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Multi-Scale Analysis of Erosion and Sediment Transfer Processes on Grand-Lahou Beach

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Abstract

This study was carried out to report on the hydro-sediment dynamics of Grand-Lahou beach at different time scales over the last twenty-five years. It is based on two complementary methods: the method of sediment reworking based on continuous altimetric monitoring of posts during a tidal cycle and in situ tracing using fluorescent-coloured sand, and the method of monitoring changes to the beach based on topographical profiles at different time intervals (seasonal, annual, multi-year, ten-year). The sediment balances were established by determining the areas eroded and/or greased using the trapezoidal or triangular surface calculation method to precisely quantify the sediment movements in the profile and the associated dynamics. The results obtained show that the dynamic swash zone varies according to the phases of the tide. On the ebb tide, this zone is reduced to the low foreshore and a few points on the mid-foreshore, depending on the tide-swell couple. When the tide is flowing, the zone widens, taking into account the high foreshore. The morphology of the submerged zone changes constantly as the tide passes over it. The low offshore shows a trend towards stability with weak erosion episodes. The mid-foreshore shows a predominance of fattening, with the highest movements of instantaneous reworking (RrI) on the foreshore. The maximum amplitude of sediment movement of 25.5 cm was obtained at mid foreshore. The morpho-sedimentary monitoring of the beach reveals that the most important retreats, estimated at 25 m.an-1 were observed during exceptional events including storms. Erosion in the area around the mouth of the Bandama River is the main threat to the people living along the river, given the damage that has been caused.

Keywords

Reworking, Amplitude, Sedimentary Balance, Erosion, Fattening

1. Introduction

The coastal area represents only 5% of the land area [1]. Yet more than 20% of the world's population lives less than 30 km from the coast [2]. It is impacted by various human activities but also by the effects of climate change such as sea level rise, changes in storm regimes and the risks of submersion and floods [3]. The evolution of sandy coastlines is generally dominated by a trend towards erosion. Studies conducted in recent years in different regions of the world show that the erosion of sandy coasts is a global phenomenon. According to Bird (1993) [4], More than 70% of the world's sandy beaches are thought to be eroding. It is, therefore, a fragile environment that must be protected. In Côte d'Ivoire, some coastal areas show worrying signs of destabilization. Such is the case of Grand-Lahou beach. Indeed, the erosion of the coast of Grand-Lahou is worrying. Initially located on the cordon near the mouth of the Bandama, the city was relocated to 18 km on the north shore of the lagoons due to erosion. Coconut plantations and historic buildings (gendarmerie, civil prison, sub-prefecture, hospital, maternity, school, lighthouse, etc.) have not escaped the destruction caused by erosion. The disappearance of the rocky banks under the mud at Grand-Lahou beach would leave this area without any natural defences and particularly vulnerable to erosion [5]. Erosion is exacerbated by a lateral (east-west) migration of the mouth of the Bandama River [5]-[7]. Since 1993, 765 m of coastline has been destroyed [7]. Between 1912 and 1955, the mouth of the Bandama would have moved about 2 km [8]. Despite the extent of the damage, the local population, due to its main activity which is fishing refuses to leave the cordon. It moves as the sea advances. The retreat of the shoreline inherent in the migration of the pass has the corollary of destroying habitats and reducing the space available for construction. A loss of 10.7 ha, including 4 ha of built area between 1993 and 2006 was estimated by Hauhouot (2008) [6]. The population is watching helplessly as the Lahou-Kpanda cemetery is destroyed. The Catholic mission that houses a primary school is threatened with destruction due to migration from the past. Shorelines and beaches are systems that evolve at different scales of time and space depending on forcing agents such as waves, tides and associated currents [9]. In order to better characterise the evolution of the beach and surface reworking processes, monitoring was carried out on several time scales. The study is based on a number of in situ measurement campaigns, which make it possible to monitor changes in the surface sediment cover, and to highlight erosion and deposition phases as a function of tide gauge conditions on the foreshore [10] [11]. For short-term sedimentary evolutions (tidal cycle), single-tidal sediment level variation measurement devices have been implemented in the swash zone [12] [13]. Specific hydrodynamic processes in the swash determine the direction of sediment movement, towards the coastline where deposition can occur, or towards the inner zone, with the sediment potentially being dispersed offshore [14]. Swash oscillations (shore jet, retreat sheet) play a significant role in beach morphology [15]. For the medium-term follow-up (annual scale), long-term (multi-annual scale) profiles were made in some stations (mouth, catholic mission...) along the radials. These measurements make it possible to monitor erosion-sedimentation rhythms and relate them to episodes of greater agitation [10] [16]. This additional study of the hydrosedimentary processes will enable us to highlight the evolutionary trends on different spatiotemporal scales that will be useful for managing the Grand-Lahou coastline.

2. Materials and Methods

2.1. Main Characteristics of the Study Area

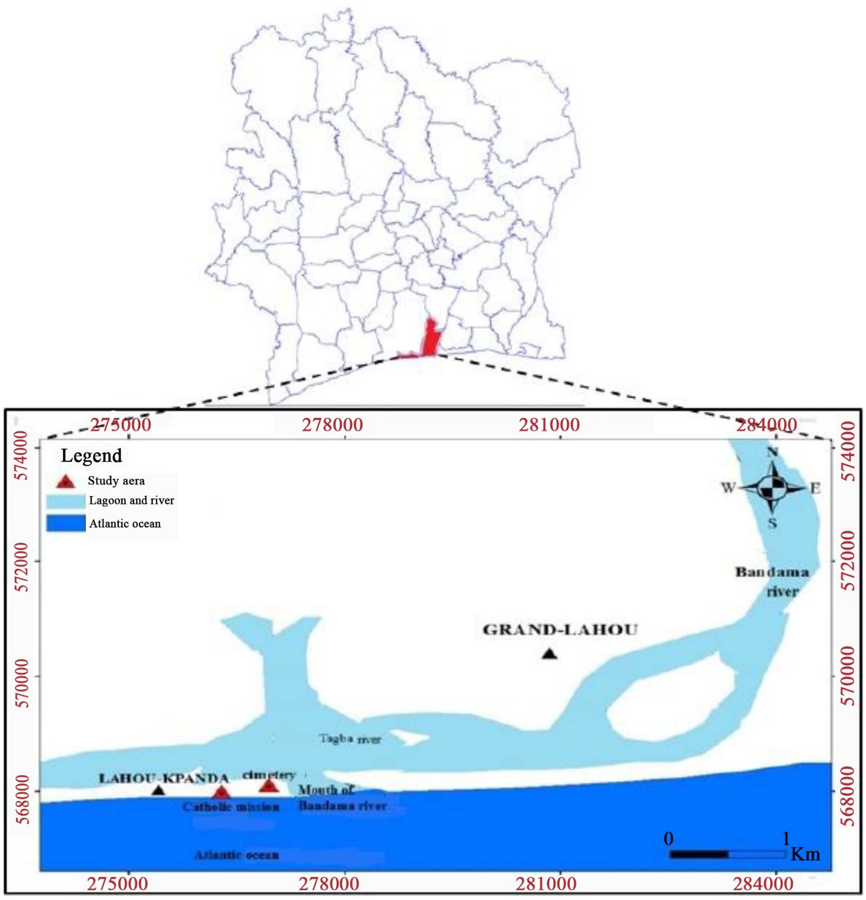


Figure 1. Grand-Lahou coastal zone.

The study area (**Figure 1**) is part of the Ivorian sedimentary basin, which covers 3/5 of the country's Atlantic coastline [17]. Located between latitudes 5˚9 North and 5˚12 North and longitudes 4˚56 West and 5˚20 West [18]. It is oriented in an average direction of 81˚, parallel to the Atlantic Ocean. This configuration is the very type of barrier cordon that isolates a body of water. The area to the west of the mouth of the Bandama river is the chosen study zone (**Figure 1**). In the region, the shoreline is frequently battered by swells with amplitudes of between 0.80 and 2.00 m and periods of 10 to 12 seconds. Exceptionally, larger swells with periods of up to 20 s break on the coast [19]. They are very destructive. The swells that usually break in the region, despite their average characteristics, have significant morphological effects on the coastline in the current dynamic context. They approach the shore from a preferential south-westerly to southerly direction. The swells approach Grand-Lahou-Abidjan stretch of coast at an angle of 60˚ [20], so that there is a strong littoral drift estimated at 800.000 m^3 of sand per year [21]. It is therefore a section of the coast dominated by sedimentary transport. In 1952, the Bandama river enters the Tagba lagoon and digs a passage through the cordons [19]. There are three channels in the estuary [18]. To the south, the river channel, whose depth varies between 7 and 8 m, runs alongside the Braffedon spit. It is crossed [22] by sometimes antagonistic currents (flow, downstream). To the north, the lagoon channel is 6 m deep. At the pass, the lagoon channel has a depth of 5 m. These channels are generally made up of medium to fine sands [23]. The grain size of beach sands varies between 409 µm and 719 µm [23].

2.2. Morphological Evolution of the Beach

The fieldwork carried out in 1998, 1999, 2006, 2007, 2008, 2017, 2018, 2022 and 2023 consisted of surveying the profiles perpendicular to the shoreline using a level (or theodolite), a mire and a tripod. The surveys were carried out so that they could be compared with previous data obtained from topographic profiles set against reference benchmarks. Profiles are set using topographic nails placed on stable areas [24]. The accuracy of the measurements is in the order of centimeters with a maximum vertical error of 2.2 cm [24]. The surveys were carried out at low tide to explore the maximum width of the beach. In this study, the beachbreak was taken as the reference line representative of the coastline. In the case of sandy coasts, the beach ado proves to be the most reliable [25]. It is marked by an easily identifiable break in the slope. The sedimentary balance sheets were carried out by comparing the first and the last profiles taken for the seasonal, annual and decennial scale. The aim is to quantify the sediment balance over the longest study period. Sediment balances were established from the determination of eroded and/or greased areas by the trapezoid method [26] to precisely quantify sedimentary movements in the profile and associated dynamics.

2.3. Sedimentary Reworking

The study focuses on determining the layer (thickness) of sediment equivalent to the total balance of hydro-sedimentary mobilisation and transport processes at the water-sediment interface**.** It is based on the sediment reworking method, using continuous altimetric monitoring of the stakes (every 5 minutes) during the tidal cycle of 22/12/2018. This cycle is 12 hours on the ivorian coasts. The tidal range deduced from the water levels described by the shom on behalf of the port of Abidjan is 0.746 m. The daily average significant wave height (Hs) obtained from the ERA programme is 1.083 m. These measurements enable us to study the response of the beach to wave loads by quantifying erosion depths and the thickness of the moving sediment layer [11].

2.4. Altimetric Monitoring of Beaches

The evolution of the beach during a tidal cycle has consisted of high-frequency topographic measurements made on stakes following a cross-shore profile [27] [28]. The main originality of this study consists in measuring the topographical changes of the Grand Lahou beach when it is subjected to the action of hydrodynamic forcing (tide, swell, etc). The process was inspired by the method developed by Sallenger and Richmond (1984) [27]. Morphological variations in the beach, monitored by means of topography, are measured in relation to an initial state, using stakes as reference points. The stakes were placed at low tide across the beach at 2 m intervals. A control profile on which 13 pickets were implanted allows a relevant interpretation of the results. Readings are taken on each stake every five minutes, limiting measurement errors and providing precise information on changes in beach morphology [27]. However, reading errors related to the manual method may still occur. These errors are less than half a centimetre.

2.5. Movement Envelope Curve

The states of each profile are superimposed. The points with the greatest difference in height on all the superimposed profiles are marked. They define the upper envelope curve. The lowest points in elevation are also identified. They define the lower envelope curve. The superposition of the upper and lower envelope curves gives the envelope curve of sediment movements on the profile.

2.6. Amplitudes of Sediment Movements in the Tidal Cycle

The difference between the heights of the stakes fixed in the ground (RrI) is calculated consecutively for the monitoring period at the time of the waves. The cumulative resulting reshuffle (RrC), which accumulates the values of the instantaneous resulting reshuffle (RrI) over the follow-up time, is also calculated. These two parameters provide information on the amplitude of sediment movements in the tidal cycle. the greatest value between the instantaneous resultant reshuffle (RrI) and the cumulative resultant reshuffle (RrC) represents the maximum amplitude of sedimentary movements at a point.

3. Results

3.1. Beach Dynamics on the Scale of the Tidal Cycle

3.1.1. Amplitude of Movement of Sediments in the Catholic Mission Low Foreshore

a. Amplitude of movement at station A

Instant resulting reshuffle (RrI)

Point A11 is 24.7 m from the coastline (TC). On the ebb, the RrI curves of A11 and A12 are very tightly jagged with slight steep undulations but no peaks (**Figure 2**). The extremes are −2 cm and 3 cm at point A12. These curves show a beach area that is tending to stabilise. No real trend can be seen at these two points on the lower foreshore. At the flow, that is to say from 10h45mn the curves RrI are presented in sawtooth with very pronounced teeth and sometimes strong peaks. The extremities are 6 cm and -5 cm at point A11. We gradually attend the immersion of the pickets until total immersion for A12 at 13 h 20 mn and at 14 h 05 mn for A11. As wave energy is very high due to the approach of high tide, it is difficult to read the values of posts A11 and A12, which makes it difficult to carry out a complete study of the instantaneous reshuffle of the low foreshore. The maximum amplitude of sediment movement could reach 11 cm for the RrI. The low foreshore is more dynamic at this phase of the tide.

Cumulative resulting reshuffle (RrC)

At the flow, the measurement of the low shore pickets is practically impossible because the pickets were submerged. The trends will therefore be more visible than at ebb tide. During this phase, points A11 and A12 behave differently. A11 becomes progressively fatter until high tide, when it erodes, reaching a peak of -9 cm. A12, on the other hand, erodes until high tide, when it begins its fattening phase, reaching a peak of 11 cm. The maximum amplitude of sediment movement is 15 cm for the RrC.

b. Amplitude de mouvement sur la station témoin (station B)

Point B11 is 21.4 m from the coastline (TC).

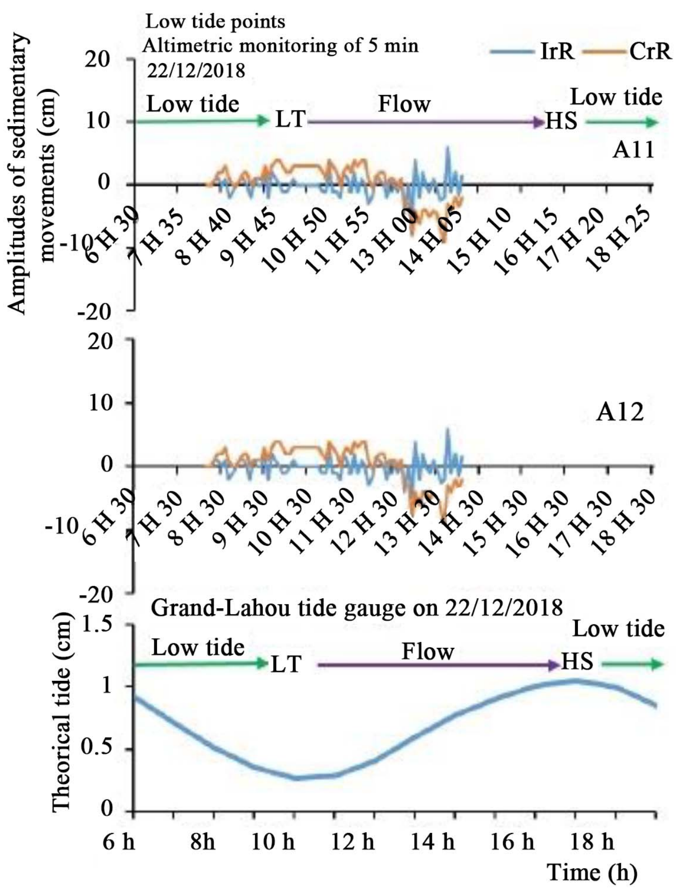


Figure 2. Continuous monitoring curves from the beach to the low foreshore at station A.

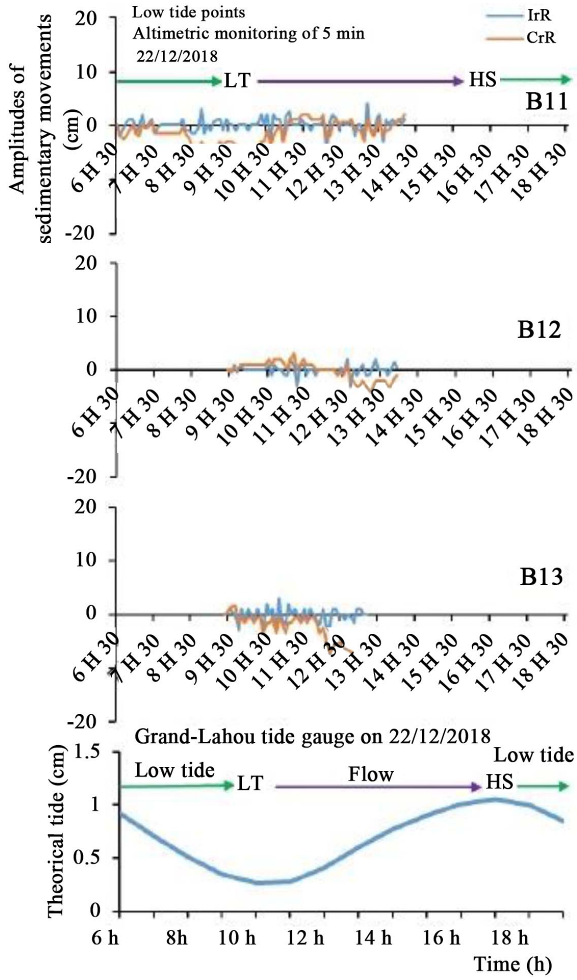


Figure 3. Continuous monitoring curves from the beach to the low foreshore at the control station.

Instant resulting reshuffle (RrI)

During the flow, points B13 and B12 could not be implanted due to the height of the waves on the low foreshore. It was only possible to implant them at low tide. The RrI of B11 shows stabilization with slight peaks (Figure 3). The movements are less equivalent to compassassions. The observed extremities are −3 cm and 3 cm. The RrI curve for B13 obtained at ebb tide shows that the movements are quite strong at this point. The tight sawtooth morphology is evidence of this. The RrI curve for B12 has an irregular sawtooth shape with no peaks. The RrI curve for B11, which is close to the mid-foreshore, shows trends with peaks at 4 cm and −4 cm. The maximum amplitude of sediment movement is 8.5 cm for the RrI.

Cumulative resulting reshuffle (RrC)

At the flow, the presence of a strong water column on the low foreshore makes it difficult to understand the morphology of this part of the foreshore. For the time period monitored, the RrC curve for B11 is below the initial altimeter level. The other two points, B12 and B13, show curves that differ very little from the initial level. The low foreshore is therefore eroding very little and is tending towards stability in the direction of the sea. The extremities are −6 cm and 0.5 cm. These values confirm a low erosion range that tends towards stability. On the ebb tide, the low foreshore points show a generally stable trend with occasional episodes of slight erosion. The extremes are observed at point B13 with −8.5 cm and 1.5 cm. The maximum amplitude of sediment movement is 10 cm for the RrC in this part of the foreshore.

3.1.2. Amplitude of Sediment Movement at the Catholic Mission Mid-Foreshore

a. Amplitude of movement at station A

Instant resulting reshuffle (RrI)

On the ebb, the RrI curves are straight with slight saw-tooth shapes and no peaks (**Figure 4**). This absence of peaks is due to the fact that wave movements are not strong enough to reveal peaks in the curves. The curves for the ebb tide show a phase of stability with episodes of low fattening. The extremes are observed at point A9 and are −11.5 cm and 7.5 cm. At flow, the RrI curves are narrow and peaks with medium to very strong trends as we approach the low range (A6 to A9). These curves show the morphological construction process. The RrI curve at A9 has no peaks because it is very close to the low foreshore. The extremes are −8 cm and 6 cm at point A8. The maximum amplitude of sediment movement is 19 cm for the RrI.

Cumulative resulting reshuffle (RrC)

On the ebb tide, the curves of RrC indicate that all the pickets in the middle are fattening. As posts A6, A7, A8 and A9 are no longer accessible to waves during low tide, their morphology is the result of previous processes. During the flood, three (3) phases can be identified for A10: the fattening observed during the ebb continues until 13:20 when, as the water rises, there is sudden erosion followed by a second phase of fattening. During the flow, three (3) phases can be identified for A10: the fattening observed during the ebb continues until 13:20 when, as the water rises, there is sudden erosion followed by a second phase of fattening. After 2.30 pm during high tide, the A10 picket is inaccessible. Stakes A7 and A8 are also going through the same phases as stake A10, but at different stages. For posts A6 and A9, there is no general trend towards increased sedimentation. The maximum amplitude of sediment movement is 15.5 cm for the RrC.

b. Amplitude of movement at the control station (station B)

Instant resulting reshuffle (RrI)

On the ebb, the RrI curves also appear, as at station A, in the form of tiny sawtooth shapes with no peaks (**Figure 5**). The RrI values are zero at the end of the ebb tide for B6, B7 and B8 because the wave energy is low enough to reach them and cause movement. B9 and B10 continue to be submerged without any real trends emerging. In the flow, the RrI curves of B6, B7 and B8 have very pronounced sawtooth shapes reaching extremes of 5cm and −3.5 cm. B9 and B10, on the other hand, have slight saw teeth with no peaks. The maximum amplitude of sediment movement is 12 cm for RrI.

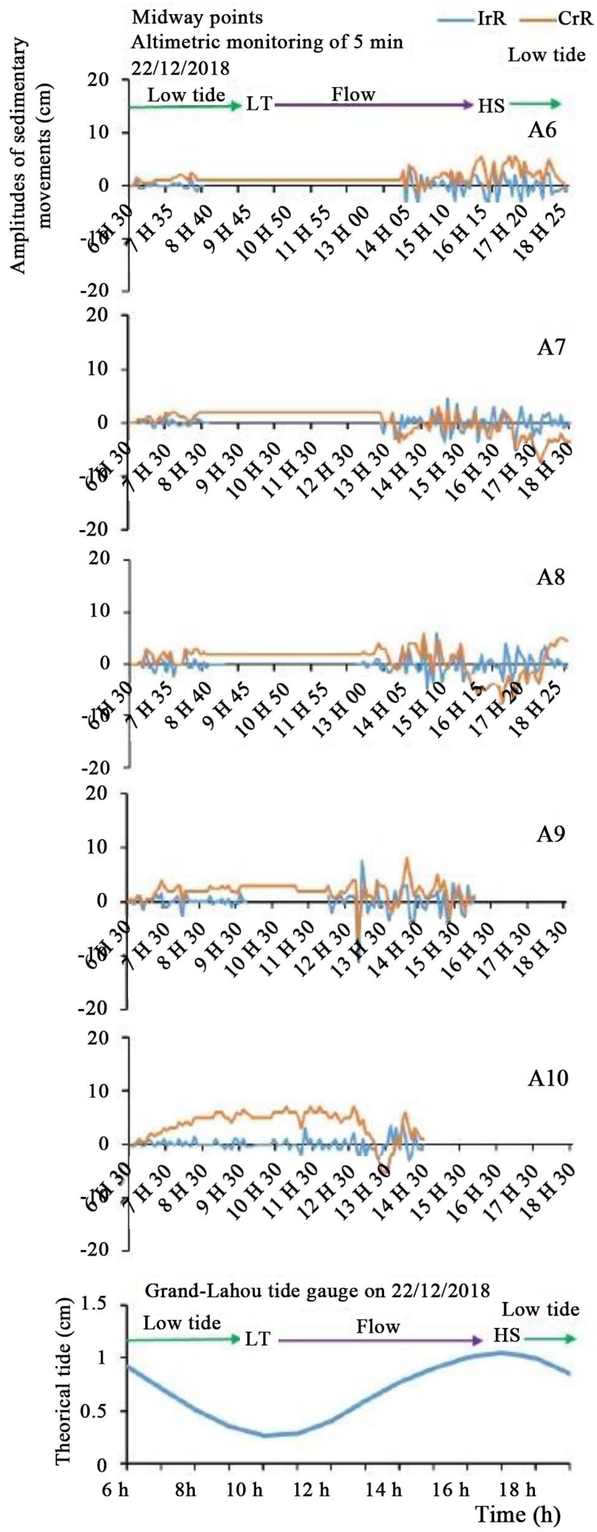


Figure 4. Continuous beach monitoring curves for the mid-foreshore at stations A.

Cumulative resulting reshuffle (RrC)

On the ebb, the general trend is towards accretion, which is clear at certain points (B6, B9 and B10), while other points (B7 and B8) show less accretion, to the extent that a sort of stability can be felt at these points. B9 and B10 continue to accrete before being eroded. Then a new phase of accretion begins for both posts before they are submerged. B7 shows no real trend during the flood until high tide, when the sediment input is so great that it reaches a maximum peak of 25.5 cm. B7 is the stake that is the most fattened of all the mid-foreshore stakes. For points such as B8, which show no trend, this is due to the fact that they are located at the point where the waves fall during the flow. The maximum amplitude of sediment movement is 25.5 cm for RrC.

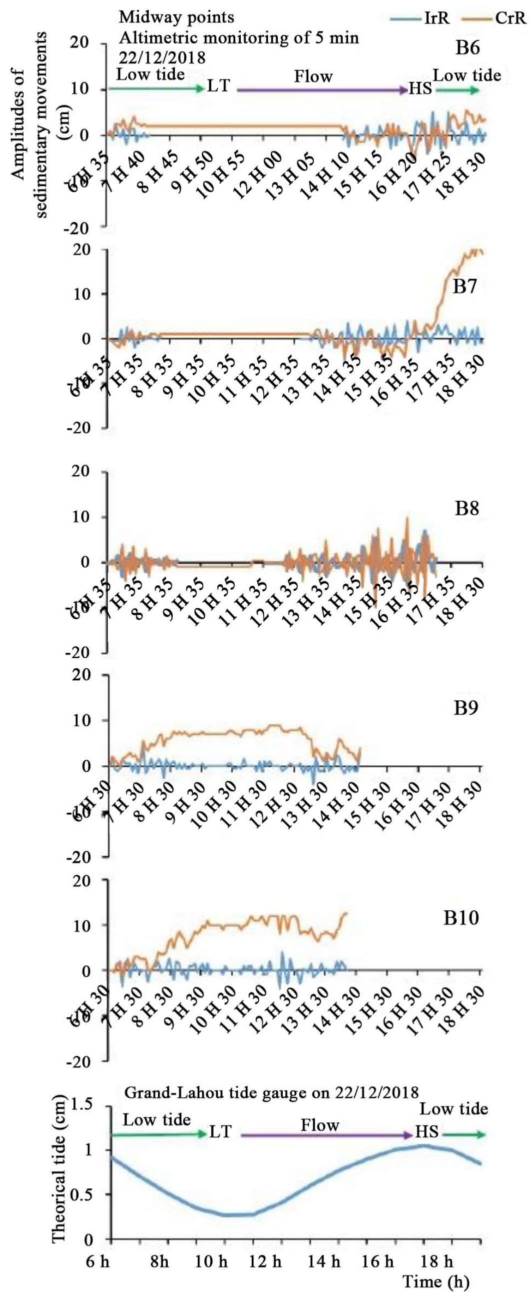


Figure 5. Continuous monitoring curves from the beach to the mid-foreshore of the control station.

3.1.3. Amplitude of Movement of Sediments on the High Foreshore of the Catholic Mission

a. Amplitude of movement at station A

Instant resulting reshuffle (RrI)

As the pickets were not submerged, this part of the shoreline remained stable.

Cumulative resulting reshuffle (RrC)

On the ebb tide, the RrC curves show stabilisation on all the picket of the high foreshore because the wave energy is too low to reach the picket, so the amplitude of mobilised sediment remains constant. This results in straight lines. Stakes A3, A4 and A5 are fattened until the end of the measurements (Figure 6). The extremes are 0 cm and 9 cm at point A5. The maximum amplitude of sediment movement is 9 cm for the RrC of profile A on the high foreshore.

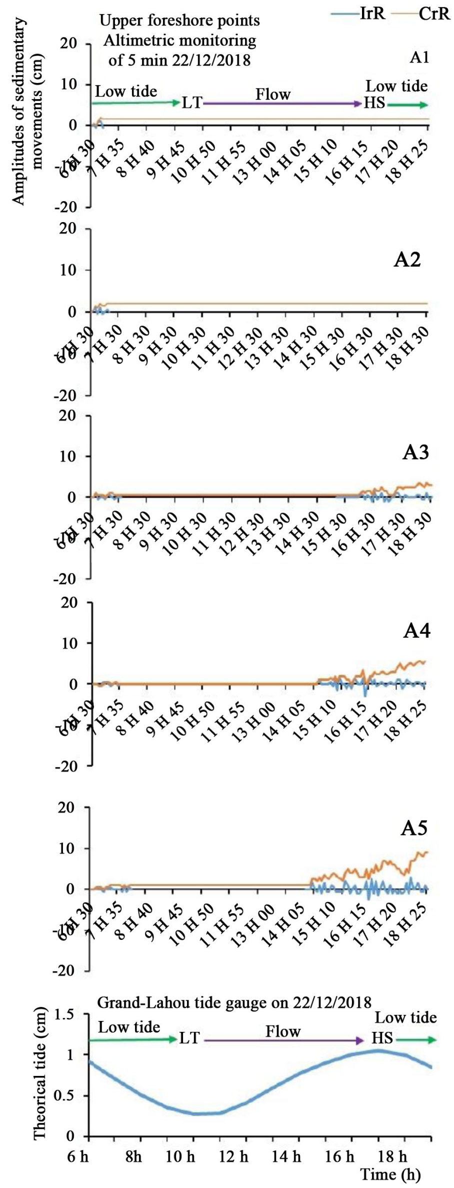


Figure 6. Continuous monitoring curves from the beach to the high foreshore: station A.

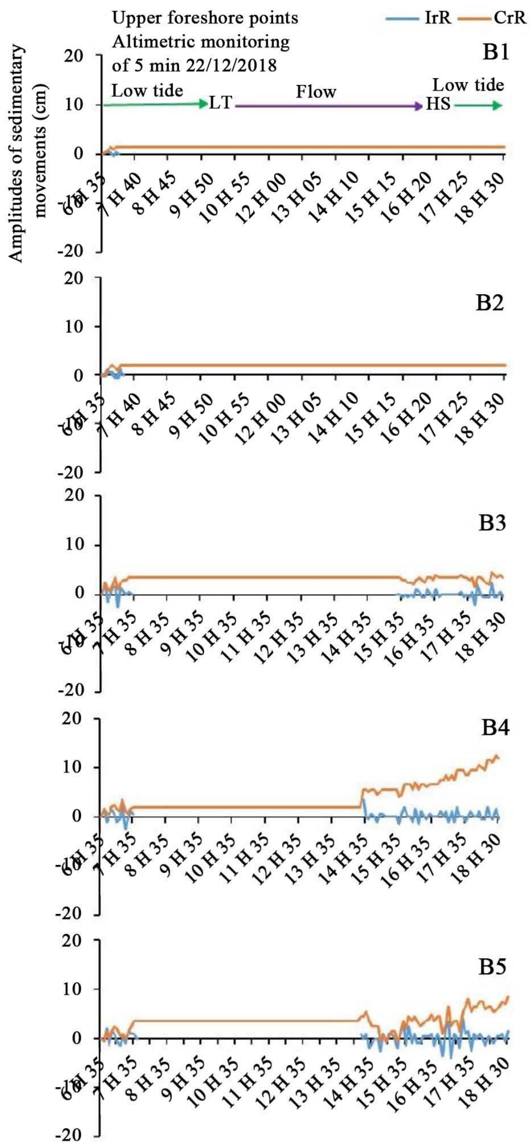
b. Amplitude of movement at station B

The picket at station B are B1, located 24.5 m from the coastline, B2, B3, B4 and B5.

Instant resulting reshuffle (RrI)

At ebb tide, all the pickets stabilise during the short time they may have been submerged by the waves. The straight lines show the constancy of the sediment in the absence of wave action.

At the flow, no trend emerged for B1 and B2 as the wave energy was too low to affect them. B3 became slightly fatter until the end of the measurements. B4 and B5 also became fatter, but in a progressive manner (Figure 7). All these accretions took place during high tide because the wave energy was powerful enough to reach pickets B3, B4 and B5. The extremes were observed at point B4 with 0 cm and 12.5 cm. The maximum amplitude of sediment movement was 12.5 cm for the RrC on the high foreshore.



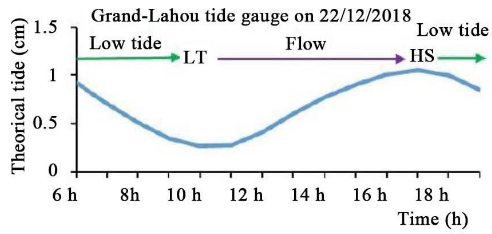


Figure 7. Continuous monitoring curves from the beach to the upper foreshore: control station.

3.1.4. Amplitude of the RrI and RrC in Stations A and Controls in One Tidal Cycle for a Follow-Up of 5 Min

The RrI curves show lower values than the RrC curves at all stations A and B except for points A7, B11 and B13 (Figure 8). The determination of the maximum amplitude of rearranged sediments at a point in the profile should take into account the greater of these two parameters (RrC and RrI).

For station A, the amplitudes of the RrI increase from A1 (1.5 cm) to A9 (19 cm). This amplitude falls at point A10 (7.5 cm), rises again at point A11 (11cm) before falling again at point A12. The amplitudes of RrC are also increasing from A1 (2 cm) to A9 (15.5 cm) with a slight drop at point A6. There is a drop at point A10 (12.5 cm) before a return to stabilization between A10 and A12 (15 cm).

For station B, the amplitudes of RrI and RrC increase together up to point B8. After the drop at point B9, the different amplitudes tend to stabilise. The maximum amplitude shows the points at station A becoming fatter. The maximum amplitude is 19 cm at point A9 on the mid-foreshore. For station B, all parts of the foreshore are getting fatter despite a few falls. The maximum amplitude is 25.5 cm at point B7 on the mid foreshore (Table 1).

Table 1. Maximum sediment amplitudes on profiles A and B in the tidal cycle for a 5mn monitoring on 22/12/2018.

	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	
Rrl mini	−0.5	−0.5	−1	−3	−2.5	−4	−5	−5	−11.5	−3	−5	−5	
RrI max	1	1	1.5	2	3	4	4.5	6	7.5	4.5	6	4	
RrC	0	0	0	−0.5	0	−1.5	−7.5	−8	−7.5	−5.5	−9	−4	
Rrc	2	2	3.5	5.5	9	5.5	3	6	8	7	4	11	
Ampl	1.5	1,5	2.5	5	5.5	8	9.5	11	19	7.5	11	9	
Ampl	2	2	3.5	6	9	7	10.5	14	15.5	12.5	13	15	
Ampl	2	2	3.5	6	9	8	10.5	14	19	12.5	13	15	
	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13
RrI mini	−0.5	−0.5	−2.5	−2.5	−4	−4	−5	−5	−4	−4	−4.5	−3	−3
RrI max	0.5	1	2.5	3	4	5	4	7	4	4	4	2	3
Rrc	0	0	0	0	−0.5	−5.5	−4.5	−10	0	−6	−6	−4	−8.5
Rrc	1.5	2	4.5	12.5	8.5	5.5	21	10	9	2	2	3	1.5
Ampl	1	1.5	5	5.5	8	9	9	12	8	8.5	8.5	5	6
Ampl	1.5	2	4.5	12.5	9	11	25.5	20	9	8	8	7	10
Ampl	1.5	2	5	12.5	9	11	25.5	20	9	8.5	8.5	7	10

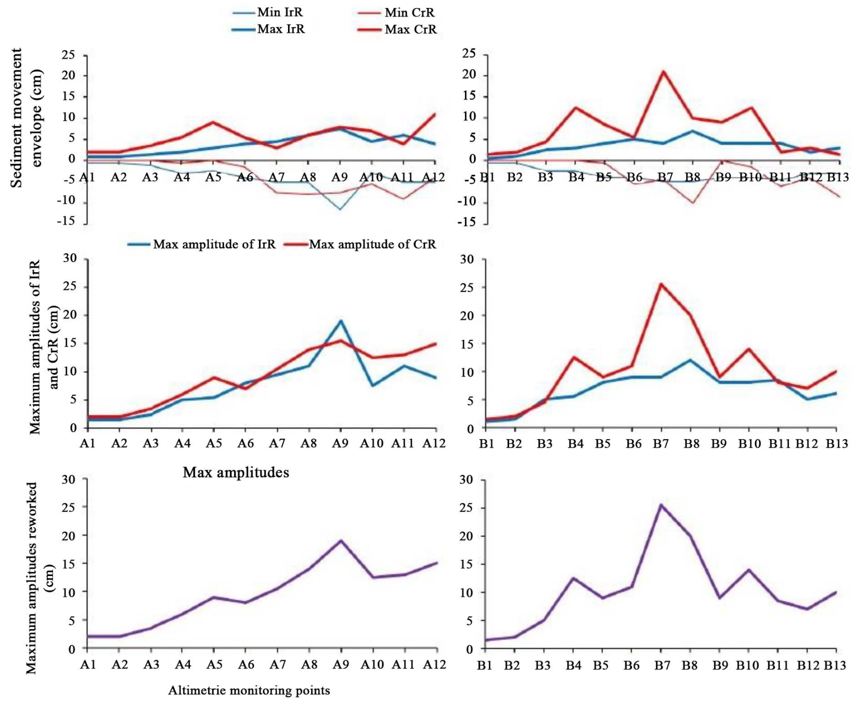


Figure 8. Amplitudes of the resulting instantaneous and cumulative reworking on Grand-Lahou beach

3.2. Annual Beach Dynamics

A comparison of the 1998 and 1999 profiles (**Figure 9**) shows that the coastline at Mission Catholique is stable. The low foreshore is eroding in favour of the high beach. The sediment balance is negative by −6.55 m^3 ml^{-1} of linear metre. A comparison of the 2006 and 2007 profiles (**Figure 10**) shows that the coastline has retreated by around (5.3 m). The sediment balance is very negative at 29.65 m^3 ml^{-1} linear metre. Superimposing the profile of 18/10/2017 and that of 22/12/2018 shows that the coastline has remained stable. Generally speaking, it can be seen that the beach at the Catholic mission is becoming deeper. The volume of the eroded surface was −3.51 m^3 ml^{-1} per linear metre, compared with a deposit of 88.32 m^3 ml^{-1} per linear metre. This gives a positive volume balance of 84.81 m^3 ml^{-1} m^3 linear metre of sediment. The shape of the GL1 profile indicates the presence of strong movements at the level of the cemetery with several subtleties. There is no eroded sediment, but there is a considerable input of sediment. Superimposing the two profiles (18/10/2017 and 22/12/2018) shows that the cemetery beach is growing adequately with a volume balance of 107.87 m^3 ml^{-1} per linear metre. The coastline remains stable. The mid foreshore and low foreshore will erode in favour of the high beach between October 2022 and July 2023.

3.3. Beach Dynamics in the Medium and Long Term (2 Years; 10 Years)

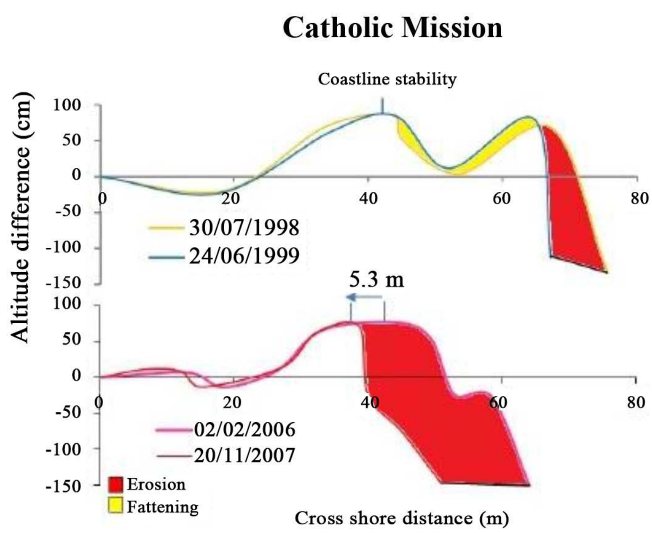
A comparison of the February 2006 and July 2008 profiles shows a concave profile in July 2008 as a result of severe erosion of the foreshore, with an estimated retreat of around 5 m during this period (**Figure 11**). The sediment balance was negative at −15,28 $m^3 ml^{-1}$ per linear metre. A comparison of the July 1998 and November 2007 profiles shows that erosion predominated during the 1998-2007 decade. The retreat of the coastline is estimated at around −4.8 m during this period. The sediment balance was negative by −30,35 $m^3 ml^{-1}$ of linear metre.

3.4. Beach Dynamics on a Storm and Seasonal Scale

Between May and August 2008, the shoreline retreated by an estimated 1.9 m (**Figure 12**). The erosion slope, which was around fifty metres from the lighthouse in May 2006, was only a few centimetres away in September 2008 (**Figure 13**). The coastline is retreating at an unusual rate, estimated at an average of 25 m.year/an between May 2006 and September 2008. The storms recorded in August 2007 undoubtedly had a considerable impact on this stretch of coastline. Twenty years after the construction of the 2nd lighthouse following the destruction of the first by heavy swells in July 1989, the authorities were obliged to build a third. In fact, given the threat of erosion, the lighthouse was dismantled and rebuilt twice as a precautionary measure. The enormous losses, generally located in the mouth area, have resulted in the destruction of the colonial heritage and the village cemetery... (**Figure 14**, **Figure 15**).

4. Discussion

The results show that the mobile layer on Grand-Lahou beach is between 4.5 cm and 12.5 cm on the upper beach and between 9 cm and 25.5 cm on the mid-shore. On the low foreshore, the mobile layer is between 7 cm and 15 cm with little sediment movement. This study reveals that the maximum amplitude of sediment movement corresponding to the thickness of mobilised sediment (25.5 cm) is acquired at mid-foreshore. The present study reveals a maximum effective reworking (Re) of 22.5 cm. These various sedimentary movements were also noted by [30] in his study of Port-Bouët beach.



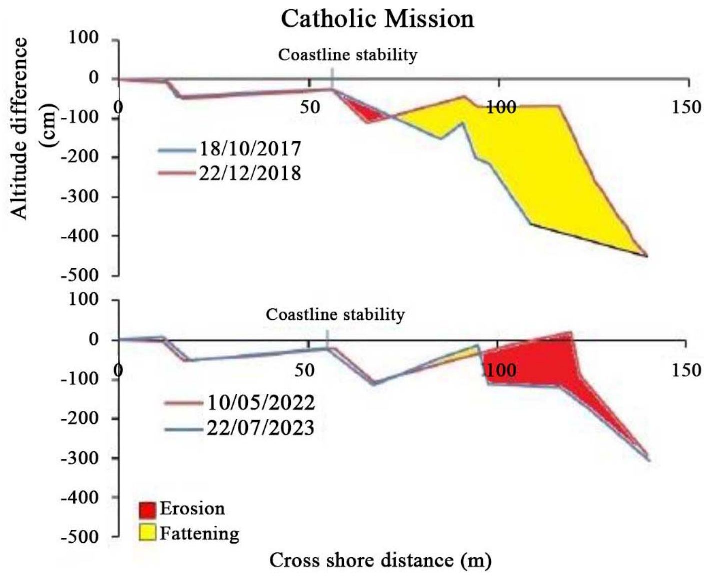


Figure 9. Interannual sediment evolution (1998-2023) of the foreshore and coastline on a coastal section of Grand-Lahou.

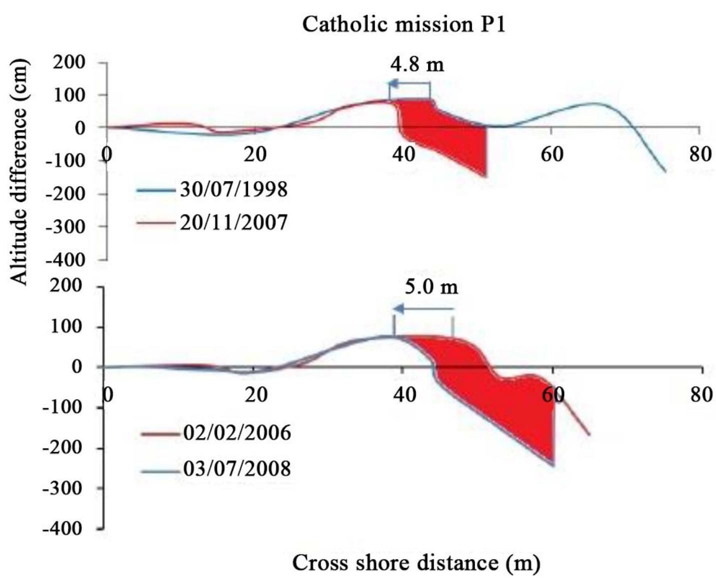


Figure 10. Interannual sediment trends (1998-2008) in the foreshore and coastline of the Catholic mission of Grand-Lahou.

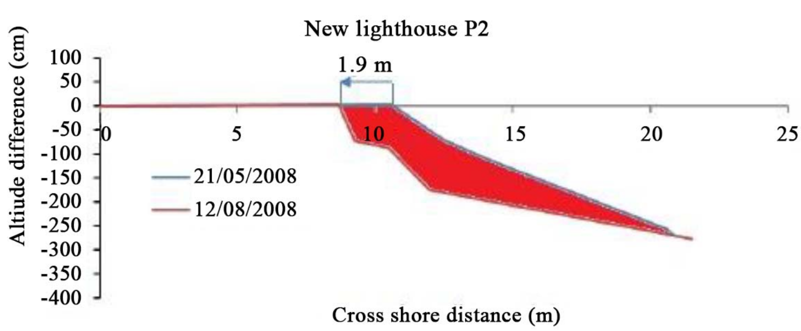


Figure 11. Evolution of the beach during heavy swells.

Figure 12. Erosion slope 50 m from.

Figure 13. Erosion slope at the lighthouse the lighthouse in May 2006 on 25 September 2008.

Figure 14. Well exposed at the mouth (May 2007).

Figure 15. Destruction of graves by erosion at Lahou-Kpanda (December 2018).

However, the maximum amplitude of sediment movement was 53 cm at mid-foreshore on Port-Bouët beach, compared with 25.5 cm on Grand-Lahou beach. The beach at Grand-Lahou is said to be less steep than that at Port-Bouët [21] [31]. It is characterised by concave topo-bathymetric profiles with medium to very steep slopes. The foreshore and underwater beach (−10 m) are made up of coarse to very coarse sands [32]. The coarsest and best sorted sediments are located in the Port-Bouët area. The grain size of beach sands varies between 764 µm and 1419 µm [5]. Studies have shown that the tide and beach morphology influence sediment dynamics in the swash zone [33]. The three factors involved in the morphodynamics of the swash zone are: hydrodynamics, slope and the granulometric characteristics of the beach. The behaviour of the swash zone is thought to be governed by various hydrodynamic and environmental factors such as wave height in the surf zone and beach slope, which change over the tidal cycle [34]. The morphology of the area submerged by the tide is constantly changing as the waves pass over it [9]. At each point of the profile, the beach has the necessary slope to allow the amount of wave energy to develop and thus have a volume of suitable size mobilisable sediment. Sediment transport intensifies as the slope increases until it reaches a maximum value. The value of this optimum slope depends on the speed of the current and on how far the river can progress over the sand [15]. The beach at Port-Bouët would have the necessary slope to allow the amount of wave energy to develop and thus have a greater volume of mobilisable sediment than the beach at Grand-Lahou. The beach of Grand-Lahou is also subjet to a rate of fattening during the tidal cycle considered to be much more pronounced in mid-offshore. A few episodes of minor erosion have nevertheless been recorded, but these are minimal compared with the sediment input. These results show that the dynamic swash zone, subject to major sediment flows, varies according to the phases of the tide. On the ebb tide, this zone is reduced to the low foreshore and a few points on the mid foreshore depending on the tide-swell conditions. At the flow, the area widens taking into account the upper shore. Generally speaking, on the scale of a tidal cycle, the flow of sediments transported increases with the tidal coefficient and is greater during the semi-diurnal tides of agitated to very agitated spring tides than during the semi-diurnal tides of calm to slightly agitated neap tides. The flow phase characterized by strong currents (tide and swell) is the most turbid [9]. The superposition of profiles at annual scale at the Catholic mission level shows that the coastline is stable. Generally, gains in sediment outweigh losses. However, between 2006 and 2007 there was an estimated retreat of 9m. We can therefore attest to the erosive nature of the beach during this period. The decade 1998-2007 at the level of the Catholic mission is marked by a retreat in the coastline estimated at 4.8 m. The retreat is estimated at 5 m between 2006 and 2008. These results show a decline that varies over time. Erosion is more pronounced at the mouth. Work by Koffi (2017) [29] revealed that the village cemetery area is experiencing the greatest shoreline regression with recession rates of −4.6 m/yr. Erosion at Grand-Lahou is exacerbated by a lateral (east-west) migration of the mouth of the Bandam river [5]-[7]. This study confirms this trend, with the corollary of destroying the lighthouse and the village tombs. The disappearance of the rocky banks under the mud at the mouth of the river would leave this area without natural defences, particularly vulnerable to erosion [5]. The sediments eroded in the cemetery sector were transported towards the western sector and the Catholic mission by an east-west longshore drift reported by Wognin (2004) [23]. This allows us to establish a relationship between sediment budgets and hydrodynamic forcing (waves). This could explain the dynamics of the Grand-Lahou beach, which, according to [23] and [5] is eroding in areas close to the mouth while rebuilding in areas further away. Apart from the so-called natural forcings (hydrodynamics, meteorological flows, morphological), another limiting factor of the advance of the coastline is the anthropogenic factor. Beach erosion is sometimes constrained by human constructions that provide additional protection against marine hydrodynamic forcing [9]. Areas that appear to be less dynamic reflect either the stability of these areas or accretion that is equivalent or almost equivalent to the erosion they are undergoing. When an annual time step is considered, the sediment balances are variable, sometimes positive, sometimes negative, which shows the variability and importance of the different hydrodynamic forcings acting on Grand-Lahou beach. These observations are consistent with those in the literature [3] [9].

5. Conclusion

The quantification of the sedimentary balance by zone and time period made it possible to highlight the sedimentary evolutions of the Grand-Lahou beach between

1998 and 2023, that is 25 years. The synthesis of the results allows us to observe the evolutionary trends of each zone by crossing their dynamics for different time steps (tide cycle, storm, year: 10 years). On the scale of a tidal cycle, the curve of the maximum reworked amplitude shows a marked deepening at mid-foreshore with a maximum amplitude of 25.5 cm compared with amplitudes of 15 cm and 12.5 cm respectively at low foreshore and high beach. The maximum effective reworking was 22.5 cm. The quantitative balance of the sedimentary reworking shows that overall, the beach is fattening. However, there is partial erosion of the coloured sediments. On an annual scale, the balances are rather variable, sometimes positive (2017-2018) and sometimes negative (1998-1999 and 2006-2007), reflecting the influence of different forcings (swell, tide) which vary from one period to another. On a ten-year scale (1998-2007), the retreat of the coastline is estimated at around 4.8 m. We have concluded that the beach is generally eroding over this period. However, the relatively low sediment balance indicates that the beach is relatively stable at this time scale. This sector does not therefore appear to be subject to any significant evolutionary trends at this time step. At the scale of the study area as a whole, the results show that the coastline is not evolving in the same way on the beach, as the different sectors are not exposed to forcing in the same way. The Catholic mission area is less subject to strong marine hydrodynamic forcing than the mouth area. The Catholic Mission sector, which appears to be relatively undynamic over the entire study period, shows low sediment balances, in line with its relative stability. The most significant retreats were observed at the mouth and during exceptional events such as storms. The retreat of the coastline, estimated at 25 m.yr-1 between May 2006 and September 2008, is thought to have been caused by the storms recorded in August 2007. The mouth of the river is located in an area where hydrodynamic forces have the most energy and are likely to cause severe erosion, even on the upper beach. Lateral migration of the mouth of the Bandama River is the main cause of erosion of the Grand-Lahou beach and therefore the main threat to the local population, given the damage recorded at the cemetery during the study period.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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