Using Hydrodynamic Modeling for Estimating Flooding and Water Depths in Grand Bay, Alabama

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Abstract. This paper presents a methodology for using hydrodynamic modeling to estimate inundation areas and water depths during a hurricane event. The Environmental Fluid Dynamic Code (EFDC) is used in this research. EFDC is one of the most commonly applied models to Gulf of Mexico estuaries. The event with which the hydrodynamic model was tested was hurricane Ivan. This hurricane made landfall at the Alabama Gulf Coast in September 16, 2004. Hurricane Ivan was the most severe hurricane to hit eastern Alabama. Results show that the EFDC model is able to generate instances of flooded areas before, during and after a hurricane event (Ivan hurricane). The model also estimated water depths and water surface elevation values consistent to measured data reported in the literature, and comparable to model-estimated data from a meso-scale Slosh model for the region (also reported in the literature).

Keywords: Grand Bay, Hydrodynamics, EFDC, modeling, grid generation, flooding, inundation.

1 Introduction

Floods and storms are intrinsic components of the natural climate system and climate variability and, as such, are a part of a natural disturbance regime, which is an important determinant of an ecosystem structure and function, particularly in the long run [1]. While floods are generally perceived as having negative effects (due to damage to the human environment), floods also contribute to enriching the flood plain soil with nutrients and humidity that are very important for agriculture or natural ecosystems. The most commons causes of flooding are the overflow of streams and rivers and abnormally high tides (resulting from severe storms) into the normally dry land area adjoining rivers, streams, lakes, bays, or oceans [2]. Those dry land areas in the nearby of water bodies are also called floodplain.

Coastal floods are usually primarily caused by storm surges but typically result from a combination of coastal tidal action, storm surge, rainfall, heavy surf, tidal

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B. Murgante et al. (Eds.): ICCSA 2012, Part II, LNCS 7334, pp. 578–588, 2012.

piling, tidal cycles, topography, shoreline orientation, bathymetry, river stage, runoff and presence or absence of offshore reefs or other barriers [1].

The catastrophic loss of life and property by several hurricanes across Florida in 2004 and along the Gulf of Mexico coast during the summer of 2005 emphasizes the importance of accurate storm surge forecasts in highly populated coastal environments [3]. Among the weather events from that season, hurricane Ivan (the strongest hurricane of 2004) was composed by winds of more than 200 km per hour and devastated much of Gulf Coast in the southeastern US. The hurricane reached its peak strength on September 11, 2004, and made landfall at the Alabama Gulf Coast in the early morning hours of September 16. Hurricane Ivan was the most severe hurricane to strike eastern Alabama, western in many decades, approximating or exceeding design flood conditions along the Alabama shoreline, damaging severely the buildings closest to the coast [4].

The use of mathematical models is well established in the estimation of floodplains and inundation areas during hurricanes. Surge models and hydrological models are used by regulatory agencies (such as the US Federal Emergency Management Agency) to forecast potential floodplains for several types of storms. Hydrodynamic models of estuaries and bays are also used in conjunction to large scale surge models.

This paper presents a methodology for using the Environmental Fluid Dynamic Code (EFDC) for estimating flooded areas in the coast of Grand Bay, Mississippi (US) during the Ivan hurricane.

2 Methods

2.1 Study Area

Grand Bay is an estuary located in the northern Gulf of Mexico, at the border of the states of Mississippi and Alabama, USA (Fig. 1). It covers a geographical area of approximately 4300 hectares. The average depth is close to 1.1 m, although there are two areas where depths could reach 4.5 m (MLLW). The estuary receives waters from several small streams, being the two most important the Bayou Heron and the Crooked Bayou. The water depth at Bayou Heron ranges from 0.16 m to 1.69 m (depth readings represent the water depth above the depth sensor, which is located 0.5 m above the bottom). In terms of flooding, the effect of these small streams is negligible when compared to the impact of the ocean tides.

Grand Bay houses healthy estuarine salt marshes and fire-maintained pine savannas (some of the most biodiverse habitats in North America), environments that support many important species of fish and wildlife such as: finfish, shellfish, brown shrimp, speckled trout, oysters, sea turtles, bottlenose dolphin and, manatees and many species of carnivorous plants and orchids [5].

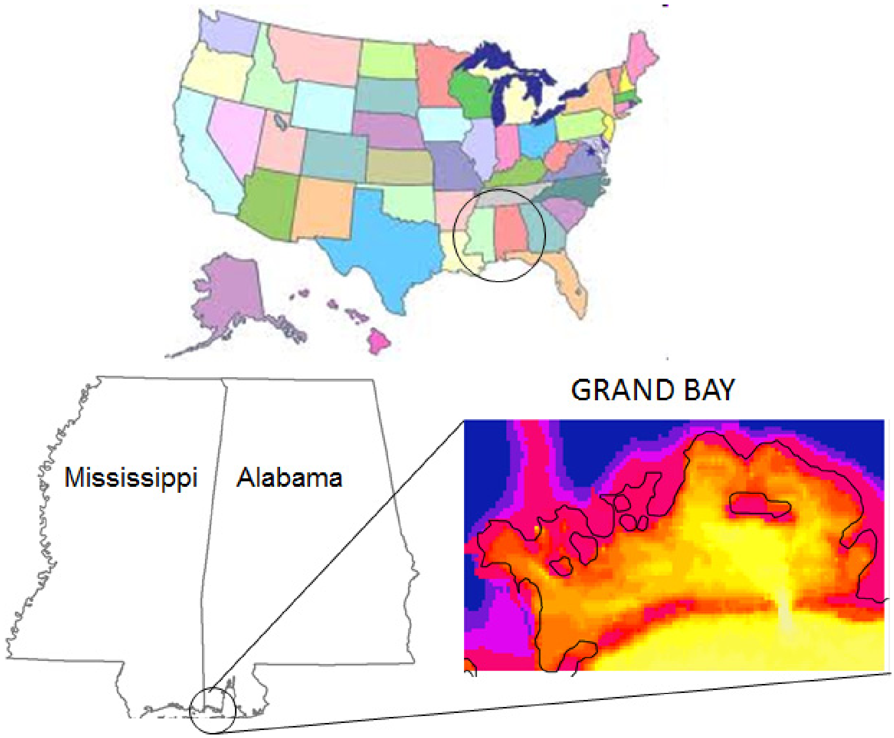

Fig. 1. Study area. The Grand Bay estuary is located at the border of Mississippi and Alabama

2.2 Computational Mesh

The bathymetry data used for producing the computational mesh for Grand Bay was downloaded from the NOAA-NOS Estuarine Bathymetry database. The dataset detailing the bottom topography of Grand bay provided by NOAA was referenced to the Mean Lower Low Water level (a tidal datum representing the average of the lower low water height of each tidal day observed over the National Tidal Datum Epoch). The grid generator for EFDC (GEFDC), capable of producing structured rectangular and curvilinear meshes [6], was applied for creating a structured grid of Grand Bay for hydrodynamics modeling.

The bathymetric information was downloaded in ASCII raster format. Manipulation of the raw ASCII bathymetry data was performed using ArcGIS and tailor-made C codes. This facilitated the production of one of the main input data required by GEFDC for the generation of the grid: the cell.inp file. This file specifies the interconnection between finite-difference cells, the type of cell (water, boundary, dry land, etc.), and whether it is a quadrilateral or triangular cell. Other files required by GEFDC such as dxdy.inp (specifying grid coordinates correspondence to bottom depths, cell dimensions, and bottom roughness), lxly.inp (cell center coordinates and orientation), etc., were also produced by those tailor made codes.

All pre-processing for the generation of the required GEFDC input files was performed in UTM Zone 16N coordinates. Figure 2 illustrates the process.

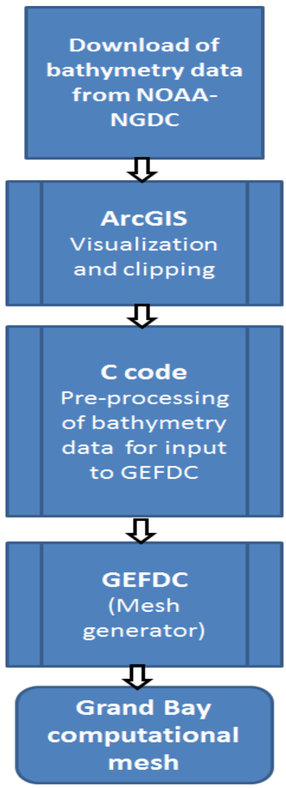

Fig. 2. Geo-processing of the bathymetry data for generation of the computational mesh for Grand Bay using the grid generator GEFDC and other computational tools

2.3 The Environmental Fluid Dynamic Code (EFDC)

The Environmental Fluid Dynamic Code (EFDC) is used in this research. EFDC is arguably the most commonly applied model to Gulf of Mexico estuaries for regulatory purposes. Ongoing or recent EFDC applications include the Back Bay of Biloxi, MS [7]; Bay St. Louis, MS [8] [9], Escatawpa and Pascagoula Rivers, MS [10]; Mobile Bay, AL [11][12]; Weeks Bay, AL (ongoing studies by GOMA, NGI), Tampa Bay [13], FL (and ongoing studies by GOMA) and many others.

The EFDC model is a public-domain surface water modeling system incorporating fully integrated hydrodynamics. It is used for 1D, 2D, or 3D simulations of rivers, lakes, reservoirs, estuaries, coastal seas, and wetlands [6]. It is currently used by federal, state and local agencies, consultants and universities [5].

2.4 Ivan Hurricane Data

Ivan was one of the strongest hurricanes of the first decade of this century. It landed at the Alabama Gulf Coast in September 16 of 2004. Figure 3 shows the Ivan hurricane path and the location of the study area.

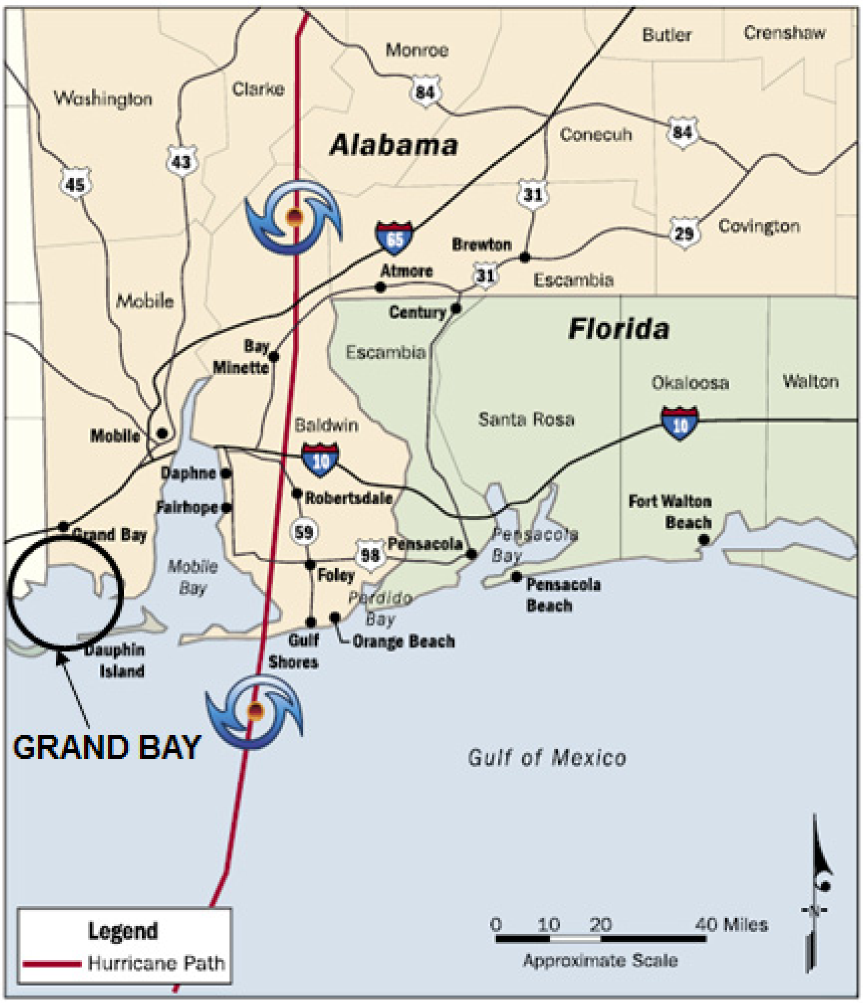

Fig. 3. Path of the Ivan hurricane and location of the study area (modified from [4])

A time series of tidal elevations was downloaded in ASCII format from the NOAA-NGDC website. The tidal data was referenced to the MLLW sea level in order for the vertical datum to be the same as the Grand Bay bathymetry. The closest station to Grand Bay that has records of water surface elevations occurring during the Ivan event is the Dauphin Island NOAA station. Since this station is approximately at the same latitude to Grand Bay, the data was used without further processing (spectral analysis or extrapolation) for hydrodynamic modeling simulation.

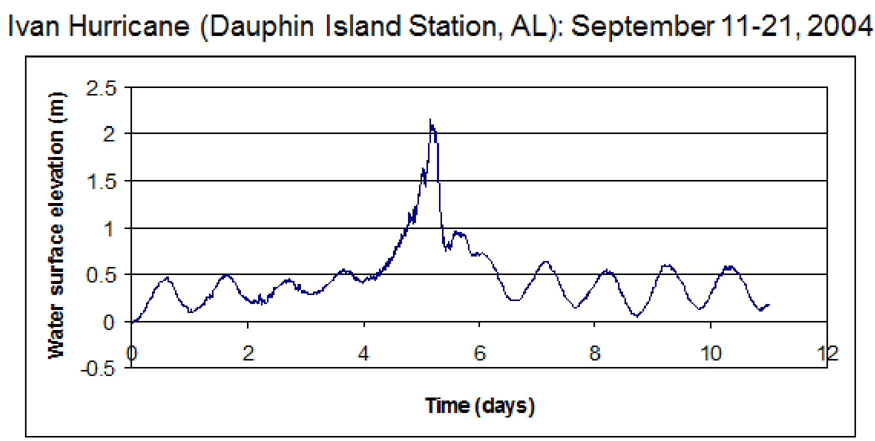

Fig. 4. Tidal heights recorded at the Dauphin Island NOAA station during Ivan hurricane. Water surface elevations are shown referenced to the Mean Lower Low Water level (MLLW).

3 Results

3.1 Computational Mesh for Grand Bay

Fig. 5 shows the structured grid developed for input into the EFDC model for simulating hydrodynamics in Grand Bay. The mesh consists of 8190 square cells (of 84.98 m per side) and covers not only Grand Bay but the dry land area surrounding the bay (floodplain). The figure also shows the location of ocean boundary conditions and freshwater boundary conditions. The model was set up with tidal ocean boundaries in the form of time-series of water surface elevation input at each cell shown as “ocean boundary” in Fig. 5. The fresh water boundary conditions corresponding to Bayou Heron (upper left boundary), and Crooked Bayou (lower left boundary) were input as time-series of stream flow occurring at those streams during the Ivan hurricane.

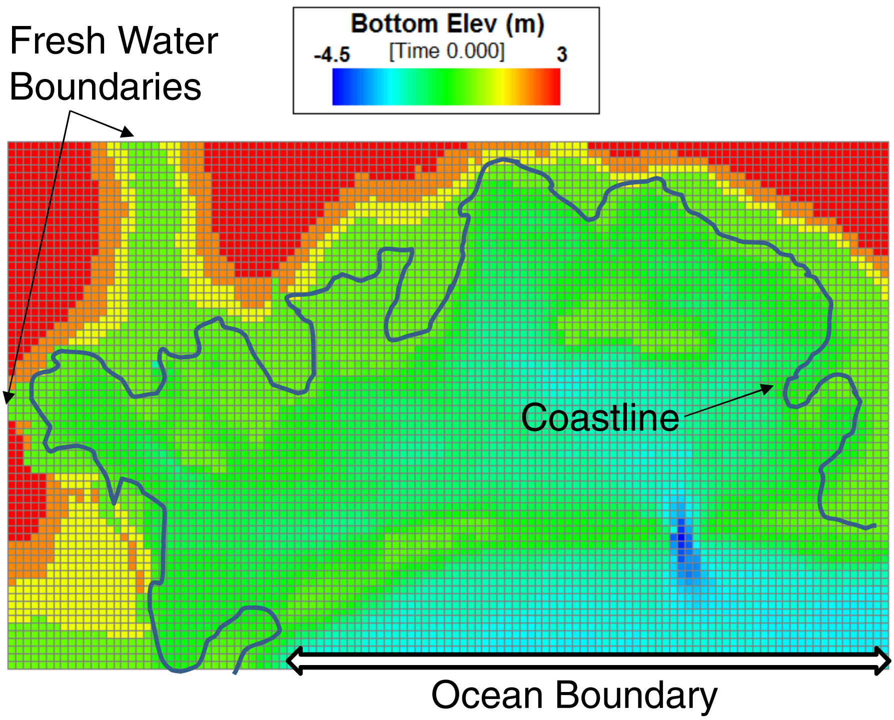

Fig. 5. Computational mesh for the EFDC hydrodynamic model of Grand Bay

3.2 Estimation of Flooded Areas during the Hurricane Peak

Fig.6 shows water depths occurring in Grand Bay at two instances: before the Ivan hurricane (top) and during the peak of the hurricane (bottom). The fact that square of known dimensions cells were used in the creation of the computational mesh for grand Bay greatly simplifies the estimation of flooded areas before and after the weather event. Raster operations for detecting active and inactive cells for the two instances shown in Fig. 6 were performed and the results are shown in Table 1.

Table 1. Estimation of flooded area

Instance	Number of active cells	Area in hectares
Before Ivan	6187	4467.84
At the peak of Ivan	8190	5914.28
Flooded Area		1446.44

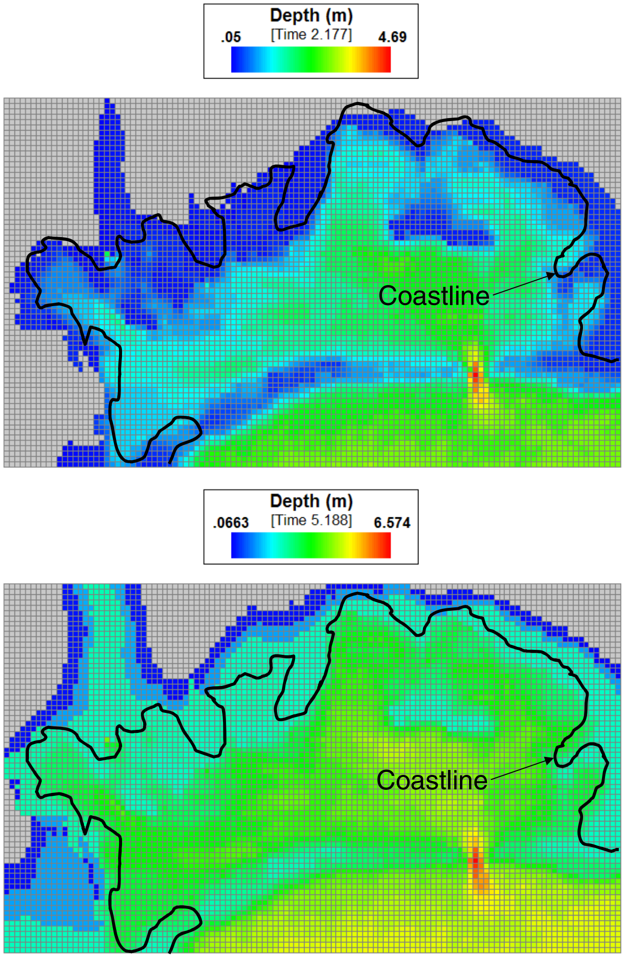

Fig. 6. Water surface elevations before hurricane Ivan (top) landing and at the peak of the hurricane (bottom)

A comparison of estimated water depths estimated using EFDC against measured water depths occurring during the hurricane is not feasible because of the lack of recorded data. However, and indirect validation of the results of this research is possible by comparing the water depths and inundated areas to meso-scale surge models. SLOSH (Sea, Lake and Overland Surges from Hurricanes) is a computerized model run by the National Hurricane Center (NHC) to estimate storm surge heights and winds resulting from historical, hypothetical, or predicted hurricanes by taking into account [14]. The US Army Corps of Engineers compared Slosh model results to high water marks observed after the Ivan event [15]. The report includes “inside high water marks” records inside of structures, which estimate storm tide elevation without the effect of waves, and “outside high water marks” which estimate the combined effect of storm tide and wave set up and run up. Outside high water mark elevations are generally higher than inside high watermarks because of the added wave effects [15]. The USACE report concluded that the comparison of observed storm surge hydrographs to the SLOSH model calculated storm surge hydrographs showed reasonable results. In this paper, the EFDC-estimated water depths are compared to Slosh model predictions of water depths for Grand Bay.

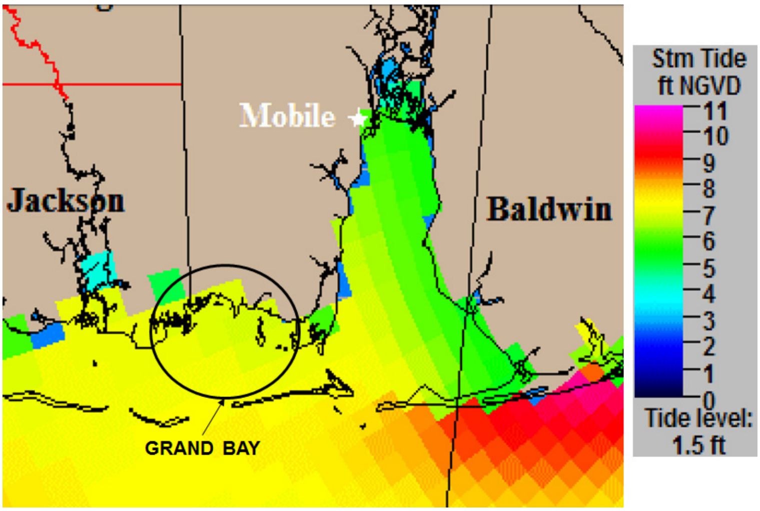

Fig. 7. The SLOSH model predictions of High Water (HW) tide levels showing the location of Grand Bay (modified from [15])

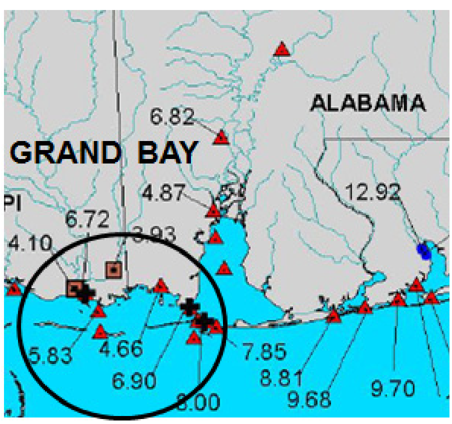

Fig. 8. USACE Mobile District tide gages peak elevation during Hurricane Ivan. In feet (modified from [16]).

As seen in Fig. 7, the Slosh model predictions for Grand Bay for tide levels (high water, HW) occurring during the Ivan hurricane average 2 m (6.5 ft.). Fig. 8 shows actual tidal elevations recorded by the USACE tidal stations in the Grand Bay area. Averaging the tidal elevations values for the Grand Bay study area results in a measured water depth of 1.8 m (5.9 ft.). The EFDC model for Grand Bay presented in this paper estimates water depths ranging from 2.07 m to 4.15.m (mean 2.7 m, median 2.5), as shown in Fig. 6.

4 Conclusions

This paper shows the potential of using shallow-water hydrodynamic models to estimate floodplain areas in coastal regions. The EFDC model is shown to be able to generate instances of flooded areas before, during and after a hurricane event (Ivan hurricane). Based on those calculations, the model estimates that the flooded area at the peak of the hurricane was 1446 hectares.

The model was also used to estimate water depths and water surface elevation values. The results of this computational exploration show that the EFDC model provides water depths estimations for the Grand Bay estuary (during the Ivan hurricane) consistent to measured data reported in the literature, and comparable to model-estimated data from a meso-scale Slosh model for the region (also reported in the literature). However, this indirect verification of results is insufficient for applying the technique to real inundation events. Actual validation of the methodology and flooded area estimates will be topic for future research.

Acknowledgments. This research was funded by the Northern Gulf Institute, and the NSF-EPSCOR grant number 1010578.

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