Identification of Beach Erosion in Colombo- North Coast Line: Effectiveness of the Engineered Solutions

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***Abstract*— Coastal erosion is a silent disaster in Sri Lanka due to the loss of valuable land. Coastal erosion management measures have been implemented since the 1960 decade and millions of rupees spent on the protections. This study was conducted to assess the long-term effectiveness of those engineered solutions, especially focusing on the Colombo-North region, considering the coastline relevant to the Gampaha district. The effectiveness was assessed by comparing erosion rates in the last 20 years with available historical data. Shorelines of the last 20 years were observed and digitized by Google Earth image analysis and erosion rates were calculated by GIS and Digital Shoreline Analysis (DSAS) tools. The evolution of the structures was observed and analyzed by satellite image analysis and other available data from reliable sources such as reports produced by the Government. Cost estimation for the observed structures was carried out using BOQ analysis through discounted methods. Results showed that more than 60 numbers of structures have been constructed during the last 20-30 years along the study area. Uswetakeyyawa to Estuary of Kelani River stretch was identified as the region with the highest structure density. When analyzing the results, it was revealed that the structures built in that region have reduced the erosion rate (0.43 m/year) compared to the 1996 rates (2.5 m/year). Digital shoreline analysis further indicated effectiveness as most of the protected areas from Negombo to Maha Oya estuary have been accreted during the last 20 years while unprotected areas from Uswetakeyyawa to Negombo lagoon, have been subjected to erosion. According to cost estimations, approximately Rs 1.23 billion have been spent in the last 20-30 years on the entire study area. Further, the cost analysis of the Uswetakeyyawa to Kelaniya stretch revealed that the investment for 1m accretion was Rs 28.5 million. However, the cost-effectiveness of the structures should be further assessed against the land loss value with an integrated Coastal Vulnerability Index.**

Keywords—Coastal erosion, Digital shoreline analysis, Engineered Coastal protection, Sri Lanka

I. INTRODUCTION

Sri Lanka is blessed with 1620 km of coastline that encircles the whole island and is rich in lagoons, estuaries, salt marshes, sand dunes, Coral reefs and beachlines as well as a substantial biodiversity. Sri Lanka highly relies on its shore for fishing, recreational, and tourism activities [1]. These resources offer a tremendous amount of benefit for the nation's economic growth. The region along the coast where people live takes approximately one-third of the total population, and the population density in the coastal area has increased alarmingly (from 77 per km^2 in 1990 to 87 in 2000) and is expected to reach 134 per km^2 in 2050[2]. Hence the coastal economy system can be identified as a highly sensitive component of the nation [3].

Coastal erosion can be identified as a major threat to the coastline. Coastal erosion is termed as the shoreline's landward displacement driven by the forces of currents and waves [3]. Even while coastal erosion is a natural phenomenon, it currently poses a serious threat to all built shorelines not only across Sri Lanka but also around the world. It currently poses a serious threat to all built shorelines not only across Sri Lanka but also around the world. Beach erosion affects all environmental, economic and social sectors [4]. The erosion process reduces the amount of beaches available for recreation, such as swimming, sunbathing, and surfing [5]. This can have a negative impact on the quality of life for coastal residents and visitors. Especially tourism sector is especially affected by beach erosion. Tourists are less likely to visit beaches that are eroding and polluted. This can make an immense impact on the economy of Sri Lanka.

The shoreline stability is determined by the sediment budget of the coastal area. The sediment budget is balanced with sediment supplies and losses in natural ways[6]. Positive net sediment balance always results in stable accretion beaches while negative net sediment balance results in erosion. Seasonal fluctuations of the beach area can be observed due to natural and climatic reasons such as variation of littoral drift according to the monsoon conditions [7]. Human activities, including land reclamation, port development, dam construction, river diversion, sand mining, and coral mining, can significantly exacerbate coastal erosion. Alterations along the coast disrupt natural sediment transport, reducing the supply of sediment to coastal areas and increasing erosion[8]. Since river sand supply is dominant over other all sand supplying ways, the deficit of the river sand supply has mainly caused the imbalance of the sediment budget. Therefore, natural beaches are eroding continuously as a result of less sand supply. Hence engineering solutions are essential to manage beach erosion.

Both hard and soft engineering solutions such as revetments, detached breakwaters, submerged breakwaters groins, seawalls, artificial headland, coastal revegetation, and implementing beach nourishment schemes are adopted to manage coastal erosion [9]. Several studies have been carried out to assess the effects of these protection measures. Groins focuses on sediment accumulation and shoreline stabilization[10], revetments dissipate wave energy and protect infrastructure, and detached breakwaters attenuate waves and contribute to beach restoration. Beach nourishment is an alternative method which is used to mitigate beach erosion by adding compatible sand or sediment to an eroding shoreline. But this method is more expensive than other methods and also the effective life span depends on the various natural factors[11].

All of these structures contribute for the management of erosion in different extents. But previous studies have been conducted to assess the long-term negative impacts. Groyns disrupt sediment transport, leading to beach accretion on one side and erosion on the other [10]. Revetments impede natural beach dynamics, causing downstream erosion and altering coastal habitats[12]. Detached breakwaters trap sediment, creating buildup and loss patterns, while also affecting marine ecosystems. Visual aesthetics may suffer, and navigation challenges can arise. Hence engineered solution should be designed after comprehensive study.

To the date, few studies have been conducted to assess the effectiveness of the coastal protection structures especially in Sri Lankan context. Samarasekara et. al [14] conducted a study ion the erosion management focusing Marawila beach and highlighted the importance of an integrated coastal erosion management plan. Abeykoon et.al [15] assed the effectiveness of the coastal protective hard structures in Western and North Western coastlines considering 2015-2019 period and concluded that hard structures have little capability to control erosion. Azoor et. al [11] studied the effectiveness of the beach nourishment after the Palliyawatte Uswetakeyyawa beach nourishment projects and after considering the erosion rates, concluded that beach will return back to pre- nourished state after 12 months. Jayathilka et. al [13] have reviewed the coastal protection structures in West coast of Sri Lanka. They specially concerned about the assessment of the sustainability and ecological effects of existing coastal measures, aiming to inform stakeholders and enhance future defenses against erosion.

However, to the date, little study has been done to assess the long-term effectiveness of the coastal protection measures in Sri Lanka. Hence it is important to assess the long-term effectiveness of the built coastal protection structures. In terms of methodology, a case study approach was selected to evaluate effectiveness of the protection methods with respect to economical perspective based on available data. The Colombo- North coastline was selected as the study area to identify the effects of erosion and to analyze the historical evolution of erosion management and the impacts of engineered solutions. The results of this study reflect the long-term effectiveness of the engineered solution and allowing the author to make some recommendation to improve the effectiveness of the structures in the area. Ultimately, the result can be utilized for making managerial decisions of coastal protection measures.

II. METHODOLOGY

Figure 1 shows the methodology flow chart which was followed in the study.

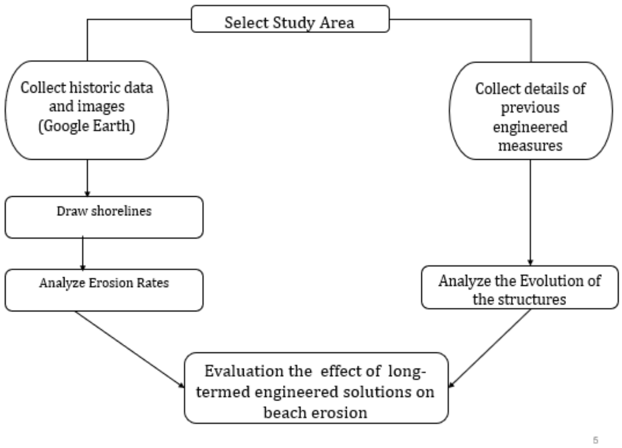

Figure 1: Methodology Flowchart

A. *Study Area*

The Colombo- North coastline which is relevant to Gampaha district coastline (See figure 2) was selected as the study area of the case study as it is the coastline of the most populated district in SL as well as provide livelihoods and recreations for millions of people. Then the study area was divided in to 2 cells.

- Cell1- Estuary of Maha Oya to Negombo Lagoon-8.05 km
- Cell 2- Negombo Lagoon to Estuary of Kelani River-28.5 km

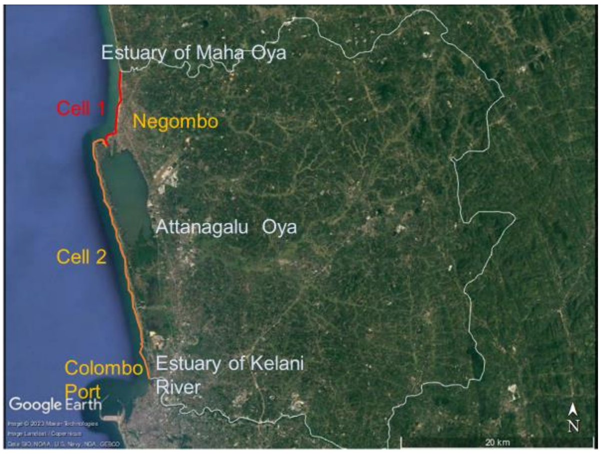

Figure 2: Geographical boundaries of the Gampaha district and relevant coastal area which is divided into 2 cells (Cell 1- From Estuary of Maha oya to Negombo lagoon, Cell 2- From Negombo lagoon to Estuary of Kelani river

The coastline belongs to Gampaha district which extends from Estuary of Kelani river to Estuary of Maha oya takes prominent place because it immensely contributes for the economy of Sri Lanka as a result of having several economic hotspots including beaches and harbours. This area serves as a magnet for tourism, boasting popular destinations like Negombo, Wattala, and Waikkal that draw global visitors, contributing substantially to the district's and Sri Lanka's overall economy.

Some coastal stretches in this zone have been identified as hotspots for erosion under Master Plan for Coastal Erosion Management (1986 and 1996)[16]. Because of the value of this coastline, several actions have been taken to save the commercial value of this stretch. Numerous erosions mitigating measures have been constructed in this coastline to conserve the coastal infrastructures. Therefore, the Gampaha coastline is a best region to study coastal erosion evolution and impacts of the erosion management solutions.

B. Collecting Historical Images and Shoreline Status

To construct a comprehensive historical perspective, high-resolution Google satellite images were utilized through Google Earth Pro for data acquisition. Subsequently, shoreline status maps spanning the years 2001 to 2022 were generated.

Erosion rates, a vital metric in understanding coastal dynamics, were quantified using Geographical Information System (GIS) software, specifically ArcGIS, in tandem with the Digital Shoreline Analysis System (DSAS) tools. The digitalized shorelines were entered into the Digital Shoreline Analysis System (DSAS – version 5.1) for further computation of shoreline change between 2001 and 2022. The Net Shoreline Movement (NSM) which is the distance(m) between oldest and youngest shorelines with reference to pre-defined baseline was used for the calculation of erosion and accretion during the considered period.

C. Collecting Details of Previous Engineering Measures

Data on previous engineered measures were gathered from published journal articles and authoritative sources such as Coastal Conservation and Coastal Resource Management Department (CC&CRMD). Satellite images from 2001-2022 were also used to identify evolution of the structures. The existing structures of each cell were marked with defined notation (Refer figure 3) and mapped in Google Earth- Pro.

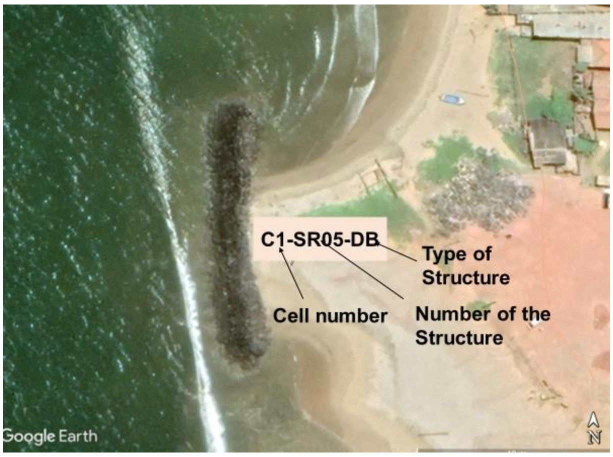

Figure 3: The notation used for mapping structures
(C_n – cell number, SR_n- Structure number, DB- Detach Breakwater, REV- Revetment, GRO-Groyne)

The figure 4 shows an example satellite image analysis and accordingly the structure has been constructed during 2004-2010 time period. Likewise, the evolution of the structures along the cell 1 and cell 2 conducted accordingly.

Figure 4: Satellite images analysis, to assess the construction period of structures.

D. Estimating the Cost of Built Structures

As it is unable to find the details of exact costs spent for each structure which have been constructed over last 3 decades, possible approximate costs were calculated for each observed structure based on Bill of Quantities (BOQ) values provided by CC&CRMD. The possible cost was estimated using base cost and adjustment factors.

TABLE I. DETAILS OF BASE STRUCTURES(CC&CRMD)

Structure	Base Length (m)	Constructed year	Cost (Rs Million)
Detach Breakwater (DB)	80	2015	**23**
Groyne (GRO)	15	2015	**25**
Revetment (REV)	40	2015	**40**

The cost for previous structures were estimated based on cost of structures built in 2015. Estimation was conducted by adjusting base cost trough adjustment factors (Length Factor, Timely Cost Factor).

Length factor was used to consider the difference of length by assuming cost is proportional to the length of the structure.

Length Factor (L_f) =Length of the structure / Base length

Timely cost Factor (T_f) was calculated according to Equation (1.a) and (1.b). The equation (1.a) was used to estimate the cost of the structures built before 2015 and equation (1.b) was used to estimate the cost of structures built after 2015 based on inflation rates (Average annual inflation rates were considered based on world bank data).

$$T_f = \frac{1}{(1+r)^n} \qquad (1.a)$$

$$T_f = (1 + r)^n \qquad (1.b)$$

Then the possible cost was calculated according to equation 2.

$$\text{Possible Cost}(C) = \text{Base cost } (C_b) \times \text{Length Factor } (L_f) \times \text{Time Factor}(T_f) \qquad (2)$$

E. Evaluation the Effectiveness of Structures

The effectiveness of the Structures was assessed based on comparison of the erosion rates and economical effectiveness was assessed by analyzing invested values.

III. RESULTS AND DISCUSSION

A. Evolution of Coastal Management

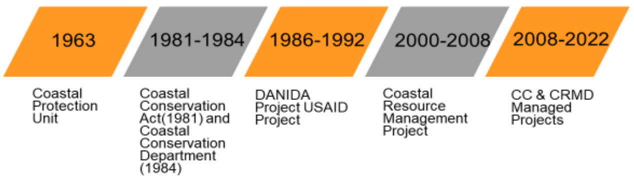

Figure 5: The timeline of the evolution of coastal management projects in the study area.

Figure 5 shows the previous protection projects which have been conducted from 1960 to the date. According to the analysis of the data, the coastal protection and erosion management has been commenced at the end of 1950 decade. Key milestones include the establishment of the Coastal Protection Unit, the enactment of the Coastal Conservation Act in 1981, and the subsequent formation of the Coastal Conservation Department in 1984. As mentioned in table II, few protection structures have been constructed in most vulnerable places before 1986.

TABLE II. STRUCTURES CONSTRCUTED BEFORE 1986(CC&CRMD)

Location	Type of structure	Length (m)	Year of Construction
Pittipana	Rev		1960
Duwa	Rev	100	1984
Kuttiduwa	Rev	100	1984
Mipura	4 Gro	30	1984
Kamachchai	5 Gro		1984
Poratota	Gro		
Dickowita	Rev4 Gro	75& 15	1986
Prithipura	Gro		

International projects, such as the DANIDA (Danish International Development Agency) Project and the USAID (United States Agency for International Development) Project, have played a crucial role in implementing engineering measures along the study area. The DANIDA and USAID projects in Sri Lanka's coastline have been instrumental in coastal protection and resource management. Approximately Rs 1520 million have been spent during 1985- 1999 period including DANIDA, USAID projects to protect coastlines over the Island [16]. Despite exact amount cannot be found, it can be assumed that, approximately Rs 600-700 million might be spent for the Colombo- North coastal region during this period. Both projects have contributed significantly to safeguarding coastal areas from erosion, preserving critical ecosystems, and building community resilience in 1990 decade. Apart from those projects, continuous maintenance and restoration works conducted for existing structures by CC&CRMD.

B. Current Status of the Coastlines

The figure 6 shows the existing structures which were mapped after analysis of the google satellite images. Approximately 54 structures were identified in the analysis.

Figure 6: (a)Observed structures in cell 1 at 12-2022- 19 Nos
(b) Observed structures in cell -2 at 12-2022-33 Nos

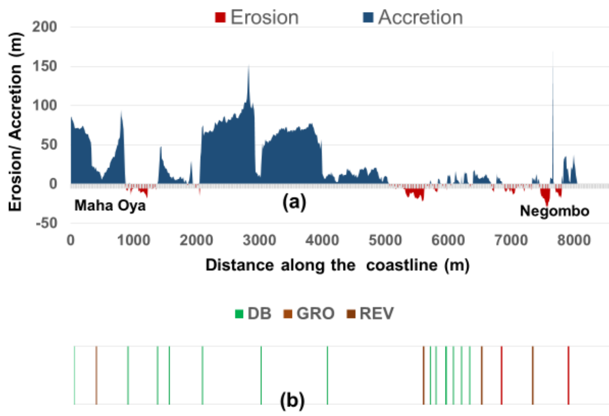

Figure 7: (a)Cell1-Net Shoreline Movement (NSM) from 2001-2022
(b) Types of structures along the cell 1

Figure 7 shows the results of digital shorelines analysis related to cell 1. As per the comprehensive analysis conducted using the Digital Shoreline Analysis System (DSAS), the assessment of Net Shoreline Movement (NSM) during the interval spanning from 2001 to 2002 reveals prevailing accretionary trends across a majority of the examined coastal areas. Particularly noteworthy is the maximum accretion observed, which attains a substantial magnitude of 160 m. This significant accretion event primarily manifests in the vicinity of structures denoted as C1-SR06-DB, C1-SR7-DB, and C1-SR8-DB, strategically situated within the Negombo beach area. These structures have evidently played a pivotal role in facilitating and augmenting shoreline advancement during the considered timeframe.

Conversely, localized areas of erosion were also identified, with the most extensive erosion registering at -30 m. Furthermore, the analysis unveils noteworthy rates of shoreline alteration. The maximum recorded accretion rate reached 1.86 m/yr, underscoring the dynamic nature of coastal accretion processes. In contrast, the maximum erosion rate was observed at -0.40 m/yr, the inherent vulnerability of certain coastal stretches to erosional forces.

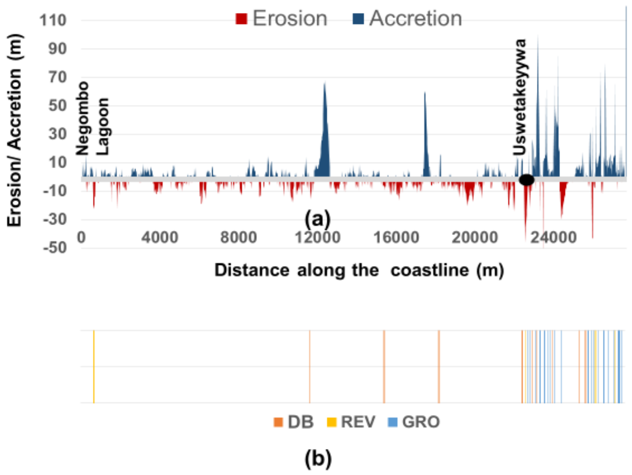

Figure 8: (a)Cell2-Net Shoreline Movement (NSM) from 2001-2022
(b) Types of structures along the cell 2

Figure 8 shows the results of digital shorelines analysis related to cell 2. In contrast to the observations in cell 1, the analysis of Net Shoreline Movement (NSM) during the period between 2001 and 2002 unveils predominant erosion trends across the majority of the observed coastal regions. Notably, the most substantial erosion recorded reaches -58.7 m, while the maximum accretion measures 102 m. The average erosion value is 6 m, juxtaposed with an average accretion of 10 m. These findings translate into an average erosion rate of -0.35 m per year and an accretion rate of 0.55m/yr.

C. Economic Effctivenes of the Structures

In 1984, the Coastal Conservation Department, with support from international agencies like DANIDA and USAID, initiated coastal safeguarding efforts, particularly in Negombo. The Negombo project aimed to restore a 7-kilometer stretch of coastline using 400,000 cubic meters of offshore sand. To ensure long-term effectiveness and cost reduction, the project incorporated two groins and four 250-meter offshore breakwaters. In total, 16 kilometers of shoreline in Negombo and Moratuwa were revitalized at a cost of Rs 322 million. Approximately Rs 150 million was allocated for Gampaha district in Phase 1 (1987-1989) of the DANIDA project. Phase 2 (1990-1992) continued these efforts in Colombo North, underscoring the commitment to coastal protection and conservation. These initiatives played a crucial role in preserving the coastal environment and mitigating erosion.

The GTZ (German Technical Cooperation) provided financial support in three stages, with Rs. 120 million in Stage I (1990-1991), Rs. 90 million in Stage II (1991-1993), and another Rs. 90 million in Stage III (1994-1995). Their efforts primarily aimed to address institutional weaknesses within the Coastal Conservation and Coastal Resource Management Department focusing on data collection, expertise enhancement, and technology transfer, rather than directly contributing to erosion mitigation. Subsequently, the Coastal Resource Management Project (2001-2008) worked to prevent coastal erosion and stabilize critical segments from Galle to Chilaw, employing various strategies such as groynes along the Kelani river mouth, compartmentalization in Dikkowita, and T-groyne installations. The estimated possible expenditures for structures in Cell 1 and Cell 2 over the past 20 years were mentioned in Table III.

TABLE III. ESTIMATED COST FOR CELL 1 AND CELL2

Cell NO	**Observed Structures**	**Estimated Cumulative Investment up to 2022 (Rs Millions)**
Cell 1	19 Nos	**337**
Cell 2	33 Nos	**881**

As the above table shows, approximately Rs 337 million have been spent for the cell1 while Rs 881 million spent for cell 2 during last 3 decades.

With refer to the figure 7, it can be highlighted that accretion occurred in most of the areas in cell 1 and, noticeable erosion can be observed in the areas where the protective structures are not provided. In comparison to cell 1, cell 2 has been dominated by erosion (Refer figure 8). But accretions can be observed where the structures built, especially from Kelaniya to Uswetakeyyawa stretch. The average accretion 28 m, while the average erosion is -7 m in this stretch. According to the cost calculations, approximately Rs 790 million has been spent for the construction of hard structures from Kelaniya to Uswetakeyyawa. Hence approximately Rs 28.5 million has been spent for 1 m accretion in this region.

Table IV shows comparison between previous erosion rates and calculated erosion rates in hotspots in the cell 2.

TABLE 4:EROSION RATES FROM 1986-2022 [17]

Coastal Stretch	MPCEM 1986	MCPEM 1996	2010 (DSAS)	2022 (DSAS)
Colombo North-Estuary of Kelani River to Uswetakeyyawa	-1.2 m/yr	-2.5 m/yr	-0.48 m/yr	-0.42 m/yr

As the table 4 shows, that erosion rate is reduced in the Kelaniya to Uswetakeyyawa stretch in last two decades compared to the 1986-996 rates. But the rest stretch from Negombo Lagoon to Uswetakeyyawa to Negombo lagoon has been undergone erosion at -0.29 m/yr average rate in last 20 years. Notably that stretch can be identified as less protected since currently only 5 major structures are available in that stretch.

The stretch from Uswetakeyyawa to Kelani river is the most suitable region to assess the financial effectiveness of the structure concerning numbers of structures as well as availability of historic erosion data.

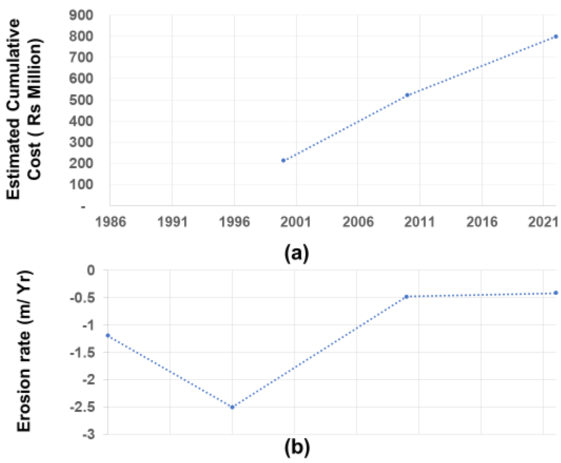

Figure 9: (a) Estimated cumulative cost to construct structures from Uswetakeyywa to estuary of Kelani River
(b) Variation of erosion rates since 1985 in the area.

Figure 9 reflects the effects of the investments on the average erosion rate from Uswetakeyyawa to Kelani river stretch. It is clear from the data in the figure above, the erosion started in the middle of the 1980s and peaked in the middle of the 1990s. The government-initiated beach protection efforts as far back as the 1980s, with projects funded by DANIDA and the USAID. However, while we have access to the total investment figures, specific values for erosion control measures on Gampaha Beach are not available.

Cost analysis based on satellite imagery from the early 2000s demonstrates that substantial investments have been made to effectively reduce erosion. Nevertheless, recent years have witnessed an acceleration in erosion drivers, necessitating a continued significant investment to maintain minimal erosion rate.

Some human activities in the study area such as offshore sand mining, river sand mining, and unauthorized constructions can be adversely affected for the sediment budget. Hence beaches can be continuously get eroded especially during the monsoon periods. Therefore, the existing protection structures should be maintained properly. Erosion rates can be accelerated if these activities are not properly managed.

D. Limitations

This project was conducted based on the Satellite images and GIS analysis. One of major limitations is, the lack of availability of images with high resolution especially before 2010. The authors based this study on the analysis of GIS and remote sensing data. Basically, the digitization relied on visual interpretations, and errors can occur in the final results if the remotely sensed data do not undergo correct preprocessing.

Further, lack of availability of the previous data and studies regarding shoreline changes and in cooperated maintenance and management costs details was a challenge in this study. And also, the sufficient cost details related to structures were not available. As a result of that, cost had to be estimated based on known BOQ values using discounted methods. But obtaining accurate discounted values became difficult because of the uncertain fluctuations of the country's macroeconomic parameters such as inflation and currency values.

IV. CONCLUSION

The study was conducted to assess the effectiveness of the

engineered coastal protection as a case study focusing coastline of Gampaha District (SL). Since several protection structures have been constructed over last 3 decades, the long-term effectiveness was expected to be assessed. According to the results, most of the regions in the cell 1 have been subjected to accretion while cell 2 has been dominated by erosion. The stretch from Uswetakeyyawa to Kelaniya can be identified as the area with highest density of structures. A comparison was conducted based on the available past data from Kelaniya to Uswetakeyyawa and results shows that structures constructed in last 20-30 years have reduce the rate of erosion (-0.43 m/yr) compared to rates in 1996 (2.5 m/yr). Digital shoreline analysis further indicates positive effectiveness as most of the protected areas from Negombo to Maha oya estuary have been accreted during last 20 years. Unprotected areas from Uswetakeyyawa to Negombo lagoon, have been subjected to some erosion (-0.29 m /yr).

However, the fact revealed from the cost analysis, Rs 28.5 million for 1m accretion from Kelaniya – Uswetakeyyawa stretch indicates that enormous amount of investments has been put for the coastal protection and to reinstate the beach. Hence the cost effectiveness of the protection measures has to be further assessed along with the loss values of the particular lands by developing a vulnerability index. A comprehensively developed vulnerability index which integrated with all engineering, managerial and social aspects would extensively reflect the effectiveness of the structures. Hence the author recommends to develop such vulnerability index to assess the effectives of existing and previous structures as well as forecast the effectiveness of the future projects.

Further, this study can be developed in to robust exploration in coastal erosion mitigation. Priority lies in stakeholder engagement, integrating social impacts, and understanding local perspectives for a comprehensive view. Evaluating long-term sustainability against climate-induced changes like sea-level rise and heightened storm frequency is vital for future-proofing interventions. Augmenting data integration through ground-level surveys, community insights, and historical coastal data will enrich the study's depth. Addressing these aspects in future developments will refine the study's impact, fortifying strategies for sustainable coastal protection measures in study areas as well as entire Sri Lankan coastline.

V. ACKNOWLEDGMENT

This study was conducted by Research Center for Coastal Infrastructure Studies (RCCIS)- Faculty of Engineering, University of Sri Jayewardenepura under the funds provided by Science and Technology Human Resource Development project (STSHRD). Hence the author would loke to express thanks to all those parties including University of Sri Jayewardenepura, STSHRD project officials. Further, special gratitude is awarded to the Eng. D.T Rupasinghe, the head of monitoring and evolution department of Coastal Conservation and Coastal Resource Management, for providing valuable documents for the study.

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