Summary of Work Performed by Ayres Associates in Support of URS Storm Surge Modeling for FEMA Region 4

26 August 2007

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1 Introduction

Ayres Associates was contracted by the URS Corporation to consult with URS staff and to provide several deliverables as part of URS' ongoing storm surge simulation for FEMA Region 4. The scpe of work for this FEMA modeling effort specified use of the ADCIRC and SWANN computer codes on a highly resolved numerical mesh along the Alabama and Mississippi coasts. Ayres assisted in constructing the numerical mesh and in generating specific inputs as required to run the computer models. Specifically, Ayres Associates performed the following tasks; de-refine the ADCIRC grid east of the Mississippi River, develop input files for the ADCIRC model, and develop "Vegetation" coverage input for the SWAN model. Details of work performed in completion of these tasks is provided below.

2 De-refinement of ADCIRC grid west of the Mississippi River

URS sought to maintain consistency with the FEMA Region 6 modeling effort which has been undertaken simultaneously by others (ref FEMA-6 document). Consequently, URS was provided with the highly detailed model developed by the FEMA Region 6 team to serve as a starting point for the Region 4 model. In particular, the topographic, bathymetric, and frictional definitions have been preserved between the two models for all areas east of the Mississippi River. The Region 6 model needed to maintain high accuracy across the Mississippi and Alabama coast due to the complexity of surge propagation across Lake Borgne and the Pearl River basin and within the numerous barrier islands along the Mississippi coast. In contrast, the fine details required in western Louisiana by the Region 6 modeling effort were not required and did not impact the surge calculations along the Mississippi and Alabama coast. Therefore, Ayres Associates undertook the task of de-refining the grid west of the Mississippi River. Locations of levee structures were maintained, but the grid spacing was doubled along all structures and within all regions in the west of the grid. Figure (1) shows the original ADCIRC grid and identifies by the red lines the region to be de-refined. The new elements in the de-refined areas maintained all mesh quality standards. The grid scale on the east levee of the Mississippi river was preserved and the gradation of grid scale was imposed manually across the width of the Mississippi river resulting in a gradually varied grid scale that does not introduce numerical errors other than larger truncation error associated with larger grid scale. See Figures (2) and (3) for examples of the grid in the Mississippi river before and after the de-refinement. The

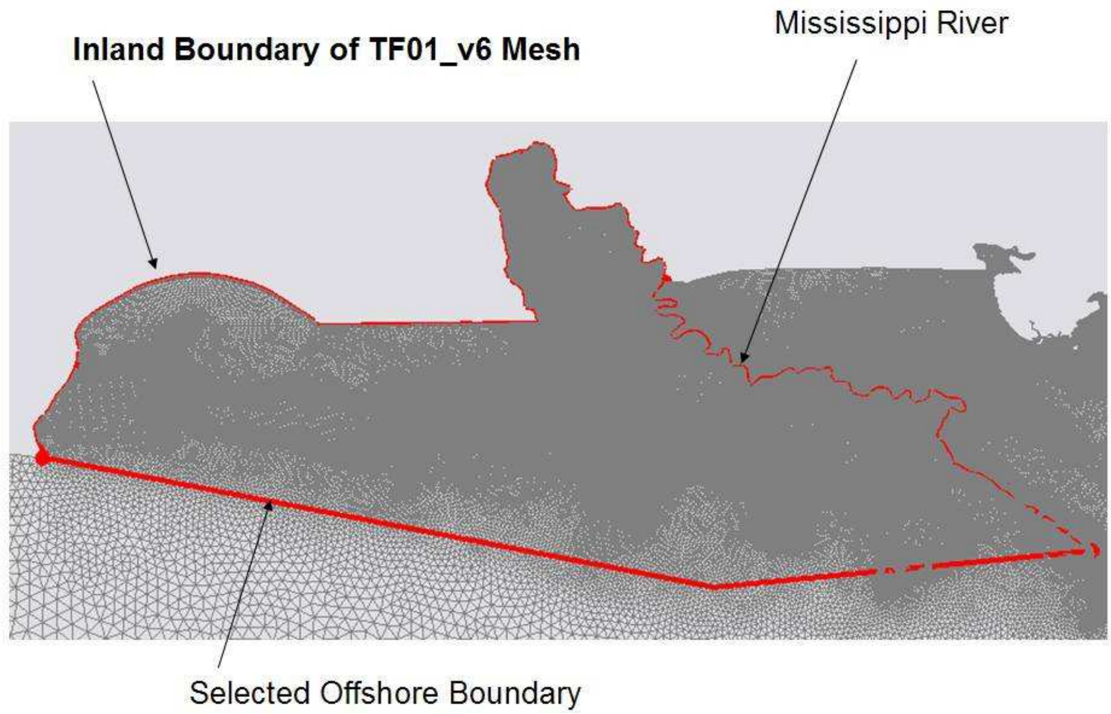

Figure 1: Original grid with red outline showing the limits of de-refinement.

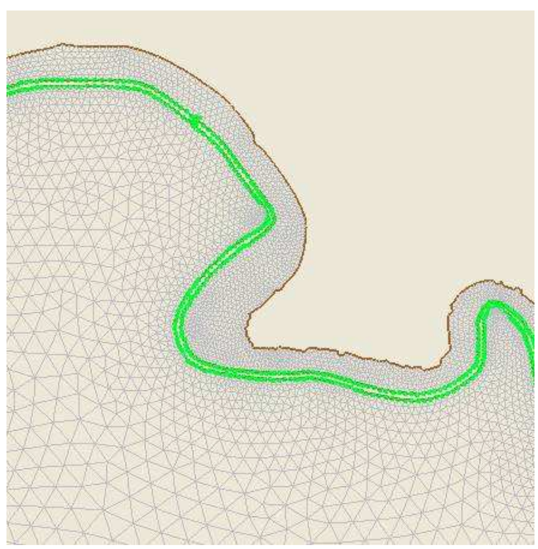

Figure 2: Sample of the original grid scale in the Mississippi River prior to de-refinement.

resulting Region 4 grid has identical grid resolution as the Region 6 grid east of the Mississippi and has approximately half of the grid resolution to the west of the Mississippi River. The goals of this approach are to reduce computational expense by eliminating fine resolution where it is not needed, yet retaining high resolution where it is needed. The consistency in resolution in Mississippi and Alabama between FEMA Region 4 and Region 6 permits easier comparison between the two efforts

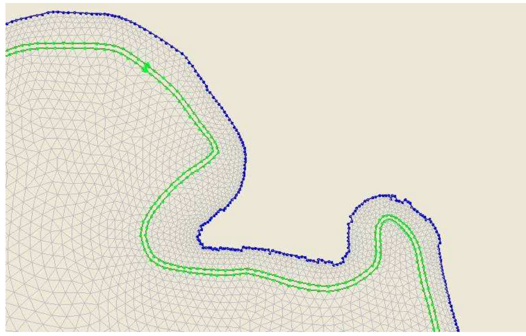

Figure 3: Sample of the new grid scale in the Mississippi River after de-refinement.

and allows Region 4 to directly benefit from the extensive validation exercises performed by the Region 6 modeling team. The URS team separately validated the derefined grid through hindcasts of hurrican Katrina for which the Region 4 results matched the high water mark data very well, thus confirming that the detail removed from the west of the Mississippi River did not adversely affect the computed surge for storms on the Mississippi and Alabama coasts.

3 Develop ADCIRC Input Files

The fort.13 input file is required to run the latest versions of the ADCIRC model which contains a number of improvements that depend upon carefully generated input files to describe the physical properties of the upland regions. These input data sets that are included in the fort.13 file define the spatial distribution of wind roughness coefficients (z_0), Manning-n, vegetation canopy, τ_0, and the wet/dry intial condition, across the gulf coast flood plain. These parameters are fully defined by assigning nodal values for every ADCIRC node. The frictional parameters were derived from USGS land-use maps as described below. The specific parameters used in generating the grid-scale averages were chosen to correspond with the parameter values used in the FEMA region 6 modeling effort. In this way, the Region 4 and Region 6 models define similar characteristics. In fact, for the regions of the URS model that were not de-refined, the nodal parameter values are identical. In regions where the URS model was de-refined, the values will be different due to the different scales of averaging between the coarse and refined grid. The differences are due solely to the differences in resolved scales as the underlying frictional coefficients are identical.

3.1 Parameterizations of Frictional Resistance

Large scale simulation of overland flooding on coastal floodplains requires accurate description of the surface over which the flow occurs. Recently, there has been increased interest in using detailed computer modeling to establish innudation limits and design levee heights along the Gulf Coast's hurricane prone regions. The widely used ADCIRC model is being used to discretize the Gulf of Mexico and the coastal flood plain with a triangular finite element mesh. The mesh (also called the "grid") is used 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 meterologic parameters that describe frictional resistance to water and wind must be defined on the same spatial scale at which the equations are being solved. New techniques were created to compute the grid scale averages of standard roughness coefficients required for accurate simulation of hurricane storm surge on the Louisiana 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 due to friction and free surface shear stress due to winds. Bottom stress has been parameterized with the standard Manning-n coefficient and free surface stress has been parameterized with the use of Garrett'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, by adjusting land roughness according to the depth of local inundation, and by accounting for the existence of heavily forested canopies.

The effect of land cover and friction 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,

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} - fu = -g\frac{\partial}{\partial x}\left(\frac{\partial P}{\partial g\rho} + \zeta\right) - \frac{\tau_{bx}}{\rho H} + \frac{\tau_{sx}}{\rho H} + \frac{1}{H}\left(M_x + D_x - B_x\right) \tag{1}$$

in the $x-$ direction and,

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + fv = -g\frac{\partial}{\partial y}\left(\frac{\partial P}{\partial g\rho} + \zeta\right) - \frac{\tau_{by}}{\rho H} + \frac{\tau_{sy}}{\rho H} + \frac{1}{H}\left(M_y + D_y - B_y\right) \tag{2}$$

in the $y-$ direction. The bottom stress terms are approximated as,

$$-\frac{\tau_{bx}}{\rho H} = -g\frac{n^2}{H^{\frac{1}{3}}}\frac{\sqrt{u^2+v^2}}{H}u \tag{3}$$

where n is the Manning-n parameter and must be specified for every ADCIRC node.

The surface stress terms are approximated as,

$$-\frac{\tau_{sx}}{\rho H} = \frac{C_d}{H}\frac{\rho_{\text{air}}}{\rho}\|W_{10}\|W_{10} \tag{4}$$

where C_d is a standard drag coefficient defined by Garratt's drag formula for wind stress (Garratt, 1977) and W_{10} is the wind velocity at a 10m 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, he 10m wind velocity is replaced by a reduced wind velocity, W_{land}, to account for surface roughness. The W_{land} velocity is found by

$$W_{land} = f_d \cdot W_{10} \tag{5}$$

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

$$f_d = \left(\frac{z_{marine}}{z_0}\right)^{0.0706} \tag{6}$$

where z_{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-HAZUS study.

Second, the influence of local land cover also enters the computations is by defining regions of vegetative canopy. It has been shown that very little wind momentum thransfers through heavily forested canopies The effect to vegetative canopy is included by reducing W_{land} to zero in the presence of landuse classes that contain trees and thick shrubs. This amounts to the assumption that the branches, leaves, and trunks absorb or deflect the momentum of the wind, thereby preventing that momentum from being transfered to the underlying water column.

Finally, the ADCIRC model is typically coupled to a wave model which will compute wave radiation stresses which are included as a momentum source term in ADCIRC. The radiation stresses are used to calculate the wave setup as a component of the total surge. However, in the presence of thick vegetation, the plant structure (trunk, branches, leaves, etc) will absorb a portion of the wave momentum, thus reducing the wave setup. The influence of the vegetation will depend upon the total depth of water because when the flow depth is much greater than the vegetative elements, the waves will travel unhindered over the vegetation. Therefore, the land-cover maps are used to estimate vegetation heights for all the ADCIRC nodes. The wave radiation output from any of the available wave models can be adjusted as necessary by taking into account local flow depth and vegetation height.

Considering that the most recent ADCIRC models contain more than 2.2 million computational nodes, an automated method to assign the values is necessary. There are too many nodal values to assign manually. This study seeks to compute values of Manning-n, z_0, canopy, and vegetation height for all of the computational node in an ADCIRC model.

3.2 Land-Cover Data Sets

Several land-cover data sets are available in the scientifc literature. The work presented here focuses on two sets; the National Land Cover Dataset (NLCD) and the state-by-state datasets from the GAP Study. Both of these data sets are products of the United States Geological Service (USGS) and both attempt to define land cover on a 30m averaging scale. Each of the 30m cells are assigned a single land-use type such as urban, residential, grassland, forest, etc. See figure (4) for the classifications of the NLCD set. Each of the data sets defines its own classification of land-cover classes into which

National Land Cover Dataset Classification System Legend

Color Key	RGB Value	Class Number and Name
	102, 140, 190	11 - Open Water
	255,255,255	12 - Perennial Ice/Snow
	253, 229, 228	21 - Low Intensity Residential
	247, 178, 159	22 - High Intensity Residential
	231, 86, 78	23 - Commerical/Industrial/Transportation
	210, 205, 192	31 - Bare Rock/Sand/Clay
	175, 175, 177	32 - Quarries/Strip Mines, Gravel Pits
	83, 62, 118	33 - Transitional
	134, 200, 127	41 - Deciduous Forest
	26, 129, 78	42 - Evergreen Forest
	212, 231, 177	43 - Mixed Forest
	220, 202, 143	51 - Shrubland
	187, 174, 118	61 - Orchards/Vineyards
	253, 233, 170	71 - Grasslands/Herbaceous
	252, 246, 93	81 - Pasture/Hay
	202, 145, 71	82 - Row Crops
	121, 108, 75	83 - Small Grains
	244, 238, 203	84 - Fallow
	240, 156, 054	85 - Urban/Recreational Grasses
	201, 230, 249	91 - Woody Wetlands
	144, 192, 217	92 - Emergent Herbaceous Wetlands

Figure 4: Legend of the NLCD Classifications

all of the 30m averages must conform.

The NLCD is a "national" dataset which has the advantage of consistency across all 50 states.

With its consistent classification, NLCD is most reliable at large regional averages and it is not intended for capturing local details. In addition, the FEMA HAZUS study has carefully assigned and validated a z_0 length scale for the NLCD classifications which provides a uniform source for defining z_0 over the entire region of interest.

In contrast, the classifications of the GAP study are not consistent across the region. The focus of the GAP study has been to identify local habitat and bio-diversity. According to the USGS, GAP has been field checked by biologists and botanist and is considered to be more reliable than NLCD for resolving small scale variability. However, each state has its own charaterization of habitat so GAP data does not have the level of consistency across the Gulf Coast as the NLCD set has. An additional downside is that the areal coverage of GAP data is not as widespread as NLCD and may not be available for all states or regions. In this effort, the GAP data has been favored over NLCD and it used to compute the Manning-n values because GAP better characterizes the small scale variation of vegetation types near the coastal margin. (Please note this study looked only at GAP/NLCD within TX, LA, AL, MS.) Despite its prefered level of detail, GAP must be supplemented with NLCD for computing the z_0 and canopy parameters. Consequently, we have resorted to using both data sets for obtaining our total representation of frictional parameters.

When using any of the data sets, the land-use classifications are not used directly. ADCIRC nodes are not assigned a "land type". Rather, ADCIRC nodes need to be assigned a numerical value for each parameter. Thus, each land-use class is assigned a specific value of the friction coefficients appropriate to the land-use. The friction parameters cooresponding to the land-use classes are shown in Table (1), Table (2), and Table (3).

Class 95 was constructed from the GAP data for Louisiana becasuse NLCD did not have coverage for a certain kind of wetland forest called "Cypress". Therefore, the appropriate GAP data classes were extracted and merged into the NLCD set to create a new class which effectively incorporated the the Cypress Forest land type within the NLCD data.

Both the NLCD and GAP data sets are available as geo-referenced tiff images in which each pixel of the tiff image represents one of the 30m averaged cells. Rather than work directly with the tiff images, standard GIS tools are used to convert the array of pixels to a collection of overlapping ascii text files. The text files contain the latitude and longitude of each pixel plus an integer identifying the pixel's land-cover classification. All tiff files are topologically rectangles and therefore the pixels in a tiff file can be stored as a two dimensional array with each pixel uniquely identified by its row and column indicies.

Each tiff file is very large, representing many millions of pixels. Because the region of interest is confined to the coastal zone, much of the tiff content is extraneous. To facilitate manipulation of the large data sets, the tiff files were divided into slightly overlapping "tiles" that covered only the areal extent of the ADCIRC model. Each tile preserves the rectangular topology associated with tiff files but each array is orders of magnitude smaller than the original tiff.

In order to efficiently locate the closest NLCD or GAP pixel to an ADCIRC node, a relationship was derived between a pixel's latitude and longitude and its row/column indexing within the pixel array. Thus, given the coordinates of an ADCIRC grid point in latitude and longitude, it is possible to instantly locate the closest pixel in the tiff image. By extension, this technique works to identify pixels contained within control volumes and along directional rays. In general, the rows and columns of a pixel tile are not aligned with lines of constant longitude and latitude. Consider the tile of pixels in Figure (5) where the rectangle denotes the areal extent of the array of pixels and the dots represent 16 sampling locations. The points indicated in Figure (5) are chosen at equal distributions of the row and column indicies for a tile. Since the longitude (x) and latitude (y) are know for all the pixels, this provide 16 points for which both coordinates and indicies are known. Now consider the quadratic polynomials

$$i \;=\; \alpha_1 + \alpha_2\, x + \alpha_3\, y + \alpha_4\, xy + \alpha_5\, x^2 + \alpha_6\, y^2 \qquad (7)$$

and

$$j \;=\; \beta_1 + \beta_2\, x + \beta_3\, y + \beta_4\, xy + \beta_5\, x^2 + \beta_6\, y^2 \qquad (8)$$

CLASS	z_0	n	Description
11	0.001	0.020	open water
12	0.012	0.022	ice snow
21	0.330	0.120	low residential
22	0.500	0.121	high residential
23	0.390	0.050	commercial
31	0.090	0.040	bare rock/sand
32	0.180	0.060	gravel pit
33	0.180	0.100	transitional
41	0.650	0.160	deciduous forest
42	0.720	0.180	evergreen forest
43	0.710	0.170	mixed forest
51	0.120	0.070	shrubland
61	0.270	0.100	orchard/vineyard
71	0.040	0.035	grassland
81	0.060	0.033	pasture
82	0.060	0.040	row crops
83	0.050	0.035	small grains
84	0.040	0.032	fallow
85	0.050	0.030	recreational grass
91	0.550	0.140	woody wetland
92	0.110	0.035	herbaceous wetland
95	0.550	0.145	Cypress Forest

Table 1: Manning-n and z_0 Assignments for NLCD Classifications

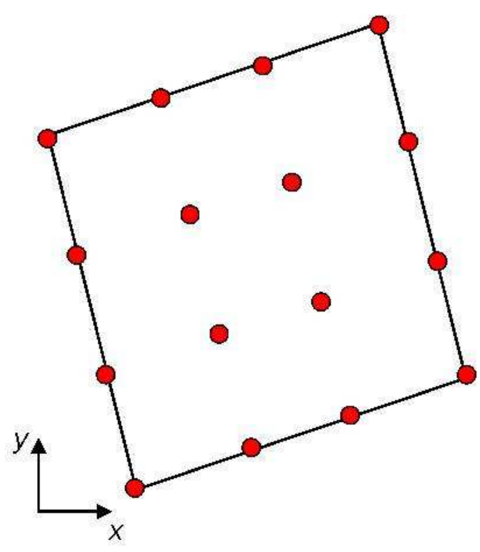

Figure 5: Schematic of the 16-sampling points on an arbitrary tile of pixels.

CLASS	n	Description
1	0.045	Fresh Marsh
2	0.040	Itermediate Marsh
3	0.040	Brackish Marsh
4	0.035	Saline Marsh
5	0.140	Wetland Forest - Deciduous
6	0.160	Wetland Forest - Evergreen
7	0.150	Wetland Forest - Mixed
8	0.160	Upland Forest - Deciduous
9	0.180	Upland Forest - Evergreen
10	0.170	Upland Forest - Mixed
11	0.180	Dense Pine Thicket
12	0.060	Wetland Scrub/Shrub - Deciduous
13	0.080	Wetland Scrub/Shrub - Evergreen
14	0.070	Wetland Scrub/Shrub - Mixed
15	0.070	Upland Scrub/Shrub - Deciduous
16	0.090	Upland Scrub/Shrub - Evergreen
17	0.080	Upland Scrub/Shrub - Mixed
18	0.040	Agriculture - Crops - Grass
19	0.120	Vegetated Urban
20	0.120	Non-Vegetated Urban
21	0.030	Wetland Barren
22	0.031	Upland Barren
23	0.025	Water

Table 2: Manning-n Assignments for LA GAP Classifications

where i is the row index and j is the column index. A least-squares approach is used to find the α_k and β_k constants by enforcing equality for the 16 known points. With α_k and β_k known, then for coordinates within the coverage of a pixel tile, the row and column address of any latitude and longitude can be found instantly. This greatly improves the efficiency of performing the required averaging for the millions of ADCIRC grid points.

3.3 Manning-n

Manning-n is an isotropic scalar parameterization used to approximate flow resistance from a variety of physical mechanisms including form drag and skin friction. For the depth-averaged ADCIRC model, the Manning-n value should correlate to roughness of the landuse type at the spatial scale of the computed flow. Where the finite element mesh is highly refined, finer details of the underlying landform will be represented and when the finite elements are large, a larger scale average will be provided. The manning-n parameters are not directionally dependent so the Manning-n values for all the pixels within a control volume around each ADCIRC node are found and averaged, see Figure (6). By ideintifying the pixels with each nodal control volume, the resultant Manning-n field is defined at the appropriate grid scale, ie: finer discretization produces a more detailed characterization of the roughness while coarser discretization captures a larger scale average.

There is a substantial body of literature with regard to accepted ranges of Manning-n values for many classes. The final values used for this study to characterize the bottom friction in south

CLASS	n	Description
1	0.060	agriculture
2	0.025	fresh water
3	0.045	aquaculture
4	0.025	estuarine water
6	0.035	farmed wetlands
7	0.050	estuarine emergent
8	0.060	estuarine woody
9	0.055	palustrine emergent
10	0.140	bottomland hardwood
11	0.060	riverine swamp
12	0.160	pine savannah
13	0.070	fresh water shrub/scrub
14	0.030	palustrine non-vegetated
15	0.032	transportation
16	0.150	high density urban
24	0.025	urban fresh water
25	0.040	wet soil / water /shadow ?
26	0.180	urban pine
27	0.160	urban hardwood
28	0.070	urban low herbaceous
29	0.035	urban grassy / pasture
30	0.120	bare urban I
31	0.120	bare urban II
32	0.036	clear cuts
50	0.160	low density pine
51	0.180	medium density pine
52	0.200	high density pine
53	0.150	medium density hardwood
54	0.170	high density hardwood
55	0.160	mixed forest
56	0.052	recent harvest
57	0.180	cypress / tupelo
60	0.060	agriculture (see class 1)
61	0.042	grassy / pasture / range
62	0.047	low herbaceous vegetation
63	0.080	evergreen shrub
71	0.045	wetland
80	0.030	bare
81	0.030	sand bar / beach
83	0.050	clouds

Table 3: Manning-n Assignments for MS GAP Classifications

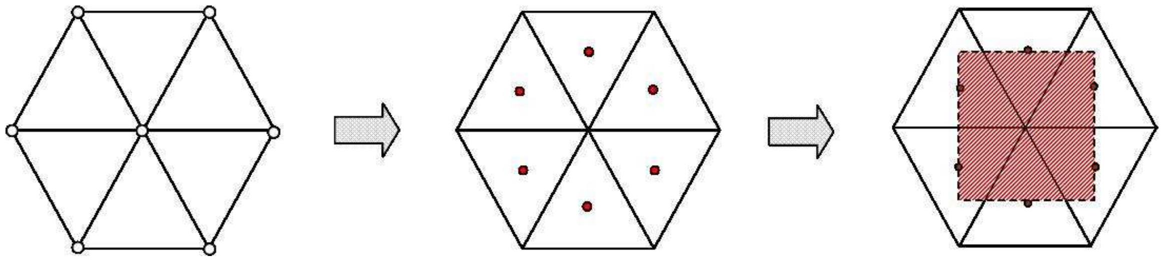

Figure 6: Approximating a control volume using centroids of surrounding finite elements.

eastern LA and western MS are shown in Table 2 and Table 3. These representative Manning-n values are all within the expected range of values for their land-use categories according to standard hydraulic texts. The final grid scale averages for the Manning-n parameter can be seen in Figure (7) and (8).

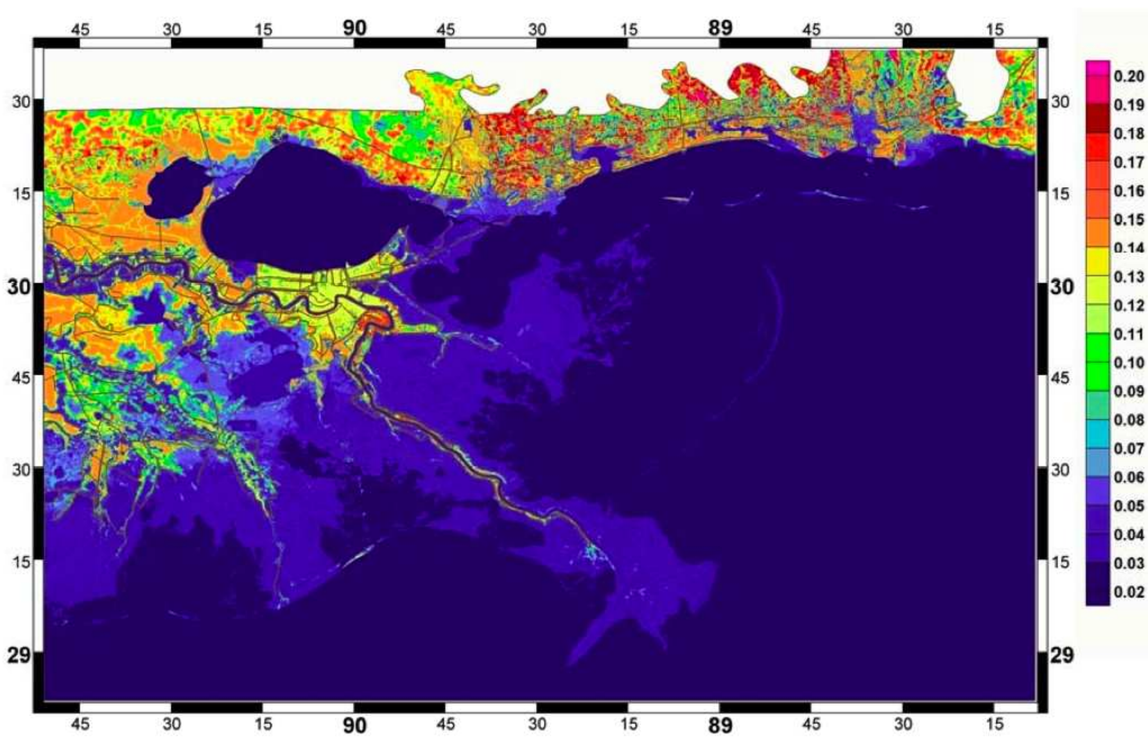

Figure 7: Grid-scale averaged Manning-n values on the ADCIRC Grid across Louisiana and Mississippi.

3.4 Wind Reduction

In contrast to the scalar valued Manning-n, the z_0 roughness length is anisotropic. The wind boundary layer depends on roughness conditions upwind of the location since the boundary layer does not adjust instantaneously to changes in local roughness. This upwind effect is particularly important in the nearshore region where winds are traveling either off/onshore and transitioning to/from open marine conditions. A land masking procedure that does not account for wind direction would incorrectly produce full marine winds in the near-shore zone when winds come from land and result in reduced marine winds overland when winds come off the water. Accurate winds are critical in these 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 height and thus the sensitivity to these winds is the greatest.

The roughness length scales are coorelated to the height of roughness elements and indicate the amount of "shielding" from the wind the water column will be provided. Short objects provide very little shielding while tall objects provide greater shielding. The Acirc formulation largely follows the work done by the FEMA HAZUS project. There are HAZUS roughness length scales defined for the NLCD classes only. Additional details may be found in an FSU thesis available here: http://etd.lib.fsu.edu/theses/available/etd-08112004-154402/unrestricted/01.lma.tableofcontents.pdf

To account for directionality in the upwind parameters, the compass is divided into 12 equal 30-degree slices and a z_0 value is computed for each of the twelve upwind directions around an ADCIRC node. Thus, full specification of the roughness length scales requires 12 values must be computed for each ADCIRC node.

To collect the land use data from the upwind directions, five linear rays are indentified within each of the 30 degree slices, starting at the coordinates of the ADCIRC node and extending radially 10km distant, see Figure (9). The ray's are located at the midline of the slice, ±15 degrees, and ±7.5 degrees. Every pixel in the NLCD set is found along the directional rays and an inverse-distance weighted average is computed according to,

$$w_i = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{d_i^2}{2\sigma^2}} \tag{9}$$

Where w_i is the weight assigned to pixel i, d_i is the distance of pixel i from the ADCIRC node, and

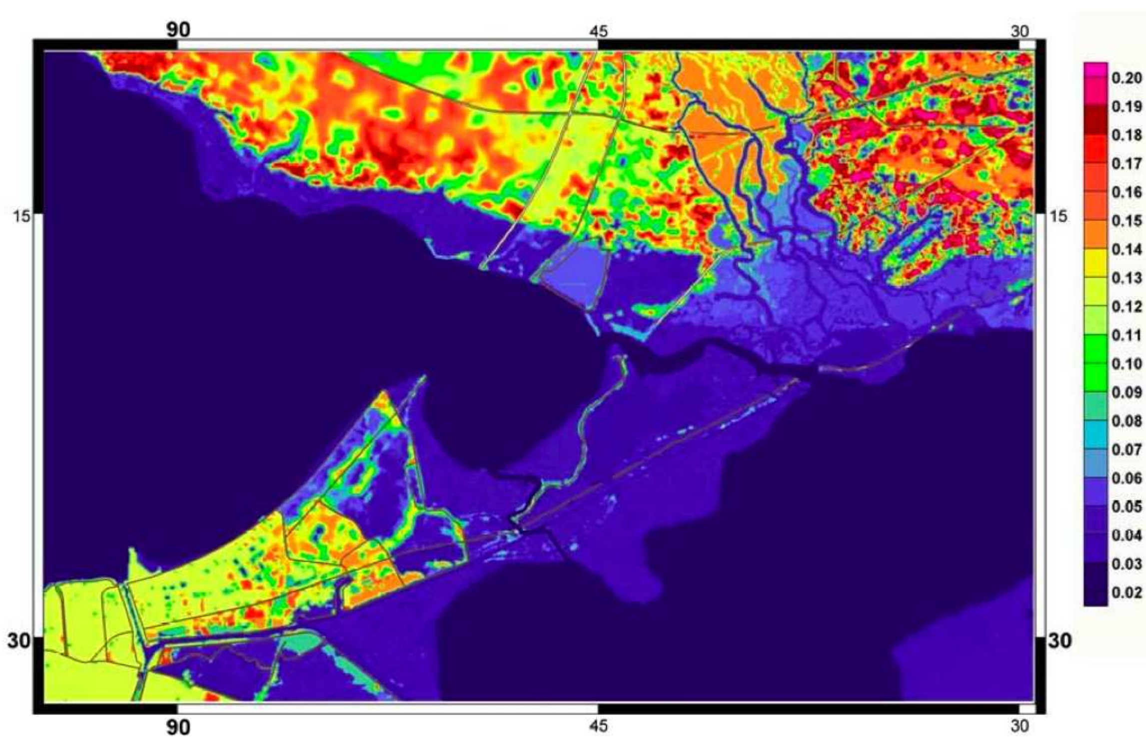

Figure 8: Grid-scale averaged Manning-n values on the ADCIRC Grid in the Pearl River Basin.

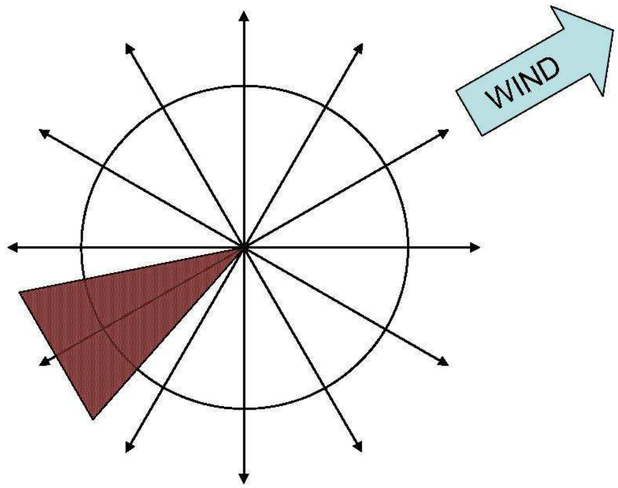

Figure 9: Region of Influence for pixels contributing to upwind roughness averaging.

σ is a scaling parameter chosen to be 6km. The influence of the σ parameter can be seen in Figure (10).

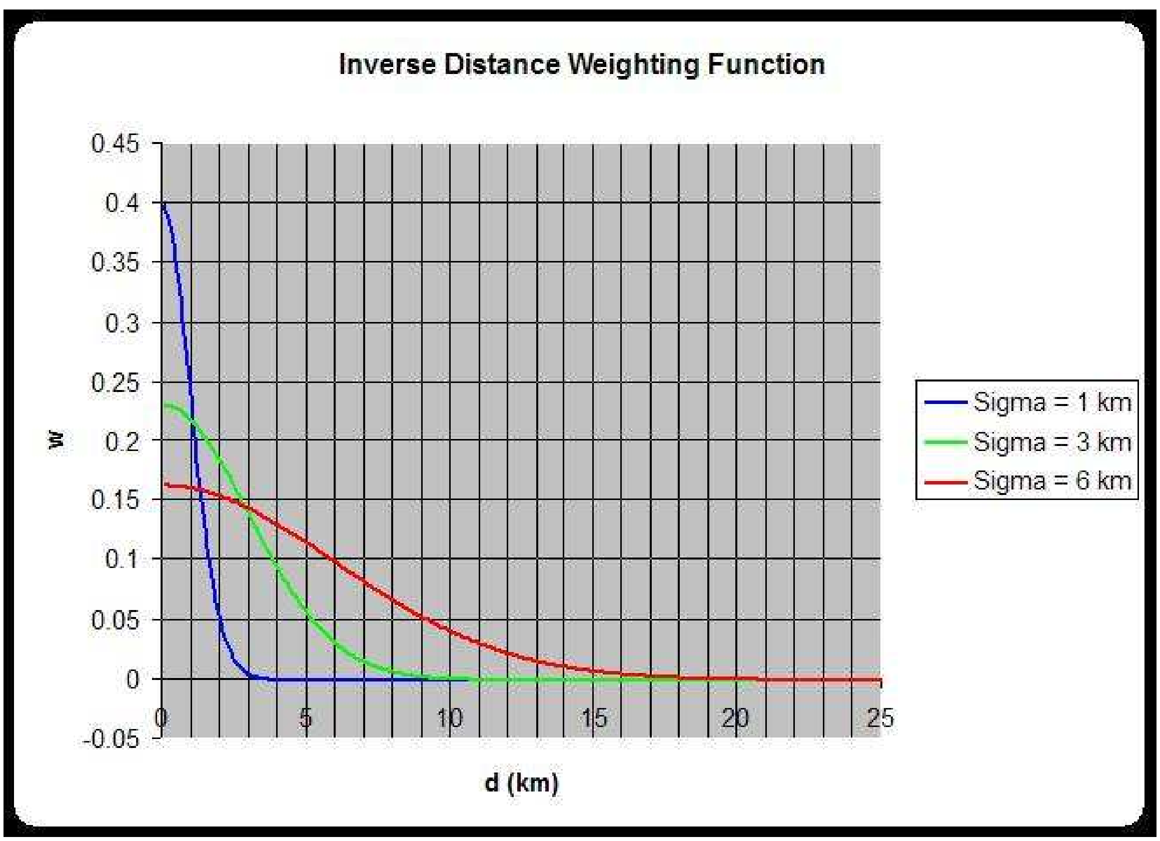

Figure 10: Sensitivity of σ in the inverse distance weighting parameter.

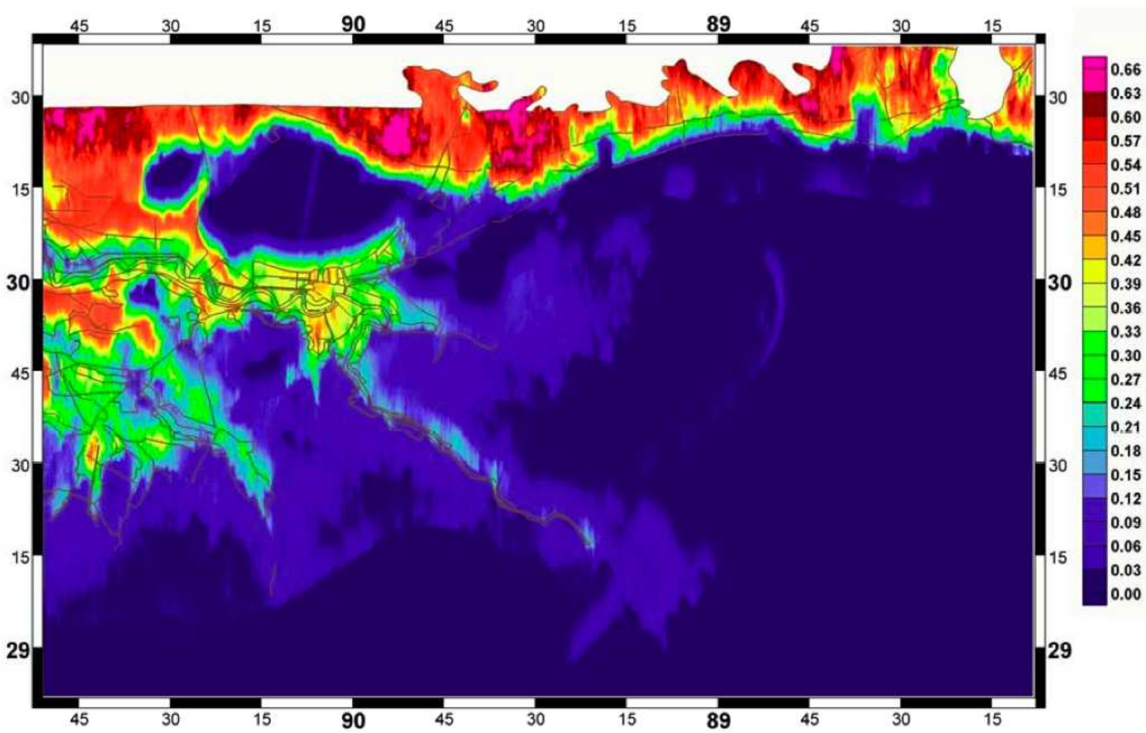

Figure 11: Directional wind reduction parameter (z_0) for a northerly wind.

The weight function is used to compute and average z_0 from the sum of all weighted z_0 pixel values according to,

$$\overline{z_0} = \frac{\sum_{i=1}^{N} w_i \, z_{0_i}}{\sum_{i=1}^{N} w_i} \tag{10}$$

Finally, the values along the rays are averaged by

$$z_{0j} = 0.5 \, z_{0mid} + 0.125 \, (z_{0+15} + z_{0-15} + z_{0+7.5} + z_{0-7.5}) \tag{11}$$

to get an average z_{0j} value for the jth slice at each ADCIRC node. Examples of two of the twelve directional parameter sets are shown in Figure (11) and (12).

3.5 Canopy

Finally, the application of the directional wind speed adjustments account for how the wind boundary layer is affected but do not characterize how the wind penetrates the physical roughness elements. There are large-scale features, such as heavily forested canopies, that shelter the water surface from the wind stress and in effect create two-layered systems. It can be demonstrated that little momentum transfer occurs from the wind field to the water column in heavily canopied areas (Reid and Whitaker 1976). Therefore, in heavily canopied regions where USGS land use maps define a roughness length greater than 0.39 (except for urban areas), no wind stress is applied at the water surface.

Following the same control volume averaging scheme as used to compute the Manning-n values, all NLCD pixels are collected for each ADCIRC nodal control volume. Pixels belonging to NLCD classes 41, 42, 43, 91, and 95 are counted as canopy pixels and all others are counted as no-canopy.

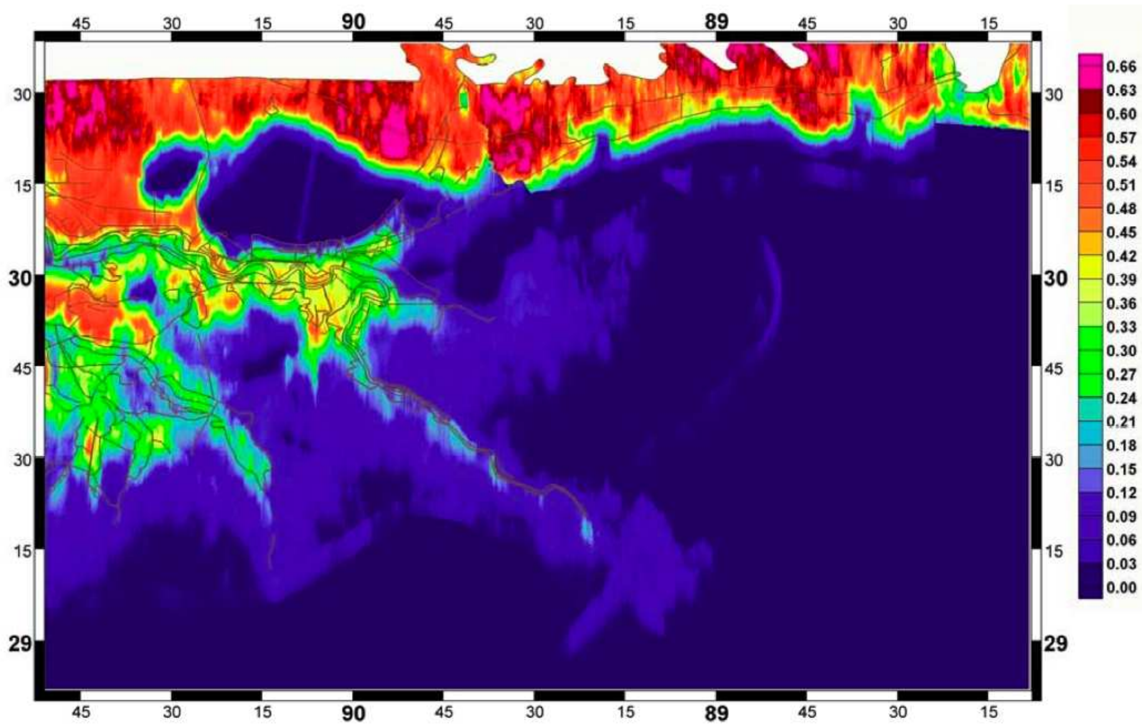

Figure 12: Directional wind reduction parameter (z_0) for a southerly wind.

If the ratio of canopy pixels to total pixels in the control volume is greater than 0.5, then W_10 set to zero for that ADCIRC node. The forested canopied areas in Southeastern Louisiana are shown in Figure (13).

3.6 Primitive continuity weighting parameter (τ_0)

The fort.13 file also contains spatial information regarding the numerical parameter, τ_0. The τ_0 parameter is an essential component of the Generalized Wave Continuity (GWC) form of the governing equations that are solved within ADCIRC and it controls the dispersion properties of the solution. Optimal values are well documented and the behavior of the algorithm is well understood (Atkinson et al. 2004). Operationally, the spatial distribution of τ_0 is set equal to 0.005 in quiescent waters deeper than 30ft outside of Southern Louisiana, Mississippi, and Alabama, $\tau_0 = 0.02$ in waters shallower the 30ft outside of Louisiana, Mississippi, and Alabama, and $\tau_0 = 0.03$ in waters shallower that 30ft and/or in rivers and inlets where higher velocities lead to higher frictional resistance within Louisiana, Mississippi, and Alabama (Feyen et al. 2000). Within the ADCIRC code, these base τ_0 parameters are modified based upon the total water column and local currents as $\tau_0 = 0.02 + 4tau_*/3$. This automated τ_0 optimization increases accuracy and robustness for the high flow speeds encountered inundation during hurricane storm surge.

3.7 Initial Condition

Finally, the fort.13 file contains an initial condition parameter to preserve as dry, those regions below sea level that are not normally inundated. Without this initial-condition parameter, ADCIRC sets the initial water surface at z=0 and all nodes lower than this elevation are considered "wet". However, many regions exist within southern Louisiana that are protected by levees (such as the city of New

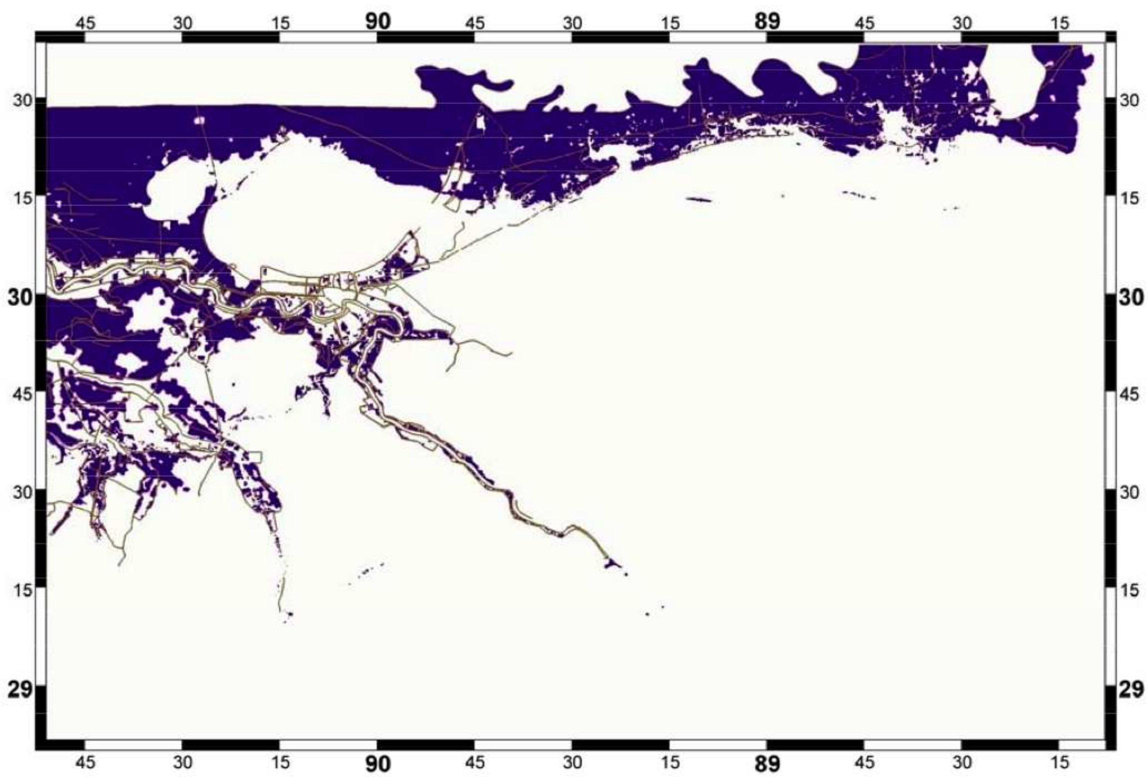

Figure 13: Regions of the LA/MS coast identified as heavily canopied (in blue).

Orleans). All such regions are identified and set dry in the fort.13 file. This does not prevent the initially dry nodes from becoming wet during a simulation; it simply establishes the correct initial condition.

4 Vegetation Height

FEMA required computation of wave setup as a component of total hurricane storm surge. For calculation of wave radiation stresses that drive wave setup, the SWAN model was used in the FEMA Region 4 modeling effort. Ayres Associates provided an additional input file to URS for the purpose of performing a sensitivity of vegetation effects on computed wave radiation stresses. It was hypothesized that the presence of vegetation, branches, leaves, and trunks would absorb some of the wave momentum. Thus, in regions of significant vegetation, the wave radiation stresses would be multiplied by a factor to account for reduction due to plants In order to systematically account for the mechanism of wave momentum absorbtion by presence of vegetation, the distribution of vegetation and vegetation height must be estimated from the land-use maps.

The GAP data sets were used to derive vegetation heights because GAP is considered superior to NLCD for defining botanical variability. The land-use classes in the USGS Gap Data set were assigned a representative height of 0, 1, 2, 5, or 10 meters based upon the kind of vegetation in a land-use class. See Table 4 for the values assigned to the vegetative classes. Following the proceedure used for averaging manning-n values, the ADCIRC nodal control volumns were used to collect and count the number of vegetation pixels for each node. The file is generated that contains 6 values for every ADCIRC node; total number of pixels associated with the node, number of vegetation pixels (defined as a pixel whose $h > 0$), and the number of pixels defining vegetation of 1m, 2m, 5m, and 10m height. The number of pixels at each of the heights is preserved so that radiation stress modification can be applied while flow depth is less than the vegetation height. Preserving the distinct vegetation heights also allows modelers to investigate the sensitivity of vegetation height on computing wave setup by using different pixel-height averages and varying the threshold for which radiation stresses are modified.

5 References

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CLASS	h(m)	Description
1	1.0	agriculture
2	0.0	fresh water
3	1.0	aquaculture
4	0.0	estuarine water
6	1.0	farmed wetlands
7	0.0	estuarine emergent
8	5.0	estuarine woody
9	1.0	palustrine emergent
10	10.0	bottomland hardwood
11	1.0	riverine swamp
12	0.0	pine savannah
13	1.0	fresh water shrub/scrub
14	0.0	palustrine non-vegetated
15	0.0	transportation
16	0.0	high density urban
24	0.0	urban fresh water
25	0.0	wet soil / water /shadow ?
26	0.0	urban pine
27	0.0	urban hardwood
28	0.0	urban low herbaceous
29	0.0	urban grassy / pasture
30	0.0	bare urban I
31	0.0	bare urban II
32	0.0	clear cuts
50	0.0	low density pine
51	0.0	medium density pine
52	10.0	high density pine
53	0.0	medium density hardwood
54	10.0	high density hardwood
55	10.0	mixed forest
56	0.0	recent harvest
57	10.0	cypress / tupelo
60	1.0	agriculture (see class 1)
61	0.0	grassy / pasture / range
62	0.0	low herbaceous vegetation
63	2.0	evergreen shrub
71	1.0	wetland
80	0.0	bare
81	0.0	sand bar / beach
83	0.0	clouds

Table 4: Vegetation Height Assignments for MS GAP Classifications