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River mouth morphodynamics and deflection over the short term: effects on spit growth and mangrove dynamics

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The river mouth shows the influence of the dynamics of sediment deposition and the processes organising the deposits. The river mouths of the Guyana coast, as with other coastal systems in the Guianas, are influenced by the deposition of mud banks from the Amazon River and other rivers. This study analysed and probed the influence of the riverine and marine influences on small river mouth morphological developments. In this study, the morphological dynamics of the system were carried out from satellite images through the comparison of the inter-annual morphodynamics of the river mouths, complemented by data from hydrodynamic processes among others. This study demonstrates that the recent advancement and availability of Synthetic Aperture Radar (SAR), remotely sensed data, allow for the classification of migrating river mouth action and processes; effective monitoring of mudflats development and spit formation; and, the exhibition of river mouth transitioning and infilling. Sentinel-1 images of the Mahaica-Mahaicony river mouth in Guyana were processed and analysed using Google Earth Engine (GEE) and ArcGIS to observe the mud dynamics and its effects on deflecting the river mouth, influencing the development of spit and mangrove dynamics. The results of the analyses show that the dynamics of the mud shoal and river mouth are governed by feedback from various estuarine and hydrodynamic processes resulting from the interactions between the river and ocean. The results have not only highlighted the importance of mud infilling and sediment build-up for spit development and river-mouth deflection but the impact of the sediment morphological dynamics on the ecosystem (mangrove) associated with the river mouth.

KEYWORDS

accretion, Google Earth Engine, Guyana, mud shoal morphodynamics, remote sensing of river mouth, spit development, synthetic aperture radar (SAR)

1 Introduction

River mouths and estuaries are both bodies of water where freshwater and saltwater mix (Perillo, 1995). However, as river mouths are formed by the flow of freshwater into the ocean, the estuaries are formed by the tidal movement of seawater into a river valley (McLusky and Elliott, 2007; Tagliapietra et al., 2009; Mikhailov annnd Gorin, 2012). River mouths play a great role in coastal water dynamics (Fagherazzi et al., 2015; Sreenivasulu et al., 2016; Taft and Evers, 2016; Li et al., 2022; Ngobeni and Knight, 2023). They are the places where freshwater from rivers mixes with saltwater from the ocean, creating unique ecosystems that support a variety of marine life (McLusky and Elliott, 2004; McLusky and Elliott, 2007; Van Niekerk et al., 2020; Broadley et al., 2022; Cañedo-Argüelles et al., 2023). Additionally, river mouths can also act as sediment traps, affecting coastal erosion and shaping the coastline over time (Dominguez et al., 1987; Anthony, 2015; Özpolat and Demir, 2019; Zhong et al., 2020; Knight, 2023; Vundavilli, 2023).

Mudbanks are one of the major coastal morphological features that have a direct influence and close impact on dynamics in the coastal area (Lefebvre et al., 2004; Parvathy et al., 2015; de Vries et al., 2022; van Bijsterveldt et al., 2023). The river mouth shows the influence of the dynamics of sediments deposition and the processes organising the deposits (Cai et al., 2022; Gardel et al., 2022; Moyano-Paz et al., 2022; Estournel et al., 2023). The morphology of these environments is dynamic and responds to variations in transportation, erosional and depositional of sediments both in space and time (Oyedotun and Burningham, 2019; Turki et al., 2021; Afentoulis et al., 2022). The river mouth environment also responds to a series of dynamics of physical factors and natural processes like changes in river process, tidal and wave energy (Wong et al., 2014; Ge et al., 2021; Ricci et al., 2022), sea level changes (Padmalal et al., 2014; Xia et al., 2020; Haque et al., 2022; Paul and Paul, 2022) or influence of anthropogenic activities (Wang et al., 2015; Manzolli et al., 2022; Syvitski et al., 2022). The morphodynamic response progresses through the significant phases of deposition and/or erosion over short, medium and longer timescales (Luijendijk et al., 2019; Roelvink et al., 2020; Elias et al., 2022).

The river mouths of the Guyana coast, as with other coastal systems in the Guianas, are influenced by the deposition of mud banks from the large and small rivers in the area, including the Amazon River and other rivers (Gardel et al., 2022). The areas in front of the mouth of large river systems have been well and extensively studied and reported in the literature (e.g., Wright and Coleman, 1974; Wang and Liang, 2000; Van Maren, 2007; Zhen et al., 2008; Fagherazzi et al., 2015; Nienhuis et al., 2016; Hashimoto et al., 2021; Polizel and Burningham, 2022; Lakshmanna et al., 2023; Li et al., 2023, etc.). However, there is limited or no study of the dynamics at the mouth of small river systems. This study is there not only aimed at highlighting the importance of mud infilling and sediment build-up at the mouth of large river systems as reported in other studies but to emphasise the dynamics of areas in front of small river systems for sediment accumulation and new landform development, e.g., spit development. This study analysed and probed the influence of the riverine and marine influences on river mouth morphological developments. This study documents the short-term morphological changes at the mouth of the Mahaica River system, Guyana, in response to smaller-scale (local) mud-bank dynamics, as a significant contribution to the understanding of morphodynamics at the mouth of a small river system. Understanding the short-term timescales of muddy movement (for accretion or erosion) and evaluating the pattern of sediment concentration and segregation in this muddy setting as it affects spit development and mangrove dynamics are the two primary objectives of this investigation.

2 Material and methods

2.1 Study area: Guyana coast and Mahaica River

Guyana, a tropical Atlantic country with a geographic area of 214,970 km^2, a 430 km coastline and a land mass extent of approximately 724 km (Figure 1) is located in the northeast of the South American continent. About 2% of the country's coastal land is below 5 m with much of which is 0.5–1 m below mean high tide (Government of Guyana, 2012; Oyedotun and Burningham, 2021). This semi-diurnal coastal system is characterised by a 1–3 m at neap and spring tide respectively (Winterwerp et al., 2020). The coastal plain of Guyana is part of the mud-dominated South America's Guianas coast (Anthony et al., 2010; 2014; Jolivet et al., 2019; Gardel et al., 2021). Although the two rivers are the largest river system in the region, there are also several small river systems (Anthony et al., 2010). However, the mud supplied by Amazon has dominated the geomorphological and geological development of the coastal terrain of this region (Dominguez, 2009; Anthony et al., 2010; Anthony et al., 2013). The Mahaica River (Figure 1), one of the small river systems in Guyana, is in northern Guyana and one of the principal coastal streams that drain into the Atlantic Ocean, and also serves as a border between Region 4 (Demerara-Mahaica) and Region 5 (Mahaica-Berbice) of Guyana. The Mahaica River's estimated flow is 1,700 cubic feet (48,138.64 L) per second during the wet season and 700 cubic feet (19,821.79) per second during the dry season (Worts, 1963). The river, whose origin is difficult to determine as it overlaps with lower watersheds of both Demerara and Berbice rivers, has smaller tributaries along its path (Vaughn, 2013) before draining into the Atlantic Ocean at latitude 6°42′26″N and longitude 57°55′14″W. This river is very important for many reasons. It is known for bird-watching activities in addition to serving as a home to many other wildlife animals like river otters, Canje Pheasant (Guyana's National Bird), and howler monkeys, among others, and used for cultivation of rice farming (Johnson, 2016).

2.2 Data used

In this study, the morphological dynamics of the system were carried out from satellite images through the comparison of the inter-annual morphodynamics of the river mouths and inlets, complemented by data from hydrodynamic processes among others. Here, this study demonstrates that the recent advancement and availability of Synthetic Aperture Radar (SAR) remotely sensed data (Marghany, 2013) allow for i) classification of migrating river mouth action and processes; ii) effective monitoring of mudflats development and spit formation; and, iii) the exhibition of river mouth transitioning and infilling (after Marghany, 2012; Marghany, 2013; Marghany, 2014; Ouchi, 2013; Matano, 2019; Devrani et al., 2022; Ghanbari et al., 2023). Sentinel-1 images of the Mahaica-Mahaicony river mouth in Guyana were acquired in

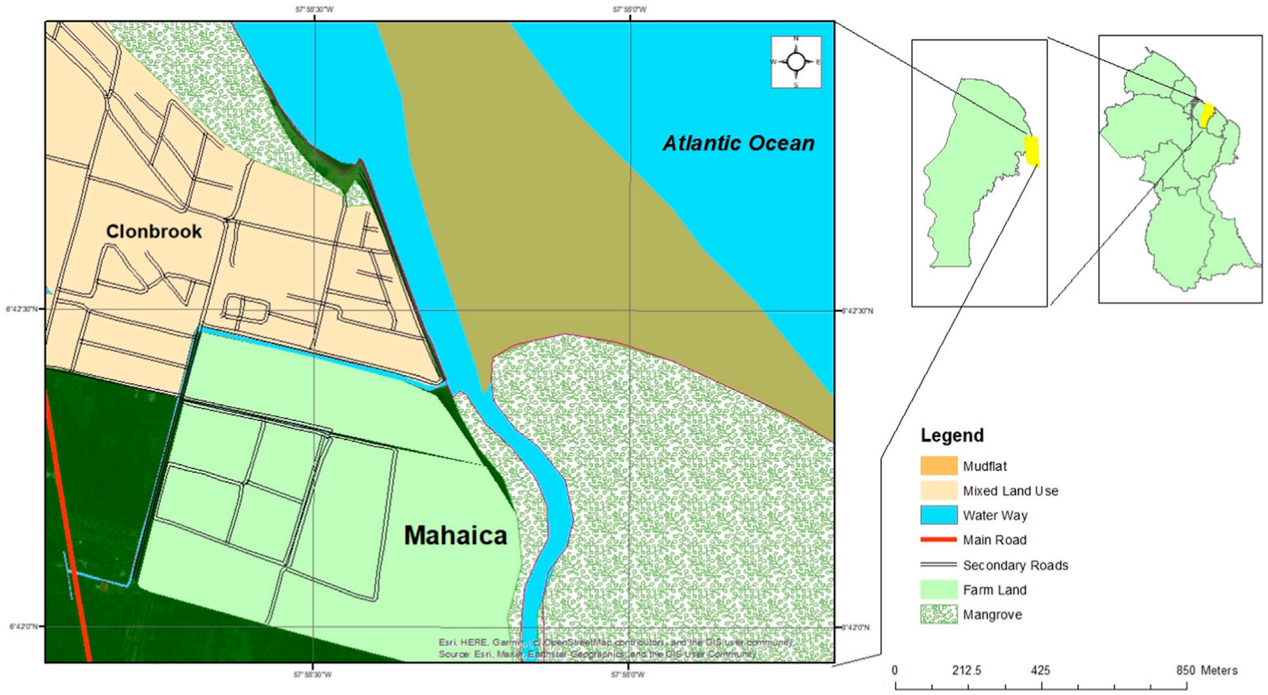

FIGURE 1
Location of the study area (Inset: Map of Guyana showing the region and the map of the region showing the study site).

TABLE 1 Sentinel-1 images captured at lowest tide for each year for study sites (2015–2020).

Sensors	Acquisition date: (dd/mm/mm)	Polarisation	Resolution (m)	Interp. tide heights (m)
Sentinel-1	23/11/2015	VV/VH	10	0.890598
	23/11/2016	VV/VH	10	1.200000
	22/05/2017	VV/VH	10	0.864519
	22/06/2018	VV/VH	10	1.000000
	11/07/2019	VV/VH	10	1.000000
	31/03/2020	VV/VH	10	1.298417
	06/02/2021	VV/VH	10	1.000922

2015, 2016, 2017, 2018, 2019, 2020, and 2021 respectively as detailed in Table 1. Sentinels Application Platform (SNAP) was used to pre-process the images through the application of the orbit file to maximise the geolocation quality of the acquired dataset of geocoding. Then the radiometric calibration of the images was done in SNAP through the application of Radiometric Terrian Correction before the radiometric flattening to remove the surface-induced radiometric distortions, after which the geometric terrain correction was applied to compensate for the distortions sensors' positions' variations. Speckle filtering was also applied in SNAP to remove the wave interference and also to enable the pre-processing of the images for detection and classification. The pre-processing steps considered in this study are after Lee et al. (1994); Filipponi. (2019); Meyer. (2019); Nedd et al. (2021). The preprocessed images were exported as a geo tiff for further processing and analyses in Google Earth Engine (GEE) and ArcGIS in observing the mud-shoal migration and its effects on deflecting the river mouth, spit evolution/development and mangrove dynamics. The datasets were acquired from the Alaska Satellite Facility (ASF) web platform (www.asf.alaska.edu). Tidal information, especially the tide height data for the study sites was retrieved from the "Tides 4 Fishing" database (https://tides4fishing.com/gy/demerara-mahaica/georgetown) and these covered the study period. The information for the wave height and wind direction was sourced from ABP Marine Environmental Research (MER) Ltd., from its openly available SEASTATES hindcast service (www.seastates.net).

2.3 Classification of migrating river mouth action and processes

The spatial-temporal dynamics of the mudbank at the Mahaica River Mouth were achieved by utilising the Jupyter Notebook and the Google Earth Engine (GEE) platform. This analysis covered the period from 2015 to 2021 focusing on the estuary of the Mahaica River. The Jupyter Notebook was used to plot the tide data to visually interpret the lowest tide for each year which coincide with the available Sentinel-1 dataset. First, the tide data for each month of the year was downloaded and displayed on an Excel spreadsheet before being saved as a CSV file. In Jupyter Notebook, the CSV files were imported, then the date and time were combined, resampled every 15 min, and then the mean was interpolated. The results were then plotted on a scattered chart displaying the available Sentinel-1 dataset for each month. The available datasets for each month were then compared against each other to determine which datasets were captured at the lowest tide and were then chosen for further analyses in GEE.

2.3.1 Processes in Google Earth Engine (GEE)

The ee.ImageCollection function was used to import the images for the years being studied. These images were then filtered by area of interest and by the date that recorded the lowest tide for every year. They were further filtered to get the vertical transmit vertical receive (VV) and horizontal transmit vertical receive (VH) dual polarization and look angle (ascending or descending), which is the orbit flight path of the satellite.

2.3.2 Constructing a random forest model

Two classes were defined and merged to run the model; those classes are non-mudflat and mudflat. The Sentinel bands were defined, then included in the model and applied to the image. Next, the samples were assembled for the model and trained using the ee.Classifier.smileCart function. The classification was then applied to the Sentinel 1 composite and clipped to the area of interest. During this stage, the results may be noisy, so a mask was created to mask out unconnected pixels. This created an image that shows the number of pixels each pixel is connected to, then filter out all pixels connected to 4 or fewer. The results were then used to update the classification and add them to the map for visual interpretation. The mudflats that were displayed as a result of the classification for the years were exported for further analysis.

2.3.3 Processes in ArcMap

The exported mudflats for each year were uploaded into ArcMap 10.5 and these were analysed to show how the mudflat eroded and accreted over time.

2.4 Land cover change

To investigate the land cover changes in the study area from 2015 to 2021, a variable dataset was created. This dataset contained all the available Sentinel-1 images for the area of interest within the study period. The study period was further broken down into minor periods which begin from January 1st to December 31st of each year. Another variable was made, and the function (.filterMetadata) was used to give each year's dataset a cloud coverage assessment of less than 25%. Bands blue (B2), green (B3), red (B4), and near-infrared (B8) were selected. The combination of the colour infrared bands is intended to highlight both healthy and sick vegetation. It is particularly effective at reflecting chlorophyll because it uses the near-infrared (B8) band. The composite image was then further filtered using the function (.filterMetadata) via the Military Grid Reference System tile (MGRS_tile). Then the function (.limit) was used to return the limited collection, which is sorted by "system: time_start" and set to false (descending order). Visual parameters were then applied to the filtered image, clipped to the area of interest, and mapped for visual interpolation. This process was carried out in Google Earth Engine (GEE).

3 Results and discussion

3.1 Short-term morphological changes at the river mouth

Figure 2 depicts the selection of the infra-red output of the Sentinel-1 satellite images of the Mahaica river mouth. The figure illustrates the success of the spatiotemporal contribution of sediment (mostly mud) from the Mahaica River system to the mouth of the system which is contributing to the morphological dynamics of the river mouth, especially in the stability of the spit at the site. One of the most dynamic coastal features is spits and their stability or otherwise are dependent on the delicate balance between the availability of sediments and/or the metocean forcings, especially the hydrodynamic forces (Dan et al., 2011). The progression of the supply of sediments at the mouth of the Mahaica river system (from 2016, Figure 2) has shown that input of sediments from onshore in a zero gradient like this system is an indication that a small river system can be an "equilibrium coastline" that promotes the development of spits (as stated by Delgaard and Fredsøe, 2005). The concept of "equilibrium coastline," which is hinged on the principles of uniform wave climate condition, the input of sediments from onshore and/or offshore sources, limited or no loss of sediments, zero gradients for the longshore and alongshore movements, etc., is one of the most important concepts that are used in understanding the stability of the dynamic depositional coastal landforms like spits (e.g., Silvester, 1960; Kolb and Schmidt, 1991; Delgaard and Fredsøe, 2005; Dan et al., 2011; Splinter et al., 2014; Deng et al., 2017). In each of the annual images (Figure 2), the continuous effect of northwestward movement of the sediment is noticed (see the river mouth from 2016 to 2021 of the output, Figures 1, 2). This observation corroborates that this system, although a small river system, responds to the regional alongshore transportation or movement of sediments pattern observed for this region (See Gardel et al., 2022).

Figure 3 depicts a spatiotemporal view of the normalized difference vegetation index (NDVI) of the study area. Here the NDVI is used to support and evaluate the coverage, short-time series and medium spatial resolution of the short-term morphodynamics of sediments and mud-bank movements at the river mouth of a small river system. The findings, here, show that on a contemporary timescale, a small river system like the Mahaica River system can divert, to varying extents, significant mud capes, especially in a

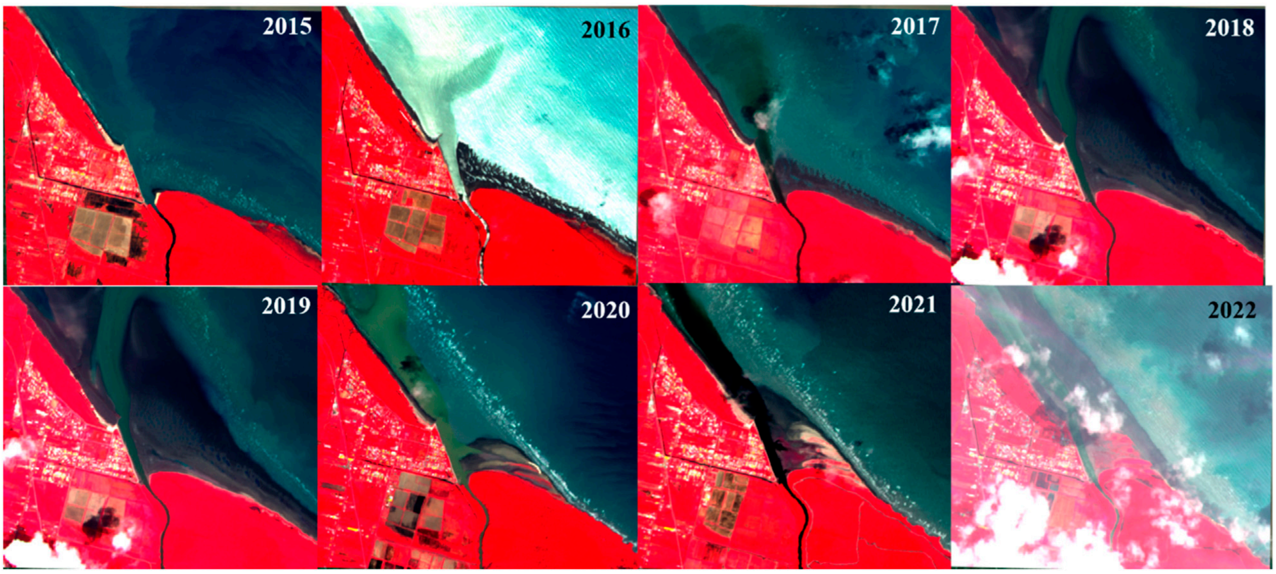

FIGURE 2
Infra-red output of the study site.

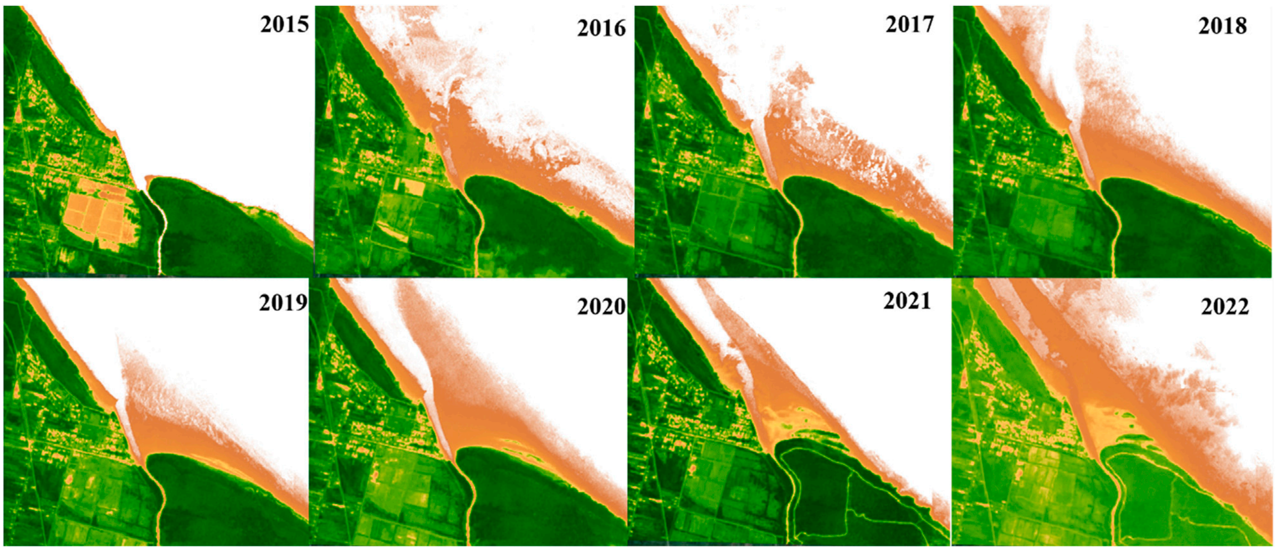

FIGURE 3
NDVI output of the study site.

system with no influence of the bedrock (Gardel et al., 2022). The time series of the dynamics presented in Figure 3 has also shown that the river mouths emerging from a confined onshore environment into an open coastal system can also contribute to the formation of coastal geomorphological dynamics like the displacement of shoreline seaward or alongshore current as variously depicted by the dynamics captured in the images.

River mouths and the coastal systems they produce (e.g., deltas, estuaries, etc.) are very important in many facets as they are mostly known to be fertile, rich in biodiversity and bio-diversified ecosystems, protect against storms, floods and submersion (Hagenlocher et al., 2018; Besset et al., 2019). However, their stability and sustainability depend on the ability of such systems to be sustained with the provision of sediments continuously from their river basins to maintain balance with the metocean forcing working on the system, maintain possible vertical sediment aggradation and promote the seaward advancement of shoreline movement (Besset et al., 2019). These are only possible under the

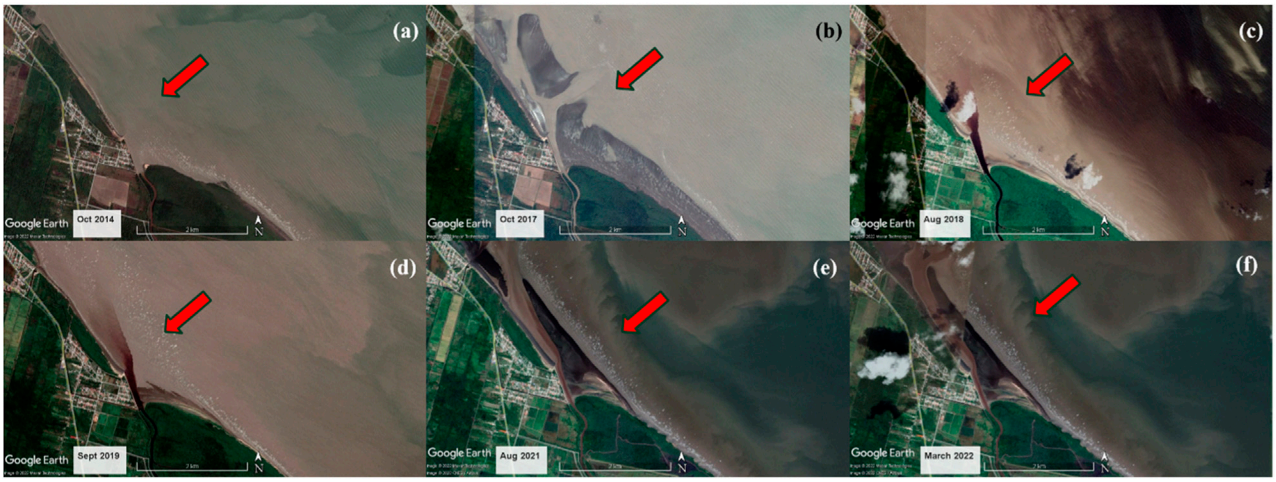

FIGURE 4
Google Earth Pro image and depiction of the idealized spit development and destruction at Mahaica river mouth on a contemporary time scale. Starting from **(A)** October 2014 when there was no indication of the development, **(B)** October 2016, **(C)** August 2018, **(D)** September 2019, **(E)** August 2021, and **(F)** March 2022.

conditions of satisfactory sediment supply in quantity and quality (Anthony, 2016). Whereas the effects of large river basins on sediments supply have received attention in recent years (e.g., Phillips, 1995; Collins et al., 1997; Lu et al., 2003; Ran et al., 2013; Wilkinson et al., 2014; Yang and Lu, 2014; Kondolf et al., 2018; Liu et al., 2018; Mushi et al., 2019; Nilawar and Waikar, 2019; Ranasinghe et al., 2019; Sun et al., 2020; Tian et al., 2020; Föeger et al., 2022; Shrestha et al., 2022; Wang et al., 2022; Kar and Sarkar, 2023; Tangi, 2023). What the findings here have shown is that small rivers in the region contribute sediment on an annual basis to the regional coastal system. However, the alongshore supply and concentrations of mud from the Amazon and the Orinoco exceeding thousands of g/L are so massive as the major source of geological and contemporary mud supply, thereby probably affecting and contributing to the sediment morphodynamics of the smaller river systems of the Guiana (Gratiot et al., 2007; Gardel et al., 2022).

Figure 4 presents the qualitative comparison of recent geomorphological changes at the Mahaica river mouth through the time series display of relatively high-resolution Google Earth Pro satellite imageries showing the dynamics at the river outlets with the observable development and destruction of sand spit at the river mouth from 2014 to 2022. Red arrows (Figures 4A–F) were used to highlight and pinpoint the contemporary and short evolution of the spit barrier at the mouth of this small river system. It is clear that the gradients in the alongshore transport of sediments deposited at the river mouth tend to align the spits evolution and development to a northwestward balance orientation, depending on the Southeast–Northwest (SE-NW) longshore current orientation of the country (Gratiot et al., 2007; Gardel et al., 2022) and not so much of the wind direction nor dominant wave direction (Figure 8). This has, possibly, led to the varied accumulation and erosion of the sand pits at this system. Other possibilities for the short-term dynamics at this site are a result of either the instability of sediment drift (after Ashton et al., 2001; Dan et al., 2011), quasi-parallel waves approaching at incidence angles (Bhattacharya and Giosan, 2003; Sundberg et al., 2013), or alongshore sediment transportation with rapid advancing/migration rates that are induced by alongshore current velocities f 0.2–0.5 m/s northwestward (Winterwerp et al., 2020).

3.2 Mudbank dynamics at the river mouth

The stability of Guyana's coastal zone is attributed to the 30 km (approximately) of long mud banks that are migrating alongshore but variously colonised at the landward side by mangroves (Winterwerp et al., 2020). Although the mangrove-mud coast of this section is noted to be generally in good condition (Anthony and Gratiot, 2012; Winterwerp et al., 2020; Gardel et al., 2022), the findings of mudbank dynamics and movements at the mouth of this river system in Figures 5–7 have shown that the mud deposits here experience localised accretion and erosion through the period under consideration (2015–2021). The annual rates of the movement of the mud as either erosion or accretion varies as estimated from the analysis of the Sentinel images. Table 2 presents the yearly estimate of the deposits of the mudbank extent at the mouth of the study area while Table presents the quantification of the yearly movements of these deposits in accretion and deposition.

The change analysis of the repeat remotely sensed surveys at the site (Figures 5–7) show lateral shifts in mud deposit position and the movement of the low amplitude of sand bars dominate the short-term river mouth dynamics. Most of the changes reported here are balanced across this river mouth system with the evidence of erosion at one location in an annual change being balanced with accretion at another year of change evaluation. This pattern of accretion and erosion could be well explained by the migration of sediment across the intertidal channel and alongshore migration. Table 3 presents the estimated volume of the magnitude of the yearly migration of

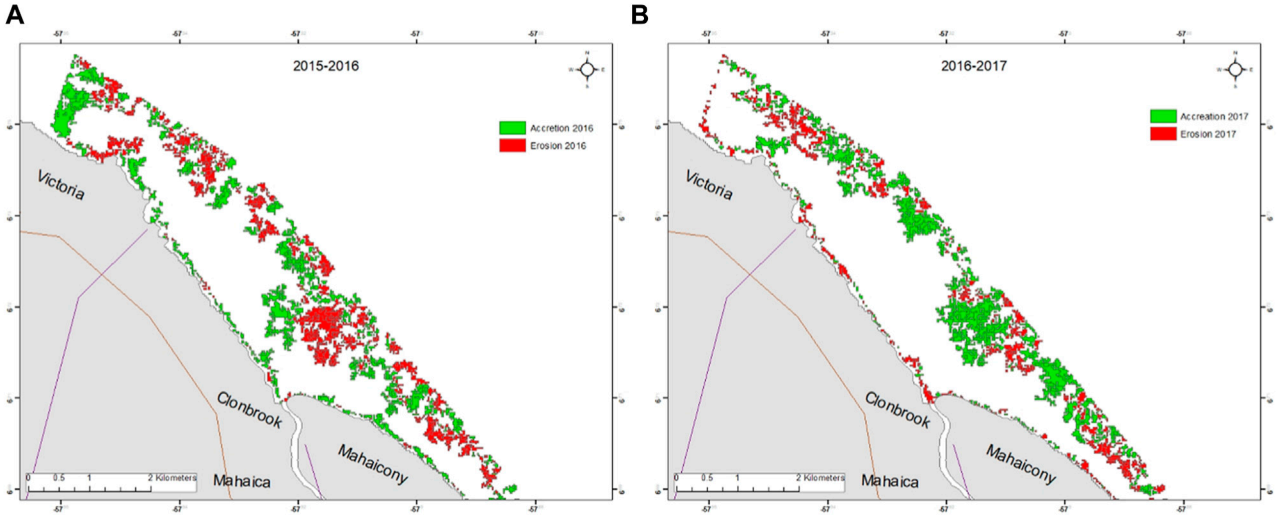

FIGURE 5
Mud-bank dynamics in the vicinity of Mahaica River, 2015–2016 **(A)** and 2016–2017 **(B)**.

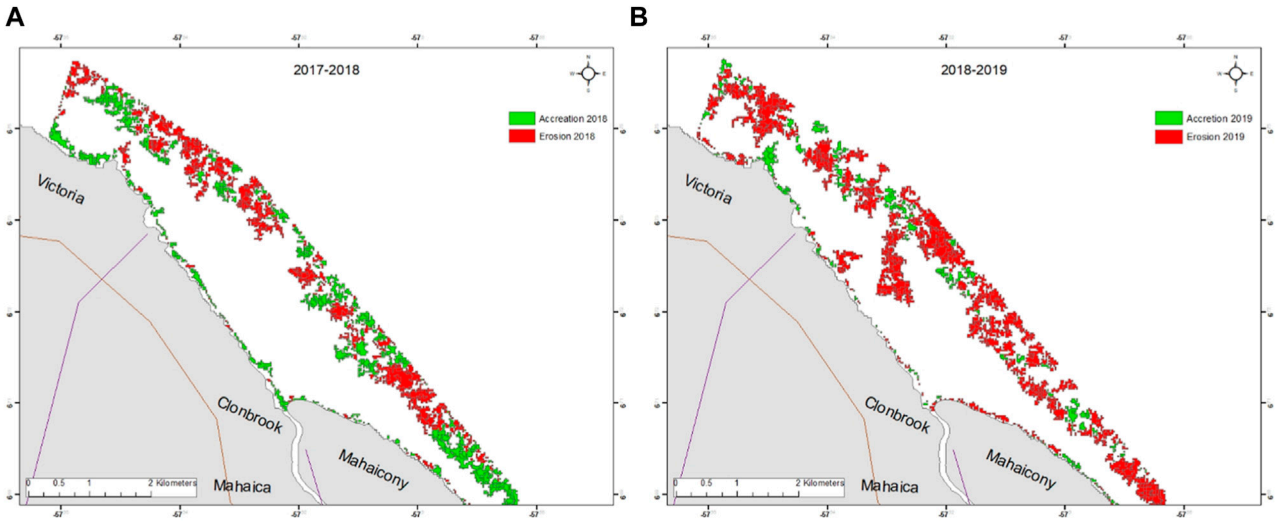

FIGURE 6
Mud-bank dynamics in the vicinity of Mahaica River, 2017–2018 **(A)** and 2018–2019 **(B)**.

sediments spatially presented in Figures 5–7. What is the sequence of events on the series of change show that the sediments are delivered seaward and these are redistributed northwestward over the 6 years (2015–2021) across the rest of the nearshore. The variable change over the 6 years illustrates the role of migrating and mobile sediments in the organisation and re-organisation of the sediment bars on the flood-delta platform. The happenings at this platform could be forced by diurnal tidal currents (Figure 9) but the supply of sediments into this river mouth drives the shifts in mudbank movements as similar to other environments (Oyedotun and Burningham, 2019).

The contemporary scale of mudbank sedimentary behaviour observed here supports the concept that a coastal-estuarine system tends towards flood dominance until when the process of sediment infilling is completed thereby forcing a switch to ebb dominance through the changes in tidal hydrodynamics (Lincoln and Fitzgerald, 1988; Kang and Jun, 2003; Oyedotun and Burningham, 2019; Eilander et al., 2020; Daramola et al., 2022; Weisscher et al., 2022; Harvey et al., 2023). What the mudbank dynamics suggest here is that shifts in mud deposits are occurring on an annual scale, particularly where areas of accretion are followed by areas of erosion within a year or two later. Sediment migration is

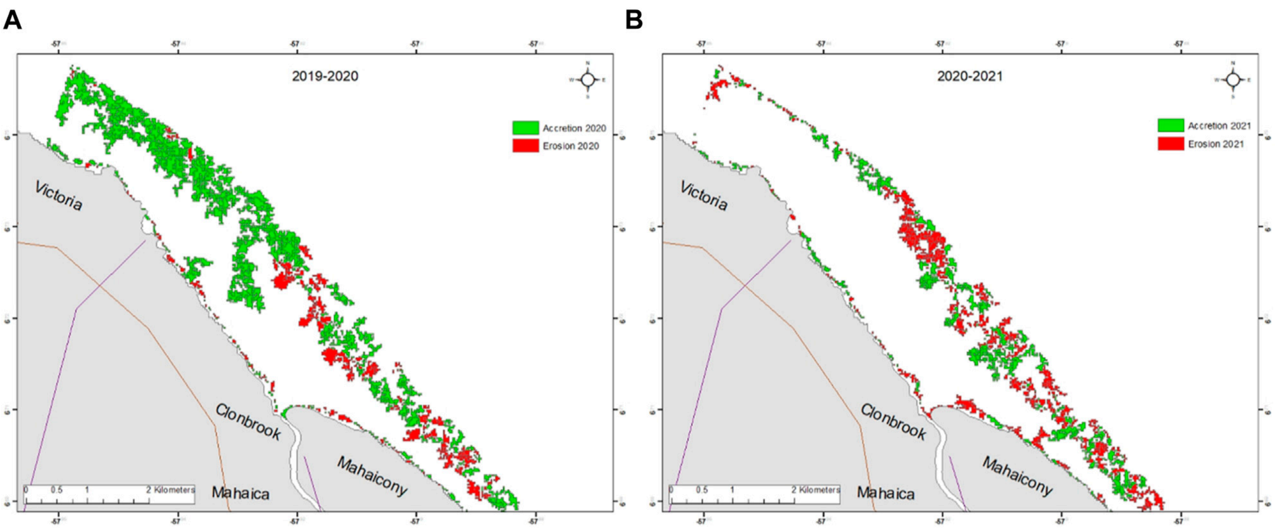

FIGURE 7
Mud-bank dynamics in the vicinity of Mahaica River, 2019–2020 **(A)** and 2020–2021 **(B)**.

TABLE 2 Estimation of the extent of mudbank deposit at the mouth of river Mahaica per year.

Year	Mud flat (sq m)
2015	20,327,574
2016	3,628,195
2017	3,937,542
2018	3,697,182
2019	1,810,055
2020	3,563,454
2021	3,485,117

TABLE 3 The extent of changes in mudbank deposits per year.

Changes between the years		
Year	Accretion (sq m)	Erosion (sq m)
2015–2016	1,126,611	1,021,838
2016–2017	1,197,490	617,543
2017–2018	547,259	902,269
2018–2019	270,556	1,265,258
2019–2020	1,480,968	346,361
2020–2021	674,862	744,504

viewed as a significant driver of erosion and accretion experienced annually in this study site. What was observed in this study is common to what has been observed in other beach and coastal system dynamics, that are at the mouth of a river system or with proximity to an inlet, with increased yearly migration, sediments movements and morphodynamics (Hicks and Hume, 1996; Van Maren, 2007; Short and Jackson, 2013; Oyedotun and Burningham, 2019; Pan et al., 2020; Glover et al., 2021; Glover et al., 2023; Yunus et al., 2022; Zhang et al., 2022; Romdani et al., 2023). Over the short-term period covered by the Sentinel—1 data considered here, no significant storm surges were recorded which could have been linked as the driver of the sudden changes. The spatiotemporal shifts in mud bank morphological systems reflect that processes operating in the river mouth of a small riverine-estuarine environment could drive a differential range of changes both in frequencies and magnitudes like other large systems already documented in the literature. The findings presented in this section have also shown that river mouth platform could recover rapidly from the either accretional or erosional process, especially if there are no major or continuous storm events that drive permanent change or that are sustained over a long period without allowing sufficient recovery time (Montreuil and Bullard, 2012).

3.3 Forcing factors of short-term morphodynamics

The recent Sentinel-1 data (2015–2021) examined for this study enabled the exploration of the short-term temporal variability of the sediment deposits at the mouth of the smaller river system. The regional climate of Guyana is principally tropical and this is dominated by the northeasterly Trade Winds with the wave direction (Figure 8A) following the same pattern at periods of between 8 and 10 s at the wave height which range from 1 to 1.7 m with the higher wave values noted between November and March (Figure 8B) (Gratiot et al., 2007; Winterwerp et al., 2020). The long mud banks of Guyana's coast have however made the system to be relatively stable (Winterwerp et al., 2020). The proportion of waves at this study site occurs from the Northeasterly/Easterly (NE/

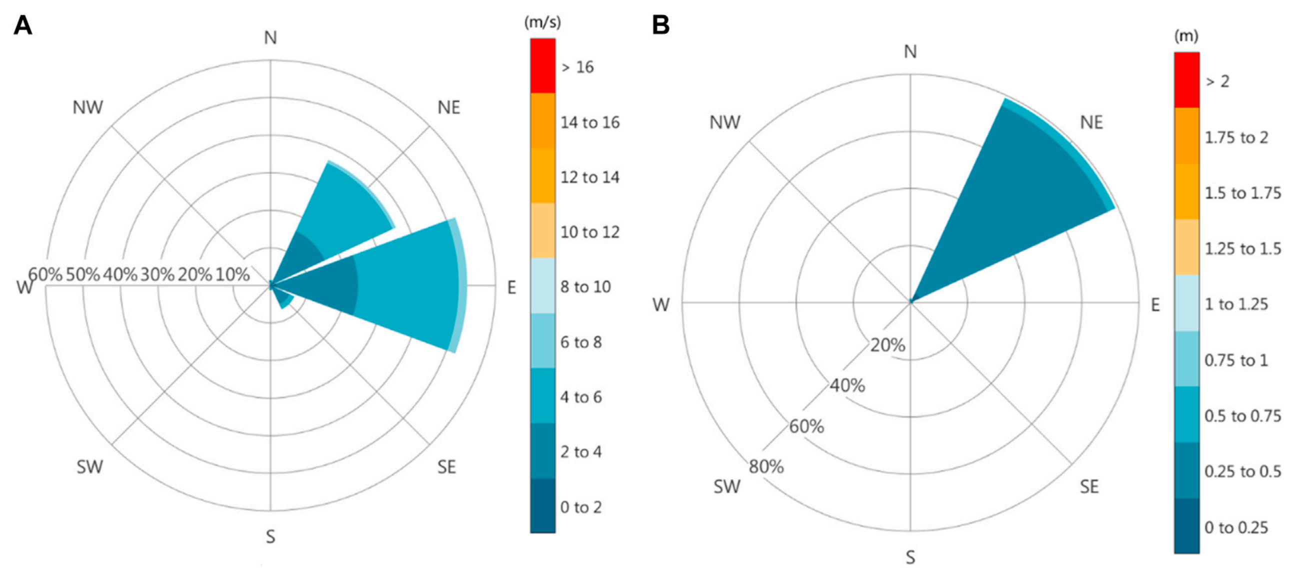

FIGURE 8
Wave roses showing the frequency of wind direction **(A)** and significant wave height **(B)** at the mouth of Mahaica River. (Source from AP MER https://www.seastates.net/explore-data/).

E) position with up to approximately 35% at NE, and 52% from the Easterly direction respectively (Figure 8A). Waves from South-East (SE) are infrequent, with ~05% and a given reduced fetch. Waves from all other directions (e.g., North, North-West, West, South-West, and South) are very rare (Figure 8A). The significant wave height at the mouth of Mahaica River is ~0.25 m with mean wave height at 0.4 m, and all are from the Northeasterly at ~80%.

The state of the tide is one of the most important coastal forcing factors that drive morphological coastline changes (Oyedotun and Burningham, 2019). The occurrence of high waves at high tide has a greater propensity to cause indelible hazards and significant modification of landforms on the coastline (Summerfield, 2014; Gardner, 2020; Swain, 2022). The semi-diurnal tide at the mouth of Mahaica River ranges from 1 to 3 m at neap and spring tide (Figure 9). Tidal currents here are generally weak (0.2–0.5 ms^{-1}). The lowest monthly water levels at the recorded period are around 0–0.5 m while the monthly maximum is around 3.0–3.5 m (Figure 9).

There was no indication of storm events, storm surges or forcing at the site during the period 2015–2021 of this study. Therefore, the continuous and relative rise in sea level of the Guyana coast (Government of Guyana, 2012), the observed relative constant semi-diurnal tidal conditions and the observed wave parameters are the natural forcing thought to drive the morphological dynamics and small changes at the mouth of Mahaica river reported in this study. Apart from extensive anthropogenic processes, whose impact on this site is limited (Winterwerp et al., 2020), sedimentary characteristics, the geological bedform framework and precursor geomorphology are thought to determine the reported sensitivity of the river mouth planform to changes in the forcing factors observed here as with other documented in published work for other environments (e.g., Blott et al., 2006; Lim et al., 2011; Hunt et al., 2015; Naylor et al., 2017; Oyedotun and Burningham, 2019; Ciarletta et al., 2021; Green et al., 2022; Nanson et al., 2022; Woodroffe et al., 2022; Georgiou et al., 2023).

3.4 Mangroves dynamics at the river mouth

Over the space of approximately a decade (1992–2001), there was a significant reduction in the number of mangroves along the Guyana coast from ~80,000 to ~22,000 ha (Conservation International, 2018; Bovell, 2019; Nedd et al., 2021). This significant reduction and depletion are a result of significant anthropogenic (economic) activities (NAREI, 2015; Conservation International, 2018; Bovell, 2019; Nedd et al., 2021) principally, and to a minimal extent, the natural phenomenon (e.g., sea level rise) (Conservation International, 2018). The institution of the Guyana Mangrove Restoration Project (GMRP) among other intervention mechanisms has led to an increase in the number of restoration mangroves along the Guyana coast to approximately 33,362 ha (Guyana Forestry Commission, 2011). Of all the regions of Guyana, the area of the study site is one of the locations noted to be in good condition that was considered to be pristine with limited economic development pressure (Winterwerp et al., 2020). Mud deposits are very important for mangrove growth and sustainability. The migrations of mud-bank involve the spatiotemporal alternations of the bank and their inter-bank phases under the influence of periodic tidal and wave recycling of muddy sediments and/or materials at the yearly/annual timescales (Anthony et al., 2010). Significant mud migration, mud advection, mud deposition and general mud-bank dynamics affect mangroves that depend on mud for their sustenance. Sediment supply is very important for accretion and the prevention of mangrove area loss (Lovelock et al., 2015; Bozi et al., 2021). This section of this study examines how the

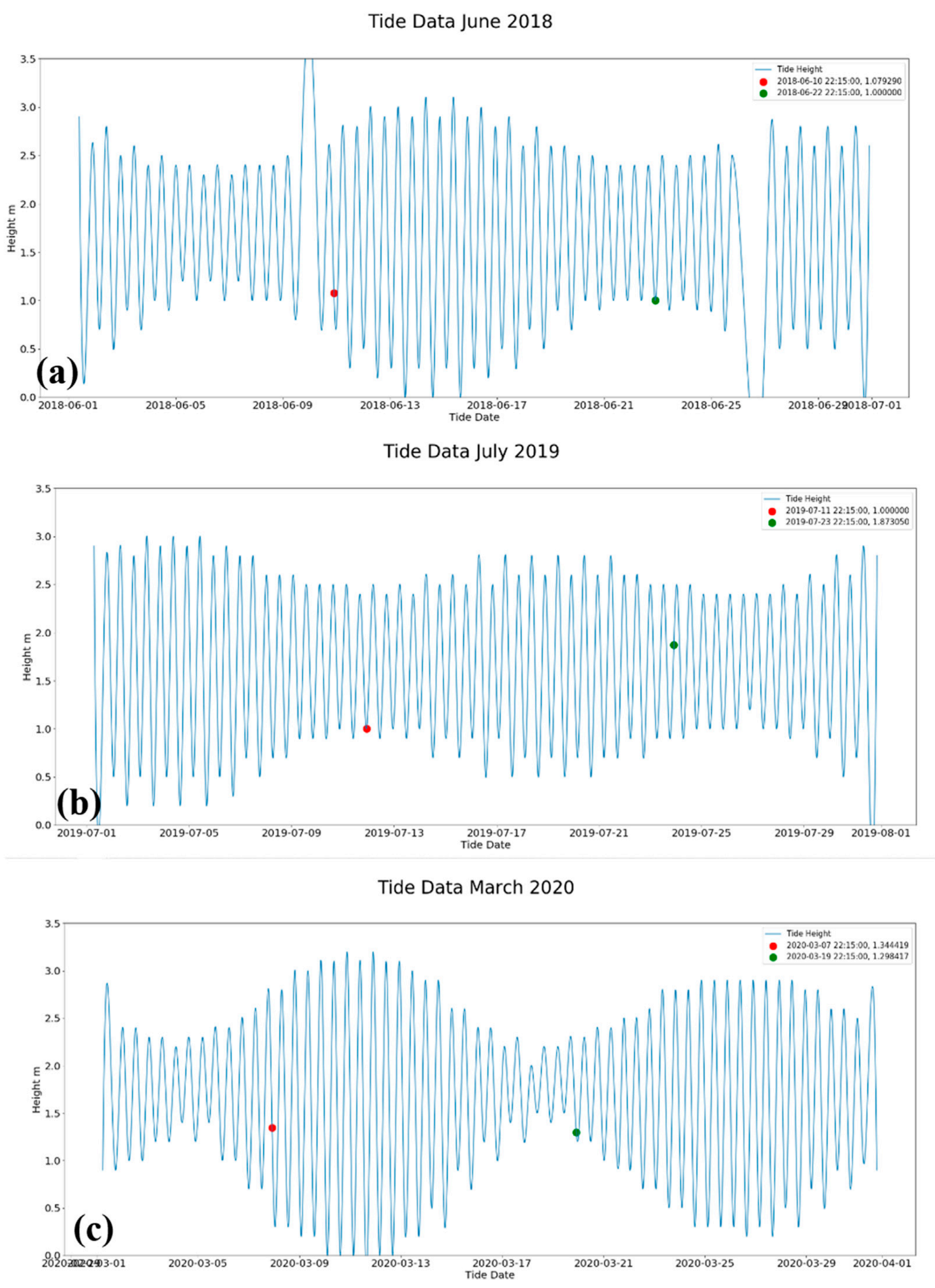

FIGURE 9
Tidal height at the mouth of River Mahaica, between 2018 **(A)**, 2019 **(B)**, and 2020 **(C)**.

mangroves in the vicinity of the study area have responded to the yearly mud-bank dynamics.

The spectral and spatial analyses of the mangrove forest cover were conducted to capture the extent of mangrove forest cover changes within the vicinity of the study. The spectral analyses were considered to avoid consideration of other flora and ecosystems, thereby preventing misclassification (after Ranjan et al., 2017; Li et al., 2019; Nedd et al., 2021). The temporal maps presented in Figure 10 illustrate the areas of spatial changes in the mangrove forest cover during the period under consideration. There was a record of differential mangrove gains and losses annually in extent and coverage during the period under consideration. Table 4 presents the estimated annual mangrove forest coverage (in square meter area extent) for the study site while Table 5 presents the estimated extent of gain and loss during the period of this study.

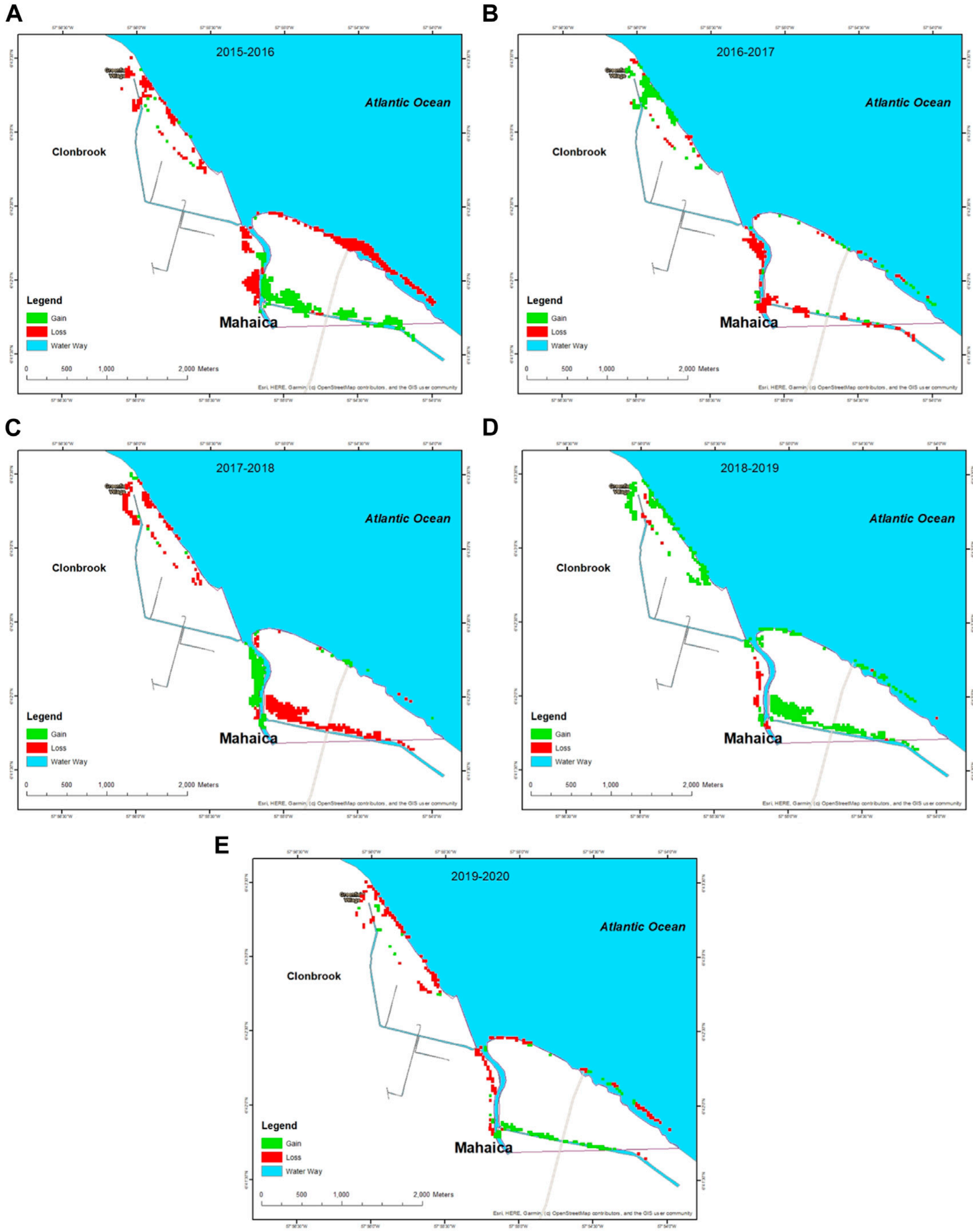

FIGURE 10
Mangrove dynamics in the vicinity of Mahaica River, between 2015 and 2016 **(A)**, 2016 and 2017 **(B)**, 2017 and 2018 **(C)**, 2018 and 2019 **(D)** and 2019 and 2020 **(E)** respectively.

Although it appears that mangrove coverage at the study site is being affected by the movement of mud deposits as indicated by the time-series analysis of the mangrove coverage changes. There should be a cautious interpretation of this phenomenon as mangrove forest cover can change under different conditions besides mud-bank migration and movements. The changes observed here could be in combination with other factors that affect other mangrove systems in the region, for example, as a response to relative sea-level rise (Cohen et al., 2009; Cohen et al., 2018; Oyedotun and Johnson-Bhola, 2019), annual average temperature changes that affect the mangrove structure and productivity (Cohen and Lara, 2003), the observed tidal diurnal range and wave action and currents along the coast (Cohen et al., 2005), coastal topography (Castro et al., 2013) and the supply of sediments to the coastal depositional

TABLE 4 Mangrove extent for the study period.

Year	Area sq m
2015	48,825
2016	104,730
2017	12,428
2018	20,418
2019	10,655
2020	14,204

TABLE 5 Changes between the years.

Year	Gain sq m	Loss sq m
2015–2016	15,976	99,405
2016–2017	114,492	20,413
2017–2018	8,876	84,315
2018–2019	4,440	38,165
2019–2020	84,318	140,232

system discussed here. It is, therefore, vital to identify the mangrove dynamics according to many changing variables along these coasts with geomorphological (Augustinus, 1995; Souza et al., 2022), metocean (meteorological and oceanography) particularities (Alfredini et al., 2013; Pezzoli et al., 2013; Reed et al., 2022), climatic dynamics (López-Angarita et al., 2016; Yao et al., 2022), vegetation and pedology changes (Alongi, 2015; Smith and Mayle, 2018; Henriques et al., 2022), mangrove diversity and the influence of mangrove pests, and various *in-situ* and adjoining anthropogenic activities (Alongi, 2002; Restrepo, 2012; López-Angarita et al., 2016; Thomas et al., 2017; Gorman, 2018; Servino et al., 2018; Pelage et al., 2019; Goldberg et al., 2020; Maina et al., 2021; Wilhelm et al., 2023), etc. as vital factors for consideration in understanding the different and annual dynamic responses presented by this unique ecosystem.

4 Conclusion

The results of the analyses show that the dynamics of the mud shoal and river mouth are governed by feedback from various estuarine and hydrodynamic processes resulting from the interactions between rivers and seas. The results of this study have not only highlighted the importance of mud infilling and sediment build-up for spit development and river-mouth deflection but the influence and morphological dynamics of the sediment (principally mud at the study site) also impact spit development at the river mouth in addition to influencing the marine ecosystem processes, especially mangrove dynamics at the study site. This study which analysed and probed the spatial and temporal structure of the river mouth forms and the mangrove coverage utilised the change detection technique in Google Earth Engine (GEE) on Synthetic Aperture Radar (SAR) images, which allowed for the identification of sediment and mud deposit changes and mangrove forest cover changes of the study area during the short-term period considered. Although there are widely established findings in the literature that indicate the influence of large rivers in modifying the river mouth morphology and dynamics, the findings reported here have shown that the mouth of a small river system also impacts river mouth morphology significantly by the sediment deposited and also by the metocean factors that contribute in the deflection alongshore of deposited sediments (mud) for spit development and mangrove dynamics.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

TDTO: conceptualization, investigation, writing—reviewing and editing; NEDD, GAN: investigation, reviewing. All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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