FINAL OUTREACH REPORT

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SECTION 1: SUMMARY OF PROJECT OBJECTIVES

The cooperative effort has achieved the following two main goals with respect to hindcast mode and will initiate hindcast and forecast modes during the 2005 hurricane season, thereby meeting all objectives.

- Goal 1) To incorporate in hindcast, real-time and forecast mode, storm surge model output as boundary conditions for FLDWAV.
- Goal 2) To expand the domain to incorporate the entire East Coast of the United States, Gulf of Mexico and Caribbean Sea.

In this report we will focus on calibration tests with the two-dimensional, depth-integrated hydrodynamic model (ADCIRC) of tide and unsteady freshwater flow interaction to examine the flow dependence of the minimum bottom friction factor as used in a hybrid formulation of the standard quadratic bottom friction parameterization. A shelf-based domain approach is employed to investigate the tidal and unsteady freshwater flow hydrodynamics within the Waccamaw River and Atlantic Intracoastal Waterway, located in the coastal region of northern South Carolina. The model is depth forced with tidal harmonic data along the open-ocean boundary, located on the continental shelf. Historical tributary and runoff inflow hydrographs corresponding to three identified freshwater river inflow scenarios, a relative low, medium, and high, are loaded into the model at upstream freshwater river inflow boundary locations. In addition, much progress has been made with the FLDWAV model.

Background

Frictional closure within the governing equations of ADCIRC-2DDI is achieved through the use of a hybrid formulation of the standard quadratic bottom friction parameterization, which allows for the bottom friction factor to change with respect to bathymetric depth. In very shallow waters, the hybrid bottom friction formulation is useful particularly when the wetting and drying

of elements is implemented since this expression becomes highly dissipative as the water depth becomes small (Luettich et al. 1992). The hybrid bottom friction formulation is defined as:

$$\tau_* = \frac{C_f \left(U^2 + V^2 \right)^{1/2}}{H} \qquad \text{where} \qquad C_f = C_{f_{\min}} \left[1 + \left(\frac{H_{break}}{H} \right)^{\theta} \right]^{\frac{7}{\theta}} \tag{1}$$

and $\tau_* =$ bottom stress; $C_f =$ bottom friction factor; $C_{f_{min}} =$ minimum bottom friction factor that is approached in deep waters when the hybrid bottom friction formulation reverts to a standard quadratic bottom friction function; $H_{break} =$ break depth to determine if the hybrid bottom friction formulation will behave as a standard quadratic bottom friction function or increase with depth similar to a Manning's type bottom friction function; $\theta =$ dimensionless parameter that determines how rapidly the bottom friction factor approaches its upper and lower limits; $\gamma =$ dimensionless parameter that describes how quickly the bottom friction factor increases as water depth decreases.



Fig. 1. Shelf-based domain boundary with contours of bathymetry (in meters), including two tidal gaging station sites (boxes) and location of Key Inlet, SC (a), with insets of local boundary and domain description (b), spatial discretization, including three freshwater river inflow locations (Conway, SC, Bucksport, SC, and Bull Creek, SC, corresponding to arrows 1, 2, and 3, respectively) and two water level gaging station sites (Nixon's Crossroads, SC and Hagley's Landing, SC, corresponding to boxes 1 and 2, respectively) (c), and bathymetric depths (d)

Domain Description, Discretization, and Bathymetry

The primary region of focus for the current study is the Waccamaw River and AIW. The Waccamaw River drains the coastal areas of southern North Carolina and northern South Carolina. The river originates at Lake Waccamaw in North Carolina and flows southward through Conway, South Carolina. From there, it continues southward to form a confluence with the AIW, through Winyah Bay, and into the Atlantic Ocean. The model domain includes the Waccamaw River upstream to Conway, South Carolina and the AIW between Enterprise Landing, South Carolina and Little River Inlet (Figure 1[b]).

Spatial discretization is accomplished by employing linear, triangular finite elements over the study area in order to adequately represent the irregularities of the system geometry and complexities of the local bathymetry (Figure 1[c]). Of particular importance, the large deepwater domain ensures that the nonlinearities of the shallow water tides are generated locally. The final version of the unstructured, finite element mesh used for the tidal computations performed for this study consists of 34,056 nodes and 56,286 elements and is resolved with maximum node spacing of 15 km along the open-ocean boundary and minimum element sizes of 10 m within the upstream river areas of the estuary. More detailed explanation on the development of this finite element mesh representing the Waccamaw River and AIW is provided by Hagen et al. (2002) and Murray (2003). Locally, average depths of the upstream portions of the Waccamaw River and along the entire length of the AIW are between 3 and 4 m. Channel invert depths along the downstream portions of the Waccamaw River vary from 4 m at Enterprise Landing, South Carolina to 6 m through Winyah Bay. (Refer to Figure 1[d] for a display of the local bathymetry corresponding to the Waccamaw River and AIW.)

Model Initialization

The following boundary condition specifications and model parameterizations apply to all simulations performed herein: a spherical coordinate system is used; simulations are begun from a cold start; advective terms are included; tidal potential forcings are turned off; eight tidal elevation forcings $(K_1, O_1, N_2, S_2, M_2, M_4, M_6, Steady)$ obtained from the Western North Atlantic Tidal model domain (Funakoshi et al. 2004, Hagen and Parrish 2004, Kojima et al. 2005) are imposed along the open-ocean boundary; unsteady freshwater river inflows are loaded as normal-flow boundary conditions, as detailed in the following paragraph; all mainland coastlines and island shorelines employ a zero-flux boundary condition (similar to infinite vertical walls); boundary forcings are ramped over a period of 6 days; 12 days of real time (corresponding to the dates of the different freshwater river inflow scenarios) is simulated. A time step of 0.25 seconds is used to ensure that the Courant number criterion (Luettich et al. 1992) is satisfied throughout the computational domain. The wetting and drying of elements is implemented with the minimum bathymetric depth set to 0.01 m (i.e., nodes and the accompanying elements with water depths less than the prescribed minimum bathymetric depth are considered to be dry). The hybrid bottom friction formulation is employed varying the minimum bottom friction factor (see Eq. [1]) according to the simulation results that follow and specifying the remaining hybrid bottom friction parameter values as maintained by Murray (2003): $H_{break} = 1.0$ m; $\theta = 10$; $\gamma =$ 1/3. Finally, horizontal eddy viscosity is set to 5.0 m/s² and the GWCE weighting parameter, τ_0 , is set to 0.020 to round out the simulation settings.

Unsteady freshwater river inflows are applied at three major tributaries to the Waccamaw River, with their locations shown in Figure 1(c): 1) Conway, South Carolina; 2) Bucksport, South Carolina; 3) Bull Creek, South Carolina. The unsteady freshwater river inflow data corresponding to these three contributing tributaries are obtained from the Southeast River Forecast Center and are organized based on three identified freshwater river inflow scenarios: a relative low (July 10, 1999, 9 p.m. – July 22, 1999, 9 p.m.), medium (September 1, 1998, 6 a.m.) – September 13, 1998, 6 a.m.), and high (February 1, 1998, 12 a.m. – February 13, 1998, 12 a.m.). Figure 2 displays the input hydrographs that are used to force the unsteady freshwater river inflow into the model. It is important to note here that the water surface elevation does not overtop the river banks for the three identified freshwater river inflow scenarios, thus providing the basis for not incorporating inundation areas into the computational domain.



Fig. 2. Input hydrographs corresponding to low (dashed line), medium (thin solid line), and high (thick solid line) freshwater river inflow scenarios at Conway, SC (a), Bucksport, SC (b), and Bull Creek, SC (c)

SECTION 2: PROJECT ACCOMPLISHMENTS/FINDINGS

Computational results presented by Hagen et al. (2002) and Murray (2003) show an accurate reproduction of the tidal harmonics at Charleston Harbor, South Carolina and Springmaid Pier, South Carolina, respectively. (The locations of these tidal gaging stations can be found in Figure 1[a].) Thus, the shelf-based domain approach used in this study is sufficient for tidal computations in the nearshore regions surrounding the Waccamaw River and AIW. Moreover, the calibration plots that follow demonstrate a good performance of the model at locations found within interior regions of the estuary.

The main simulation results presented herein include interpretations of calibration plots generated at two water level gaging stations (with their locations shown in Figure 1[c]) situated in the estuary: Nixon's Crossroads, South Carolina and Hagley's Landing, South Carolina. Historical water surface elevation data corresponding to the simulated time periods for these water level gaging stations are supplied by USGS. Figure 3(a-c) displays computed model output corresponding to different applied values of the minimum bottom friction factor (see Eq. [1]) and historical water surface elevation data corresponding to the water level gaging station located at Hagley's Landing, South Carolina. (Similar results obtained at Nixon's Crossroads, South Carolina are not included for the interest of brevity.) A 3-day time period is chosen to include six semi-diurnal tidal cycles. Also, the model has reached a dynamic steady state by this point in time in the simulation, and therefore, the water surface elevations reproduced during this 3-day time period are unaffected by the applied ramp. Figure 3(a-c) displays curves (blue and red solid lines) corresponding to the lower and upper limiting values, respectively, of the calibrated range of minimum bottom friction for each freshwater river inflow scenario. In addition, each plot contains a curve (green solid line) representative of an applied value of the minimum bottom friction factor that is greater than the upper limit of the calibrated range of minimum bottom friction. Of importance, note that all of these curves (green solid lines) exhibit an increased damping effect on the tidal ranges relative to the historical water surface elevation data. Furthermore, Figure 3(c) shows a curve (purple solid line) representative of an applied value of the minimum bottom friction factor that is less than the lower limit of the calibrated range of minimum bottom friction, which produces poor simulation results. It should also be noted that model instability arises for applied values of the minimum bottom friction factor that are less than the lower limit of the calibrated range of minimum bottom friction for the low and medium freshwater river inflow scenarios.



Fig. 3. Results of calibrated minimum bottom friction at Hagley's Landing, South Carolina for low (a), medium (b), and high (c) freshwater river inflow conditions

Several noticeable features in these calibration plots are observed. Primarily, the insensitivity of the phasing properties of the model response due to adjustments of the minimum bottom friction factor is noted. Thus, focus is concentrated on the range properties of the simulated tidal signal. A trend of amplified model sensitivity with increasing freshwater river inflow is apparent. The range of applied values of the minimum bottom friction factor varies between 0.0019 and 0.0050. (Note that an applied value of 0.0050 for the minimum bottom friction factor is applied to the low and medium freshwater river inflow scenarios; however, these results are not included because this applied value is beyond the upper limit of the calibrated range of the minimum bottom friction for these freshwater river inflow scenarios.) Of importance, it is shown here that applying a single value of the minimum bottom friction factor to all freshwater river inflow conditions is unsuitable, as the following ranges of calibrated values of the minimum bottom friction factor are determined for the low, medium, and high freshwater river inflow scenarios, respectively: 0.0019 - 0.0022; 0.0020 - 0.0025; 0.0030 - 0.0035. The flow dependence of the minimum bottom friction factor is conveniently shown through the increasing range of calibrated values of the minimum bottom friction factor as freshwater river inflows are increased (e.g., from low to high freshwater river inflow conditions). Furthermore, model instability arises for applied values of the minimum bottom friction factor that are less than the following values of the minimum bottom friction factor for the low, medium, and high freshwater river inflow scenarios, respectively: 0.0019, 0.0020, and 0.0020.

Finally, a previous 6-month report (May 5, 2004) focused on extensive simulations of the storm tide from Hurricane Hugo using the large scale Western North Atlantic Tidal model domain and is to be published in the Journal of Waterway, Port, Coastal, and Ocean Engineering (Deitsche et al. 2006). That portion of our overall effort resulted in three significant findings: 1) considerable improvements in storm surge predictions may be realized by incorporating inland flooding areas into the computational domain to allow for the inundation of coastal floodplains; 2) storm surge hydrographs are highly spatially dependent near inlets, whereas the astronomical tides reveal minimal variance in space around the inlet environment; 3) a large-domain approach provides increased benefits to storm surge modeling capabilities by more thoroughly describing the global and local flow responses arising from the tidal and hurricane-induced boundary forcings. Integrating coastal floodplains into the computational domain causes either a decrease in water surface elevations (as seen at Charleston Harbor and Bulls Bay) or an increase in water stages (as realized at Winyah Bay Inlet), and hence, the outcome of including inundation areas in the modeling approach may either follow or counter intuition. Another important fact to draw attention to includes the computational efficiency that is gained by using a coarser mesh in the large-domain approach. It is concluded then that a coarse mesh resolution of the inundation areas, in addition to providing a limited spatial coverage of the river system, is adequate in order to reproduce the open-coast storm surge hydrographs generated by the landfall and passage of the hurricane.

SECTION 3: BENEFITS AND LESSONS LEARNED: OPERATIONAL PARTNER PERSPECTIVE

SERFC's SCEP (Student Career Experience Program) employee, Jamie Dyer, developed several iterations of the FLDWAV model of the Waccamaw River, demonstrating its abilities and also demonstrating potential interactions with GIS (Geographic Information Systems). The work experience and financial benefit to Dr. Dyer aided him in completing his PhD studies at University of Georgia, and he has recently jointed the faculty at Mississippi State University.

UCF provided SERFC with tidal harmonic parameters tailored to the locations needed to support FLDWAV model input. The locations were 1) Atlantic Ocean at Winyah Bay Entrance and 2) Atlantic Intercoastal Waterway at Nixons Crossroads. These harmonic parameters enable the calculation of astronomical tide forecasts any date during the 19 year tidal epoch.

SECTION 4: BENEFITS AND LESSONS LEARNED: UNIVERSITY PARTNER PERSPECTIVE

Four UCF graduate students have been actively involved in this COMET project. Two of these graduate students used their experience to develop a Masters Thesis. As a direct result of this project the students have had the opportunity to visit the SERFC. Finally, Dr. Hagen continues to present aspects of operational forecasting to graduate and undergraduate students at the University of Central Florida.

In addition to the concluding paragraph of Section 2, two main lessons have been learned that will be addressed in our future efforts. The first is how we parameterize and implement bottom friction for systems such as the Waccamaw River. It is apparent that our present friction formulation and parametrization is not sufficient for describing riverine systems where top of bank flow includes significant grassy areas. In addition, it is recommended that an algorithm that varies the value of the minimum bottom friction factor according to freshwater river inflow conditions should be introduced into the ADCIRC code. Such an algorithm would be implemented to provide this flow dependence on a global nodal basis, which will allow for a more accurate description of the frictional processes occurring along the bottom of the shallow water system.

SECTION 5: PUBLICATIONS AND PRESENTATIONS

Journal Publications:

Dietsche, D., S.C. Hagen, and P. Bacopoulos, "Storm Surge Simulations for Hurricane Hugo (1989): On the Significance of Inundation Areas," *Journal of Waterways, Port, Coastal, and Ocean Engineering*, In Publication.

Hagen, S.C., O. Horstman and R.J. Bennett, "An Unstructured Mesh Generation Algorithm for Shallow Water Modeling," *International Journal of Computational Fluid Dynamics*, **16** (2), 83-91 (2002).

Conference Publications:

S.C. Hagen, P. Bacopoulos, and M.B. Salisbury, "A 2-D Model of Tide and Freshwater Flow Interaction for the Winyah Bay, Waccamaw River, and Atlantic Intracoastal Waterway," *Proceedings, WAVES 2005*, Madrid, Spain, July 3-7, 2005.

Hagen, S.C, "An Examination of the Influence of Inlets, Bays, Flood Plains, and Rivers on Storm Tide Hydrograph Calculations for Nearshore Regions," Proceedings of the FHWA National Hydraulic Engineering Conference, Aug. 30 – Sept. 3, 2004, Asheville, North Carolina.

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:

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

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

Invited International Presentations:

Hagen, S.C., "Tide and Storm Surge Modeling in the Twenty-First Century," *On Board the Explorer of the Seas, Royal Caribbean Cruise Line*, October 8, 2004.

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, "An Examination of the Influence of Inlets, Bays, Flood Plains, and Rivers on Storm Tide Hydrograph Calculations for Nearshore Regions," FHWA National Hydraulic Engineering Conference, Aug. 30 – Sept. 3, 2004, Asheville, North Carolina.

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

SECTION 6: SUMMARY OF UNIVERSITY/OPERATIONAL PARTNER INTERACTIONS AND ROLES

Dr. Hagen has received funding from NOAA Award No. NA04NWS4620013 to apply the WNAT model domain to incorporate the St. Johns River and is collaborating with the Southeast River Forecast Center (SERFC) and NOAA/NWS/Office of Hydrologic Development. Further, as a result of the findings from the present study, the new research efforts will include coupling a short wave model with the ADCIRC tide and storm surge model.

In addition, Dr. Hagen continues his synergistic efforts through the National Oceanographic Partnership Program (Award N00014-02-1-0150) to develop a real-time forecasting system for winds, waves and storm tides due to tropical storms and hurricanes. That system will provide winds and pressures for generating storm tide hydrographs to force the FLDWAV model for the Waccamaw River during future hurricane seasons.

The calibration of Waccamaw River FLDWAV has been improved. SERFC made corrections to the FLDWAV definition for the Waccamaw River system, including datum corrections at Longs, SC and time zone adjustments to observed hydrographs. Cross-section descriptions were adjusted to better model the propagation of the tides upstream, mainly by deepening the channel per navigation charts of Winyah Bay Entrance.

Implemented a version of FLDWAV as a segment in NWSRFS (NWS River Forecast System). NWSRFS is the operational forecast system used by SERFC in performing its operational forecast duties. This implementation allows the real-time observations of stage and simulated runoff discharges to be used by FLDWAV to forecast the stages at several locations in the Waccamaw River system. The river stage at Conway, SC is the primary focus of these forecasting efforts.

References

Funakoshi, Y., Hagen, S. C., Zundel, A. K., and Kojima, S. 2004. Driving an integrated surface, three-dimensional model. *Proceedings of the 6th International Conference on Hydro-Science and* –*Engineering*, Brisbane, Australia.

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Hagen, S. C. and Parrish, D. M. 2004. Unstructured mesh generation for the western North Atlantic tidal model domain. *Engineering with Computers*, 20, 136–146.

Kojima, S., Hagen, S. C., and Zundel, A. K. 2005. Automatic, unstructured mesh generation for tidal calculations in a large domain. *International Journal for Numerical Methods in Engineering*, in review.

Luettich, R. A. Jr., Westerink, J. J., and Scheffner, N. W. 1992. ADCIRC: An advanced threedimensional circulation model for shelves, coasts and estuaries, Report 1: Theory and methodology of ADCIRC-2DDI and ADCIRC-3DL. *Technical Report DRP-92-6*, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi.

Murray, R. R., 2003, A sensitivity analysis for a tidally-influenced riverine system, MS thesis, University of Central Florida, Orlando, Florida.