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Evaluation of the Beach Erosion Process in Varadero, Matanzas, Cuba: Effects of Different Hurricane Trajectories

Ana Gabriela Diaz, Luis Fermín Córdova, Jr., Roberto Lamazares

Abstract**—**The island of Cuba, the largest of the Greater Antilles, is located in the tropical North Atlantic. It is annually affected by numerous weather events, which have caused severe damage to our coastal areas. In the same way that many other coastlines around the world, the beautiful beaches of the Hicacos Peninsula also suffer from erosion. This leads to a structural regression of the coastline. If measures are not taken, the hotels will be exposed to the advance of the sea, and it will be a serious problem for the economy. With the aim of studying the intensity of this type of activity, specialists of group of coastal and marine engineering from CIH, in the framework of the research conducted within the project MEGACOSTAS 2, provide their research to simulate extreme events and assess their impact in coastal areas, mainly regarding the definition of flood volumes and morphodynamic changes in sandy beaches. The main objective of this work is the evaluation of the process of Varadero beach erosion (the coastal sector has an important impact in the country's economy) on the Hicacos Peninsula for different paths of hurricanes. The mathematical model XBeach, which was integrated into the Coastal engineering system introduced by the project of MEGACOSTA 2 to determine the area and the more critical profiles for the path of hurricanes under study, was applied. The results of this project have shown that Center area is the greatest dynamic area in the simulation of the three paths of hurricanes under study, showing high erosion volumes and the greatest average length of regression of the coastline, from 15- 22 m.

Keywords**—**Beach, erosion, mathematical model, coastal areas.

I. INTRODUCTION

THE need to forecast the physical changes of coasts, as well as the determination of the critical areas of sandy beaches for tourism, are rising proportionally with the population of the corresponding areas and the increase of the load on coastal systems (due to rising sea levels and the possibility of existence of severe storms).

In order to predict or determine the effects caused by such phenomena, a mathematical model called "XBeach" has been created to simulate the morphodynamics of beaches in extreme situations.

II. PROCEDURE

A. Brief Presentation of Coast Engineering System for Determining Volume of Erosion and Regression of the Coastline in Varadero Beach

In Figs. 1 and 2, the two alternatives that make up the Coast Engineering System for determining volume of erosion and the regression of the coastline in Varadero beach are shown. This system is based on the Linux Operating System, and its programs are open source.

Alternative No. 1 is characterized by having, as initial data, the output of winds fields of parametric model Holland, 1980, conducting them after to the Wave Watch III (WW3) and SWAN for wave generation and propagation according to the working domain [11].

Alternative No. 2 is characterized by having, as initial data, the meteorological fields that come from the global model GFS (Global Forecast System). These data feed the runs of MM5, which outputs of wind fields run as input in the Wave Watch III model (WW3) [5], [13], [14].

B. Xbeach

XBEACH is a program based on mathematical models (2DH) prepared to calculate the morphodynamic changes near the coast, including erosion, rupture and relining of the dune from a storm or hurricane. Providing a robust and flexible environment, this program has been written in Fortran (90/95) by institutions: UNESCO-IHE Institute for Water Education (Contractor), WL / Delft Hydraulics and Delft University of Technology, and the source code has been evaluated exhaustively in a compiled version under the Compaq Visual Fortran version 6.6 [15].

C. Model Functions

It solves the equations in shallows including the variation in time and combining the subcritical and supercritical flows. In the process of transformation of waves, the following terms are taken into account: refraction, shoaling and refraction due to current. It includes the roller model and the delay in breakage due to this phenomenon. It takes the effect of the amplitude of the wave on the speed of the wave into account. It solves the accession and diffusion equation for suspended sediment transport. The equations representing physical phenomena presented above can be found in the manual [15]. XBEACH solves the balance of wave action depending on the scale of the wave groups in short time [12].

Ana Gabriela Diaz Garrote is in cooperation with the Polytechnic Institute Jose Antonio Echeverria, Street 114, Marianao, Havana (e-mail: gabrielagarrote@gmail.com).

Dr. Luis Fermin Cordova is a professor at the Polytechnic Institute Jose Antonio Echeverria, Street 114, Marianao, Havana (e-mail: cordova@cujae.edu).

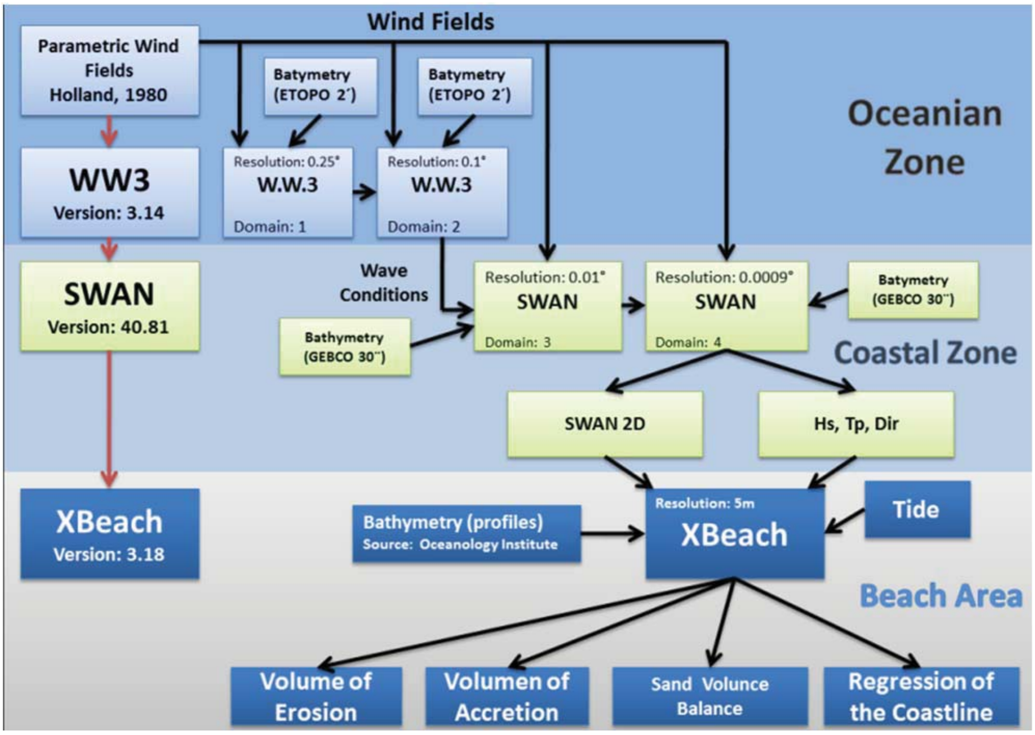

Fig. 1 Coast Engineering System Alternative 1

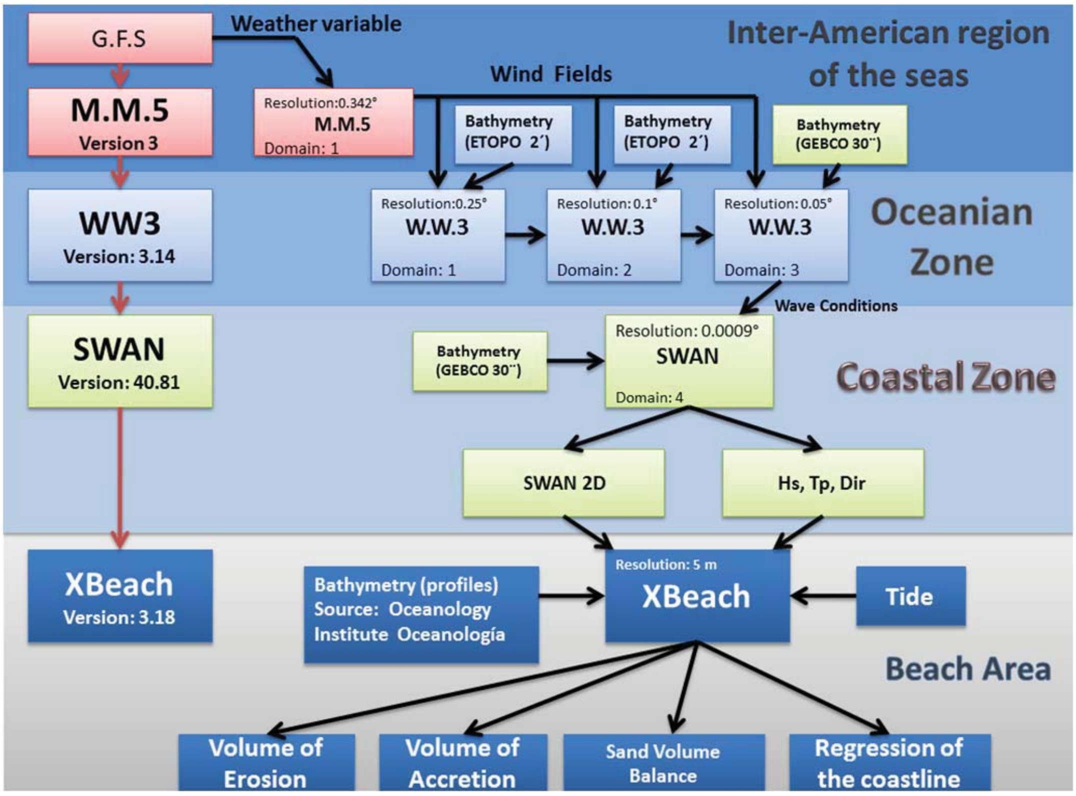

Fig. 2 Coast Engineering System Alternative 2

The balance of wave action is given as (1):

$$\frac{\Delta A}{\Delta t}+\frac{\Delta cg.xA}{\Delta x}+\frac{\Delta cg.yA}{\Delta y}+\frac{\Delta c\theta A}{\Delta \theta}=-\frac{\text{D waves}}{\sigma} \qquad (1)$$

III. GENERAL CHARACTERISTICS OF AREA OF STUDY

It is located on the northwest coast of Cuba about 130 km east of Havana and 32 km from the city of Matanzas. The peninsula has a length of 22 km, maximum width of 500 meters and with a projection of 70 degrees azimuth (SW - NE). Hicacos Peninsula has been described as a natural barrier between the bottom of the Bay of Cardenas and the waters of the Straits of Florida, and it has a total area of 1140 hectares. The Hicacos Peninsula is characterized by a strip of fine white sand and a gentle descent of the platform towards the sea, and offer the visitors, pleasant temperatures wrapped in a blue dream that identifies Varadero as the Blue Beach [6], [9].

The Cuban Institute of Oceanography is the organization responsible for all research on the erosion of the peninsula. This institute has estimated the rate of beach erosion by comparing the measured beach profiles over the years. The conclusions it has arrived are:

A loss of 50, 000 m^3 of sand per year and 1,2 m per year of regression of the coastline [6], [9].

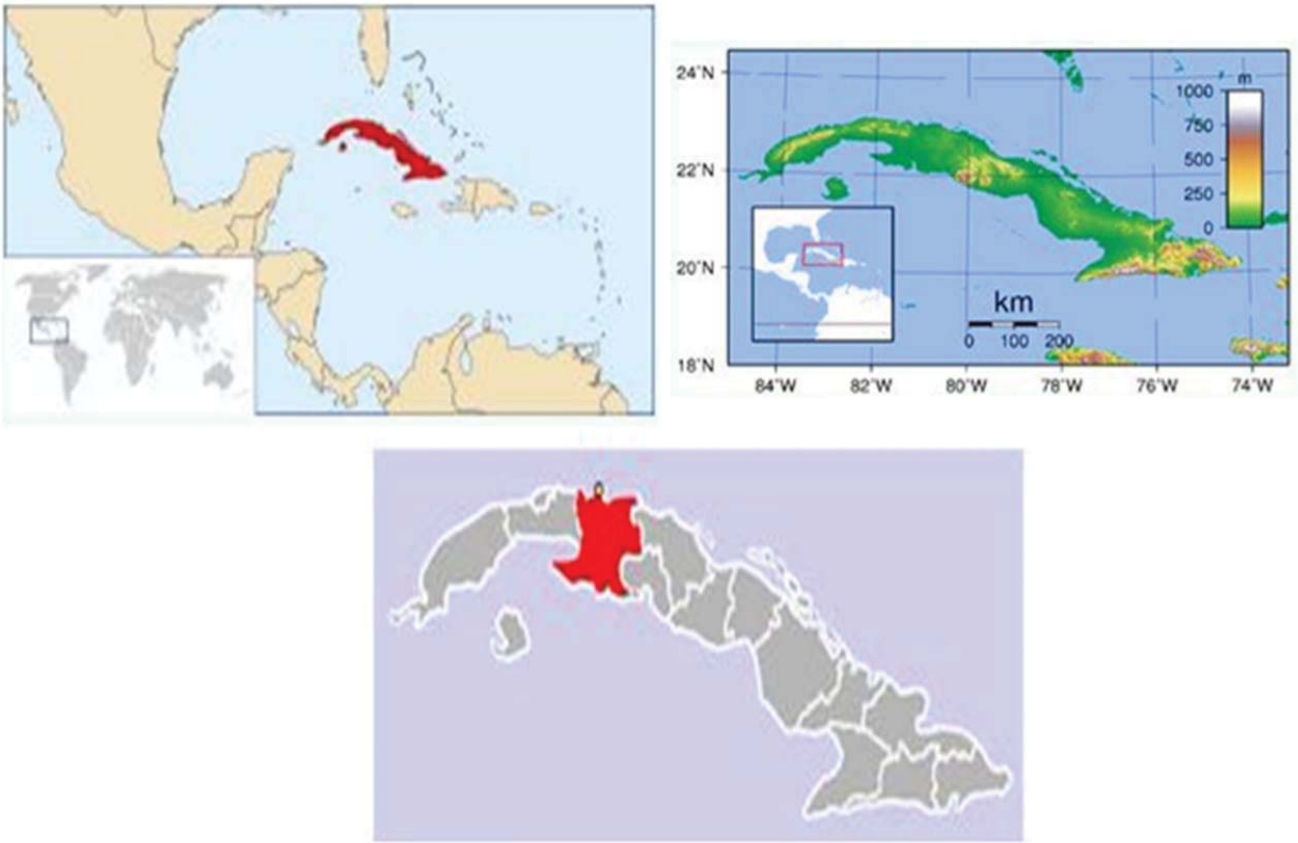

Fig. 3 Geographical location of Varadero beach, Source [9]

IV. DEFINITION OF METEOROLOGICAL VARIABLE IN VARADERO

A. Climate

In Varadero beach predominates tropical sea conditions, it is affected by waves from the sectors corresponding to Northeast, North, Northwest, and West directions with swings of periods and heights of significant wave between 4 and 12 seconds and 0.5 and 9 meters respectively. The average humidity is about 78% [16] in Varadero.

B. Temperature

The maximum average monthly temperature in Varadero is about 32 °C and the minimum is recorded in winter with 19 °C. The sea water temperature varies from 26 °C in winter to 32 °C in summer, because the variant influence of the Gulf stream, northern coastal water is usually cooler than the southern [16], [17].

C. Precipitation

The average rainfall is 1059 mm in the rainy season and 316 mm in the dry season, with an annual average rainfall of 1375 mm. It rains between 85 and 100 days in a year. Rainfall most of the time does not last long, and the duration is about 30 minutes. Although, when severe storms occur, rain can last for hours [2], [16].

D. Wind Directions and Speeds

In the Hicacos Peninsula, there are no available data on wind directions and speeds. The information presented is taken from records of measured winds at the old airport of Varadero in 1978 and 1979 [2].

E. Sea Levels

The tidal range on the peninsula is about 0.5 m, and the speed of the tide can vary between 0.10 and 0.37 m/s. In the same peninsula, a rise in net sea level of 184 mm or 1.9 mm /

year was measured by the Institute of Oceanology of the Ministry of Science, Technology and Environment (CITMA) [6].

V. BEACH PROFILES AND BATHYMETRY OF THE AREA OF STUDY

A. Beach Profiles

Over the last decade, specialists of the Institute of Oceanology of Cuba do topo-bathymetric measurements for investigations of effectiveness of the recovery work of Varadero beach. Based on these surveys, the profiles that lead to the fulfillment of the following criteria are selected for the implementation of XBeach: profiles measured before the hurricane season and with sufficient length for the whole process of transformation, wave propagation and morphological changes. To carry out research, it is working with the profile data measured in March 2001 [3], [4], [8].

B. Bathymetry

It is shown in Fig. 4 that the bathymetry of Varadero is characterized by being substantially straight and parallel to the coastline, featuring some discontinuities due to the presence of small coral heads between 15 and 30 meters deep into the western half of the Peninsula [8].

While going through the Hicacos Peninsula (West-East), underwater slope is characterized by smooth with slightly decreasing trend, this progressive decrease in slope to the northeast is due to the widening of the insular platform, that takes place from the second third of the beach [9].

C. Sedimentology

It is considered that the predominant sand of Varadero beach is formed by the fragment from 0.25 to 0.5 mm and the average grain diameter can be considered equal to 0.26 mm (native sand). Its main source is the Halimeda algae with an estimated production of 10 kg/m^2/year [6].

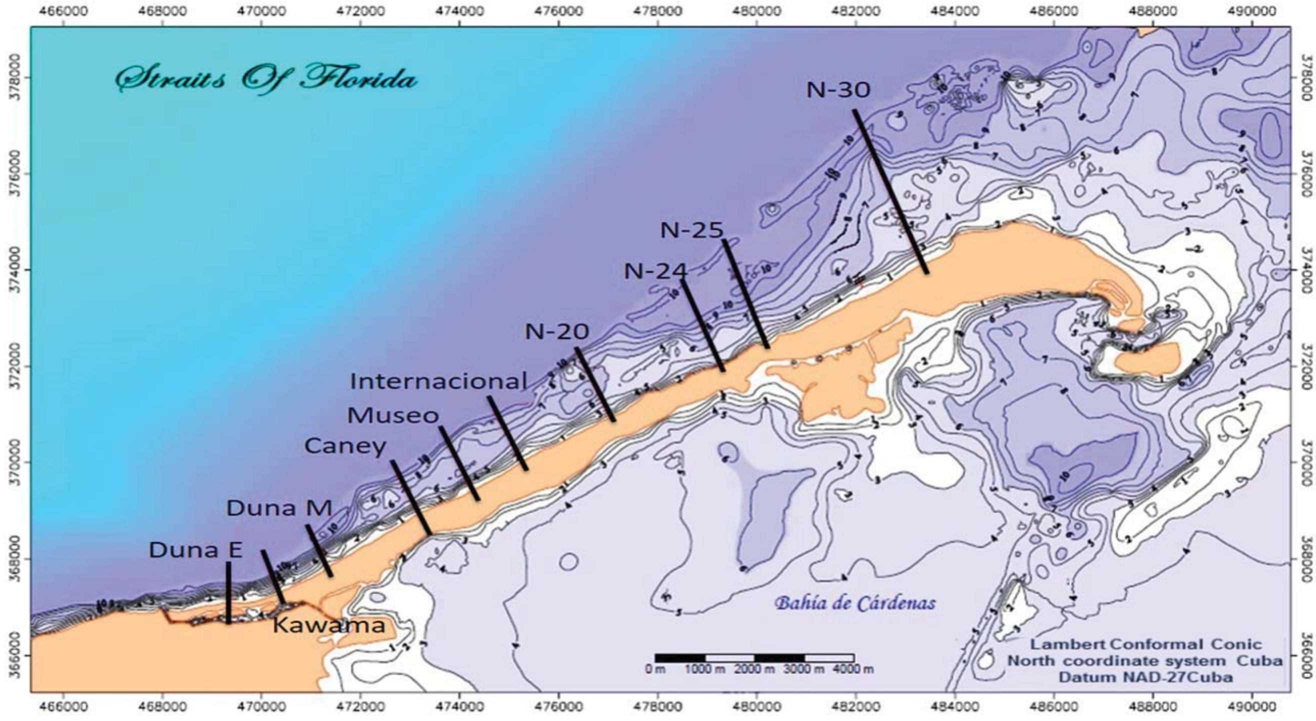

Fig. 4 Location of the selected profiles [9]

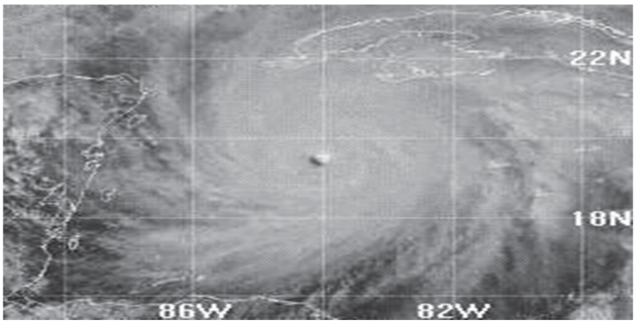

Fig. 5 Hurricane Michelle. VIS Image of GOES-8 satellite, November 3, 2001 at 19:25 UTC

VI. DESCRIPTION HURRICANES STUDIES

A. Description of Hurricane Michelle (October 29 - November 6, 2001)

Tropical depression number 15 was formed from a tropical wave in the afternoon of October 29 about 120 kilometers south of Puerto Cabezas, Nicaragua. It quickly stepped up to reach category 4 in the morning of the day 3. In the afternoon of that day, a reconnaissance plane reported a minimum pressure of 933 hPa, while the maximum wind was of 220 km/h.

In Fig. 5, the excellent structure of the cloud pattern associated to Michelle is shown at the time of its maximum depth. [1], [18], [19].

B. Description of Rita Hurricane (September 18-26, 2005)

The eighteenth tropical depression was developed in an area of disturbed weather on the night of September 17 about 135 kilometers almost to the east of Turks Islands, Bahamas.

The center of the storm had several reformations, but was gradually gaining in intensity and at 2:00 a.m. (06:00 UTC) on the day 19; it had maximum sustained winds of 95 km/h, when it was almost about 265 kilometers to the north of Punta de Maisi, Guantanamo.

On the night of day 19, it increased the travel speed up to 27 km/h passing at a distance of 100-160 kilometers from the cays, north of Camagüey, better organized, but with equal intensity. Since the end of the night until the early hours of the morning of day 20 it moved to the north of Ciego de Avila, at a distance of 100 km from Cayo Coco, with similar characteristics in both the movement and intensity of the winds.

With the route between the West and the West Northwest at a rate of 22 km/h, it crossed in the morning the north of Matanzas, being at noon about 70 kilometers north of the Hicacos Peninsula. In the meteorological station of Varadero it was recorded a minimum pressure of 997.5 hPa at 12:20 PM (16:20 UTC). In the same direction, it moved in the afternoon about 80 kilometers off the coast of Santa Cruz del Norte, Havana, with maximum wind speed of 150 km/h. At 21:25 UTC, a reconnaissance plane reported a minimum central pressure of 970 hPa and maximum wind was 160 km / h, so Rita became a Category 2 hurricane [10], [18].

C. Description of Wilma Hurricane (October 15 - October 25, 2005)

Tropical Depression 24 was developed in an area of low pressure on the afternoon of October 15 about 120 kilometers south-southwest of Montego Bay, Jamaica. The depression remained drifting westward during the rest of that day and into the night 16 when it started doing to the South, while an anticyclonic ridge was intensified in the middle levels of the troposphere over Florida and Cuba. On the early morning of day 17 it was classified as Tropical Storm Wilma, considering the convective explosion that occurred near its center [18].

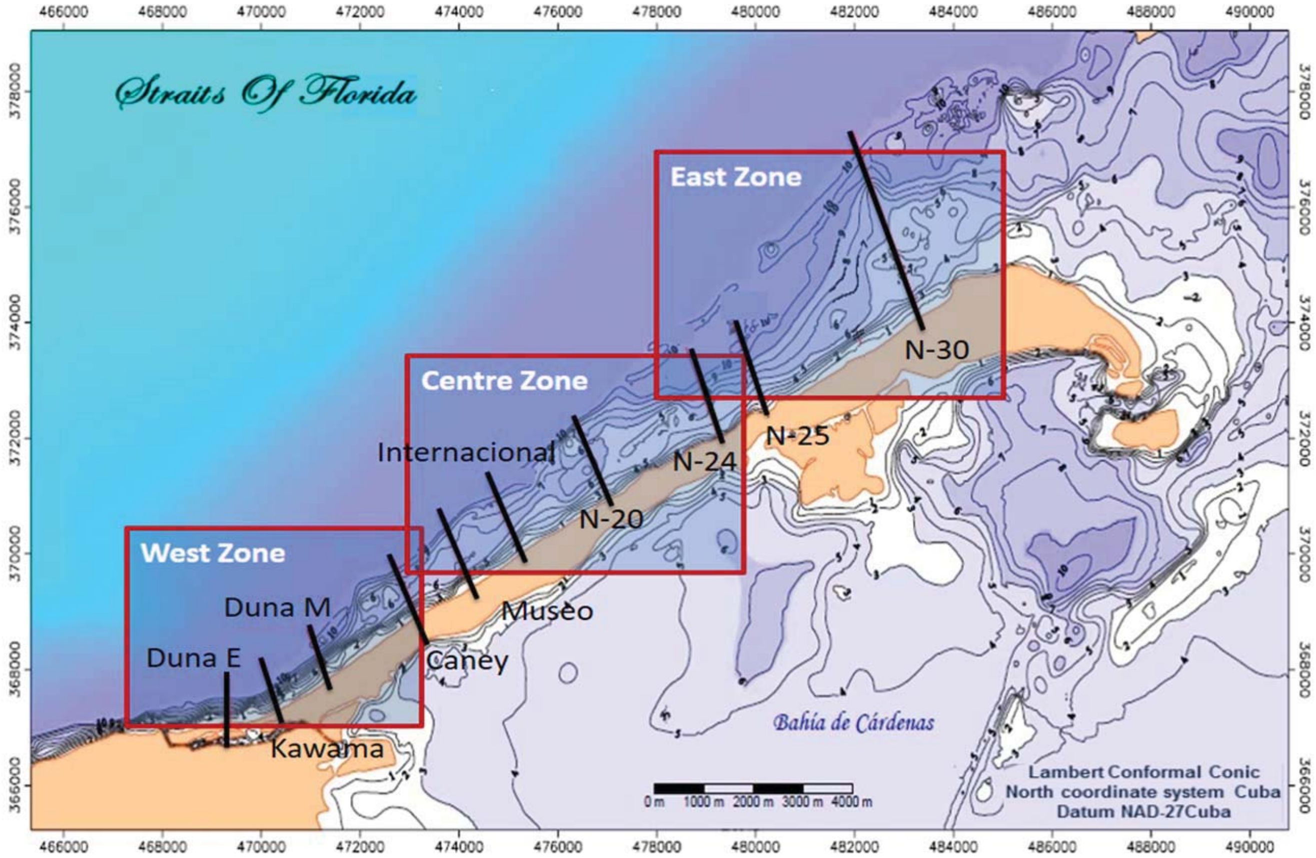

Fig. 6 Hurricane Hicacos Peninsula divided in areas [9]

VII. APPLICATION OF COAST ENGINEERING SYSTEM FOR DETERMINING VOLUME OF EROSION AND COASTLINE REVERSING IN VARADERO BEACH

The implementation of Alternative No.1 is performed to the three paths of study hurricanes that have impacted on the Hicacos Peninsula, "Michelle, 2001", "Rita, 2005" and "Wilma, 2005" as mentioned in Section VI, in the case of Alternative No. 2 it runs for Hurricane Wilma.

A. Definition of the Areas of Study

For comparison and selection of areas in which the study takes place, next criterion is applied. The profiles must exhibit similar behavior from the bathymetric point of view.

VIII. ANALYSIS OF SIMULATION RESULTS BY XBEACH MODEL

A. Analysis of Simulation Results by Xbeach Model

This paper concludes considering the results of studies [8] where comparisons of measured profiles in Varadero beach are made before and after Hurricane Michelle. It is shown that the XBeach model results are lower with regard to volume erosion and regression of the coastline compared to the reality. For this reason, a selection criterion and the boundary condition that produces the highest values of both variables are assumed in this analysis.

The wave boundary conditions used in the simulation by XBeach for Hurricane Michelle (Jonswap parameters and SWAN 2D wave spectrum) are already mentioned above in Section II-A. The comparisons between wave conditions depending on volume of erosion and length of regression of the coastline are presented [7].

B. Quantitative Comparison between Areas Depending on the Statistical Calculations

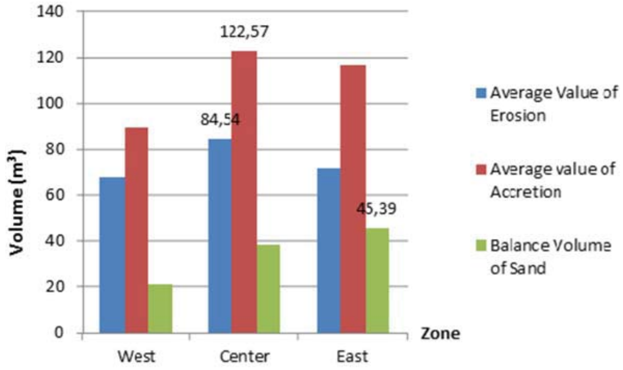

Fig. 7 Comparison between areas depending on the average values volume of erosion, sand accretion and balance

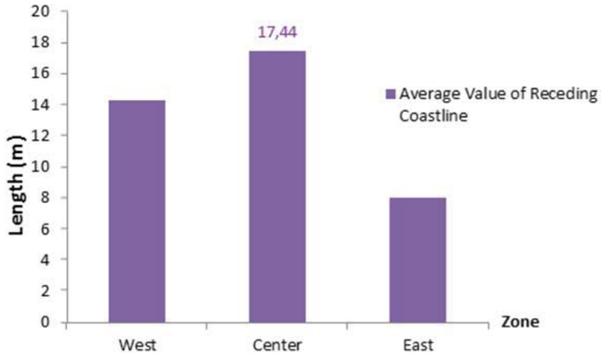

Fig. 8 Comparison between areas depending on the average length of regression the coastline

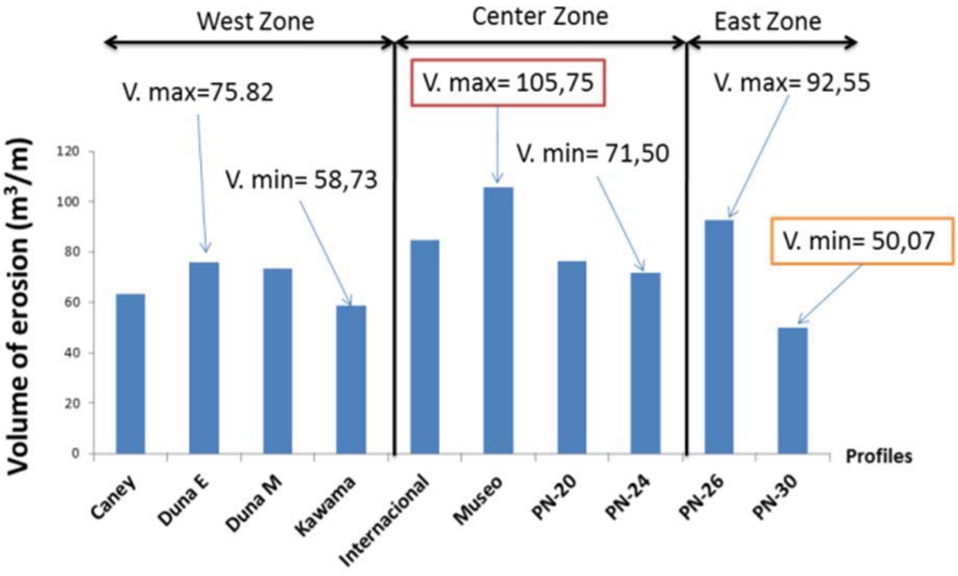

Fig. 9 Maximum and minimum volumes of erosion by area

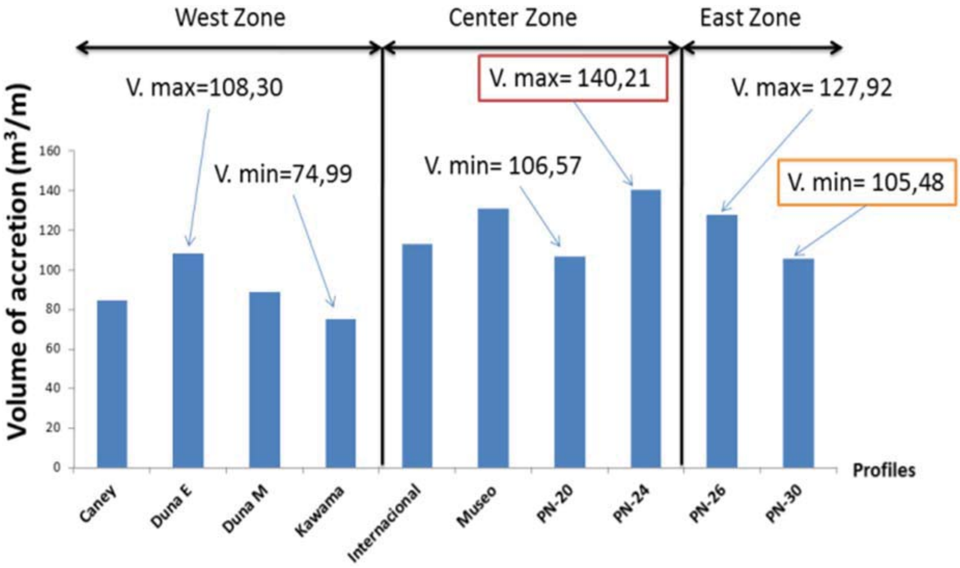

Fig. 10 Maximum and minimum volumes of accretion by area

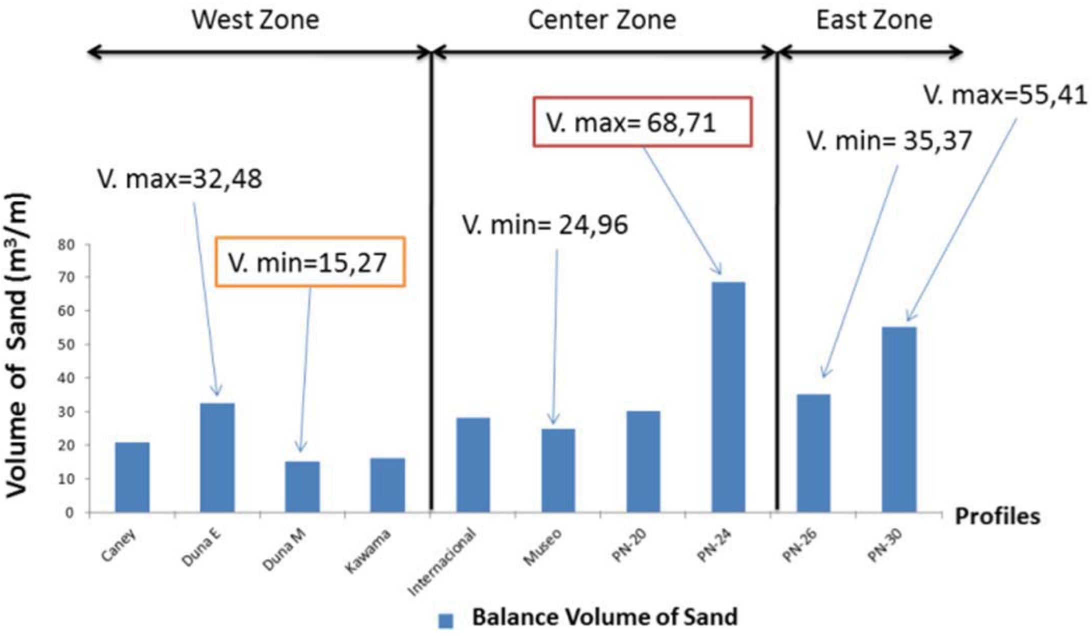

Fig. 11 Maximum and minimum volumes of sand balance

IX. CONCLUSIONS OF THE ANALYSIS

In general, the mathematical models that integrate the Coast Engineering System for determining volume of erosion and the regression of the coastline in Varadero Beach were described.

The Center area was defined as the area of greatest dynamic in simulation of the three paths of hurricanes study by showing profiles with erosion volumes up to 105.75 m^3/m and by representing between 44 and 48% of the total eroded volume for each simulated hurricane. This area is also marked as the area that presents the greatest average length of the regression of the coastline, from 15 to 22 m.

In the case of the West side, for the simulation of three hurricanes, profiles with erosion volumes up to 75.82 m^3/m, showing between 30 and 36 % of total eroded volume for each simulation of Hurricane and an average length of the regression of the coastline between 10 and 21 m were shown.

In the simulation of the three hurricanes, the East side showed profiles with the erosion volumes up to 92.55 m^3/m, representing between 19 and 23% of the total volume eroded by each simulation of Hurricane and an average length of regression of the coastline between 1 and 20 m.

As a result of the three paths of hurricanes, Kawama, PN-24 and PN-26 profiles were determined, respectively, as the most critical of each study area, based on the length of the regression of the coastline

An order between the paths of hurricanes of study is defined based on the level of damage in the simulations on the Hicacos Peninsula.

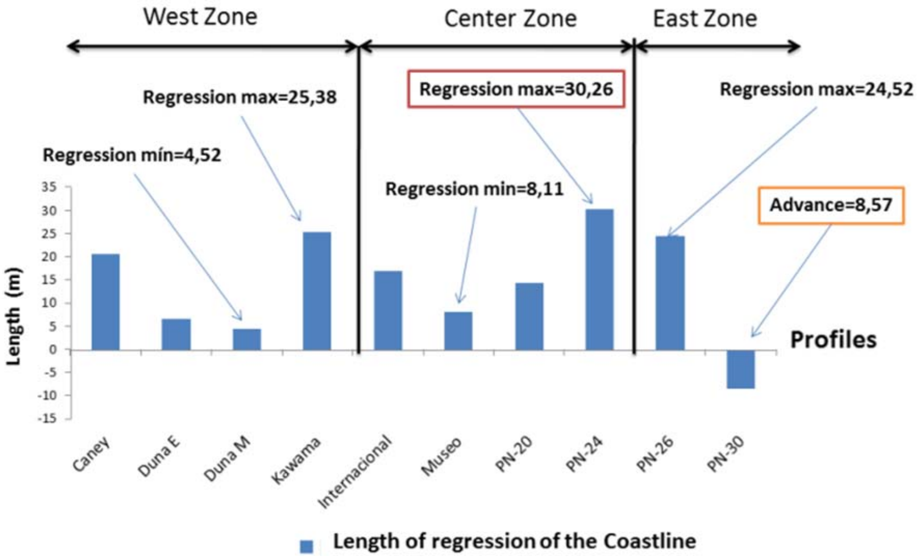

Fig. 12 Maximum and minimum lengths of regression of the coastline by area

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