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STRUCTURED MESH GENERATION ALONG LOUISIANA-MISSISSIPPI COASTLINE FOR SIMULATION OF COASTAL PROCESSES

Yaoxin Zhang[1], Yafei Jia[2], Mustafa S. Altinakar[3], Yan Ding[4], Vijay Ramalingam[5], and Soumendra N. Kuiry[6]

ABSTRACT

As a pre-process of CFD (Computational Fluids Dynamics) analysis, mesh generation plays an important role in numerical simulation in the sense that mesh quality has significant influences on simulation results. For geometrically complex domains, quality structured mesh generation still remains a challenge. This paper presents a quality structured mesh generation process in a large-scale complex domain along the Louisiana-Mississippi coast line, which is part of a numerical simulation and evaluation of coastal processes using the CCHE2D-Coast model. In this study, the study domain is about 440 km (longitude direction) x 320 km (latitude direction), and multiple-scaled objects are required to be represented in detail, which makes it more difficult for quality structured mesh generation. The characteristic mesh size for the levees, roads and as-built hydraulic structures is 10-100 m, 10-100m for Pearl River, 100-1000m for Mississippi River, and 1000-2000m for the coast and gulf. To make the mesh lines conform to these objects as much as possible (which is desired for more accurate simulation), a multi-block scheme is used to decompose the whole domain into 17 blocks, and structured meshes with different resolutions was generated block by block. The assembled final mesh with 2103 x 1088 (= 2.288 M nodes) in this large complex domain was successfully generated using CCHE-MESH, a 2D mesh generator for both quality structured and unstructured meshes. Numerical simulation of coastal storm surge using the CCHE2D-Coast model based on this mesh produced satisfactory results.

1. INTRODUCTION

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[1] Research Scientist, National Center for Computational Hydro science and Engineering, University of Mississippi, University, MS 38677, USA (yzhang@ncche.olemiss.edu)

[2] Research Professor and Associate Director, National Center for Computational Hydro science and Engineering, University of Mississippi, University, MS 38677, USA (jia@ncche.olemiss.edu)

[3] Research Professor and Director, National Center for Computational Hydro science and Engineering, University of Mississippi, University, MS 38677, USA (altinakar@ncche.olemiss.edu)

[4] Research Assistant professor, National Center for Computational Hydro science and Engineering, University of Mississippi, University, MS 38677, USA (ding@ncche.olemiss.edu)

[5] Research Software Developer, National Center for Computational Hydro science and Engineering, University of Mississippi, University, MS 38677, USA

[6] Research Scientist, National Center for Computational Hydro science and Engineering, University of Mississippi, University, MS 38677, USA

The Louisiana-Mississippi coast line is well known for its vulnerability to hurricanes. For example, on Aug. 28, 2005, Hurricane Katrina reached the Mississippi coast line and made landfall in southern Plaquemines Parish, Louisiana on the following day**.** As a result of this most destructive storm, in coastal Mississippi, over 90% towns were flooded in hours and many historic buildings were destroyed by waves [1]. To evaluate the additional coastal flooding risks on the Mississippi coast due to the loss of coastal wetlands and barrier islands during Hurricane Katrina, and the influences of the coastal protection and restoration works built for protecting New Orleans and Lake Pontchartrain in Louisiana, an integrated coastal processes numerical model, CCHE2D-Coast (Ding *et al.*, 2006 and 2011) was used to perform a series of numerical simulations along Louisiana-Mississippi coast line for storm surge and wave-induced flooding. The mesh generation is the very first task of this numerical simulation of coastal processes.

Mesh generation plays an important role in CFD (Computational Fluids Dynamics) analysis because governing equations are discretized spatially on meshes. In turn, the mesh quality has direct and significant influences on the simulation results despite the numerical model itself. For geometrically complex domains, unstructured meshes are naturally more suitable than structured meshes due to their capabilities of conforming to the complex boundaries. Quality structured mesh generation in complex domains is challenging. On the other hand, numerical solvers for PDE (Partial Differential Equations) based on structured meshes are generally much faster than those of unstructured meshes, which probably is the main reason that many numerical models were developed based on structured mesh system. The CCHE2D-Coast is one such model adopting a non-orthogonal non-uniform structured mesh system to solve the governing equations.

In this study, the quality structured mesh generation in a large-scale complex domain along Louisiana-Mississippi coast line using CCHE-MESH, a 2D quality structured and unstructured mesh generator (Zhang and Jia, 2009) is introduced. An algebraic mesh generation method based on a multi-block scheme and a stretching function (Zhang *et al.*, 2006a), and an improved nearly-orthogonal mesh generation system with smoothness control (Zhang *et al.*, 2004 and 2006b) were used to generate meshes. Simulation results have shown the final mesh generated by CCHE-MESH is satisfactory.

2. STUDY DOMAIN

As shown in Figure 1, the study domain covers a large area (about 440km x 320km) along Louisiana-Mississippi coast line, including Lake Pontchartrain, Mississippi River, Pearl River, barrier islands, etc.

Multiple-scaled irregular objects (Mississippi River, Pearl River, Levees, Roads, and Structures) exist in the study domain (see Figure 2), with characteristic sizes varying on the order of 10^0 to 10^3m. To better and more accurately simulate surge storms and waves affected by these objects, mesh lines are required to conform to their boundaries as much as possible, which increases the difficulties and complexities of the structured mesh generation significantly.

CCHE-MESH, a 2D mesh generator for both quality structured and unstructured meshes (Zhang and Jia, 2009) was used to generate meshes in this large domain. It is user-friendly and has integrated many mesh generation methods including a multi-block based algebraic generation method, numerical structured mesh generation methods for orthogonal mesh generation with smoothness controls, advanced boundary treatments, and mesh density controls, and quality Delaunay refinement algorithm for unstructured mesh generation. (It is free to the public and can be downloaded at http://www.ncche.olemiss.edu/download).

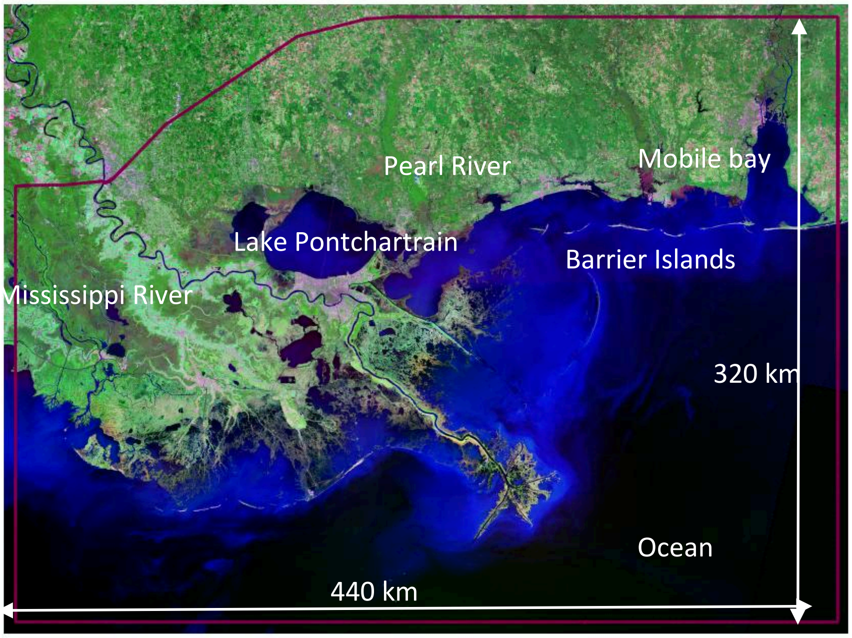


Figure 1 Study domain

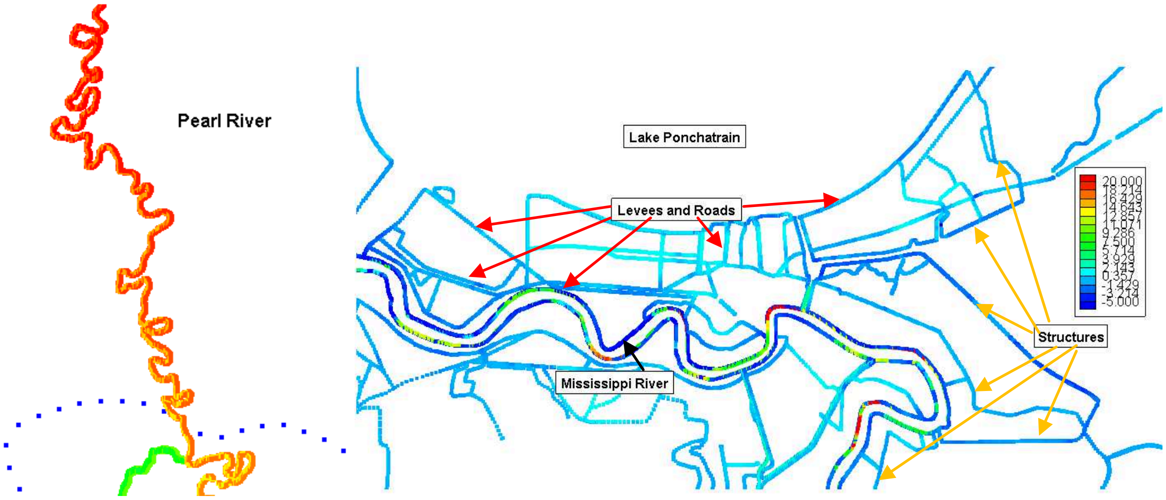


Figure 2 Multiple-Scaled Objects in Study Domain

3. ALGEBRAIC MESH GENERATION

The simplest mesh for this domain is the uniform rectangle mesh, i.e., mesh directly extracted from DEM (Digital Elevation Model) data. However, to reasonably simulate the above mentioned multiple-scaled objects, such a mesh is usually very fine because its size is depending on the smallest characteristic size of the objects. If 10m were used as the characteristic size, the size of this rectangle mesh would be 44000 x 32000 = 1.408×10^8. Obviously, most numerical models couldn't afford this huge mesh. Therefore, non-uniform structured mesh should be used to discretize the current large domain.

As can be seen in the current study, the mesh generation difficulties lie in the alignment of mesh lines along irregular multiple-scaled objects. To make it possible, a multi-block scheme (Zhang and Jia, 2009) is adopted to divide the whole domain into multiple blocks. For example, Figure 3 shows a structured mesh that was generated using three blocks. At first, the non-uniform structured meshes with different sizes (or resolutions) are generated block by block, and then all the block-structured meshes were assembled into a final structured mesh for the whole domain. The multi-block scheme is widely used in CFD analysis, such as mesh generation, multi-block computing in complex geometries, and parallel computing combined with domain decomposition (Zhang, 2009).

In this study, 17 blocks were created for this large domain (Figure 4). Each mesh block was defined to regulate and align mesh lines according to the specific generation requirements in that block. Theoretically, the more blocks are created, the more accurately the object will be defined.

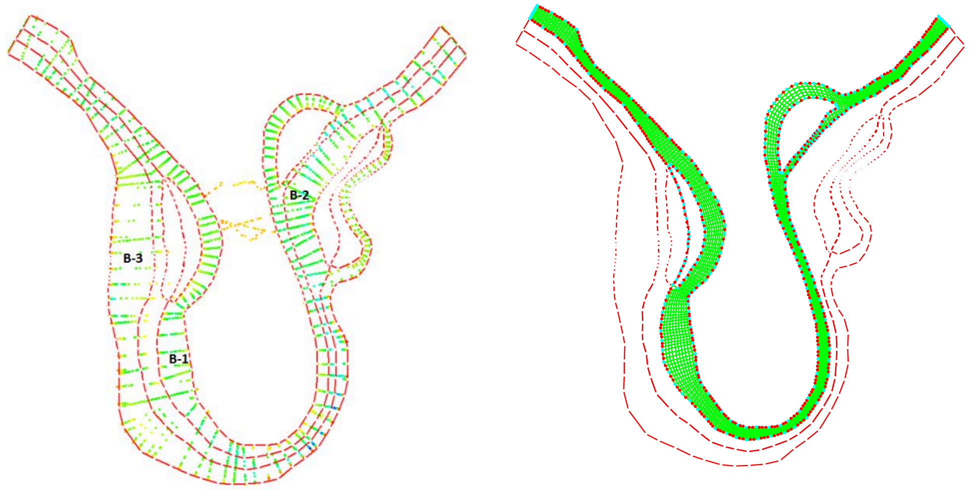
Figure 5 shows the local view of multiple blocks used to force mesh lines conform to the Mississippi River, levees, roads, and structures. As shown, the block boundaries are not exactly following the boundaries of the object. One reason lies in the physical restrictions; some roads or levees intersect each other. Another important reason is to maintain mesh quality. For example, block-1 was used to define the Mississippi River. At sharp turns, the block boundaries deviated from banks of the Mississippi River in order to obtain the smoothed turns so that mesh lines may not be skewed too much. These compromises should be considered in the creations of blocks for the sake of mesh quality.

In Figure 6, four blocks were created to define the meandering Pearl River with many sharp turns which makes it extremely difficult to align the mesh lines along its boundaries. Considering that this meandering river with large curvatures is one object within a large domain, it's impossible to use only one block to define its boundaries so that all mesh lines in it can follow one direction. With four blocks, in some parts of this river mesh lines follow I direction and others follow the J direction, which can significantly alleviate the mesh line distortion problems caused by those sharp turns.

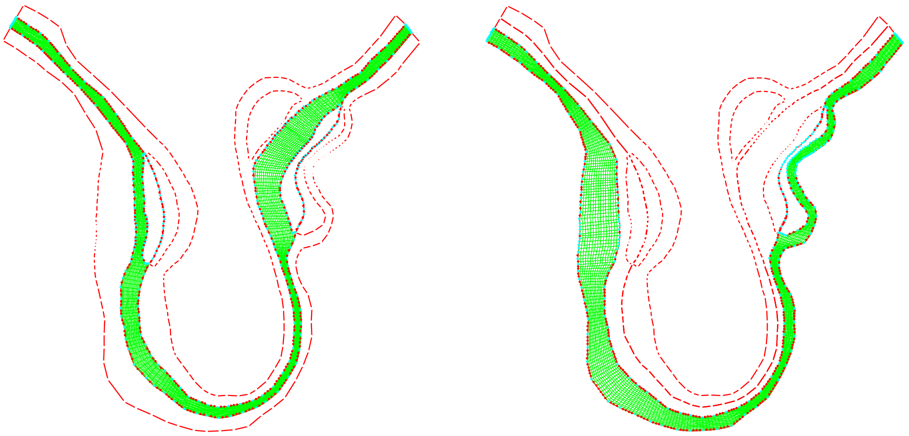
In the current study, block mesh generation is carried out in an ascending order of block levels, so it begins with the main block of the lowest level. Assembling is actually a re-numbering process to make the global indices of mesh nodes in each block satisfy a structured mesh. In this study, to simplify the assembling process, assembling always occurs between two structured meshes at one time, which means assembling can occur either between two neighboring blocks B_l and B_m denoted by $B_l + B_m = B_{l+m}$ or between a assembled mesh and a neighboring block B_n denoted by $B_{l+m} + B_n = B_{l+m+n}$. This assembling process is an iterative process described as follows:

a) The main block mesh with the lowest level is considered the base mesh to start with.
b) Go to the next level.
c) Add neighboring blocks of current level one by one to the existing mesh for assembling.
d) Go to step b until the last level is completed.

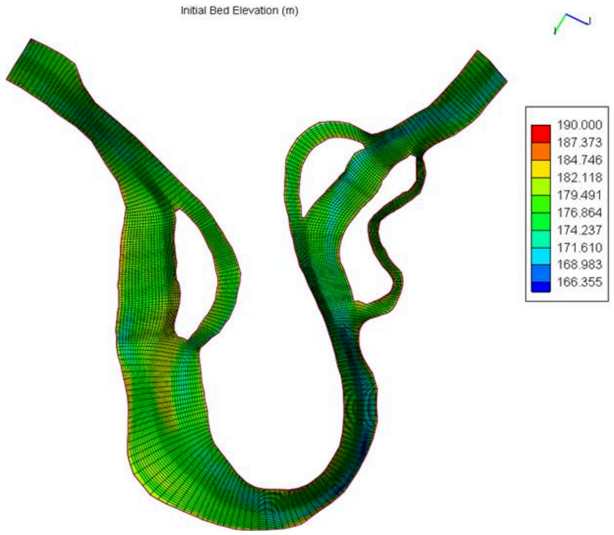
In this way, the assembling of all block meshes can be achieved.



(a)Three blocks (b) Generate mesh in block-1



(c) Generate mesh in block-2 (d) Generate mesh in block-3



(e) Assemble the block meshes

Figure 3 Multi-block Scheme

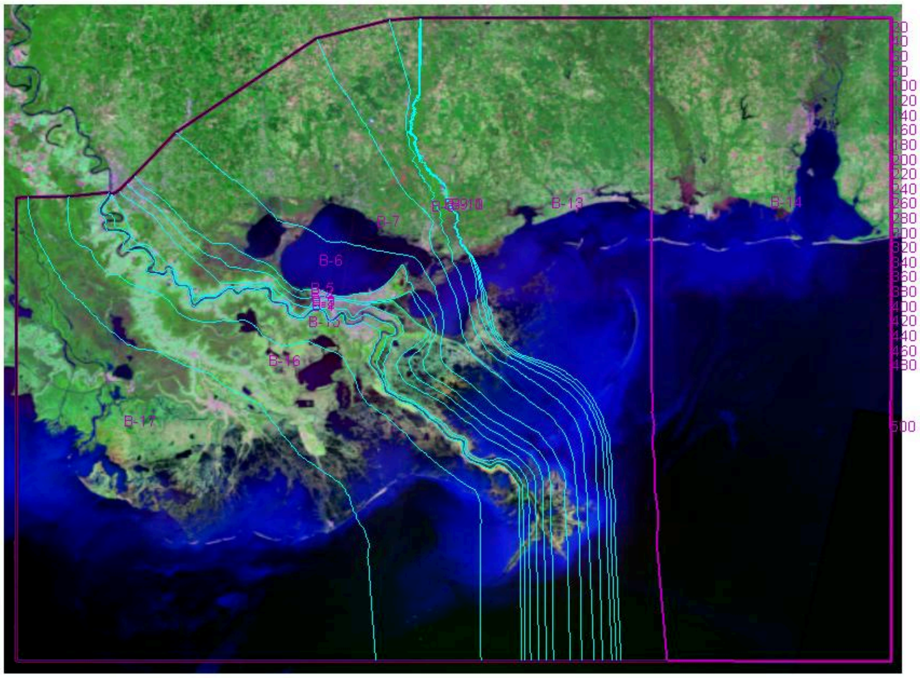


Figure 4 17 Blocks

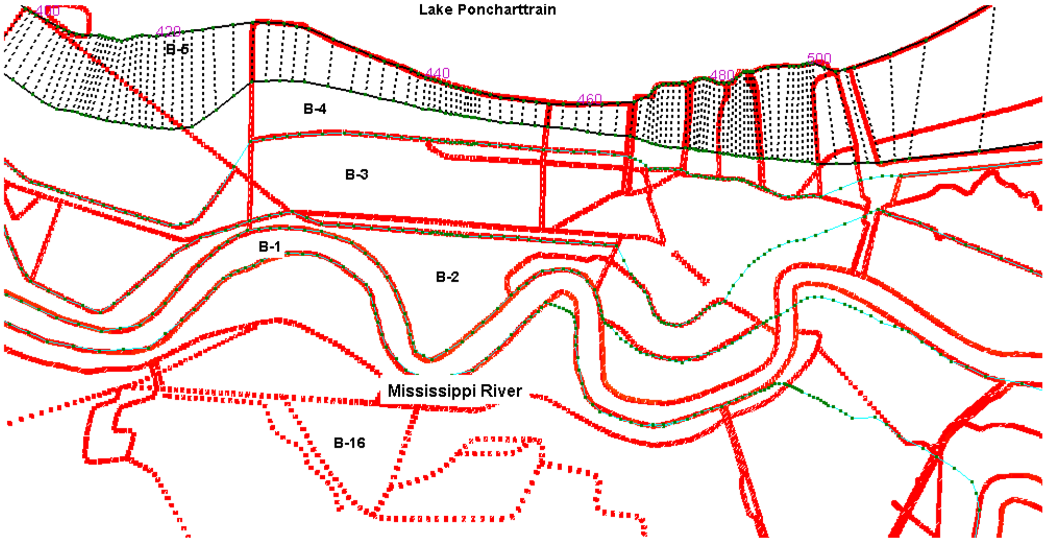


Figure 5 Multiple blocks for Mississippi River, Levees, Roads and Structures

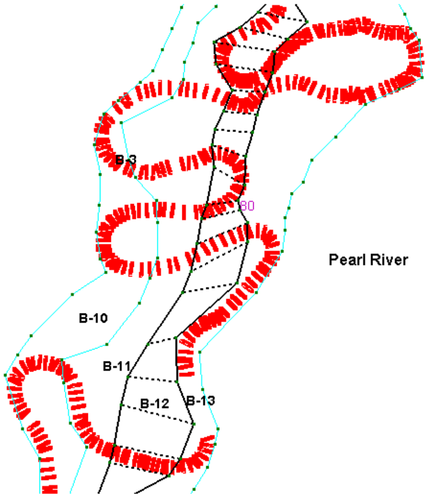


Figure 6 Pearl River Defined by 4 Blocks

4. NUMERICAL MESH GENERATION

After an initial algebraic mesh is generated, a numerical mesh generation method will be applied to smooth the mesh to further improve mesh quality. In this study, an improved RL (Ryskin and Leal, 1983) mesh generation system (Zhang *et al.*, 2006) was adopted to smooth the algebraic mesh due to its good performances in complex geometries.

$$\frac{\partial}{\partial \xi}(h_{\xi}^{\alpha} \cdot f \frac{\partial x}{\partial \xi}) + \frac{\partial}{\partial \eta}(h_{\eta}^{\alpha} \cdot \frac{1}{f} \frac{\partial x}{\partial \eta}) = 0 \tag{1a}$$

$$\frac{\partial}{\partial \xi}(h_{\xi}^{\alpha} \cdot f \frac{\partial y}{\partial \xi}) + \frac{\partial}{\partial \eta}(h_{\eta}^{\alpha} \cdot \frac{1}{f} \frac{\partial y}{\partial \eta}) = 0 \tag{1b}$$

Where $\alpha \in [0, 1]$ is an adjustable empirical parameter.

The generation system defined by Eq. (1) is usually used for nearly orthogonal mesh generation with smoothness controls. In current study, since there are multiple-scaled irregular objects required to be preserved within the domain, mesh smoothness has much more precedence over mesh orthogonality. Eq. (1) will be applied with limitations introduced by weightings to serve this purpose.

$$x_{i,j}^{new} = x_{i,j}^{old} \cdot (1 - w_{i,j}) + x_{i,j}^{p} \cdot w_{i,j} \tag{2a}$$

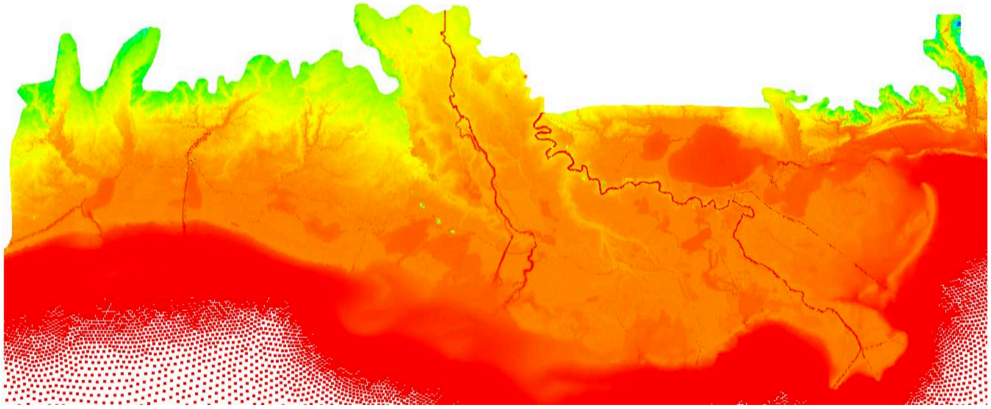
$$y_{i,j}^{new} = y_{i,j}^{old} \cdot (1 - w_{i,j}) + y_{i,j}^{p} \cdot w_{i,j} \tag{2b}$$

Where the superscript "*p*" denotes the coordinates obtained from Eq. (1), and $w_{i,j}$ is the weighting factor for each node.

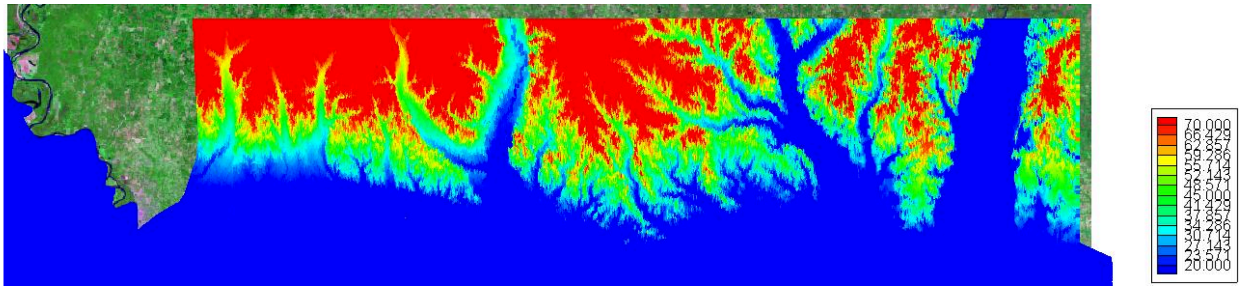
Initially, a zero weighting factor is given for those along boundaries of the preserved objects and a one value is for the other interior nodes. Then a smooth weight factor field was obtained using the Laplacian smoothing technique for the whole domain.

5. BED INTERPOLATION

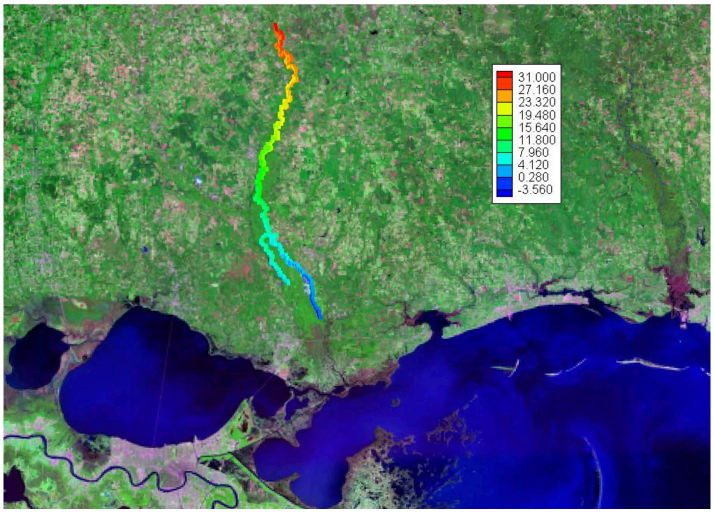
The following topography data were provided for mesh bed interpolation: 1) ADCIRC mesh for 2007 (see Figure 7a); 2) 10 m DEM data (see Figure 7b); and, 3) Channel extension data of both east and west Pearl River (see Figure 7c).



(a) ADCIRC mesh



(b) 10m-DEM



(c) Channel extension for west and east Pearl River

Figure 7 Topography Data

The final mesh is 2103 x 1088 (= 2.288 million nodes) and the cell size varies from around 5m to 2500m. Figures 8 and 9 show the global and local views of the final mesh, respectively.

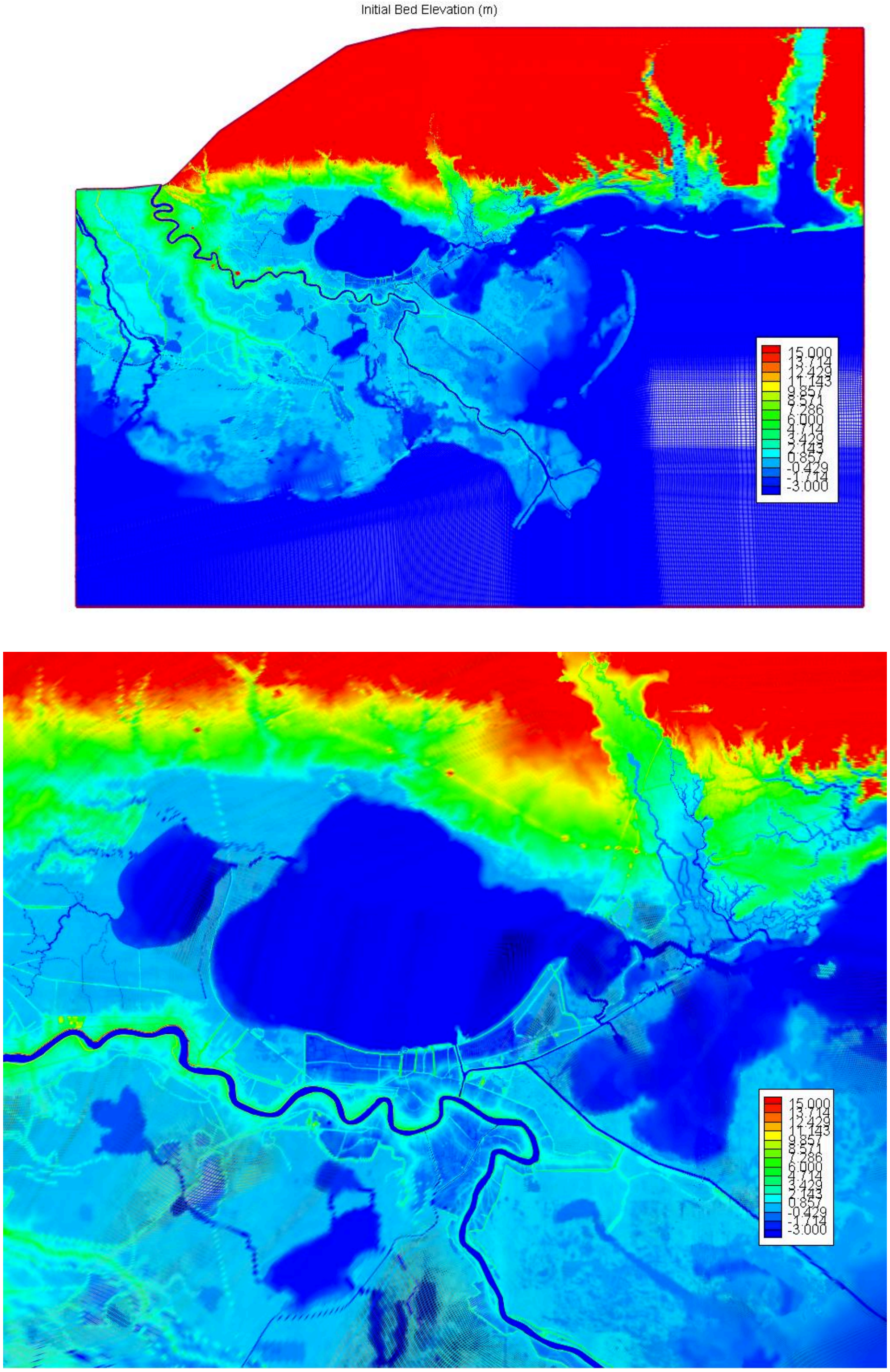


Figure 8 Global View of Final Mesh (MS_Coastal_23mm)

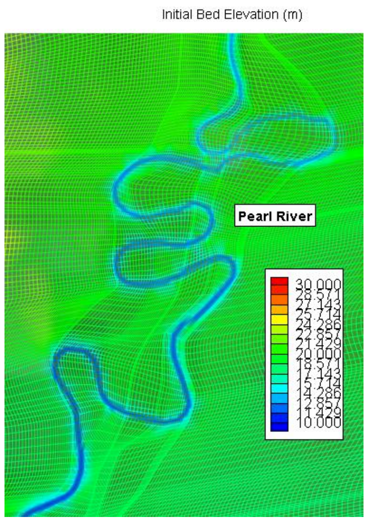


Figure 9 Local View of Final Mesh (MS_Coastal_23mm)

6. NUMERICAL SIMULATION

The CCHE2D-Coast, a 2D coastal process simulation model (Ding *et al.*, 2006 and 2011), was used to simulate the impacts of the storm surges (see Figure 10) on Mississippi coast line.

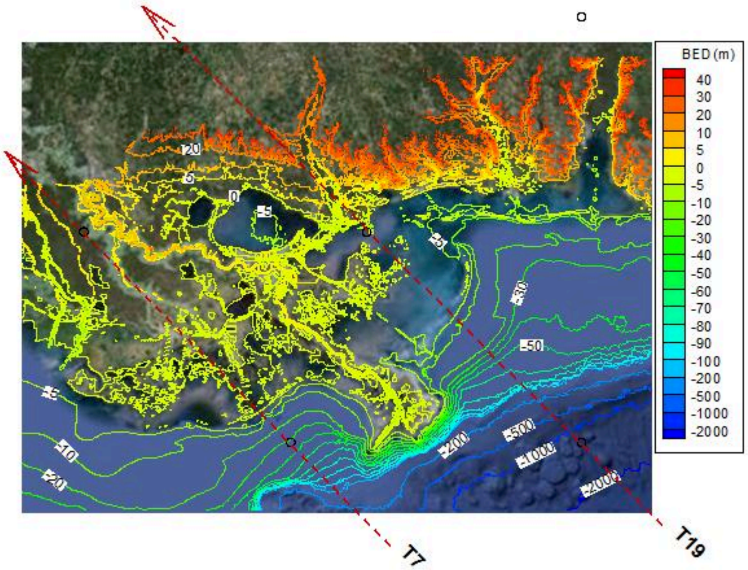


Figure 10 Tracks of Storms T7 and T19

Figures 11 and 12 show the computed maximum water surface elevations induced by storm T7 and T19, respectively.

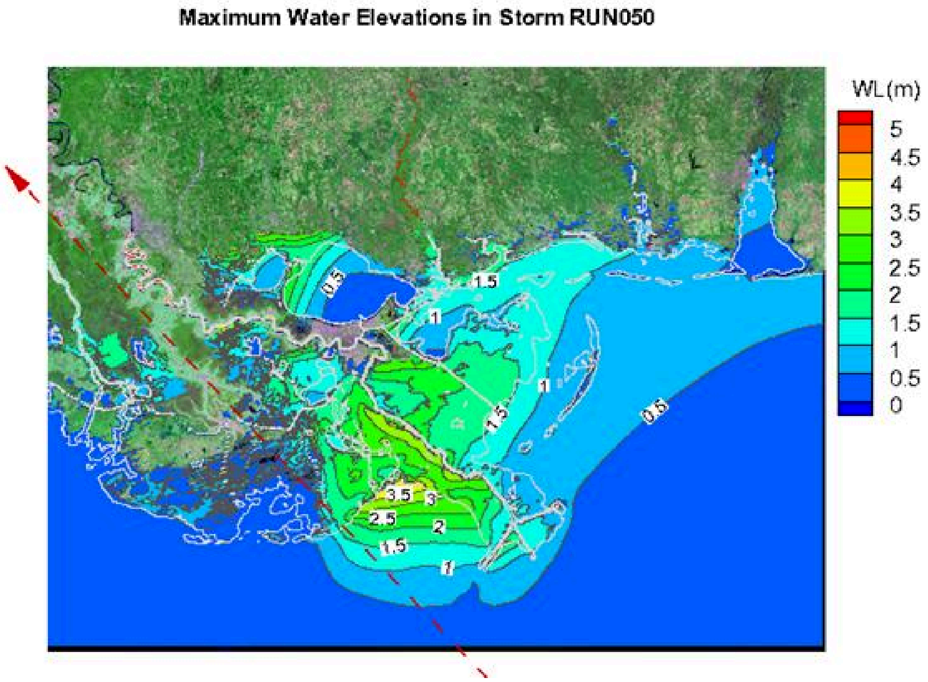


Figure 11 Maximum Water Surface Elevations by Storm T7

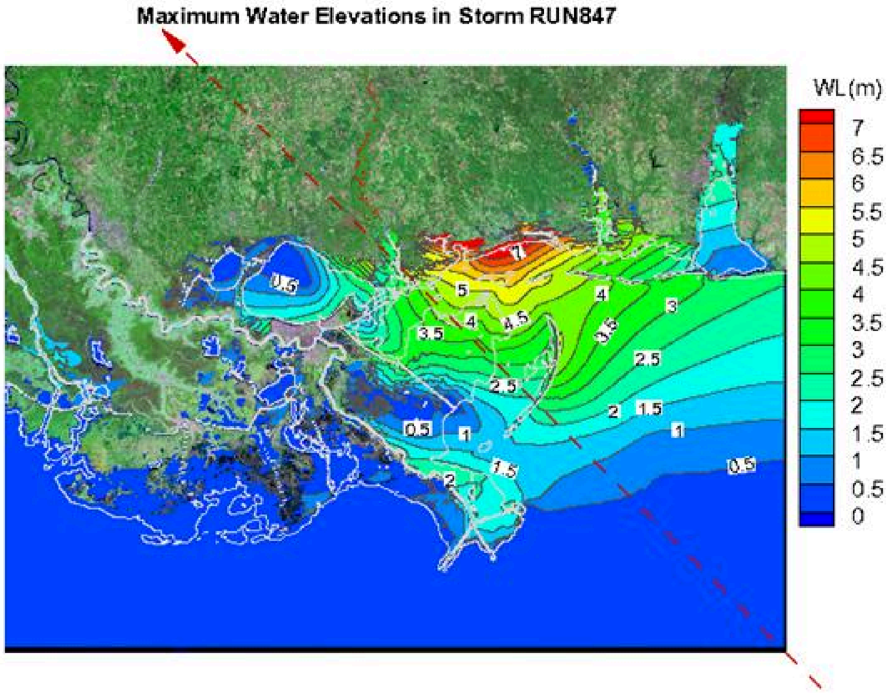


Figure 12 Maximum Water Surface Elevations by Storm T19

7. CONCLUSIONS

In this study, a 2D mesh generator for both quality structured and unstructured meshes, CCHE-MESH was applied to generate structured meshes in a large domain (440km x 320 km) with multiple-scaled objects along the Louisiana-Mississippi coast line for coastal processes simulation.

To generate an initial algebraic mesh, a multi-block method was used to define and preserve the multiple-scaled objects, such as Mississippi River, Pearl River, levees, roads, and structures, in the domain. An improved RL mesh generation system with smoothness controls was used to smooth the algebraic mesh to further improve mesh quality. Numerical simulation results based on the final mesh generated by CCHE-MESH have shown that the mesh quality was satisfactory.

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