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ARTICLE

Contribution to the Adaptation of the Submerged Dike of Avlékété to Climate Change in the Republic of Benin

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ABSTRACT

This article presents the results of various 1D simulations performed on the existing breakwater in Avlékéte, a critical erosion site for economic stability, environmental preservation, community resilience, and sustainable development, with a view to implementing innovative coastal protection measures to safeguard the coast for future generations in the Republic of Benin. To define the morphology along the coastline, different design simulations are carried out. A first design simulation was carried out, including a breakwater but without a lagoon, then a second without a breakwater as a hard element but with a lagoon, then a third smooth including a breakwater but without a lagoon and finally a fourth smooth including a breakwater and with a reduced wave height at the breakwater but without a lagoon which is the most appropriate approach. In order to study the morphological stability of the transverse profile of the breakwater, a one-dimensional XBeach simulation, Surfbeat mode, was carried out with the most difficult wave conditions while considering a breakwater as a non-erodible layer. The results from these simulations confirm those of the studies commissioned by the Ministry of Living Environment and Transport in charge of Sustainable Development (MCVT) in February 2023. The study of the morphological stability of the transverse profile of the breakwater led to a revised model, which shows a limited restructuring of the beach, a propagation towards the shore, and therefore an erosion of the breakwater. The profile retained at the end of the study is an equilibrium profile.

Keywords: Breakwater; 1D Simulation; Coastal Erosion; Climate Change

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1. Introduction

In order to protect coastal areas from coastal hazards, coastal protection structures (CPS) have been developed and implemented in several regions of the world. These coastal protection structures (CPS) are designed to mitigate the effects of waves, currents, tides, and storms in coastal areas in order to mitigate their energy on the shoreline and minimize erosion. There are two main categories of structures aimed at coastal protection: rigid structures (breakwaters, riprap, seawalls) [1,2] and soft techniques (beach nourishment, dune nourishment, revegetation) [1,3].

In the past, flexible techniques were preferred over rigid structures because they were generally less damaging to the environment. But recent studies indicate the opposite; for example, the use of piles (one of the soft options) is not effective in protecting the coastline [4].

A wave is a deformation of the free surface of water masses caused primarily by the effect of wind. Waves that form specifically due to wind action are called wind waves. These waves have major impacts on the morphology, sediment transport, and overall dynamics of the marsh ecosystem. To study this effect on the coastline, some researchers have turned to the use of wave energy to obtain a more comprehensive overview of the wave climate [5]. It is worth noting that wave energy is the most significant driving force of coastal erosion. Indeed, numerous studies have shown that there is a linear relationship between wave energy and the rate of retreat of the upper salt marsh. Some researchers have shown that this linear relationship is valid at all time scales (annual, monthly, and single-storm time scales) [6]. Waves generated in the ocean move toward the shore and interact with the seabed as they approach the shore. The energy of the incident waves and their angle of incidence influence sediment movement. In general, higher wave heights and waves more oblique to the shore (less parallel to the shore or with a greater angle of incidence) are often associated with greater sediment transport along coastlines [7]. Therefore, breaking currents are capable of modifying the shoreline, contributing to the formation and transformation of coastal features.

Several studies have shown that breakwaters are effective in coastal preservation by influencing various hydrodynamic processes in the sheltered area, such as waves and longshore currents. In fact, breakwaters can effectively attenuate the energy of incident waves, slow down the longshore current speed, and consequently promote sediment deposition in the protected area behind the breakwater [8].

Coastal erosion is a well-known phenomenon worldwide [9,10]. In the context of climate change, this phenomenon is expected to increase, particularly due to the global rise in sea level and the increase in storm intensity. Indeed, worldwide, more than two-thirds of sandy coasts are eroding [11], and the process of coastline retreat currently affects more than 70% of the planet's beaches [9]. It should be noted that 40% of the world's population lives less than 100 km from the coast and that the phenomenon is likely to have significant repercussions on them [12,13]. In Europe, erosion affects 40% of beaches [14] and more than 50% of sandy coasts in metropolitan France [15]. In the United States, at least 66% of the sandy coastline of the Gulf of Mexico is in decline [16], 45% of the beaches from Florida to North Carolina [17], and 40% of the beaches in California [18]. In Latin America, 81 to 84% of the beaches in the state of Rio Grande do Sul (Brazil) are said to be eroding [19]. Erosion phenomena have also been highlighted on Indian beaches in the Bay of Bengal [20]. Also, it is estimated that at the current rate of development, small island states in the Indian Ocean (Maldives) could be wiped off the map [13,21]. In the African continent, coastal erosion is a worrying problem. In the African continent, coastal erosion is a worrying problem. On average, 1 to 2 m of beach per year is engulfed by the Atlantic Ocean in the coastal countries of West and Central Africa [22,23]. In West Africa, the World Bank study notes, however, that the phenomenon is very uneven depending on the region, with some areas being very dynamic and preserved or even having gained ground, while other places have lost ground [24]. The study estimates that 56% of the coastline of Benin, Ivory Coast, Senegal, and Togo is subject to an average erosion of 1.8 m per year. Particularly exposed to erosion, Benin loses an average of 4 m of shoreline per year on 65% of its coasts [24]. The Intergovernmental Panel on Climate Change (IPCC) predicted, in its latest report on the oceans and the cryosphere [25], a rise in global sea level in 2100 of 48 cm for the most optimistic scenario, to 84 cm for the most pessimistic scenario [26]. To summarize, marine submersions will become more intense and more frequent, and erosion will intensify over time. All these changes disrupt the functioning of marine and coastal ecosystems and will have a strong impact on coastal areas [27].

Thus, climate change is a phenomenon that causes a rise in mean sea level (MSL) [25], and therefore, coastal dikes are exposed to waves whose height exceeds their design value. The Avlékété breakwater, located on the Beninese coast, is no exception to this situation. The phenomenon of coastal erosion or "retreat" is a major concern for public authorities, local populations, and elected officials in coastal areas [28]]. This led the Ministry of Living Environment and Transport in charge of Sustainable Development (MCVT) of Benin to initiate a study on the restoration and then the long-term maintenance of the Avlékété breakwater. Thus, an initial design developed in February 2023 required a significant volume of sand (1,650,800 m^3) behind the breakwater [29]. To address this challenge, the MCVT opted for an optimization of the February 2023 design. This optimization involves creating an embankment between the beach and the breakwater using a berm against the inside of the breakwater, based on a 1D XBeach Surfbeat simulation. The aim is to reduce the volume of sand required behind the breakwater, thereby freeing up sand on either side to improve the structure's durability.

The literature review indicates that studies by researchers [30,31] have conducted experimental and numerical modeling to investigate the impact of different breakwater configurations on the sediment accumulation ratio. The results showed that the distance between the breakwater and the shoreline is one of the most important factors influencing the variation in sediment accumulation for offshore breakwaters. They found that increasing the distance of the breakwater from the shoreline leads to a decrease in the amount of sediment deposits in the protected area. Longer breakwaters located closer to the coast tend to develop tombolos. In contrast, shorter breakwaters located far from the shoreline would form very small tombolos or even salients [32]. But their studies did not consider the effects of climate change. This justifies the validity of this article entitled "Contribution to the adaptation of the submerged dike of Avlékété to climate change in the Republic of Benin".

The objective of this article is to contribute to the innovative protection of the Avlékété coastline and the conservation of ecosystems by modeling the morphological changes of said coastline using the XBeach 1D software optimized, comparing several design scenarios, in order to allow the bathing activity planned by the Beninese authorities to take place on this site.

2. Materials and Methods

2.1. Description of the Avlékété Breakwater

The breakwater, whose adaptation to climate change is the subject of this study, is located on the Beninese coast in the village of Avlékété. The structure, designed to effectively protect the coastline, was built between 2018 and 2020. It is 5 km long, parallel to the coast, and 150 m offshore. In the years that followed, it suffered an unforeseen side effect: severe coastal erosion directly east of the breakwater. Due to the passage of time and the lack of regular maintenance, it became submerged by rising sea levels and lost its effectiveness [33], causing erosion that has spread further inland and threatens the coastal road. **Figure 1** below shows the current situation, with the erosion visible on the eastern side. **Figures 2** and **3** show the extent of erosion in 2018 and 2024, respectively. The shoreline has retreated approximately 100 m to the north since the construction of the breakwater was completed in 2020. Based on this trend, in a few years, erosion will have washed away the coastal road.

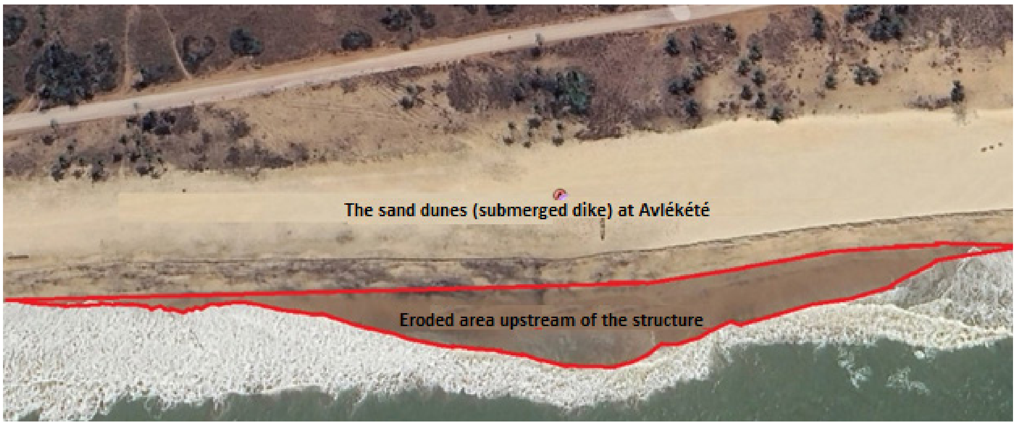


Figure 1. Submerged Avlékété Breakwater with Upstream Erosion in 2025.

Source: Babilas Hountondji.

Figure 2. Submerged Breakwater of Avlékété: Erosion in 2018.

Source: Babilas Hountondji.

Figure 3. Submerged Breakwater of Avlékété: Erosion in 2024.

Source: Babilas Hountondji.

2.2. Geographical Location of the Study Site

Information received from the Geographic Institute of Benin (IGN-Benin), Avlékété is one of the ten (10) districts of the commune of Ouidah, located in the southern part of Benin. Falling under the Atlantic department, it is west of Cotonou on the coastal strip along the sea. It is located between 6°19′ and 6°22′ North latitude and between 2°08′ and 2°18′ East longitude. It is limited to the north by the district of Pahou, to the south by the Atlantic Ocean, to the east by the commune of Abomey-Calavi, and to the west by the district of Djègbadji.

2.2.1. Relief

The district of Avlékété is part of the coastal plain relief, which is a complex of coastal strips separated by marshy lowlands and lagoons. It is crossed by the coastal lagoon, which covers an area of 12 km^2. **Figure 4** shows the geographical location of the commune of Avlékété.

2.2.2. Hydrography and Hydrogeology

The mapping carried out by the General Directorate of Water of Benin (DGEau-Benin) indicates that the study site is located in the district of Avlékété, which is characterized by a lake and lagoon system. The site is thus located between the Atlantic Ocean and the lagoon (specifically Lake Djessin). It is therefore located in the coastal strip, with a major part not subject to flooding. The flood zone has an area of approximately 7976 m^2, or less than 1% of the total surface area of the site (**Figure 5**).

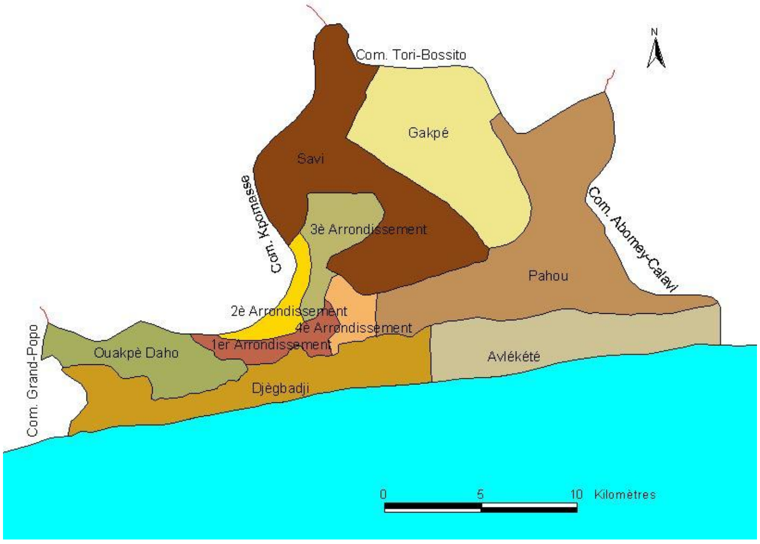


Figure 4. Geographic Location of the Commune of Ouidah.

Source: IGN-Benin.

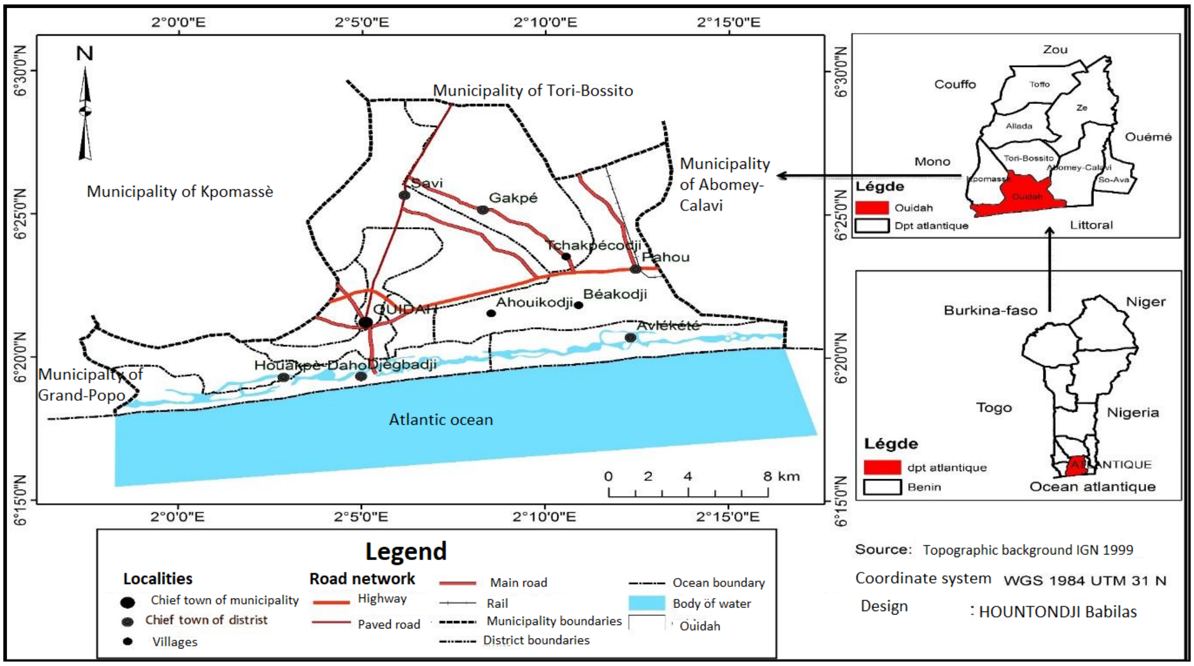


Figure 5. Avlékété Hydrographic Network.

Source: Babilas Hountondji.

2.2.3. Oceanography

- **Wave/Swell Regimes**

The wave climate along the study site located on the coast of Benin is dominated by S-SSW swell waves, specifically long-period, long-crested waves with narrow directional propagation produced by distant storms in the South Atlantic Ocean. Due to a "drawing" process associated with long-distance wave propagation, these waves have a relatively "uniform" appearance, with long-crested waves and relatively uniform wave amplitudes, periods, and directions. Persistent S-SSW swell conditions, combined with the orientation of the coastline, result in very high sediment transport along the shoreline from west to east. Local winds also produce "sea" waves, which are shorter in period, short-crested waves with high propagation. These waves, which are superimposed on top of the swell waves, have a highly irregular and complex appearance, with a range of amplitudes, periods, and wave directions. In general, sea waves are much smaller than swell waves. **Figure 6** shows a wave rose illustrating the distribution of waves offshore in different directions.

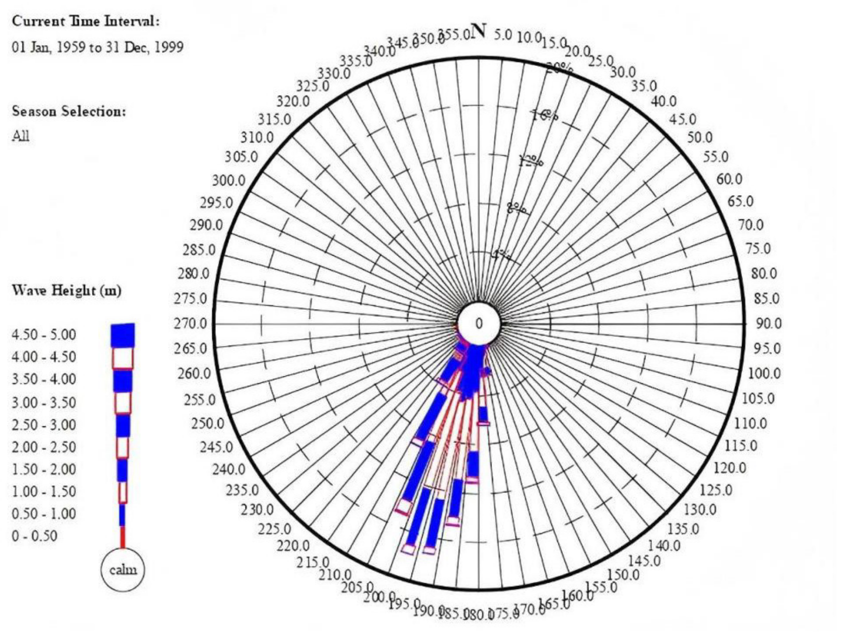


Figure 6. Wave Rose Offshore.

Source: MCVT-Benin.

The wave rose clearly illustrates the predominance of the SSW direction. Wave height (Hs) offshore ranges from 0.7 to 1.5 m (approximately 90% of the time), with a period (Tp) of 8 to 16 s (approximately 90% of the time). The maximum wave height for the 25-year period was Hs = 3.1 m (with a wave period Tp = 7.3 s), while the maximum period was Tp = 22 s (with a height Hs < 1.75 m). These results do not include locally generated waves; however, these short-period waves are of secondary importance compared to the longer and larger waves that dominate the wave climate in Benin. In general, the wave climate is mildest in the period from November to February, and most severe in July-August. An analysis of extreme values showed that offshore wave conditions could reach Hs = 3.5 m, with Tp = 14–18 s. Wave height increases as waves progress toward shallower waters; the maximum height they can reach is limited by water depth.

- **Tides**

The tides along the coast of Benin are semi-diurnal. They are characterized by two high tides and two low tides each day with almost equal amplitudes occurring at 12.5 h intervals. Nedeco/Delft (1983) provides a summary of tidal conditions along the Benin coast, based on British Admiralty tide tables. BCEOM (2002) and DANIDA/Ramboll (2003) both provide a summary of tidal levels in Cotonou, as shown in **Table 1**. Reference elevations are based on the hydrographic zero (ZH) and the National Geographic Institute (IGN) zero. The correspondence between these two levels is: IGN = ZH + 0.535 m.

Table 1. Tidal elevation.

Description	Elevation (mZH)
Mean high tide of spring tides (MHMVE)	1.8
Mean high tide during neap tides (MHMME)	1.0
Mean water level (MWL)	0.75
Mean low water at neap tide (MLWN)	0.4
Mean low tide during spring tides (MBMVE)	−0.2

Source: MCVT-Benin.

The tidal range during spring tides is therefore approximately 2 m (MHMVE = +1.8 m ZH, MBMVE = 0.2 m ZH). Local meteorological phenomena, such as the rise in water level associated with wind and/or high and low pressure, can lead to short-term local fluctuations in water levels.

- **Sediment Characteristics**

The beach in this area is highly segregated, with medium to coarse sand (D50 of 0.4 to 0.7 mm) confined to a steep upper beach above the average water level line. Flatter profiles of finer sand (D50 of 0.15 to 0.25 mm) are found offshore from this boundary.

2.3. Methodological Approach

The aim is to define the various considerations and simulations to re-evaluate the entire design proposed by the Ministry of Living Environment and Transport in charge of Sustainable Development (MCVT) in February 2023. These materials and methods will make it possible to update the wave time series with recent years, study transverse morphological stability, i.e., define the new expected transverse profile, study morphological stability along the coast, i.e., define the expected sediment flows and losses along the coast and the expected lifespan of the various enrichment components and study wave transmission, i.e., define the extent to which the design optimization (2025) reduces waves.

2.3.1. Different Considerations

- **Design Considerations**

The study is based on the development of the enrichment design proposed in February 2023 by the Ministry of Living Environment and Transport in charge of Sustainable Development (MCVT), based on the idea of accelerating the natural process of incorporation of the Avlékété breakwater and establishing a new balance. This basic design should allow for filling up to −2 m between the beach and the breakwater, adopting a sandy slope of 1:10 off the breakwater to reduce waves on it, creating a sand engine on the east side of the breakwater, and filling the west side of the breakwater with sand to create a smooth transition between the west coast and the breakwater. All for a total volume of 3.5 million m^3.

Figures 7 and **8** show the cross-section and perspective view of the basic solution proposed by the MCVT in February 2023, respectively.

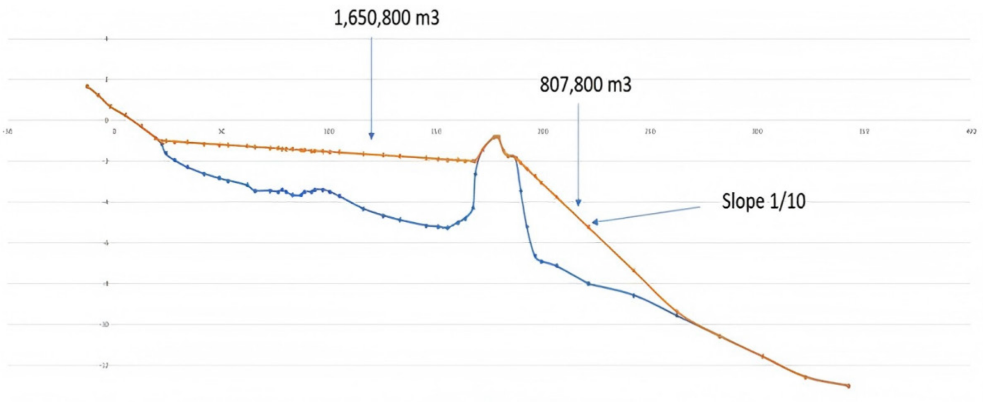


Figure 7. Proposed Cross-Section in February 2023.

Source: MCVT-Benin.

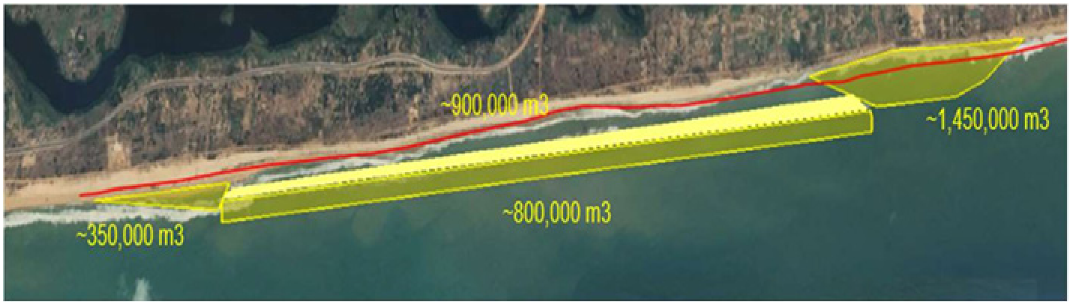


Figure 8. Proposed Perspective View in February 2023.

Source: MCVT-Benin.

- **Metoceanic Conditions**

A wave model composed of three nested grids (**Figure 9**) is used for the offshore-to-nearshore wave transformation performed internally to derive nearshore design wave conditions and nearshore operational/daily wave conditions.

- **Metoceanic Conditions—Design Waves**

Significant height is a statistical quantity used to characterize sea state. It is often abbreviated as Hs and represents the average height (measured between crest and trough) of one-third of the strongest waves. The period corresponding to the maximum spectral density is denoted Tp.

In order to define these two parameters for the Avlékété site, nine (09) locations were identified along the breakwater (**Figure 10**). The values for significant wave height (Hs) and spectral density (Tp) were obtained for location 05 and are summarized in **Table 2** below.

- **Metoceanic Conditions—Design Water Levels**

The following information was obtained from the WACA project along the Togo-Benin coast: Water level 1:1 year: +1.30 NMM and Water level 1:50 years: +1.45 NMM.

- **Operational Waves—Location 05**

The wind rose established in the study area is presented as shown in **Figure 11**.

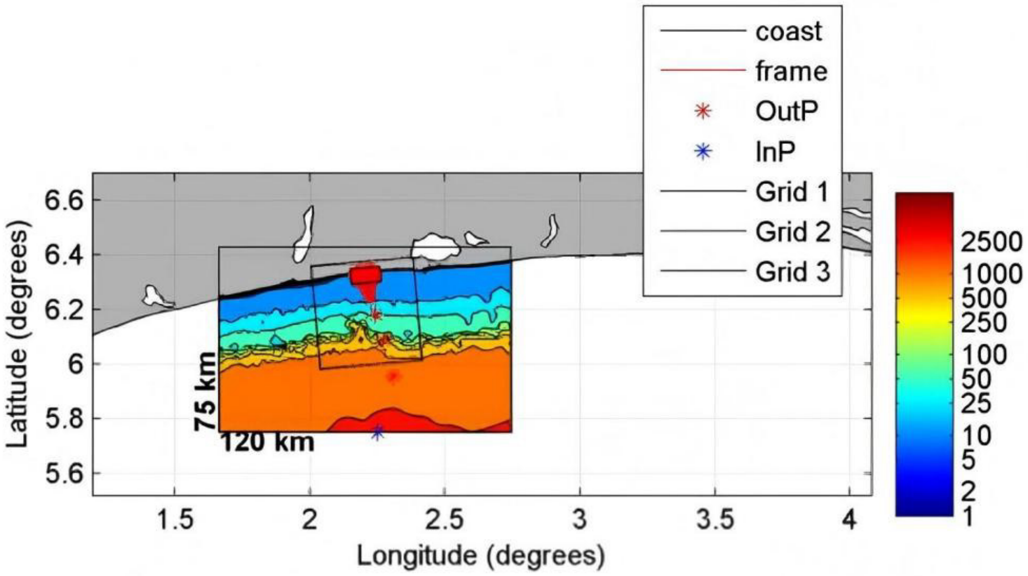


Figure 9. Bathymetry of the Grid A01.

Source: MCVT-Benin.

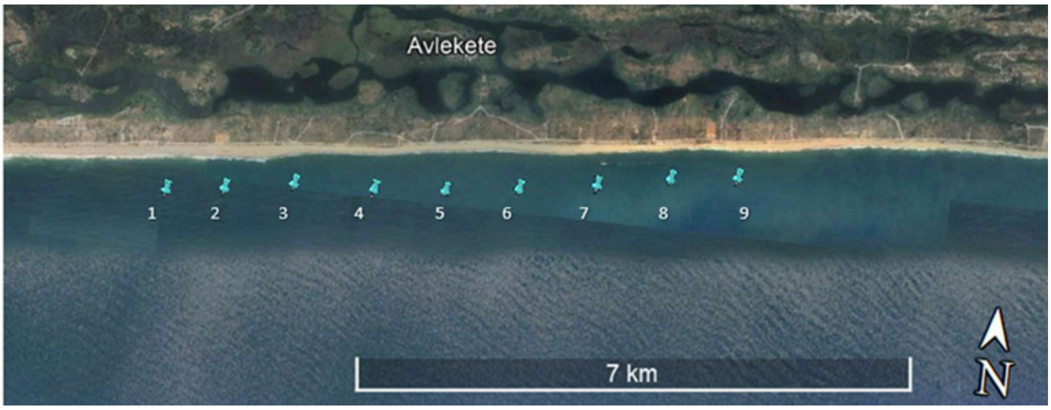


Figure 10. Map Showing the Location of Avlékété at Location 05.

Note: numbers 1–9 indicate nine (09) identified locations along the breakwater.

Source: MCVT-Benin.

Table 2. Values of significant height (Hs) and spectral density (Tp) in the study area.

Location 05—Avlékété																		
	Hs (Total Sea) (m)			**Hs (Wind Sea) (m)**			**Ass. Tp (Wind Sea) (s)**			**Wind Speed U10 (m/s)**			**Hs (Swell) (m)**			**Ass. Tp (Swell) (s)**		
RP	P10	Fit	P90	P10	Fit	P90	P10	P50	P90	P10	P50	P90	P10	Fit	P90	P10	P50	P90
1	2.08	2.16	2.25	1.54	1.68	1.84	5.31	6.28	8.18	11.64	12.53	13.42	1.95	2.05	2.17	12.88	15.76	17.75
5	2.22	2.36	2.56	1.78	1.98	2.22	5.39	6.43	8.45	15.18	16.44	17.50	2.11	2.26	2.43	13.45	16.85	18.47
10	2.26	2.44	2.67	1.86	2.09	2.37	5.40	6.45	8.48	16.44	17.50	19.49	2.16	2.32	2.52	13.72	17.29	18.65
50	2.35	2.58	2.93	2.02	2.30	2.66	5.41	6.47	8.51	19.49	19.49	n/a	2.24	2.44	2.69	14.41	18.18	18.96
100	2.37	2.63	3.03	2.07	2.38	2.77	5.41	6.47	8.51	19.49	19.49	n/a	2.26	2.48	2.75	14.75	18.47	19.75

Note: The actual values of significant height (Hs) and spectral period (Tp) used herein are, on average: Hs = 1.35 m and Tp = 14.5 s.

Source: MCVT-Benin.

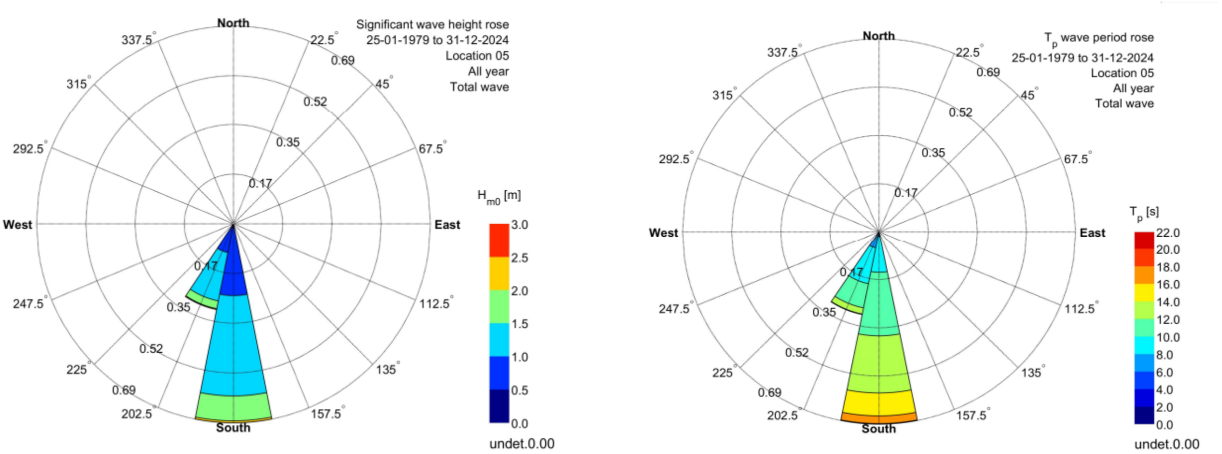


Figure 11. Wind roses in the locality of Avlékété at Location 05.

Source: MCVT-Benin.

2.3.2. Design Simulations

- **Morphology along the Coast**

Various scenarios were simulated using XBeach 1D in order to understand how the morphology of the coastline changes along a breakwater under various conditions, as this makes it possible to assess the impact of different factors such as swell, wind, and tides, and to anticipate the consequences on erosion or sediment accretion. This helps to make informed decisions about the design and management of protective structures. Four (04) scenarios were simulated. Design including a breakwater but without a lagoon (**Simulation 1**), which refers to a breakwater detached from the coastline that protects the shoreline by reducing wave energy, but is designed to allow better water circulation, thus preventing the creation of a stagnant or poorly exchanged water zone behind the structure. Design without a breakwater as a hard element, but with a lagoon (**Simulation 2**), which refers to a coastal protection approach that uses natural features such as lagoons to mitigate waves, rather than artificial structures such as concrete breakwaters. The goal is to protect the coastline using existing or created ecosystems, such as artificial reefs or mangrove areas, which reduce wave energy before it reaches the shore. Smooth design (the external appearance of the structure is harmonious, without any noticeable irregularities), including a breakwater but without a lagoon (**Simulation 3**), which describes a coastal structure where the breakwater is connected to the beach, either by a causeway or another structure, to prevent water from accumulating behind it and creating a lagoon. The smooth, wave-shaped structure allows waves to break, reducing their energy before they reach the shore, while preventing the accumulation of sediment that could create a lagoon. And a smooth design (the external appearance of the structure is harmonious, without any noticeable irregularities), including a breakwater and with a reduced wave height at the breakwater, but without a lagoon (**Simulation 4**), which means that an offshore structure is built to attenuate waves before they reach the shore, without creating calm water (lagoon) behind it. The aim is to reduce the force of waves over an area, allow sediment accumulation, and avoid the isolation effects of a lagoon.

- **Transverse Morphology**

In order to study the morphological stability of the transverse profile of the Avlékété breakwater, a one-dimensional XBeach simulation, Surfbeat mode, was carried out in the first two weeks of July 2024, with the most difficult wave conditions of the year. Thus, the design was re-evaluated and the transverse morphological stability studied while ensuring the reduction of waves. A simulation scenario of the cross-sectional profile of the breakwater using XBEACH 1D involves the following key steps, from data preparation to model execution, to model morphological changes under the effect of waves and extreme water levels, such as during a storm. The main objective is generally to simulate dune erosion, coastline retreat, or overtopping and flooding phenomena along the breakwater. This scenario takes into account the essential data for the model, i.e., topography and bathymetry, hydrodynamic boundary conditions, i.e., water level variation (tide, storm surge) over time, incident wave parameters (significant wave height, peak period, direction) at the open boundary of the model, sediment parameters, i.e., median grain size (D50): specific to the beach sediment, transport parameters: (if necessary, although the default parameters are often a good starting point), model configuration, simulation execution, and finally analysis of the results while comparing the initial profile to the final simulated profile. This scenario allows the effectiveness of coastal protection measures to be tested.

2.4. Using the XBeach Model

Since the Avlékété coastline is open, i.e., directly exposed to waves coming from the open sea, the XBeach 1D model is used to reproduce the wave transformation along the coastline and from the open sea (at a depth of 50 m) to the coast [34]. A calibration of the model is made for the morphology along the coastline between September 2018 and August 2024. As for the transverse morphology, the lack of "field" data concerning the erosion caused by different hydrodynamic conditions justifies the absence of calibration. It is necessary to simulate the effects of extreme events with XBeach 1D. This involves using the joint probability to determine a probable scenario of high-water level and waves, the statistical method of which is well known [35].

2.4.1. Model Overview

The XBeach (eXtreme Beach behavior) model is a numerical morphodynamic modeling tool for coastal areas. Its characteristics allow it to reproduce some of the phenomena occurring during storms, particularly dune erosion. XBeach is an open and free model. The source code, documentation, and test cases are available at www.xbeach.org. It was developed with funding and support from the US Army Corps of Engineers and a consortium including UNESCO-IHE, Deltares (Delft Hydraulics), Delft University of Technology, and the University of Miami.

The development of this tool became necessary for the Americans after the destructive passage of Hurricane Ivan (2004). The objective was to better predict the effects of storm events on sandy coasts and dune ridges. It is a constantly evolving tool that is used by a growing community of users and a dynamic group of developers. It simulates the physical processes that dominate the behavior of beach/dune systems during storms. This model makes it possible to process coastal phenomena for areas whose maximum extension is a few hundred meters, with a minimum resolution of the order of a meter.

The model can be used in 1D, i.e., according to a cross-shore profile, perpendicular to the coastline. But it is mainly designed to reproduce phenomena in 2DH mode (considering processes parallel to the coast and vertical processes integrated vertically). It solves the equations of wave propagation, unsteady Saint-Venant, transport, and sediment conservation (evolution of the seabed). These equations can be coupled in different ways.

Its particularity lies, among other things, in the improvement of the modeling of the shore jet, which considers the effects of infragravity waves. The circulation of the littoral in the coastal fringe is calculated by the model, which makes it possible to evaluate the sediment transport and the morphological evolutions: erosion, silting, submersion of dunes or reefs during intense meteorological events. The phenomena considered in the wave equation of the waves, also called the short-wave action equilibrium equation, are the propagation of the waves, the bathymetric refraction, the refraction due to the currents, and the breaking. Diffraction is not resolved.

Regarding the evolution of morphology, the phenomenon of sand grain avalanches is considered during dune erosion episodes caused by storms. In addition, XBeach allows the treatment of different sedimentary classes and the definition of non-erodible zones. It offers the possibility of considering processes linked to the water table, which makes it possible to consider infiltration and exfiltration phenomena that play a role in the intensification or reduction of currents in the shore jet zone.

This type of model remains a research code in development and in the improvement phase, but it nevertheless allows specific work of simulating dune erosion during storms.

2.4.2. Implementation of XBeach 1D

The XBeach numerical model testing work was initiated by a series of simulations carried out for simplified beach profiles. For each example, the beach profile is constructed from an assembly of topographic and bathymetric data. The data is simplified to consider the main morphological structures. These are therefore not real cases composed of homogeneous morphological data and measurements with maximum precision. However, the tested cases must illustrate the diversity of soft coastal environments encountered.

This modeling work appears as a preliminary approach to more in-depth work to estimate the maximum dune retreat Lmax. First, it is assumed that Xbeach can relatively correctly reproduce the erosion of the upper beach and the dune under storm conditions for cross-shore processes. In this simplifying approach, it lacks consideration of processes parallel to the coast, which can have dominant effects depending on the coastal environments studied. In addition, working on simplified coastal environments does not allow for fine calibration of XBeach by adjusting the different parameters of the model to a set of real data and observations. On the other hand, it should be noted that the implementation of this type of model for real cases requires a calibration phase, based on topobathymetric and hydro-sedimentary data collected before, after (or even during) one or more storm events.

The work implemented in this study uses the most recent version of XBeach (XBeach_v1.21.3657_Groundhog_Day) distributed in February 2014. This latest version considers a new formulation for wave boundary conditions and also makes it possible to resolve certain problems concerning the inflow induced by long waves following the orientation of the model grid. This version was implemented on the BRGM computer in parallel mode in order to optimize calculation times.

For the methodological tests, the choice was made to use the same internal model settings for the different schematic beach profiles. As a first approach, XBeach is therefore used without calibration, with its default values or with those recommended by the Deltares XBeach community (**Table 3**).

Table 3. Summary of the main settings of the XBeach model implemented for the simplified cases.

Parameters	Values
D_{50}—middle grain	0.6 mm
Smax—Shields parameter	1
Cf—coefficient of friction at the bottom	44.3 $m^{1/2}/s$
Morfac —morphological acceleration	1
form—sediment transport formula	2
muhv— factor for horizontal viscosity	1
facua—sediment transport induced by wave asymmetry	0.1
dryslp— −+ Avalanche slope in the air	1
wetslp—critical avalanche slope in a submerged domain	0.3
eps—threshold water thickness between dry and wet meshes	0.005 m
hmin—minimum depth for return current	0.2 m
dzmax—maximum erosion rate of the dune by the return phenomenon	0.5 m^2/s
hswitch—threshold depth between “dryslp” and “wetslp”	0.1 m
γ surge parameter (Roelvink formula)	0.55
n—power of Roelvink’s formula	10

Certain parameters were defined specifically for this series of tests: the maximum value of the Shields parameter (smax) was set to 1, based on studies referenced with XBeach and following discussions with the Deltares XBeach community; the bottom friction coefficient for flow (cf) was set to 0.005, which translates to a Chézy coefficient of:

$$\sqrt{\frac{g}{cf}} = 44.3\ m^{1/2}/s$$

and the morphological acceleration parameter (morfac) considered is 1, so that the evolution of the bottom is calculated at each hydrodynamic calculation time step.

The median grain size (D50) is set at 0.6 mm for each case. For each simulation, a model initialization time is required; here, it is 20 min. During this start-up phase, the values assigned to the various model variables gradually change under the action of the physical processes included in the model to reach the typical values of the studied area. This period is not considered in the proposed analyses. Once the initialization period has passed, the model outputs are set at a time step of 10 min.

3. Results

3.1. Results on Morphology along the Coastline

Calibration on the Morphology along the Coastline

The results of the calibration on the development of the coast between September 2018 and August 2024 are presented in **Figure 12**.

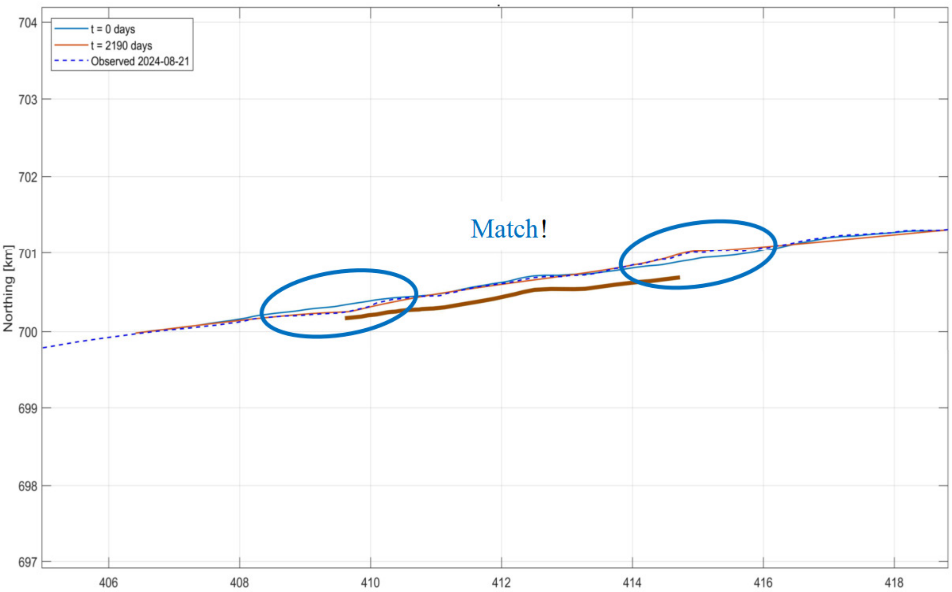


Figure 12. Calibration for morphology along the Avlékété coastline.

Figure 12 shows that there is a correspondence between the observed and modeled coastal changes at both ends of the breakwater. It also shows a sediment flux along the coast of the adjacent coastal reaches (700,000 m^3/year) and a sediment flux along the coast sheltered by the breakwater (350,000 m^3/year).

- **Simulation 1: Design including a breakwater but without a 'lagoon'**

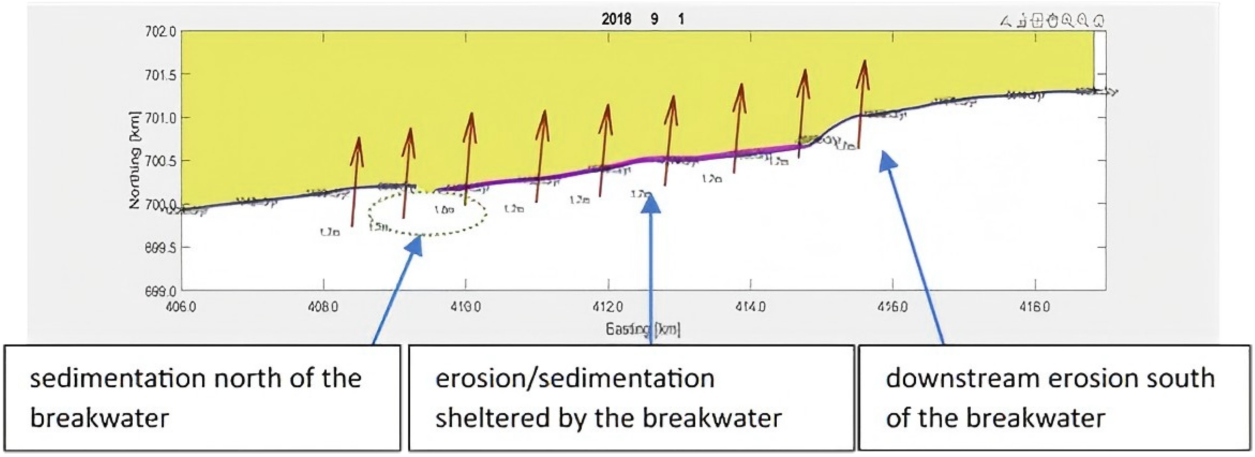
The results of **Simulation 1** are shown in **Figures 13** and **14**.

The results of **Simulation 1** for the year 2018 show that to the north of the end of the breakwater, sedimentation is observed with a volume varying between 889 and 1487 m^3/year, that in the shelter of the breakwater along the coast, erosion/sedimentation is observed with respective volumes of the order of 1578 m^3/year and 727 m^3/year, that to the south at the end of the breakwater, erosion is observed downstream with a volume of the order of 2885 m^3/year and that the wave height varies between 1.7 m and 1.8 m along the breakwater while the results of the same simulation for the year 2024, that is to say five (05) years later, show that to the north of the end of the breakwater, sedimentation is observed with a volume varying between 687 and 691 m^3/year, that in the shelter of the breakwater along the coast, there is erosion/sedimentation with respective volumes of the order of 527 m^3/year and 647 m^3/year and that to the south at the end of the breakwater there is erosion downstream with a volume of the order of 745 m^3/year. As for the wave height, it is noted that it varies between 1.5 m and 1.6 m along the breakwater.

- **Simulation 2: Design not including a breakwater but with a 'lagoon'**

The results of **Simulation 2** are shown in **Figures 15** and **16**.

The results of **Simulation 2** for the year 2018 show that to the north of the end of the breakwater, sedimentation is observed with a volume varying between 522 and 1140 m^3/year, that in the shelter of the breakwater along the coast, erosion/sedimentation is observed with respective volumes of the order of 1837 m^3/year and 1204 m^3/year, that to the south at the end of the breakwater, sedimentation is observed downstream with a volume varying between 1071 m^3/year and 1880 m^3/year and that the wave height varies between 1.7 m and 1.8 m along the breakwater, while the results of the same simulation for the year 2020, i.e., three (03) years later, show that to the north of the end of the breakwater, erosion is observed with a volume of around 384 m^3/year, that in the shelter of the breakwater along the coast, there is erosion/sedimentation with respective volumes of around 467m^3/year and 477 m^3/year and that to the south at the end of the breakwater there is an established connection and that the wave height is 1.1 m along the breakwater. There is a reduction in the rates of sedimentation, erosion, and wave height along the breakwater from 2018 to 2020.

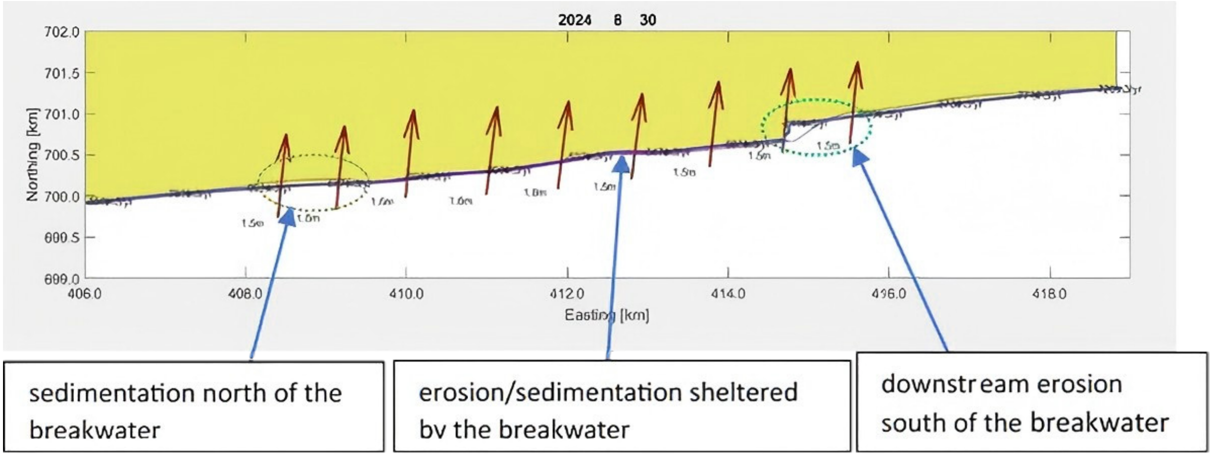


sedimentation north of the breakwater

erosion/sedimentation sheltered by the breakwater

downstream erosion south of the breakwater

Figure 13. Simulation results for the year 2018.

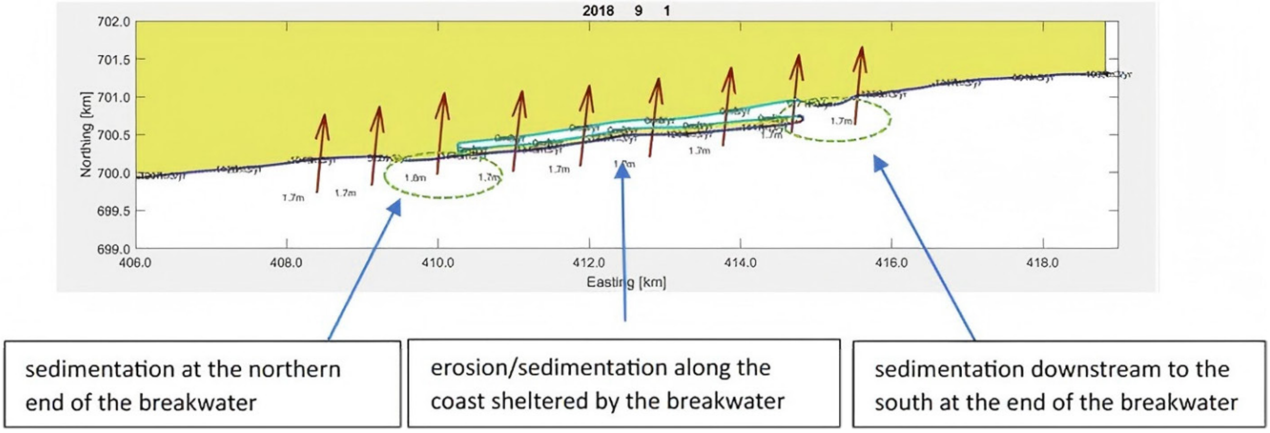


sedimentation north of the breakwater

erosion/sedimentation sheltered bv the breakwater

downstream erosion south of the breakwater

Figure 14. Simulation results for the year 2024.

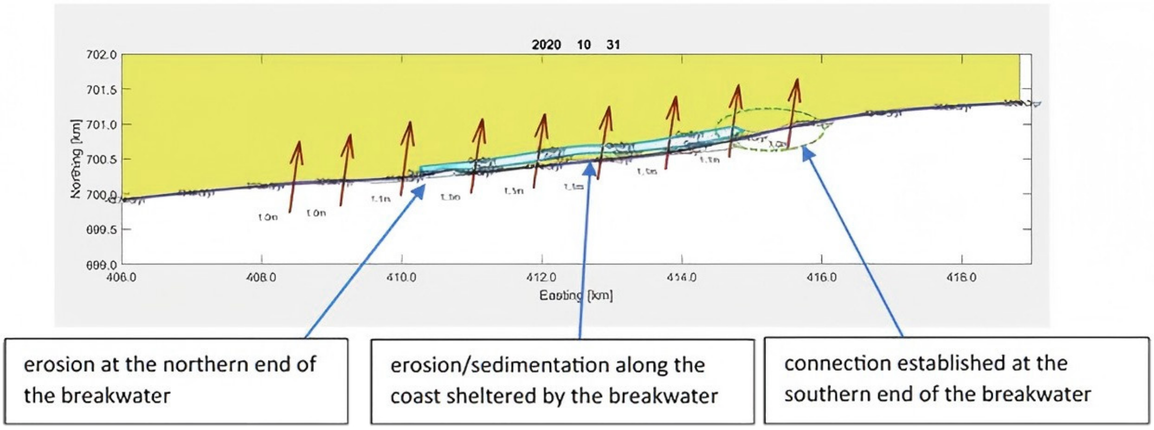


sedimentation at the northern end of the breakwater

erosion/sedimentation along the coast sheltered by the breakwater

sedimentation downstream to the south at the end of the breakwater

Figure 15. Simulation results for the year 2018.



erosion at the northern end of the breakwater

erosion/sedimentation along the coast sheltered by the breakwater

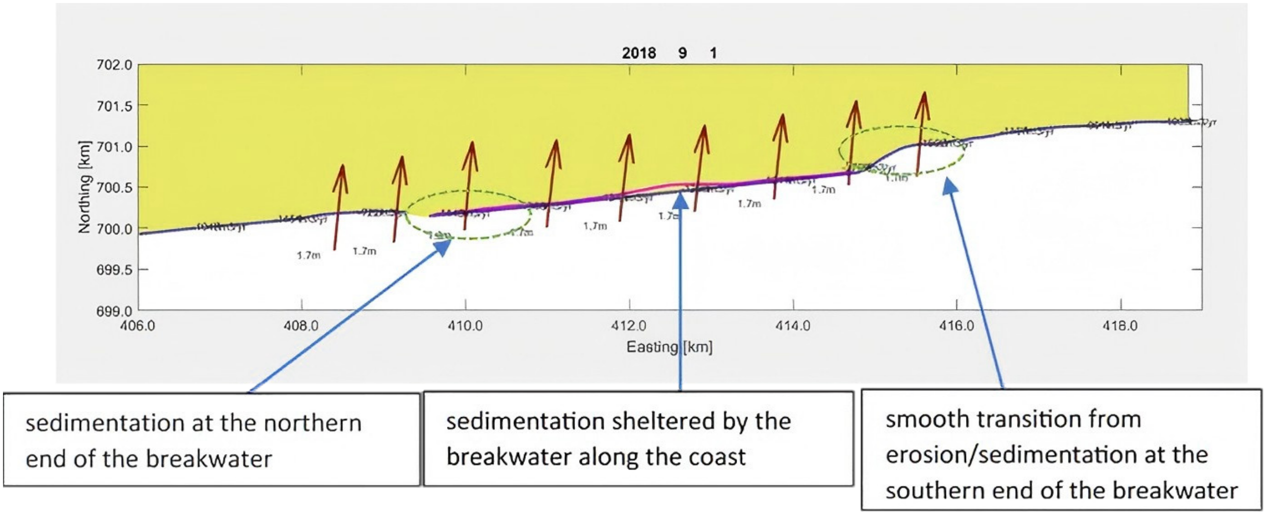
connection established at the southern end of the breakwater

Figure 16. Simulation results for the year 2020.

- **Simulation 3: Smooth coast design including a breakwater but without a 'lagoon'**

The results of **Simulation 3** are shown in **Figures 17** and **18.**

The results of **Simulation 3** for the year 2018 show that to the north of the end of the breakwater, sedimentation is observed with a volume of around 1145 m^3/year, that in the shelter of the breakwater along the coast, sedimentation is observed with a volume varying between 1298 m^3/year and 1343 m^3/year, that to the south at the end of the breakwater, a smooth erosion/sedimentation transition is observed with respective volumes of around 2779 m^3/year and 1502 m^3/year and that the wave height varies between 1.7 m and 1.8 m along the breakwater, while the results of the same simulation for the year 2024, i.e., five (05) years later, show that to the north of the end of the breakwater, sedimentation is observed with a volume of the order of 700 m^3/year, that in the shelter of the breakwater along the coast, there is erosion/sedimentation with respective volumes of the order of 465 m^3/year and 720 m^3/year and that to the south at the end of the breakwater there is erosion downstream with a volume of the order of 1030 m^3/year and that the wave height varies between 1.5 m and 1.6 m along the breakwater. There is a reduction in sedimentation, erosion, and wave height rates along the breakwater from 2018 to 2024.

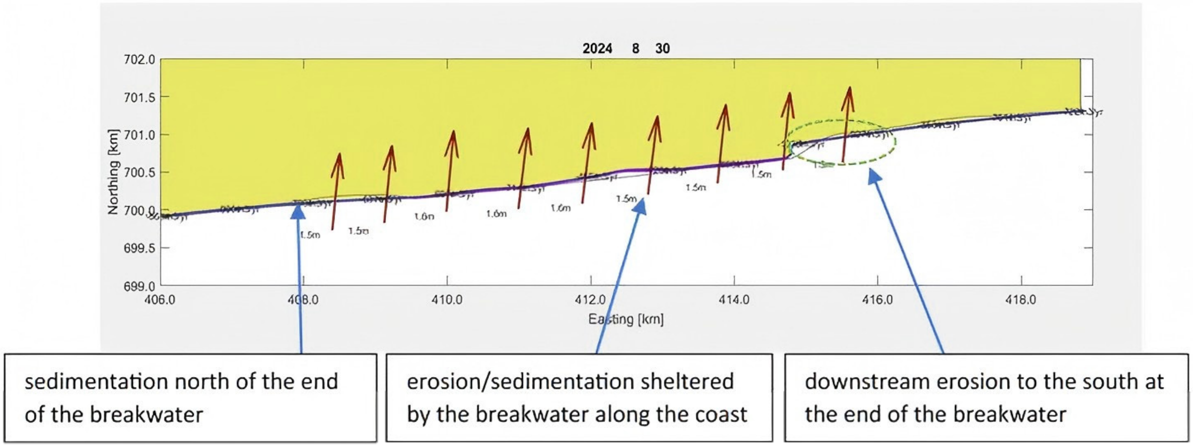


sedimentation at the northern end of the breakwater

sedimentation sheltered by the breakwater along the coast

smooth transition from erosion/sedimentation at the southern end of the breakwater

Figure 17. Simulation results for the year 2018.



sedimentation north of the end of the breakwater

erosion/sedimentation sheltered by the breakwater along the coast

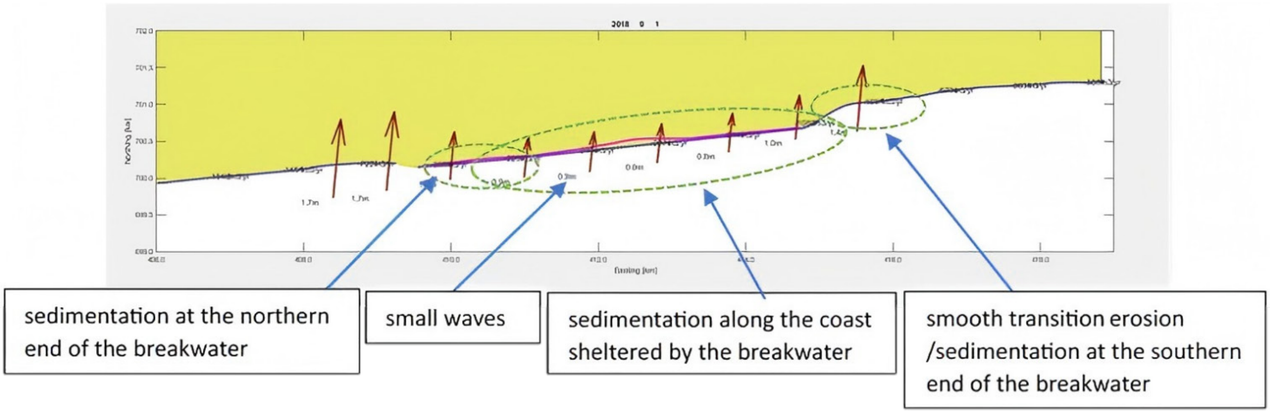
downstream erosion to the south at the end of the breakwater

Figure 18. Simulation results for the year 2024.

- **Simulation 4: Smooth Coast Design not Including a Breakwater but with 'Lagoon', Reduced Waves**

The results of **Simulation 4** are shown in **Figures 19** and **20**.

The results of **Simulation 4** for the year 2018 show that to the north of the end of the breakwater we observe sedimentation with a volume of around 308 m^3/year, that in the shelter of the breakwater along the coast, we witness sedimentation with a volume varying between 240 m^3/year and 227 m^3/year, that to the south at the end of the breakwater we observe a smooth erosion/sedimentation transition with respective volumes of around 1033 m^3/year and 1007 m^3/year and that the wave height varies between 0.8 m, 0.9 m, and 1 m along the breakwater while the results of the same simulation for the year 2024, that is to say five (05) years later, show that to the north of the end of the breakwater we observe sedimentation with a volume of the order of 239 m^3/year, that in the shelter of the breakwater along the coast, there is sedimentation with a volume of the order of 199 m^3/year and that to the south at the end of the breakwater there is erosion downstream with a volume of the order of 925 m^3/year and that the wave height varies between 0.8 m and 0.9 m along the breakwater. There is a reduction in sedimentation, erosion, and wave height rates along the breakwater from 2018 to 2024. The large arrows pointing toward the shore in **Figures 13–20** represent an inflow of energy and current caused by the swell. They indicate that the swell and current are moving toward the coast, causing coastal erosion and sand displacement in that direction. These arrows are a visual representation of the phenomenon of sediment transport initiated by the action of the swell.



sedimentation at the northern end of the breakwater

small waves

sedimentation along the coast sheltered by the breakwater

smooth transition erosion /sedimentation at the southern end of the breakwater

Figure 19. Simulation results for the year 2018.

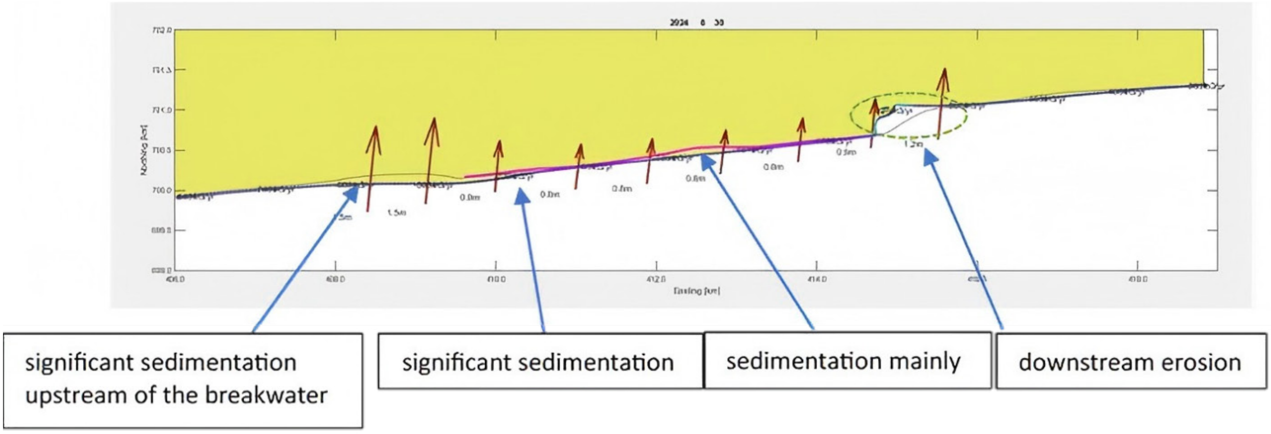


Figure 20. Simulation results for the year 2024.

3.2. Results on Transverse Morphology

3.2.1. Cross-Section of the Optimized Design: February 2025

This section (**Figure 21**) shows a −2 m embankment between the beach and the breakwater optimized into a 50 m wide berm at −1 m against the inside of the breakwater. This results in a reduced volume of sand required behind the breakwater, allowing sand volume to become available on either side of the breakwater to improve the sustainability of the proposed measures.

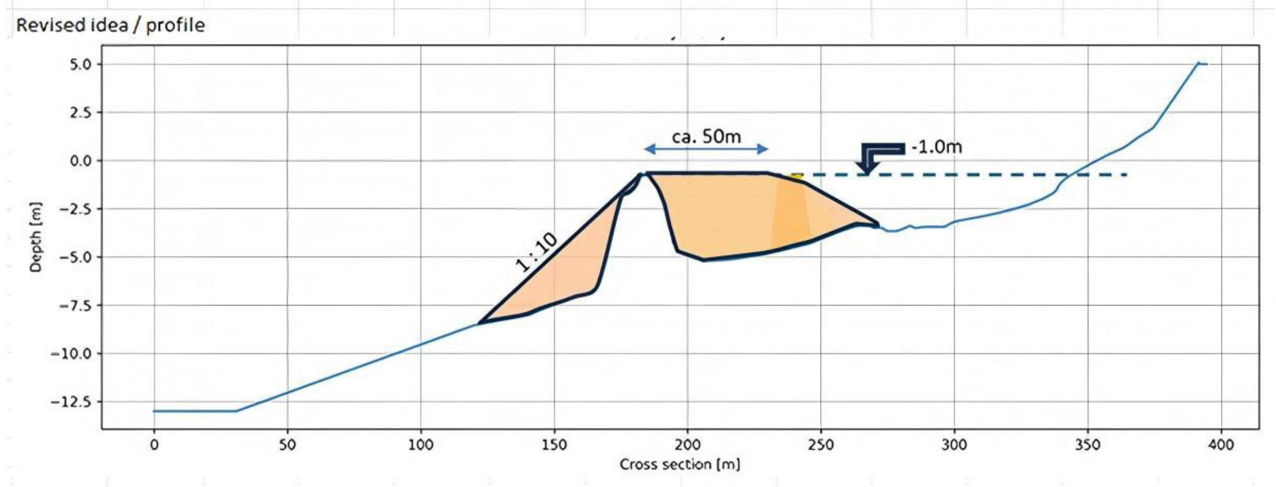


Figure 21. Cross-section of the optimized design (February 2025).

3.2.2. Evaluation of Wave Reduction

The results of the wave reduction assessment are presented here for the current situation, the proposed design for 2023 (**Option 1**), and the revised design for 2025 (**Option 2**). The following values for significant height Hs = 1.35 m, spectral density Tp = 14.5 s, and water levels of 0 and 0.75 m were used.

Figures 22 and **23** show the bed levels and wave heights for the current situation, the proposed design for 2023 (**Option 1**), and the revised design for 2025 (**Option 2**), respectively, for water levels of 0 and 0.75 m.

3.2.3. Transverse Morphology: Result after 14 Days (Revised Model)

Figure 24 below shows the results in the first two weeks of July 2025, with the most difficult wave conditions of the year. This figure shows that this is a temporary morphological stability under conditions of intense waves and that erosion at sea compromises the structural integrity of the breakwater.

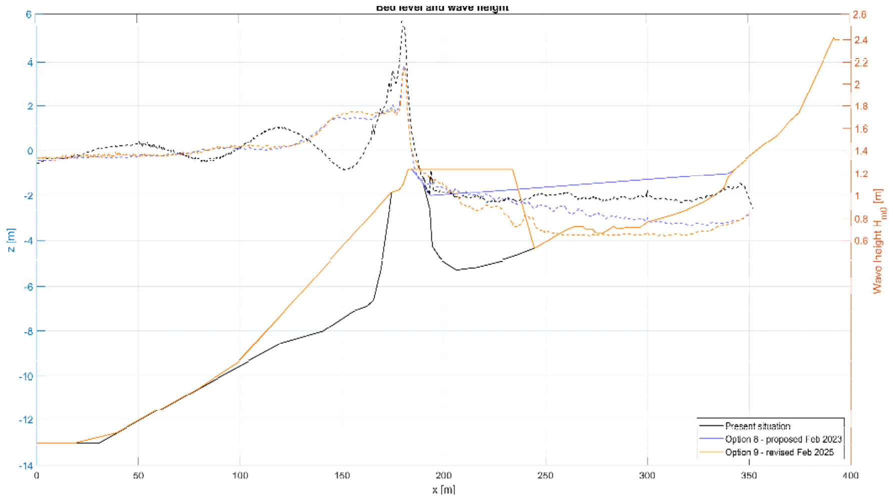


Figure 22. Bed level and wave heights for a water level of 0 m.

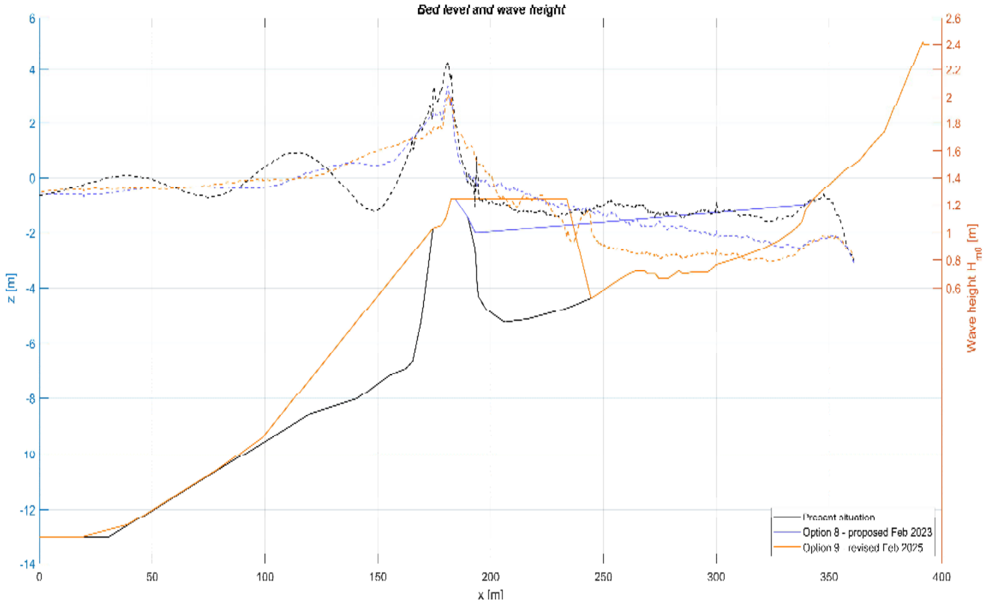


Figure 23. Bed level and wave heights for a water level of 0.75 m.

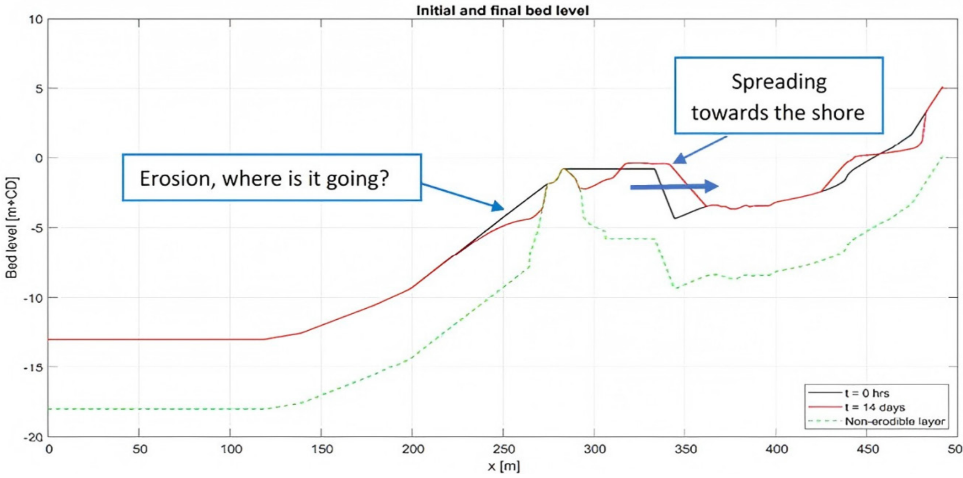


Figure 24. Erosion upstream of the breakwater after 14 days (revised model).

4. Discussion

4.1. Discussion on Morphology along the Coastline

The results of **Simulations 1**, **2**, **3**, and **4** allow us to conclude a reduction in the rates of sedimentation, erosion, and wave height along the breakwater from 2018 to 2024. The comparison of the values obtained in terms of volume for sedimentation and erosion, and in terms of wave height for the four simulations, both in 2018 and in 2024, shows that only **Simulation 4** presents low values for the volumes of sedimentation and erosion and height for waves. This allows, in view of the calibration carried out, confirming the correspondence between the observed and modeled coastal changes at the two ends of the breakwater, to retain **Simulation 4** smooth design, including a breakwater and with a reduced wave height at the breakwater, but without a "lagoon" as the most appropriate approach. The effectiveness of the combination of **Simulation 4** to reduce erosion retreat is undeniable at the Avlékété dike, and similar results confirm it [36].

4.2. Discussion on Transverse Morphology

Figures 22 and **23** shows that the revised design achieves expected reductions that are as follows: reduction in wave height compared to the current situation (27 to 34%), reduction in wave energy compared to the current situation (47 to 57%), reduction in wave height compared to the proposed Option 8 (15%), reduction in incoming wave height (38 to 52%) and reduction in incoming wave energy (61 to 77%). The recent study on the identification of sedimentary stocks at sea and hydro-sedimentary modeling along the western coast of the Miquelon-Langlage isthmus [37] considered two scenarios: beach replenishment and foreshore replenishment. The scenarios were designed based on the recommendations of the CEREMA study report [38]. The area to be replenished extends over a length of approximately 2 km between PK15, to protect the section of the natural dune cordon that has receded significantly due to the edge effect of the structure, and PK17, where the riprap section begins in the south. The simulated replenishments for the foreshore (**Scenario A**) and the beach (**Scenario B**) are shown in **Figures 25** and **26.**

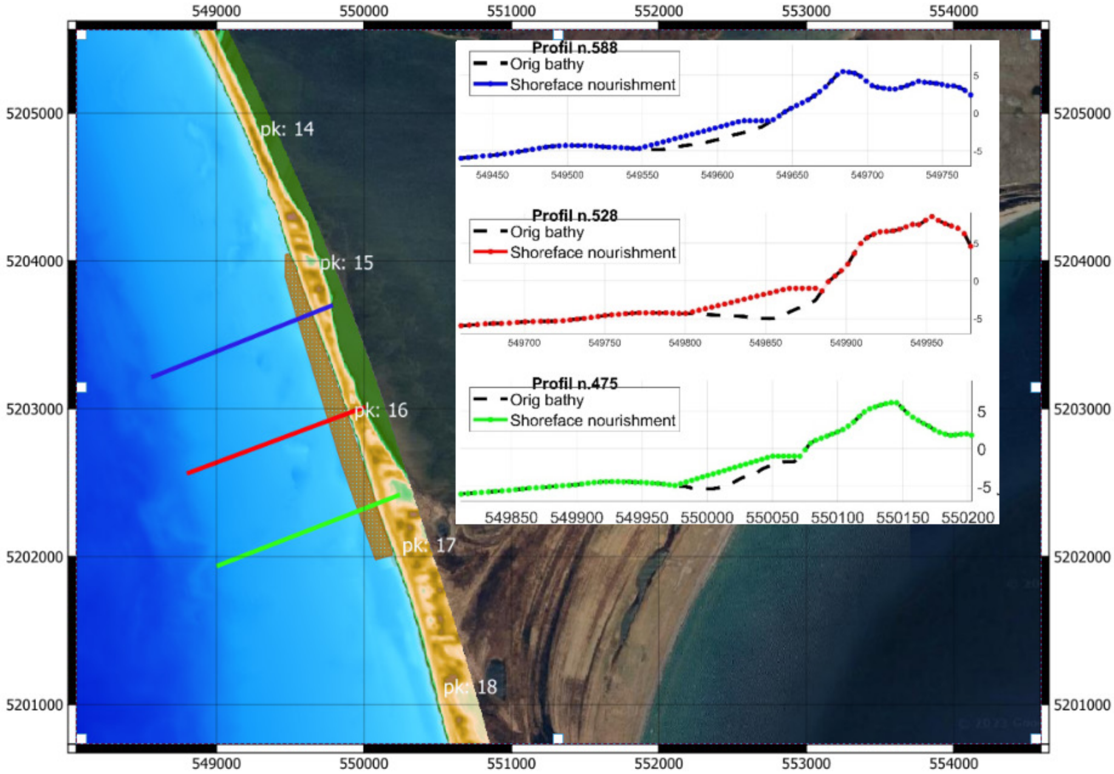


Figure 25. Modeled beachfront recharge scenario.

Note: Three representative cross-sectional profiles are extracted (blue, red, and green) from the simulated area [37].

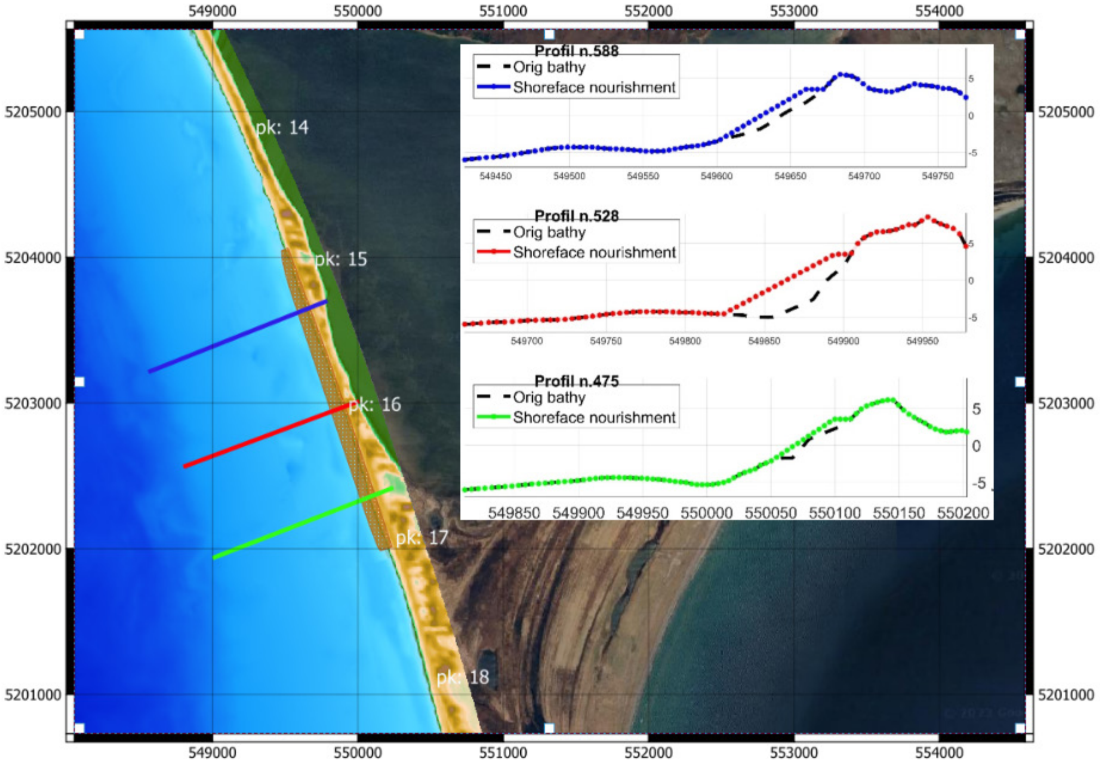


Figure 26. Modeled beach replenishment scenario.

Note: Three representative cross-sectional profiles are extracted (blue, red, and green) from the simulated area [37].

The initial and simulated profiles shown in **Figures 25** and **26** show the absence of berms (dune reinforcement) toward the land, unlike the initial and simulated profiles observed in **Figures 22, 23,** and **26**. This indicates the added value of this article.

Figure 24 shows that after 14 days on the revised model, the erosion phenomenon observed at sea presents structural risks because we observe a limited restructuring of the beach, a propagation towards the shore, and therefore an erosion of the breakwater. These observations allow us to say that the profile presented is not final and that it is only a temporary morphological stability profile. The XBeach 1D model, without the calibration phase, shows an underestimation of erosion at sea. The lack of "field" data concerning erosion does not allow us to conclude on the stability of the profile. This observation highlights the interest of calibrating the model.

5. Conclusions

In this study, we simulated the impact of climate change on port infrastructure, particularly breakwaters, using the one-dimensional XBeach model, Surfbeat mode. The first results regarding the morphology along the coastline, fulfill the initial objectives of the study which consisted of contributing to the innovative protection of the Avlékété coastline and the conservation of ecosystems through optimized 1D XBeach simulations comparing several design scenarios, because of the four (04) simulations carried out (**Simulation 1**: design including a breakwater but without 'lagoon'; **Simulation 2**: design without breakwater as a hard element but with lagoon; **Simulation 3**: smooth design including a breakwater but without 'lagoon'; **Simulation 4**: smooth design including a breakwater and with a reduced wave height at the breakwater but without 'lagoon'), **Simulation 4** presents the lowest erosion and sedimentation volumes and wave heights and therefore constitutes the most appropriate approach confirmed by the model calibration. As for the transverse morphology, the observed reduction in wave height and energy is not sufficient to confirm the achievement of the objectives. The 1D XBeach model, without a calibration phase used, not taking into account coastal sediment transport, shows an underestimation of sea erosion, which presents structural risks for the breakwater. The profile presented is not final and is only a temporary morphological stability profile. That is to say, a short-term adaptation (14 days) and does not allow extrapolation of processes to the scale of a storm or ten-year period. Therefore, the future adoption of 2DH simulations will be necessary for long-term stability and probabilistic risk assessment.

The proposed sand filling will accelerate nature's own processes to achieve a new coastal transport balance. This sand filling will have virtually no impact on local communities as it will only take place offshore. Fishermen will retain access to the sea, and construction activities on land will be limited to the temporary use of a limited area for the storage of pipelines, auxiliary equipment, and a few office containers. This sand filling will also allow for the swimming activity planned by the Beninese authorities on this site, and also ensure the temporary conservation of the ecosystems in this environment. It should be noted that this chosen sand filling profile is not definitive, and further studies will need to be conducted to define the typical profile that will truly adapt the submerged Avlékété dike to climate change.

Author Contributions

Conceptualization, B.H. and L.K.A.; methodology, B.H., L.K.A. and F.d.P.C.; validation, B.H., F.d.P.C. and M.P.A.; investigation, B.H.; resources, B.H. and L.K.A.; writing—original draft preparation, B.H.; writing—review and editing, M.P.A., F.d.P.C. and L.K.A.; supervision, B.H.; project administration, B.H.; All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

The study does not require ethical approval.

Informed Consent Statement

Not applicable.

Data Availability Statement

The authors agree to share their research data upon request.

Conflicts of Interest

The authors certify that there is no conflict of interest to declare.

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