Open Journal of Marine Science, 2025, 15(2), 100-113
https://www.scirp.org/journal/ojms
ISSN Online: 2161-7392
ISSN Print: 2161-7384

Numerical Modeling of Swell Transformation as It Approaches the Coast of Pointe-Noire

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How to cite this paper: Ndzessou, W.B., Etou, D.G., Bockou-Ekockaut, J.A. and Tathy, C.A.A. (2025) Numerical Modeling of Swell Transformation as It Approaches the Coast of Pointe-Noire. *Open Journal of Marine Science*, **15**, 100-113.
https://doi.org/10.4236/ojms.2025.152006

Received: February 28, 2025
Accepted: April 26, 2025
Published: April 29, 2025

Abstract

The aim of this paper was to describe the behavior of swell and its effects immediately offshore and along the coast of Pointe-Noire in the Republic of Congo, using the CMS-Wave model. This is a spectral wave forecasting model based on the wave action equilibrium equation and represents the two-dimensional variation of wave energy. The aim of this study was to understand the directional spectrum of wave energy and its impact on the dynamics of the coastal system in this area. The various test cases showed that the frontal incidence swell has similar effects to the non-frontal incidence swell in the northwest direction, with a slight amplification of wave height as it approaches the coast. For non-frontal swell in the south-westerly direction, wave heights are amplified as they approach the coast. This is because the coastal zone of Pointe-Noire does not receive wave energy in the counter-clockwise direction between 80˚ and 275˚. The swell responsible for the greatest drift observed in this zone is coming from the southwest. As they pass through the immediate coastal zone of Pointe-Noire, waves tend to move northwards. A comparison of wave heights was made between the values obtained by the model and those predicted by marine weather spots on June 23rd and 24th, 2024, for validation purposes. The results obtained show that the model simulates waves reasonably well.

Keywords

Modeling, Swell, Waves, CMS-Wave, Coastal Zone, Pointe-Noire

1. Introduction

The Pointe-Noire coastal zone is the scene of a moving spectacle caused by swells that originate off the North Atlantic and South Atlantic, propagating to finish their course on the Pointe-Noire coast. These swells have a considerable impact on the dynamics of the coastal process in this area [1]. Their impact can be seen in the excessive silting of the port access channel and erosion in Louango Bay [2]-[4]. Previous swell-related studies carried out in the Pointe-Noire coastal zone have focused on the annual distribution of mean wave heights over the coastal area. These studies stipulate that the swells observed in this area originate from the southwest [2].

Numerical wave modelling would enable us to understand the phenomena linked to these dynamics in this area [5]-[7].

The latest advances in computing and access to high-capacity memories have had a considerable impact on the field of numerical modelling of coastal processes [8] [9]. Their use has made it possible, among other things, to remove the difficulties encountered in setting up physical models and to predict possible disturbances to port activities linked to silting and waves [7] [10]-[13].

The aim of this article is to model the behavior and effects of swells as they approach the Pointe-Noire coast. The approach consisted of propagating project swells to the boundaries from off the coast, in order to analyze the resulting phenomena in real-time using satellite bathymetric data from the GEBCO range (NOAA). This operation was made possible thanks to the CMS-Wave spectral model from the Aquaveo group.

2. Materials and Methods

2.1. Presentation of the Study Area

The coastal zone covered by this study is 170 km long, including the Port Autonomous Guinea at 4˚67 south and 11˚97 east. It is oriented on average at 320˚ - 140˚ (**Figure 1**) in front of a continental shelf over 40 km wide [1] [14]-[16].

2.2. Data Used

2.2.1 Bathymetry

The effectiveness of numerical flow modeling in coastal areas depends on the accuracy of the bathymetric data. The bathymetric data used in this study were provided by the General Bathymetric Chart of the Oceans, grid GEBCO_08. This is a global terrain model for ocean and land at intervals of 30 arc seconds (**Figure 2**) [3].

2.2.2. Wind

The wind data used for the simulations are those predicted by the De Glisse and Ça-Baigne marine weather forecasts. They provide hourly wind speed and direction at 10 m above the water surface. A series of sampling data collected over 23 hours (0h to 22h) and 7 consecutive days by the Ça-Baigne weather station was used in the validation section. The wind characteristics used were speed in m/s and direction in deg. These values can be checked via the following links:
https://marine.meteoconsult.fr/meteo-marine/bulletin-detaille/spot-de-glisse-5623/previsions-meteo-pointe-noire-aujourdhui.

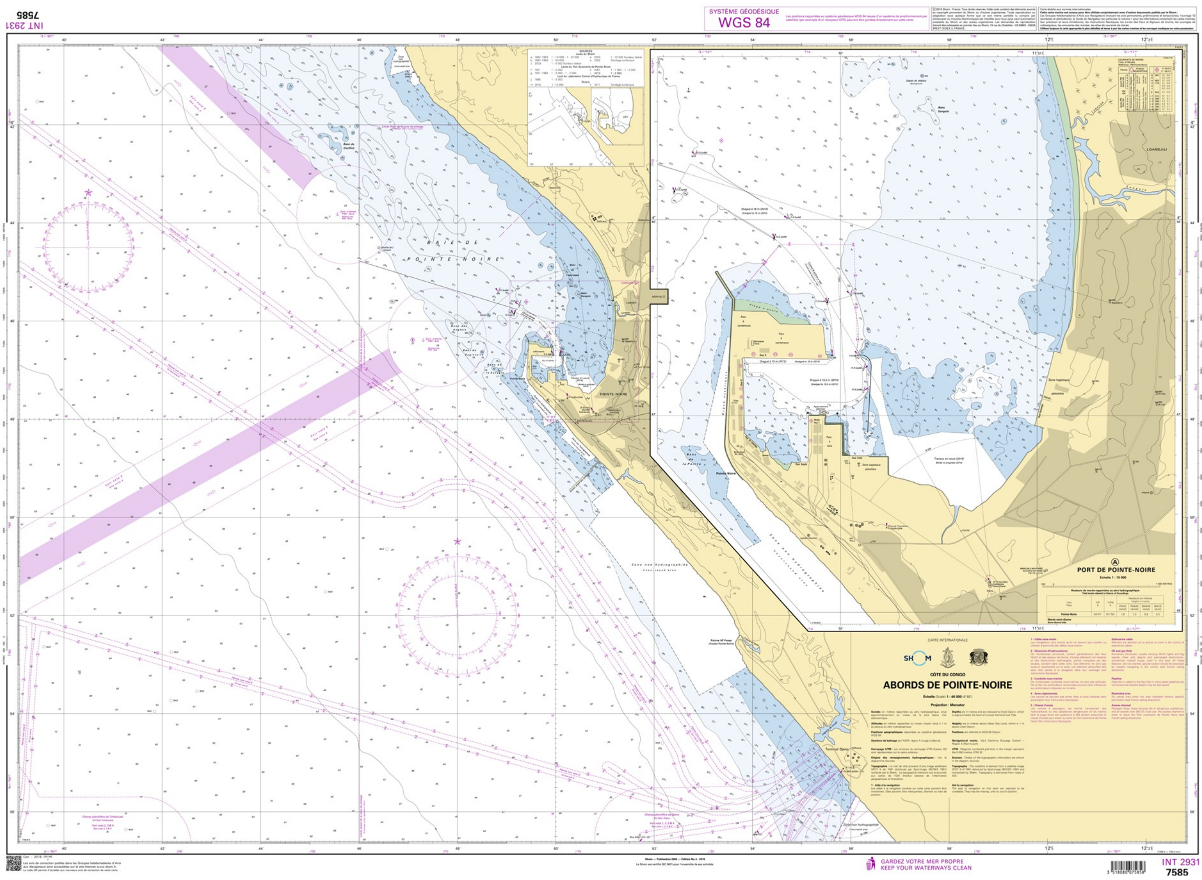

Figure 1. Pointe-Noire coastal zone.

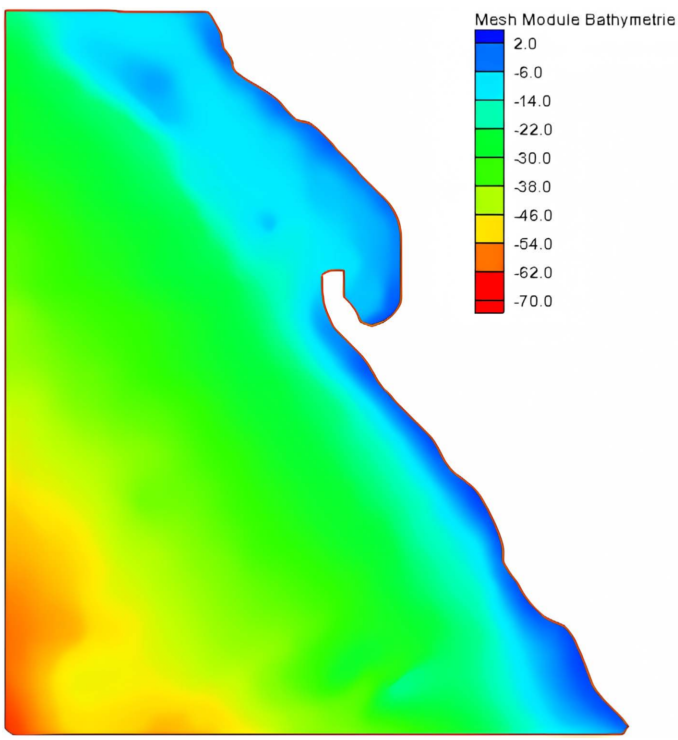

Figure 2. Bathymetry of the study area.

2.2.3. Swell and Waves

Pointe-Noire's coastline is oblique in a NW-SE direction, and the inclination of the waves in relation to the shallow water is negligible. According to the national meteorology, the Pointe-Noire coast is mostly visited by swells from the South Atlantic (SW direction) [1] [2] [4]. Wave heights range from 1 to 1.5 meters. These swell data will enable us to calibrate the swells at the boundaries.

2.3. CMS-Wave Model

2.3.1. Wave action Equilibrium Equation

The CMS-Wave model is based on the wave action equilibrium equation. It expresses the two-dimensional evolution of wave energy in space and takes into account the effect of an ambient horizontal current on wave behavior. It is written as follows [17] [18]:

$$\frac{\partial(C_x N)}{\partial x}+\frac{\partial(C_y N)}{\partial y}+\frac{\partial(C_\theta N)}{\partial \theta}=\frac{\kappa}{2\sigma}\left[\left(CC_g\cos^2\theta\frac{\partial N}{\partial y}\right)_y-\frac{CC_g}{2}\cos^2\theta\frac{\partial^2 N}{\partial y^2}\right]-\varepsilon_b N-S$$

with

$$N=\frac{E(\sigma,\theta)}{\sigma}$$

where

- C : wave velocity [m/s];
- C_g : group velocity [m/s];
- C_x , C_y , C_θ : characteristic velocity with respect to x, y, θ , respectively [m/s];
- κ : empirical parameter representing the intensity of the diffraction effect (in the present study for strong diffraction $\kappa = 4$);
- ε_b : wave energy dissipation parameter;
- θ : wave direction [˚];
- σ : angular frequency in relative reference;
- N : wave action density (depends on θ and σ) [m^2/hz];
- $E(\sigma, \theta)$: wave energy per unit area of water per frequency and direction interval [m^2/hz];
- S: additional source term $S = S_{in} + S_{ds} + S_{nl}$;
- S_{in} : wind input force (depends on wave speed and direction, group speed, wind speed and direction);
- S_{ds} : wave energy dissipation term (takes into account the effect of turbulent viscosity due to current. It also takes into account frictional head losses);
- S_{nl} : non-linear interaction term (CMS-Wave uses the theoretical formula proposed by Jenkins and Phillips [19]).

2.3.2. Wave Incidence Angle

Since this study involves analyzing the behavior of swells near the coast, it is necessary to understand the effect of the swell's angle of incidence in relation to the coast. A swell is said to be frontal when its direction of propagation is perpendicular (an angle of incidence of 0˚) to the coast, and non-frontal for a swell with an oblique direction (an angle of incidence not zero) in relation to the coast.

2.4. SMS Software Interface

SMS (Surface-water Modeling System) is a comprehensive program for building and simulating free-surface flow models. It is a graphical user interface and analysis tool that enables engineers and scientists to visualize, manipulate, analyze, and interpret numerical data and associated measurements.

Many SMS software tools are generic. They are designed to facilitate the establishment and operation of numerical models of rivers, coasts, inlets, bays, estuaries, and lakes. The site enables 1D and 2D modeling and a unique approach to conceptual models.

Models currently supported by SMS include ADCIRC, BOUSS-2D, CGWAVE, CMS-FLOW, CMS-WAVE (WABED), FESWMS, GenCade, PTM, STWAVE, TABS and TUFLOW [18].

2.5. Wave Model Parameterization

- Geographic zone: UTM, zone 32 S, NAD83, meters.
- Number of grid points: 2533.
- Domain area: 3456 km^2.
- Spatial resolution: $\Delta x = 50$ m and $\Delta y = 50$ m.

Boundary wave forcing condition:

- edge conditions are constituted by a south-western spectral coverage;
- significant height;
- direction (frontal, non-frontal southwest, and non-frontal northwest);
- peak period.

3. Results and Discussion

The bathymetry of the model area is shown in **Figure 3**. The physical aspect of the seabed on the Pointe-Noire coast is a slope whose depth decreases as it approaches the shore.

3.1. Model Validation

Due to a lack of wave data and measurements in the Pointe-Noire coastal area for validation purposes, we were forced to use satellite information provided by weather spots in the study area.

The wind data (wind speeds and directions) predicted by the weather spots on June 24 and 24, 2024, are used as model input data. The wave outputs obtained using the model are compared with the waves predicted by the spots on these two days. The spots present hourly mean values of wave heights, periods, and directions, while the model presents these values in different areas of the Pointe-Noire coast. Three points were chosen near the Pointe-Noire coastal zone to observe changes in swell characteristics. The first point is to the north of the port (Songolo), the second is in front of the port, and the third is near the outer breakwater

(Côte Sauvage).

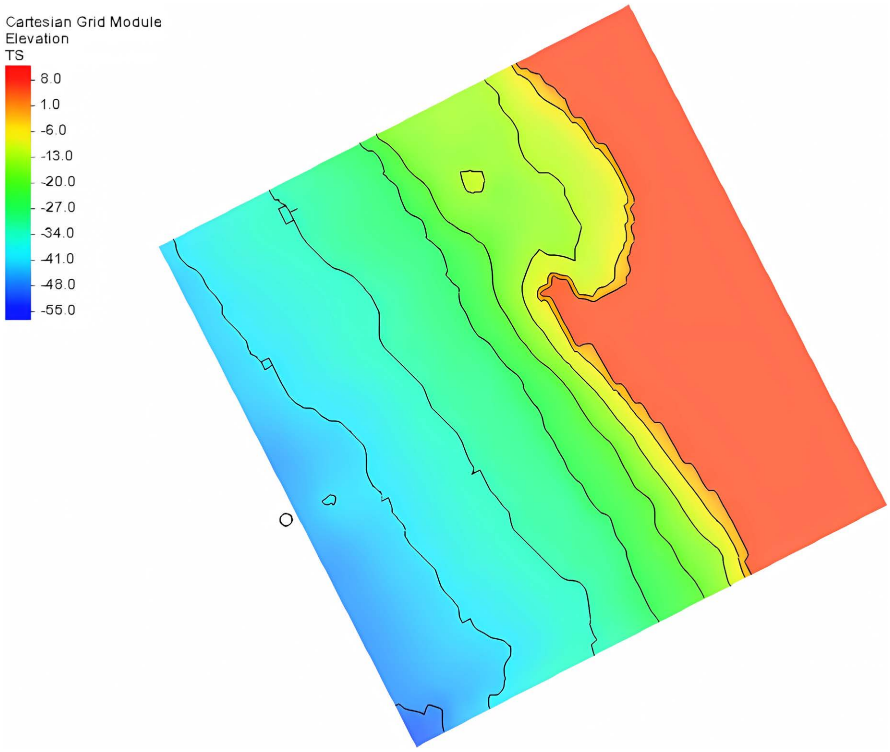

Figure 3. Water depth in meters in the model right-of-way.

Figures 4-9 show the changes in wave height and direction simulated by the model and those predicted by the De-glisse and Ça-baigne marine meteos for these two days on the Pointe-Noire coast. The model simulates wave heights and directions at every point in the study area, while the meteorological spots propose an average value for the entire coastal zone.

These different curves show that characteristic swell grades depend not only on bathymetry, but also on weather conditions and the location where they are observed.

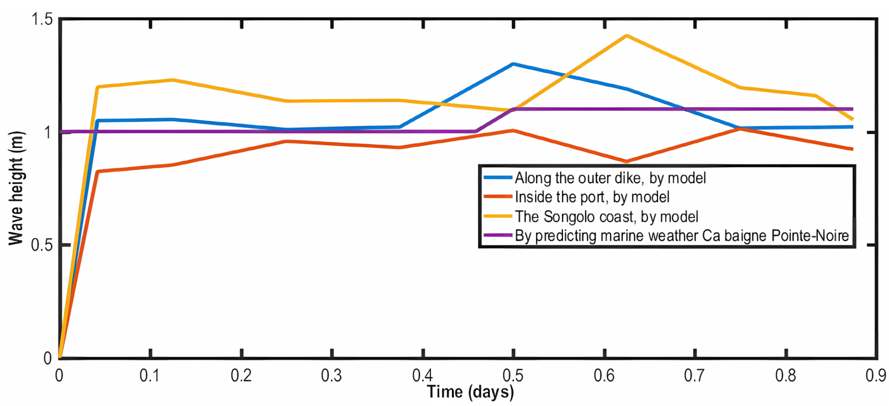

Figure 4. Comparison between the evolution of wave heights simulated by the model and that predicted by the Ça-baigne marine weather spot on June 23, 2024.

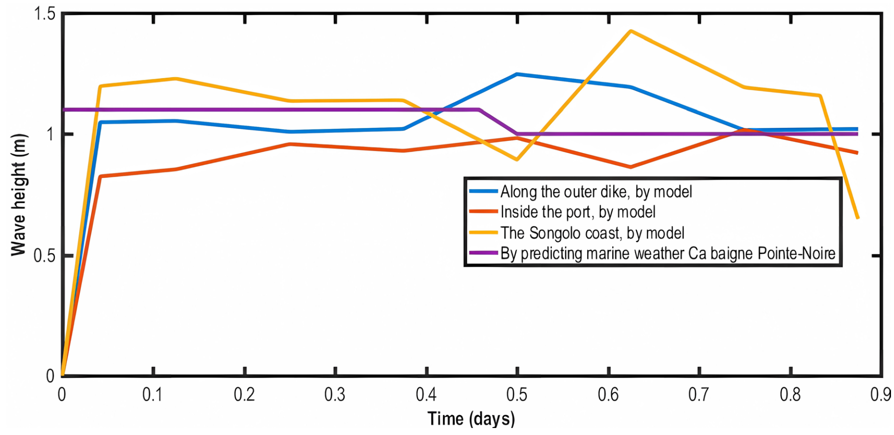

Figure 5. Comparison between the evolution of wave heights simulated by the model and predicted by the Ça-baigne marine weather forecast on June 24, 2024.

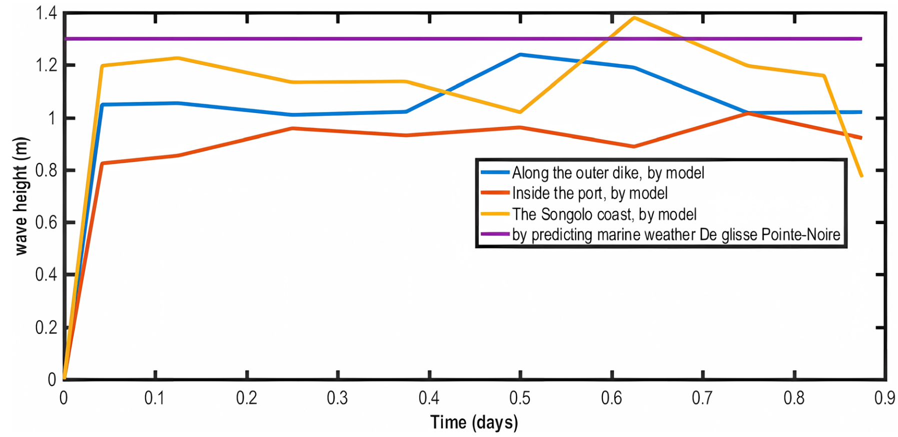

Figure 6. Comparison between the evolution of wave heights simulated by the model and predicted by the De Glisse marine weather spot on June 23, 2024.

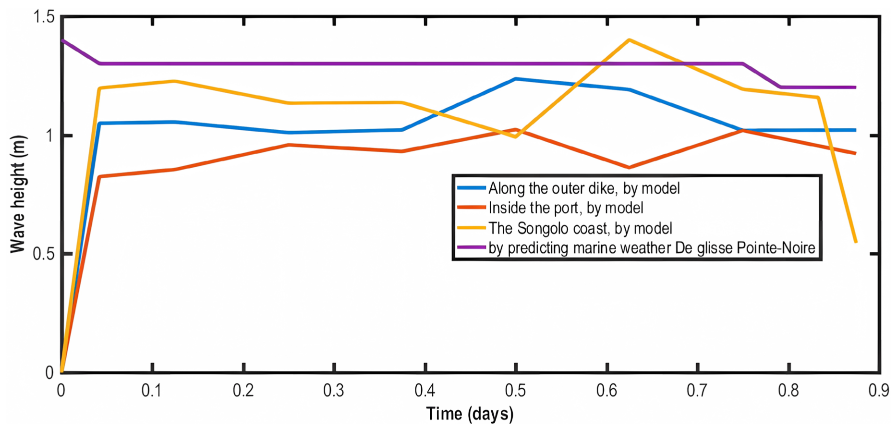

Figure 7. Comparison between the evolution of wave heights simulated by the model and predicted by the De Glisse marine weather spot on June 24, 2024.

Figures 4-7 show that wave heights in the Pointe-Noire coastal zone vary according to time and place for a 1 m frontal swell. The highest wave heights are observed near the open beach of Songolo, followed by those along the outer dike.

The lowest wave heights were observed in the harbor area. The average values predicted by the meteorological spots remain less variable during this period. The average difference between the values simulated by the model and those predicted by the weather remains very small.

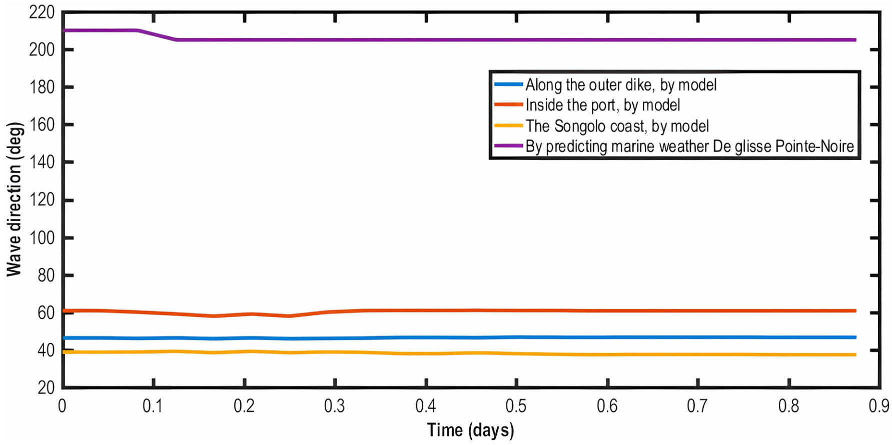

Figure 8. Comparison between the evolution of wave direction simulated by the model and predicted by the De Glisse marine weather spot on June 23, 2024.

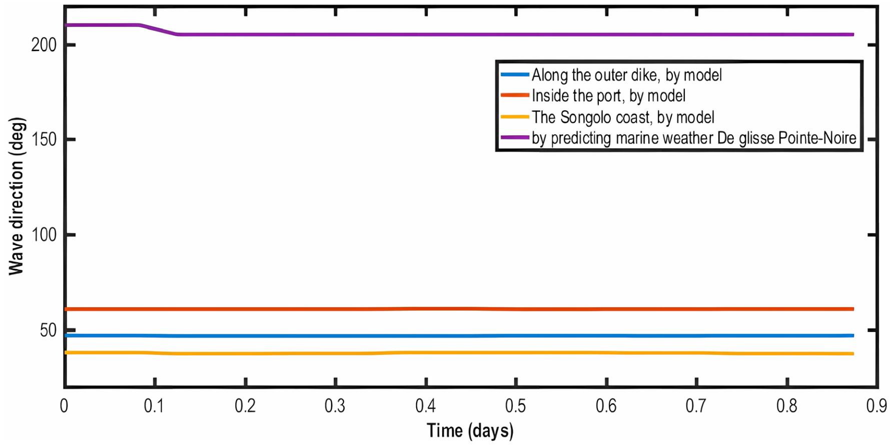

Figure 9. Comparison between the evolution of wave direction simulated by the model and predicted by the De Glisse marine weather spot on June 24, 2024.

Figure 8 and Figure 9 show the evolution of wave direction for the same swell characteristics at the boundaries. Wave direction varies according to location but remains constant throughout the observation period. These observations highlight the fact that waves tend to move northwards during their propagation as they approach the shore. The values predicted by Meteo De Glisse that are compared with those simulated by the model are seen under the third dial, while those of the model are on the first dial. Reading these values on the same dial shows that they remain very close.

3.2. Directional and Frequency Spectrum of Wave Energy

The evolution of the wave energy spectrum as it approaches the coast depends exclusively on the angle of incidence (see Figure 10 and Figure 11) or the frequency (see Figure 12) of the wave.

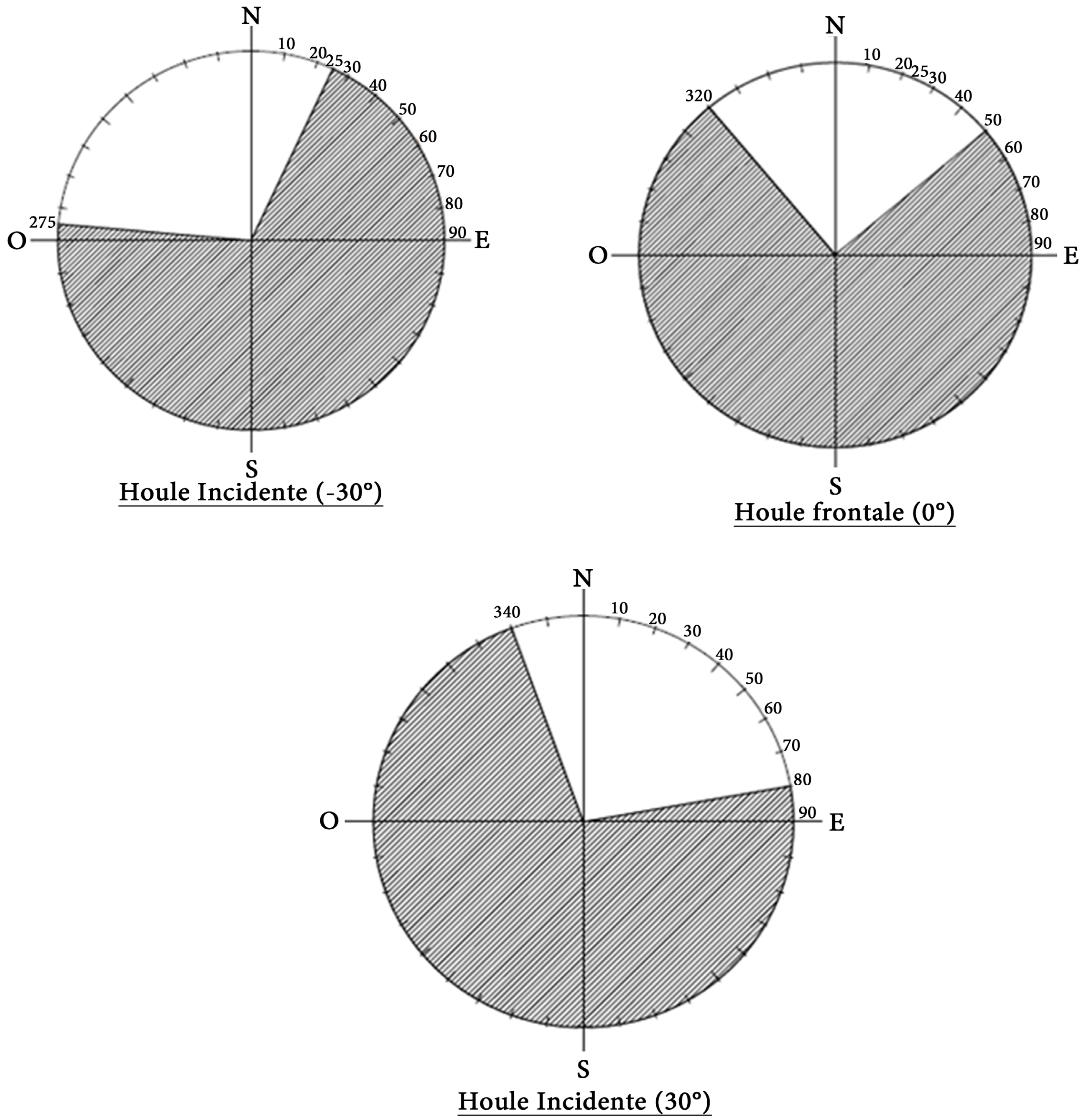

Figure 10. Angular spectrum of swell on the Pointe-Noire coast.

For a frontal swell, the coast receives wave energy in counter-clockwise directions from 50˚ to 320˚. For a south-westerly oblique swell, the coast receives wave energy in counter-clockwise directions from 80˚ to 340˚. For a non-frontal swell of northwest incidence, the coast is visible for wave energies in directions between 25˚ and 275˚ counter-clockwise.

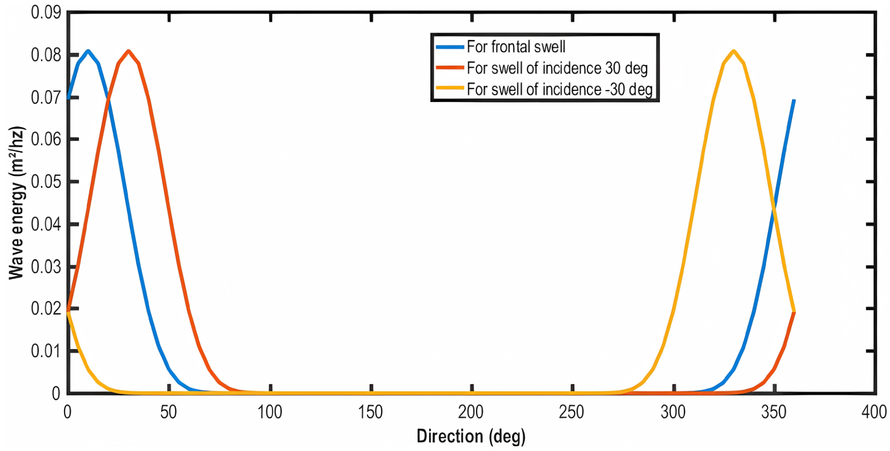

Figure 11. Directional spectrum of wave energy.

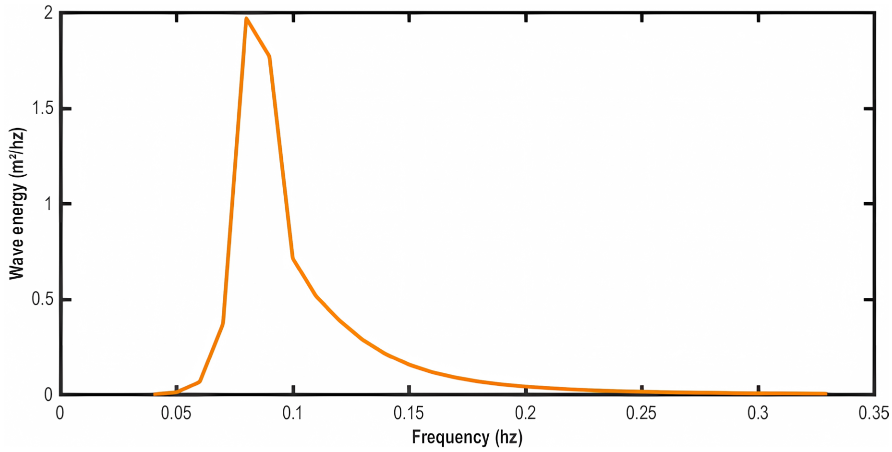

Figure 12. Frequency spectrum of wave energy in the coastal zone of Pointe-Noire.

The layout of the Pointe-Noire coast is such that it is in a blind spot for waves coming in a counter-clockwise direction between 275˚ and 80˚. Waves with an angle of incidence in this direction are parallel to the Pointe-Noire coast.

3.3. Wave Height

The test cases carried out with the three angle incidences (frontal, non-frontal, northwest, and southwest) of swell at the boundaries with significant height $H_s = 1.5\ \mathrm{m}$ and peak period $T_P = 12\ s$ (**Figures 13-15**) show that the largest waves are observed along the outer dike and near the Songolo coast. For both frontal and non-frontal swell incidence in the northwest direction, wave height decreases relative to the value set at the boundaries, while for non-frontal swell incidence in the southwest direction, wave height increases relative to the value set at the boundaries as the waves approach the coast.

Wave height remains constant during propagation to the immediate open sea, only to increase near the coast due to the elevation of the bathymetry and adjacent structure of the area. The harbor enclosure is characterized by a very calm situation, as the wave dissipates during its interaction with the protective structure of

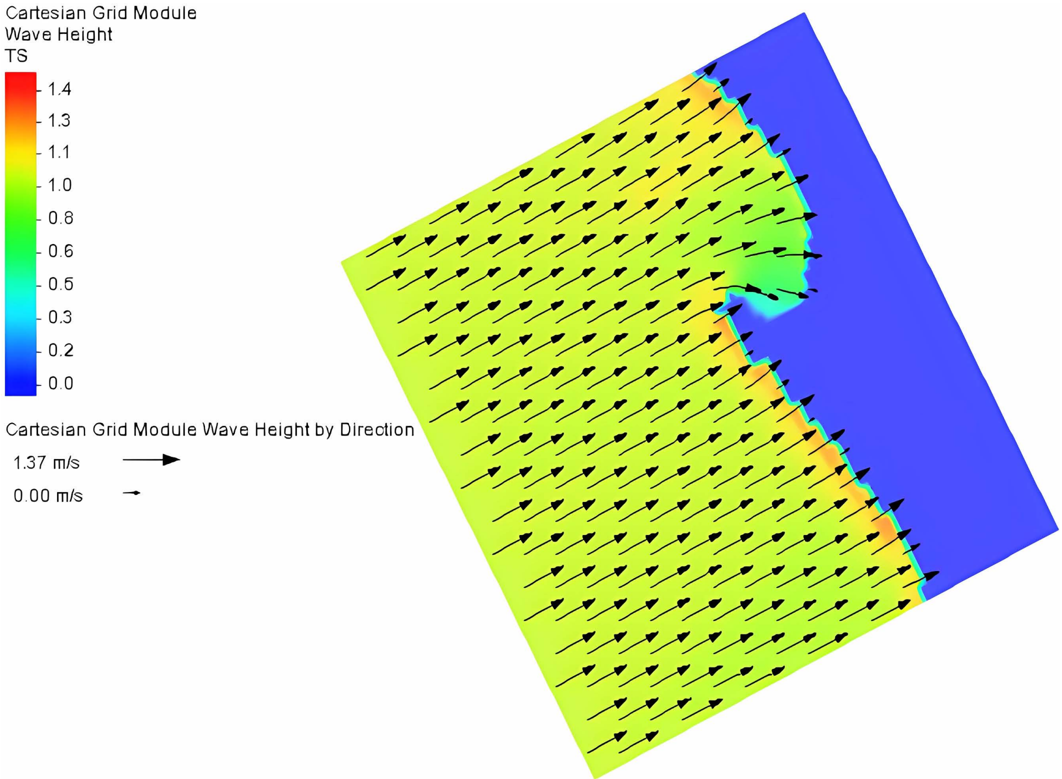

Figure 13. Evolution of height along the coastal zone for a frontal swell of Hs = 1 m.

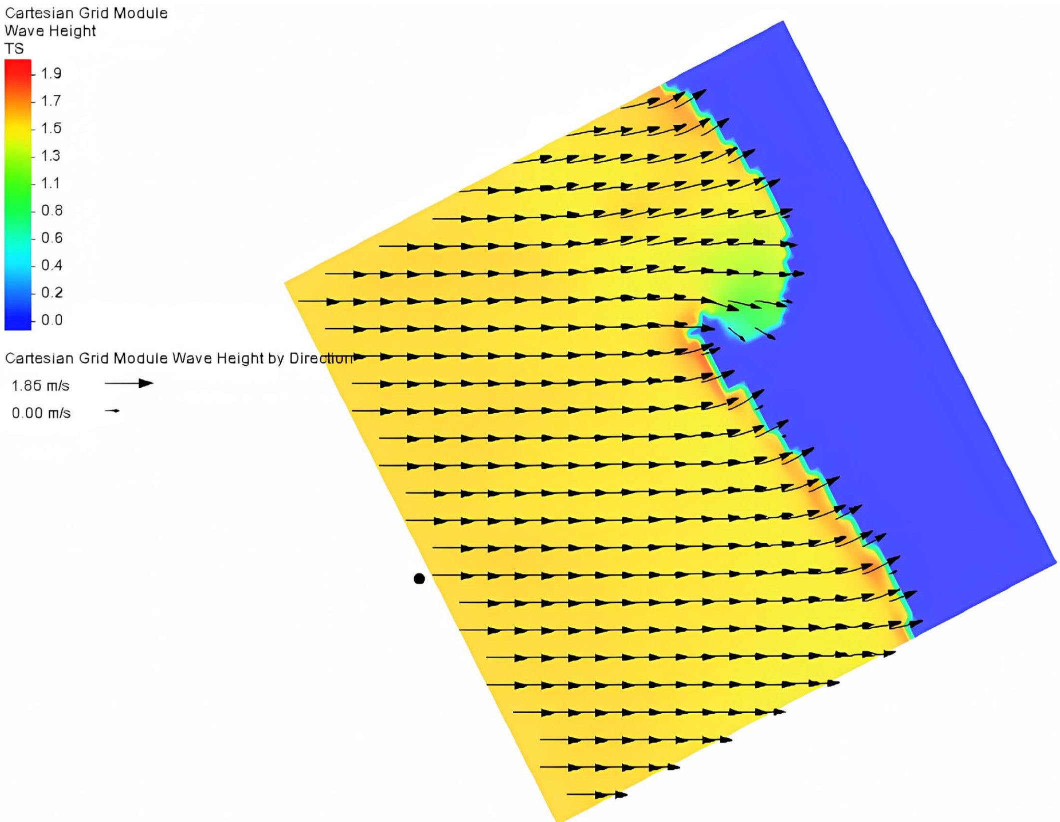

Figure 14. Wave height evolution for a non-frontal swell with the angle of incidence −30 deg and Hs = 1.5 m.

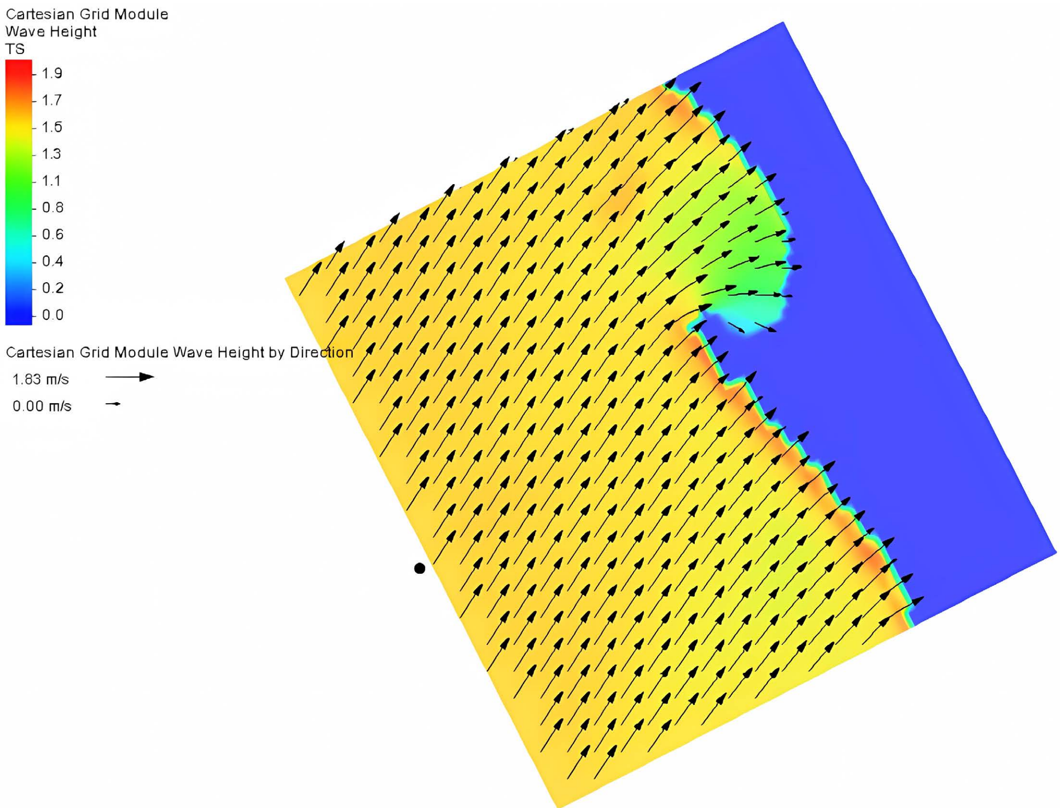

Figure 15. Wave height evolution in the coastal zone for a non-frontal swell with the angle of incidence 30 deg and significant height Hs = 1.5 m.

the harbor access channel.

The presence of high wave heights at the level of the large dike (southeast zone of the port) and the Songolo coast (northeast zone) is responsible for the drift currents that cause the drainage of sediments from the savage coast and erosion in Loango Bay.

4. Conclusions

The various test cases carried out have enabled us to understand the impact of swell direction on the behavior of waves as they approach the coast.

Non-frontal swells in a north-westerly direction have similar effects to frontal swells. Southwesterly swells are responsible for the greatest drift in the Pointe-Noire coastal zone. They are largely responsible for the hydro-sediment dynamics in this area. The extension of the seawall protecting the port access channel has a considerable impact on attenuating the energy of the southwesterly swell, which leads to a calm water surface in the port area.

Analysis of swell behavior as it approaches the coast of Pointe-Noire depends significantly on the evolution of bathymetry and the shape of the beach, whether completely open or protected by a seawall. This bathymetry, characterized by a slope, has an effect on the amplification of swell height as it approaches the coast.

In the area protected by the seawall, part of the wave energy is dissipated by wave reflection off the structure. In the open zone not protected by a seawall, waves cross the coast with the highest heights and break on the beach. The swash phenomenon is observed in this zone.

The present study represents a milestone in the understanding of coastal hydro sedimentary dynamics on the Pointe-Noire coast. The prospects opened up will be oriented towards accurately assessing the contribution of all oceanic forcing (waves, tides, and currents) to the functioning of this coastline, using a coupled hydro-sedimentary model.

Conflicts of Interest

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

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