Simulation of Storm Surge in the Mississippi Gulf Coast Using an Integrated Coastal Processes Model

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ABSTRACT

This study uses an integrated coastal processes model to simulate hydrodynamics driven by storms, tides, river inflows, and winds in a large-scale domain covering the Mississippi and Louisiana Gulf Coasts. By using existing bathymetric data and DEM topographic data, a high-resolution mesh is generated to represent structures, roads, rivers, barrier islands, and lakes. For study of flooding and inundation of hurricanes in the inland areas of the Mississippi Gulf Coast, the Pearl River and its floodplain are included in the mesh with a detailed river course. Using two synthetic storms, four hurricane scenarios are simulated by using this model. Computed maximum storm surges without the Pearl River are compared with those with the river inflow. Differences between the storm surges indicate that the inclusion of the river inflow is imperative in order to obtain accurate predictions on flood and inundation due to storm surges in the Mississippi Coast community.

INTRODUCTION

The Mississippi Gulf Coast bears the brunt of attacks by ocean waves, tides, and storm surges. This coast is specifically vulnerable during hurricane seasons. Hurricane Katrina in 2005 made a tremendous damage in properties and caused hundreds of human causalities. Existing numerical modeling studies of flooding along the Mississippi coastline during a hurricane event mostly focus on storm surge and wave effects (e.g. Bunya et al. 2010). They are generally unable to accurately resolve inland flooding resulting from river floods and backwater effects due to lack of sufficient resolution of a coastal watershed.

To have a better assessment on the impact of storm surges and waves by hurricanes in the Mississippi coastal region, a large-scale simulation domain is taken to cover the Louisiana Gulf Coast, and the high-resolution bathymetry/topography in the watershed of the Pearl River, the lower Mississippi River, and the Atchafalaya River are included. The integrated model is applied to simulate storm surges and waves over this large area due to various storm tracks. By adopting a high-resolution
mesh for watersheds in the land area, a special focus is to study the storm surges in the watershed region of the Pearl River. Simulation results can be useful for better planning and management for flood/inundation protection in a wider area of the Mississippi Gulf Coast including the inland watershed.

An existing integrated coastal processes model is enhanced to simulate waves, surges, and currents driven by combined hydrological forcing such as storm wind, tide, and river inflow. Spatio-temporal variations of atmospheric pressure and wind during a storm/hurricane period are simulated using a parametric storm wind model. A multidirectional wave spectral model is developed to consider wind energy input to wave spectral energy. Young’s hurricane wave model is implemented to generate the offshore wave boundary condition for specifying wave spectrum. The wave model is seamlessly coupled with the hydrodynamic model by sharing a single non-orthogonal mesh. Hence, simulations for wave-current interactions do not need to switch models for waves and currents. The computational efficiency has been significantly improved by implementing advanced numerical simulation algorithms and implicit matrix solvers. Storm surges with wave effect and inland flooding during a multiple-day storm can now be simulated at the regional scale on a personal computer.

DESCRIPTION ON CCHE2D-COAST

CCHE2D is an integrated package for two-dimensional simulation and analysis of river flows, non-uniform sediment transport, morphologic processes, coastal processes, pollutant transport and fate, and water quality. These processes are solved with the depth integrated Reynolds equations, transport equations, sediment sorting equations, bed load and bed deformation equations. This model is based on the Efficient Element Method, a collocation approach of the weighted residual method. Internal hydraulic structures, such as dams, gates and weirs, can be formulated and simulated synchronously with the flow. Dry and wet capability enables one to simulate flows with complex topography with ease. Three turbulence closure schemes are available: depth-averaged parabolic, mixing length eddy viscosity model and k-e model. The numerical scheme can handle subcritical, supercritical flows and their transition. A comprehensive and user-friendly mesh generator is available for generating structured quadrilateral mesh on the background of bed topography and the bed elevation data. A Graphical User Interface (GUI) is also available with a detailed manual and documentation. Starting with a computational mesh, the GUI helps users to set up parameters and boundary conditions to run the simulations and visualize the computational results.

Based on the numerical methods of CCHE2D and its GUI development platform, CCHE2D-Coast has been developed for simulations of coastal processes together with riverine processes and metrological and oceanographic processes during a tropical storm or a hurricane. It is an integrated coastal/estuarine process model consisting of three principal modules for simulating irregular wave deformations, tidal and wave-induced currents, and morphological changes. It has been extensively validated by using experimental data and field observation data (e.g., Ding et al., 2006; Ding and Wang, 2008), and has been applied to evaluate and design coastal structures for flood prevention and erosion protection in coasts and estuaries (e.g.
A multi-directional spectral wave transformation equation with diffraction effect terms is adopted for simulating irregular waves. The following wave deformation/transformation processes are available in this wave spectral model: refraction, diffraction, shoaling, wave breaking, wave transmission through structure, bottom friction, wave-current interaction, vegetation attenuation effect, etc. In order to track hurricanes, the hurricane pressure field and surface wind velocity induced by the pressure gradient have been implemented into the model following Holland (1980). The integration of hurricane pressure field into the momentum equation helps to incorporate sea level change induced by the atmospheric pressure gradient.

CCHE2D-Coast includes all the necessary boundary conditions for coastal flow simulations. In general, a typical computational domain in a coastal and estuarine region is surrounded by four types of boundaries: shoreline, offshore boundary, two open cross-shore boundaries, and river inflows at upstream. Inside the domain, island shorelines or offshore structure boundaries may exist. The impermeable condition of currents is used at shorelines. At the offshore boundary, the incident wave spectra TMA (Bouws et al., 1985) and B-M (Mitsuyasu 1970) can be specified to compute the wave field. To generate tidal flows, the tidal elevations can also be imposed at the offshore boundary. The known values of velocities or discharges can be imposed on the corresponding cross-shore boundaries. Upstream of a river, a steady or time varying discharge or depth can be specified. The cold start may be used to generate initial condition for tidal, wave-induced currents and storm surge simulations.

For the hydrodynamic simulations in coasts and estuaries, two-dimensional, depth- and shortwave-averaged shallow water equations are employed to simulate the currents driven by wave radiation stresses, tides, storm surges, surface winds, river inflows, the Coriolis force, and turbulence in surf zones and tidal zones. Since CCHE2D-Coast was developed under the platform of CCHE2D, it has the following major capabilities for simulating coastal hydrodynamic and morphodynamic processes:

- Non-orthogonal mesh that can model complex coastlines
- Irregular wave deformations with optional offshore wave spectrum inputs
- Tidal currents and river flows
- Hurricane tracks
- Nearshore currents induced by short waves
- Sediment transport due to a combination of waves and currents
- Morphological changes in coastal and estuarine areas
- Morphological changes around coastal structures, e.g., groins, offshore breakwaters, artificial headlands, jetties, artificial reefs (submerged dikes on coasts)

It is important to note that the hydrodynamic model and the wave model in CCHE2D-Coast are integrated seamlessly so that all the modules share one grid system for simulating coastal processes in sequence. Thus, unlike the model steering operation used in some models, CCHE2D-Coast does not need to switch executable codes of the modules. As a result of this advantage, CCHE2D-Coast avoids possible errors and loss of information resulting from interpolation and extrapolation of the results between two grid systems for two different computational models. All the
coastal process modules in CCHE2D-Coast share the same non-orthogonal mesh which allows general quadrilateral grids. This non-orthogonal structural mesh can model irregular coastlines in a more flexible way, in comparison with the rectangular mesh used in some commercial and in-house wave simulation models.

When the model is applied to simulate storm waves generated by hurricanes, the waves at the deepwater can be calculated by a deepwater wave model, such as WAM. However, the CCHE2D-Coast wave model can work within the deepwater zone, if the boundary conditions for the wave spectral distributions at the offshore can be given. To do so, Young’s ocean wave model, which is a parametric wave model, is usually employed to create the wave spectral boundary conditions at the offshore (Young 1988, Young and Burchell 1996). The significant wave heights are calculated based on JONSWAP spectrum.

CONDITIONS FOR SIMULATING STORM SURGES

Computational Domain and Bathymetric/Topographic Data

As shown in Figure 1, the computational area selected for the present study extends from south east Louisiana to the eastern end of Bon Secour Bay in Alabama. The southern open sea boundary extends 440 km (273.4 miles) in a west-east direction. The computational domain extends 323 km (200.70 miles) in a south-north direction. It covers the Mississippi and Louisiana Gulf Coast region.

The basic data for generating bed elevations in the study domain was provided by an existing grid used in the ADCIRC storm-surge simulations, which is a finite elemental mesh data. This computational grid called SL15 was received from the USACE-ERDC. It has been used to study storm surges in the Gulf of Mexico (e.g. Bunya et al. 2010). It covers a very large area including Gulf of Mexico, Caribbean Sea and part of the Atlantic Ocean up to Maine and Nova Scotia. The SL15 mesh has 2,137,978 nodes and 4,184,778 triangular elements in total. It includes all the existing coastal structures such as dikes, seawells, etc. as of 2007 in the MS/LA Gulf coast. The grid resolution is higher near the structures. The sizes of the elements near the structures are about 40-50m.

Figure 1. Computational domain and the portion for which the topography was extracted from the SL15 ADCIRC 2007 base scenario grid.
The bathymetric/topographic data needed for the generation of the computational mesh in this area came from three different sources:

1. The topography of a large portion of the computational domain was extracted from the SL15 ADCIRC 2007 base scenario grid provided by the USACE-ERDC. Figure 1 shows the portion of the computational domain for which the topographic data was obtained from the ADCIRC grid.

2. As it can be seen in Figure 1, the ADCIRC 2007 base scenario grid did not extend into the land as far as the north boundary of the selected domain. Topography of the white area in Figure 1 was extracted from USGS DEM (Digital Elevation Model) tiles with 10m-resolution. Figure 2 shows the topography extracted from the DEM with 10m resolution.

3. The SL15 grid is too coarse to represent the channel geometry of the East and West Pearl Rivers. The channel geometry is not fully represented by the 10m resolution DEM either. Surveyed channel cross sections exist for the navigable portion of the East Pearl River extending from the John C. Stennis Space Center to the coast. This data is described in McKay and Blain (2010). Upon request from the National Center for Computational Hydroscience and Engineering (NCCHE), the authors kindly provided the surveyed cross section data. For the reach upstream of the John C. Stennis Space Center, synthetic cross sections were generated from 10m DEM using a simple rule which relates the depth of a point in the cross section to the 1/3 power of the distance from the closest bank. The river centerline profile was obtained from the outlines of Hancock and Pearl River counties in Mississippi. The length of the river reach from the point last surveyed cross sections to the northern boundary of the computational domain is about 222 km. The width of the river along this length varies from 85m near the John C. Stennis Space Center to 50m at the northern boundary of the computational domain. The river slope was obtained as $1.40048 \times 10^{-4}$. The channel centerline was approximated by a cubic spline to generate the synthetic cross sections at 10m intervals. A total of 22,108 synthetic cross sections were, thus, generated. Each cross section had 30 points.

Near Bogalusa, MS, the East Pearl River bifurcates into East and West Pearl Rivers. According to McKay and Blain (2010), a large portion of the Pearl River discharge flows through West Pearl River. The West Pearl River is only partially represented in the current model. The cross sections were generated using an average cross section width of 119m. A total of 7,264 cross sections were generated with 10 m interval. There were 30 points in each cross section. The length of the synthetically generated reach was 72,998m.
The topography data for the entire computational domain, which was obtained by integrating data from three different sources as explained above, is plotted in Figure 3.

**Figure 2.** DEM data with 10-m resolution, which was used to complete the topography of the computational domain.

**Figure 3.** Topography of the computational domain obtained by integrating data from three different sources. The datum of bed elevations is NAVD 88

**Computational Mesh for CCHE2D-Coast**

The preparation of the computational mesh is a very important and challenging process given the complicated coastline. The presence of various important features, such as rivers, coastal protection structures, roads, etc., should be accurately represented. The following general guidelines were adopted for the generation of the computational mesh:

- Cell sizes varying from 10 to 100m for representing levees, roads, coastal protection structures, etc. and the areas around them,
- Cell sizes varying from 50 to 100m to represent the Pearl River,
- Cell sizes of about 1,000m to represent Mississippi River, and
- Cell sizes equal to or larger than 1,000m to represent the sea.

The computational mesh was created using the CCHE-MESH program (Zhang and Jia 2009). The multi-block methodology was employed to decompose the computational domain into 17 subdomains, which were meshed separately. This was necessary to be able to accurately represent various features at various scales.

The final mesh shown in Figure 4(a) has a total of 2,288,064 nodes (2103 grid points in the horizontal direction and 1088 grid points in the vertical direction). The
enlarged views of the computational mesh around Lake Pontchartrain and the Pearl River are shown in Figure 4(b) and Figure 5(a). Figure 4(b) provides a good example of the level of detail achieved around the coastal protection structures, roads, etc. Figure 5(a) clearly shows the level of resolution used in the present simulations to represent the river with sufficiently high accuracy. Figure 5(b) shows magnification of a portion of the final computational mesh around the Pearl River to give a better idea on the element sizes.

![Figure 4.](image)

**Figure 4.** (a) Computational mesh consisting of 2,288,064 nodes; (b) Enlarged view showing the Lake Pontchartrain and the Pearl River.

![Figure 5.](image)

**Figure 5.** (a) Enlarged view showing the high-resolution topography in the Pearl River. (b) Enlarged view showing the mesh in the Pearl River.

**Simulation Scenarios**

Two storm scenarios (i.e. Run 050 and Run 847) are selected from the storm suite used in the MsCIP report (Table 2.4-3, Page 107, Vol.5 – Appendix E:
The storm track T7 of Run050 is a hypothetical track which makes landfall at the south Louisiana Coast, and is very close to the path of Hurricane Gustav (2008). The second storm following the track T19 makes landfall in the Mississippi Gulf Coast. The storm parameters of the two storms are listed in Table 1.

The storm size in the table, $R_{\text{max}}$, is defined as the radius of the cyclone from the storm eye to the place with the maximum wind velocity. The two storm tracks (T7 and T19) going through the computational domain are depicted in Figure 3. A symmetrical storm wind model, i.e. Holland’s cyclone model (Holland 1980), is used for generating air pressure fields and wind fields for driving the wave and current models in CCHE2D-Coast.

<table>
<thead>
<tr>
<th>Run Number</th>
<th>Central Pressure (mb)</th>
<th>Radius $R_{\text{max}}$ (nm/km)</th>
<th>Forward Speed (knots/km/h)</th>
<th>ID Number of the Storm Track in MsCIP Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run050</td>
<td>960</td>
<td>18.2/33.7</td>
<td>11.0/20.4</td>
<td>T7 (Run 050)</td>
</tr>
<tr>
<td>Run847</td>
<td>960</td>
<td>24.6/45.6</td>
<td>11.0/20.4</td>
<td>T19 (Run 847)</td>
</tr>
</tbody>
</table>

**Boundary Conditions**

River Flow Data

The present study considers the Mississippi River, the Atchafalaya River and the East Pearl River in the computational domain. The discharges of these three rivers are specified as boundary condition.

Only the daily average discharges for these three rivers are available from the USGS website Water Data for the Nation (http://waterdata.usgs.gov/nwis). The stream gage USGS 07374000 Mississippi River at Baton Rouge, LA, provided the daily average discharges for the Mississippi River. For the Atchafalaya River, the daily discharges were obtained from USGS 07381490 Atchafalaya River at Simmesport, LA. The discharges measured at these two stations during Hurricane Gustav (2008) are used as river inflow boundary conditions along the northern boundary of the computational domain.

The present numerical simulations considered the East Pearl River and its daily average discharge. The discharge in East Pearl River was obtained based on the discharges measured at the river gages “USGS 02492110 East Pearl River AB Wilson SL at Walkiah Bluff, MS”, which is located upstream of the bifurcation, thus carries the total East Pearl River discharge, and “USGS 02492111 Wilson Slough Near Walkiah Bluff, MS, Weir Headwater”, which is located downstream of the bifurcation, thus diverts part of the discharge to the West Pearl River. Figure 6 shows the discharge hydrographs at the stations USGS 02492110 (discharge of the Upstream East Pearl River) and USGS 02492111 (discharge of the flow diverted by the weir) during the period of Hurricane Gustav. The difference in discharges between the two gages provides the discharge for the downstream reach of the East Pearl River, which is also plotted in the same figure. As it can be seen, the discharges plotted in Figure 6 almost doubles at the end of August and beginning of September, 2008.
Based on the river discharges measured by USGS stream gages, the average discharges for the period of Hurricane Gustav (2008) are obtained as follows:

- Atchafalaya River, LA, 3,800 m³/s
- Mississippi River, LA, 9,800 m³/s
- East Pearl River, MS, 150 m³/s

These average discharges were used as steady river inflow boundary conditions during the simulation period considered in the present study.

Manning’s coefficient in the Pearl River Valley and channel was set to be $n = 0.035$ m⁻¹/³s. For the Gulf of Mexico, the value of $n = 0.02$ m⁻¹/³s was used. A linear longitudinal variation was assumed where the Pearl River channel transitions into an estuary channel.

**Tide Data**

Based on the observations of tidal elevations at NOAA’s tidal gauges at the south Louisiana Coast (http://tidesandcurrents.noaa.gov/gmap3/), the tidal range before Hurricane Gustav is about 40cm. Therefore, it is assumed that the tidal boundary condition at the offshore (the south boundary) is a M2 tide with a 40cm tidal range.

**Wave Data**

Wave set-up induced by storm winds can cause an additional increase in water surface elevation and increase the extent of inundation area and depth. To understand the features of waves driven by hurricanes, the wave parameters such as significant wave heights, peak periods, and mean wave directions during Hurricane Gustav (2008) were collected. The observed hourly significant wave height, dominant wave period and average wave period were downloaded from the National Data Bouy Center (NDBC), NOAA. It can be observed during Hurricane Gustav, the maximum significant wave heights reaches 7.47m at the gauge 42039, and 10.32m at the gage 42040, respectively.

By using the wave model in CCHE2D-Coast, the wind-induced wave fields are computed over the entire computational domain as shown in Figure 3.
simulations of storm surge by coupling the wave model with the hydrodynamic model, the wave field was recomputed every one hour based on the latest flow results.

On the offshore boundary, wave parameters as the wave boundary conditions are computed by a deep water wave model, Young’s hurricane wave model (Young 1988, Young and Burchell 1996). The model assumed that the JONSWAP (Hasselmann et al, 1973, 1976) relationship, originally developed for fetch limited conditions, could also be applied in hurricane wind fields with the specification of a suitable ‘equivalent fetch’. Therefore, the significant wave height ($H_s$) and peak period ($T_p$) are computed by the JONSWAP spectrum. As long as the wave parameters are computed on the offshore boundary, the multidirectional wave spectral density at every offshore boundary node is calculated based on the given hurricane wind directions and the Bretschneider-Mitsuyasu (B-M) spectrum (Mitsuyasu 1970).

NUMERICAL RESULTS ON STORM SURGE

This integrated coastal model has been validated by simulating tidal currents, wave deformation and transformation, nearshore currents, and morphodynamic processes in laboratory cases and real coasts and estuaries. For the details on the validations of CCHE2D-Coast, one may refer to Ding et al. (2006), Ding and Wang (2008, 2011), and Ding and Wu (2011). Meanwhile, it also has been successfully validated by simulating waves and currents due to hurricanes in the MS/LA Gulf Coasts. For further details on the model validation by simulating storm surges due to Hurricane Gustav (2008), one may refer to Ding et al. (2012).

Before a storm surge simulation starts, the model has to be initialized, or spun up, so that a well-developed sea state is created for flow dynamic simulations. The spin-up consists of two steps: the first step is to generate a steady state flow condition, for which the constant river discharges are given to the three rivers including in the domain, and the water surface elevation at the offshore boundary (the south boundary) is assumed to be at the datum NAVD88. The three discharge are 9800 m$^3$/s for the Mississippi River, 3800 m$^3$/s for the Atchafalaya River, and 150.0 m$^3$/s for the Pearl River. The steady flow condition is developed by running the model for sufficiently long time (approximately 10 days) before introducing tide at the offshore boundary.

The second step is to spin up the model by running 10 tide cycles so that a well-established flow condition is developed and the results are used as initial condition for simulating storm surges.

The conditions for these four simulations, which are numbered from 1 to 4, are listed in Table 2. The first two simulations were carried out with the synthetic storm track T7 and the last two with the synthetic storm track T19. All four simulations are performed assuming an M2 tide of 0.4m magnitude. The same steady discharges were used for the Mississippi River and the Atchafalaya River in all four simulations.

For each storm track two simulations are carried out. Cases 1 and 3 do not consider the discharge of the East Pearl River, which is set to zero. In these simulations, storm surge propagates on dry land. The difference between these two simulations and the corresponding ADCIRC simulations is that, in the present case the channel topography is represented with much higher resolution. Cases 2 and 4
consider a steady discharge of 150 m$^3$/s for the East Pearl River. This discharge is introduced as inflow boundary condition along the north boundary of the computational mesh. A weir on the right bank of the East pearl near Walkiah Bluff (south of Parker Bayou) diverts part of the East Pearl River discharge into West Pearl River. A smaller discharge flows in the downstream reach of the East Pearl River. In these preliminary simulations no attempt was made to accurately control the partition of the discharge between the flow diverted into the West Pearl River through the weir and the discharge continuing to the south in East Pearl River.

Table 2. Simulation Cases and Conditions

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Storm</th>
<th>Tide (Tidal Range (m))</th>
<th>Discharge in the Pearl River $Q_{PR}$ (m$^3$/s)</th>
<th>Discharge in the Mississippi River (m$^3$/s)</th>
<th>Discharge in the Atchafalaya River (m$^3$/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>T7</td>
<td>M2 (0.4)</td>
<td>0.0</td>
<td>9800.0</td>
<td>3800.0</td>
</tr>
<tr>
<td>2</td>
<td>T7</td>
<td></td>
<td>150.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>T19</td>
<td></td>
<td>0.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>T19</td>
<td></td>
<td>150.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The storms are introduced into the computational domain from the south boundary, and the simulations of storm surge are performed for 40 hours. The track of the storm T7 makes an angle of 133.995° counterclockwise with the direction east. At the beginning of the 40-hour storm surge simulation, the center of the storm T7 is located 188.711 miles away from the southern boundary of the computational domain along its track. Given that the advance speed of storm is 11 knots (12.659mph), it takes 14.91 hours for the eye of the storm to appear in the computational domain. The track of the storm T19 makes an angle of 135° anticlockwise with the direction east. At the beginning of the 40-hour storm surge simulation, the center of the storm T19 is located 88.25 miles away from the southern boundary of the computational domain along its track. Given that the advance speed of storm is 11 knots (12.659mph), it takes 6.97 hours for the eye of the storm to appear in the computational domain.

Since an implicit scheme in CCHE2D-Coast allows a longer time step size, the computational time step for the simulations is two minutes. All the simulations were performed on a laptop computer with Intel quad core TM i7 CPUs @3.20GHz. Only a single CPU was used for the simulations. The CPU time for simulating a 40-hour surge tide over the mesh with 2,288,064 nodal points is about 3 hours and 20 minutes. Thus, the simulation runs 12 times faster than real time. It is interesting to note that CCHE2D-COAST can efficiently perform these storm surge simulations on a laptop computer without costly parallel computing resources on a supercomputer.

Due to the limit of the paper length, the simulation results presented below do not include the effect of the waves. The wave effect is reported in another paper which will be published in the near future.

Storm Surges by Storm T7

For Cases 1 and 2, the computed maximum water elevations driven by T7 are shown in Figure 7(a) and (b), respectively. The dashed line is the track of the storm. The gray line represents the coastline where the bed elevation is -1.5m. In Case 2 the
Pearl River discharge is imposed as an inflow boundary condition. In Figure 7(a), the Pearl River bed is completely dry due to the fact that the Pearl River discharge was assumed to be zero. Figure 7(b) shows the presence of water flow in the Pearl River. Comparison of the maximum water elevations in Figure 7 shows that a visible difference exists only in the estuary of the Pearl River. Elsewhere in the computational domain, the maximum water elevations are almost the same.

For Cases 1 and 2, enlarged views of the distribution of the computed maximum water depths in the riverine area close to John C. Stennis Space Center are shown in Figure 8(a) and (b), respectively. In Figure 8(a), the initially dry channel bed shows water depths. This indicates that the storm surge was able to penetrate inland by using the dry channel of the Pearl River as a preferential pathway. In Figure 8(b), the storm surge generates higher depths even on the north side of the Old US Hwy 11, as indicated by the lighter shaded (yellow) colored area. Generally, higher flood depths are partly due to the storm surge and partly due to the backwater effect created by the storm surge. Comparison of Figure 8(a) and (b) shows that the inundated area is larger when the discharge of the Pearl River is considered.

The difference between the maximum storm surge flood depths between Case 2 and Case 1 is plotted in Figure 9. As it can be seen, consideration of the Pearl River discharge increases the flood depths by a non-negligible amount. Near the northern edge of the image the difference in flow depths can reach 1.5m to 1.9m. Since the storm surge does not propagate so far inland, the depth increase must be due to backwater effect.

Based on these observations one can state that T7 can produce flooding of the floodplain due to the combined effect of the storm surge and the backwater curve of the Pearl River flow. In fact, during the landfall of Hurricane Gustav on 9/1/2008 at 5:00pm, a large amount of rainfall was observed in the area, and the discharge of the Pearl River increased from 100 m$^3$/s on 8/22/2008, up to 200 m$^3$/s on 9/2/2008. The computed results clearly show that consideration of this Pearl River discharge in the simulations is important and may significantly affect the flood depths and the extent of the flooded area.

(a) Case 1 (Storm: T7, QPR =0.0m$^3$/s)     (b) Case 2 (Storm: T7, QPR =150.0m$^3$/s)

Figure 7. Computed maximum water elevations for (a) Case 1 and (b) Case 2
Storm Surges by Storm T19

Cases 3 (Pearl River is dry) and 4 (Pearl River has a discharge of 150m$^3$/s) were carried out with the storm T19, which was designed to make landfall at Heron Bay, MS, close to the river mouth of the East Pearl River. Since the size of the storm is about 45 km, the maximum wind lands at Biloxi, MS, and creates the highest storm surges to the east side of the Pearl River.

The computed water surface elevations for Cases 3 and 4 are plotted in Figure 10(a) and (b), respectively. The dashed line is the track of the T19 storm. The gray line represents the coastline where the bed elevation is -1.5 m. As it can be seen in these figures, the storm creates storm surge elevations of more than 7 m above NAVD88 over a wide stretch of Mississippi Gulf coastline extending from Bay St. Louis to Biloxi Bay. Comparison of the water surface elevations in Figure 10(a) and (b) shows that, except in the estuary and floodplain of the Pearl River, there are no visible differences between the water surface elevations of these two simulations.
For Case 3 and 4, enlarged views of the distribution of computed maximum water depths in the riverine area close to John C. Stennis Space Center are shown in Figure 11(a) and (b), respectively. Figure 11(a) shows that, when the inflow of the Pearl River is not considered the storm surge was unable to cross over Old US Hwy 11. The flooding is restricted to the area south of Old US Hwy 11.

Figure 11(b) shows that, when the discharge of the Pearl River is considered (Case 4) the resulting inundation area is significantly different. The storm surge flood overtops the Old US Hwy 11 and the flooding extends to the northern side of the road. The inundated area is significantly larger. Comparison of Figure 11(b) with Figure 8(b) shows that, the storm T19 inundates a much larger area than the storm T7. The flood depths for storm T19 are also higher.

The difference between the maximum storm surge flood depths between Cases 3 and 4 is plotted in Figure 12. As it can be seen, consideration of the Pearl River discharge increases the flood depths by a non-negligible amount. The maximum flood depth differences in the East Pearl River are as high as 2.0 m. It can be seen that the large differences in flood depth begin almost immediately north of Old US Hwy 11 and continues to the northern edge of the figure. Comparatively, in Figure 9 for storm T7, the flood differences of 2.0 m begin further north.

The simulation results with storm 19 also show that the consideration of the Pearl River discharge in the simulations is highly important. The simulations run on dry land underestimate the flood depth and extent of the inundated area, even if the channel geometry is represented in the computational mesh, which is the case for these preliminary simulations. It must be underlined that, the SL15 ADCIRC grid used for the simulations in the LACPR and MsCIP studies does not even accurately represent the channel bed (LACPR 2009, MsCIP 2010). The computational grid is too coarse for that purpose. In our opinion, it is not possible to make an accurate assessment of the local flooding conditions in the floodplain of the East Pearl River based on the results of ADCIRC simulations using the SL15 grid.

![Maximum Water Elevations in Storm RUN&1T](image)

(a) Case 3 (Storm: T19, QPR =0.0m³/s)  (b) Case 4 (Storm: T19, QPR =150.0m³/s)

**Figure 10.** Computed maximum water elevations in Case 3 and Case 4.
CONCLUSIONS AND DISCUSSIONS

A new computational mesh, called NCCHE 2007 mesh, with 2.288 million nodes was generated based on the SL15 ADCIRC Grid (for 2007 base scenario) received from USACE-ERDC. This mesh extends 440km from west to east and 323km from south to north, which covers the Mississippi coastline and parts of the Louisiana and Alabama coastlines and extends inland to include the six Mississippi counties. The representation of the coastal protection structures corresponds to the 2007 base scenario. This resolution of the new mesh is 10 times higher than that of the SL15 ARCIRC mesh. The channel topography of the Pearl River is represented in the new mesh based on surveyed cross sections and synthetic cross sections generated from 10m DEM.
For simulations of storm surges due to hurricanes in the region, two synthetic storm tracks were used. The storm track T7 follows a path very close to Hurricane Gustav (2008) and makes landfall at the south Louisiana coast near Timbalier Bay. The storm track T19 follows a track almost parallel to T7 and makes landfall at Heron Bay, MS, close to the river mouth of the East Pearl River. Since the size of the storm is about 45 km, the maximum wind lands at Biloxi, MS, and brings the highest storm surges to the east side of the Pearl River.

By using CCHE2D-Coast, an integrated coastal process model, two simulations were carried out with each storm track. One simulation was to compute the storm surges driven by all the hydrological conditions, but without inflow from the Pearl River. Another was to simulate the hydrodynamics with the same conditions, but with the inflows of 150 m$^3$/s from the Pearl River. The simulation results show that the channel geometry of the Pearl River in the computational mesh and consideration of its discharge as boundary condition are highly important for adequately predicting the local flooding conditions in Hancock County. When the river discharge is considered, the combined effect of storm surge and backwater curve leads to higher flood depths. The inundated area is also larger.

The comparison of the water surface levels for the same storm track provides an appreciation of the importance of the consideration of the East Pearl River discharge on the flooding conditions and inundation patterns in and around the river. Since the SL15 mesh used in LACPR and MsCIP studies does not include all the channel geometry and floodplain of the Pearl River, the simulation scenarios for these studies were not able to consider the discharge flowing in the Pearl River. The results of the simulations for LACPR and MsCIP studies, therefore, cannot be used for evaluating the inland flooding in the Pearl River and its floodplain.

The simulations presented in this paper were designed to demonstrate the effect of the omission of the Pearl River discharge on the flood depths and inundation patterns in Hancock County. They were all done using a mesh that represents the status of structures in 2007. They do not, therefore, provide any information whether the coastal protection and restoration works thus far completed in Louisiana, especially around New Orleans and the Lake Pontchartrain area, are causing an increased flood risk and increased flood levels in certain areas along the Mississippi coastal counties (Hancock, Harrison, and Jackson), especially in Hancock County along the east bank of the Pearl River.

ACKNOWLEDGEMENTS

This work was a result of research sponsored by the Mississippi Department of Marine Resources and The University of Mississippi. The authors thank Ty Wamsley at USACE-ERDC for providing the SL15 mesh data, and Paul McKay and Cheryl Ann Blain at Naval Research Laboratory, Stennis Space Center, MS for providing the cross section data in the Pearl River. The authors also thank Vijay Ramalingam and Marcus McGrath for providing the DEM data for modeling the Mississippi Coasts, and Xiaobo Chao for collecting the river discharge data.
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