Identification Of The Causes Of The Seabed Dynamics (Cotonou Coast/Benin)

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Received: Jul. 19, 2024; Accepted: Oct. 19, 2024

Due to the issues related to the evolution of the seabed, the determination of the retreat or advancement of the ocean has been the subject of numerous scientific studies. Coastal areas are among the most dynamic places on the planet. Most of the coasts in the world are affected by the phenomenon of coastal erosion, in particular the coast of Benin. On the coast of Benin and in the Gulf of Guinea in general, the dynamics of the coastline is not a recent phenomenon but its scale has increased over the last decades. This erosion is the consequence of the impact of the swells. Identifying the causes of seabed dynamics in coastal areas is essential to understanding the physics of the phenomenon. This work emphasizes the different parameters that influence the morphodynamic evolutions of the beach and the coastline in this coastal area. The study is based on data obtained from the IRHOB (Institute of Halieutic and Oceanographic Research of Benin) of the CBRST (Benin Center for Scientific and Technical Research) on swells. This data was recorded with a time interval of 5 minutes; this allowed us to model the evolution of the coastline of the Benin coast. The results obtained show the major causes of the dynamics of the seabed on this coast in recent years.

Keywords: Coastline; Coastal dynamics; Swell direction; wave parameters; Benin Coastline

http://dx.doi.org/10.6180/jase.202509_28(9).0014

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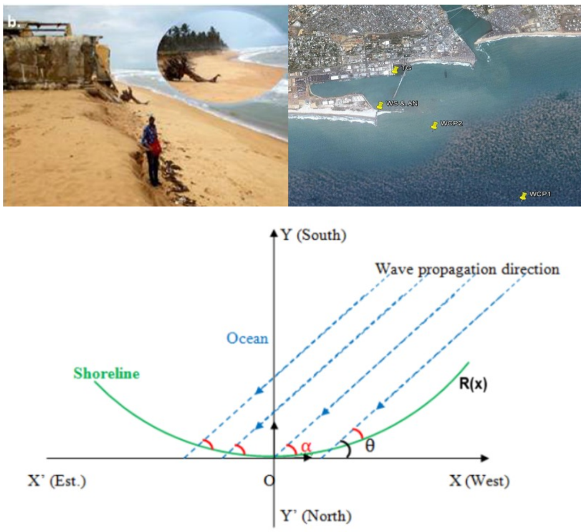
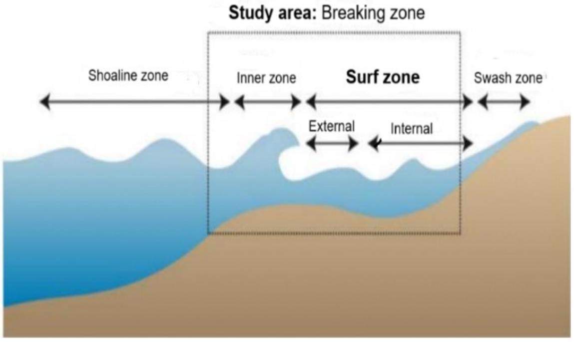
1. Introduction

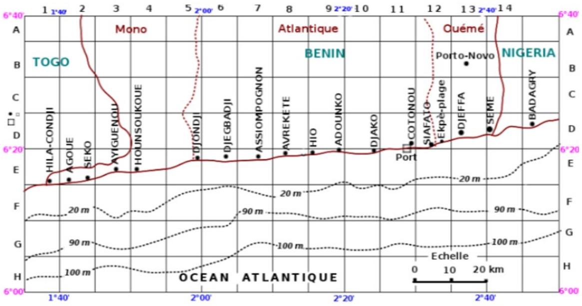
Coastal erosion has posed significant challenges to sustainability and socio-economic stability along Senegal's coastline, leading to substantial infrastructure losses [1]. The measurement of longer-term trends in coastal erosion is of particular importance for the management of the world's coastlines [2]. Coastal zones are unique and dynamic environments that are increasingly anthropized and inhabited due to their socio-economic importance. Excessive accretion in the wave-protected area and severe erosion are also observed occurring simultaneously [3]. Several studies have shown that these environments are also subject to varying degrees of natural and anthropogenic morphological variation, thereby increasing the vulnerability of these areas and the risks to property and people [1]. The very high vulnerability of some coastal environments remains a major concern in view of the intensification of extreme wave and surge events and sea level rise due to climate change [4]. Beach erosion has become an urgent issue for the all coastal cities to mitigate the overwash effect and stabilize the sand [5]. The coast is the meeting place between the continent, the ocean and the atmosphere, three environments controlled by multiple physical processes and which interact at the level of the littoral [6]. The land-ocean interface is an extremely fragile environment. The profile of a coast results from complex actions exerted by the wind, the waves, the tides, the currents [7]. These areas constitute very fragile environments due to their position and therefore, due to the multitude of elements likely to upset the balance between marine and terrestrial processes. Most coastal environments in the world are in dynamic equilibrium between depositional and erosional phenomena, the general characteristics varying very slowly at the macro scale [8]. The most common approach taken by researchers over the years is to simplify the effect of vegetation as a change in shear stress in the boundary layer or mixed layer near the shoreline bed [9]. Thus, the response of a beach to a variation in hydrodynamic forcings depends on its morphology [8] and the grain size distribution constituting it [10]. On a global scale, BIRD (1985) already estimated, more than three decades ago, that about 70% of sandy coasts were subject to erosive processes. In general, sandy coastlines are more fragile due to the nature of their grain size [11]. Coastlines attracting an increasingly significant fraction of the world's population [12, 13], the multiple consequences of sea level rise and coastal erosion will have a human (public health, migrations, etc.) and economic (fisheries, tourism, industries, floods, saline water intrusion, etc.) cost. considerable [14, 15] requiring very heavy territorial planning efforts, which are often difficult to implement [13]. The mobility of the coastline already reached 250 meters east of the Eastern spur (or Safiato spur) in 1976, then 400 meters in 1987, 500 meters in 1994 and 570 meters in 2000 [16]. To these major coastal upheavals due to the installation of major infrastructures are added other natural or human parameters which also influence the evolution of the coastline. Locally, sediment removal from the beach has accelerated coastal erosion [6, 8, 17]. If the exploitation of these coastal sand quarries to satisfy an ever-increasing demand for construction material (most often near coastal towns which are experiencing extremely rapid population growth) was regulated and most often prohibited in the 2000s, some observers have doubts about compliance with these laws. In reality, this exploitation seems to be more confidential than in the past [18]. Later, Laïbi et al. [8], for their part considered that the influence of the port of Cotonou on coastal erosion was only significant on the first ten kilometers downstream of the port; the rest of the coastline towards Nigeria being assumed to be stable. Coastal erosion causes shoreline retreats with appalling consequences [19]. In Benin, the ocean engulfs nearly 40 meters of coastline each year, washing away a



(a) Diagram of the reference point and direction of waves in the study area



(b) Representation of the different coastal zones in the study area



(c) Bathymetric map of the Benin coastal zone

Fig. 1. Coastal zone and location of the Cotonou port (Benin) with the various measurement stations (WCP1 and WCP2. . .)

large number of villages and constructions [11]. Benin's coastline has for several years been subject to a series of extreme swells, resulting in the collapse of buildings, the displacement of the population and the early cessation of fishing activities [20]. However, the effective protection duration in the tidal zone which encounters wind, wave, tide and reflow was about 24 days, and would thus need to be reinforced periodically over time to obtain long-term protection [21]. Coastal erosion threatens homes, infrastructure located on the coast, the entire lagoon ecological system and therefore the people who live there [22]. Aware of the seriousness of the damage caused by this coastal erosion at the economic, social and environmental levels, the Beninese State has adopted a development policy in order to limit the impact of the waves. The present study sets as objective the identification of the various parameters constituting the major causes of the dynamics of the seabed in Benin. It emerges from the study that the different parameters identified significantly influence the morphodynamic evolutions of the beach and the coastline in the Benin coastal zone.

2. Materials and methods

2.1. Presentation of the study area

Benin is a country of the Gulf of Guinea located between the parallel 6°15 ′and 12°30′ north latitude on the one hand and meridians 1° and 3°40′ east longitude on the other hand [23]. It has gotten a coastal area that is 125 km from Hillacondji in the west, to Kraké in the east. Benin coast is more or less linear and cut off in two places, namely, the Bouche du Roy and the channel mouth of Cotonou. Its coastal zone is between latitudes 6°15′ and 6°23′ north [12, 24].

The bathymetric map obtained at the CBRST (Benin Centre for Scientific and Technical Research) shows the evolution of the local water depth in the coastal area of Benin and predicts the average slope and macroscopic variability of the seabed, see Fig. 1c. This map shows that the seabed in the coastal area is almost flat and sloping. It is a gently sloping seabed $p = \tan\beta$ as $0.001 < \tan\beta \leq 0.1 \Rightarrow \tan\beta \approx \beta$. The slope in the shoaling zone corresponds to the following on average $\beta_m \approx \frac{100}{2000} = 0.05$ [12, 24] see Fig. 1c.

2.2. Data Sets Used

Waves parameters, significant wave height $(\mathrm{H_s})$, and peak period $(\mathrm{T_p})$ are recorded every 30 min [23]. The gravity on the coast of Benin is approximately $g = 9.79\ \mathrm{N/kg}$ and the density of sea water is $\rho = 1025\ \mathrm{kg/m^3}$ [25]. During a measurement campaign carried out over two consecutive years from June 2015 to April 2016 by NORTECKMED in collaboration with the Millennium Challenge Account (MCA) and the Autonomous Port of Cotonou, two measurement stations were moored near the port of Cotonou, at a depth of 13.5 m at coordinates N6°20.118 ′ and E2°27.257′ (station WCP1) and at a depth of 13 m at coordinates N6^{2}0.373′ and E2^{2}6.140′ (station WCP2). This system is supplemented by a meteorological and tide gauge station installed in the port (Fig. 1).

2.3. Modeling of Sediment Flow Movement

The work carried out at « Coastal Engineering Research Center», led to the proposal of the sediment flow formula $Q\,(H_b, \alpha)$ which takes into account the height H_b of the swell during breaking, its camber in deep waters and the obliquity function $f(\alpha)$ [11].

$$Q\,(H_b, \alpha) = Q_o f(\alpha) \tag{1}$$

$$\text{With} \begin{cases} k = 0,2 \quad ; \quad n = 0,4 \\ Q_o = \frac{k\rho_a}{16(\rho_s - \rho_a)(1-n)} \sqrt{\frac{g}{\gamma}} H_b^{5/2} \\ \gamma = \left(\sqrt{\frac{L_o}{H_o}} \tan\beta \right)^{0,21} = \left(\sqrt{\frac{g}{2\pi H_o}} \mathrm{T} \tan\beta \right)^{0,21} \\ H_b = \gamma d_b = \left(\sqrt{\frac{g}{2\pi H_o}} T \tan\beta \right)^{0,21} d_b \end{cases}$$

The theoretical obliquity function $f(\alpha) = \sin(2\alpha)$, which corresponds to the power transmitted by the swell, passes through its maximum for $\alpha = 45°$. However, the work of the Central Hydraulic Laboratory of France (LCHF) proposed by J. Larras and Bonnefille; Barbaro Giuseppe; Chadwick A. J. have shown that this maximum is reached when $50° \leq \alpha \leq 55°$ independently of the swell conditions which only influence the value of this maximum. They suggest using:

$$f(\alpha) = \sin\left(\frac{7\alpha}{4}\right) \tag{2}$$

Assuming that the sediments move in the direction of the increasing abscissa and that the sediment flow depends only on the obliquity of the swell on the beach, the distance $y(x, t)$ of the shore in relation to the initial shore verifies the following differential equation:

$$\frac{\partial y}{\partial x} = \tan\left(\alpha - \alpha_o\right) \approx \alpha - \alpha_o \tag{3}$$

In which α designates the obliquity of the swell in relation to the coastline and α_o the obliquity of the swell in relation to the initial coastline. By deriving the previous equation with respect to x along the coastline, the variation in the flow rate of sediment transport is written as:

$$\frac{\partial Q}{\partial x} = Q_o f'(\alpha) \frac{\partial^2 y}{\partial x^2} = Q_o f'(\alpha) \frac{\partial}{\partial x} \tan\left(\alpha - \alpha_o\right) \tag{4}$$

Considering that accretion or erosion takes place over a constant thickness h, we obtain the differential equation below:

$$h\frac{\partial y}{\partial t}dxdt = \frac{\partial Q}{\partial x}dxdt \Rightarrow$$
$$\frac{\partial y}{\partial t} = \boldsymbol{Q}_o\frac{f'(\boldsymbol{\alpha})}{h}\frac{\partial^2 \boldsymbol{y}}{\partial x^2} = \boldsymbol{A}\frac{\partial^2 \boldsymbol{y}}{\partial x^2} \tag{5}$$

The general solution to this differential equation is:

$$y(x,t) = C_1\left[\sqrt{\frac{4At}{\pi}}e^{\left(-\frac{x^2}{4At}\right)} + \epsilon x \cdot \mathrm{Erfc}\left(\frac{|x|}{\sqrt{4At}}\right)\right] + C_2$$

$$\text{Where}\begin{cases} A = Q_0\frac{f(\alpha)}{h} \\ C_1 = \pm\tan(\alpha - \alpha_o) \\ C_2 = C\,\mathrm{ste}(t) \end{cases} \tag{6}$$

Before the arrival of the waves, let $R(x)$ be the equation which translates the initial shape of the coastline and D the distance of the strip over which the waves hit the coastline. Taking the middle of the affected strip as the origin of space, the boundary conditions of the problem are:

- $x = 0$ is the middle of the coastal strip hit by the swell after its breaking.
- When

$$t \to 0s \quad , \quad y(x, t \to 0) = R(x) \tag{7}$$

At infinity, the coastline remains unchanged, so we have: $y(x \to \pm\infty, t) = R(x)$.

- $C_1 > 0$ for accretion and $C_1 < 0$ for erosion.
- When the movement of the coastline is accentuated in the direction of the increasing abscissa (x) $\epsilon = +1$. In the opposite direction, $\epsilon = -1$.

By applying these boundary conditions to the previous general solution, on a site where coastal erosion is more accentuated in the direction of decreasing abscissa, we obtain:

$$y(x,t) = R(x) - C_o\left[\sqrt{\frac{4At}{\pi}}e^{\left(-\frac{x^2}{4At}\right)} - x \cdot \mathrm{Erfc}\left(\frac{|x|}{\sqrt{4At}}\right)\right]$$

$$\text{With}\begin{cases} C_o = \tan(\alpha - \alpha_o) \\ A = Q_o\frac{f'(\alpha)}{h} \end{cases} \tag{8}$$

2.4. Beach Erosion or Accretion Conditions

Two important parameters that control sediment transport are their velocity of fall and the slope of the seabed. Using these parameters, the onshore-offshore transport direction and beach profile in the Surf zone is expressed as follows [11]: $G_o = \frac{gT}{W_s}\frac{H_o}{L_o}\tan\beta$ with $W_s = \sqrt{\frac{4gD_m(\rho_s - \rho_a)}{3C_d\rho_a}}$ as $L_o = \frac{gT^2}{2\pi}$ then we have:

$$G_o = \frac{\pi H_o}{T}\sqrt{\frac{3C_d\rho_a}{gD_m(\rho_s - \rho_a)}}\tan\beta \tag{9}$$

W_s is the fall velocity of a sediment of median diameter D_m and C_d the drag coefficient.

- If $G_o = 0,5$ then the coastline is stable,
- For $G_o > 0,5$ there is silting: the beach is accumulating,
- If $G_o < 0,5$, there is coastal erosion.

Another parameter, which takes into account the slope of the seabed of the beach $\tan\beta$ and the camber $\gamma_o = \frac{H_O}{L_o}$ of the swell in deep waters is given from the work of Tokpohozin et al. [11] improved later in the literature: $G_s = \frac{H_o}{L_o}(\tan\beta)^{0,27}\left(\frac{D_m}{L_o}\right)^{-0,67}$ as $L_o = \frac{gT^2}{2\pi}$ then we have:

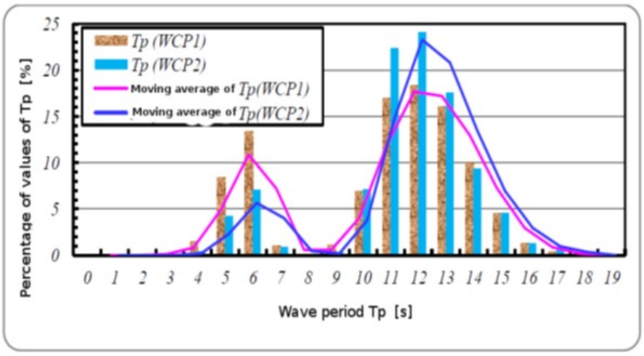
$$G_s = \frac{2\pi H_o}{gT^2}(\tan\beta)^{0,27}\left(\frac{2\pi D_m}{gT^2}\right)^{-0,67} \tag{10}$$

For accretionary beaches $G_s < 9$ while $G_s > 18$ for those that are in erosion.

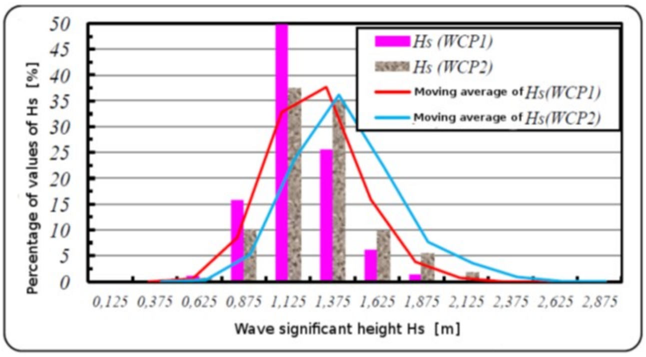
3. Presentations, analysis and discussion of the results

3.1. Presentations of Results

Data analysis yielded the following diagrams which respectively reflect the period T , the peak to valley height H and direction of propagation of swells off the Benin coast.



(a) Period of swells in the coastal zone of Benin



(b) Height of swells in the coastal zone of Benin

The diagram in Fig. 3 indicates the direction of wave propagation in the coastal zone of Benin from December 2015 to October 2016.

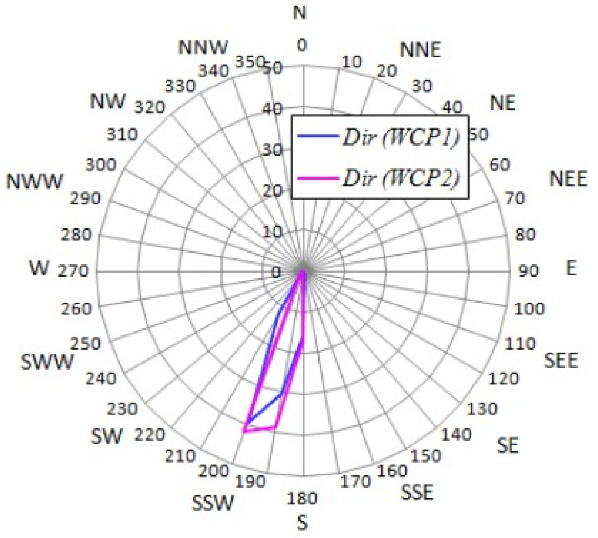


Fig. 3. Propagation direction of swells in Benin coastal

The curves in Fig. 4 below represent the influence of the different parameters on the evolution of the coastline in the coastal zone of the Gulf of Guinea in Cotonou from December 2015 to October 2016.

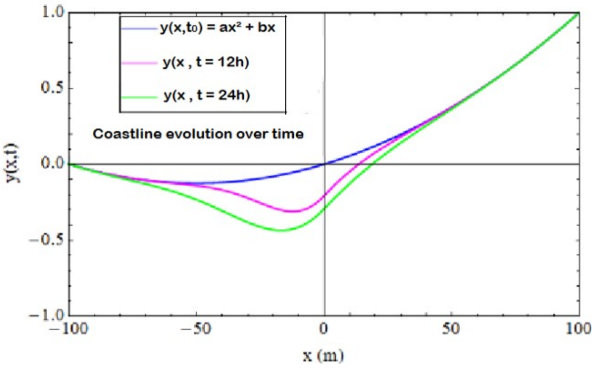
3.2. Analyzes and Discussion of the Results

From the analysis of these curves, it appears that the swells in the Gulf of Guinea in Cotonou have:

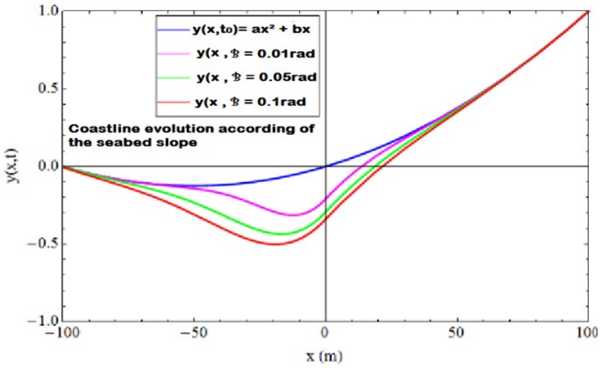
- A period of peak that ranges between 8*s* and 18*s* ($8s \leq T \leq 18s$) and whose average value is about 12 s ($Tm \approx 12$ s) Fig. 2a;
- A height that varies between 0.4m and 2m ($0.4m \leq H_o \leq 2m$) with a common average value of about 1.1 m ($H_{\text{om}} \approx 1.1$ m) Fig. 2b;

This diagram shows that the dominant direction of wave propagation on this coast is South-South-West (SSW) Fig. 3. However, we observe a spread between the South-West (SW) and South directions on either side of the South-South-West (SSW) direction. In the Gulf of Guinea in Cotonou, the main direction of wave propagation is that of South-South-West (SSW). This direction makes approximately an angle $60° \leq \theta \leq 70°$ relative to the West-East direction.

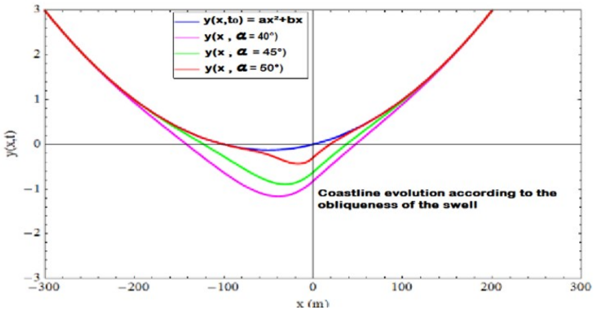
On the Fig. 4, the blue curve represents the coastline at the initial time, and in accordance with the beach of Benin, it orients its concavity towards the ocean. All the curves reveal that the coastline in Benin is retreating significantly. Erosion on the coastal strip, affected at a given time, is more accentuated towards the East. This erosion is almost absent



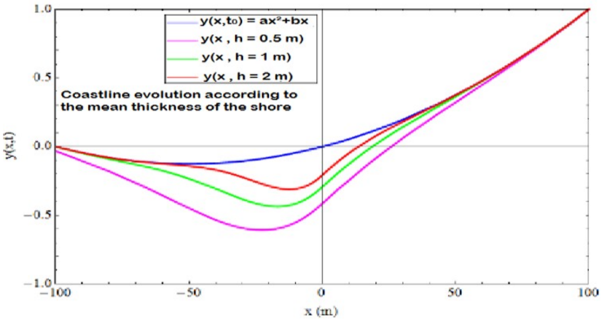
(a) Evolution of the coastline over time



(b) Influence of seabed slope on the evolution of the coastline



(c) Influence of the obliquity on the evolution of the coastline



(d) Influence of the average thickness of the shoreline on the evolution of the coastline

Fig. 4. Caption for this figure with two images

towards the ends of the coastal strip hit by breaking waves.

- The curves in Fig. 4a, reflect the evolution of the erosion phenomenon over time. For a coastal strip that continuously receives waves, the coastline can experience a retreat ranging from $0.01m$ to $0.5m$ for 24 hours. This phenomenon also causes the shape of the coastline to change and increases its concavity over time.
- The curves in Fig. 4b highlight the influence of the slope of the seabed on the evolution of the coastline. They reveal that coastal erosion increases with seabed slope. The increase in seabed slope in the Surf and Swash zones increases coastal erosion.
- The curves in Fig. 4c reflect the influence of obliquity on the evolution of the coastline. They show that coastal erosion on the beach of Benin is a decreasing function of the obliquity of the swell. The decrease in the obliquity of the waves causes a rapid retreat of the coastline and a significant increase in the width of the eroded coastal strip. The obliquity of the swell is one of the main factors which cause and which accentuate the coastal erosion caused by the sudden breaking of the waves.
- The curves in Fig. 4d reflect the influence of the average thickness of the shoreline on the evolution of the coastline. They show that the displacement of the coastline decreases when the average thickness of the shoreline increases. Coastal erosion is therefore a decreasing function of shoreline thickness.

All in all, the curves of Fig. 4 reveal that the decrease in the obliquity α of the swell, the increase in the slope β of the seabed and the period T of the swell, and the local water depth of the place of breaking d_b have negative and significant effects on the evolution of the coastline. These different parameters actively accelerate coastal erosion on the coast of Benin. As for the average thickness of the shoreline h, its increase attenuates coastal erosion.

4. Conclusions

The evolution of the coastline in Cotonou has shown that the coastline of the Gulf of Guinea is subject to active sedimentary dynamics. Coastal dynamics is a phenomenon that is very sensitive to a large number of parameters, in particular offshore wind velocity.v , swell period T, deep water wavelength L_0, seabed slope β, crest-to-trough swell height H, swell obliquity α, local water depth d, the average diameter of the sediment D_m. The direction of wave propagation is between the South-West and the South; However, the dominant direction of propagation is that of the South-South-West which induces the erosion observed towards the East. The dissipation of energy on the seabed instead of breaking and in the Surf zone is the major cause of the morphodynamic evolution of the coastal strip on the study site.

5. Authors contributions

This work was carried out in collaboration between the author and all co-authors. "The main author" and the "first three co-authors" designed the study, performed the statistical analysis, and wrote the protocol and the first draft of the manuscript. The "last co-author" supervised and coordinated the work. The other co-authors performed the calculations and analyses of the study. All co-authors read and gave final approval for publication.

6. 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.

7. Acknowledgements

The authors are indebted to NORTECKMED in collaboration with the Millennium Challenge Account (MCA) and the Autonomous Port of Cotonou, for the databases made available to us.

8. Data availability

The datasets generated during and/or analyzed during the current study are available from the authors at reasonable request.

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