INTEGRATION OF MORPHODYNAMIC MODELING WITH FIELD OBSERVATIONS OF HURRICANE IMPACTS ON NATURAL AND HYBRID INFRASTRUCTURE

QIN CHEN[1], NAVID JAFARI[2], LING ZHU[3], JIE HUANG[4], JACK CADIGAN[5], JASMINE BEKKAYE[6], AND BRITT RAUBENHEIMER[7]

1. *Department of Civil and Environmental Engineering, Marine and Environmental Sciences, Northeastern University, Boston, MA 02115, USA. q.chen@northeastern.edu.*
2. *Department of Civil and Environmental Engineering, Louisiana State University, Baton Rouge, LA 70803, USA. njafari@lsu.edu.*
3. *Department of Civil and Environmental Engineering, Northeastern University, Boston, MA 02115, USA. l.zhu@northeastern.edu.*
4. *Department of Civil and Environmental Engineering, Northeastern University, Boston, MA 02115, USA. huang.jie1@northeastern.edu.*
5. *U.S. Army Engineering Research and Development Center, Vicksburg, MS 39180, USA. jack.a.cadigan@usace.army.mil.*
6. *Department of Civil and Environmental Engineering, Louisiana State University, Baton Rouge, LA 70803, USA. jbekka1@lsu.edu.*
7. *Department of Applied Ocean Physics and Engineering, Woods Hole Oceanographic Institution, Falmouth, MA 02543, USA. braubenheimer@whoi.edu.*

Abstract: Guided by field observations collected during and after Hurricane Laura (2020), the XBeach model is used to simulate the hurricane impact on morphodynamics, including shore erosion and overwash, with and without the low-crested breakwater at the Rockefeller Wildlife Refuge in southwestern Louisiana, USA. The field data demonstrates the spatiotemporal variation in overland flow and storm surge and wave attenuation (flood protection) provided by the natural and nature-based infrastructure at the study site. The model result shows the importance of modeling wetland vegetation effects properly. Vegetation biomechanical properties need to be incorporated into the numerical models to accurately simulate the impact of hurricanes on natural and hybrid infrastructure.

Introduction

The protection of U.S. coastal communities, economic hubs, and infrastructure networks is critical to our national security and long-term prosperity. Engineered solutions to mitigate hurricane impacts have relied on gray (hard) approaches, with specific design and performance metrics informed by the geotechnical and coastal engineering community conducting extensive numerical, experimental, and field investigations of levees, floodwalls, breakwaters, and seawalls. While well-designed and constructed gray infrastructure can be effective during hurricanes, they are not only expensive to build but also costly to maintain and retrofit. In contrast, natural and nature-based infrastructure (NNBI) consisting of dunes, salt marshes, mangroves, coral or oyster reefs, and barrier islands mitigate coastal flooding and shoreline retreat caused by wave action and storm surge at lower cost. However, the effectiveness of NNBIs as a “line” of coastal defense alone or in combination with hard infrastructure to provide flood risk reduction remains unknown. New models are needed that can quantify the response and effects of NNBI to coastal storms, capture the interaction of NNBIs and hard structures that form a hybrid solution, and provide decision support tools for coastal communities.

Hurricane Laura, a category 4 hurricane, made landfall on the southwest Louisiana coast near Cameron, LA at 6:00 UTC on 27 August, 2020. Prior to Laura’s landfall, we deployed an array of surge and wave sensors, collected unmanned aerial vehicle (UAV) imagery, and conducted pre-event topographic surveys at the Rockefeller Wildlife Refuge (RWR) which was Laura’s hardest hit area. After the surge water receded, the field team retrieved the sensors, collected elevations and multispectral UAV imagery, and surveyed infrastructure damage along the southwest corridor of Louisiana, from Abbeville to Cameron. Only six weeks after Hurricane Laura, the Category 3 Hurricane Delta made landfall 20 miles west of the RWR. The field team conducted another post-storm reconnaissance to collect repeat elevations as well as geotechnical and ecological data. These field observations from both hurricanes as documented in Cadigan et al. (2022) form the basis for this study that integrates the field measurements with numerical modeling.

The objective of this study is to advance our understanding of the morphodynamic response of NNBI to extreme events. We are focused on the spatial variability of surface waves and morphological change caused by the two major hurricanes with and without the presence of low-crested breakwaters in southwest Louisiana. A multi-disciplinary approach that integrates event-driven field observations of storm surge, waves, geomorphological change, and ecological response with high-resolution numerical modeling based on Delft3D, SWAN and XBeach is employed to answer three key research questions: (1) What is the spatiotemporal variation in overland flow and storm surge and wave attenuation (flood protection) provided by the NNBI? (2) What is the efficacy of current numerical models to predict coastal erosion and sediment transport across a natural landscape that protects coastal communities and civil infrastructure? (3) How do geotechnical properties, stratigraphy, and vegetation biomechanical properties control the magnitude of Gulf Coast Chenier Plain (GCCP) shoreline retreat to hurricanes? This paper is focused on the first two questions and documents some preliminary modeling results.

Study Site and Field Data

The Rockefeller Wildlife Refuge (RWR) is a state-managed wildlife refuge, located in Cameron and Vermillion Parishes, Louisiana (Fig. 1A-B). The average rate of erosion-driven shoreline retreat is approximately 14.5 m/yr between 1998-2017, with extreme rates of 19 m/yr and 25.5 m/yr during the years when Hurricanes Rita (2005) and Ike (2008) struck (Yao et al., 2018). Comparisons between shoreline positions from the U.S. Department of Agriculture (USDA) National Agricultural Imagery Program (NAIP) aerial images (Fig. 1C-D) show an approximate shoreline retreat of around 15m/yr. This fragile shoreline is heavily impacted by storm events. Hurricane Laura, a category 4 hurricane, made landfall on the southwest Louisiana coast near Cameron, LA on 27 August, 2020. Before the landfall of Hurricane Laura, a collaborative team of members from Louisiana State University, Northeastern University, Woods Hole Oceanographic Institution, and the University of North Carolina at Wilmington deployed instrumentation at the RWR. Two instrumentation transects shown in Fig. 1C-D are the primary interest for this study: one represents the protected shoreline by the breakwater (Transect A), and one represents the natural shoreline that is not fully protected by the breakwater (Transect B). To understand the performance of NNBI, the two transects were established and visited for instrumentation staging and data reconnaissance on 25 August 2020, about 36 hours before the landfall of Hurricane Laura, and on 4 September 2020, 8 days after the landfall of Hurricane Laura.

The breakwater and natural transects were surveyed with a GPS-RTK system to measure elevation profiles from the shoreline inland to infer geomorphological changes and sediment deposition on the marsh platform. In the breakwater transect (Transect A), three gauges were placed at equal spacing from the shoreline inland. In the natural shoreline transect (Transect B), four wave gauges were placed from the shoreline inland. The wave gauges were sampled at 10 Hz to take continuous absolute pressure data. The raw pressure was firstly converted to gauge pressure using the atmospheric pressure measured at a nearby NOAA station (8768094) in Calcasieu Pass, LA, about 51 km northwest of the offshore wave gauge. The continuous time series of gauge pressure was divided into bursts with each burst containing 30-minute data. For each burst, the gauge pressure data were corrected and transformed from the time domain to the frequency domain by using the Ocean Wave Analyzing Toolbox, OCEANLYZ V2.0 (Karimpour and Chen, 2017). Characteristic wave parameters, such as the zero-moment wave height (H_{m0}) and peak wave period (T_p) were obtained from each data burst.

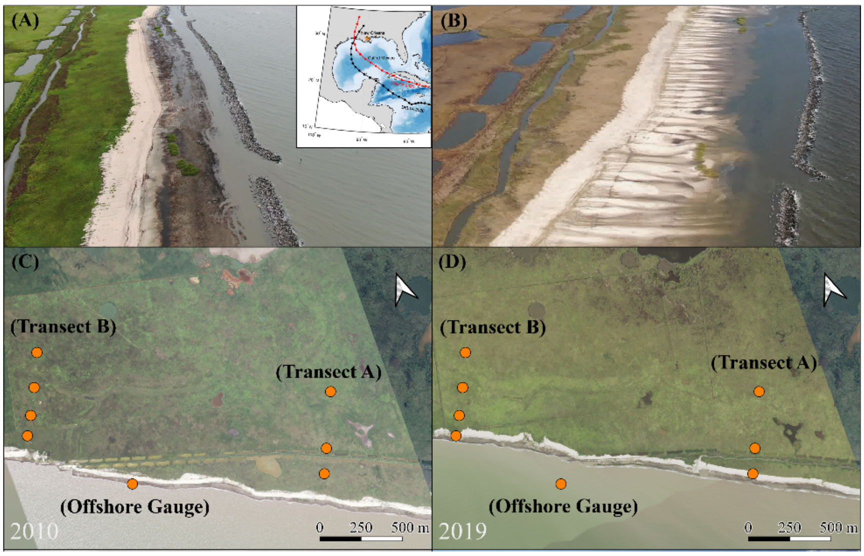

Fig. 1. Overview of study site at Rockefeller Wildlife Refuge, LA: (A) Shoreline pre- Hurricane Laura showing from (right to left) low-lying breakwater, mudflat, beach, and wetlands; (B) Change in morphology after Laura indicates shoreline retreat, sediment transport, and wetland damage; (C) and (D) Location of pre-deployment sensors to measure surge, waves, and soil pressures (red circles) overlaid on satellite images from 2010 and 2019, respectively.

Numerical Models

The two-dimensional, depth-averaged version of Delft3D-FLOW (Lesser et al. 2004), spectral wave model SWAN (Simulating WAves Nearshore, Booij et al. 1999) and morphodynamic model XBeach (Roelvink et al. 2009) are coupled to simulate overland flow and morphodynamics of the Chenier Plain with unique eco-geological characteristics in response to hurricanes. To build a coupled overland flow and morphodynamic modeling system, a nested modeling approach is used that integrates the physical processes of hurricane wind, waves, storm surge, sediment transport and overwash. The overall modeling effort is threefold: (a) modeling of overland flow generated by waves and surges of Hurricanes Laura and Delta using Delft3D and SWAN explicitly taking wetland vegetation into account, (b) modeling of sediment transport and wetland bed level changes caused by both hurricanes, and (c) modeling of overwash and shoreline retreat using XBeach.

For (a), the two-level nested grids as in Johnson et al. (2021) are employed to allow finer grid resolutions near the shoreline while reducing the overall computation time. To account for the vegetation effects on surge and wave attenuation, the physical properties of each vegetation type, obtained from the insitu measurements and the USDA herbaceous plant database and the literature, are incorporated into the coupled Delft3D-FLOW and SWAN model. The vegetation cover is based on the 2007 US Geological Survey aerial survey (Sasser et al. 2008). The meteorological forcing (i.e., wind velocity and atmospheric pressure) are generated by merging a tropical cyclone model (Holland et al. 2010), based on the National Hurricane Center's best track data for Hurricane Laura and Delta, with background wind velocities and pressure fields provided by the NCEP North American Regional Reanalysis (NARR).

For (b) and (c), a local XBeach model of the RWR is nested within the Delft3D-FLOW and SWAN model grid (see Fig. 2). XBeach is executed in the "surf-beat" (SB) mode which solves the non-linear shallow water equations at the wave group time scale. The computational grid for operational runs is curvilinear with spatially varying resolution to resolve the natural and hybrid infrastructure. As an initial trial, we use a rectilinear mesh with a uniform resolution of 10 m. The simulation duration covers a period from 26 August (01:00 UTC) to 28 August (00:00 UTC), 2020. The test domain spans approximately 9 km in the alongshore direction and 11.5 km in the cross-shore for a total area of 130 km^2, which fully covered the two cross-shore instrumentation transects at the RWR. The total number of grid cells of the testing domain is 1,035,000. The subaerial topography, as input, is generated by using the 2022 Coastal National Elevation Database (CoNED) digital terrain model (DTM) (OCMP 2022). The bed friction was represented by the Manning coefficient, with 0.045 for the wetlands and 0.02 for the beach and seabed.

As the first step of this study, the hindcast from CERA (Coastal Emergency Risks Assessment) based on the ocean circulation model ADCIRC (Luettich and Westerink 2004), as opposed to the results from the coupled Delft3D-FLOW and SWAN model, are utilized as alternative offshore boundary conditions to provide offshore water levels and wave conditions to force the XBeach model. ADCIRC model solves the depth-averaged barotropic form of the shallow water equations for water levels and momentum. ADCIRC has been validated for a variety of storm events that stroke the Southern Louisiana coastline (e.g., Dietrich et al. 2010, Sebastian et al. 2014). Here, the hourly water levels and wave heights from the ADCIRC stations (as shown in Fig. 2) are linearly interpolated across the XBeach model boundaries. Hourly wave period from the offshore gauge (OF) station (Fig. 1C) serves as the offshore wave period condition of the model. The JONSWAP spectrum is applied at the offshore boundary. Wave directions are confined to shore-normal incident. Zero gradient flow and wave energy conditions are specified on the lateral boundaries. Absorbing-generating boundary conditions, which allow low-frequency oscillations in the water level to pass out of the domain, are used on the landward and seaward boundaries (van Dongeren and Svendsen, 1997) by following Johnson et al. (2021).

The model accuracy is quantified through two standard statistical quantities: (1) the bias or mean error (denoted as "*bias*"), which describes the overall tendency of overprediction or underprediction; and (2) the root-mean-square-error (denoted as "*RMSE*"). The two quantities are calculated as:

$$bias = \frac{\sum_{i=1}^{N}(M_i - O_i)}{N} \tag{1}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(M_i - O_i)^2}{N}} \tag{2}$$

where N is the sample size, M and O are the model results and observations, respectively, and i is the index in a series of data.

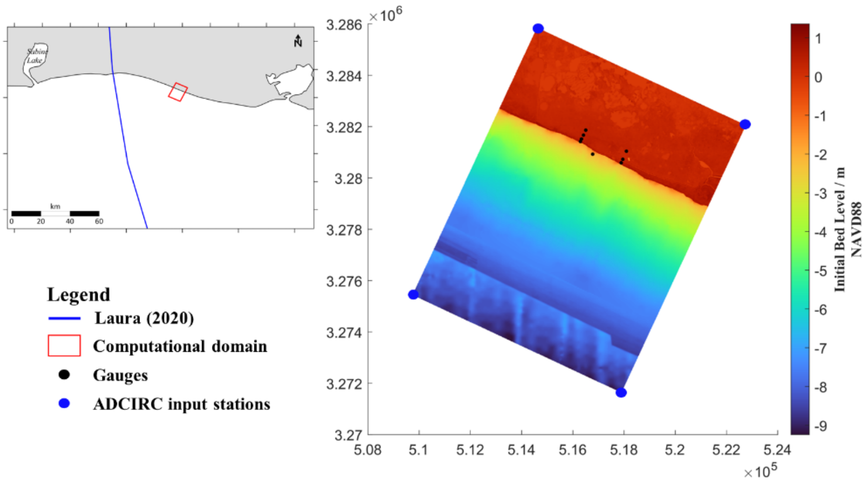

Fig. 2. XBeach model test domain, locations of the deployed wave gauges and the ADCIRC input stations (2 offshore and 2 onshore), and Hurricane Laura's track.

Results and Implication

Spatial Variations of Wave Height Along Two Cross-shore Transects

The temporal variations of water depth and H_{m0} at the offshore wave gauge and wave gauges along the two transects are shown in Fig. 3. At the offshore wave gauge location, the maximum H_{m0} of 2.7 m and the maximum water depth of 7.0 m were recorded around 06:00 UTC on 27 August, 2020, about the same time as Hurricane Laura made landfall near Cameron, LA. Both transects show wave height reduction as waves propagate landwards. Although protected by the low-crested light-weighted breakwaters, wave gauge BW-1 measured slightly larger waves than did NAT-1 on the natural transect because of the combined three-dimensional effects of wave-structure-bathymetry interaction when the breakwaters were submerged. The breakwaters may lead to wave amplifications as observed by Zhu et al. (2020) among others.

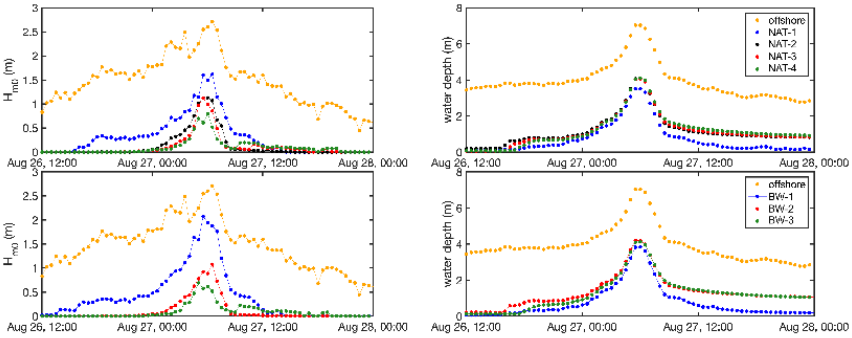

Fig. 3. Comparisons of measured zero-moment wave heights and water depth at the offshore wave gauge, and wave gauges along the two cross-shore transects.

Numerical Model Results

As a preliminary test, we show numerical results from the XBeach model that is forced by the offshore hydrodynamic conditions from CERA. The modeled water levels and wave heights are compared with the observational data collected by wave gauges at the study site. The XBeach model of the test domain reproduces the water level observations with *RMSE* in the range of [0.25 m, 0.72 m] and *bias* in the range of [-0.44 m, 0.68 m]. The largest *RMSE* occurs at wave gauge BW-1. The model accurately captures the peak water level (both in phase and magnitude) but underestimates the water level prior to and after the peak (Fig. 4). Wave gauge NAT-1 also has a consistent offset in water level prior to and after the hurricane landfall. This could be explained by the erroneous bed elevation measurements at these two onshore wave gauges due to possible settlement or onshore movement of the instruments. The model-data comparisons show good agreement at other wave gauge locations.

The modeled and observed significant wave height are in phase, but the magnitude is consistently overestimated at all wave gauges, especially at onshore wave gauges (Fig. 5). The *RMSE* ranges from 0.24 m to 0.45 m and the *bias* ranges from -0.24 m to -0.08 m. The discrepancies between modeled and measured wave heights are plausibly attributed to a few factors including the inaccurate offshore boundary conditions from CERA, inadequate representation of the vegetation effects by the chosen bottom friction factors, and the large spatial resolution used in the test domain. Given that the 10-m grid resolution is not sufficient to resolve the breakwaters, the XBeach model resolution will have to be significantly increased along the breakwaters and shoreline in the next step to improve the model accuracy.

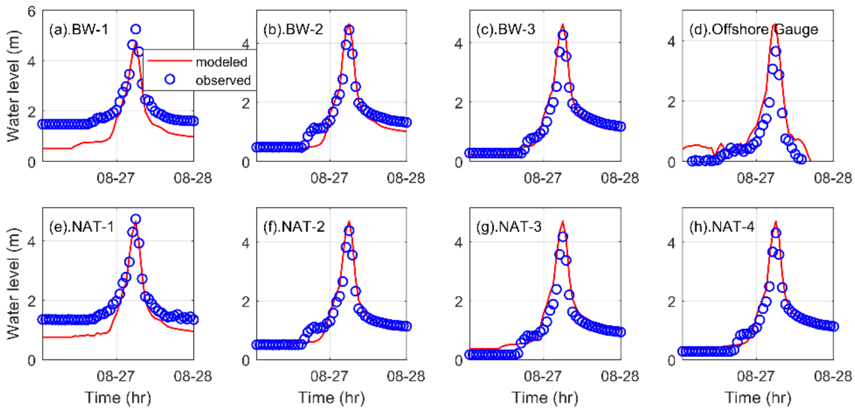

Fig. 4. Comparisons between the modeled and measured water levels (NAVD 88).

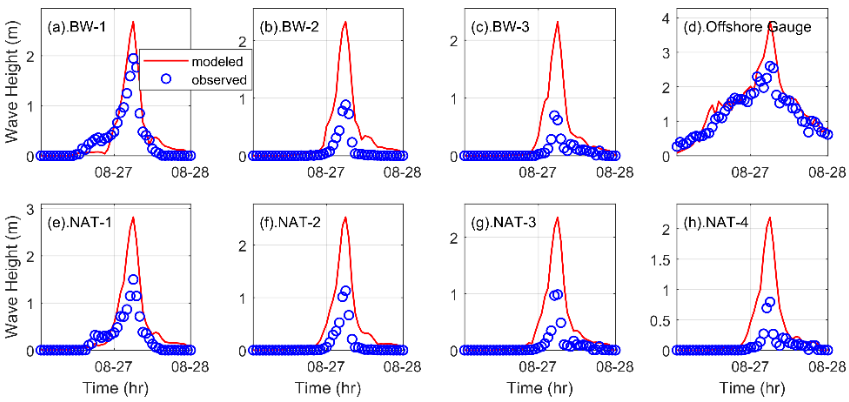

Fig. 5. Comparisons between the modeled and measured significant wave heights.

Discussion and Conclusion

Event-driven coastal morphodynamics are controlled by the hurricane characteristics, and regional and local geomorphic and geotechnical conditions. During the hurricanes, the total water level (i.e., astronomical tide, storm surge, and wave runup) at the shoreline exceeded the elevation of the Chenier Plain, resulting in the overwash and inundation regimes of beach ridge response to offshore waves. The land cover condition of the barrier influences the onshore sediment transport caused by overwash. Because the Chenier Plain is a low-lying coastal system with limited sand supply, this study adopts a similar numerical approach to Liu et al. (2018) and Johnson et al. (2021) to quantify the impact of Hurricanes Laura and Delta. The preliminary results indicate that CERA does not provide accurate enough offshore wave boundary conditions to force the XBeach model. Thus, we will have to run the coupled Delft3D and SWAN models as the next step to hindcast the offshore wave field more accurately, especially the wave periods and incident wave directions, for the XBeach model. Secondly, the result of the initial trial with a 10-m resolution in the XBeach test domain indicates that much finer spatial resolution is definitely needed to resolve the breakwaters and sand ridges appropriately. Third, the effects of wetland vegetation need to be properly included in Delft3D, SWAN, and XBeach in the next step of our study. It is expected that the spatial variability in the sand layer thickness on the beach greatly affects the morphological response of the Chenier Plain shoreline to hurricane waves and storm surges. Integration of the morphodynamic modeling system (Delft3D, SWAN, and XBeach) with the field data collected during and after Hurricane Laura has the potential to transform our understanding of NHI solutions to coastal resilience for deltaic coasts.

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