UNIVERSITY: **University of Central Florida**

NAME OF UNIVERSITY RESEARCHER PREPARING REPORT: **Scott C. Hagen**

NWS/AFWA/NAVY OFFICE: **NWS Southeast River Forecast Center; 4 Falcon Drive; Peachtree City, GA 30269**

NAME OF NWS/AFWA/NAVY RESEARCHER PREPARING REPORT: **Edwin Wylie Quillian and Reggina Cabrera Garza**

PARTNERS OR COOP.: **Coop Program** SUBAWARD NO.: **UCAR S01-32794**

DATE: **May 2004**

SECTION 1: PROJECT OBJECTIVES AND ACCOMPLISHMENTS

Channel routing is currently used by the National Weather Service River Forecast System (NWSRFS) in their overall flood-forecasting model to predict the characteristics of a flood wave as it propagates. At present, the waves that originate from tidal fluctuations in the Waccamaw River are not accounted for in the hydrologic storage routing model set up for this site. For river forecasting in the coastal areas this lack of input has proven to be problematic. FLDWAV is being set up for this location in order to address this problem. We include tidal fluctuations by providing boundary conditions for FLDWAV from a tidal model.

The Southeast River Forecast Center (SERFC) and the University of Central Florida cooperated to pursue two main goals:

> Goal 1) To implement the FLDWAV model using output from a tidal model and conduct real-time flood forecasting for the Waccamaw River.
>
> Goal 2) To include output from a simulation of the storm surge due to Hurricane Hugo in the FLDWAV model for the Waccamaw River, which will lay the groundwork for the inclusion of real-time simulations of tides and hurricane storm surge in flood forecasting efforts of the SERFC and other NWS Forecasting Centers that border on coastal areas.

These two goals comprise two phases of cooperative effort. This final report will detail how **Phase I** was addressed in the first year and **Phase II** in the second year.

Phase I

Phase I began on August 1, 2001, ended on July 31, 2002, and accomplishes three major tasks. Each of these tasks required coordination between the tidal modeling efforts and the FLDWAV model application. Task 1) Dr. Scott C. Hagen's team at the University of Central Florida conducted ADCIRC model simulations to forecast tides for two locations on the Atlantic Intracoastal Waterway (AIW). Task 2) Ms. Reggina Garza, who has implemented FLDWAV for a St. Johns River application in Florida, and Mr. Wylie Quillian of the SERFC worked with graduate students from the University of Central Florida to gather information and set up the FLDWAV model on the Waccamaw River and AIW. Task 3) FLDWAV will be executed operationally in real-time by the SERFC for future forecasts that utilize predictions of the tide-stage hydrograph from the tidal model.

The project area is located in the northern region of the South Atlantic Bight along the southeast coast of the United States. The Waccamaw River drains the coastal areas of southern North Carolina and northern South Carolina. The river leaves Lake Waccamaw in North Carolina and flows southward through Conway, South Carolina. From there, the river flows southward to the confluence with the Great Pee Dee and Black Rivers, through Winyah Bay, and into the Atlantic Ocean as shown in Figure 1.

An existing finite element mesh (SC-1) was modified to include the Waccamaw River from Conway, South Carolina. Figure 2 displays the resulting mesh (SC-2) that was employed in a series of tidal model simulations. In addition, this mesh was refined in the riverine and estuarine areas to permit the simulation of eddy currents. Historical and assumed riverine inflows were included and the tidal model was calibrated for bottom friction and eddy viscosity.

Figure 3 presents the location of all USGS stations that were implemented in this study and defines the locations where the tidal model will provide boundary conditions for FLDWAV. Figure 4 displays a schematic of the FLDWAV model.

Phase II

Finite Element Mesh Development

Four different South Carolina meshes (SC-1, SC-1-FP, SC-2, and SC-2-FP) were used in order to compute the storm tide stages. Two meshes (SC-1-FP and SC-2-FP) include inland topography that was employed through the wetting and drying of elements. The different study domains all accommodate important inlets along the South Carolina coast. The shoreline and riverbanks were obtained from the National Geophysical Data Center (NGDC) Coastline Extractor at http://rimmer.ngdc.noaa.gov/coast/. All meshes include the same semi-circular arc at the open-ocean boundary. The endpoints were located at Hilton Head Island, South Carolina and Cape Fear, North Carolina (see Figure 5). The arc extends about 100 km into the Atlantic Ocean. The mesh elements within the Atlantic Ocean and the majority of the continental shelf remain the same for all domains. Slight grid alterations had to be made along the coast and estuaries, insignificant to the computational results. The maximum element size for all meshes was 14 km.

Both domains including floodplains; SC-1-FP and SC-2-FP were based on the previous developed meshes SC-1 and SC-2. The appending of the meshes was established by defining an inland boundary, far enough inland from the river and coastline boundary that covers the observed inundation areas. Large portions of pertinent tributaries basins (Pee Dee River, Black River, Sampit River, and Santee River) were included within these boundaries as well. Information regarding inundated areas, during Hurricane Hugo, was obtained from anecdotal records, depicted inundation areas, surveyed high water mark maps and topographic maps from the U.S. Geological Survey (USGS) agency.

Elevation data was obtained from the NGDC Coastal Relief CD-ROM, Volume 2, Version 1.0 (1999). The NGDC collects the data from several sources. Land elevations come from the United States Geological Survey/National Image Mapping Agency 1:250,000 or 1-degree Digital Elevation Models of the states. Soundings for each volume of the Coastal Relief model series are compiled from hydrographic surveys conducted by the National Ocean Service and from various academic institutions. The CD-ROM provides a database of 3-arc-second (approx. 90 m) resolution elevations in 1-degree grids for the U.S. coastal areas. One is able to specify grid boundaries to the nearest minute of longitude and latitude, grid resolution from 3- seconds to 1-minute, a water datum reference, and file download formats. For all South Carolina meshes, the water datum reference is Mean Sea Level (MSL), and a precision of 1/10 of a meter is used. In order to minimize the vast amount of elevation data a 3-arc-second resolution was employed adjacent to the Waccamaw River, AIW, and along the ocean's shore. A 6-arc-second resolution was used far inland, where the mesh size is coarser (see Figure 6).

After the construction of the finite element mesh, the elevation data was interpolated onto the nodes of the mesh. Figure 7 shows the ocean's bathymetry and inland topography obtained from the elevation data. The meshes including inland topography were accomplished by deleting all nodes with elevations exceeding 6.1 m. Figure 8 and 9 show mesh differences between the four South Carolina meshes at Bulls Bay (Figure 8) and at Winyah Bay (Figure 9). The insets clearly show the increased mesh-resolution within the Winyah Bay region, while for the Bulls Bay area the mesh resolution remains about the same for all meshes. In addition, Table 1 shows the characteristic of the four South Carolina meshes engaged in this study.

Hurricane Hugo (1989) Wind Field

In 1989, Hurricane Hugo, which made landfall near Charleston, produced major inundation and destruction along the coast of South Carolina. The hurricane was the strongest storm to strike the United States since 1969 (DOC, 1990). It was also one of the costliest in U.S. history accounting for $9.7 billion in damage. Although the number of casualties was kept low due to good weather information, planning and evacuations, the hurricane's intensity directly caused 49 fatalities. South Carolina suffered the greatest number of deaths with 13 lives lost. More than 200,000 families were affected by the hurricane with homes destroyed or damaged. However, it should be noted Hugo's hazardous winds and storm surges had the potential of a heavy death toll.

All necessary wind field data was computed and provided by Oceanweather Inc. (http://www.oceanweather.com) using a tropical wind model established and described by Cox and Cardone (2000). An exponential pressure law was employed in order to compute a circularly symmetric pressure field located at the center of the storm. The wind speeds were computed by equations of horizontal motion and vertically averaged through the planetary boundary layer. The computed wind field drives then the shallow water equation model ADCIRC. Wind speeds and atmospheric pressure were interpolated to each node of the finite element mesh at each specified time step. For this study, the translation wind speed to wind stress was accomplished by applying the relationship proposed by Garratt (1977) integrated in the ADCIRC code.

Figure 10 shows the extent of the Hurricane Hugo wind field (applied to all South Carolina meshes) with respect to the Western North Atlantic Tidal model domain. Figure 11 illustrates an inset of the wind field vectors (15-min. averaged), around the time of landfall, between Winyah Bay and Charleston harbor. In addition, Table 2 provides further information regarding the utilized wind field.

Results

Two main simulation results are presented: 1) inundation areas within the region of Winyah Bay computed with the SLOSH model and the ADCIRC-2DDI code, and 2) four storm tide hydrographs along the South Carolina coast at Charleston harbor, Bulls Bay, Winyah Bay inlet, and McClellanville.

Figure 12 presents a comparison between a SLOSH computed inundation extent developed by the U.S. Army Corps of Engineers (USACE) (Figure 12.a) and an ADCIRC generated output (Figure 12.b) Note that when Hurricane Hugo made landfall it was a Category 2 storm. Therefore, in the SLOSH output the blue colored areas have to be compared with the ADCIRC output. It is not known on what assumptions the USACE generated the SLOSH data, i.e., topographic information; forward speed of the storm; hurricane landfall region; and at what angle did the hurricane hit the coastline, etc.

Both figures show about the same extent of flooding. At the Winyah Bay inlet, SLOSH indicates the overtopping of a large barrier island. Clearly this was not the case during Hurricane Hugo (Schuck-Kolben and Cherry, 1995). Another difference is shown in the Pee Dee River Basin. The ADCIRC computed surge extends further up the basin. Also, it seems ADCIRC does a better job in predicting the flooding along the AIW and the Waccamaw River. The SLOSH figure does not indicate any inundation along the two rivers due to a Category 2 storm. However, SLOSH indicates inundation between the AIW basin and the Pee Dee River basin, i.e., the location of the Bull Creek. Both figures reveal about the same size of flooding within the Sampit River basin and the Black River basin. The inundated areas southwest of Winyah Bay show similar patterns.

The calculated storm tide hydrographs within the Atlantic Ocean include simulation results from all four meshes utilized in this study (SC-1, SC-1-FP, SC-2, and SC-2-FP). The inland storm tides at McClellanville were computed by using the floodplain meshes only. Figure 13 illustrates the location of the four locations of interest.

Figure 14 displays the results at Charleston harbor. Deviation from mean sea level (MSL) in meters is plotted against time (Date and Time). The thin black line represents historical data recorded at the Charleston harbor tide station. The four other graphs (see legends for colors) allow distinction to be drawn between the four separate meshes.

Since the storm surge occurred at nearly high tide (see Figure 14) it is important to point out that all meshes accurately simulate the tidal signal leading up to the storm surge event that began at approximately midnight on September 21, 1989 (9/22/1989 0:00 on Figure 14). Still a phasing error is evident that is applicable to all the meshes used. The two meshes that do not allow inland flooding (SC-1 and SC-2) result in the highest peak of the storm tide (approx. 3.0 m). Due to the no-flow boundary conditions (equivalent to an infinite vertical wall) specified at all shorelines these results seem reasonable. The no-flow boundary constrains the water mass within the vertical walls. It also can be noted that the SC-1 and the SC-2 domains result in an artificial second peak (indicated by letter A in Figure 14) due to a sloshing effect caused by the no-flow boundary. The two domains that allow inland flooding (SC-1-FP and SC-2-FP) produce lower peak surge than the SC-1 and SC-2 meshes.

None of the models accurately capture the rising limb of the storm tide hydrograph. At the zero hour on September 22, 1989 the recorder stages are above MSL (see letter B, Figure 14). This shortcoming is due to the absence of short wave action, which could be included in future efforts by incorporating wave radiation stress terms from short wave calculations in order to produce setup. The storm surge peak may also increase as a result of including short wave action.

Figure 15 shows the calculated hydrographs at Bulls Bay. Recorded station data is not available for this location. After Hurricane Hugo the USACE surveyed high water marks along the coast of South Carolina. The USGS reports sea elevations of about 6.0 m above MSL within Bulls Bay (Schuck-Kolben and Cherry, 1995).

Close examination of Figure 15 reveals that all meshes produce about the same tidal signal. Again the two meshes without inland topography produce higher peaks (approximately 5.1 m) than the SC-1-FP, and SC-2-FP (4.4 m, and 4.3 m). The lower peak computation of the floodplain meshes is reasonable, since the inland areas allow the water to flow into the floodplains (see Figure 16 and 17 that show contour plots of the water elevations at Bulls Bay, with and without floodplain).

A discrepancy is noticed for the recession curves (see letter A, Figure 15). The graphs representing the floodplain meshes have a higher recession limb due to inland areas that hold the storm tide longer. A small artificial second peak (see letter B, Figure 15) produced by the SC-1 and SC-2 domain is shown. As before, these peaks are caused by a sloshing effect from the no-flow boundary conditions at the shoreline.

None of the meshes produce sea elevations of 6 m above MSL at the center of Bulls Bay. Again, this shortcoming is due to the absence of short wave action that produces setup. Therefore, including the short wave action and the associated setup could likely produce peak elevations of 6 m above MSL within the Bulls Bay.

Figure 18 presents the generated hydrographs at Winyah Bay inlet. High water mark information is used in order to assess the computed sea stages. At Winyah Bay inlet and within the middle of the bay elevations of 3.7 m above MSL were reported (Schuck-Kolben and Cherry, 1995). Again a clear distinction can be made between the meshes with and without inland topography at the time of peak. Unlike the two previous locations, the storm peaks are now higher when they include floodplain areas. The SC-1-FP and the SC-2-FP meshes produce water stages of 3.3 m to 3.4 m above MSL. While the SC-1 and SC-2 meshes show peaks of 3.0 m above MSL.

The two meshes without floodplains (SC-1 and SC-2) are not able to capture these extensive inundation processes due to no-flow boundaries at the shorelines. Note that the incorporation of inland topography does not always create lower water elevations (see Charleston harbor and Bulls Bay). Including inundation areas can also have an opposite effect on the water stages (Winyah Bay region).

The floodplain meshes are able to allow extensive inundation that leads up to higher water elevations within the bay and its entrance. The high storm tide at the center of Winyah Bay is a result of the water surging in from its former North inlet. The North inlet comprises of barrier islands of low elevations and therefore allows the storm surge to enter the bay from the northeast. In addition, large amounts of water stream in overland from the southwest causing an additional increase in water stages. At the same time, water is entering the bay from its present inlet and piles up against the elevated water body at the bay's center. This piling-up effect is strengthened due to a massive barrier island at the entrance to the bay (Schuck-Kolben and Cherry, 1995). Water is restricted from flowing back in the ocean.

Another feature to become aware of is an increase in water stages at the end of the recession limb (see letter A, Figure 18). The elevated stages are produced due to water backflow that surged into the bay form the northeast and the southwest. The SC-2-FP hydrograph shows a relative small increase in water stage (around MSL). While the SC-1-FP mesh produces much higher water elevations (about 0.9 m above MSL). The reason for the difference in sea stages is caused by the domain size of the SC-1-FP and the SC-2-FP. The SC-2-FP domain incorporates extensive reaches of the AIW and the Waccamaw River. Therefore, the storm surge propagates farther inland and the relevant water backflow occurs much later in time than with the SC-1-FP mesh. Note that this is the only downside to using SC-1-FP domain.

Figure 19 shows computed water elevations at McClellanville. The village is located northeast of Bulls Bay (see Figure 13), is inland and was subject to severe flooding (Metts, 1989). High water marks reached elevations of about 4.9 to 5.5 m above MSL (DOC, 1990). Figure 19 shows only a short time-period of the computed hydrograph. Water starts to rise around 4 a.m. The peak of the storm surge occurs around 4.45 a.m. and produces water elevations between 5.2 m to 5.5 m above MSL. Figure 17 represents the size of inundation around 4 o'clock in the morning of September 22, 1989. The depicted elevations are computed by using the SC-2-FP mesh. The SC-2-FP domain generates a slight lower peak (5.2 m) than the SC-1-FP mesh (5.5 m). Also, a slight time discrepancy is noticed between the rising limbs of about 10 minutes.

Lessons Learned

The primary focus of this study was to assess the inclusion of inland topography thereby allowing inundation of areas along shorelines and within the Winyah Bay and Waccamaw/AIW riverine system. The floodplain meshes are compared with meshes that include no-flow boundary conditions (not allowing any flooding processes) in order to examine whether including inland topography significantly improves the predicted storm tide stages. The aim was to accomplish a computationally efficient mesh (i.e. small number of nodes) with a good prediction accuracy of water elevations, both of which help us to define exactly where

FLDWAV boundaries should be located and how the boundary conditions (i.e., hydrographs from tide and storm surge model) should be determined.

Three main conclusions may be drawn from this research:

1. Inundation areas near the coastal shoreline must be included
2. Present storm tide studies lack critical short wave components
3. The storm tide hydrograph should be generated at the exact location it will be applied to FLDWAV.

All plotted hydrographs related to the four different meshes (SC-1, SC-1-FP, SC-2, and SC-2-FP) show clear distinction between the models including inland topography (SC-1-FP, and SC-2-FP) and the models without inland topography (SC-1, and SC-2). The inland topography meshes obviously achieve better results where inundation occurred. Inundation either causes a decrease in water elevations, at Bulls Bay, or an increase, at Winyah Bay inlet. In addition, simulated sea elevations all show lower storm tide elevations when compared with historical data. The fact that the applied numerical code, ADCIRC-2DDI, does not include short wave action explains the reduced sea stages. In the final analysis, incorporation of inland topography is significant and should be included for predicting near-shore storm tides, and at a minimum, wave radiation stress terms from a short wave model should be incorporated.

Another important fact to draw attention to is that the SC-1-FP mesh (with 14,500 nodes) produces virtually the same results as the SC-2-FP mesh (with 118,000 nodes) near the shorelines. Therefore, storm tides can be predicted with good accuracy with a less computationally expensive mesh and still include pertinent inland topography. The only drawback noted is in the recession limb of the storm tide hydrographs; however, the peak is unaffected.

It is noted that the SC-2-FP incorporates a larger riverine body than the SC-1-FP mesh and much of the increased node number is a result of the incorporation of these river reaches. It is also recognized that including extensive river reaches makes it necessary to include at least three elements across a river channel in order to approximate the cross-section. Besides describing the usually trapezoidal shape of the river channel, a good propagation of the storm surge is guaranteed, which results in less simulation instabilities.

SECTION 2: SUMMARY OF UNIVERSITY/ NWS/DOT EXCHANGES

August 13, 2001: Dr. Hagen and two graduate students from the University of Central Florida visited the Southeast River Forecast Center. The purpose of this visit was to discuss the project status and future work. The graduate students were exposed to a general explanation on NWSRFS to engender a better understanding and appreciation of the project. In addition, it helped them understand how we will be using the outputs from the tidal model in combination with FLDWAV. During this visit, it was planned that the SERFC would provide Dr. Hagen, as soon as possible, with the existing data (stages and/or discharges) in the vicinity of the Pee Dee, Bulk Creek, and Waccamaw areas.

December 12 to 14, 2001: A seminar and site visit were held at Conway, South Carolina. Coastal Carolina University hosted representatives from the SERFC, University of Central Florida, Horry County Engineering, the NWS at Wilmington, NC, U.S. Army Corp of Engineers, Horry County Code Enforcement and Emergency Management, Georgetown County EPD, and the USGS. Mr. Wylie Quillian and Dr. Hagen presented at an afternoon seminar on December 12 and a boat tour of the Waccamaw River was made on December 13. This meeting and boat tour enabled data acquisition from the USGS and yielded detailed firsthand descriptions of the river.

January 18, 2002: NWSRFS and Flood Wave training was conducted at the University of Central Florida by Reggina Cabrera Garza. The training consisted of a detailed explanation about the different components of NWSRFS and then specifically addressing the technical background of the FLDWAV operation. The package given to the students included notes, technical material, examples of setting the St. Johns River, example of the initial work for the Santa Fe River and general considerations to setup FLDWAV.

March 1, 2002: Dr. Scott Hagen presented research in using a tide and storm surge model in the western Atlantic basin as well as the Gulf of Mexico. Among the results from the modeling, he showed an animation of Hurricane Betsy's inundation in the New Orleans area. He provided an explanation of the storm surge and inland flooding model. Dr. Hagen explained how the model could be very useful for simulating the effects of storm surge in the major canals, e.g., around Lake Okeechobee.

May 17, 2002: Dr. Hagen visited the National Weather Service Southeast River Forecast Center to present progress to date and discuss data needs and future efforts.

June 6 and 7, 2002: Reggina Cabrera Garza visited the University of Central Florida and worked with Dr. Hagen and his students to set up the input file for the FLDWAV model. A generic input file was developed and implemented, and will be updated as more data is made available.

August 15, 2002: Mr. John Feldt and Dr. Hagen visited the National Weather Service Office of Hydrologic Development in Silver Springs, MD to present on the SERFC/UCF collaboration and discuss future efforts that may be explored in cooperation with the NWS Office of Hydrologic Development.

September 15 and 16, 2003: The second Flood Wave Coordination meeting (FWCM) was held at the SERFC on September 15 and 16, 2003. Dr. Hagen and Mr. Daniel Dietsche visited the National Weather Service Southeast River Forecast Center to present progress to date and discuss data needs and future efforts. The purpose of this meeting was to describe the status of each project in which the SERFC is a partner. Currently two projects are being discussed, the Tar River Basin and the Waccamaw River at Conway. It was decided that SERFC will work in the development of the FLDWAV for the Waccamaw River and AIW reach and Jamie Dyer and Reggina Cabrera Garza will work on this task. The FLDWAV schematic developed in combined effort with Mr. Ryan Murray (former UCF student) will be the starting point. The cross section data will be revised, the period of calibration for different magnitude of flows will be determined and Dr. Hagen will provide the tidal boundaries for those periods.

January 15 & 16, 2004: Mr. Wylie Quillian and Mr. Jamie Dyer visited Dr. Hagen and his graduate students at the UCF Compaq Water Resources Simulations Laboratory to discuss progress to date and future efforts.

May 10 and 11, 2004: Mr. Daniel Dietsche and Dr. Hagen will visit the SERFC to make a final presentation on UCAR S01-32794 and to present progress-to-date and discuss future work with regards to UCAR S03-44675.

SECTION 3: PRESENTATIONS AND PUBLICATIONS

Invited International Presentations:

Hagen, S.C., “Storm Tide Hindcasts for Hurricane Hugo: Into an Estuarine and Riverine System,” *Sixth International Conference on Hydro-Science and –Engineering*, Brisbane, Australia, May 30 – June 4, 2004.

Invited National and Local Presentations:

Hagen, S.C., "A Computationally Efficient Hindcast of Storm Tides from Hurricane Hugo," *58th Interdepartmental Hurricane Conference*, March 1-5, 2004, Charleston, South Carolina.

Hagen, S.C., “Tide Predictions for the Waccamaw River Including the Atlantic Intracoastal Waterway,” *2003 Georgia Water Resources Conference*, held April 23-24, 2003, at the University of Georgia, Athens, Georgia.

Quillian, E.W., “The National Weather Service River Forecast System,” Coastal Carolina University, Conway, SC, Dec. 12, 2001.

Hagen, S.C., “Hurricane Storm Surge and Tide Predictions for the Waccamaw River,” Coastal Carolina University, Conway, SC, Dec. 12, 2001.

Refereed Conference Presentations:

Hagen, S.C., D. Dipersia, R. Murray, and D.M. Parrish, “Tide Predictions for the Waccamaw River Including the Intracoastal Waterway,” 7th International Conference on Estuarine and Coastal Modeling, St. Pete Beach, FL, November 5-7, 2001.

Journal Publications:

Hagen, S.C., M. Salisbury, P. Bacopoulos, and R. Murray, “A Sensitivity Analysis for Tide and Riverine Flow of the Waccamaw River,” *Journal of Waterways, Port, Coastal, and Ocean Engineering*, In Preparation.

Dietsche, D., and S.C. Hagen, “Influence of Inland Flooding Areas on Near-Shore Storm Tide Hydrographs,” *Journal of Waterways, Port, Coastal, and Ocean Engineering*, In Preparation.

Hagen, S.C., O. Horstman and R.J. Bennett, “An Unstructured Mesh Generation Algorithm for Shallow Water Modeling,” *The International Journal of Computational Fluid Dynamics*, **16**, 83-91 (2002).

Conference Publications:

Hagen, S.C., D. Dietsche, and Y. Funakoshi, "Storm Tide Hindcasts for Hurricane Hugo: Into an Estuarine and Riverine System," *Sixth International Conference on Hydro-Science and – Engineering*, Brisbane, Australia, May 30 – June 4, 2004.

Hagen, S.C., H.C. Graber, V.J. Cardone and A. Cox, "A Computationally Efficient Hindcast of Storm Tides from Hurricane Hugo," *58th Interdepartmental Hurricane Conference*, March 1-5, 2004, Charleston, South Carolina.

Murray, R. and S.C. Hagen, "Tide Predictions for the Waccamaw River Including the Atlantic Intracoastal Waterway," *Proceedings of the 2003 Georgia Water Resources Conference*, held April 23-24, 2003, at the University of Georgia. Kathryn J. Hatcher, editor, Institute of Ecology, The University of Georgia, Athens, Georgia.

Masters Theses:

Ryan M. Murray, "A Sensitivity Analysis for a Tidally-Influenced Riverine System," graduated Summer 2003.

Daniel Dietsche, "Storm Tide Simulations for Hurricane Hugo (1989): On the significance of Inland Flooding Areas," graduated Summer 2004

SECTION 4: SUMMARY OF BENEFITS AND PROBLEMS ENCOUNTERED

4.1 As a result of this research, Dr. Hagen has learned more about the needs of the forecasting office with regards to the forecasting of tides and storm surge, which will enhance our future collaborative efforts and permit the implementation of a real-time forecasting model for tides and storm surge.

Dr. Hagen has presented aspects of operational forecasting to students in his Hydrology class (CWR 4101) at the University of Central Florida. Two UCF graduate students and three undergraduate students were actively involved in this COMET project. As noted above, the students also visited the SERFC on multiple occasions with Dr. Scott C. Hagen and discussed the work-to-date, future plans and began learning about the operational tasks associated with the SERFC's mission. The graduate students have used their experience to develop their Masters Theses and the undergraduate students have gained skills that help to prepare them for successful graduate studies. Finally, this research has also benefited other undergraduate and graduate students at UCF.

The only problems that have been encountered are with respect to stage, discharge and cross-sectional data. The USGS is producing archived stage and discharge data at 15-minute intervals, which is required due to tidal fluctuations in the river. Acquisition of this data has been a time-consuming process, at best. Cross-sectional data for the Waccamaw River from Longs, SC to the Winyah Bay region has been acquired from decades-old Flood Insurance Studies by FEMA. To the best of our (SERFC and UCF) knowledge there is no up-to-date cross-sectional data available at this time. It is recommended that we pursue additional funding to hire Coastal Carolina University students to acquire new cross-sectional data.

4.2 The waves that originate from tidal fluctuations in the Waccamaw River are not accounted for in the present NWSRFS model for this region. However, the NWSRFS does have the capability of incorporating such effects by employing FLDWAV. The storm tide model developed as part of this COMET project will improve the river forecasting at the Waccamaw River because of the accurate boundary conditions that were produced and are needed to run FLDWAV.

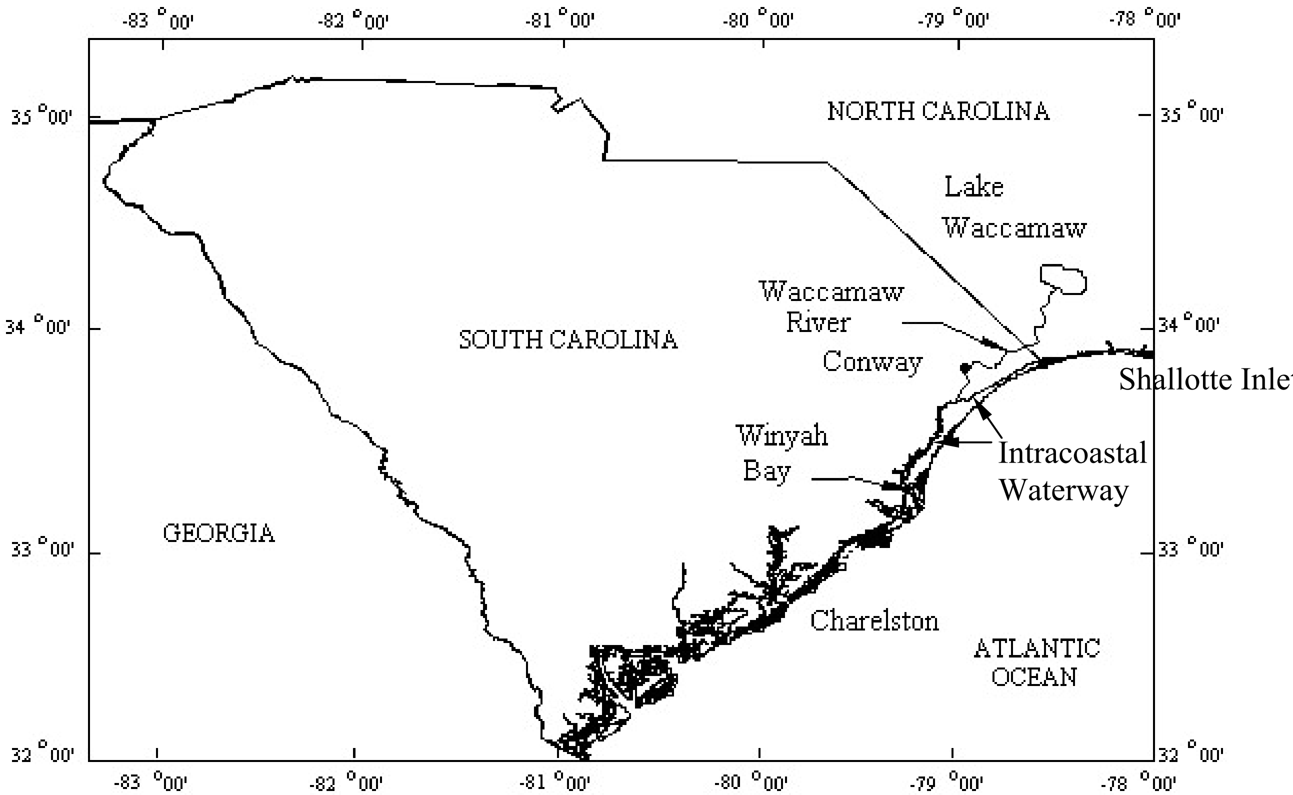

Figure 1. The coast of South Carolina, Waccamaw River, and the Atlantic Intracoastal Waterway from Winyah Bay to Shallotte Inlet.

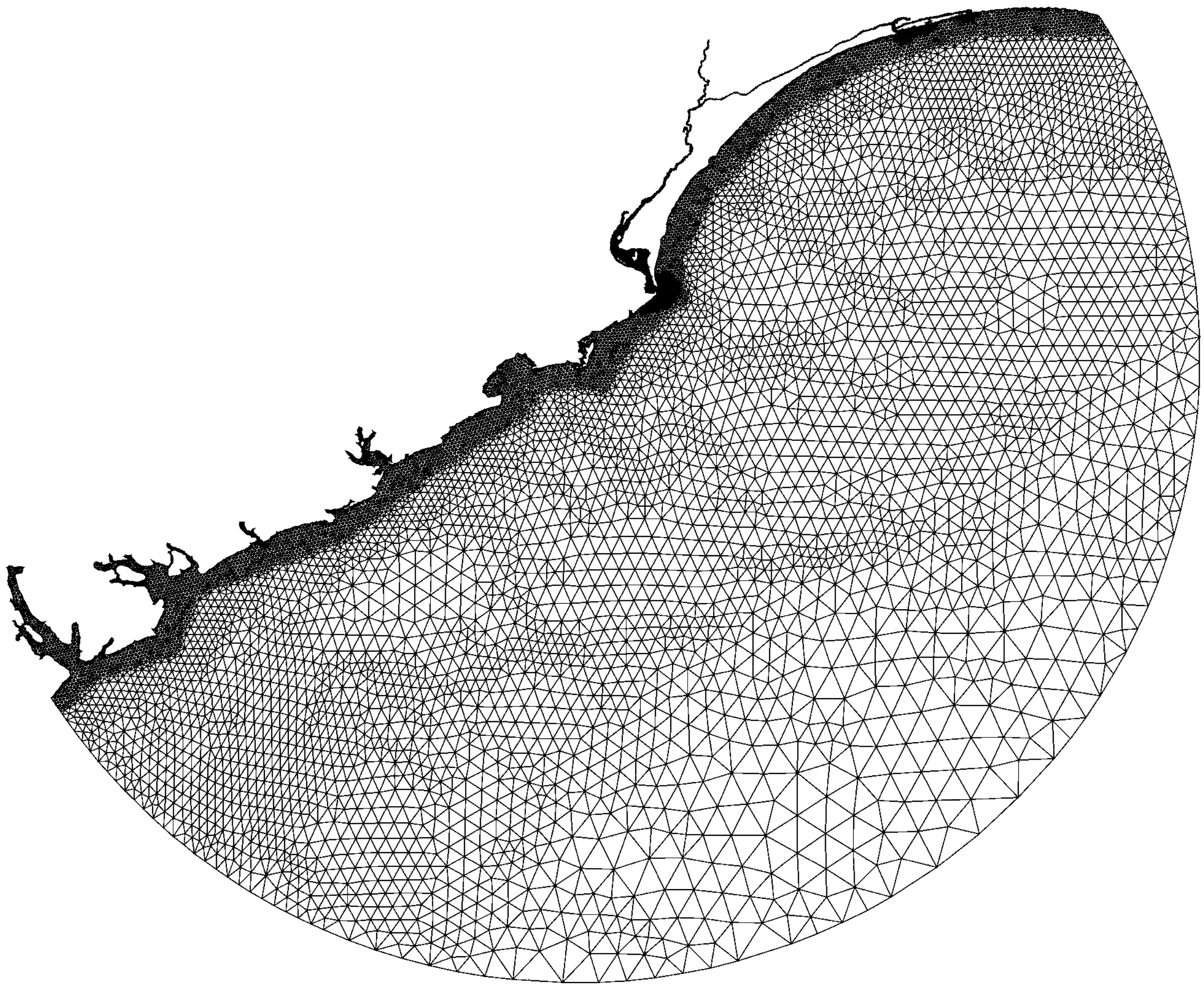

Figure 2. Finite element mesh for the coast of South Carolina, the Waccamaw River from Conway, SC, and the Atlantic Intracoastal Waterway from Winyah Bay to Shallotte Inlet.

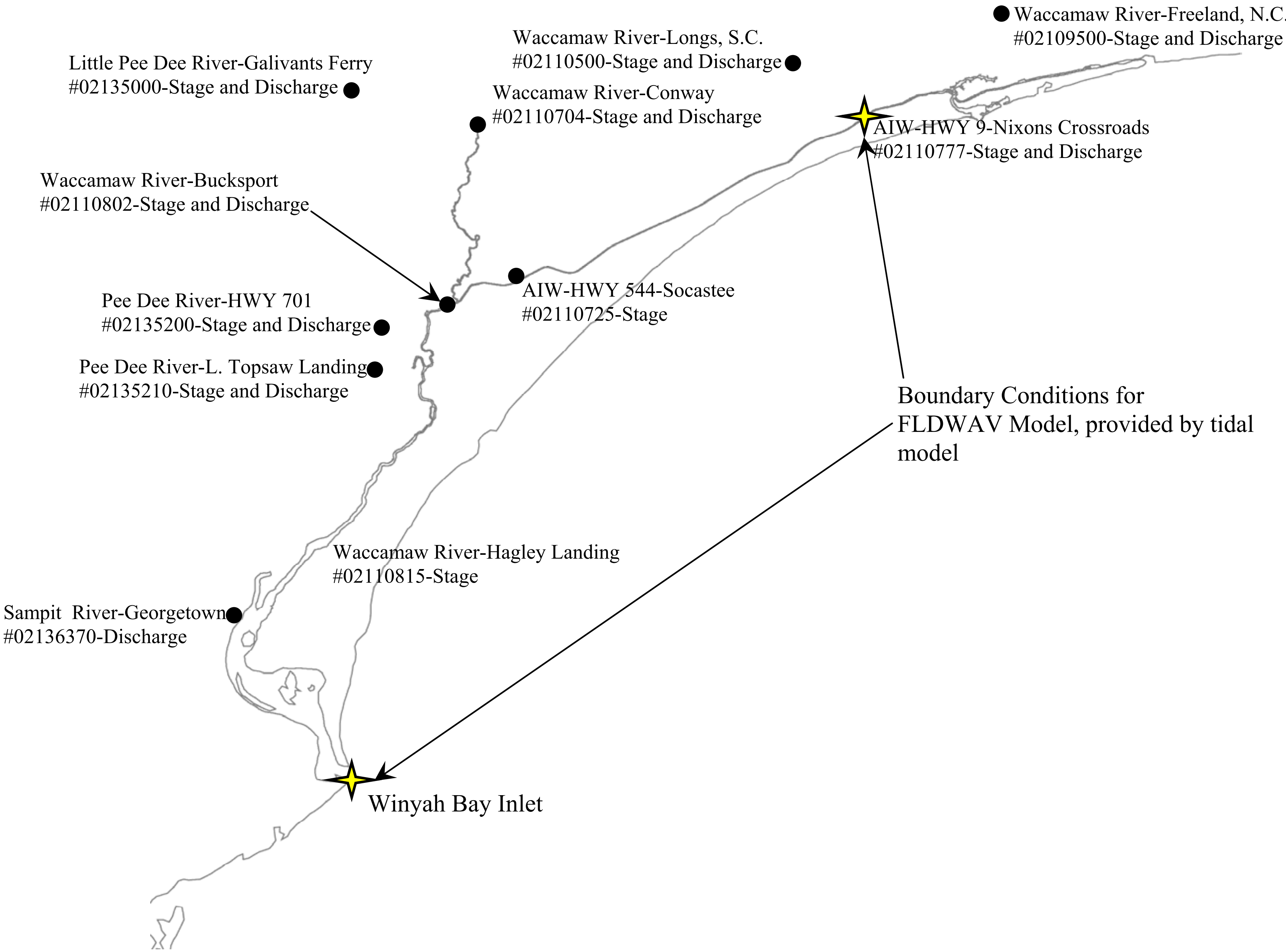

Figure 3. Detail of the Waccamaw River from Conway, SC, and the Atlantic Intracoastal Waterway from Shallotte Inlet to Winyah Bay, showing USGS gage locations and locations for the FLDWAV boundary conditions.

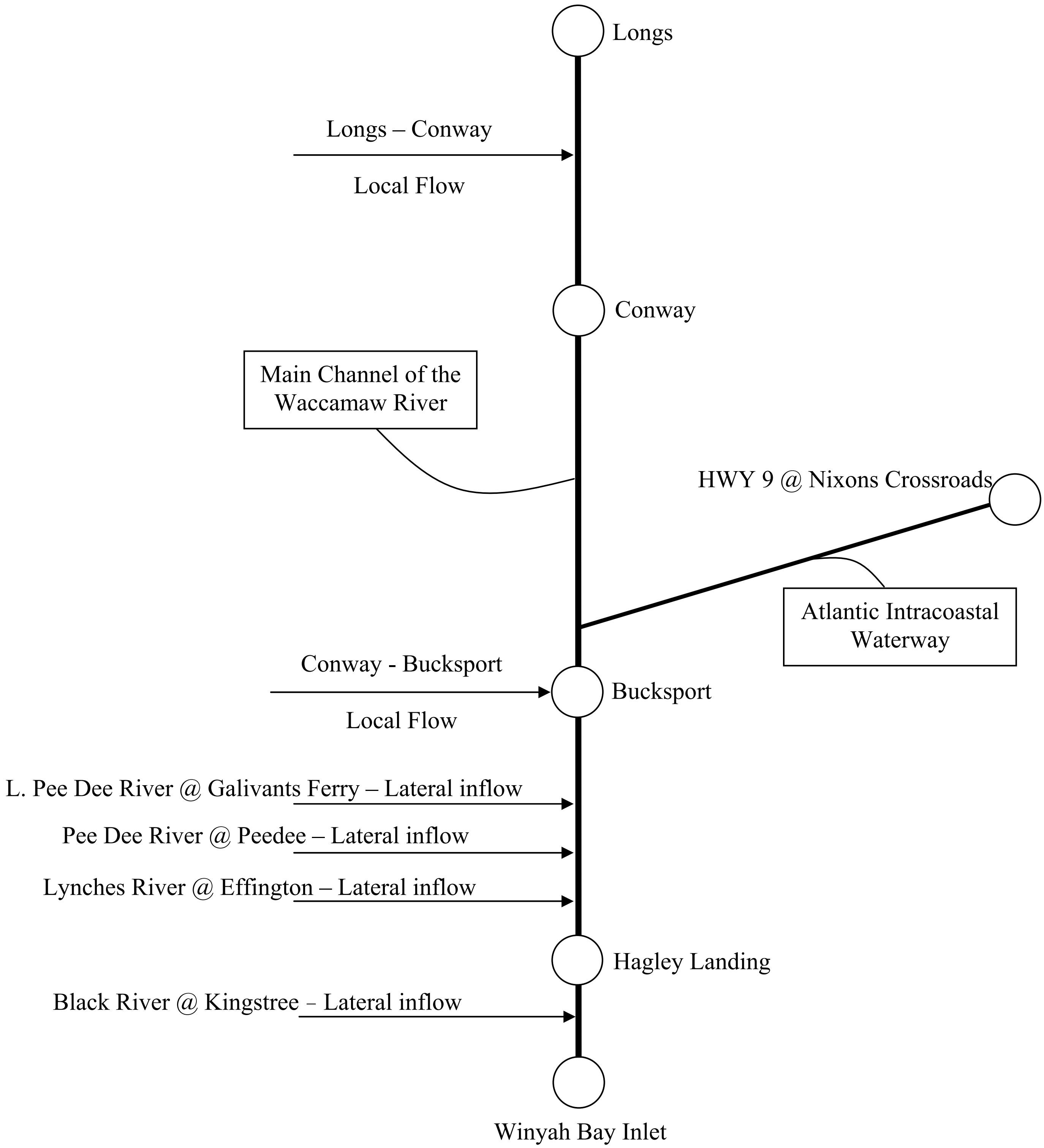

Figure 4. Schematic for the FLDWAV model of the Waccamaw River from Longs, SC, and the Atlantic Intracoastal Waterway from Nixons Crossroads to Winyah Bay Inlet.

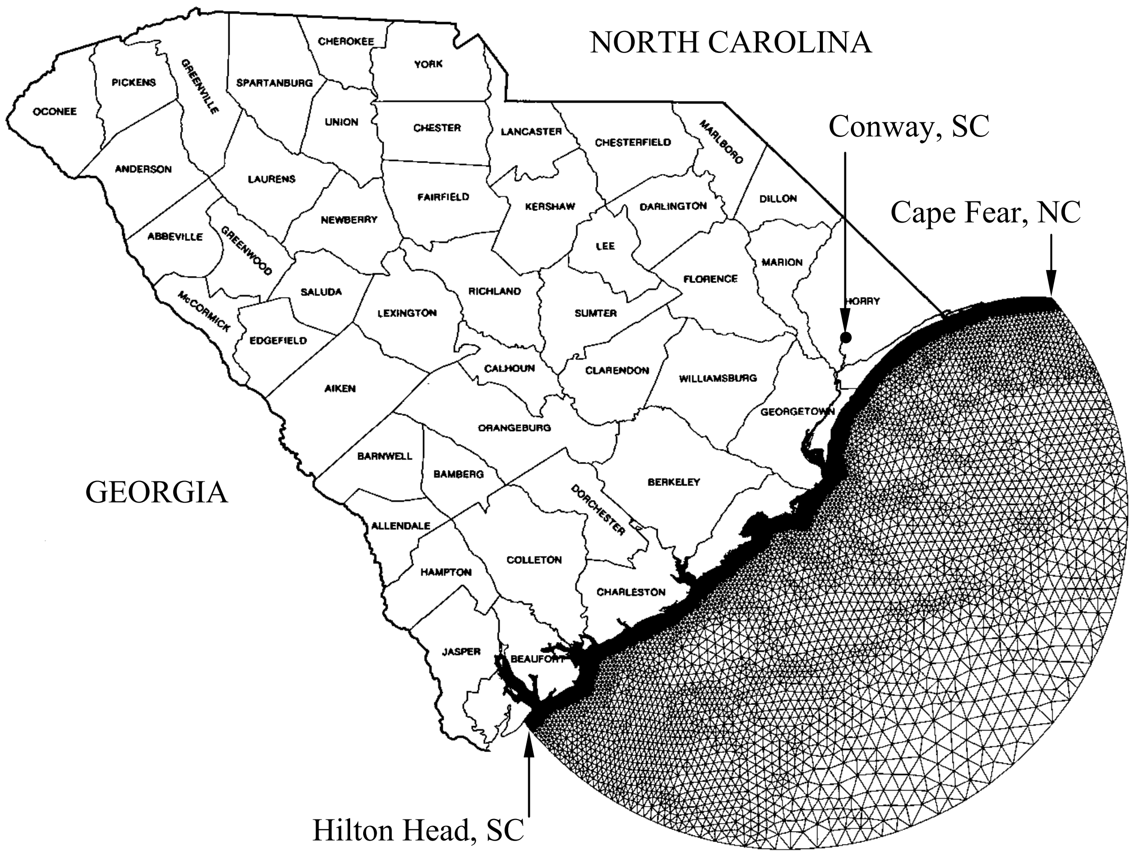

Figure 5. South Carolina mesh location with respect to the State of South Carolina.

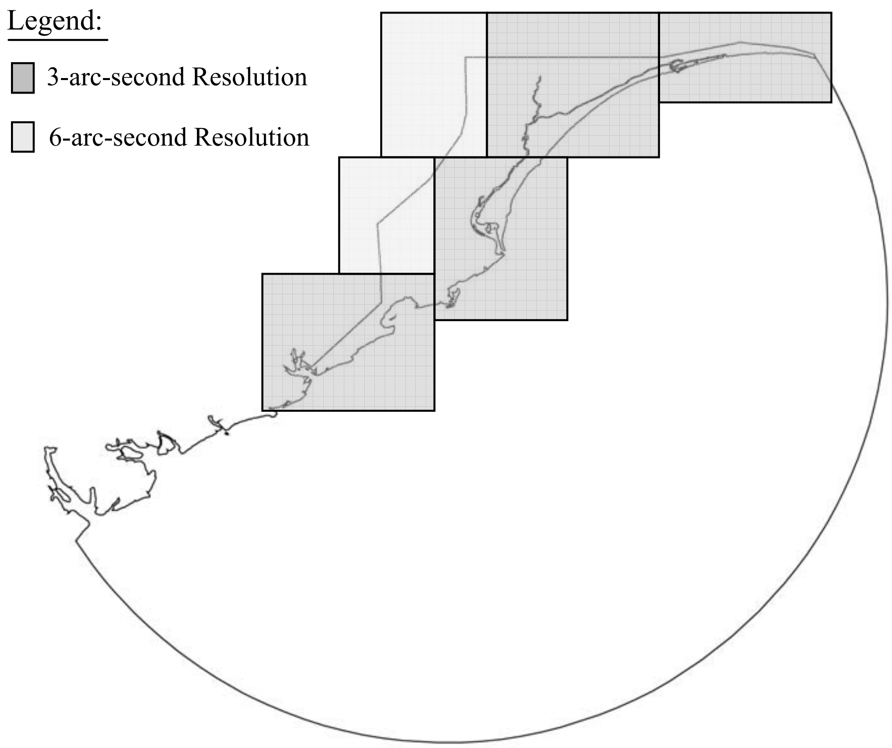

Figure 6. Elevation data set resolution.

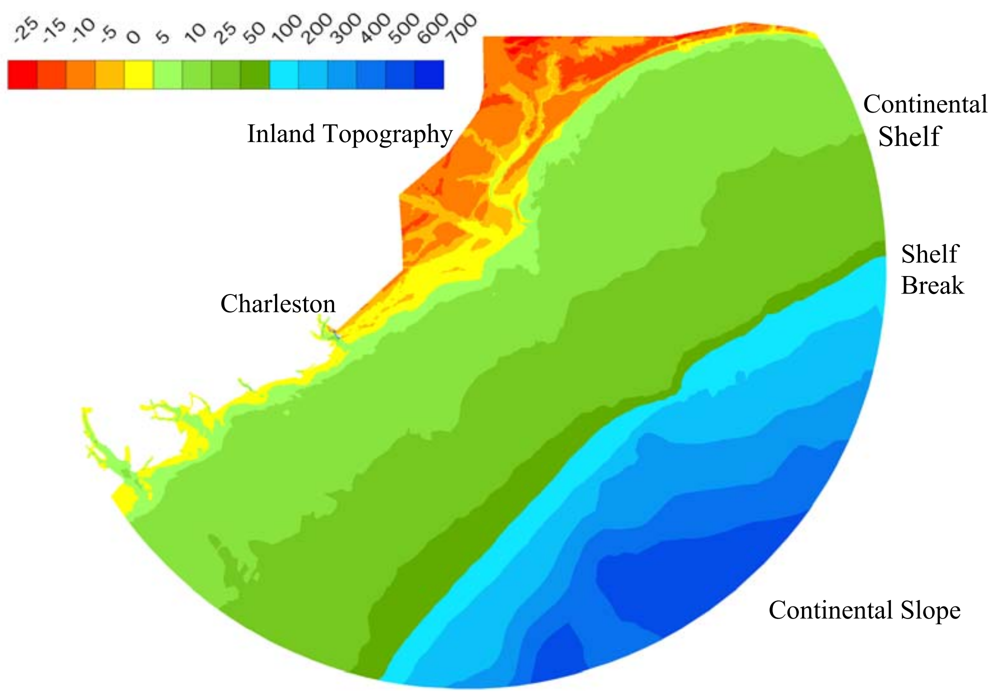

Figure 7. Bathymetry (in meters) and inland topography South Carolina study domain.

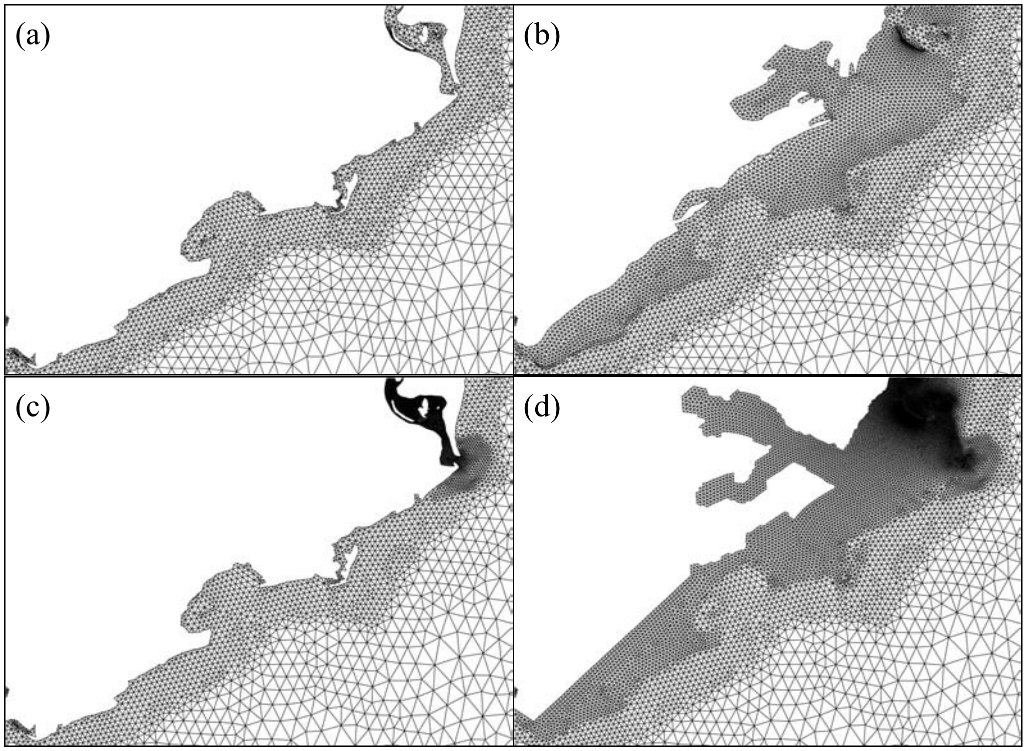

Figure 8. Mesh distinction Bulls Bay (a) SC-1, (b) SC-1-FP, (c) SC-2, (d) SC-2-FP.

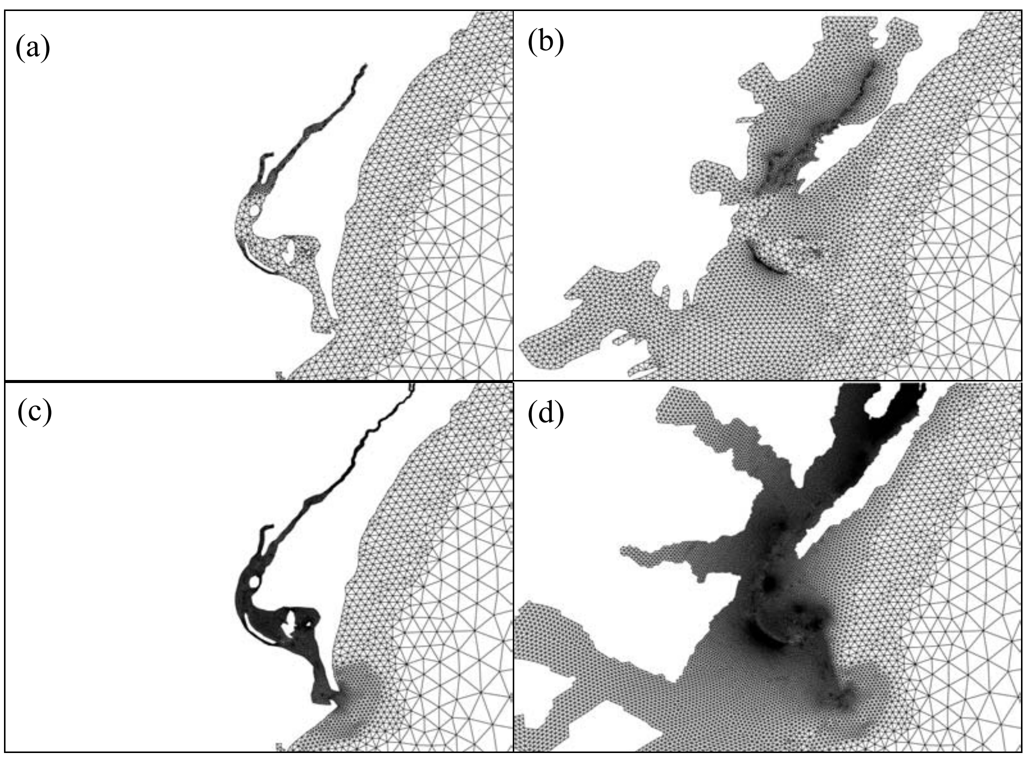

Figure 9. Mesh distinction Winyah Bay (a) SC-1, (b) SC-1-FP, (c) SC-2, (d) SC-2-FP.

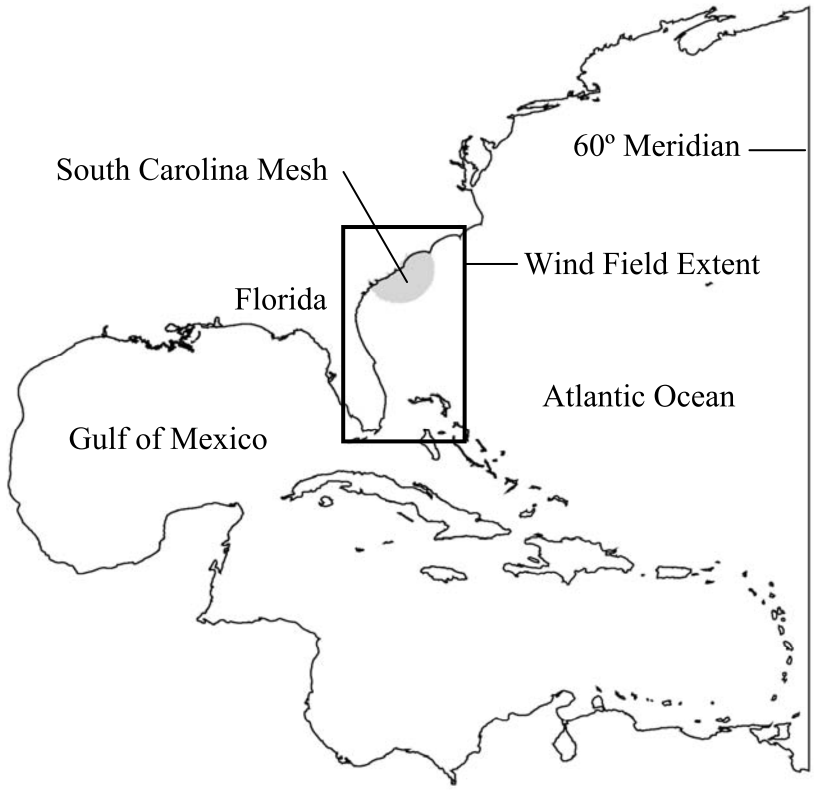

Figure 10. Wind field extent with respect to the Western North Atlantic Tidal (WNAT) model domain.

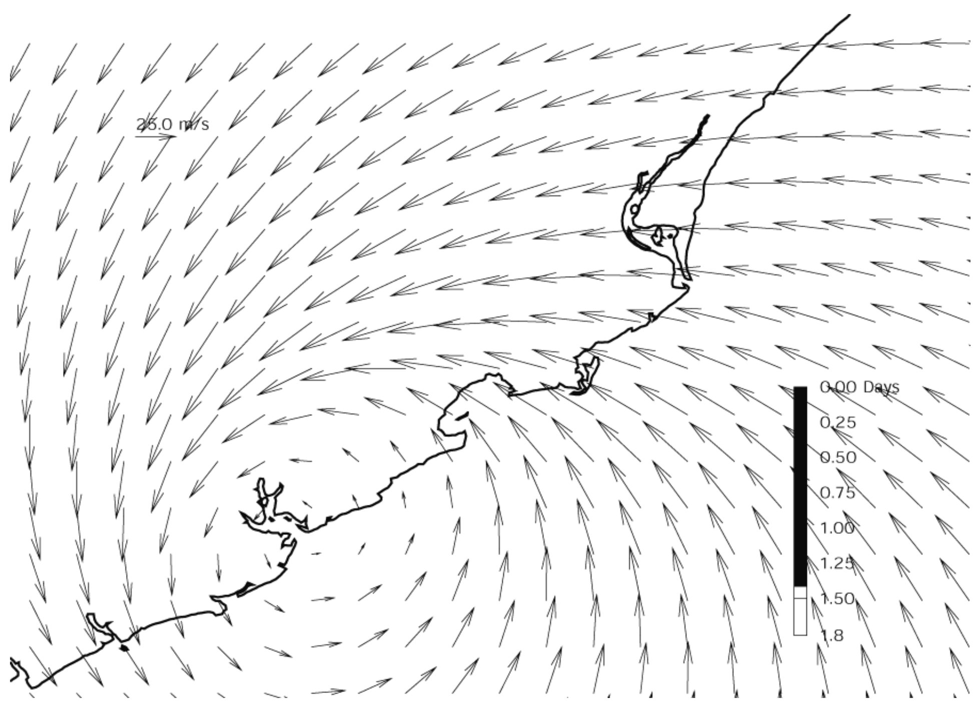

Figure 11. Computed wind field vectors at time of landfall, Charleston Harbor.

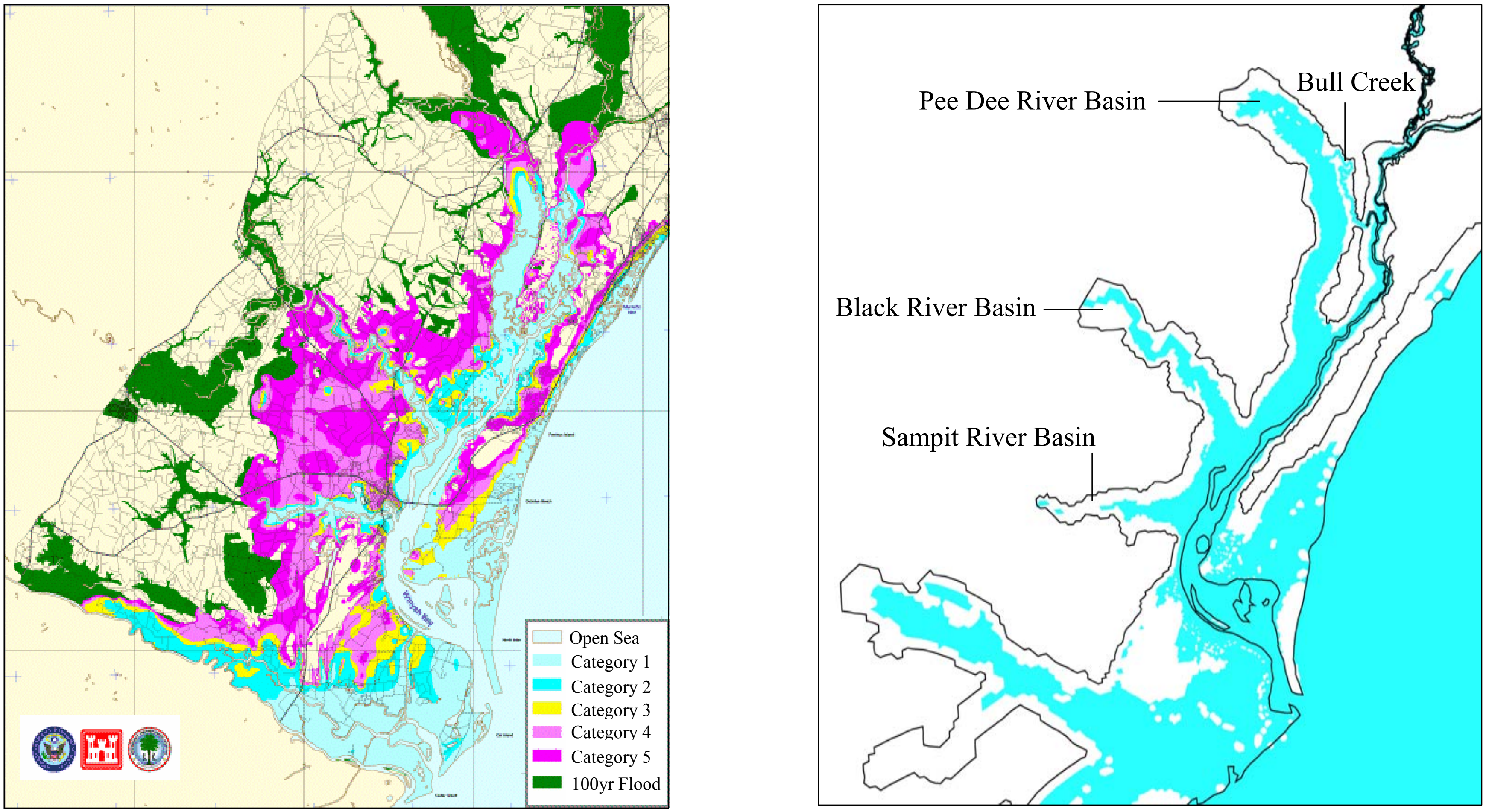

Figure 12. Computed flooding extent for Hurricane Hugo (a) SLOSH Output (USACE, 2004), and (b) ADCIRC Output.

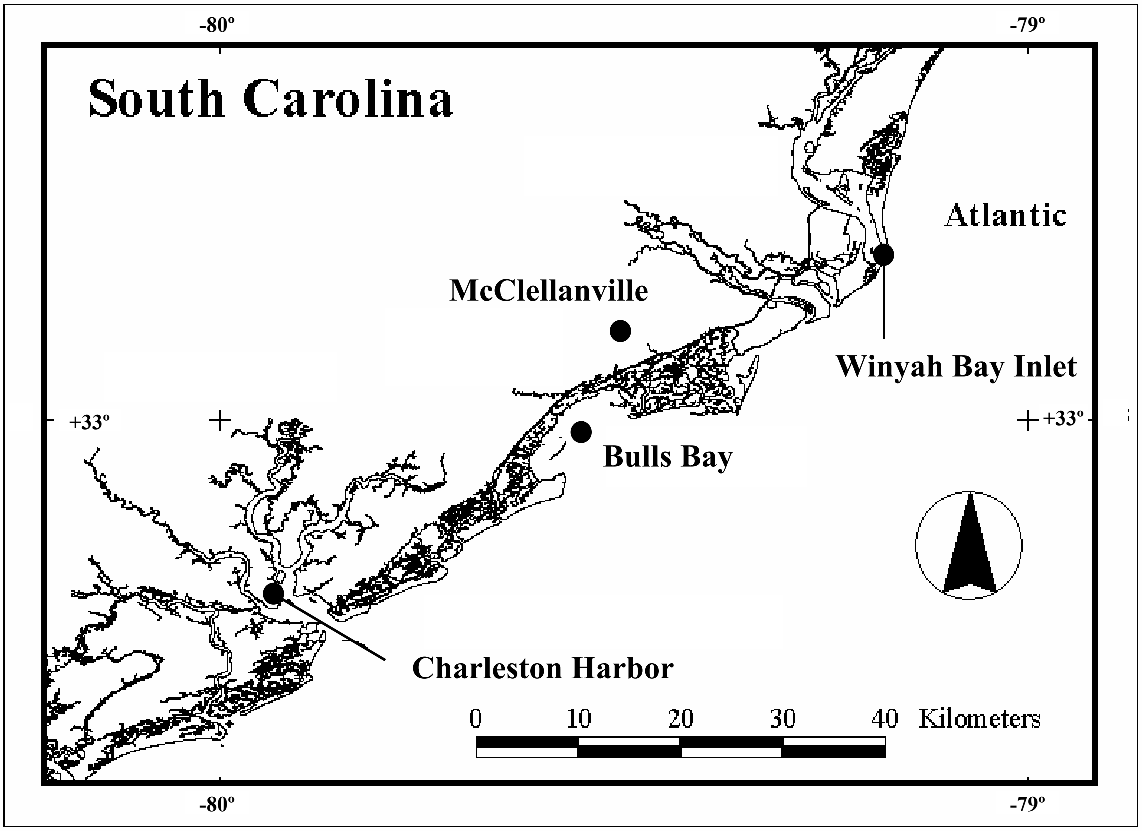

Figure 13. Locations of interest for storm tide hydrographs along the South Carolina coast.

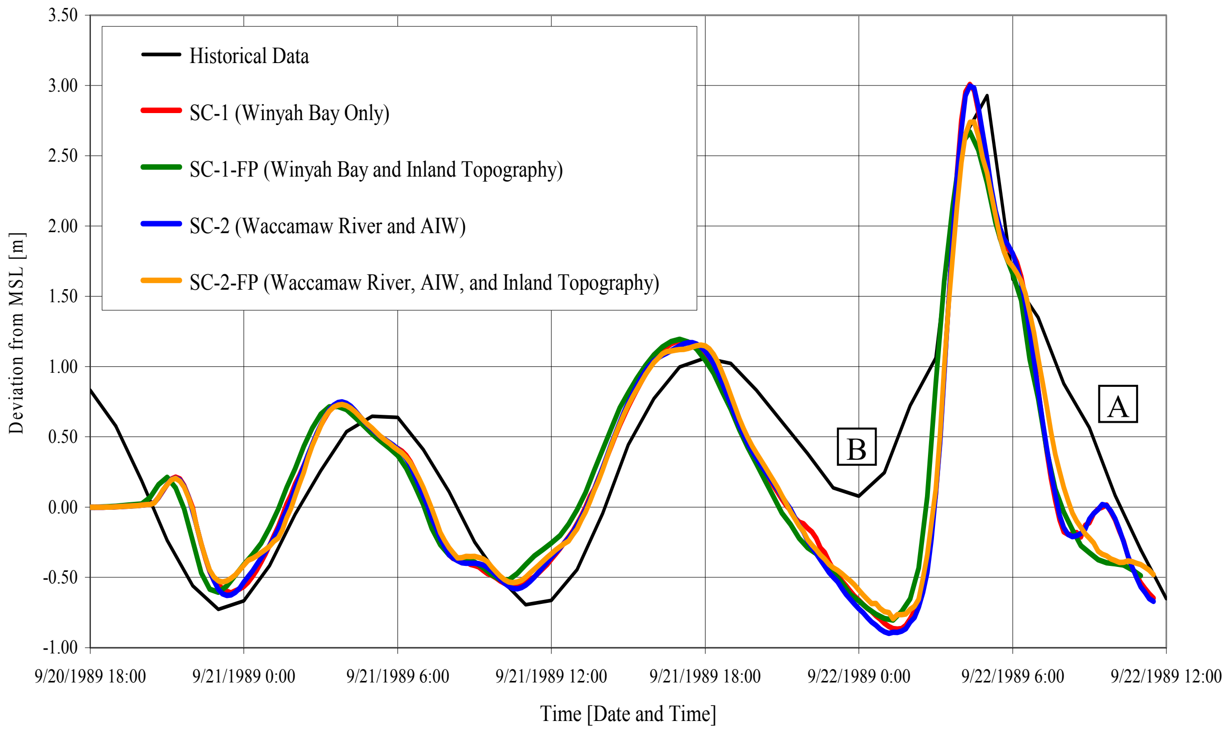

Figure 14. Storm tide hydrograph from Hurricane Hugo at Charleston Harbor tide gage.

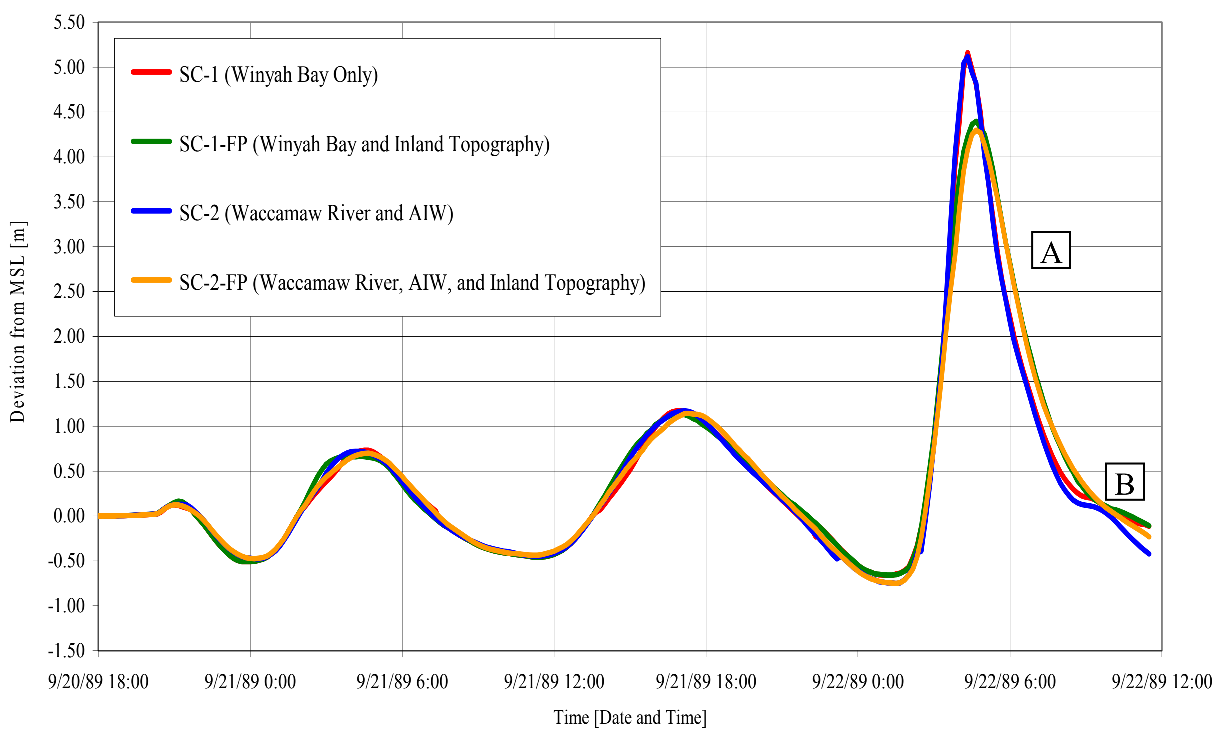

Figure 15. Storm tide hydrograph from Hurricane Hugo at Bulls Bay middle.

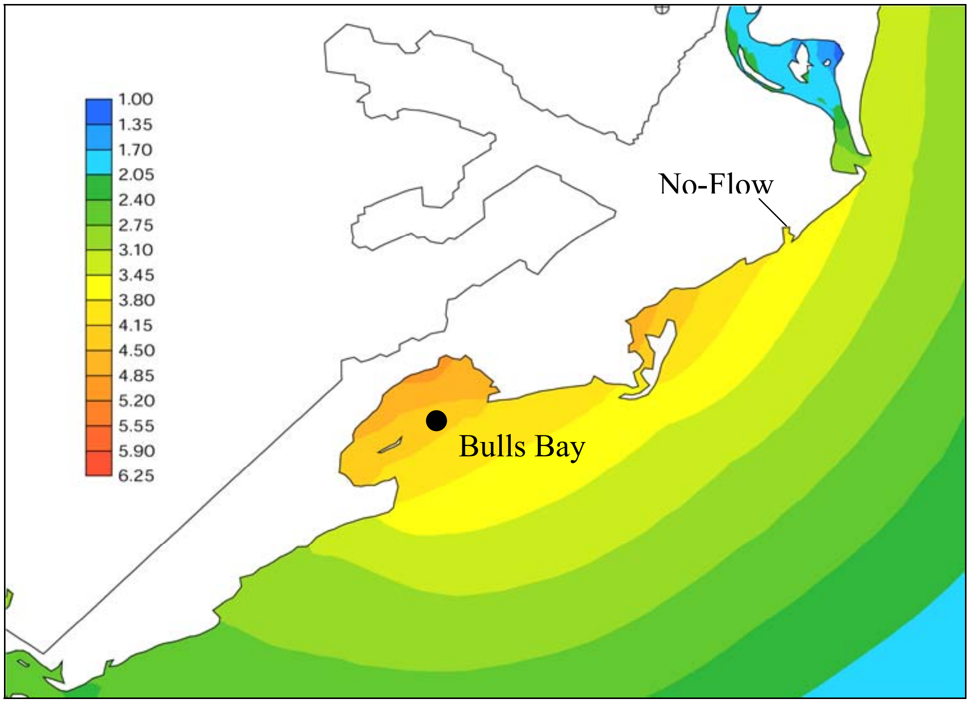

Figure 16. Bulls Bay water stages at time of hydrograph peak (SC-2 mesh).

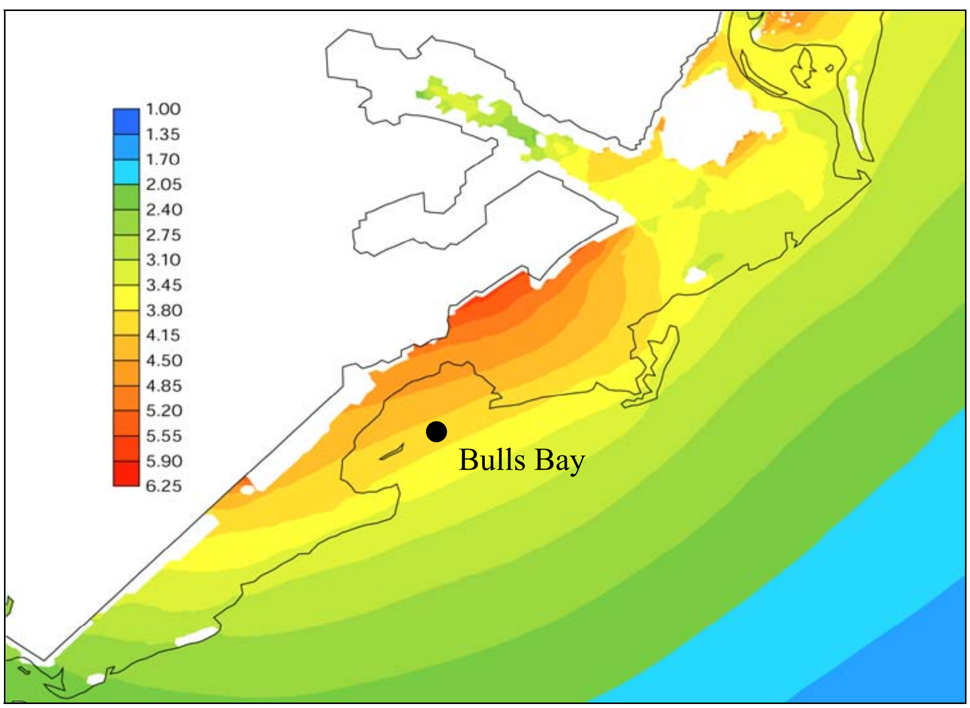

Figure 17. Bulls Bay water stages at time of hydrograph peak (SC-2-FP mesh).

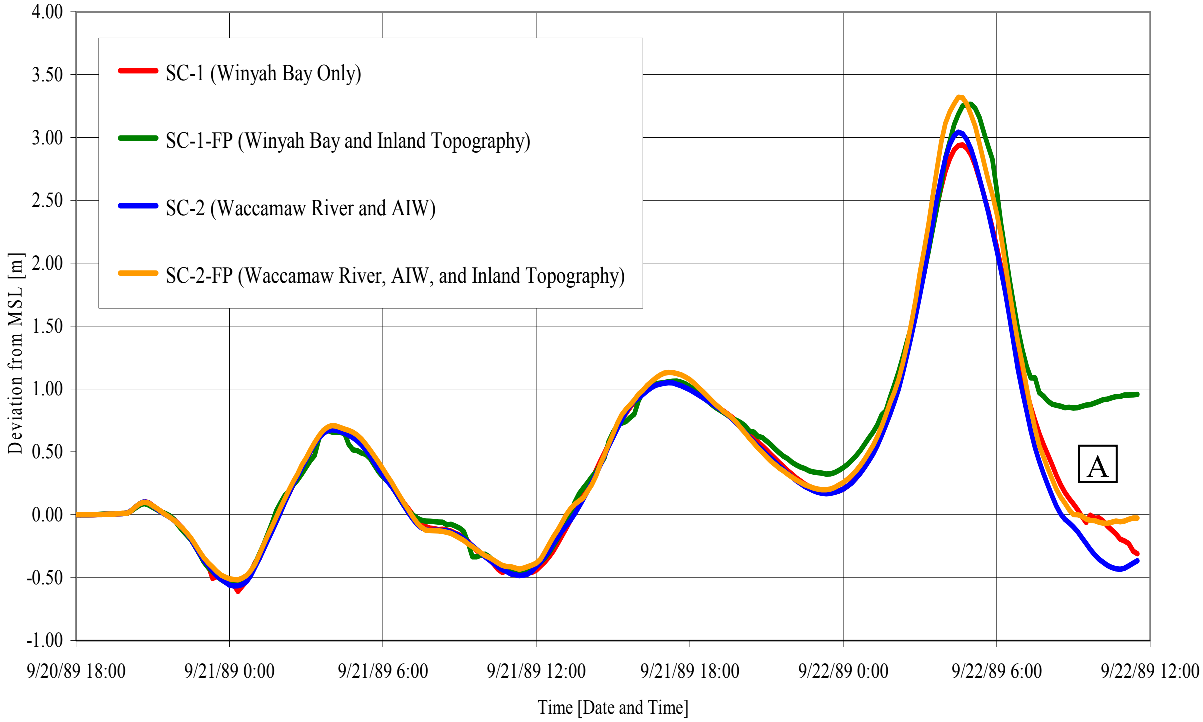

Figure 18. Storm tide hydrograph from Hurricane Hugo at Winyah Bay Inlet.

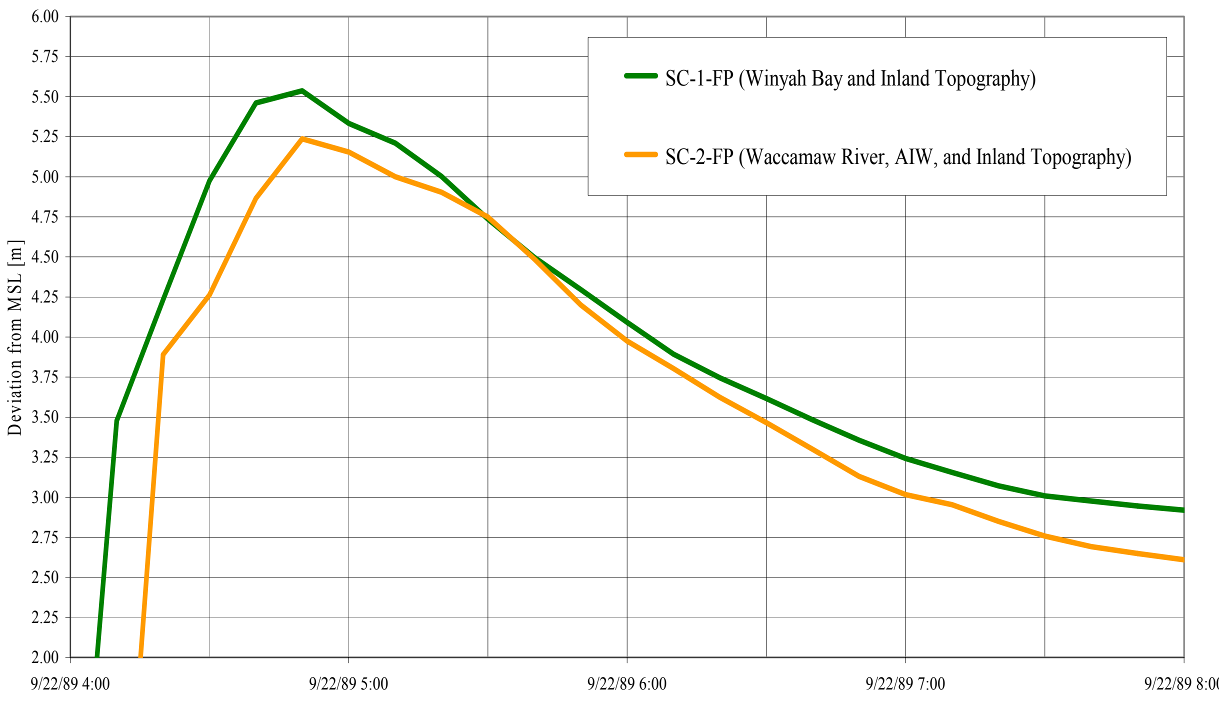

Figure 19. Storm Tide Hydrograph from Hurricane Hugo at McClellanville.

References

Coastal Relief Model, Vol. 02: U.S. South East Atlantic Coast (Version 1.0) [CD-ROM]. (1999). Boulder, CO: National Geophysical Data Center.

Cox, A. T., and Cardone, V. J. (2000). Operational Systems for the Prediction of Tropical Cyclone Generated Winds and Waves. *Proceeding of 6th International Workshop on Wave Hindcasting and Forecasting*. Monterey, California.

Dietsche, D., Hagen S. C., and Funakoshi, Y. (2004). Storm Tide Hindcast for Hurricane Hugo: Into an Estuarine and Riverine System. *6th Conference on Hydro-Science and Engineering*, Brisbane, Australia, May 30 to June 4, 2004.

Garratt, J. R. (1977). Review of the drag coefficients over oceans and continents. *Monthly Weather Review*, 105. 915-929.

Metts, G. (1989). Hurricane Hugo - An Eyewitness Account. Retrieved April 15, 2004 from: http://www.publicaffairs.noaa.gov/grounders/hugo.html.

Schuck-Kolben, R. E. and Cherry, R. N. (1995). Hydrologic Aspect of Hurricane Hugo in South Carolina, September 1989. *Hydrologic Investigation Atlas HA-733*, U.S. Department of the Interior, U.S. Geological Survey.

Surface-water Modeling System (2002). Surface-water modeling system reference manual. Brigham Young University, Environmental Modeling Research Laboratory, Provo, UT.

U.S. Army Corps of Engineers (USACE, 2004). *Hurricane Surge Maps, South Carolina.* Retrieved April 10, 2004 from: http://www.csc.noaa.gov/products/sccoasts/html/surge.htm.

U.S. Department of Commerce, (DOC, 1990). *Hurricane Hugo September 10-22, 1989*, Natural Disaster Survey Report, May 1990. Washington, DC: Department of Commerce.