Deriving Frictional Parameters and Performing Historical Validation for an ADCIRC Storm Surge Model of the Florida Gulf Coast

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Introduction

Updates are in process for FEMA’s Digital Flood Insurance Rate Map (DFIRM) for three Florida coastal counties - Wakulla, Jefferson, and Franklin - that are subject to flooding from hurricane-driven storm surge. To assess the statistical frequency of inundation for the coastal counties, a finite element computer model, Advanced Circulation Model (ADCIRC), is used to simulate storm surge flooding for a large number of hurricane scenarios. This article is a companion to other articles in this issue that discuss aspects of the modeling developed for FEMA in the study region. One of the important components of modeling flood inundation from hurricane storm surge is to correctly model the surface roughness characteristics in the region of interest. The following provides details on the development of the frictional inputs for the ADCIRC model and an example from the surface model validation.

Parameterizations of Frictional Resistance

Large-scale simulation of overland flooding on coastal floodplains requires accurate representation of the topography and roughness of the surface over which the flow occurs. Vegetation in the coastal zone can have an impact on the magnitude of storm surge (Wamsley 2010) and must be represented in the simulation. For this FEMA FIS study, the widely used ADCIRC model is being used to discretize the Gulf of Mexico and the coastal floodplain with a triangular finite element mesh. The mesh is used not only for solving the equations of motion but is also used to define the surface topography and the frictional characteristics of the region. Therefore, standard hydraulic and meteorological parameters that describe frictional resistance to water and wind must be defined on the same spatial scale at which the equations are being solved. ARCADIS has applied mesh scale averaging tools to compute the mesh scale averages of standard roughness coefficients required for accurate simulation of hurricane storm surge on the Florida Gulf Coast.

The physical processes in the ADCIRC hydrodynamic model are described by the depth-averaged shallow water equations. These equations are widely used to describe coupled storm surge, tides, and riverine flows in the coastal ocean and adjacent floodplain. Processes that exist at the physical boundaries of the water column are parameterized; these include bottom shear stress and free surface shear stress due to winds. Bottom stress has been parameterized with the standard Manning’s n coefficient and free surface stress has been parameterized with the use of Garratt’s drag law. Modification of hurricane wind fields by land roughness has been included by quantifying the wind boundary layer adjustment through an upwind directional land roughness parameterization. The roughness parameter is reduced for increasing depth of local inundation. Finally, the wind stress is also reduced by accounting for the existence of heavily forested canopies.

The effect of land cover and land use types enter into the
computations in several ways. First, the resistance to flow appears as surface and bottom stress terms in the depth averaged momentum equations in the x-direction:

\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + f u = -\frac{g}{\rho} \frac{\partial \left( \frac{P}{\rho g} + z \right)}{\partial x} - \frac{\tau_{bx}}{\rho H} + \frac{\tau_{bx}}{\rho H} + \frac{1}{H} \left( M_x + D_x - B_x \right)
\]

and in the y-direction:

\[
\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + f v = -\frac{g}{\rho} \frac{\partial \left( \frac{P}{\rho g} + z \right)}{\partial y} - \frac{\tau_{by}}{\rho H} + \frac{\tau_{by}}{\rho H} + \frac{1}{H} \left( M_y + D_y - B_y \right)
\]

The bottom stress terms are approximated as:

\[
\frac{\tau_{bx}}{\rho H} = -g n^2 \left( u^2 + v^2 \right) u
\]

in the x-direction and similarly in the y-direction where n is the Manning’s n parameter and must be specified for every ADCIRC node. The surface stress terms are approximated as,

\[
\frac{\tau_{bx}}{\rho H} = C_d \frac{\rho g W_{10}^2}{\rho} W_{10}
\]

where \( C_d \) is a standard drag coefficient defined by Garratt’s drag formula (Garratt, 1977) for wind stress and \( W_{10} \) is the wind velocity at a 10-m height sampled at a 10-minute time period (Hsu, 1988). The \( W_{10} \) value is the wind velocity for full marine conditions as provided by an appropriate wind model (Powel et al, 1996). To account for the effect of land roughness, the 10-m wind velocity is replaced by a reduced \( W_{\text{land}} \) velocity to account for surface roughness. The \( W_{\text{land}} \) velocity is found by

\[
W_{\text{land}} = f_d \cdot W_{10}
\]

where \( f_d \) is the ratio of full marine roughness to the roughness of the land surface and is expressed as,

\[
f_d = \left( \frac{z_{\text{marine}}}{z_0} \right)^{0.0706}
\]

where \( z_{\text{marine}} \) and \( z_0 \) are the marine and land roughness length scales, respectively. The \( z_0 \) length scale varies with land cover and has been quantified by a variety of land classifications as part of the FEMA Hazards US (HAZUS) study.

Second, the influence of local land cover enters the computations via the definition of regions of vegetative canopy. It has been shown that very little wind momentum transfers through heavily forested canopies. The effect of vegetative canopy is included by reducing \( W_{\text{land}} \) to zero in the presence of land use classes that contain trees and thick shrubs. This amounts to the assumption that the branches, leaves, and trunks absorb the momentum of the wind, thereby preventing that momentum from being transferred to the underlying water column.

Land-Cover Data Sets

The finite-element mesh being developed for Wakulla, Jefferson, and Franklin counties extends well beyond their political boundaries. The model contains extensive regions on the coastal floodplain within and adjacent to the study area so that inland penetration of surge can be represented within the model. In addition to characterizing parts of coastal Florida, the model also includes all of the Gulf of Mexico, the Caribbean, and the western North Atlantic. The vast areal extent of the model domain is appropriate to capture the large-scale effects of hurricanes as the storm systems enter the Gulf of Mexico from the Atlantic and Caribbean (see Salisbury et al in this issue for more detail). The ADCIRC mesh created for the three-county region contains 855,445 computational nodes; thus there are too many nodal values to assign manually. An automated method is necessary to compute the appropriate averaging of and assignment of nodal values. Moreover, consistent and dependable data sets are required from which to derive the frictional parameters. The methodology and data sources are described in this section.

The friction coefficients used in the ADCIRC model must realistically describe the three-county region of interest. To achieve this, the relevant model parameters are derived from existing data sets that accurately map the variations in land cover for the region of interest. Several land cover databases exist in the literature. The particular dataset used in this study was assembled by the Florida Fish and Wildlife Commission (FWC) specifically to describe the diversity and distribution of vegetation within Florida (http://research.myfwc.com/features/view_article.asp?id=29764). The dataset was derived from Landsat imagery and contains 43 separate land cover classifications. Last updated in 2004, the FWC data set is considered to be the best available source for land cover data in the region.

Given a land cover data set, the individual classifications of land cover type must be converted into appropriate values of the three frictional parameters. In this way a relationship is established to correlate model input with the land cover data set. To be consistent with other FEMA studies, parameter assignments for the FWC data set were selected to match frictional values used for similar classifications in other FEMA studies. In similar surge modeling studies for FEMA Regions IV and VI in MS, LA, and TX, the USGS National Land Cover Data (NLCD) and USGS GAP data have been used. The NLCD set has a well-established set of values for the \( z_0 \) parameter derived from the HAZUS program. Like the FWC data, the GAP data were created to document local habitat and bio-diversity and thus have been shown to have more accurate local detail and well-defined vegetation sub-divisions than the nationally uniform NLCD set. ADCIRC nodes are not assigned a land cover type; rather the classifications within the data sets must be converted to hydraulic parameters. Standard hydraulic texts (Acrement 1989, Barnes, 1967) have been consulted to establish bottom friction Manning’s n values for all the classifications in the GAP data. To promote consistency, biology experts at the University of Central Florida have been consulted to translate NLCD/GAP to the FWC classifications. Through careful comparison of the classification definitions, nearly identical friction definitions have been obtained for the FWC data set.

Once the friction parameter values were established for the FWC data, the data itself were sub-divided into overlapping tiles that fully cover the inland region of the ADCIRC mesh. The tiles provide the longitude, latitude, and classification code for each pixel within the image tiles. By sub-dividing the data and exporting to a text format, custom codes can read and manipulate the data much easier than working with the raw graphics format. Using the text-formatted data, the custom codes perform the necessary spatial averaging for computing individual nodal values of Manning’s n, \( z_0 \), and canopy. Each pixel in the FWC data set has a class and each class has an associated value for the needed friction parameters. This allows the pixel coordinates to be used to spatially locate the appropriate data points that contribute to each ADCIRC node.

Manning’s n

Manning’s n is an isotropic scalar parameter used to approximate
resistance to flow from a variety of physical mechanisms, including form drag and skin friction. For the depth-averaged ADCIRC model, the Manning’s n should correlate to roughness of the landscape at the same spatial scale as the computed flow. When the finite element mesh is highly refined, finer details of the underlying landscape can be represented and when the finite elements are large, a larger scale average is appropriate. Thus, the nodal Manning’s n value is approximated as an arithmetic average of all the individual data points within a control volume surrounding the ADCIRC node. The control volume is sized by the mid-points of all the finite elements to which the node is attached. The Manning’s n values for all the collected pixels are averaged to generate the nodal value. An example of the Manning’s n distribution in the ADCIRC model for the study area is shown in Figure 1.

Directional z0

As described above and in the FEMA HAZUS report, the z0 value is anisotropic. The wind boundary layer depends upon conditions upwind of the node, as it can take more than 3 km to adjust to changes in ground roughness. This upwind effect is particularly important in the near-shore regions where winds are traveling either offshore or onshore and transitioning to and from open marine conditions. A land-masking procedure that does not account for wind-directionality and upwind effects would incorrectly apply full marine force winds at all locations. Using accurate winds in the model are especially critical in the near-shore and low-lying overland regions that experience either drawdown or flooding because the wind-stress term in the shallow-water equations is inversely proportional to total water column depth and thus the sensitivity to winds in shallow regions is the greatest.

The z0 parameter has units of length and may be thought of as a roughness length scale correlated to the height of roughness elements on the surface; the larger the value, the greater the amount of "shielding" from the wind. The assignment of length scale to the FL-FWC classes is consistent with the definitions in the FEMA HAZUS report. To implement assignment of z0 nodal values, land cover pixels are collected in a wedge-shape region on the upwind side of the node several kilometers distant from the node. To account for directionality of the upwind parameters, the compass is divided into 12 directions and an upwind z0 value is computed for each of the directions. Each node is assigned 12 values of the z0 parameter. During runtime the ADCIRC model applies the wind-reduction value appropriate to the instantaneous wind direction at each node. Two examples of the model input are provided in Figure 2 for Direction Number 7 (wind blowing east to west) and in Figure 3 for Direction Number 1 (wind blowing west to east). Note that the directionality can be most easily seen by comparing the difference between the images in the area of influence of barrier islands and coastal regions.

Canopy

The canopy parameter accounts for additional wind adjustment. While the z0 value accounts for the wind boundary layer adjustment, the canopy parameter accounts for the wind penetration of the roughness elements. There are large-scale features, such as heavily forest canopies, that can shelter the water surface from the wind stresses and in effect create two-layered systems. It has been demonstrated that minimal momentum transfer occurs from the wind to the water column in dense forest (Reid and Whitaker, 1976). Therefore, ADCIRC makes use of a canopy parameter which is a direct multiplier of the wind stress term. If the nodal canopy value equals unity, the full wind stress is applied, and if canopy equals zero, no wind stress is applied in the momentum balance at that node. In this formulation of ADCIRC, fractional canopy values are not used, rather, the canopy parameter is either 0 (canopy) or 1 (no canopy). Following the control volume averaging scheme used to

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Average the Manning’s n values for the ADCIRC mesh, all FL-FWC land-use data points are collected for each ADCIRC control volume. All of the canopy values within a nodal control volume are averaged. In the case that the average is greater than 0.75, the nodal canopy value is set to unity. Otherwise the canopy is set to zero.

Tidal Validation

Tidal validation is performed to assess the ability of the model to replicate the low-energy hydrodynamic processes of the study area. For this study area there have been many previous published studies performed using ADCIRC to assess how well the model captures astronomical tides. The ADCIRC model used in these previous studies formed the base for the ADCIRC model in this study (Parrish and Hagen, 2007, 2009).

For this study a tidal simulation was set up to simulate 45 days of tides using a 1-second time step. No normal-flow constraints (with free tangential slip) are enforced along all coastlines and floodplain margins. Tides enter the domain in the deep ocean through the boundary forcing imposed along the 60° west meridian, which consists of seven principal tidal constituents (K1, O1, M2, S2, N2, K2, and Q1) interpolated from the global ocean tide model of Le Provost et al. (1998). Tidal potential forcing associated with these same seven constituents is applied over the surface of the domain.

There are four National Ocean Service (NOS) tidal gauging stations within the study area. The NOS reports 37 tidal constituents for each of the four tidal gauging stations. Model output consists of 23 tidal constituents (Westerink, 1994). Figure 4 displays re-synthesized observed and simulated tidal signals for the four NOS tidal gauging stations within the focus area. The model captures the amplitude and phase of the tide as well as its mixed, i.e., diurnal and semi-diurnal, character. Note that tides in the Gulf of Mexico are chiefly diurnal since the basin configuration allows for a natural period close to 12 hours, though there is partially a semi-diurnal response due to direct astronomical forcing (Reid and Whitaker, 1981).

Historical Storm Validation

To evaluate the ADCIRC model performance, several historical hurricanes were simulated and model results compared to the available historical storm surge data. For these hindcasts, meteorological inputs were supplied by Oceanweather Inc. and the effect of surface waves is included via radiation stress inputs from the SWAN nearshore wave model (see Slinn in this issue). High Water Mark (HWM) data have been supplied by FEMA and historic reports and hydrograph data have been supplied by NWFWM and NOAA. One of the limitations of evaluating the accuracy of the ADCIRC model is that the storm history as well as the HWM data is sparse for the region of interest. In addition, data from the older storms often have an unknown datum which can make comparisons a challenge. Nevertheless, comparison of the simulated surge to the available time series hydrograph data reveals very good agreement.

Another limitation when comparing model results to HWMs and to tidal gauge hydrographs is the unknown amount of wave effects included in the measurements. Both gauges and HWMs can have varying amounts of wave setup included in them, depending on the geographic location. This makes comparison to the modeled storms difficult. To account for wave setup, radiation stresses are included in the ADCIRC model from the 2D wave model SWAN. The wave radiation stresses account for a majority of the wave setup component. However, wave setup may be slightly under-predicted due to components of the wave setup not included in the wave radiation stress, such as mass transfer.

HWMs may also contain effects such as wave runup and overtopping. These are also based on observations which can be very subjective. The HWMs were reviewed and filtered to obtain only the HWMs of the highest quality and that contain only the total storm

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surge without wave runup or overtopping effects as best as can be accessed from the available data and descriptions of the HWM. There may also be datum issues with some of the older data sets.

Note that this exercise was not a calibration in the sense that model parameters were not adjusted in an attempt to tune the model to force a closer match. Rather, the model parameters were derived from accepted values in the literature and fixed for the duration of the hindcasting. There are many sources of uncertainty in the hindcasting procedure such as errors in the data collection, meteorology, wave model, surge model, and topographic data. Because of the multiple sources of uncertainty, calibration and model tuning could result in compensating for one deficiency by non-physical adjustment of parameters. To avoid this, calibration was not performed.

The four historical storms available for this study region are Agnes (1972), Kate (1985), Opal (1995), and Dennis (2005). Agnes passed along the western border of the study area and induced surge primarily in Wakulla and Jefferson counties. Kate also passed west of the study area, but Kate produced stronger winds, thus generating more surge than Agnes. Opal made landfall near Alabama, which is far west of the study site. For Agnes, Kate, and Opal, there are very few measured HWMs and minimal time series hydrograph data. No gauge data are available for Kate.

Since it is the most recent storm, more data exist for Hurricane Dennis than for the earlier storms. Hurricane Dennis made landfall west of the study area on July 10, 2005 as a Category 3 storm. Dennis’ maximum wind speed was 150 mph with a minimum central pressure of 930 mbar. The hindcast of Dennis produced a peak surge of 17.12 feet. A contour plot of the maximum simulated surge is presented in Figure 5. A map showing the location of time-series hydrograph data is provided in Figure 6 and Figure 7 provides examples of the measured water surface elevation at three locations for Hurricane Dennis. See Figure 8 for location map.
and simulated surge levels at gauge locations 572, 8728690, and 8727520. Overall the comparison between model and historic data appears reasonable. Modeled results compare very well with gauge hydrographs while maximum difference in HWMs range from 1 to 2 ft with the model results biased lower which seems typical and expected based on the known physical and limitations of the modeling.

Summary

As part of the development of a storm surge model for use by FEMA in updating DFIRMs within Wakulla, Jefferson, and Franklin counties Florida, inputs for the ADCIRC model have been developed to account for the surface characteristics of the region. Nodal values of Manning’s-n, anisotropic wind shielding, and vegetative canopy have been derived from available land-cover datasets. The resulting model has been used to hindcast several historic hurricanes. The validation results compare well to the available data.

References


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