Influence of manmade effects on geomorphology, bathymetry and coastal dynamics in a monsoon affected river outlet in Southwest coast of Sri Lanka

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Abstract

A complex coastal environment with a river outlet, a sand spit barrier and an estuary of such coastal features is controlled by wave-induced hydrodynamics and sediment dynamics. The coastal dynamics patterns can be changed by natural or anthropogenic activities. This study is mainly focused on understanding the significant changes of geomorphology, bathymetry, and the coastal dynamics originated due to human influences in a monsoon affected Kalu Ganga (River) outlet in Sri Lanka. In this research project, bathymetric variations before and after the collapse of sand spit barrier were analysed to understand the extent of the erosional and depositional effects. High-resolution satellite images in Google Earth Pro were also used to qualitatively analyse beach boundary changes before the collapse of the sand spit barrier. Temporal and spatial changes of beach boundary positions after collapse of the sand spit barrier were measured using high precision GPS surveying in river outlet including the evolving sand spit barrier. Nested wave model (Delft3D modelling suite) was applied to understand the wave climate changes. The data obtained from all methods were analysed to understand the geomorphological, bathymetric and coastal dynamic changes of the study area. The results show significant and widespread deepening of bathymetry up to 1-2 m extending as far as 2 km offshore from the river outlet initiated after the collapse of the sand spit barrier. Further, the study shows separation from the mainland and buckling of the sand barrier was initiated by anthropogenic activity coupled with the release of riverine floodwater and strong waves during southwest monsoon season. The weakened and buckled sand spit barrier was migrated and welded to the mainland during calm weather of northeast monsoon. This has resulted complete change of coastal dynamics in the Kalu Ganga (River) outlet area. Since the sediment dynamics and hydrodynamics completely changed, even after 2 years, the sand spit barrier across the river outlet has not been recreated naturally. Therefore, important structures in Kalutara coastal area were threatened due to severe erosion. This study shows understanding such coastal morpho-dynamic and hydrodynamic changes are vital to implement proper coastal prevention management strategies.

Keywords: Coastal erosion, River outlet, shoreline changes, Nested wave model, Sand spit barrier

1.0 Introduction

The coastal zone generally consists of sandy beaches, estuaries, lagoons, salt marshes, and sand spits. A sand spit is a type of narrow and elongated sand barrier aligned almost parallel to the shoreline and connects to landmass from one end and usually the other end extends to the open waters (Davis and Fitzgerald 2004; Allard et al. 2008). Further, the main factor of sand spit formation is wave-induced nearshore hydrodynamics and sediment dynamics (e.g. King 1970; Schwartz 1982). Besides, several factors can control the formation of sand spits such as geology, sea-level fluctuations, local wind, tide, and anthropogenic activities (Ollerhead and Davidson-Amott 1995; Honeycutt and Krantz 2003; Lorenzo et al. 2007; Park and Wells 2007; Allard et al. 2008; Hereher 2015; Palamakumbure et al. 2020). The main advantage of the sand spit is to protect the main landmass from the energetic waves during storms and tsunamis (Allard et al. 2008). In addition, several world-famous tourist destinations (e.g. Spurn point – United Kingdom, Arabat spit – sea of Azov, La Manga del Mar Menor – Spain, Dungeness spit – Washington) are located in sand spit barriers providing recreational and residence facilities (Ciavola 1997; Armaitiene et al. 2007). Several natural sand spit barriers have developed in Sri Lanka across river outlets (e.g. Puttalam and Negombo - west coast, Kalutara - Southwest coast and Batticaloa - southeast coast). However, human interventions can alter their natural dynamic patterns, demolishing these fragile but important coastal landforms (Skilodimous et al. 2002). An important sand spit barrier developed across Kalu Ganga (River) outlet at Kalutara, Sri Lanka was destroyed due to removal of a part of the sand spit barrier resulting severe erosion of important structures located in mainland.

Kalutara is a commercially important coastal city in the western province of Sri Lanka (Fig. 1). A sand spit running across the Kalu Ganga (River) outlet, and the estuary are the most attractive tourist destinations in Kalutara. The sand spit was approximately 2 km long sand spit barrier developed across the Kalu Ganga (River) outlet (Fig. 1a). This elongated defensive barrier was also a place for recreation, fishing and tourism. The Kalu Ganga (River) opens to the Indian Ocean through the outlet channel at Kalutara after traversing about 129 km (Ampitiyawatta and Guo 2009). The Kalu Ganga (River) basin is located 6.32° and 6.90°N latitude, and 79.90° and 80.75°E longitude. The annual rainfall in the river catchment exceeds 4,000 mm, and the highest precipitation obtains from May to July during the southwest monsoon period (Kanchanamala et al. 2016). Furthermore, the heavy rainfalls are received into Kalu Ganga (River) basin during southwest monsoon season (May to September) and considerable amount of rainfall receives during second inter-monsoon season (October to November). However, less amount of rainfall receives during northeast monsoon season (December to February) compared to the southwest and second inter-monsoon into Kalu Ganga (River) basin (Ampitiyawatta and Guo 2009). Therefore, rainfall data support that the southwest monsoon season supplies more sand to the Kalutara coastline through the Kalu Ganga (River) than the northeast monsoon season as observed in the study of 2018 et al. (2013). In addition, coastal geomorphology in Kalutara coast is mainly controlled by the monsoon changes with high waves (beach erosion is evident) occurring in southwest monsoon from May to September, and calm waves (beach accretion is evident) occurring in northeast monsoon from December to February (Amalan et al. 2018; Ratnayake et al. 2018b, 2019). The mean tidal range of Sri Lanka's coastal area (including Kalutara) is about 0.5 m (micro tidal) (Ratnayake et al 2013; Duong et al. 2018).

In May 2017, a portion of the sand spit barrier connecting to the land in Kalu Ganga (River) outlet was removed to control the flood water due to heavy rain in the river upper catchment. This has led to complete destruction of the sand spit barrier (Fig. 1b and 1c). Saltwater intrusion along the Kalu Ganga (River) has also intensified after this anthropogenic event (Personal communication, Local people in the study area). Historical sites, road and railway bridges, and several government buildings are also now threatened due to erosion in the exposed area. Consequently, the destruction of sand spit barrier has a negative impact on the economy of Sri Lanka declining tourists' attraction, lack of space for recreation activities, etc. In fact, understanding influence of coastal sediment and hydro dynamics on geomorphological changes of the area is vital to decide proper coastal prevention mechanism.

Accordingly, this investigation is focussed to understand geomorphological changes and the changes of coastal sediment and hydro dynamics in Kalu Ganga (River) outlet, by means of bathymetric profile surveys, qualitative analysis of time series high-resolution satellite images in Google Earth Pro, temporal and spatial changes of beach boundary position surveys and numerical wave modelling. Our study shows drastic changes of coastal geomorphology, bathymetry in the immediate offshore area and coastal dynamics initiated with the unplanned flood mitigation measure. This investigation would help to take required future management decisions by relevant authorities to develop river mouth mitigation strategies.

2.0 Methodology

2.1 Bathymetric profiles

Two Bathymetric survey data sets which were collected on 8 January 2017 (before demolition of the sand spit barrier) and on 1 December 2017 (after demolition of the sand spit barrier) provided by the Department of Coast Conservation and Coastal Resource Management (CCCRM), Sri Lanka, were used to produce bathymetry of the study area. Initial bathymetric profiles were obtained perpendicular to the coastline as per the given Figure 2. These bathymetric survey data were collected using single beam echo-sounder with an accuracy of 1 cm, 0.1%

of depth value, corrected for sound velocity based on the International Hydrographic Organization (IHO) standards for hydrographic surveys (Standards for Hydrographic Surveys, Edition 6.0.0).

2.2 Qualitative comparison of geomorphological changes of river outlet and newly formed sand spit barrier

Time series high resolution Google Earth (Digital Globe) satellite images were used to qualitatively compare geomorphological changes of the river outlet and the sand spit barrier since 2004 to 2018. Google Earth Pro was used to extract high resolution Google Earth (Digital Globe) satellite images from same image resource (Maxar Technologies) with approximately similar spatial resolution (0.30 m – 0.70 m). The river outlet position of Kalu Ganga (River) on 1 January 2004 was marked on each extracted image by two red dots (Fig. 3) to understand the evolution of the sand spit barrier.

2.3 Beach boundary surveys

A time series beach boundary survey of the visible beach along the high-water line was carried out to understand quantitative geomorphological changes of the river outlet and the sand spit barrier starting from 2018 to 2019 covering Northeast monsoon, 1st inter-monsoon and Southwest monsoon periods (Table 1**.** The high-water line can be easily identified as wet-dry boundary on the beach surface (Zhang et al. 2004). In fact, field surveys can help to get better understanding about morphological changes of the coast (Meyer et al. 2016; Selvan et al. 2019) and beach boundary can be identified based on bluff edges, vegetation lines, high water line, beach crust, dune crust and beach scarp (Morton and Speed 1998; Pajak and Leatherman 2002).

Global navigation satellite system (GNSS) technology (TOPCON GR5 GNSS receiver) with Sri Lanka Continuously Operating Reference Station Network (SLCORSnet) correction was utilized to obtain accurate coordinates (Horizontal accuracy – 0.007 m) on the high-water line during low tide at daytime in each survey date to demarcate the beach boundary. Moreover, the network real time kinematic (NRTK) survey mode in TOPCON GR5 GNSS receiver was used to collect coordinates (Grid coordinates based on Sri Lankan Datum 1999) along the beach boundary.

The sand volume, area and perimeter of newly formed sand spit barrier were calculated using Prismoidal formula, coordinate method, and grid coordinates respectively based on the beach boundary survey data (Grid coordinates based on Sri Lankan Datum 1999) collected in different monsoon seasons during 2018 to 2019 considering Mean Sea Level - MSL as base elevation.

2.4 Numerical modelling

Sediment transport and morphological changes in nearshore area can be assessed quantitatively by understanding wave climate (Murthy and Pari 2009). In addition, if the wave climate data in the nearshore area is sparse, wave modelling techniques can be used to estimate the wave climate in the nearshore area. Simulation of wave climate in Kalutara coast was performed by Delft3D WAVE model (Nested wave model), which is the third generation SWAN model (Holthuijsen et al. 1993; Lesser et al. 2004). The Delft3D version number 4.01.01.rc.03 was used for the present study.

2.4.1 Pre-preparations of nested wave model

Nested wave model boundary (Model domain) was demarcated as large area and small area (Fig. 4a). The model boundary of large area (for coarse grids) is extended from Negombo to Hikkaduwa along the west and southwest coast of Sri Lanka, and its length and width is 115 km and 40 km respectively. Such a large model domain was selected to avoid wave shadowing effect at lateral boundaries (Duong et al. 2017) and this model domain has three open boundaries (northwest, southwest, and southeast) and a closed boundary (northeast, the land boundary). Further, grids of the model were generated by means of RGFGRID tool in Delft3D (Fig. 4b) and average grid size is 200 m X 200 m as well as total number of grids are 104,976 within the domain.

The model boundary of small area (for finer grids) is focused Kalutara coastal zone including Kalu Ganga (River) outlet as well as either side of river outlet along the coast and adjacent nearshore zone. The length and width of the model boundary is 10 km and 2 km, respectively. This model domain is comprised three open boundaries (northwest, southwest, and southeast) and a closed boundary (northeast, the land boundary). In addition, grids of the model were generated using RGFGRID tool in Delft3D and average grid size is 50 m X 50 m including 2,816 of total number of grids.

The curvilinear grids were used along the closed boundary of the domain (grids of large area and small area, nested grids) and it was facilitated to reduce artificial diffusion by ‘staircase’ boundaries (Hu et al. 2009). Furthermore, the model depths (Fig. 4c) were generated by means of QUICKIN tool in Delft3D using bathymetric data those provided by Department of Coast Conservation and Coastal Resource Management, Sri Lanka (field survey data) and GEBCO online database. Furthermore, model depths were generated separately for the large area and small area boundaries.

The model boundaries in southwest and northwest directions of nested wave model were forced by wave climate parameters (significant wave height - Hs, peak wave period - Tp, mean wave direction - Dir). Further, the wave climate parameters during 1 January 2017 to 31 December 2017 proximity to model boundary of large area in Kalutara were downloaded from Copernicus Climate Change Service Climate Date Store (ERA5 data) and meta data of the downloaded wave climate parameters is shown in Table 2. Furthermore, the downloaded wave climate parameters were organized as time varying and spatial uniform wave boundary condition file (*.bcw) to force the model boundaries. Moreover, in nested wave model, wave model computations of large area were executed first, and wave model computations of small area uses large area wave model computation results to determine their boundary conditions.

2.4.2 Setting-up of nested wave model

The nested wave model was set up to reproduce nearshore wave climate in Kalutara coast during 1 January 2017 to 31 December 2017 (before and after demolition of the sand spit barrier). In addition, appropriate model parameters of the nested wave model were decided after several tests runs of the model (Table 3). Accordingly, the nested wave model was executed as stationary computational mode and output wave parameters were calculated in nearshore area in Kalutara based on both computational model grids (Large area model and Small area model).

2.4.3 Validation of nested wave model

The model validation was performed quantitatively comparing output wave parameters (significant wave height and mean wave direction) based on small area computational grid during month of August 2017, and downloaded wave parameters from Copernicus Climate Change Service Climate Date Store (ERA5 data) in nearshore area, Kalutara (Table 2) during the same month. In fact, downloaded wave parameters used for the model validation are considered as observed wave parameters due to lack of observed wave parameters in nearshore area of this study. In addition, the nested wave model was validated qualitatively comparing high resolution Google Earth image and modelled mean wave direction in nearshore area during same period. Moreover, nested wave model accuracy was analysed statistically using calculated root mean square error (RMSE) and average bias based on the methods used by Williams and Esteves (2017).

3.0 Results

3.1 Bathymetric profiles

Bathymetric profiles on 2017/01/08 (Green line – before demolition of the sand spit barrier) and on 2017/12/01 (Red line - after demolition of the sand spit barrier) are illustrated in Figure 2b based on different profile locations along the coast in Kalutara. Further, seabed erosion varying from 1 to 2 m is shown throughout the 9 bathymetric profiles placed in between 8 km length along the coast at regular interval. Erosion has taken place up to maximum of 2 km from the coastline in some bathymetric profiles whereas it was eroded up to 400 m in some other profiles. At least a 1 m erosion can be seen from each of the bathymetric profiles at 400 m distance offshore from the coastline. The most significant erosion is located along the bathymetric profile number 4 which was placed perpendicular to the original river outlet before the demolition of the sand barrier. Deposition at a maximum of 2 m is characteristics at several locations in an around 800 m, 1000 m, and 1800 m from the coastline in different bathymetric profiles. In fact, the profiles in south of river outlet indicate less erosion of the seabed than the profiles in north of river outlet.

3.2 Qualitative comparison of geomorphological changes of river outlet and newly formed sand spit barrier

Based on the time series changes of the high-resolution satellite images in Google Earth Pro with two red dots marked on each image indicating the position of the river outlet on 2004-01-01, the river outlet of Kalu Ganga (River) moves south and the outlet is permanently open during all monsoon seasons (Fig. 3). The demolition of the sand spit barrier was commenced in May 2017 due to the inappropriate flood mitigation measure. Further, based on the image extracted on 2017-12-17 shows the breached sand spit barrier and other images (extracted after 2017-12-17) are indicating the movement of the sand spit barrier towards the landside.

3.3 Beach boundary variations

The beach boundary variations of study area were analysed from beach boundary survey records. Accordingly, four locations related to extensive variations in beach boundary were identified (Fig. 5a, 5b, 5c, and 5d). The measured beach boundaries of the location ‘m’ where old sand spit barrier (available before May 2017) connected to the land, shows significant erosion (Fig. 5a). Further, the distance between the oldest records (2018-12-16) and the youngest records (2019-08-18) of beach boundaries along the transect from ‘m’ to ‘n’ is 1.5 km. Further, beach boundary survey clearly showed severe beach erosion along the coastline up to 1 km towards the north from point ‘m’ during both southwest and northeast monsoon season in which this beach was stable before the demolition of the sand spit barrier.

Sand accretion was evident in the location near to the bridge connecting Colombo-Matara at Kalutara inside the river mouth (Fig. 5b). The maximum accretion among all beach boundary lines was 130 m measured along transect from ‘p’ to ‘q’ and those beach boundary lines were measured on 2018-12-16 and 2019-07-21. However, sand erosion can be observed by measured beach boundary lines (on 2019-07-21 and on 2019-08-18) in the location.

The gradual sand accretion is evident in the location that is illustrated by Figure 5c and sand accretion in the location is confirmed by six temporal beach boundary lines those were moving towards the ocean. In fact, the distance between old (2018-12-16) and young (2019-08-18) beach boundary lines are 80 m measured along the transect from ‘u’ to ‘v’.

The most southern portion of newly formed sand spit barrier is illustrated by Figure 5d and sand accretion is evident in this location. Moreover, six temporal beach boundary lines in the location can be observed very clearly providing details to prove the sand accretion process. In addition, the distance between old (2018-12-16) and young (2019-08-18) beach boundary lines are 100 m measured along the transect from ‘x to ‘y’.

3.4 Variation of volume, area, and perimeter of newly formed sand spit barrier

Temporal variations in volume, area, and perimeter of newly formed sand spit barrier were tabulated in Table 4. The maximum and minimum sand volumes of newly formed sand spit barrier is 200,972 m^3 (on 2019-07-21) and 100,688 m^3 (on 2019-05-26), respectively. Similarly, maximum and minimum area of newly formed sand spit barrier is 0.18 km^2 (on 2019-08-18) and 0.12 km^2 (on 2019-01-27 and 2019-05-26), respectively. Further, maximum and minimum perimeter of newly formed sand spit barrier is 4.5 km (on 2019-08-18) and 3.95 km (on 2018-12-16), respectively.

3.5 Numerical Modelling

In quantitative validation, resultant graph in Figure 6a is indicating well compared with modelled significant wave heights and observed significant wave heights during August 2017. Similarly, resultant graph in Figure 6b is indicating well compared with modelled mean wave directions and observed mean wave directions during August 2017. In qualitative validation, the wave propagation direction displayed on the high-resolution Google Earth image (Fig. 6c) is well compared with modelled mean wave direction during same time period (Fig. 6d). In addition, the modelled mean wave direction based on the monsoon seasonality in nearshore area of this study is illustrated in Figure 7. The extent and direction of arrows in Figure 7 is representing the significant wave height and wave direction respectively. Moreover, calculated root mean square error (RMSE) and average bias of the nested wave model were 0.18 and 0.03, respectively.

4.0 Discussion

4.1 Vertical changes in the seabed after the demolition of the sand barrier

Demolition of sand barrier has caused wide-spread erosion with the sudden removal of riverine flood water, eroding and deepening the seabed as far as 2 km from the coastline at some of the surveyed locations. Some sand removed from the seabed deepening along with demolition of sand spit barrier has carried with the strong flood currents and deposited as irregular and discontinuous offshore sand beds at 800 m, 1000 m and 1800 m from the coastline as per the figure 2(b). Furthermore, displacement of the existing underwater sand beds to the offshore indicates that the very energetic cross-shore currents (riverine flood currents) were generated after demolition of the sand spit barrier (Fig. 2b). The sand erosion at seabed is significant in south part of the outlet (bathymetric profiles) compared to north part of the outlet (bathymetric profiles) indicating existence of underwater river mouth sand spit barrier up to certain extent that has directed riverine flood water towards the southern part even after demolition of sand barrier.

In fact, deepening of the nearshore zone can cause breaking of waves very near to the coastline. This might also lead to generate new refraction and diffraction patterns resulting differential coastal accretion and erosion scenarios (Pinet 2009).

4.2 Seasonal variations of wave climate

Validated nested wave model provides mean wave direction in nearshore area (Fig. 7). Consequently, the longshore current direction was determined using mean wave direction in the study area based on monsoon seasonality; (i) towards north during 1st inter-monsoon season, (ii) towards north during southwest monsoon season, (iii) towards north during 2nd inter-monsoon season, and (iv) towards south during northeast monsoon season.

The RMSE of the model indicates that the lower values are representing less residual variance and therefore, better model performance (Williams and Esteves 2017). If RMSE < 0.2, the model is statistically significant. The RMSE value of nested wave model is 0.18 and it is less than 0.2. Hence, the nested wave model is statistically significant with 95% confidence level. Similarly, the average bias of a model based on the Williams and Esteves 2017, *"Difference between an estimator's expectation and the true value of the parameter being estimated"*. If the average bias is less than 0.2, the model is statistically significant (Williams and Esteves 2017). The average bias of the nested wave model is 0.03 and then, it is indicating that the model is statistically significant with 95% confidence level.

4.3 Geomorphological changes before the demolition of sand spit barrier

The high-resolution satellite images of the period before demolition of sand barrier reveals that the Kalu Ganga (River) outlet was permanently open while moving towards south (Fig. 3). Similar observations have been made by Doung et al. (2018). Furthermore, partial removal of sand from the river mouth sand spit barrier (Calido beach) to control flooding in the Kalutara area for several years in the past when there were heavy rains was a general practice and the opening of the sand spit was usually filled with time. In May 2017, to mitigate the flooding in the area due to heavy rain, a portion of the sand spit barrier was removed by using heavy machinery (Fig. 1). However, the opening was not filled and reconnected by sand migration with the longshore drift (Fig. 3).

Wave model results of May 2017 shows high energetic waves from southwest direction acting on Kalutara coast (Fig. 7b). Also, the high-resolution satellite images in Google Earth Pro indicate just below where spit barrier that connects to the land is very thin (Fig. 3). Hence, it can be suggested that highly energized waves acting on southwest monsoon and heavy river discharge, weakened and buckled, the disconnected sand spit barrier and with the onset of calm weather during north western monsoon cause the disconnected spit barrier to migrate and merge to the mainland.

4.4 Geomorphological changes after the demolition of sand spit barrier

To depict the significant changes of the study area, after the demolition of the sand spit barrier, changes of beach boundary position of four locations (a, b, c, and d of Fig. 5) would be discussed.

At location ‘a’ (Fig. 5a), coastal erosion is significant where old sand spit barrier (available before May 2017) was connected to the land at the northern side of the river outlet. Not only that, about a kilometre along the shoreline towards the north side of the river mouth is affected by severe erosion during both the southwest and northeast monsoon seasons. In fact, this sand erosion is due to lack of sand supply through longshore currents due to the absence of sand spit barrier (Fig. 8c and 8d), and possible intensification of wave force due to deepening in the nearshore zone causing sea waves to break very near to the coastline (Fig. 2). Further, accretion of sand in the location ‘b’ (Fig. 5b) near the bridge connecting Colombo-Matara at Kalutara is observed due to the longshore currents moving towards north during southwest monsoon season transporting sand back into the river along the newly formed back beaches. These accreted sand inside the river mouth was previously drifting towards northside beaches along the demolished sand barrier with the longshore current during the southwest monsoon replenishing and maintaining the equilibrium of the beaches. The results of the nested wave model (Fig. 7b) further support that the dominant direction of the waves is towards the northeast during the southwest monsoon season and therefore the longshore transport of coastal sediments to the north. However, sand erosion took place between 2019-07-21 to 2019-08-18 could be due to energetic waves acting on the location ‘b’ during southwest monsoon season and some of the sand got eroded to offshore by strong back-swash with the wave breaking near the coast due to the absence of sand spit barrier.

The location ‘c’ (Fig. 5c) shows sand accretion due to the sand accumulation process by longshore currents moving towards north during southwest monsoon season and moving towards south during northeast monsoon season. The longshore current direction during northeast and southwest monsoon seasons are confirmed by nested wave model results (Fig. 7).

The location ‘d’ (Fig. 5d) at the south end of newly formed sand spit barrier extends towards south by sand accretion process based on longshore currents during both monsoon seasons (northeast and southwest). In addition, south end of spit barrier turns southeast direction gradually (Fig. 5d) due to the wave refraction by the headland located south to the Kalu Ganga (River) outlet.

The calculated area and perimeter of the newly formed back beach and the sand spit barrier has gradually increased with time. However, calculated volume of the sand spit barrier is significantly varied with and within monsoon seasons (Table 4). Changes of sediment supply to sand barrier could be varied due to river sand supply, changes of longshore current direction, and strength of the wave climate.

In general, the headland area of the southern coast (Fig. 5) was stabilized by construction of breakwaters shows steady state beach condition with accretion (due to the calm weather) during northeast monsoon season and erosion (due to the stormy weather) during southwest monsoon season.

4.5 Coastal dynamic patterns before the demolition of the sand spit barrier

The coastal dynamic pattern in Kalu Ganga (River) outlet before the demolition of the sand spit barrier is characterized during southwest monsoon (Fig. 8a) with (i) substantial sand supply to the down drift river outlet due to heavy rain and transport them to offshore ebb delta with the energetic river current, (ii) partly feed the spit barrier by sand from south direction due to longshore current, (iii) partly drift sand to the north along the spit barrier due to northerly longshore current supplying sand to the north of the river outlet to keep therein beaches in steady state.

Similarly, coastal dynamics patterns during northeast monsoon season are characterized (Fig. 8b) with (i) feeding of sand to the spit barrier due to onshore transport of sediments with the calm weather swells (ii) sand movement from south of the outlet towards south due to longshore current (iii) partially supply the spit barrier with a small amount of sediment from the beaches north of the outlet due to the southerly longshore current. However, there is less sediment supply from the north of the outlet to the spit barrier, as most of the sand is impassable due to the breakwater built as part of the Colombo Harbor Expansion Project (40 kms from north of outlet) and lack of main rivers in north of outlet up to the Colombo Harbour breakwater (Ratnayake et al. 2018a).

Generally, the effective duration of southwest monsoon season on west and southwest coast of Sri Lanka (May to September) is longer than effective duration of northeast monsoon season (December to February). Accordingly, coastal geomorphological features like sand spit barrier in Kalu Ganga (River) outlet should be formed towards north based on the long effective duration of southwest monsoon season (longshore currents towards north). Although, the spit barrier in river outlet has been formed towards South. Therefore, the orientation of the sand spit in Kalu Ganga (River) outlet is providing better evidence to prove the coastal processes of hydro-sedimentary dynamic patterns associated with monsoon seasons in the study area.

4.6 Coastal dynamic pattern after the demolition of the sand spit barrier

The coastal dynamic pattern in Kalu Ganga (River) outlet after the demolition of the sand spit barrier in May 2017 is characterized during southwest monsoon (Fig. 8c) with (i) change of the location of the river outlet with the complete collapse of the sand spit barrier and therefore moving the deposition of ebb delta deposits further to the north (ii) partly drift sand to the north due to northerly longshore current in the beaches south of the outlet and deposit inside the river mouth (however absence of sand spit barrier now has suppressed the sediment drift towards beaches north of the outlet) (iii) partly, drift sand from the beaches in the north of the outlet move to the north due to northerly longshore current further starving these beaches.

Similarly, coastal dynamic pattern in Kalu Ganga (River) outlet after the demolition of the sand spit barrier in May 2017 is characterized during northeast monsoon (Fig. 8d) with (i) feeding of sand to the newly formed spit barrier, due to onshore transport of sediments with calm weather swells (ii) partly feeding sand to the newly formed spit barrier relocated further south both from southerly longshore current and Kalu Ganga (River) currents.

5.0 Conclusion

Time series satellite images suggested that sand spit barrier in Kalu Ganga (River) outlet was stable and robust until January 2017 absorbing drastic changes of wave climate and river run-off with the monsoonal changes. However, in order to take flood mitigation measures, a part of the sand spit barrier was cut-opened near to the mainland connection in May 2017 resulting gradual destruction of the sand spit barrier. That has completely changed the hydrodynamics and sediment dynamics in the Kalu Ganga (River) outlet. This study concludes,

- Anthropogenic interference has initiated breaching of the sand spit barrier located across the Kalu Ganga (River) outlet.

- Flood water release and the existing stormy wave climate during the southwest monsoon period has separated the sand spit barrier from the mainland.
- Weakened and buckled sand spit barrier was transported and welded to the mainland during the calm weather of northeast monsoon period.
- This has completely changed the hydrodynamic and the sediment dynamic pattern of the Kalu Ganga (River) outlet preventing redevelopment of sand spit barrier across the river outlet.
- Demolition of the sand spit barrier has resulted 1-2 m under water erosion maximum up to 2 km offshore from the river outlet.

This study further concludes, time series field measurements such as beach boundary survey associated with accurate positioning system is vital to understand geomorphological changes in a rapidly changing river outlet estuary. Further, numerical modelling using Delft3D with nested wave model provides an important information for reproducing the nearshore wave climate. Similarly, the model outputs can be used with field records for better understanding of the hydro-sedimentary dynamics in the area. This study provides important technical data for the re-establishment process of the sand spit barrier across the Kalu ganga (River) outlet similar to the period before May 2017.

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Figure Captions

Fig. 1 **(a)** Study area of present investigation (Kalutara coastal zone, Western province, Sri Lanka), **(b)** inserted map showing the sand spit barrier in Kalutara (before demolition), and **(c)** inserted map showing the sand spit barrier in Kalutara (after demolition)

Fig. 2 Offshore bathymetry of Kalu Ganga (River) outlet **(a)** Locations of bathymetric profiles (Red lines are not in scale, only represent orientation of the bathymetric profiles), **(b)** Bathymetric profiles in Kalutara coastal stretch, before (2017-01-08) and after (2017-12-01) demolition of the sand spit barrier

Fig. 3 Available high-resolution Google earth satellite images from 2004 to 2018 in the Kalu Ganga (River) outlet

Fig. 4 The nested wave model, Delft3D WAVE pre-preparation stage for the Kalu Ganga (River) outlet offshore area **(a)** Modal boundary (Large area for coarse grids and small area for finer grids), **(b)** Model Grids, and **(c)** Model depths. (Coordinate System: Universal Transverse Mercator [UTM])

Fig. 5 The Beach boundary survey map prepared for 2018 to 2019 (different monsoon seasons) in the Kalu Ganga (River) outlet area. The images a, b, c, and d represent enlarged locations.

Fig. 6 Wave model validation for the Kalu Ganga (River) outlet offshore area **(a)** Comparison of significant wave height - modelled versus observed (downloaded), **(b)** Comparison of mean wave direction - modelled versus observed (downloaded), **(c)** High resolution Google Earth satellite image on 2017-12-08 (northeast monsoon season), **(d)** Modelled mean wave direction in northeast monsoon season

Fig. 7 The mean wave directions during different monsoon seasons obtained from Delft3D WAVE model (Nested) in the Kalu Ganga (River) outlet offshorea area. **(a)** 1st inter-monsoon, **(b)** Southwest monsoon, **(c)** 2nd inter monsoon, **(d)** Northeast monsoon

Fig. 8 Schematic diagram of the Coastal dynamic patterns before and after the demolition of sand spit barrier. **(a)** before the demolition of sand spit barrier during southwest monsoon season, **(b)** before the demolition of sand spit barrier during northeast monsoon season, **(c)** after the demolition of sand spit barrier during southwest monsoon season, **(d)** after the demolition of sand spit barrier during northeast monsoon season

Declaration

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All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by GP Gunasinghe, Lilani Ruhunage, NP Ratnayake, AS Ratnayake, GVI Samaradivakara, and Ravindra Jayaratne. The first draft of the manuscript was written by GP Gunasinghe and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.