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Investigating the Temporal Cross-Shore Beach Profile Evolution Using CSHORE on a Sand Beach on West-Central Florida's Barrier Islands

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Abstract

Predicting the beach response to an extreme storm is important in planning and management of beach environment and helps in hazard control. Coastal dunes and sand beaches provide protection against sea waves and rising water levels to many coastal communities especially during a storm event. Barrier islands along the West of Florida constantly face wave action and when a severe storm is added to the forcing, the islands face severe erosion. In this study, the numerical model CSHORE was applied to predict the short-term cross-shore profile evolution on Sand Key Beach located on the barrier islands west of Florida. The initial beach profile used in the study was measured after a beach nourishment project on the barrier islands. In a few years, the coast experienced severe storms including Hurricane Ian. Beach profiles were measured post the hurricane period and therefore this study investigated how the cross-shore beach profile was affected due to sediment transportation dynamics caused by the climate. Coastal Hazard Systems storm data sets were used as forcings on the beaches to assess the response of the beaches to the conditions. The results were compared to the field measurements taken across transects on the beach cross sections.

Keywords

Beach Erosion, CSHORE, Sand Beach, Beach Recovery, Numerical Model

1. Introduction

This paper investigated the temporal bed profile change and sand dune evolution on a sand beach. The sand beach studied was Sand Key Beach located on a barrier island in west central Florida and falls under the administration of Pinellas County.

The west central Florida coast is composed of an extensive barrier island chain including both wave dominated and mixed energy barrier islands [1]. According to [2], the beach zone for barrier islands in Pinellas County includes the area from the shoreline to the dunes and the area offshore where active sand movement occurs. Therefore, these barrier islands were no exceptions to impacts of hurricanes. Sand Key Beach was reported to have lost approximately 140,000 cubic yards of sand since the last renourishment.

Other barrier islands in the same location with Sand Key Beach such as Passage Key, Pass a Grille, Sunset Beach, Treasure Island, and Honeymoon Island all were reported to have the same condition of erosion and deterioration of sand beaches. After the Tropical Storm Eta, Sunset Beach was reported to have lost approximately 15 feet of sand dunes. The cost of renourishing Pass-a-Grille beach was estimated between 6 and 7 million dollars [3]. The value of barrier islands emanates from their nearly continuous beaches which nest to turtles, crabs and hoppers and many other creatures [4]. However, they are always subject to actions of wind and water and when those forces are driven by storms, the consequences are catastrophic [5].

A study by ref1a showed that by June 2022, about half of the 825 miles of the coastline surveyed in Florida had signs of critical erosion. With the sea level constantly rising, there has been an increased frequency of hurricanes and storms, thus increasing the coastal storm risk to the coastal communities. [6] supported that climate change will be the main driver of the increasing frequency of extreme storms and beach erosion will therefore continue to be a major problem for many coastal communities.

In this study, coastal erosion was investigated using a time-averaged numerical model CSHORE. The model can predict the beach profile and dune profile changes given some characteristic storm with inputs including storm waves, water surface elevations and currents [7]. The simulation done included one in which some set of parameters were changed to try to suit the conditions in the study area and then another simulation was conducted in which the default parameters of the model were used. Results were analyzed to compare with field measured data to generate conclusions.

2. Study Area

Sand Key is located on a barrier island in west central Florida on the Gulf of Mexico in Pinellas County. It starts just south of Clearwater Pass and continues down the island about 2 miles to where the Clearwater ends and Bellair Beach begins south of Dan's island. The western side of Sand Key faces the Gulf of Mexico and Gulf beaches and the eastern side faces the Intercoastal Waterway and Clearwater Harbor [8]. The beaches in Pinellas County are the foundation for the County's thriving tourism industry [9]. Recorded historical storms that have impacted Sand Key up to Madeira beach date back to 1848 when a severe 100-year tropical storm cut through John Pass [10]. In 1921, the barrier islands experienced a 50-year storm and the Indian Pass was reported to have filled up with sand joining upper Sand Key to lower beaches. Another severe storm was experienced on September 1 to 7 of 1950 and the groins and seawalls were constructed whilst annual maintenance started in the 1960s. Hurricane Gladys hit the islands in 1968 and was followed by Hurricane Agness in 1972. Beach nourishment was done in 1985 after Hurrican Elena a 10-year tropical storm. The beach nourishment extended for 2.1 miles from shoal offshore Johns Pass. Sand Key has been nourished every 6 - 8 years with the two recent nourishments in 2012 and 2018 [11]. Even though there have been historical beach nourishment projects on the beaches on the islands, [12] argued that beach nourishment seemed problematic on the islands that had experienced significant long-term recession. Barrier island and inlet morphology is greatly influenced by the longshore transport of sediment. Wave climate and availability of sediment at the time plays a big role in the process. The most important wave variables include wave height, velocity, angle and direction [10]. **Figure 1** below shows the location of the study area.

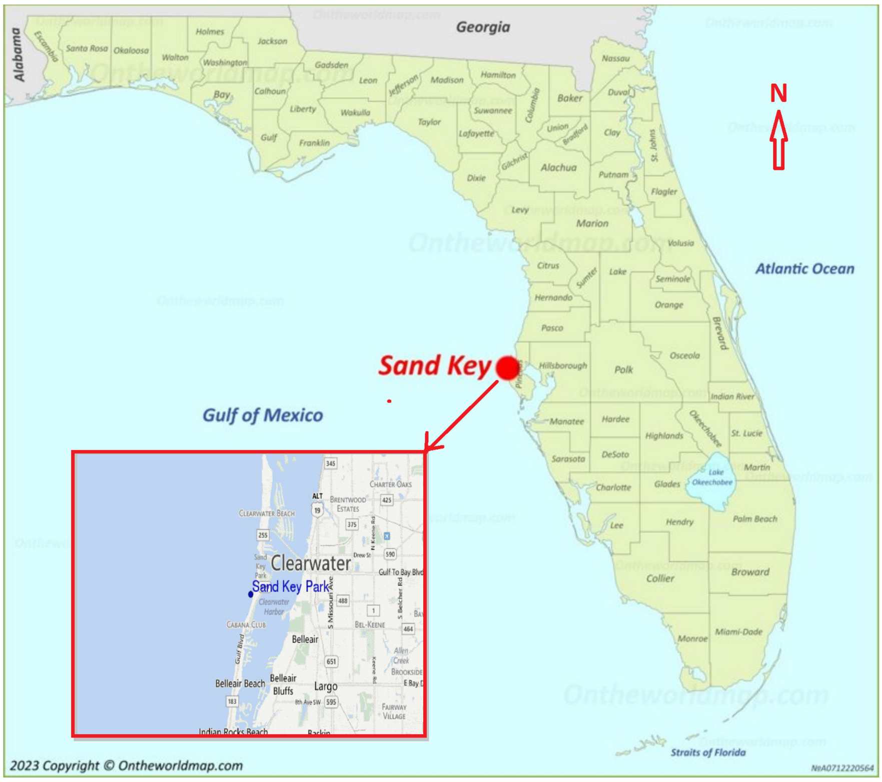


Figure 1. Map showing location of Sand Key Beach, Florida [13].

3. Methods

In this study, the time-averaged cross shore numerical model CSHORE was used to run simulations on different beach profiles along Sand Key Beach to investigate the temporal cross-shore profile changes. Numerical modelling was selected as the choice method to investigate the beach profile changes due to its simplicity and coast and time advantages over physical or analytical models. However, [6] argued that the major challenge in numerical modelling of sediment transportation emanates from the fact that there is yet no governing equations that can describe the motion of sediment particles. This was attributed to the complexity of coastal morphology due to the variation of properties of sediment particles which increases the difficulty to accurately determine and predict actual sediment movement. Even though hydrodynamic modelling of the nearshore environment has reached a very advanced stage with improved accuracy over the past decade, modelling of sediment transport has however not yet reached a similar level of accuracy [14]. Analytical methods have been used in previous research as another means to investigate coastal dune and beach erosion due to the simplicity of the methods. However, numerical methods also have their advantages over other methods in that they reduce the need for physical model requirements which are costly. But the positive side of using numerical models is that numerical methods have the ability to model conditions which are rather difficult to recreate in physical models and they reduce the extensive work needed compared to field measurements [15].

3.1. CSHORE Numerical Model

CSHORE is a beach and dune morphological model developed by [16] to predict the transformation of irregular nonlinear waves using the time-averaged continuity equations. The model was previously used by many authors and researchers to determine temporal cross-shore beach profile evolution due to either wave action or an extreme storm event. It has been useful in determining sand dune response to storms and changes in tidal currents. Though CSHORE is limited only to cases of alongshore uniformity, it was found to be simple and robust to its purpose. According to [7], the model uses linear wave theory and the Gaussian probability distribution to reduce the degree of empiricism. In his research, CSHORE was calibrated to predict the run-up of irregular waves, and the overtopping that can occur on coastal protection structures such as dykes and sand dunes as well as beaches. To that effect, 137 wave run-up tests were conducted and 97 wave overtopping tests.

Again, [16] came up with the continuity equations of bottom sediment which was written as follows.

$$\left(1-n_p\right)\frac{\partial z_x}{\partial t}+\frac{\partial q_x}{\partial x}=0 \tag{1}$$

And

$$\left(1-n_p\right)\frac{\partial z_y}{\partial t}+\frac{\partial q_y}{\partial y}=0 \tag{2}$$

where,

n_p = porosity of the bottom sediment normally taken as $n_p = 0.4$.

t = slow morphological time for change of the bottom elevation.

q_y = longshore total sediment transport rate.

And again, the bottom elevation change Δz_y during the interval Δt is expressed as

$$\Delta z_y = \frac{-\left|\Delta z_x\right|}{\left(1-n_p\right)A_x}\frac{\partial V_y}{\partial y} \tag{3}$$

where,

$$A_x = \int_0^x \left|\Delta z_x\right| \mathrm{d}x\,; \tag{4}$$

and

$$V_y = \int_0^{x_m} \mathrm{d}x \int_t^{t+\Delta t} q_y \mathrm{d}t \tag{5}$$

where,

Δz_x = bottom elevation change based on Equation (2) during time t to ($t + \Delta t$).

A_x = sum of the absolute value of Δz_x across the cross-shore line.

x_m = cross-shore distance of the line starting from the seaward boundary x = 0.

V_y = longshore sediment volume across the entire cross-shore line during time t to ($t + \Delta t$).

These and all other mathematical derivation equations for the model were given in Kobayashi (2013).

3.2. Model Tests and Calibration

CSHORE was modified to allow for simultaneous computation of more than one cross shorelines during calibration in experiments carried out at Dewey and Rehoboth in Delaware [7]. The bedload parameter b at a value of 0.002 was found not to cause sufficient erosion in the profile above MSL. This was attributed to the fact that the bedload parameter changes the profile thus affecting the computed hydrodynamics as well as the sediment transportation offshore of the beach. A value of b = 0.001 was found to give a better prediction of the erosion without accretion. The accretion volume was however predicted much better at b = 0.003 but the challenge was that at b = 0.003, no erosion was predicted. [17] indicated that the accurate prediction of both erosion and accretion is difficult due to the small differences between the bed-load transport and the transportation of sediments suspended in water. **Figure 2** below shows the location of Dewey Beach in North Carolina.

And again, **Figure 3** below shows model test results conducted during this investigation to qualify CSHORE for model tests on the study area.

One critical issue for most models was the assumption that during a storm event, the mean sea level remains constant while the profile change was only in the vertical so that the equilibrium of the dune profile was assumed to be based on the vertical profile change only [19]. However, [20] argued that numerical models were not very accurate since they tended to overestimate the actual volumes of sediment or rates of dune erosion [14]. [15] made a few suggestions to create large-scale physical data for dune erosion and some of the steps towards achieving better results were considered as follows.

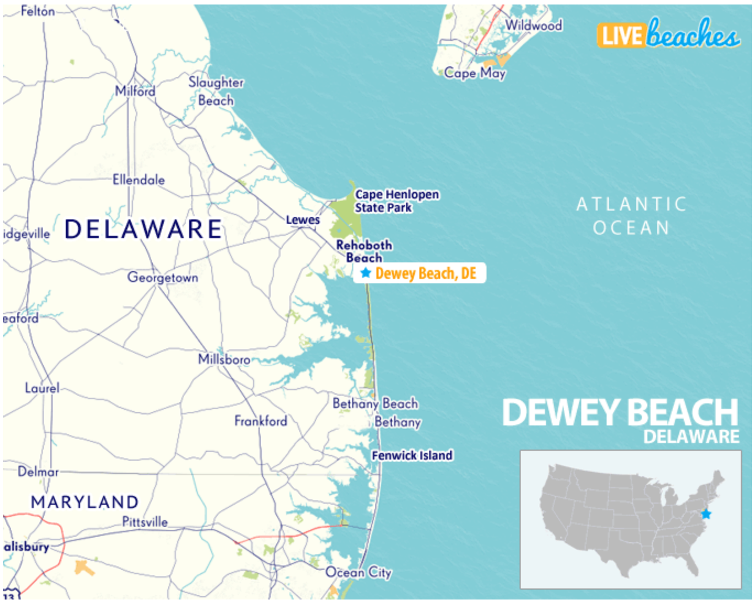


Figure 2. CSHORE was previously tested and calibrated at Dewey and Rehoboth beaches by [16] shown above [18].

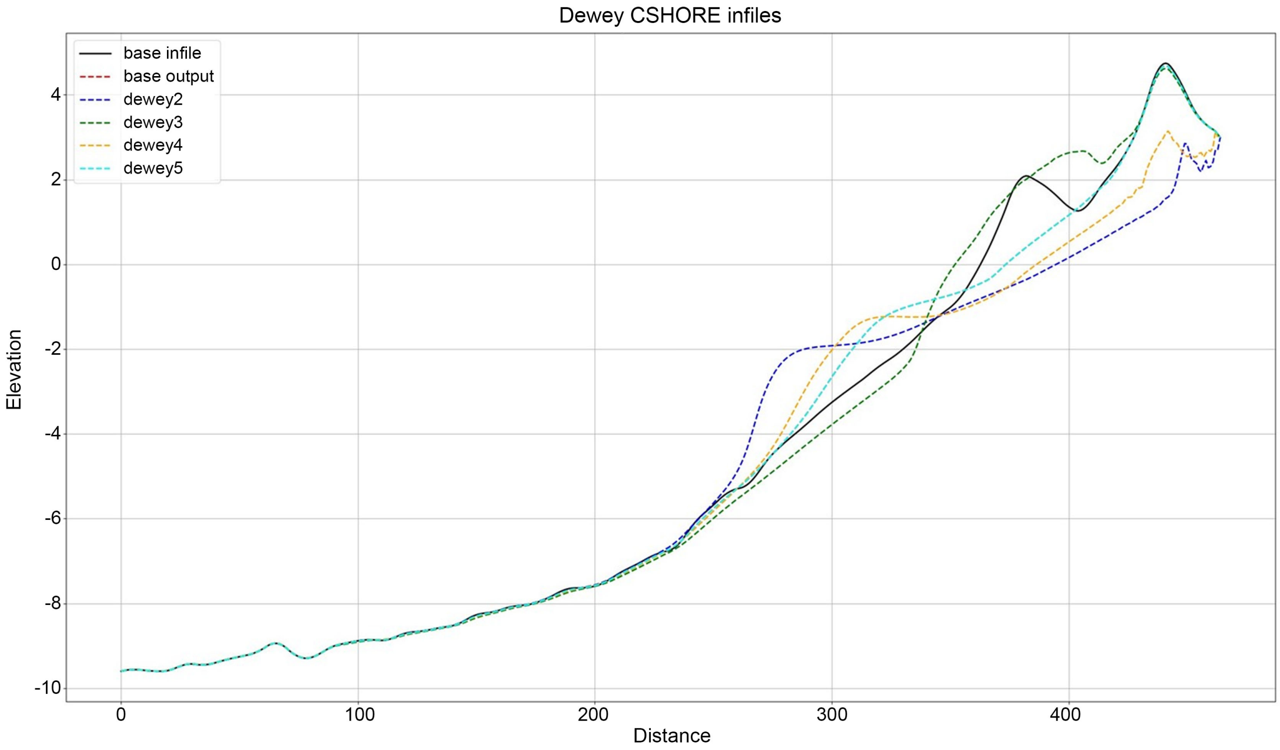


Figure 3. CSHORE results for model simulations using different parameters and data for Dewey beach profiles.

- Investigating more patterns of the interaction between waves and the sand dune and then take note of findings and observations.
- Changing load parameters and make a sensitivity analysis. Parameters that were targeted included water depth, significant wave height and wave period.
- Calibrating the numerical model using more accurate data sets collected on

the study area prior to modelling.

- Analyzing the relationships and concluding new empirical formulas that would relate the findings as applicable to the investigation.

Physical models have been used too over the years but are costly and not easy to make. However, many empirical formulas were derived from observations and analysis obtained from physical modelling. Physical modelling provides a basis for calibration and validation of numerical models.

An alternative solution to solving coastal engineering problems was the use of analytical models. Again, [15] pointed out that analytical models solved problems easily by utilizing marked simplifications in forcing conditions such as input data and boundary conditions. The advantage that analytical models will possess would be the simplicity in application which is assumed to be handy when initial conditions estimates are needed to drive the remainder of the model to give solutions. These models investigate the relationships between parameters and investigate causes and effects. Another basic assumption was proposed by [21] called the impact wave theory which assumed a linear relationship between the force F applied on the dune and the weight W of the sediment volume from the dune as follows:

$$\Delta W = CEF \tag{6}$$

where,

CE was assigned as an empirical coefficient.

In the relationship, the weight ΔW could also be written as:

$$\Delta W = \Delta V \rho s (1 - p) g \tag{7}$$

where,

ρs = sediment density.

p = porosity.

g = acceleration due to gravity.

As suggested by [15], analytical models could be calibrated based on the observed values from a physical model and application of the proper analytical method such as Least Square Method to derive optimum values of coefficients. Then, validation of the analytical model would include comparing between observed and calculated values for selected tests to determine if the values showed good agreements.

3.3. CSHORE Test on the Adjacent Barrier Island (Madeira Beach)

CSHORE was applied to model other beaches with known and measured field data on one of the barrier islands adjacent to the study area. The idea was to carry out as mant tests as possible and compare the results to known measured data and assess the validity of using CSHORE on the study area. Results proved assuring with an increased confidence to using CSHORE as the model for the investigation. Findings pointed out to the effect of longshore sediment transportation as a major force influencing erosion of the barrier islands. [4] noted that the prevailing direction of approach of the waves acting on the barrier islands was from the southeast which caused the south to north direction of longshore sediment. However the overall predominant direction of longshore sediment transport was from north to south but there were several cases where the predominant direction of sediment transport was from south to north [22]. Clearwater Beach Island and Caladesi Island into Hurricane Pass and as well as Sand Key and portions of Honeymoon Island up to Estero Island all experienced direction reversal of sediment transportation. Sea level rise has become a major reason the frequency of storm events has increased in the past years and many coastal communities will experience increased occurrences of storms and with high intensity. Many sandy beaches will suffer continued erosion and, in most cases, the cross-shore profile changes by retreating landward. Eroded sediments may be washed offshore but remain in the erosive condition or in the case of overtopping, may be deposited landward. [19] noted that the changes of the shoreline in the long shore were directly proportional to the sea level rise. Understanding dune evolution on a sand beach is therefore an important issue to accurately predict the flow circulation and the changes to the bathymetry. However, their evolution is still poorly understood due to their complex behavior [23]. **Figure 4** below shows the details of transects at Madeira Beach as per measured field data.

Figure 4. Madeira beach showing transects for field measurements [24].

Model simulations for Madeira beach using different parameters were conducted and the results are as shown in **Figure 5** below as a comparative analysis of the CSHORE performance and justification for use in this investigation.

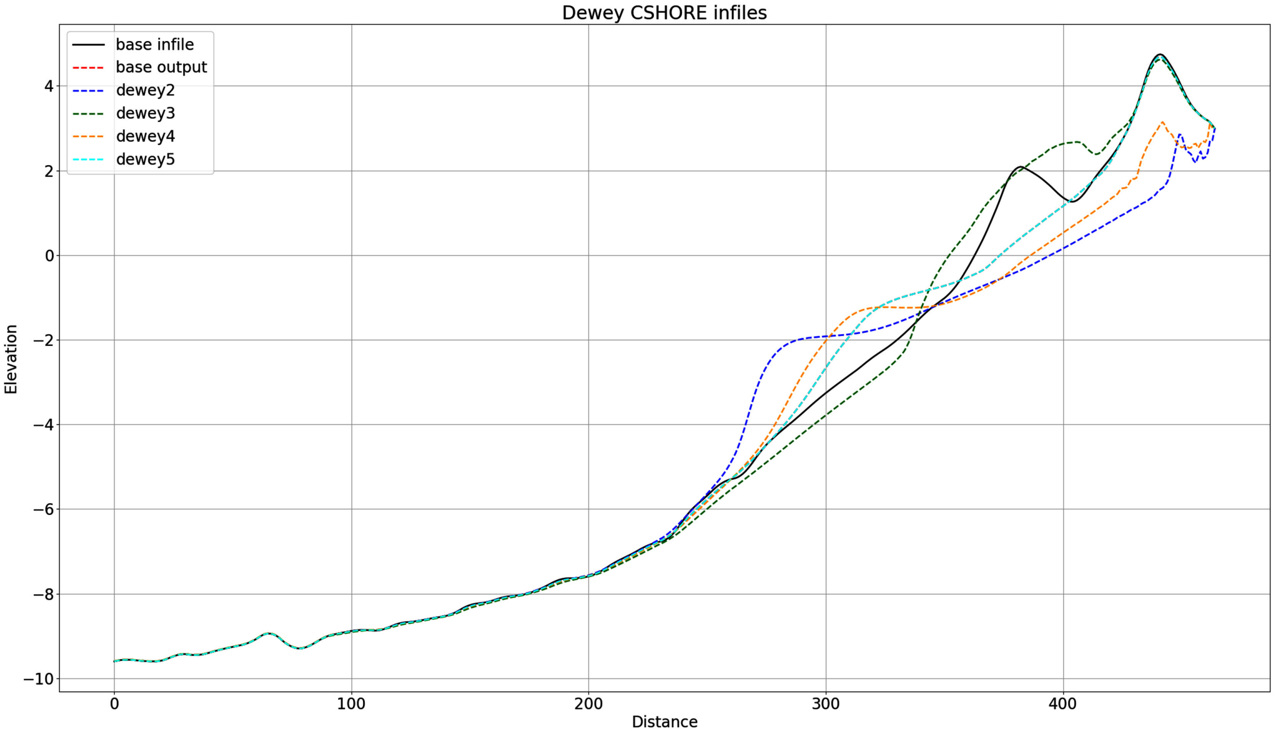


Figure 5. Results obtained from a model test for Madeira Beach.

3.4. Set-Up of the CSHORE Numerical Model

Water elevations, water circulation and tidal currents data sets were obtained from the Coastal Hazard Systems (CHS) and these inputs were used in running of the CSHORE model. On the CHS data website, data sets were obtained from points in the ocean at offsets less than 5 miles from the Sand Key beach. These points were appropriate because they would provide the exact wave climate data for waves that affected the study area by means of a set of input parameters derived by [17] as per the governing equations of the model. Some of the important parameters to be considered in the model which were detailed in [16] include:

Gamma (Υ)—an empirical factor used to adjust the variation of the model wave height against the actual measured wave height and ranges between 0.5 to 1.0. It is suggested to use a conservative value of 0.7 if, in the study area, there is no measured wave height data.

Mean grain size (D50)—the median sediment diameter of the beach sand soil in mm.

Wf—sediment fall velocity measured in m/s.

SG—sediment specific gravity of the beach sand.

EFFB—suspension efficiency due to wave breaking and the suggested range between 0.002 and 0.01.

EFFF—suspension efficiency due to bottom friction with a typical value of 0.01.

SLP—suspended load parameter with a range of 0.1 - 0.4.

SLPOT—suspended load parameter associated with the wave overtopping rate which ranges between 0.1 and 3.6.

Tan phi—the sediment limiting slope value measured as tan Ø and calibrated in the range of tan Ø.

BLP—bedload parameter determined to range between 0.001 to 0.004 and typically 0.002.

RWH—runup wire height (m).

JCREST—initial crest location for L = 1 which is the crest node of the maximum bottom elevation for the input bottom profile.

RCREST—initial crest height (m) for L = 1 which is measured from the input bottom elevation and usually corresponds to an input of the elevation data into the model.

AWD—swash velocity parameter which expresses the horizontal velocity U as a function of the water depth h in the wet and dry zone.

EWD—output exceedance probability which compares measured values corresponding to 2% of incident irregular waves and ranges between 0.01 and 0.015.

Table 1 below shows values used in the setting up of the numerical model for the Sand Key beach.

Table 1. Data used in setting up the CSHORE model.

Parameter	Value
Gamma (ϒ)	0.8
Mean grain size (D50)	0.3 mm
Wf	0.0448 m/s
Specific gravity (SG)	2.65
EFFB	0.005
EFFF	0.01
SLP	0.5
SLPOT	0.1
Tan phi	0.63
BLP	0.002
RWH	0.02
JCREST	145
RCREST	2.042
AWD	1.6
EWD	0.015

The depth at seaward boundary (m) was 3.2 m and the friction factor for the bottom interaction between water and seabed was 0.015. The value of the Still water level (SWL) above the elevation Z = 0 m was 0.573 m. Tidal currents were incorporated in the data for water elevations hence the cross-shore volume flux associated with the temporary variation of the still water level was included.

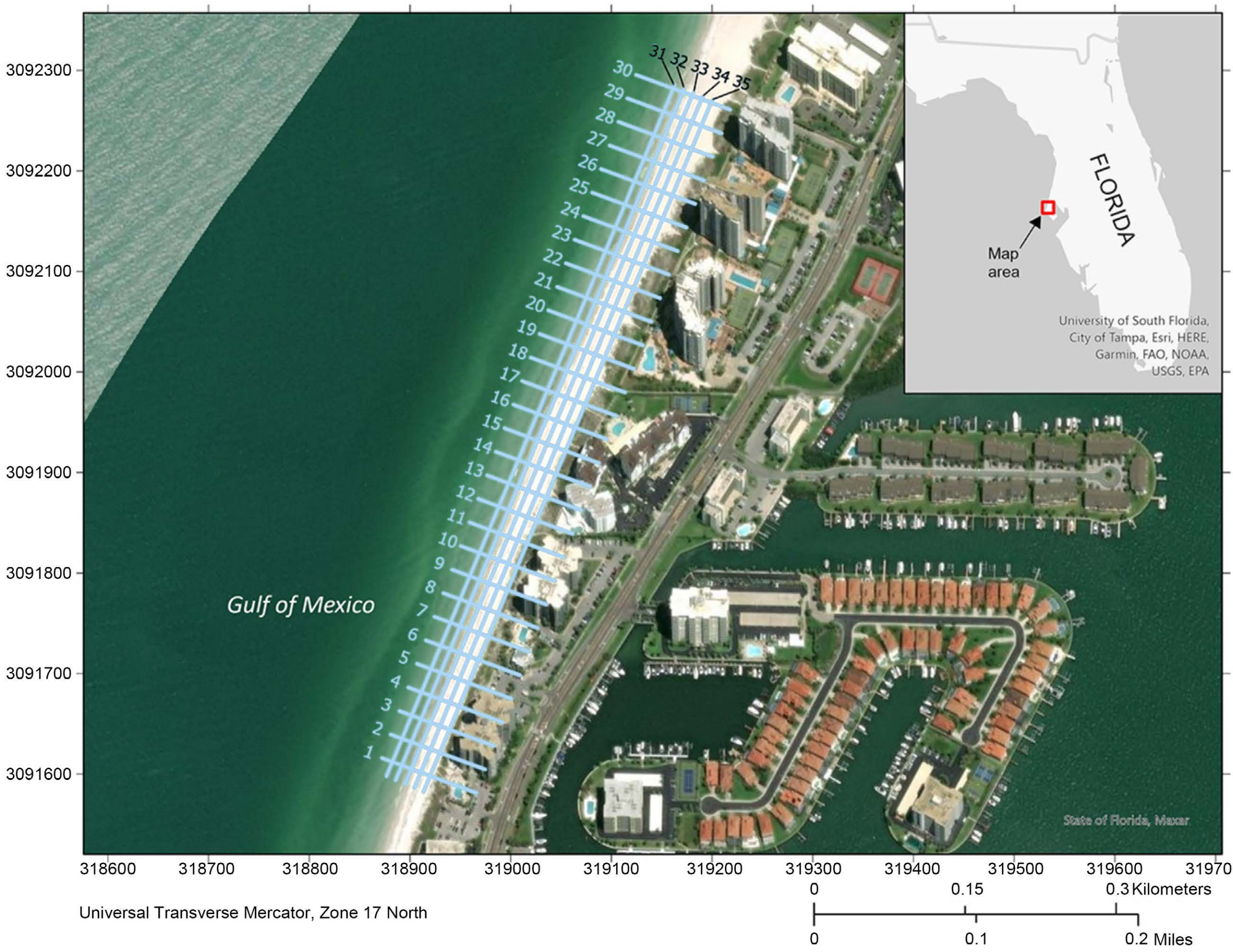
Assumptions

Some of the assumptions used in this study according to [16] include the following:

- The bottom of the beach profiles was assumed to be an impermeable bottom.
- No wind shear stresses were included.
- No vegetation was included in the computation domain.
- There are no seawalls or emerged coastal structures in the zone hence it was assumed that there would be no standing water or wave overtopping in the landward wet zone.

3.5. Field Data

Beach profile data used in the validation of the model performance at Sand Key Beach was the data measured and recorded by the USGS from 17 October 2018 until 11 September 2023. A series of profiles were surveyed as shown in **Figure 6** below. The model simulation was run with beach profiles extracted at approximately the same profile lines and results were analyzed.



University of South Florida, City of Tampa, Esri, HERE, Garmin, FAO, NOAA, USGS, EPA

State of Florida, Maxar

Figure 6. Image showing transects of profiles during field measurements [24].

3.6. Wave Data and Water Circulation

And again, Figure 7 below shows the water circulation conditions, and wave climate of the period selected in the simulation. From the data provided, the maximum wave height recorded was approximately 3.4 m whilst the maximum tidal elevation reached up to about 1 m.

Wave analysis was conducted using the Surface Water Modelling System (SMS) software with a grid angle set to 112.0 degrees. The reference time matching that of the simulation period was set to model the wave energy at Sandy Key Beach. The model showed that the frequency of waves ranged from a minimum of 0.04 to 0.4 Hz which translated to 3.0 to 25 second waves. The method used to generate waves was the shallow water method for generating a spectrum from parameters from the Coastal Hazard Systems to generate wave energy frequency and direction. Figure 8 below shows the wave spectra of the wave conditions.

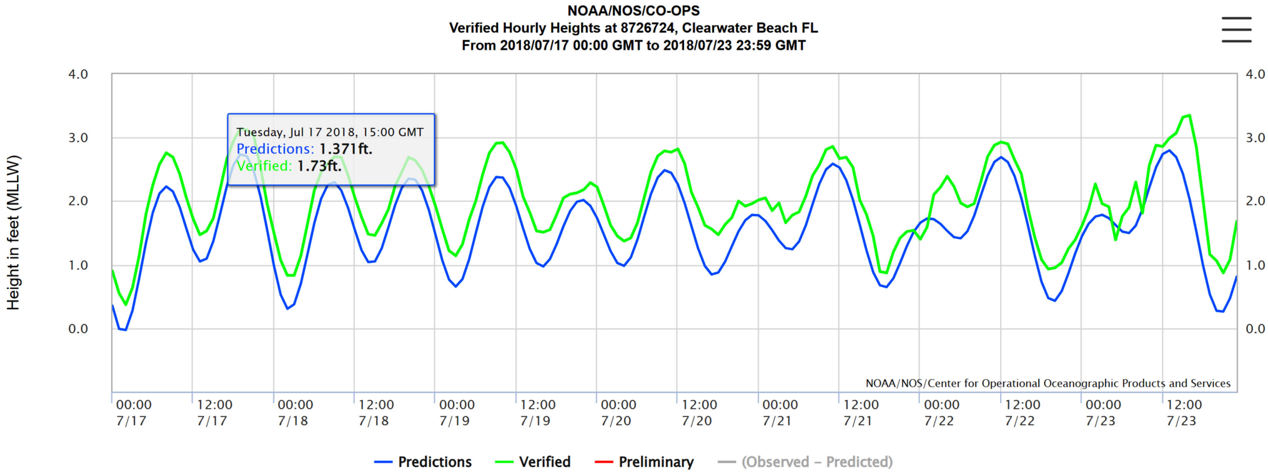


Figure 7. Timeseries plot of water level conditions at the time period of the model simulation in the inestigation [25].

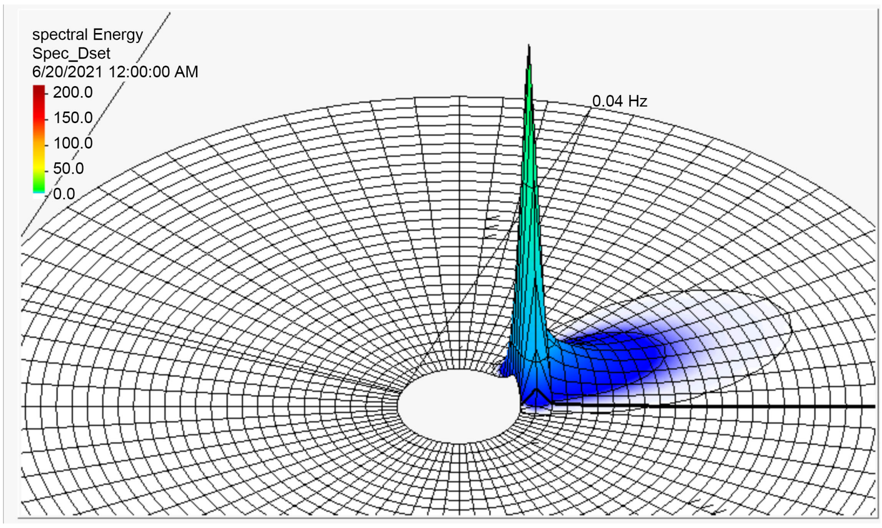


Figure 8. Wave spectrum energy grid for wave frequencies experienced during the period as viewed in Surface water modelling system.

Subsequently, Figure 9 below shows the distribution of wave energy vs frequency and direction for the parameters modeled in the SMS interface during analysis of wave conditions.

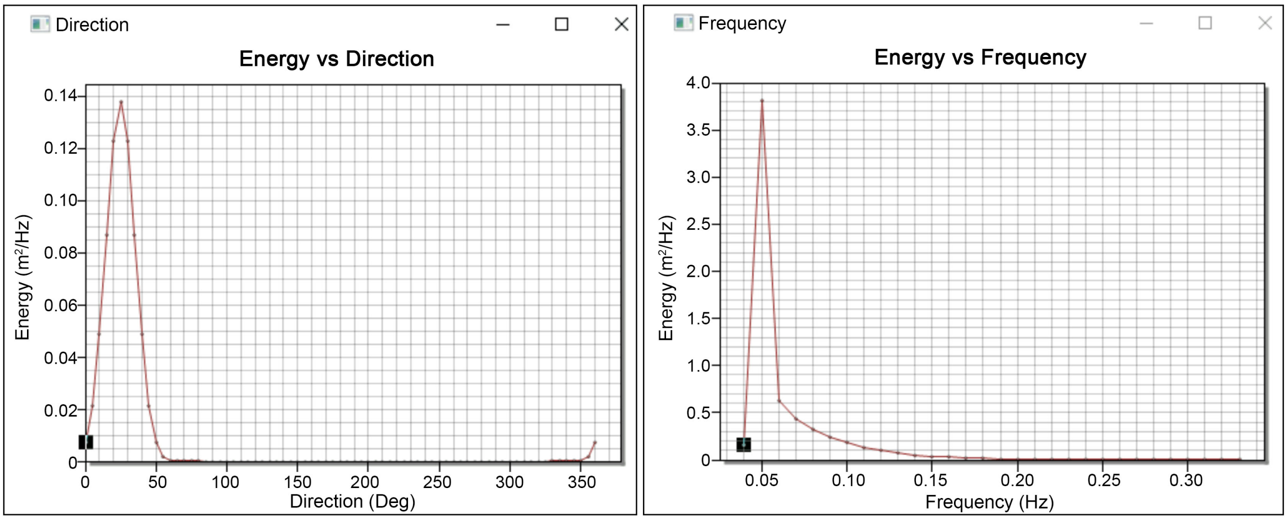


Figure 9. Distribution of wave energy and frequency as well as energy and direction from the model.

4. Results

In this study, storm events were identified as periods where the significant wave height exceeded 3 m and these were used in the model. The plots of predicted beach bottom profile were compared to the measured profiles and the plots indicated some discrepancies when visually compared with the measurements.

In the Figures below, the black dotted line represents the measured beach profile in 2018 after the beach nourishment project. The red line represents the beach profile from the measured field data. The field data measurements were collected in 2022 post-Hurricane Ian. The green line represents the CSHORE model prediction of the beach profile. The model generated the profile by using an input profile generated using an automated Python script application program interface designed to download data from the NOAA data viewer data sets using digital elevation model technology.

4.1. Beach Profile Line-01 to Line-08

Figure 10 below shows variation of model results to the actual measured data. The model output (green line) over-predicted erosion and deviated from the actual measurements. The model representation of the bed perturbations showed a steeper landward shift of the sand berm. The shoreline retreats further towards the land and there is significant sand loss when compared to the nourished beach profile. The overall changes are however not caused by a one-time storm event but a compounded effect of wave condition variations and seasonal changes. As depth increased below the 1m depth level, the model reproduced the bed slope movement a meter deeper than the actual measurements.

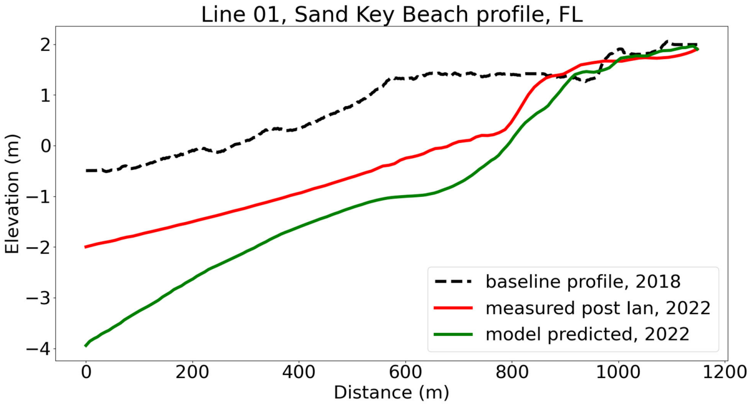


Figure 10. Model results vs Measured data for beach profiles of lines 01 to 08.

4.2. Beach Profile Line-09 to Line-10

The changes across both the measured data and the model results which agree at the sand dune slopes give evidence of the cross-shore processes such as over wash of the sand dune. This was illustrated by both onshore and offshore changes of the bed profile. Deviation of the model results to the actual measured data in the swash zone was observed though the magnitude was not as great as compared to Line 01-08 results. Model results showed a good agreement in the bed profile variations along the cross-shore profiles especially on the sand dune zone as well as on the slope direction and angle of the sand berm as it retreated landward. Figure 11 below shows the results.

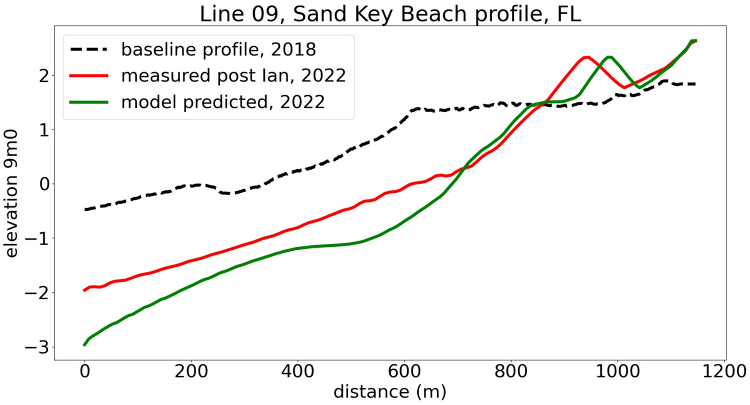


Figure 11. Model results vs Measured data for beach profile of Lines 09 to 10.

4.3. Beach Profile Line-11 to Line-14

Localized variations of the model predictions against the actual measured data were identified. Compared to the cases in line 01-08 results as well as line 09-10 results the model results did not show a wider margin of deviation from the measured data but a balance between eroded profile and accretion along the cross shoreline. As depth increased, the measured data showed a uniform sediment flux with a constant gradient whilst the model indicated the potential for more sediment transportation at lower depths before merging into a final bed form with a constant or no slope. **Figure 12** below shows the results as plotted.

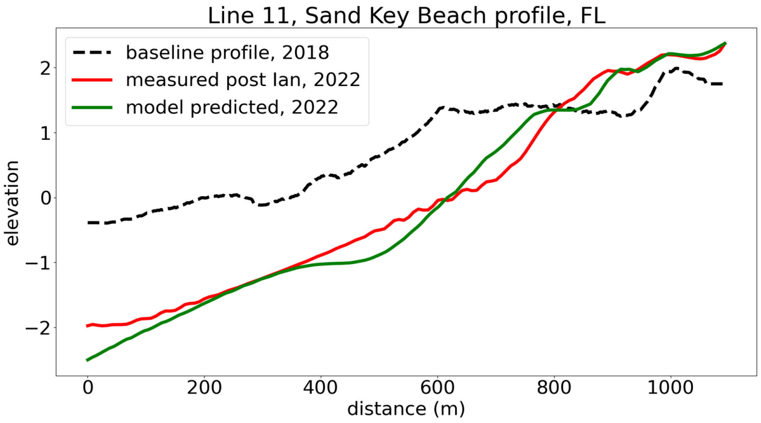


Figure 12. Model results vs Measured data on beach profiles from Lines 11 to 14.

4.4. Beach Profile Line-15 to Line-19

Model results showed a good agreement with measured data. The bigger size of the sand dune provides more protection to the landward sand. More erosion resistance was generated and there was less sediment migration back into the ocean. The results in the model supported the conclusion by [3] that bed slope temporal evolution was dependent and influenced by dune slope and height and position. **Figure 13** below shows the plot of the results.

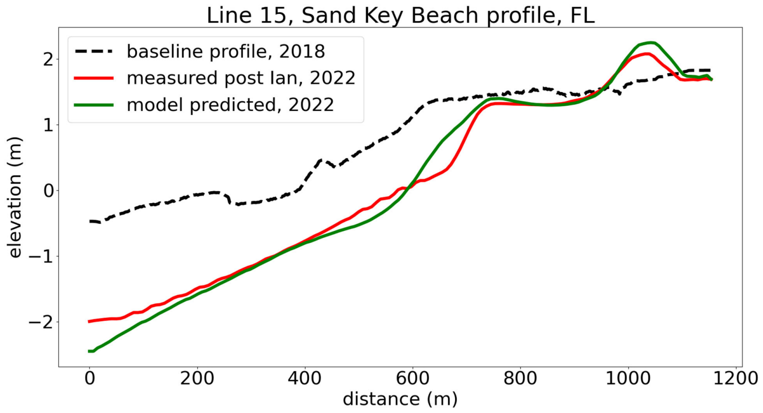


Figure 13. Model results vs Measured data for beach profiles of Lines 15 to 19.

4.5. Beach Profile Line-20

The overall trend and magnitude of contour change of both the model and the measured profile followed closely with one another and showed a similar pattern as shown in **Figure 14** below. The slope of the sand berm at elevation 0m was comparatively steeper for the measured data than the model prediction. It is worth noting that the cross-shore profile changes show a landward retreat of the shoreline therefore beach nourishment helps the recovery process of the beach and minimizes the shift of the shoreline as caused by the influence of the longshore transport gradient.

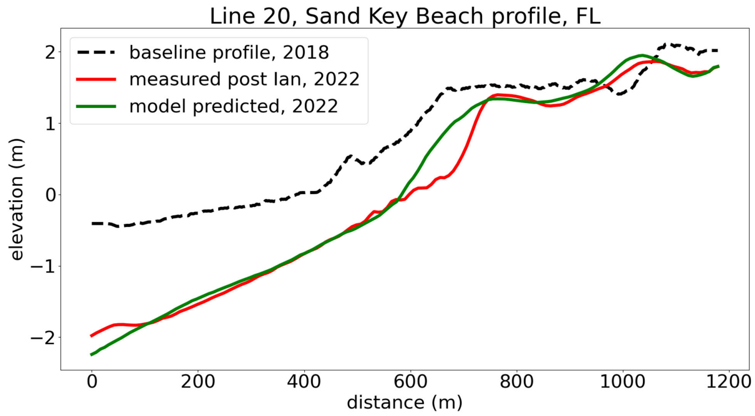


Figure 14. Model results vs Measured results for beach profile of Line 20.

4.6. Analysis of the Model Performance

The root mean square error (RMSE) and the mean absolute error (MAE) were computed and Table 2 below shows values for the model error.

Table 2. Root mean square and Mean absolute error computations.

Beach profile line number	Root Mean Square Error (RMSE)	Mean Absolute Error (MAE)
Line 01	0.85	0.71
Line 02	0.67	0.55
Line 03	0.67	0.55
Line 04	0.53	0.43
Line 05	0.46	0.37
Line 06	0.37	0.31
Line 07	0.36	0.32
Line 08	0.39	0.35
Line 09	0.46	0.39
Line 10	0.39	0.32
Line 11	0.23	0.18
Line 12	0.18	0.13
Line 13	0.32	0.26
Line 14	0.20	0.14
Line 15	0.17	0.12
Line 16	0.28	0.23
Line 17	0.24	0.19
Line 18	0.21	0.12
Line 19	0.18	0.13
Line 20	0.18	0.10

However, other methods could be employed such as the Bayesian method, where parameter distributions are estimated, though the method will not allow statistically independent events to merge [26]. The low values of the root mean square error indicate that the model fits the actual measured data. Observations showed that beach nourishment in 2018 had a huge positive impact in fortifying the beach berm hence a wider and higher beach berm as shown on the initial beach profiles measured in 2018. Model predictions generally show that the cross-shore model over-predicts the erosion compared to the actual data. This over prediction is more common where the beach profile is submerged. CSHORE generates forcing in the swash zone by hydrostatic oscillations of short waves of different period therefore synthesizing wave groupings. Because CSHORE is a time averaged numerical model, the time averaging of the swash generates errors that cannot be accounted for only when the correct parameters are used in the model input data [27]. As a result, a monochromatic wave could simulate the wave energy and sediment transportation to some good extent but will give a lower prediction of the wave run up under random wave conditions [28]. **Figure 15** below shows model evaluation using 5% and 10% error bands.

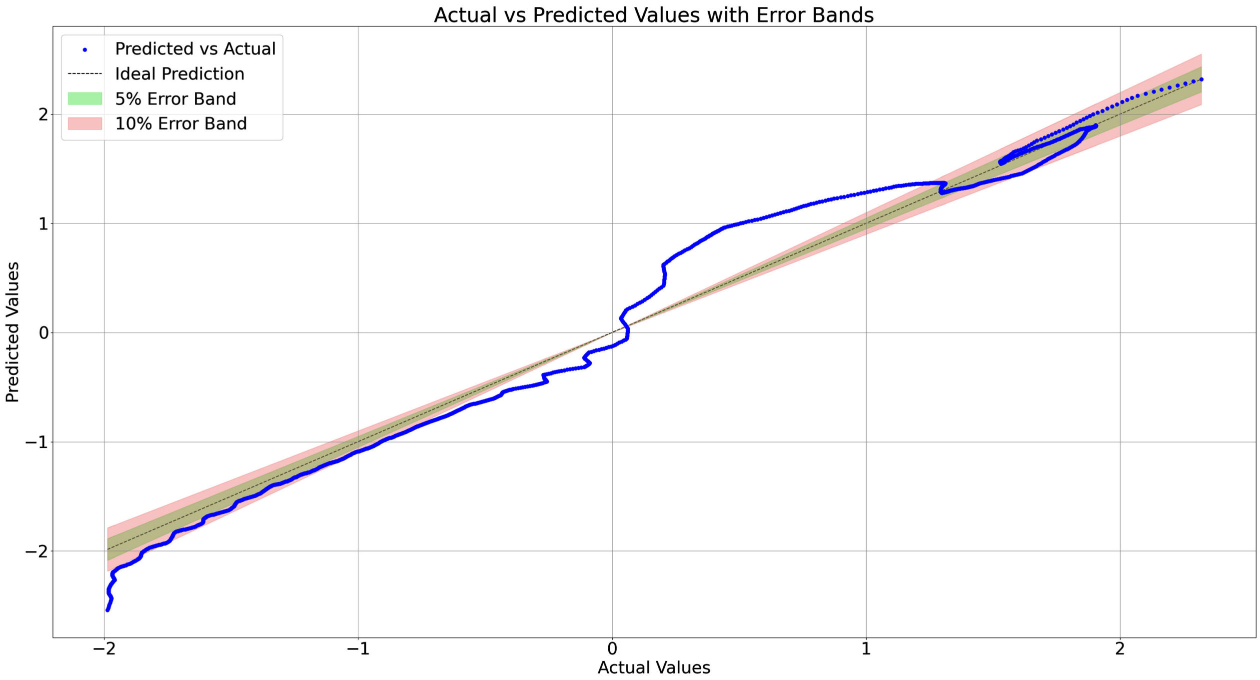


Figure 15. Error analysis using 5% and 10% error bands.

Error bands showed model deviations in the positive spectrum thus raising a validation question on the results. It is important to note that, further investigations would need to be carried out using different models that predict cross shore sediment transportation. However, the better results on the sand dune do not justify the complexities at the profiles below the MS and since the model does not do better in modelling accretion which introduces beach recovery in later periods as the water depth is forced to change rapidly in the swash zone, the model limitations are acknowledged in the investigations. However, in a bid to give a more accurate idea on what can be expected on a beach after a severe storm, the model gives a better understanding of what to expect from impacts of a storm on a temporal basis for better decision-making during design and maintenance of sand beaches.

According to [12], beaches have a resilient feature that they are partially self-healing. During storms, some berm sand moves offshore thereby creating large bars that cause waves to break further offshore reducing damage to dunes and infrastructure. Within months following a storm, the sand is returned to the beach by calm weather waves. Increasing sea level rise due to global warming adds significant risk to beach recovery. In the barrier islands, there is high development such that retreat is impossible. A more likely approach would be to maintain the groin systems to aid the beach in trapping sand to counteract the effects of the rising sea level. Due to the increased frequency of severe storms, the barrier islands no longer recover at a fast pace than before human influence hence beach nourishment after some period would help the beaches recover from the changing climate. Beach nourishment would also raise nearshore profiles [3]. The refurbishment of the groin system helps in that the new groins are designed with the rising sea level in mind and hence will be able to help in the recovery of the beach in the long term before the next phase of refurbishing the groins several years in the future. It is important to note that when modelling beach response and recovery, two or more storm events affect the beach erosion and recovery dynamics because it is likely that two or more storm events occurring within a few days of each other may yield more extensive beach erosion than a single event [29]. The compounding effect of many storms has the effect of causing the particles to transition from a very low flow state to an extremely high flow state thus resulting in more erosion [30].

5. Conclusions

This study used the cross shore numerical model (CSHORE) to reproduce beach erosion at Sand Key Beach in Florida for the period year 2022 post Hurricane Ian. The base line beach profile used was the beach profile measurements made in 2018 soon after the beach nourishment project done on the beach. The findings showed that significant erosion can occur after an extreme storm. More erosion increases with time due to wave action on the sand beach and also the compound effect of minor storms throughout the year. However, beach nourishment helps restore the beach and plays a major role in the beach response to a severe storm. It also helps in the beach recovery and adds to the sand budget of the beach berm thus fortifying the cross-shore beach profile against severe storms and wave action.

The evolution of the seabed floor from the initial profile can be attributed to the hydrodynamic conditions used in the modelling. The dune was severely eroded and at the interface of the seabed and the landward zone, the erosion was complemented by sediment accretion in the shallow water region. The geometry shows that the dune slumped inwards resulting in sediment transport. In the erosive zone, the eroded sand however slumped offshore direction but remained in the region without further transportation in the cross-shore direction.

The numerical model CSHORE was compared to small scale field data to predict beach morphology for a short-term period and as was previously demonstrated. CSHORE's application to coastal engineering problems. Further characterizing the seasonal changes in event frequency from the changing climate is essential for a more plausible simulation.

6. Recommendations

Though beach nourishment can be expensive and needs to be maintained, it is practical on shorelines sufficiently developed such that it has high returns on investment in terms of local economic development. Maintaining wider beaches should be sufficient for Sand Key Beach to ensure an effective way to dissipate wave energy. This way, the destructive force of waves will fall on the beach rather than on the structures. Monitoring performance of sand beach profiles with the changing wave climate is very important to assess the suitability of current structures given the rising sea levels and increased frequency of coastal storm risks. In this study, a synthetic tropical storm was used and applied on the same initial profile, introducing an error source. The CSHORE model over predicted the effects of the storm on the beach profile. An improvement would be to use different initial profiles thus effectively modelling a storm event forcing on the sand beach. However, numerical modelling will in most cases have variable results even when calibrated with the correct parameters. Evaluation of the model error however showed very low root mean square error indicating that CSHORE model predictions gives an accurate and good representation of the cross shoreline temporal evolution. The model application is significant in designing beach nourishment and coastal storm risk analysis. Further studies to quantify the total volumetric loss of the sand beach from the nourishment period would be important in order to assess the recovery of the beach and aid in the future planning of nourishment projects.

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Conflicts of Interest

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

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