in the Poonakary Divisional Secretariat Division (DSD) in Northern Province, just below the Jaffna Lagoon. *Poonakary Fort, or Pooneryn Fort,* is an ancient colonial Dutch *Fort* established by the Portuguese to protect its possessions in Jaffna. Poonaryn area is located at an elevation of 2-4 m above sea level. During the mid-Holocene and late Holocene high sea levels, the whole lowlands were submerged (Katupotha 1988a, 1988b and 1995). During that time, the Poonaryn Peninsula was a small island, and Holocene high sea levels submerged the Miocene rock outcrops, which were covered by palaeotidal mud and gradually filled with superficial deposits. Recently, due to sea level fluctuations, the Poonaryn Peninsula emerged as a separate island covered with windblown sands oriented in the northeast direction. The dunes on the island rise approximately 17 meters above the present mean sea level (MSL). The leeward side of the Peninsula was subjected to tidal wave action from the Jaffna Lagoon. Additionally, all pre-Quaternary deposits are referred to as bedrock. These rocks rest on older deposits or rocks, mainly Miocene limestones.



Non-barrier Delta Estuaries with Seasonal Rivers
1 Mandekal Aru
2 Pullawarayankaddu Aru
3 Pali Aru
4 Chippi Aru
5 Parangi Aru
6 Nay Aru
Bar-built Perennial Delta Estuaries
7 Malwattu Oya Aruviaru)

Figure 2. Study area from North (Poonaryn) to South (Mendakal Aru, Pallawarayankaddu Aru, Pali Aru, Chippi Aru, Parangi Aru, Nay Aru and the Malwathu Oya (Aruvi Aru).

Table 1. Main river estuaries between the Poonarun and Malwatu Oya Estuary.

Basin No	River Basin Name	Basin Hight (m)	Area Sq. km	Average basin rainfall (mm)	Rainfall volum in (MCM)	Discharge volume to sea in MCM	Runoff/ Rainfall Ratio %	Flow into
84 (1)	Mandekal Aru	60	297	1181	351	111	32	Palk Bay
85 (2)	Pallawarayan Kadu	60	159	1134	180	60	33	Palk Bay
86 (3)	Pali Aru	84	451	1096	494	163	34	Palk Bay
87 (4)	Chippi Aru	16	66	1230	81	25	31	Palk Bay
88 (5)	ParangiAru	150 <	832	1233	1026	312	30	Palk Bay
89 (6)	Nay Ary	150 <	560	1110	616	210	34	Palk Bay
90 (7)	Malwatu Oya	300<	3246	1332	4324	142		Gulf of Mannar

Basin Numbers, Arumugam 1968. National Atlas of Sri Lanka (Survey Department, 2007).

The administrative secretariat divisions along the NWCZ include Poonakary (Killinochchi District), Mannar (east, mainland), Manthai-west, Nanattan and Musali (Mannar District). The Poonaryn to Malwathu Oya estuary includes seven river basins (Table 1; Figure 1): North (Poonaryn) to South (1) Mendakal Aru, (2) Pallawarayankaddu Aru, (3) Pali Aru, (4) Chippi Aru, (5) Parangi Aru, (6) Nay Aru and (7) Malwathu Oya (Aruvi Aru). The whole area of the NWCZ is less than 30 m in elevation, and the area included in the flat terrain (Katupotha 1989). It is composed of incipient dunes, barrier beaches, beach ridges, lagoons, and lakes of the lowest part of the flood plain. The incipient dunes and barrier beaches of this terrain are composed of recent beach materials. The basic information of the rivers is shown in Table 1. In addition, 65 water entrances from the Poonaryn Peninsula to the Malwatu Oya estuary were identified (Katupotha and Sachith 2023).

The beach from the Poonaryn Peninsula to the Malwathu Oya estuary is indent due to low dunes, beach ridges, river estuaries, tidal creeks and pools, beach mangroves and salt marshes. Within the 120 km coastal stretch, different small-scale landforms can be seen along the backshore, on shore and foreshore. The shore or beach portion of the profile is subjected to wave action and is exposed sub aerially at least some of the time. The spring low tide-line defines the seaward limit, and the landward limit is defined by the limit of swash uprush, during normal storms. The landward limit is often taken as the vegetation line. The foreshore portion of the beach is subjected to wave action during non-storm conditions. The backshore portion of the beach is subjected to wave action only during storms. During non-storm conditions, aeolian action and the beach may rework sand for recreational purposes (Davidson-Arnott 2010).

The tide of the area was examined based on available secondary data. The study area contains low-relief sedimentary environments that are flooded and drained during the rise and fall of tides (Wijeratne. and Pattiaratchi, 2006). This cyclic regime of energy results in alternating transport conditions between the bedload and suspended load. Tides in the Gulf of Mannar and in Palk Bay are very different: there is almost a twelve-hour difference in the tides, although they are close together. The oceanic

tides are mixed semidiurnal with a spring tidal range of 0.40-0.60 m. Smaller ranges appear in the northeastern part of Sri Lanka, possibly due to the wider continental shelf in that region (Wijeratne. and Pattiaratchi, 2006).

Estuaries from Mandekal Aru to Malwatu Oya, a sufficient supply of fine-grained sediment (i.e., clays, silts, and fine to very fine sands) by ebb tides, and tides and tidal currents dominate over the other hydrodynamic forces. In many estuaries in the area, fine-grained sediment is generated by rivers and discharged into adjacent coastal areas; erosion on the seabed and cliff recession provide additional sources of sedimentary materials; and organisms living in coastal waters and salt marshes produce shell debris and particulate organic matter. In tidal flats, soft sediments (muds) form coastal ecosystems that are deposited by river runoff or ocean tides. Salt marshes are saline ecosystems with characteristic geomorphologies and sedimentary environments. Soil texture is very fine, and relatively flat topography, herbaceous vegetation and diverse invertebrates and birds colonized those enviroments (Zedler, et al 2008). The mentioned tidal levels and sediments and the position of the tide in the area are identical for seagrass beds, beach mangroves and other mangrove patches, tidal creeks, salt marshes and shellfish, including crustaceans and mollusks.

The geology was inspected using detailed geological maps obtained from the Geological Survey Department of Sri Lanka in 1982, the Geological Survey and Mines Bureau (1:250,000), and the National Atlas of Sri Lanka in 2007. Mesozoic-Cenozoic cover covers the underlined rock of the NWCZ. The Mandekal Aru, Pali Aru, Pullawarayankaddu Aru, and Chippi Aru Basins are underlain layers composed of biotite gneiss, hornblende biotite gneiss, migmatite, and granitic gneiss. The rocks of the basin are amphibolite-facies rocks of the Vijayan Complex. In addition, some ferruginized gravel deposits extend as ridges and patches. The main underlying bedrock types of the Parangi Aru, Nay Aru and Malwathu Oya Basins include hornblende-rich Charnockitic gneisses with garnet and Granite gneiss and Biotite-hornblende migmatites (medium to dark grey migmatite; plagioclase, etc.). Additionally, the subsurface of the Aravi Aru Delta is covered by Miocene limestone deposits and recent and paleosupficial deposits. As younger deposits, alluvial and lagoonal clay, silt and sand, beach and dune sand appear as overlain deposits (Cooray and Katupotha 1991).

Using Sri Lanka Coastal Habitats maps (Sri Lanka's Coastal Habitats: Geographical Location and Extent) and through limited fieldwork and on-site interviews in November 2017, the authors identified beach mangroves and other mangrove forests/patches in inland tidal flats, salt marshes, covered and uncovered (vegetated) dunes, beaches, barrier beaches and spits, lagoons, riverine estuaries, and salt and brackish water pools as significant coastal habitats in the study area (Sri Lanka's Coastal Habitats: Geographical Location and Extent). The water availability and demand for potable water and agricultural water vary spatially and temporally. Groundwater is widely used across shallow aquifers in coastal areas and was discussed by Panabokke and Perera (2005). Ranawana et al, (2021), checked mangroves, salt marshes, mud flats, and dunes of the coastal area from Malwathu Oya to Pooneryn in NWCZ. During the postwar period (1983-2009), widespread activities, such as the encroachment of natural ecosystems, rapid development activity, and population influx from other areas, occurred. These activities are carried out in total disregard of the environmental sustainability of the area. Such activities will also deny the benefits of these rich ecological resources to future generations.

In relation to shoreline dynamics over the last three decades and predictions for 2032 and 2042: Nadarajapillai et al. (2023) explain a

spatial analysis along the coastal stretch of Aruvi Aru and Kal Aru, the southern part of the study area. The shoreline changes consisted of three phases: data acquisition, shoreline demarcation, and shoreline change calculation. Thus, the above researchers adopted various techniques to determine the geology, groundwater, fauna and flora from the Poonaryn Peninsula to the Malwathu Oya estuary, but no noteworthy shoreline change studies have been carried out at these study locations. Present study aimed to (a) identify the areas affected by erosion and accretion and, (b) predict future shoreline changes. Additionally, the results of this study could aid coastal experts and decision-makers in determining the importance of lagoon fisheries, beach mangroves, sea grasses, and other activities.

The soils of the Mandekal Aru to Malwathu Oay basin are coated by red, reddish brown earth and reddish brown sand ridges as Pleistocene deposits. The Reddish-Yellow Latosols are found in slightly undulating terrain, but Solodized-Solonetz, Solonchaks and Grumusol soils are found in flat coastal terrain. Alluvial soils are common along riverbanks. Alluvial soils with varying textures and drainage conditions are found along the riverbanks. The soils of the studied coastal belt from Poonakary to Malwathu Oya were identified by Moormakn & Panabokke (1961), Panabokke and Perera (2005), and Mapa (2012).

The hydrology of the study site can be described as surface water and groundwater resources. The surface water sources are rivers and irrigation tanks (village tanks), a large number of small tanks and a few reservoirs organized into cascade systems. The largest river in the study area is Malwathu Oya, which feeds the right-bank and left-bank irrigation facilities. There are two types of groundwater in the area: shallow aquifers in coastal sand and deep confined aquifers (Panabokke and Perera, 2005) in the limestone basement. The four deep confined aquifers identified in the coastal area are the Kondaichchi Basin, Murukkan Basin, Mulankavil Basin and Paranthan Basin. In addition, the Poonaryn Basin and Silavaturai Basin are also significant hydrogeological areas for extracting groundwater resources from the Miocene sedimentary belt (Davies and Herbert 1988, Miththapala, 2012, ABD 2012).

The study area is in semiarid (dry climate subtype) and dry zones. A semiarid climate that receives precipitation below potential evapotranspiration, but not as low as a desert climate. The “dry zone” of Sri Lanka gets between 1200 and 1900 mm of rainfall, mainly through the northeast monsoon, and the semiarid zone (northwestern and southeastern coasts) receives the least amount of rainfall, which is between 800 and 1200 mm (Alahacoon and Mahesh 2021). The area from Vedithalatu to Poonaryn gets 1200-1900 mm of rainfall, and from the Malwathu Oya to Vedithalatu coasts, the lowest rainfall occurs between 800 and 1200 mm.

The land use in each estuary is depicted in Figure 3. These methods are very useful for identifying different habitats and human activities in the study area. Furthermore, these data represent the economic and cultural relationships in each estuary. Thus, the main land use components of the region, Figure 4.1 to Figure 10.2 in Figure 3 are beneficial for identifying landform hangers as well as land use changes.

3. Results and Discussion

From Poonaryn to Manwathu Oya estuary, 120 km coastal zone is composed of high dunes in Poonaryn peninsula, incipient dunes, barrier beaches, beach ridges, lagoons, lakes and the lowest part of the flood plain. The dune sand and barrier beaches of this terrain are composed of recent beach materials together with calcareous materials. All tidal creeks, mud flats, of estuaries creates many sub habitats, e.g. sea grass meadows,

beach mangrove strips, mangrove forests, inter tidal mud flats, salt marsh pockets etc. Seagrass meadows are underwater ecosystem formed by seagrasses. Seagrasses are marine (saltwater) plants found in shallow coastal waters and in the brackish waters in front of estuaries. As well, tidal creeks or tidal channels are a narrow inlets or estuaries that are affected by the ebb and flow of ocean tides. Thus, it has variable salinity and electrical conductivity over the tidal cycle, and flushes salts from inland soils. This is a significant effect of the study area. Beach mangrove forests are unique habitats in the study area especially from Chippi Aru to Nay Aru intertidal zone. All locations are close to most of the associated ecosystems such as coral reefs and patches, seagrass beds, and cultural sites, e.g. St. Jamaes church, Thriketheeswaram Kovil and other Temples.

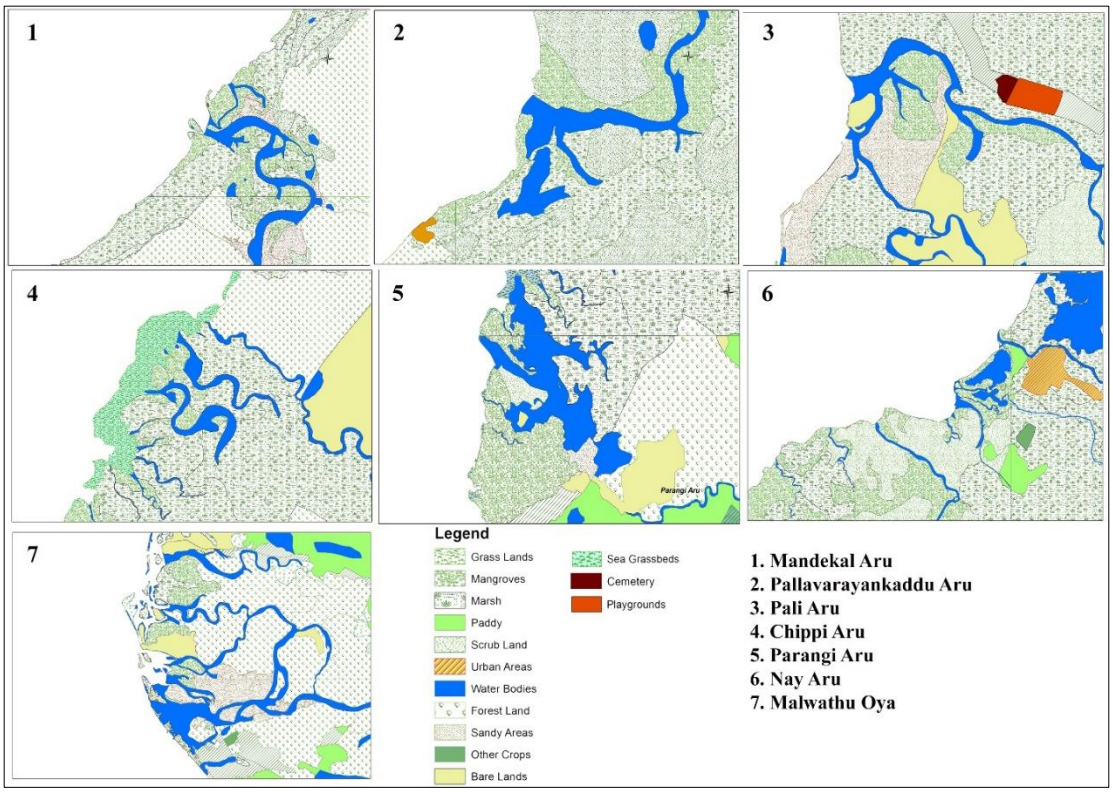


Figure 3. Land use patterns of seven estuaries in the study area.

From Vidathalativu fishery harbour to the south and north, many locations are suitable for promoting mangrove-based ecotourism. Field observations and onsite interviews at the Poonaryn mud flats (Jaffna lagoon site), Mandekal Aru estuary, surrounding Vidathalativu fishing harbour and beach mangrove area and Vankalai site identified the real circumstances of the sites for opportunities to promote ecotourism, sustainable fisheries, and other socio-economic-cultural activities that can contribute to the well-being of local communities while preserving the environment. However, it is obvious that there is no proper guidance or sponsorship for this purpose.

Waves, water level, and sediment grain size are the main controlling factors of beach profile shape. Beach profile changes occur subsequent to coastal and ocean engineering projects such as Surf zone and swash zone hydrodynamics; 1.Breaking waves, Long wave forcing, 3. Stormsurge run-up, 4. Sediment transport processes, and Beach morphology. A long-standing rule (the Bruun rule) to determine beach recession under sea level rise has never been tested in NWCZ. Bruun (1962) proposed the following equation for the equilibrium shoreline retreat, R, of sandy coasts that will occur as a result of sea level rise, S: R = S L /(h_{cl}+B). One of the great strengths of the Bruun Rule is that it provides a clear explanation for why the risks from sea-level rise are not simply the direct effects of inundation, but also takes account of the accompanying erosion and shoreward recession of the coast. The coastal profile in Sri Lanka is generally accompanied with storm surges, windstorms, and flooding hazards, and it can be exacerbated by human activities such as boat landing, shoreline hardening, artificial water features (e.g., breakwaters), and dredging. Such changes have occurred over irregular time periods, and possible to identify from Google images in each river estuary.

Based on above exact detailed information, and encompassing various characteristics, many similarities/disparities of the river estuaries can be observed in the study area, and we provide information for angler, residents, researches, academics and for policymakers.

Mandekal Aru

The Mandekal Aru rises in the western part of the Mullativu District and empties into Palk Bay (Figure 4.1). As a non-barrier delta estuary with a seasonal river, it stretches across the northern dry zone lowland, characterized by flat to slightly undulating terrain. The Mandekal Aru meanders with narrow bends and curves and empties into the ocean through two outfalls located at 9°27'03"N, 80°09'27"E (1) and 9°26'57"N, 80°09'27"E (2) within 260 m. Both outfalls were divided into two branches before entering Palk Bay, but no considerable major changes were observed in the images from 2010 and 2017 (Figures 4.1 and 4.2). The lower basin is characterized by extensive mudflats at the estuary, but there are scattered salt marshes in the coastal flat land. No beach is visible at the outfalls, and the sea is very shallow and full of seagrass. The mangrove vegetation of the coastal belt creates habitats for avifauna and act as coastal defense barriers against storm surges and high waves. Due to the 8–9-month dry period, the marine entrance is governed by the intertidal level as well as spring tides. The fine sediment and mud particles formed by the ebb and flood currents were deposited as tidal flats on both sides of the estuary.

Since there is distinct habitat diversity, which includes riverine, lacustrine (e.g., villu), marshy (e.g., saline mud flats) and dune habitats, the flora and fauna may be very specific and numerous. The mangrove forests around the river mouths are tightly packed, and the dominant species are *Avicennia marina, Lumnitzera racemosa, Pemphis acidula, Rhizophora ucronata, Sonneratia caseolaris* and *Xylocarpus granatum.* The occurrence of beach mangrove in this area can be attributed to several factors, such as shallow sea conditions, poor littoral drift, restricted wave action and fluvial inputs from the hinterland. Seagrass meadows are very dense in the shallow sea at the outfalls of the river because of the shallowness of the sea and the clear water column. Several species of seagrass have been reported (*Enhalus acoroides, Thalassia hemprichii)* and *Syringodium isoetifolium)* from this estuary area (Miththapala, 2012).

Most of the scattered salt marshes in the estuary area are covered by non-woody, salt-tolerant small plants, including Suaeda maritimeis and Suaeda vermiculata; an extremely high faunal diversity has been reported in these areas (land use map in

Figure 3.1). Ecological equilibrium in estuarine areas supports the biological production of the nearshore. Mangroves and seagrass meadows support traditional fisheries such as *koodu* (traps) and kraal fisheries, which are predominant in the area. Nevertheless, other potential socioeconomic values, such as ecotourism, inspirational values and recreation, have not yet been explored. However, there is significant potential to promote whale and dugong watching as well as ecotourism. Coastal lowlands are subjected to multiple natural hazards, such as erosion, severe waves, storms and flooding, over the long term and due to climate change; additionally, these lowlands threaten the lives, livelihoods, property, health and economic development of coastal inhabitants.

Figure 4.1. Marine entrance of the Mandekal Aru shows the ebb tidal mud flat formation in 2002, (Google Image).

Figure 4.2. Marine entrance of the Mandekal Aru shows the ebb tidal mud flat formation in 2017. 2 &1 represent the lower and upper entrances (Google Image).

Figure 5.1. The estuarine changes of the Pallawarayankaddu Aru marine entrance in 2011, (Google Image).

Figure 5.2. Pallawarayankaddu Aru marine entrance in 2019. The estuary has (1) entrance, (Google Image).

There is no noticeable coastal engineering projects surrounding the estuary area. Coastal profile changes occur through storm surges, ebb and flood tides and fishing activities by locals.

Pallawarayankaddu Estuary

The basin of Pallawarayankaddu Aru is an elongated and northwestwardly oriented small watershed (159 sq. km). It is located exclusively in the northern lowland dry zone of the island (Figure 1.2). The river flows only during the rainy period (October-December). The lower reach of the Pallawarayankaddu basin is characterized by extensive mudflats in the lowlands, but there are scattered salt marshes in the coastal plain.

The midpoint of the opening is 9°17'39"N, 80°07'20"E. Sand patches are visible on protruding spits at the outfall, and the sea is very shallow and full of sea grass. The mangrove vegetation of the coastal belt acts as an eco-region where thick mangrove forests create habitats for avifauna, crustaceans, reptiles, etc. Mangrove strips and forests act as coastal defense barriers against storm surges and estuary erosion. Due to the 8-9-month dry period, the marine entrance is governed by the intertidal level as well as by spring tides. The fine sediment and mud particles formed by the ebb and flood currents were deposited as flats. Mudflats, mangrove fringes and islets, salt marshes and barren lands mainly cover these areas. During terrestrial flood times and storm surges, the area is almost submerged, and during long dry periods, the soils experience hypersaline conditions during years around ebb deltas (Figure 5.1 and Figure 5.2).

The mangrove species composition is also unique to the area, as there are only five species of mangroves dominated by *Avicennia marina*. Intensive fishing operations around the outfall are an indication of the occurrence of well-grown sea grass meadows. The Kunchimunai fishing village is situated approximately one kilometer south of the marine entrance. The major land use types in the Pallawarayankaddu Aru estuary include sandpits, beach mangrove forests, mudflats, salt marshes, saline pools, irrigation tanks and small tidal pools. The nearshore area of the Pallawarayankaddu marine entrance is a productive fishing area. Certainly, the ecological equilibrium in estuarine areas supports the biological activity of nearshore coastal areas. Mangroves and sea grass meadows also support traditional fisheries such as *koodu* (traps) and kraal fisheries, which are predominant in the nearshore area. Nevertheless, the dependency of the farming community on river water is apparent, as the irrigation tank is located 1.2 km upstream of the marine entrance. Other potential socioeconomic values, such as ecotourism. There is significant potential to promote other socioeconomic activities like whales, dugongs and bird watching. There are no coastal engineering projects in surrounding area around river estuary. The coastal profile changes are due to natural process and fishing activities.

Pali Aru Delta Estuary

The northwest-oriented watershed of the Pali Aru (Table 1) is located exclusively in the northern lowland (dry zone) and the Pali Aru river flows only during the rainy period, mainly from October to December. The marine entrance of the Pali Aru Estuary has two openings at the marine entrance located 1.2 km apart. Both openings are more or less similar in width, approximately 30-40 m, and can reach the sea through narrow sandy beaches. The lower opening has a northward-extended canal but remains closed by a dune sand bar during most of the period. It opens only during severe floods. There are more beach mangroves in the lower outfall area (1) than in the upper outfall area (2), as shown in Figures 6.1 and 6.2. The midpoints of the two openings are 9°10'35"N, 80°6'13"E and 9°10'01"N; additionally, 80°06'05"E and sand spits are prominent at both outfalls, and they

are subjected to seasonal coastal processes. The nearshore sea of Palk Bay in this area is very shallow (1-3 to 5 m) and full of sea grass meadows. During heavy rains, the whole area is submerged by floodwater, which carries very fine organic and inorganic sediments.

Considerable changes occurred in marine entrances 1 and 2 of Pali Aru in 2002 and 2016 (Figures 6.1 & 6.2), but there are no coastal engineering projects.

The accretion and erosion of micro-level sand spits and lobs, the behavior of tidal canals, and the development of mangrove forest patches are significant features. The riparian mangroves along the stream banks are noticeably dense.

Figure 6.1. Entrances 1 and 2 of the Pali Aru in the year 2002 [(marine entrances 1 & 2), Google Image]

Figure 6.1. Entrances 1 and 2 of the Pali Aru in the year 2002 [(marine entrances 1 & 2), Google Image]

Figure 7.1. Fishing methods at Pali Aru marine entrance. The Photo was taken Nov. 2017.

Figure 7.1. Fishing methods at Pali Aru marine entrance. The Photo was taken Nov. 2017.

The composition of the mangrove species is unique to the area, and sea grass meadows comprising *Enhalus acoroides*, *Thalassia hemprichii*) and *Syringodium isoetifolium* carpeted the bottom of the coastal area in front of the river outfalls (Figure 7.1 and Figure 7.2). Habitat diversity within estuarine areas is relatively low. There is not much variety of land use types within the estuary of the Pali Aru. Shrub lands, dry forests with water holes are noticeable between the two branches of the river. The mangrove vegetation between the river branches has been degraded due to human interventions. In addition, oceanic actions such as storm surges, waves and tides have moderate impacts on river outfalls and beach vegetation. The environmental threat to estuaries is mainly associated with stream flow regulation by creating Vavuni Kulam as the reservoir, which retains sediment and the command area that mobilizes nutrients. In addition, the ecological equilibrium of coastal areas at marine entrances could be affected by illicit fishing. Beach mangroves and sea meadows are damaged by coastal inhabitants and tidal fluctuations and seasonal floods.

The Chippi Aru is a small coastal river basin, and the Pali Aru and Parangi Aru skirt the watershed. Intertidal channels are well developed due to the low relief (> 3 m below height) of the area. The river flows only during the rainy period from October to December. The elevation of the watershed ranges from sea level to 16 m above MSL; it includes flat, slightly undulating flat terrains. The whole basin area is exclusively confined to the dry zone.

The right-wing river channel flows further north westward as the Periya Aru reaches approximately 3.2 km and empties into the sea through the beach mangrove forest (Figure 7.1). The left-wing river channel meanders southwestward as Chippi Aru approximately 4 km while further branching and connecting with the branch channels of the Parangi Aru and emptying into the sea through the beach mangroves. The Chippi Aru Estuary has multiple openings at the marine entrance surrounded by mangrove islands, creeks and brooks. Five openings reach the shallow Polk Bay within 800 m from the North (9°09'16"N 80° 05'48"E) to the South (9°08'51"N, 80°05'17"E). No sandy beaches are available in this coastal stretch, and well-grown mangroves skirt the coastal margin. They also act as coastal defense barriers against storm surges and tsunamis. Due to the 8–9-month dry period, the marine entrance is governed by the intertidal level as well as by spring tides. The fine sediment and mud particles formed by the ebb and flood currents were deposited as mudflats.

The Chippi Aru and the Parangi Aru connect through tidal creeks during floods at several places. Considerable changes occurred at the entrance of the Chippi Aru and surrounding coastal areas by tidal creaks, as shown in Figures 2010 and 2017. Seasonal dry forests, scrublands, riparian forests, mangrove forests, and seagrass meadows (Figures 8.1 and 8.2) cover the Chippi Aru basin. Although the main channel of the Chippi Aru empties into Palk Bay, it connects with the Parangi Aru Delta with a meandering pattern in flat and low undulating terrains. Mollusc shells in the streambed may be attributed to mid-Holocene sea-level rise and subsequent inundation. Mudflats behind beach mangroves are also predominant.

The composition of the mangrove species is unique to the area dominated by Avicennia marina. Seagrass meadows (comprising Enhalus acoroides, Thalassia hemprichii and Syringodium isoetifolium) carpet the bottom of coastal areas in front of river outfalls (Miththapala, 2012).

The beach mangroves, sea grass meadows, mudflats and salt marshes are the dominant floral habitats of the Chippi Aru. No human settlements are found within the estuary. It can be assumed that the mangrove vegetation between the river branches has been surges,

waves and tides have moderate impacts on river outfalls and beach vegetation (Figure 9). degraded due to human interventions. In addition, oceanic actions such as storm.

Figure 8.1. Entrance of the Chippi Aru and surrounding coastal areas (tidal creaks) in 2008. Mud flats and sea meadows appeared along the border of the coast (Google Image).

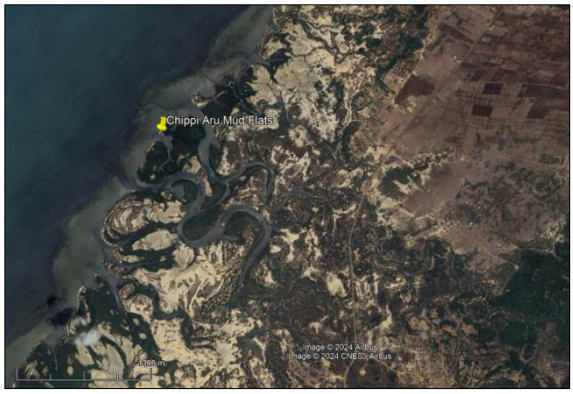


Figure 8.2. Entrance of the Chippi Aru and surrounding coastal areas (tidal creeks) in 2023. Mudflats and sea meadows have less developed around 2023 (Google Image).

Figure 9. Chippi Aru deltaic morphology and associated habitats: 1. Seagrass meadow with tidal mud flats, 2. Beach mangrove forests in intertidal mud flats, 3. Temporal sand ridges, 4. Mud flats covered with salt marshy plants, and mangroves, 5. Low elevation sandy flats, and 6. Ebb and flood tidal and rainwater discharge channels. Similar morphology and habitats are in other estuaries of the study area (Google Image).

Parangi Aru Delta Estuary

The watershed (832 sq km) of Parangi Aru is confined to the northern dry zone, which includes semiarid areas. The entire landform is undulating, flat, or slightly undulating or flat inland. After feeding irrigation tanks, an approximately 66 km long river flows northwestward, intercepting thick scrub jungles in the Vavuniya and Manner Districts (Figure 2). The mainstream bifurcates 5.4 km from the coast, and the right wing river channel flows further northwestward as Punkadu Aru, while the left wing river channel continues as Parangi Aru. The axial length of the river is 46 km. The whole Parangi Aru Basin area features flat to undulating terrain (A.i., A.iii and B categories). Based on micro morphology, sedimentation pattern and the elevation, the river basins in Sri Lanka can be divided into two units (A) and (B). The area "A" can be divided into three groups again: (A.i) Flat Terrain, < 5m; (A.ii) Flat to Slightly Undulating Terrain, <10 m; and (A.iii) Moderately Undulating Terrain. Moderately undulating terrain (10-30 m) is the river plain and lower planation surface. The unit "B" also represents the undulating features < 30m, but the height increases gradually towards the inland from the coast with mangrove forests, riparian forest strips, forest patches, scrublands and *villu*. (Katupotha 1994).

Figure 10.1. Part of the deltaic estuary of the Parangi Aru in 2008

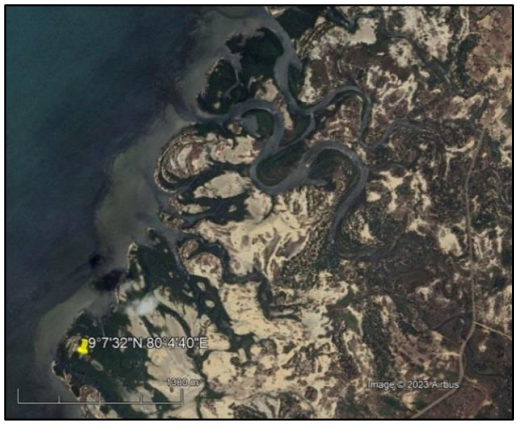


Figure 10.2. Part of the deltaic estuary of the Parangi Aru in 2023

With its multiple openings, the Parangi Aru estuary spans 5.8 km from the North (9°08'34"N; 80° 05'08"E) to the South (9°05'58"N; 80°04'29"E) at the marine entrance, and empties into Polk Bay through lush green beach mangrove forests (Figures 10.1 & 10.2). The mangrove species of the coastal belt act as buffer zones and eco-regions where there are thick forests of mangroves, which create rich habitats for reptiles, avifauna, etc. Due to the 8-9-month dry period, the marine entrance is governed by an intertidal level as well as spring tides, which form ebb and flood currents, and fine mud deposits, which form as mud and tidal flats: Geo-morphologically, from the coastal area to the hinterland (the land behind the coast, the lands are almost flat and have low undulating terrains), flatlands (A.i., < 5 m). The wide valley bottoms are covered with abundant tanks and water pools, which are completely dry for approximately 8-9 months during the dry season. The southern part of the deltaic estuary of Parangi Aru shows that the existence of mangrove forests decreased from 2008 (Figure 9.1) to 2023 (Figure 9.2).

As shown above, the marine entrance to the southern part of the deltaic estuary of Parangi Aru (from coordinates: 9°5'57"N, 80°4'39"E to coordinates: 9°7'32"N, 80°4'40"E) shows that the "fan-shaped delta" spread over an approximately 4 km long coastal stretch. Tidal creeks, mud flats and flood canals formed a wide delta during the rainy season. Parangi Aru is rich in a lush green beach mangrove forest, which covers more than 1000 ha, making it the largest mangrove area of the six delta estuaries from Vidattaltivu to Pooneryne. The extent of sea grass meadows is also greater than that in the other estuaries. The mud flats behind the beach mangroves are also widespread. The composition of the mangrove species is unique to the area with five species dominated by *Avicennia marina.* The other four species were *Lumnitzera racemosa*, *Pemphis acidula*, *Rhizophora mucronata, Sonneratia caseolaris*, and *Xylocarpus granatum.* The sea grass meadows comprising Enhalus *acoroides*, *Thalassia hemprichii*) and *Syringodium* isoetifolium carpeted the bottom of the coastal area in front of the river outfalls. The finfish and shellfish fauna are poorly understood. No significant land use change was noticeable in the estuarine area (Figure 3.6). The main land use types are five species of beach mangroves, seagrass meadows comprising three species and scattered mudflats. Meandering brackish water creeks that intercept beach mangroves are a noticeable land use feature in estuarine areas (Figure 6.1). The surrounding communities also remove beach mangroves in an *ad hoc* manner, which has been under control to a greater extent.

Nay Aru Delta Estuary

The watershed of the Nay Aru River receives an average annual rainfall of approximately 1238 mm, with the peak coinciding with the northeast monsoon. The river discharges only 312 MCM to the Indian Ocean, which is 30% of the basin's annual precipitation volume (1026 MCM). The Nay Aru mainstream has been dammed, creating a cascade of irrigation tanks (viz. Periya Thampanai Kulam, Periya Pandivirachchan Kulam, Thachchna Maruthamadu, Periya Madu and Velimarudamadu Tanks), some of which are hypertrophic. Because they are located in cascades, the river channel between irrigation tanks remains empty most of the time. The right bank canal of the Welimarudamau Tank and the terminal water body of the cascade, located 8.5 km upstream of the coast, continue as the Nay Aru flows along the northern border of Vidataltivu village before it empties into the sea through the beach mangrove forest (Figures 11.1, 11.2 , 12.1 and 12.2).

From the coastal area toward the hinterland, the lands show almost flat and low undulating terrains (A.i and A.ii, <10 m). From these terrains toward the Venkalacheddikulam area, moderately undulating terrain (30–90 m, B category) is located further inland, and rock nobs and outcrops are sparsely distributed. The wide valley bottoms are covered with used and abundant tanks and water pools, which dry out completely for approximately 8-9 months during the dry season. The coordinates at 9°00'53"N, 80°01'38"E in 2010 and 2017 according to the Google images (Figures 10.1 and 10.2) show the existence of mangrove forests and dry soil cover, which have expanded over the years. During heavy rains, the whole area of the Nay Aru entrance and its surroundings are submerged in floodwater, which carries very fine organic and inorganic sediments to the lower reaches and the nearby shore. These transported materials were deposited very slowly due to the flatness and low gradient of the continental shelf. During long dry months, the strips of mud flats become dry beds. The inorganic sediments (quartz and other mineral sand particles) are supplied from the western and northwestern coasts (from Puttalam Lagoon, the Dutch Bay area and along the Mannar Bay) through tidal channels, long shore currents and wave-induced currents. These materials are

supplied to the deltaic coast through the Palk Strait and are distributed into the mangrove forest area by flood tidal currents. Based on this information, the Nay Aru marine entrance can be identified as a fan-shaped deltaic estuary.

The unique ecological features of the estuarine area are well-grown sea grass meadows in the shallow sea, thick beach hangover forests, and mudflats. The natural areas have changed noticeably since this coastal township was under the Liberation Tigers of Tamil Elam (LTTE) for several years.

Some of the mangrove areas have been completely removed, facilitating navigation, as Vidataltivu was the seaport of the sea tigers of the LTTE.

Figure 11.1. Changes of the Nay Aru deltaic estuary in 2010

Figure 11.1. Changes of the Nay Aru deltaic estuary in 2010

Figure 12.1. The LTTE has cut a canal from Vedithalathiu fishing harbor to the sea through mangrove forest (The photo was taken Nov. 2017).

Figure 12.1. The LTTE has cut a canal from Vedithalathiu fishing harbor to the sea through mangrove forest (The photo was taken Nov. 2017).

The Vidataltivu is a commercially important fishing village with a fisheries harbor for anchorage. The harbor is active with fishing boats that specialize in catching crabs just offshore. In addition to fisheries activities, ecotourism can be promoted in this area because of its ecological significance. Nevertheless, accessing the area is still difficult without prior approval from the Defense Ministry.

The jurisdiction of the coastal area of the Vidataltivu has recently been transferred to the Department of Wildlife Conservation (DWC).

Figure 12.1. Beach mangrove forests of the Vedithalathiu coast. The photo was taken November 2017.

Figure 12.1. Beach mangrove forests of the Vedithalathiu coast. The photo was taken November 2017.

The increased population in this area has resulted in the excessive use of mangroves for various purposes. The younger generation of Vidataltivu semiurban townships is aware of the importance of mangroves and sea grass meadows for sustaining fish populations, but they do not bother the environment (Marynathan et al. 2017). Nevertheless, the destruction of mangroves in this area is still in progress. The Vidataltivu Ecotourism Society is a small organization that started with the objective of helping to protect the area's mangroves, sea grass beds and coral reefs from unsustainable fishing practices and human interventions, in addition to large quantities of plastic waste on roadsides, lagoons and beaches. It is clear that issues related to non-biodegradable solid domestic waste pose a serious challenge in this area.

Malwattu Oya (Aruvi Aru) Delta Estuary

The Malwattu Oya or Aruvi Aru (Kadamaba Nadhi) is a historical river that is strongly linked to ancient hydraulic civilization and water heritage and originates from Ritigala Hills. The basin is referred to as Malwattu Oya in the upper reaches and Aruvi Aru in the lower reaches (Arumugam 1968). Although it is the second largest watershed on the island and is located in the monsoonal area of the northern dry zone, the yield from the basin is not very large. There are approximately 1400 functional tanks of different sizes in the basin, including Nacchiduwa, Nuwara Wewa, Tissa Wewa, Mahakanadara, Pavat Kulam, Iratperiya Kulam, and Giant's tank, the major irrigation reservoirs in the north central dry zone. The basin ascends up to 854 m above MSL. The watershed of Malwattu Oya receives an average annual rainfall of approximately 1332 mm, with the peak coinciding with the northeast monsoon from October to December. The river discharges only 172 MCM to the Indian Ocean, which is 4% of the basin's annual precipitation volume (4324 MCM). The lower reaches of the Mawattu Oya, which is Aruvi Aru, are characterized by extensive delta channel meandering through lush green islands forested with mangroves.

The Malwathu Oya River flows toward the coast as a single river channel through the Maraivalattaknadal and Sakkiliyanmoddai mashes and empties into the sea at Umanakari, a Gramaniladhari division of the Nanattan DSD of the Mannar District. Near the coast, the main river channel divides into several meandering branches sheltered by

spits and sand barriers. The wide delta of the Aruvi Aru is a deposition of the sediment transported by the river as well as by waves, tides and longshore currents. Most of the delta creeks are landward-oriented channels rather than extensions of the main river channel. The densely populated Arippu village is situated immediately south of the main river entrance. The uppermost delta channel, called Kovajj Odai, empties into the sea in front of a northward-oriented spit near Achchankulam. There are approximately seven channel openings from the Malwathu Oya delta, which spread nearly 3 km from the south to the north. The marine entrance of Malwathu Oya shows significant features from the main entrance to the north (from the southern to the northern ends). The tidal influence and normal terrestrial flood area extend approximately 2.0 km into the hinterland (Figure 13.1 and 13.2). However, northward, it extends approximately 2.5–3.0 km. Based on the tidal channels, tidal water flowing to the inland, ebb and flood currents of the Malwathu Oya marine entrance, the lower part of the river can be recognized as "deltaic estuary" (Figures 14.1 and 14.2).

At least 07 major and minor entrances (1:50000 topographic sheet and Google images) cross the Malwattu Oya estuary from the southern entrance to the northern entrance. These two entrances are approximately 3 km in length along the indented coastal belt. Tidal channels, mud flats and flood canals are active during the rainy season and during spring tides. During heavy rains, the delta area of the river is submerged by floodwater, and flood problems further intensify with tidal level. During floods, the water carries very fine organic and inorganic sediments to the lower reaches and to the near shore. Inorganic sediment (quartz sand particles) flows to coastal and nearshore regions from the western and northwestern coasts (from Puttalam Lagoon, the Dutch Bay area and Mannar Bay) through tidal channels, long shore currents and wave-induced currents and is deposited on the deltaic coast. Aruvi Aru, a wide delta on the northwestern coast with several openings, has a variety of habitats, such as narrow sandy beaches, spits and sand barriers, fringe and scattered mangoes, mudflats, barren areas and water pools. In addition, there are seasonal tanks and small water holes designated as villi located behind the mudflats. These habitats provide excellent nurseries and refugia for wild animals, including finfish and shellfish.

The British had a keen desire to hold sway on the northwestern coast of the island mainly because of the pearl fishery in the Gulf of Mannar and particularly from Kondachchi to Vankalai, with the Bay of Arippu serving as the epicenter of the pearl fishery (Katupotha 2019). The historical or archaeological importance of the Arippu was not recognized during the recent past, as there was no access to reach the Arippu because of the ethnic conflict of Tamil Elam.

There are a variety of land use types (viz. sandy beaches, spits, sand bars, mangrove fringes, mudflats, rivers, tidal creeks, seasonal tanks and villi) within the estuarine area of the Aruvi Aru. Mangrove vegetation has been eliminated to a greater extent than cultivated vegetation, although riparian mangroves still exhibit good shapes. Human settlements in the Umanakari and Achchankulam villages have not yet been re-established. One or two crab fattening ponds can be seen within the estuary near the Arippu. Illegal sand mining in riverbeds and mangrove destruction are the main environmental threats in estuarine areas. The disposal of solid waste, including plastics, and mangrove destruction are common features near Arippu. The coastal ecosystems where the land meets the sea include a diverse set of habitat types, such as mangroves, coral reefs, seagrass beds, flood tidal and ebb tidal muds, lagoons, and backwaters.

Figure 13.1. Malwattu Oya estuary showing at least 07 major and minor entrances from Arippu Village to the north in 2014 (Google Earth View)

Figure 13.2. Malwattu Oya estuary showing at least 07 major and minor entrances from Arippu Village to the north in 2017 (Google Earth View*)*

Figure 14.1. Opening of the main Malwathu Oya entrance (delta), Photo taken November 2017.

Figure 14.2. Opening of the main Malwathu Oya entrance. Photo: taken November 2017.

These ecosystems provide a wide range of services for the welfare of humans both directly and indirectly, including provisioning services (fisheries), regulating services (carbon sequestration, prevention of erosion, moderation of extreme events), supporting services (element and nutrient cycling), and cultural services, especially for tourism and recreation. The quality of the ecosystem services depends on the resilience of the ecosystems, but many locations in the study area have been drastically changing and converting into shrimp ponds, land reclaimed for agriculture, housing schemes, road construction, and tidal channel conversion. Accordingly, local people and different power groups destroy tidal channels, tidal creeks, tidal flats, mud flats, sea grass beds, beach mangroves, and salt marshes. The public has faced drinking and potable water deficits for a long time. Due to coastal erosion, climate change, human influence, and low water

quality, groundwater aquifers available along coastal belts are responsible for human health. Although these problems have not been resolved during the last 6-7 decades, owing to the increasing population and increasing dryness, it is necessary to develop reliable development plans for the people. Therefore, the central government and local authorities should pay attention to solving water problems in the area.

4. Conclusion and Recommendation

The northwestern coast of Sri Lanka, particularly from the Poonaryn Peninsula to the Malwathu Oya (Aruvi Aru) estuary exhibits significant dynamic coastal changes due to natural processes such as wind, waves, sea currents and tidal fluctuations. The coastal landforms, including sandy beaches, sand dunes, spits, and coral reefs, have evolved over time and the changes are further exacerbated by human activities. This evolution is closely tied to geological periods, particularly Pleistocene period to the Holocene Epoch. The study highlights the ongoing geomorphological processes shaping these landforms, emphasizing the importance of these natural features in maintaining ecological balance and supporting coastal livelihoods. Specific areas within the study region, such as the Mandekal Aru and Pallavarayankaddu Aru estuaries, have experienced notable erosion and accretion patterns. These changes are evident in the shifting positions of marine entrances and the formation of tidal mudflats over the years. Such transformations affect local ecosystems and human activities, including fisheries and agriculture.

Mangroves and seagrass meadows play a critical role in coastal defense and ecological stability. They act as natural barriers against storm surges and erosion while providing habitats for diverse marine and avian species. The preservation of these habitats is crucial for maintaining the ecological integrity and economic benefits derived from fisheries and potential ecotourism. Vellankulum (Pali Aru), Vidathalativu and Vankalei were found to be the most suitable areas in the NWCZ to promote mangrove-based ecotourism.

The postwar period saw increased human activity, including development projects and population influx, which have put significant pressure on natural ecosystems. These activities often occur without adequate consideration of environmental sustainability, risking long-term ecological damage and loss of natural resources that are vital for future generations. Effective coastal management strategies are essential to mitigate the adverse effects of both natural processes and human activities. This includes the implementation of long-term plans to prevent and manage erosion risks, promote sustainable use of coastal resources, and enhance the resilience of coastal communities to environmental changes. The study underscores the potential for sustainable development in the northwestern coastal region. By leveraging the unique coastal landforms and habitats, there are opportunities to promote ecotourism, sustainable fisheries, and other socio-economic activities that can contribute to the well-being of local communities while preserving the environment.

Acknowledgments: Our sincere thanks are due to Prof. Iven Silva, who helped us to collect information on estuaries and beach mangroves during our fieldwork in 2016/2017. In addition, our thanks are to Mr Anton Jayakody and Ms Dharani Wijesundara, Senior Geologists for the informative discussions on superficial deposits and Miocene limestone in the area. We thank Ms. HKAE Prasadika for her great help with this manuscript.

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