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Article

Numerical Evaluation for Coastal Community Storm Surge Flood Control Infrastructure

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Abstract: The Lower Rio Grande Valley, South Texas is considered one of the more vulnerable coastal areas to flooding related with abrupt climate changes. From 1980-2017, there were 7 flooding events, 57 severe storm events, and 8 tropical cyclone events with losses exceeding $1 billion in the State of Texas, according to NOAA NCEI. Coastal flooding is typically a result of storm surge and heavy rainfall produced by hurricanes and tropical storms. In this study, the two-dimensional hydrodynamic flow circulation model is developed to predict the Lower Rio Grande Valley coastal area inundation due to the hurricane storm surge, especially in the case of Hurricane Beulah, 1967. The tropical cyclone properties and tidal constituents were assigned to the updated watershed geographic information with the bottom bathymetric and roughness data. For model validation, the Hurricane Dolly 2008 storm surge due to Hurricane Beulah at the coast and the storm surge reaches up to approximately 40 kilometers west from the coast through a natural river channel. This model can be used for a reliable engineering tool for the coastal hazard emergency management and disaster mitigation.

Keywords: Hurricane storm surge, emergency management, coastal inundation, numerical model, South Texas

1. Introduction

The year 2017 marks the 50th anniversary of Hurricane Beulah, a Category 5 hurricane that caused an estimated $1 billion ($7.3 billion value in 2017) in damages and extensive flooding caused by its slow traversal of the Lower Rio Grande Valley (LRGV) watershed in Texas. In 2017, another catastrophic tropical storm, Hurricane Harvey dropped about 60 inches of rainfall in southeast Texas, breaking the all-time U.S. tropical cyclone rainfall record and causing an estimated $180 billion damage due to the disastrous flood. Hurricane storm surge is an abnormal rise in sea level that destroys coastal lands due to the extensive eroding caused by the rapid flow circulation of a hurricane, as well as overland floods caused by the abnormal rise in the ocean. Flood Insurance Rate Map is an official map of a community within the United States that displays the floodplains, more explicitly special hazard areas and risk premium zones, as delineated by the Federal Emergency Management Agency [1]. National Storm Surge Hazard Maps developed by National Hurricane Center (NHC, NOAA) displays a seamless national map of near worst-case storm surge flooding scenarios using the National Weather Service storm surge model [2]. This study presents a numerical development of coastal storm surge over the Lower Rio Grande Valley coastal watershed. Figure 1 shows six historical hurricane tracks that caused significant coastal storm surge to the Lower Rio Grande Valley watershed highlighted in the box. The solid nodes describe the observed time-

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dependent properties and arrows on the solid line illustrate the direction of the hurricane eyes. The color contour represents the seafloor topography of the Gulf of Mexico.

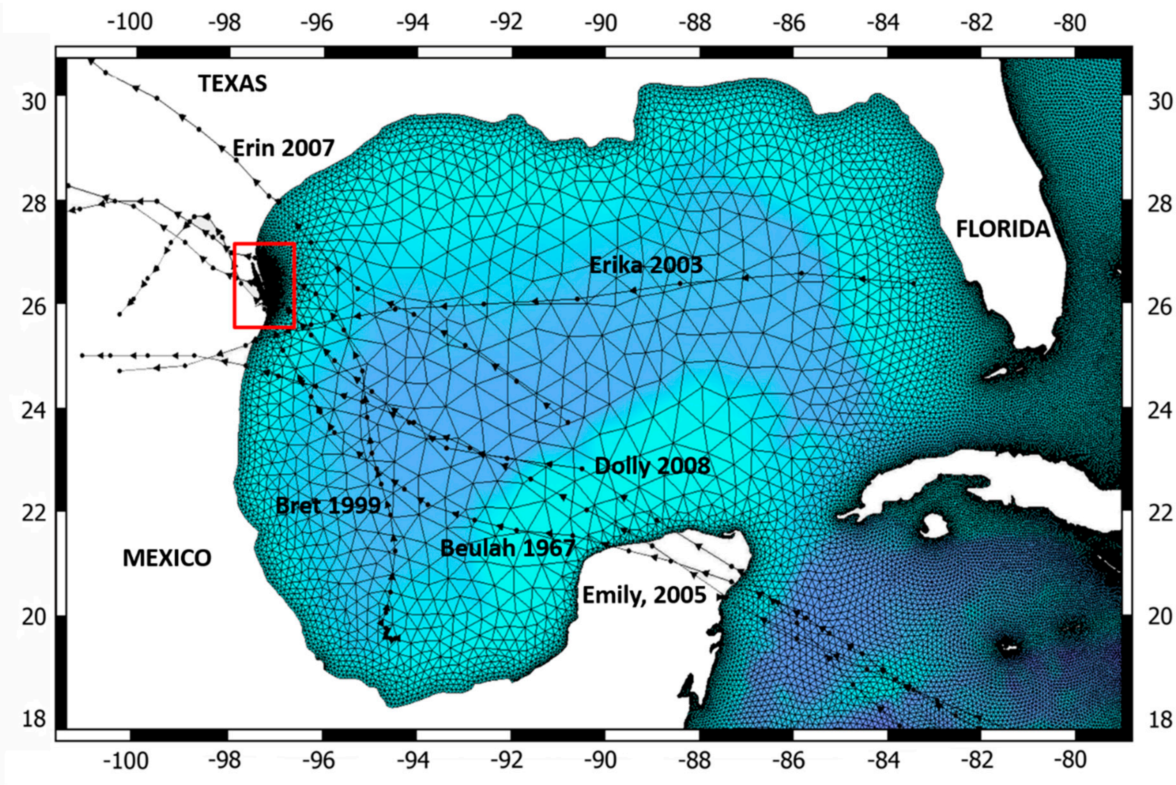

Figure 1. The Lower Rio Grande Valley watershed location map with historical hurricane tracks

2. Materials and Methods

For the flow circulations, the model implemented was an ADvanced CIRCulation (ADCIRC) model developed by U.S. Army Corps of Engineers. ADCIRC solves two-dimensional finite element forms of the Navier-Stokes equations with geoid free surface, Coriolis parameters, and baroclinic pressure gradient. The model has been employed to coupled wind, wind-wave, tide and river-line flow simulations on instructed meshes [5]. For the geospatial input data, a single raster data was created by merging two sources, due to the large scale of the model's domain. Bathymetric data was obtained from two sources. A 1/3 arc-second raster was achieved from the NOAA National Center for Environmental Information, which entails with detail the Lower Laguna Madre raster [6]. A 30 arc-second Gulf of Mexico seafloor raster SRTM3_PLUS V6.0 was obtained from Scripps Institution of Oceanography, University of California San Diego [7]. The Lower Laguna Madre model 2-D mesh was created with nodal elevations interpolated from the merged raster and assigned the tidal and wind forcing data. The SMS (Surface water Modeling System, U.S. Army Corps of Engineers) was adopted for the model pre- and post-processing of the numerical domain finite element mesh creations, model control and properties editing, and computation visualization. The model provides an integrated graphical environment for performing surface flow, contaminant fate and transport, and project design evaluations [8]. Figure 2 depicts the finite element grid of the model watershed boundary of the Lower Laguna Madre, the Lower Rio Grande Valley inland, and the western Gulf of Mexico. Its preliminary grid, Eastcoast 2001, includes the Western North Atlantic and Caribbean Sea [9]. The grid was modified by adding the meshes of the model boundary and by removing the eastern

Gulf of Mexico for effective computations of the South Texas coast tropical cyclone tracking. Figure 2 is a magnified mesh of the Lower Laguna Madre.

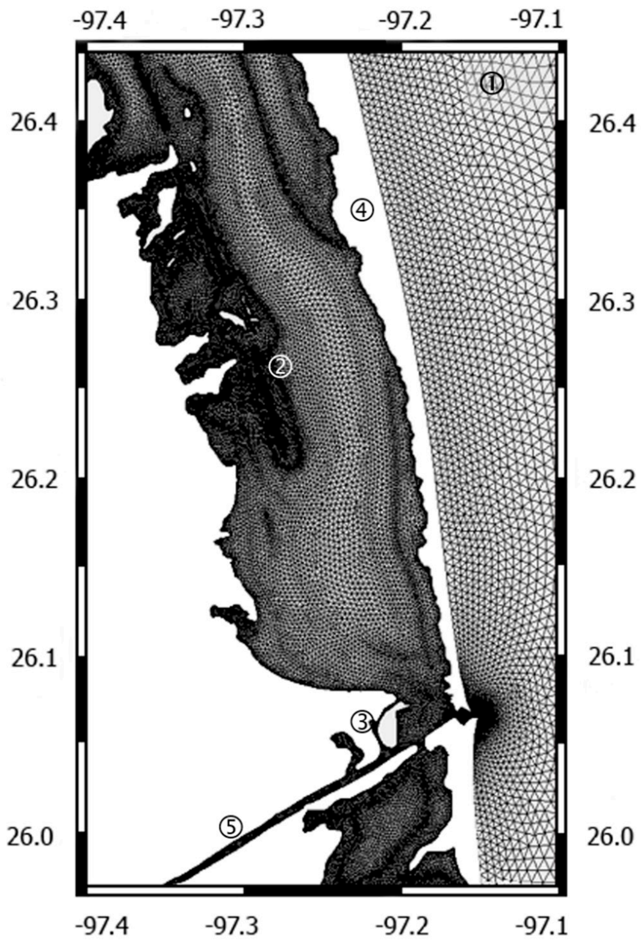

Figure 2. The Lower Rio Grande Valley coastal area storm surge model finite element mesh.

Legends ①, ②, ③, ④, and ⑤ indicate the Gulf of Mexico, the Lower Laguna Madre, the Port Isabel NOAA buoy station, the South Padre Barrier Island, and the Brownsville Ship Channel, respectively.

For the finite element meshing, node strings were created first to build a geographic boundary of the domain. This is done in order to dictate the computation areas of water and land, and to assign numerical boundary conditions by enclosing meshes. Along the Lower Laguna Madre and South Padre Island shorelines, the node strings were tighter together; furthermore, the node strings were relaxed along the Gulf of Mexico to assure effective computations of the large domain modeling. The togetherness of node strings causes finer mesh, while the more relaxed node strings brought coarser mesh. The two sources of bathymetric data of the domain were merged into a single raster file and then converted into a scatter data set format for the grid meshing process. This Lower Laguna Madre scatter data was merged into the modified Eastcoast 2001 grid scatter file, which was converted from the preliminary mesh. The model finite element mesh was built based on the merged scatter data. After meshing the geometric grid of the entire domain, the bathymetric data was assigned to the merged scatter points to create a raster data file. With the latitude and longitude coordinates, the mesh interpolated nodal elevations from the raster file. The hurricane tracking data (Best Track Data, HURDAT2) was available for download at the National Hurricane Center (NHC), NOAA [10]. NHC provides within the Historical Hurricane Archive a northeast and north central pacific database text file with all recorded hurricanes from 1946 to 2017. The HURDAT file includes parameters such as the date/time of each recorded hurricane, the coordinate location, the direction the hurricane is going,

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wind speed, atmospheric pressure, radius of last isobar, speed of hurricane, and the pressure of the hurricane [10]. The other major flow forcing is the tidal constituent boundary conditions. The dominant tidal constituents are the diurnal constituents, K1, O1, P1, Q1, and S1, and the semidiurnal constituents, M2, N2, and S2. The Eastcoast 2001 database defines the computed elevation and velocity amplitude and phase for the O1, K1, Q1, M2, S2, N2, and K2 astronomical tidal constituents, in addition to the steady M4 and M6 over tides [9]. Ocean floor bottom roughness can be assigned by nodal attribute input file, fort.13. The finite element amplitude and advective terms are controlled through fort.15 control input file. The ADCIRC model creates 22 principal output files, e.g., water surface elevation data at a recorded observation point, elevation/bathymetry time series, velocity time series, atmospheric pressure time series, and wind velocity time series.

3. Results

3.1. Model Verification

The Hurricane Dolly 2008 event was used for the Lower Rio Grande Valley model verification. The model's computation of water surface level was compared with the measurements form NOAA buoy station (Port Isabel, ID: 87798880) [11] by adjusted the tidal constituents (K1, O1, P1, and Q1) and coastal floor bottom roughness. One second of computational time step was assigned for a total of seven days of runtime. The HURDAT2 fed the Hurricane Dolly 2008 tracking over the simulation period of July 22-24, 2008. The color contour and arrows represent the mean sea level pressure changes (range from 963 to 1,1016 millibar) and two-dimensional velocity vectors of the cyclone. Figure 3 (c) depicts the HURDAT2 wind velocity and atmospheric pressure based on the Google Earth rendering when the hurricane approached to South Padre Island at 6:00am July 23, 2008.

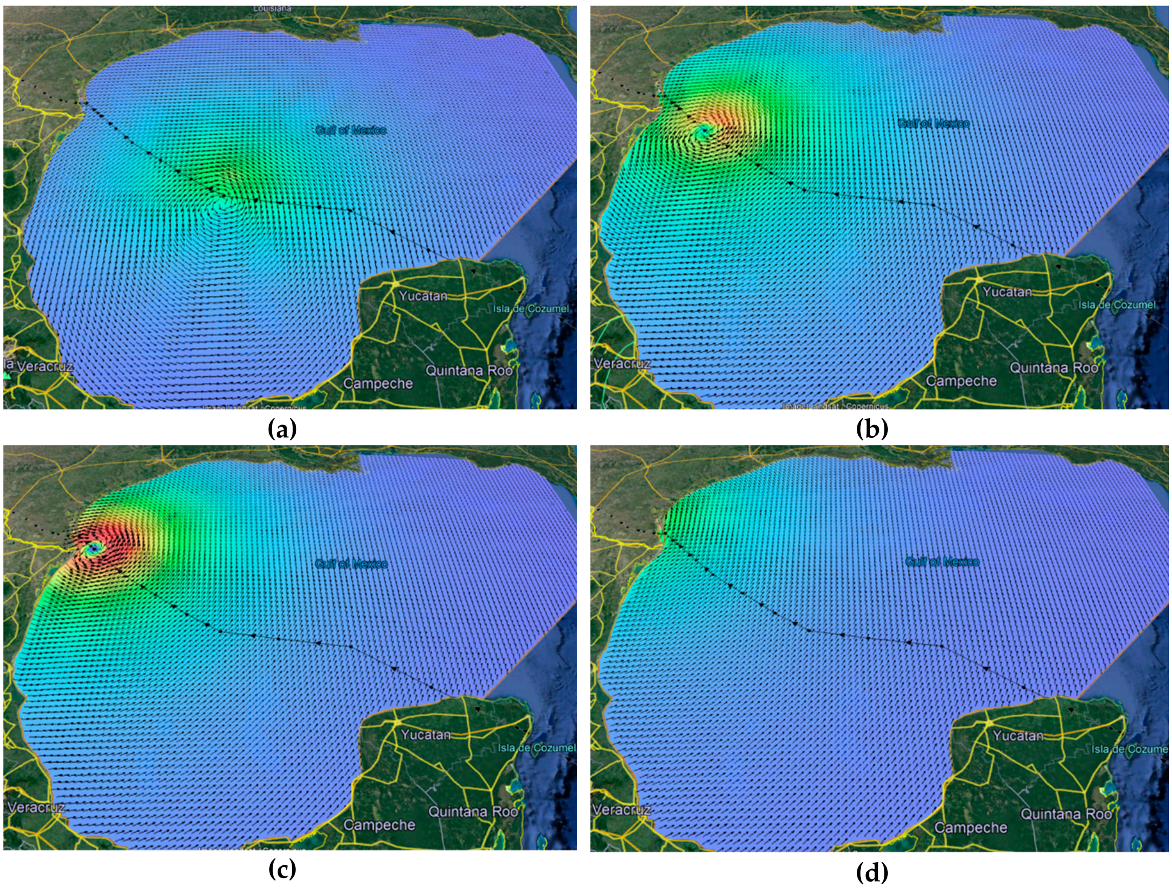

Figure 3. The Hurricane Dolly 2008 tracking: atmospheric pressure and wind velocity shown on Google Earth.

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The computed water surface levels (blue color line) in Figure 4 show a very good agreement with the NOAA buoy station measurements in orange color line. The maximum storm surge was over estimated slightly as 1.21 meters than 0.78 meters of measurements. However, the Lower Rio Grande Valley model predicted promising storm surge trend and timing of the Hurricane Dolly.

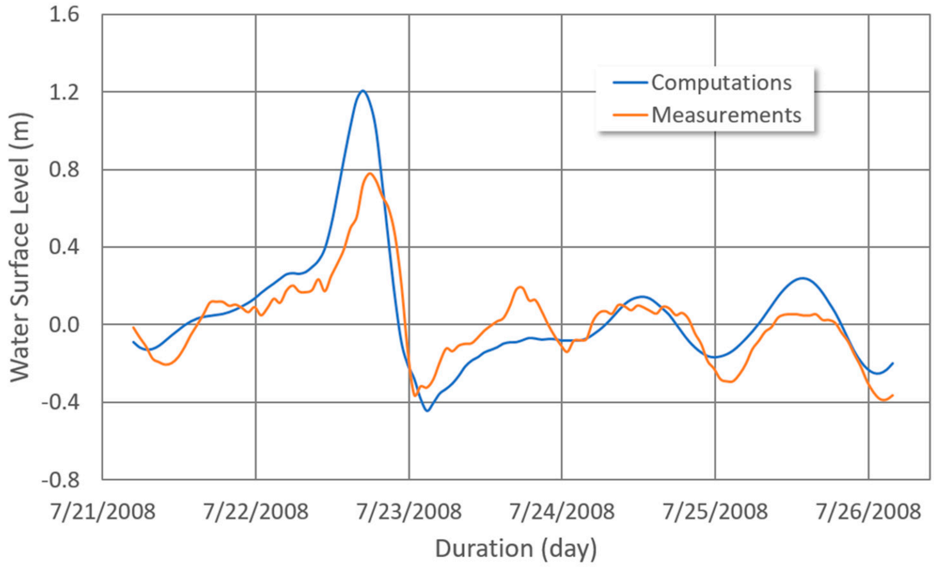
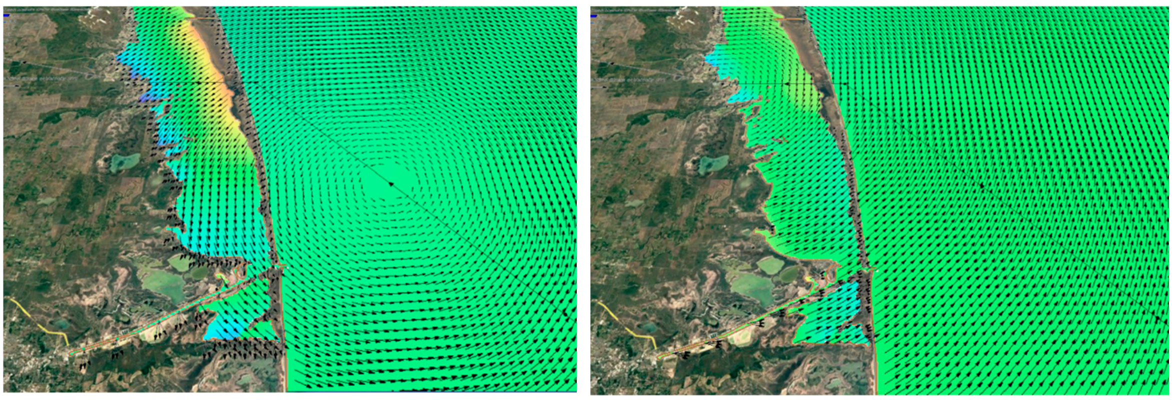


Figure 4. The Lower Laguna Madre Hurricane Dolly 2008 storm surge prediction at (a) 13:00 on July 23, 2008 and (b) 17:00 on July 23, 2008.

The Lower Rio Grande Valley flow circulation model simulated the coastal hurricane storm surge reasonably. The counter clockwise cyclone pushes the shallow water of the Lower Laguna Madre from the east side (South Padre Island) as shown in red contoured area, when the cyclone is approaching to the coast in Figure 5 (A). The two-dimensional vectors represent its' wind magnitude and directions. The propelled shallow water hits the west shoreline of the Lower Laguna Madre as shown in blue contoured area. The computed maximum storm surge height was about 3.8 meters at the west shoreline. When the cyclone passes the Laguna Madre, the counter clockwise wind pushes the shallow water from the west to east reversely as Figure 5 (b). The water surface level along the west shoreline is decreased, while the east shoreline is overflowed.

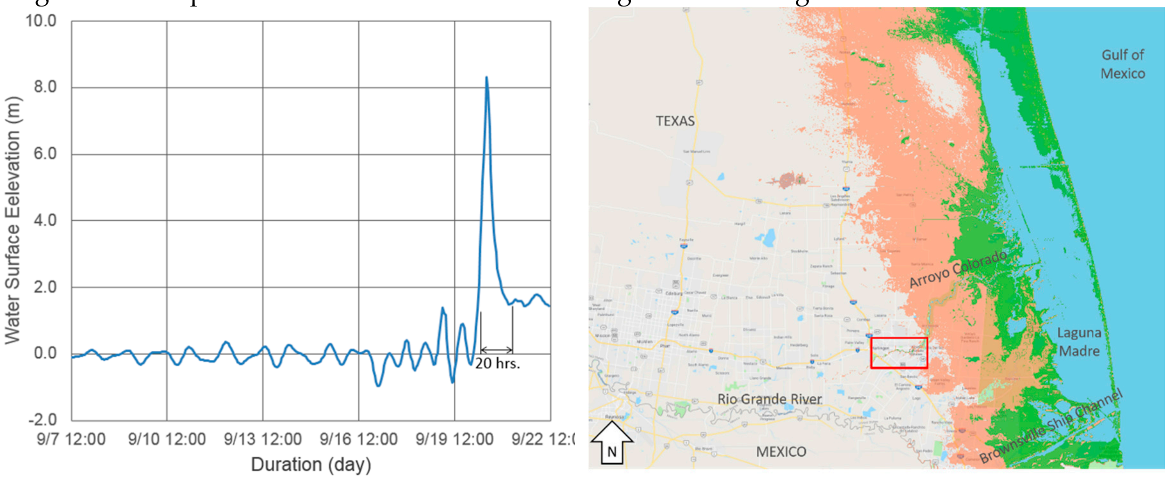


(a) **(b)**

Figure 5. The Lower Laguna Madre Hurricane Dolly 2008 storm surge prediction on the Google Earth at (a) 13:00 on July 23, 2008 and (b) 17:00 on July 23, 2008.

3.2. Model Implementation

The validated Lower Rio Grande Valley model was used for Hurricane Beulah (1967) storm surge prediction. For the hurricane tracking, the HURDAT2 data was adopted on to the finite element mesh without changes of the tidal constituents. The model used constant quadratic bottom roughness with 0.0025 friction coefficient. Figure 6a demonstrates the computed water surface levels during the Hurricane Beulah storm event. The buoy station was not available for recording during the hurricane. Due to the hurricane's slower movement near the coast, the model simulated a total of 12 days of runtime to predict the entire hurricane storm surges. Figure 6b depicts the simulation results on Google Street Maps to indicate the affected areas along the Lower Laguna Madre.



(a) **(b)**

Figure 6 . The Lower Laguna Madre Hurricane Dolly 2008 storm surge prediction at (a) 13:00 on July 23, 2008 and (b) 17:00 on July 23, 2008.

The time dependent water surface levels exported to the GIS (Geographic Information System) model to develop the storm surge maps as shown in Figure 6b. The green and orange colored contours represent the 5.6-meter water surface level at 1:20am on September 19 and a maximum level of 8.4 meters at 1:00pm on September 20, 1967, respectively.

The maximum storm surge reaches up to the City of Los Fresnos, which is marked with a blue solid circle in Figure 6b, and it is approximately 18.6 kilometers west form the City of Port Isabel. The model predicts that the hurricane submerges the Port of Brownsville by 4.4 meters for 7.5 hours during the hurricane. The red box in the figure indicated the Arroyo Colorado drain canal passing the City of Harlingen, which is one of the major flood control channels (approximately 145 kilometers long, [12]) of the Lower Rio Grande Valley watershed. Since it drains into the Lower Laguna Madre, the water surface level at the estuary is a critical factor of the channel flow, e.g., backwater from the Lower Laguna Madre. Figure 7 depicts the Lower Laguna Madre model prediction of the Arroyo Colorado watershed flooding event impacted by the Hurricane Beulah storm surge coverage. It causes watershed lateral inundation overflow from the Arroyo Colorado to the low-lying areas. The zoomed red box in the left top corner shows the submerged road networks highlighted in yellow lines within the figure.

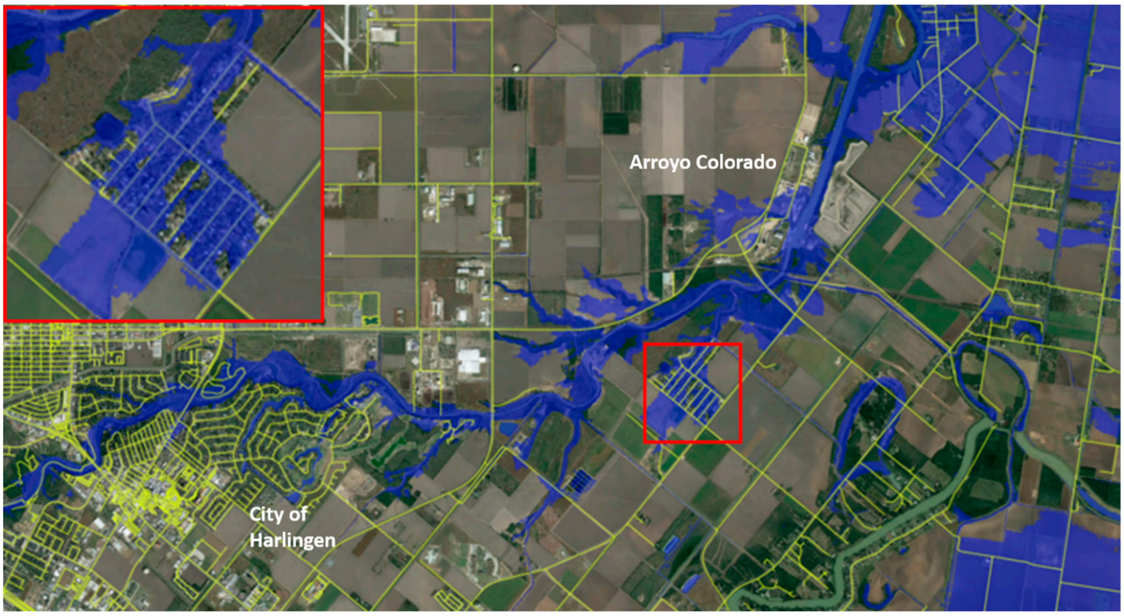


Figure 7. The Hurricane Beulah 1967 storm surge watershed lateral inundation through the Arroyo Colorado flood drain canal .

4. Discussion

The shallow water flow-circulation model is a useful tool for prediction of hurricane storm surge and related lateral inundation over the coastal areas. The model computes fundamental information of hurricane storm surge analysis including hurricane tracking over the modeling domain, two-dimensional velocity vectors of wind and flow, and dynamic water surface level during the hurricane period. The Lower Rio Grande Valley model application of the Hurricane Dolly 2008 storm, the water level computations depicted very good agreement with the buoy station measurements in its trend. The Hurricane Beulah modeling provides valuable information: hurricane storm surge near the Lower Laguna Madre shorelines and drain channel lateral inundation over the Lower Rio Grande Valley coastal areas. The model predicts 8.4 meters of maximum storm surge due to the Hurricane Beulah 1967 storm at the city of Port Isabel. The storm surge reaches to the City of Harlingen 37.6 kilometers west from the Lower Laguna Madre shoreline through the Arroyo Colorado drain canal. In this study, the modeling performance was promising; however, to fill the information gap regarding the impact of a hurricane storm surge on coastal inundation, the Lower Rio Grande Valley model needs to be substantially improved by model parameter calibrations.

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Conflicts of Interest: n/a.

References

1. "Flood Insurance Rate Maps", Federal Emergency Management Agency, U.S. Department of Homeland Security, https://www.fema.goc/flood-insurance-rate-map-firm, Retrieved February 21, 2008.
2. Zachary, B.C., W.J. Booth, J.R. Rhome, and T.M Sharon, (2015), A National View of Storm Surge Risk and Inundation, Weather, Climate, and Society, 7(2), 109-117.
3. David M. Roth (2010), "Texas Hurricane History", National Weather Service, National Oceanic and Atmospheric Administration.
4. "Major Hurricane Beulah September 20th, 1967", National Weather Service Office Corpus Christi, Texas, https://www.weather.gov/crp/Beulah, Retrieved November 16, 2017
5. Dietrich, J.C., S. Tanaka, J.J. Westerink, C.N. Dawson, R.A. Luettich Jr, M. Zijlema, L.H. Holthuijsen, J.M. Smith, L.G. Westerink, H.J. Westerink (2011). "Performance of the unstructed-mesh, SWAN+ADCIRC model in Computing hurricane waves and surge" J Sci. Comput., http://dx.doi.org/10.007/s10915-011-9555-6.
6. "National Center for Environmental Information", National Oceanic and Atmospheric Administration, https://www.ncei.noaa.gov/, Retrieved May 4, 2017.
7. "STRM3_PLUS STRM30, Coastal & Ridge Multibeam, Estimated Topography", Scripps Insitution of Oceanography, University of California San Diego http://topex.ucsd.edu/WWW_html/srtm30_plus.html, Retrieved May 4, 2017.
8. "SMS - Surface-water Modeling System", Engineer Research and Development Center, U.S. Army Corps of Engineers ,https://www.erdc.usace.army.mil/Media/Fact-Sheets/Fact-Sheet-Article-View/Article/919656/sms-surface-water-modeling-system/, Retrieved August 1, 2018.
9. [9] Mukai A.Y., J.J., Westerink, R.A. Luettich, and D. Mark, (2002), "Eastcoast 2001, A tidal constituent database for Western North Atlantic, Gulf of Mexico, and Caribbean Sea", Engineering Research and Development Center, U.S. Army Corps of Engineers, Vicksburg, MS.
10. "NHC Data Archive", National Oceanic and Atmospheric Administration, https://www.nhc.noaa.gov/data/#hurdat, Retrieved May 20, 2018.
11. "Tides and Currents", Center for Operational Oceanographic Products and Services, National Oceanic and Atmospheric Administration, https://tidesandcurrents.noaa.gov/stationhome.html?id=8779770, Retrieved May 4, 2017.
12. "Arroyo Colorado about the Watershed", Arroyo Colorado Organization, http://arroyocolorado.org/about-the-watershed/, Retrieved August 11, 2018.
13. "U.S. Billion-Dollar Weather and Climate Disasters (2018), NOAA National Centers for Environmental Information (NCEI), https://www.ncdc.noaa.gov/billions/, Retrieved April 9, 2018.