Region II Storm Surge Project - Mesh Development

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This document was prepared by:

A JV of Dewberry, URS, and ESP
RAMPP
Risk Assessment, Mapping, and Planning Partners
RAMPP
8401 Arlington Blvd.
Fairfax, VA 22031

FIGURES

APPENDICES

2D	two-dimensional
ADCIRC	ADvanced CIRCulation Model for Oceanic, Coastal and Estuarine Waters
DEM	Digital Elevation Model
ESRI	Environmental Systems Research Institute
FEMA	Federal Emergency Management Agency
GIS	Geographic Information System
ITR	Independent Technical Review
LED	Linear Element Detection
LTEA	Linear Truncation Error Analysis
MSL	Mean Sea Level
m	Meter
NAVD88	North American Vertical Datum of 1988
QA/QC	Quality Assurance/Quality Control
QMP	Quality Management Plan
Risk MAP	Risk Mapping, Assessment, and Planning
RAMPP	Risk Assessment, Mapping and Planning Partners
SWAN	Simulating WAves Nearshore
SMS	Surface Water Modeling System
UnSWAN	Unstructured version of SWAN model
USACE	U.S. Army Corps of Engineers

SECTION ONE INTRODUCTION

The Federal Emergency Management Agency (FEMA) contracted Risk Assessment, Mapping, and Planning Partners (RAMPP), a joint venture of Dewberry, URS, and ESP, under its Risk Mapping, Assessment, and Planning (Risk MAP) program to provide comprehensive floodplain mapping, Geographic Information System (GIS), and hazard risk mitigation services. This report summarizes the methodologies used in the development of a regional storm surge model mesh to support the coastal hazard analysis and Flood Insurance Studies (FIS) in Region II.

For the storm surge modeling effort, a two-dimensional (2D) hydrodynamic storm surge model and 2D wave model were used to model tropical and extratropical storm events. The ADvanced CIRCulation (ADCIRC) computer model and the Unstructured version of Simulating WAves Nearshore (UnSWAN) computer model were used for this study.

The ADCIRC model, which runs on an unstructured, triangulated mesh (sometimes referred to as a grid) that covers a defined spatial extent and allows for detailed representation of narrow flow features and major obstructions. The mesh triangles are called elements, and each element consists of three nodes. The ADCIRC model is sensitive to the mesh design (element size, connectivity, area changes, depths at nodes, etc.), and an ill-designed mesh can cause instability issues.

Recent developments allow for the close integration of two models: the Unstructured version of Simulating Waves Nearshore (UnSWAN) and ADCIRC, which can operate on the same mesh. Because of this capability, the ADCIRC-UnSWAN model was used for the Region II storm surge study. Although the UnSWAN model is not as sensitive to mesh design as the ADCIRC model, some additional constraints on element size along wave breaking zones are required. ADCIRC mesh development can, in some ways, be considered an art and changes are often made to the mesh after model validation begins. Knowing this, the RAMPP study team developed a detailed guidance document and an extensive Quality Assurance/Quality Control (QA/QC) procedure to design a robust ADCIRC mesh with consistent mesh design throughout the domain. This report discusses the mesh development process and the resulting final mesh. Details on the underlying bathymetry and topography data, as well as details on the ADCIRC-UnSWAN model parameters and validation are discussed in the Region II Storm Surge Project - Coastal Terrain Processing Methodology and the Region II Storm Surge Project -Model Calibration and Validation Report (RAMPP, 2014a, 2014b).

SECTION TWO MESH DEVELOPMENT GUIDELINES

Most regional-scale ADCIRC storm surge projects begin the mesh development process with one of the Western North Atlantic Tidal Database ADCIRC meshes: Eastcoast 1995 (Westerink et al., 1994) or Eastcoast 2001 (Mukai et al., 2002). The domain is identical for these two meshes. The boundary extends to the 60-degree west meridian and includes the U.S. Atlantic coast, the Gulf of Mexico, and the Caribbean Sea. The main difference between the meshes is the resolution. The Eastcoast 1995 mesh has approximately 30,000 nodes, while the Eastcoast 2001 mesh has approximately 250,000 nodes. Typically, one of these meshes is selected as the base, and then additional resolution and overland areas are added in the region of interest. This approach was followed to complete FEMA storm surge projects in Mississippi, Louisiana, Texas, Florida, South Carolina, North Carolina, and the FEMA Region III study from North Carolina to New Jersey (including the Chesapeake and Delaware Bays). The RAMPP study team's approach began with the Eastcoast 1995 base mesh, extended the mesh overland, and increased the resolution for the study area along the New Jersey and New York shorelines.

Although high-performance computers are used to run the ADCIRC model, even with ample computing resources it is still a computationally intensive model. Run time is directly tied to the number of nodes in the mesh and minimum size of the elements. With additional nodes come more calculations and longer run times. For model stability, the minimum node spacing must be balanced by a small time step—smaller element sizes in the mesh lead to smaller time steps and longer run times. Therefore, one goal while developing an ADCIRC mesh is to decrease the element size to a number small enough to sufficiently show the major waterways and flow barriers, while keeping the elements as large as possible to decrease run time. To decrease the number of nodes, in areas far offshore, or far from the project area (such as the Caribbean Sea), the node-to-node spacing was increased. The largest elements in the deep ocean are approximately 5 miles wide (approximately 8 kilometers (km)). In the project area, the maximum spacing inland was set at 1,650 feet (approximately 500 meters), and the minimum spacing was set at 260 feet (approximately 80 meters (m)); however, in some limited areas, the smallest node-to-node spacing is 95 feet (approximately 30 meters).

The RAMPP study team worked with the Surface Water Modeling System (SMS) program version 10.1 to build the ADCIRC mesh, because parts of this software are specifically designed for this task. A series of lines, or feature arcs, was created and nodes were distributed along these arcs at a prescribed density. This density could vary along the arcs. The boundaries of the arcs were closed to create a polygon. Using the polygons, the SMS program created additional nodes in the domain interior and triangulated these nodes. A seamless bathymetry and topography dataset was created for this project, and the elevation data were incorporated at the mesh nodes using the SMS program. The bathymetric data were converted to the North American Vertical Datum of 1988 (NAVD88) and combined with the topography for a seamless NAVD88 terrain product. Because the ADCIRC model is run in the Mean Sea Level datum (MSL), the RAMPP study team utilized the National Oceanic and Atmospheric Administration's VDatum program to convert the data in the final mesh from NAVD88 to MSL. Details of this dataset are provided in the Region II Coastal Terrain Processing Methodology report (RAMPP, 2014a).

The ADCIRC mesh was designed by a team of engineers and scientists, each working on different sections of the domain at the same time. To allow multiple mesh developers on the RAMPP study team to work simultaneously, the domain was broken into sections based mainly on county boundaries (with some smaller counties grouped together). For the offshore area between the 0-foot NAVD88 contour and approximately the 500-foot NAVD88 bathymetric contour (i.e., -500-foot NAVD88 contour), the mesh was developed as one section. For areas farther offshore, the mesh resolution was gradually transitioned until it matched that of the Eastcoast 1995 mesh and the two meshes could be merged.

Guidelines were set up to provide consistency in the meshing approach across these sections. These guidelines were broken into two parts: (1) Feature Arc Development, and (2) Polygons and Mesh Generation. During feature arc development, the mesh "shell" is developed with arcs along boundaries, including flow channels and flow barriers. During polygon and mesh generation, the area between the arcs is filled in with nodes and elements, and the bathymetry and topography data are interpolated to the mesh. The sections below describe these two processes in detail.

2.1 FEATURE ARC DEVELOPMENT

Feature arcs were developed along the landward and shoreline boundaries to create sub-domains, which were produced by different mesh developers. Feature arcs were also placed along major flow channels and flow barriers in the interior of these sub-domains. The guidelines for each of these feature arc types are described below.

2.1.1 Interior Boundary

The inland extent of the ADCIRC mesh was developed from the 25-foot NAVD88 contour taken from a 2-meter Digital Elevation Model (DEM). The RAMPP study team aimed for a node distribution of 1,650 feet along this line in areas that are far inland and where: 1) it was less likely that the surge would reach the location, and 2) the area was not in close proximity to a waterway (river or stream) or the shoreline. This coarse spacing of the nodes along the feature arcs reshaped the boundary and created sharp angles. The mesh developers smoothed these boundaries through manual adjustment where necessary after redistributing the nodes to prevent mesh quality issues.

When the interior boundary was near the shoreline, the node spacing for the shoreline was mimicked in the interior boundary. In cases where the boundary was less than one element width away from the shoreline, as shown in Figure 1, the boundary was adjusted to allow for at least two elements between the shoreline and the inland boundary. Figure 2 shows how the shape of the interior boundary was adjusted to allow at least two elements between the shoreline and the interior boundary.

Figure 1. Example of interior boundary close to shoreline

Figure 2. Example of edited interior boundary close to shoreline

When the interior boundary arc was adjusted to a coarse spacing of 1,650 feet, the new boundary cut off some streams and valleys that were less than the 25-foot NAVD88 contour. This was acceptable only if the areas being cut off were less than 250 feet wide (the approximate minimum node spacing). If these areas were wider than 250 feet, the boundary was adjusted to include these areas, and therefore some areas above the 25-foot NAVD88 contour were included in the mesh.

2.1.2 Interior Islands

Interior islands that were surrounded by an area below the 25-foot NAVD88 contour were defined as localized hills. These areas were included in the mesh if they were less than 5,000 feet in length and would add fewer than 1,000 nodes to the mesh. If the islands were longer or would create more mesh nodes, they were excluded from the mesh. An example of two interior islands (highlighted with yellow arrows) less than 5,000 feet in length that were included in the mesh is shown in Figure 3.

In cases where an interior peninsula was created, similar guidelines were applied. If the peninsula was less than 5,000 feet in length and would add fewer than 1,000 nodes to the mesh, then it was included.

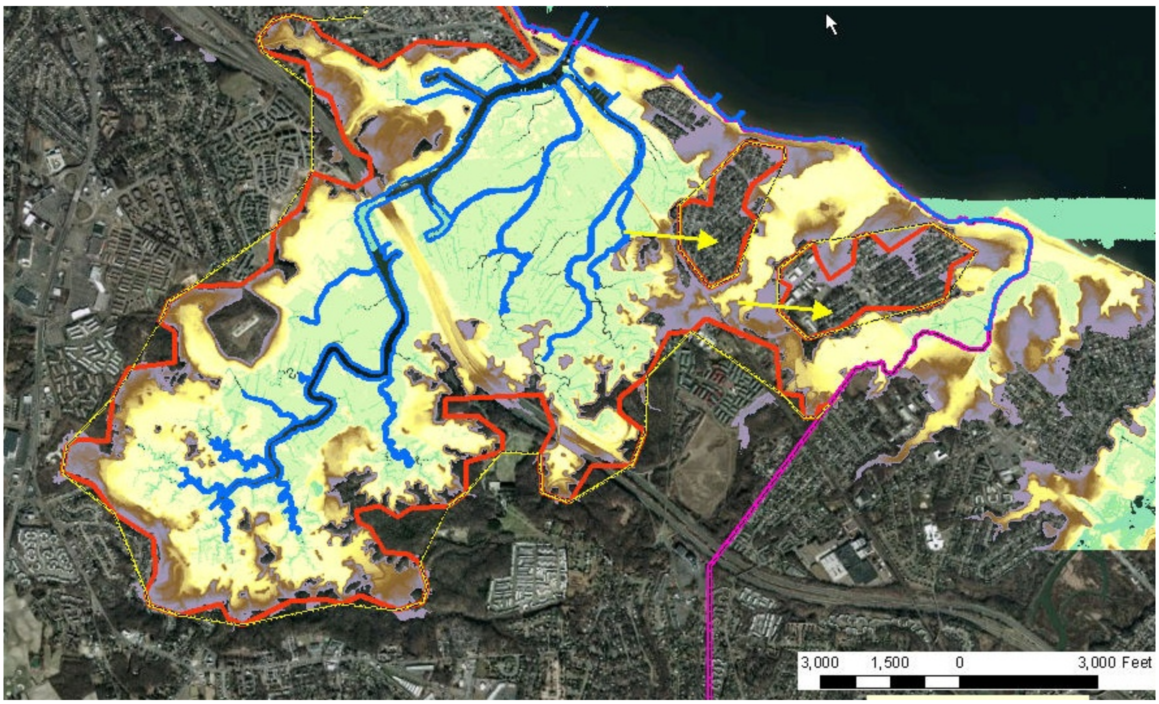


Figure 3. Example of interior "islands" that are less than 5,000 feet long and should be included in the mesh

2.1.3 Shoreline or Ocean Boundary

Shoreline arcs were placed to best represent features to be modeled in the project area. The node spacing along the ocean boundary varied depending on several factors. For straight, simple shorelines the spacing was set at approximately 650 feet. For complex, irregular shorelines the spacing was decreased to between 325 and 500 feet as necessary to capture changes in shoreline features. For shorelines in urban areas, the nodes were spaced approximately 325 feet apart. For areas where wave setup effects were anticipated (i.e., dunes, levees, breakwaters, seawalls, and other locations with steep slopes), the shoreline spacing was reduced to the minimum node spacing of 260 feet.

Rivers, lakes, marshes, and other water bodies landward of the ocean shoreline were included in the overland sections of the mesh development. To include these areas, the mesh developer closed the inlets with a string of nodes connecting the land where the inlet entered. An example is shown in Figure 4.

Figure 4. Inlet with closed boundary highlighted with the red arrow

Features that were too small (i.e., less than 260 feet wide) to be explicitly captured in the mesh were removed from the shoreline file, as shown in Figure 5. Treatment of narrow streams and channels is further discussed in Section 2.1.7.1.

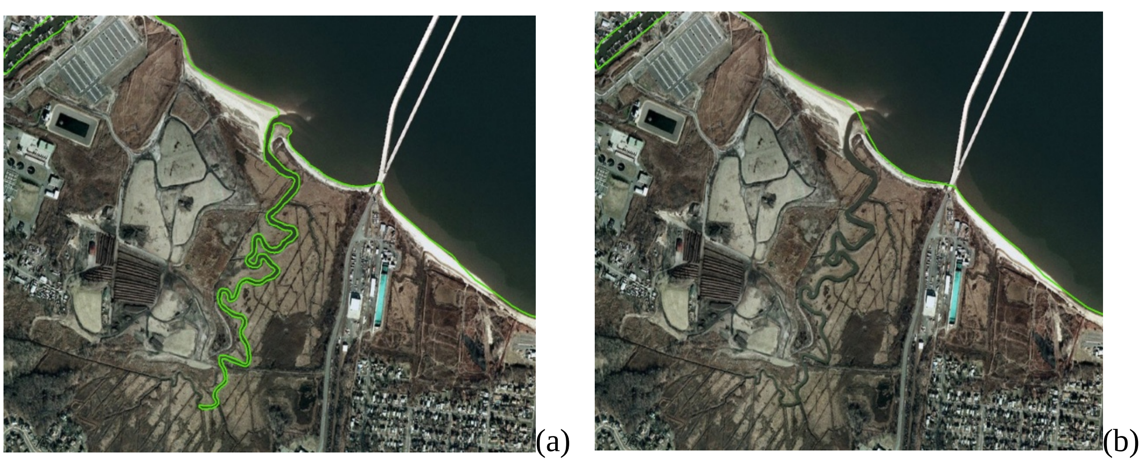


Figure 5. (a) Shoreline in green representing a narrow stream and (b) final shoreline with narrow stream removed

2.1.4 Slope Change Line

The UnSWAN model requires more detailed mesh resolution over the surf zone than the ADCIRC model. Because the models used the same mesh, the resolution of the joint mesh needed to be increased in the areas where wave breaking was expected to account for the

UnSWAN model needs. The RAMPP study team identified an area along the shoreline that followed the slope change along the coast. Along this slope change line, the resolution was set to the minimum node spacing of 260 feet to ensure consistent mesh spacing along this line and just offshore, which is adequate for the UnSWAN model. An example of the slope change line in Cape May County is shown in Figure 6.

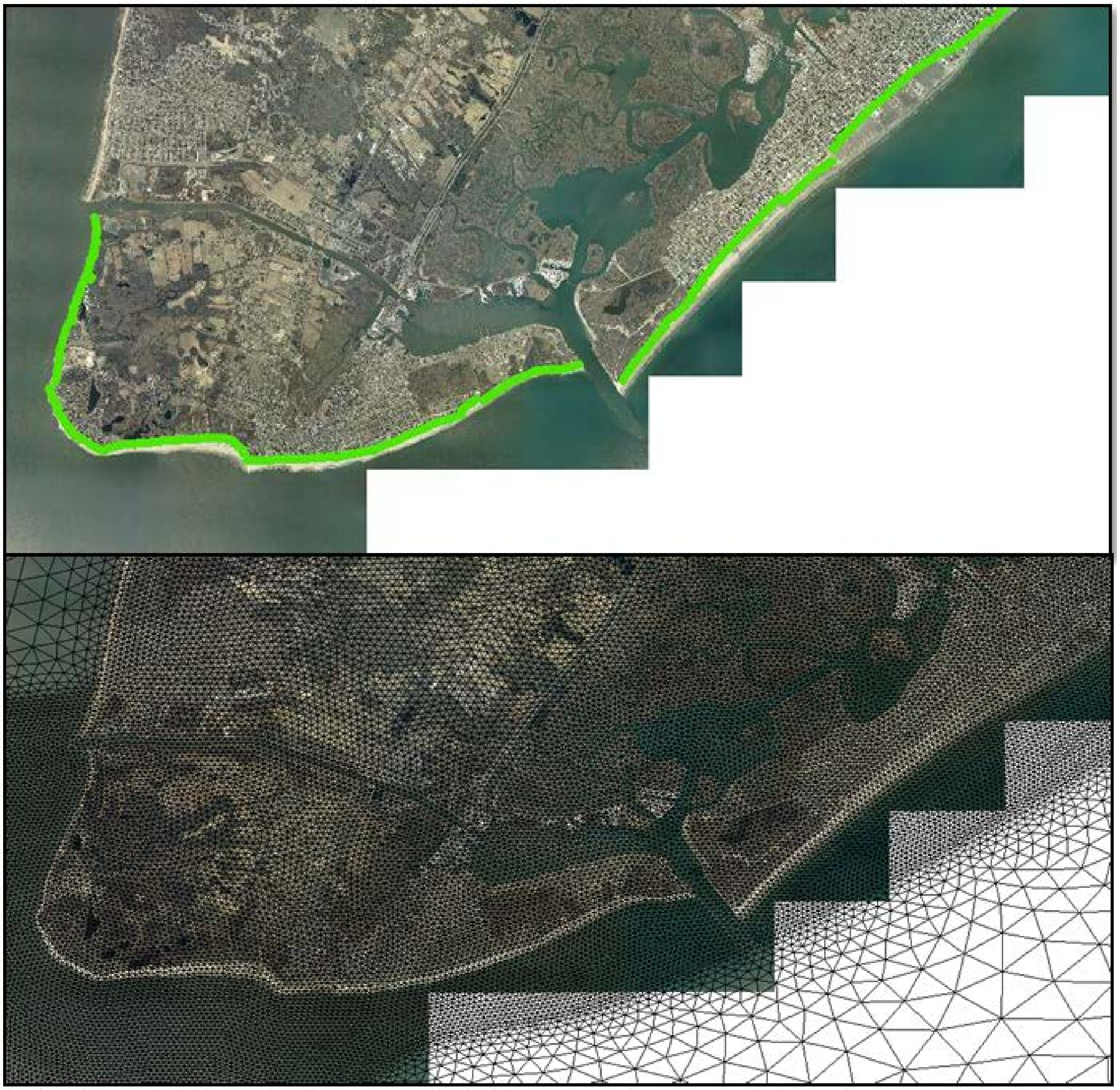


Figure 6. Slope change line (shown in green in upper panel) as delineated along the southern coast of Cape May County, NJ, and the resultant mesh resolution (shown in lower panel)

2.1.5 Jetties

Jetties were modeled with a single string of nodes across the structure's highest elevation. The node spacing was set to the same spacing as the shoreline near the jetty, which ranged from 260 to 500 feet. Figures 7 and 8 show a sample mesh section. In Figure 7, the jetty is not included (meaning nodes were not aligned down the centerline of the jetty). Figure 8 demonstrates how jetties were modeled by the RAMPP study team for inclusion in the mesh; the jetty is depicted with a single line of nodes along the peak of the structure.

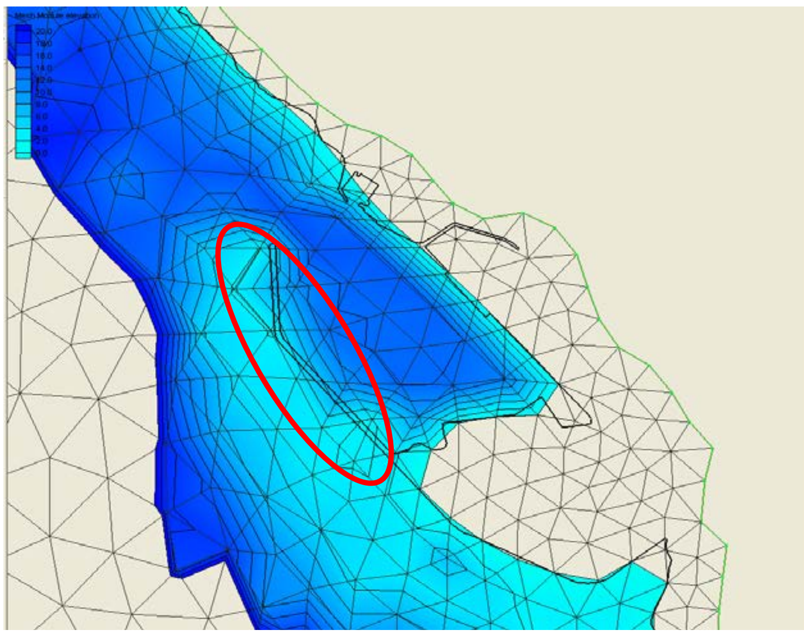


Figure 7. Sample mesh with bathymetry data (blue) and shoreline (black) with jetty ignored in the mesh

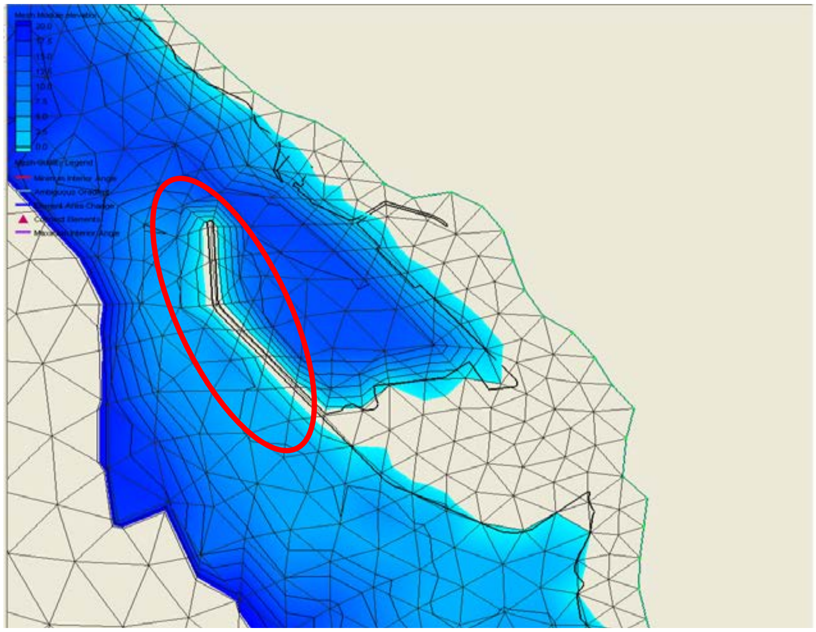


Figure 8. Sample mesh with bathymetry (blue) and shoreline (black) with jetty modeled by a single line of nodes down the center of the structure

2.1.6 Piers and Pilings

Piers on pilings were not included in the mesh as topographic features; these features were included in the mesh as bathymetry. The mesh developer consulted field reconnaissance notes and checked software and online mapping programs that show 3-dimensional views to confirm the status of the piers.

2.1.7 Rivers and Streams

The tightest node spacing (approximately 260 feet) occurred along rivers and inlets. Mesh developers sometimes refer to nodes having an elevation below the 0-foot contour of the selected datum as “wet” nodes, and nodes above this elevation as “dry” nodes. This document follows that convention. For rivers, the goal was to have at least three wet nodes across the stream and two dry nodes on the stream bank. Figure 9 shows a cross section of the ideal scenario. In this figure, the nodes are shown as red dots, and the blue line indicates the water level in a cross-section view of a river. (Elements are not shown in this view.) With a node spacing of 260 feet, the minimum width of the river is approximately 1,000 feet.

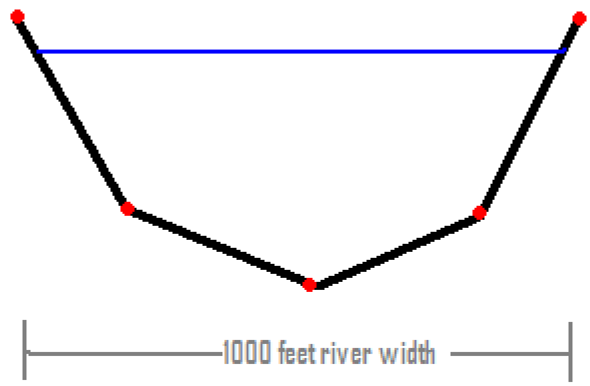


Figure 9. Simplified river cross section with three wet nodes and two dry nodes

Many rivers in the region were smaller than this and could be represented with only two wet nodes. Figure 10 shows a simplified cross section of this scenario. With the node spacing at 260 feet, the minimum width of the river is approximately 750 feet.

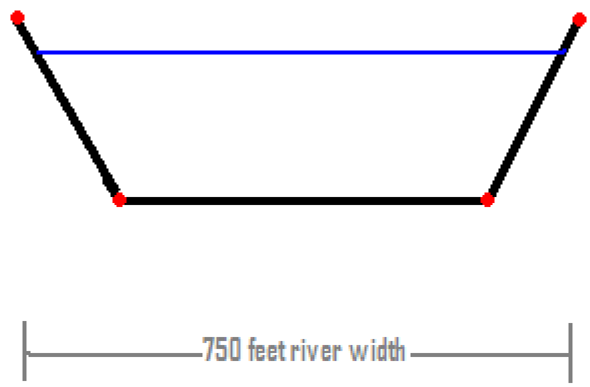


Figure 10. Simplified river cross section with two wet nodes and two dry nodes

For areas similar to the examples shown above, the mesh developer worked with the feature arcs to redistribute the nodes along the shoreline. For rivers approximately 500 feet wide, the river can be represented with three wet nodes across the width of the river. However, because the dry nodes in the cross section were not placed directly on the bank, depending on the floodplain and bank slopes, the wet area may be distorted. Figure 11 shows a simplified original profile and the modified profile created when nodes are not placed directly on the banks.

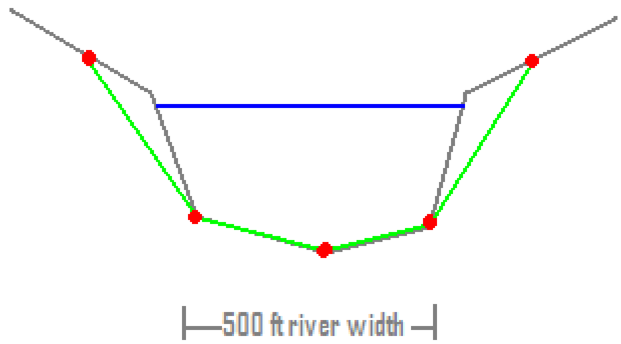


Figure 11. Simplified original topography in gray and modified topography based on node placement in green, with a three-wet-node-wide channel

A similar profile could be created with only two wet nodes across the width of the river, as shown in Figure 12. This increased the distortion, but allowed rivers as narrow as approximately 250 feet wide to be represented in the mesh.

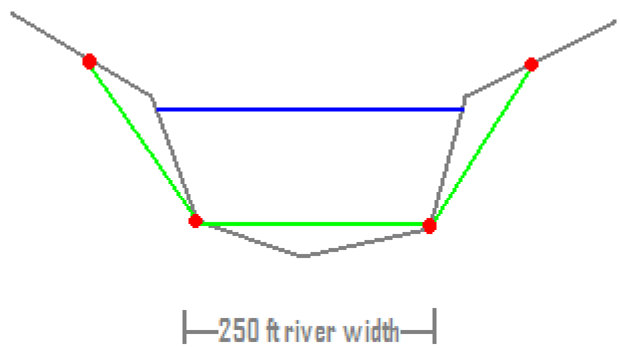


Figure 12. Simplified original topography in gray and modified topography based on node placement in green, with a two-wet-node-wide channel

For most streams, a string of nodes was not placed along the shoreline. Instead the feature arcs were placed in the river. In the case of a three-node-wide channel, one string of nodes was placed down the stream centerline. In the case of the two-node-wide channel, there were a few options. The first option was to use two feature arcs placed on either side of the stream centerline (Figure 13). Sometimes when the mesh was generated in SMS, an extra node (and element) was placed between the arcs, requiring manual removal of the extra nodes. As discussed in the Polygons and Mesh Generation section (Section 2.2), using the patch technique could eliminate these issues. Another option was to place a feature arc on only one side of the river (Figure 14). When the mesh is generated using this option, the other line of nodes is automatically created at a distance equal to the node spacing along the feature arc. This sometimes necessitates manual manipulation to keep the other line of nodes inside the river banks.

Figure 13. Sample narrow river with two feature arcs with nodes down either side of the channel

Figure 14. Alternative solution for a narrow stream with only one feature arc, with nodes placed on one side of the river

Because moving the nodes off the banks can distort the topography, it is not recommended for densely populated areas. This approach is more appropriate for marshes or floodplains that contain few if any nearby buildings and where the vertical differences are small.

Figure 15 is a schematic drawing of a tapering water body. The schematic on the left is a map view, and corresponding elevation cross sections are shown on the right. The cases are labeled and identified in the left column.

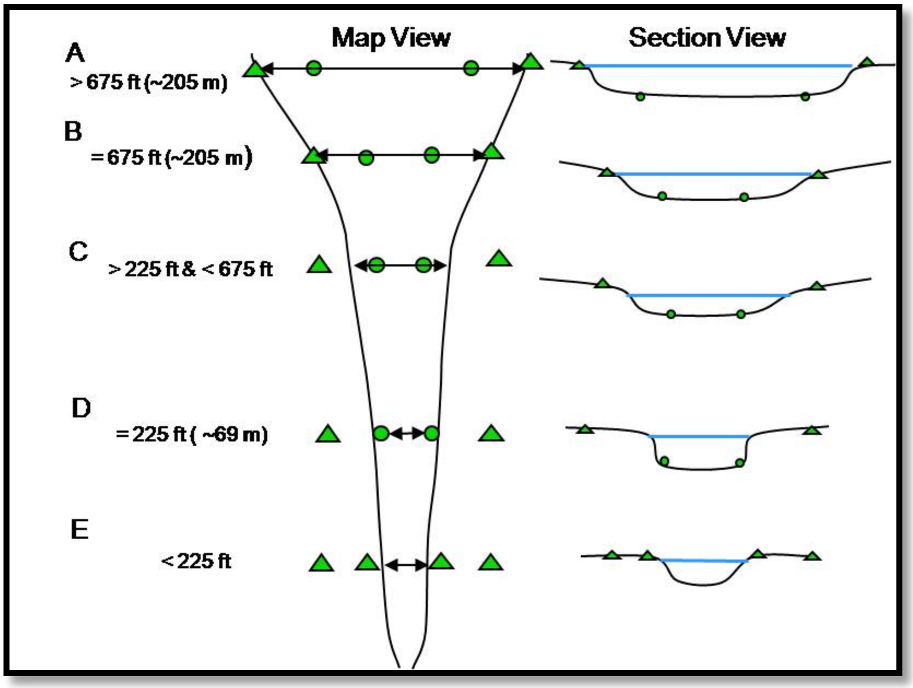


Figure 15. Schematic of a tapering water body where mesh nodes on banks are shown with triangles and those below water surface are shown with circles

In Case A, the water body is wide enough to allow the use of large elements along the center of the water body. For wide water bodies, multiple nodes were placed across the underwater area.

In Case B, the water body is the right width to fit the two wet nodes using the acceptable minimum node spacing.

In Case C, the two nodes on the banks were pushed out so that the water body looks wider in the mesh than in map view.

In Case D, the river is only 225 feet wide, but it can still be modeled. In this case, two feature arcs were drawn on either side of the channel, as close to the bank as possible while still remaining in the water. The elevations for the nodes along these feature arcs were manually lowered to match the elevation of the nearest bathymetry data. These nodes were then connected by lines to create the elements (automatically using the SMS program). Although the node spacing along the feature arc was set to 260 feet, the nodes down the other arc were shifted in order to manipulate the horizontal distance down to 225 feet. Figure 16 illustrates how this node configuration can support node-to-node spacing along the side of the element of 260 feet while keeping the channel width (shown as length “x” in the figure) at only 225 feet.

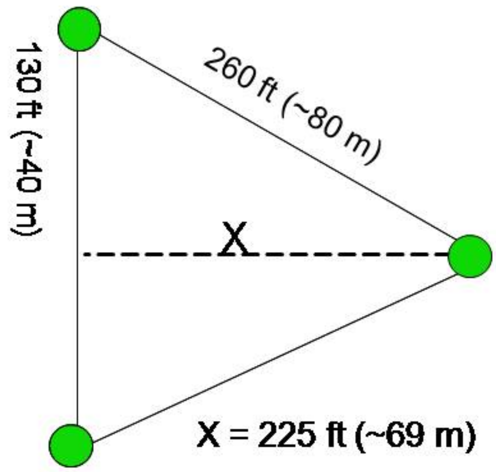


Figure 16. Equilateral element configuration to allow cross-river node spacing of 225 feet

For water bodies narrower than 225 feet, such as that shown in Figure 15 - Case E, no attempt was made to represent the channel. Because the water body is narrower than 225 feet, the feature arcs were drawn on the banks so that no mesh node would fall within the water body.

2.1.7.1 Narrow Streams

In cases where the stream channel was less than 225 feet wide, placing a wet node down the center of the stream would result in an element configuration resembling a "v," which is known to cause stability problems in the ADCIRC model. The RAMPP study team mesh developers did not use a v-notch channel with only one wet node in the cross-section profile, as shown in Figure 17.

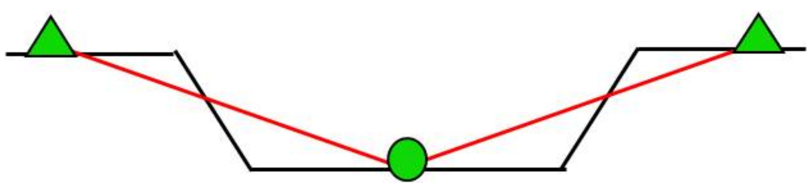


Figure 17. "V-notch" configuration with one wet node (circle) and two dry nodes (triangles)

To avoid the v-notch configuration, a special layout of the mesh elements was needed. Feature arcs were used to create a chain of elements with nodes on either side of the channel. Figure 18 shows a chain for gently curving channels and Figure 19 shows meandering channels. (The narrow channel is illustrated with a dark blue line in these figures.) Two feature arcs were placed down either side of the channel, and each of the three nodes of a triangular element was placed in the floodplain in areas with similar elevations.

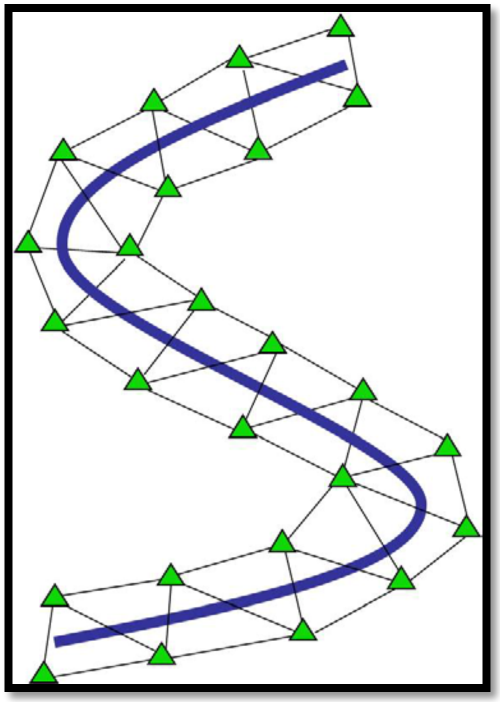


Figure 18. Chain of elements covering a gently curving channel

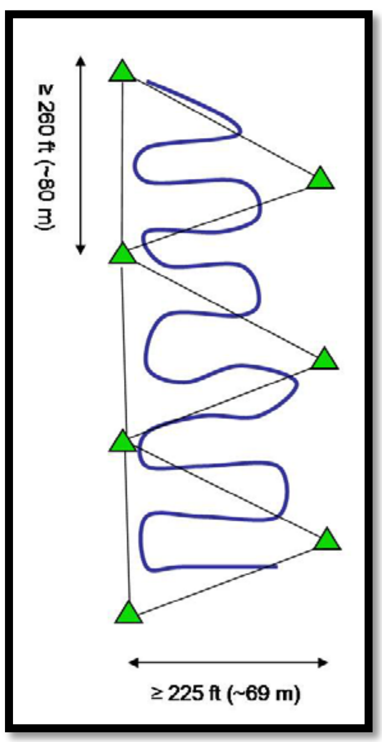


Figure 19. Chain of elements covering a meandering channel

In areas where stream widths changed so that consistent node spacing could not accomplish the desired result, the mesh developers varied node spacing along the feature arcs as shown in Figure 20.

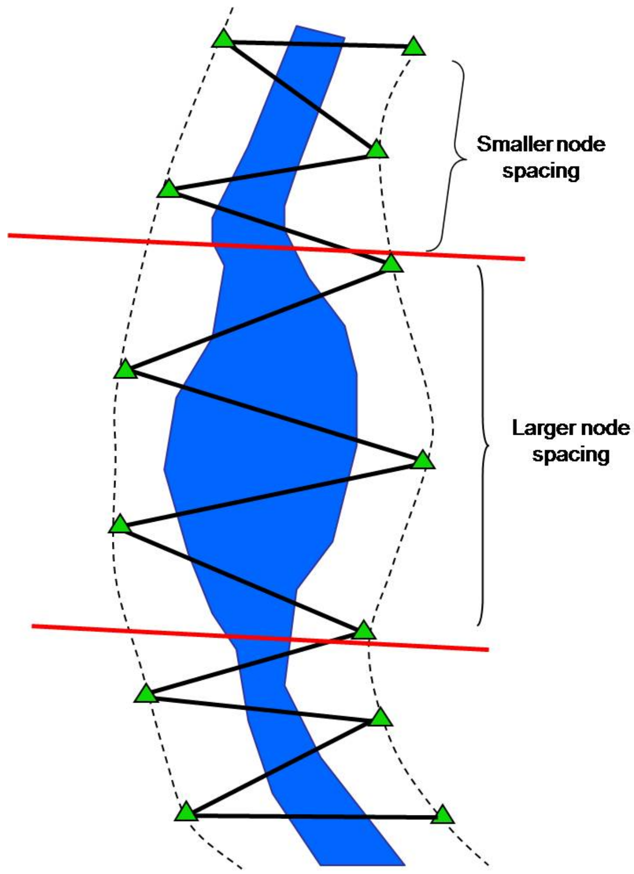
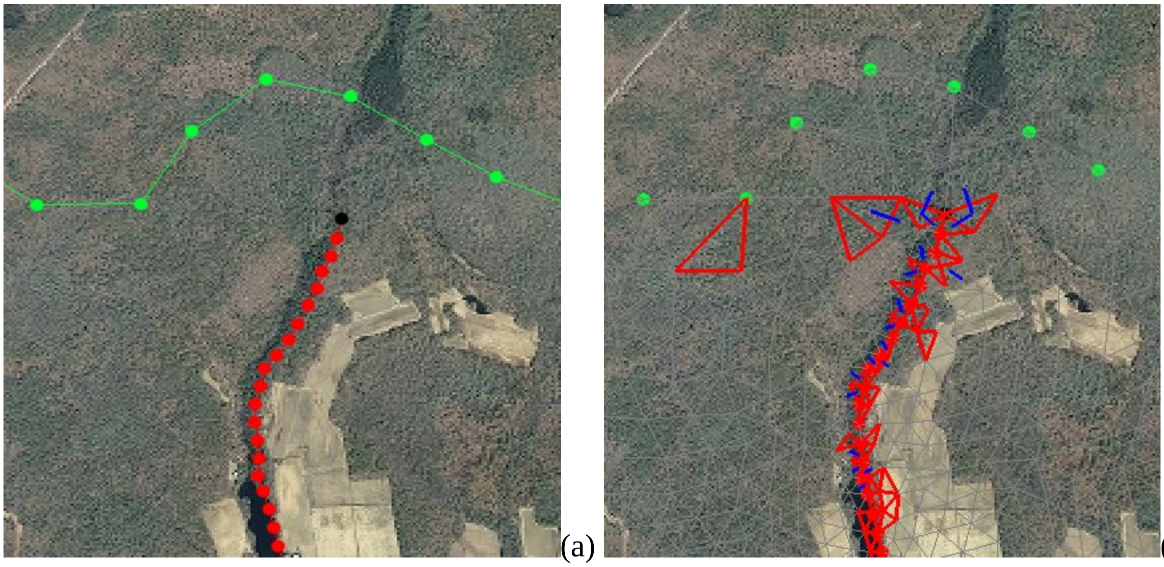


Figure 20. Varying node spacing of a feature arc to adjust for varying stream width

For small creeks (less than 225 feet wide) connected to wider upland streams that should be represented in the mesh, the narrow channel was artificially widened. In these instances, care was taken to ensure hydraulic connectivity, and depths were adjusted to best represent the channel conveyance.

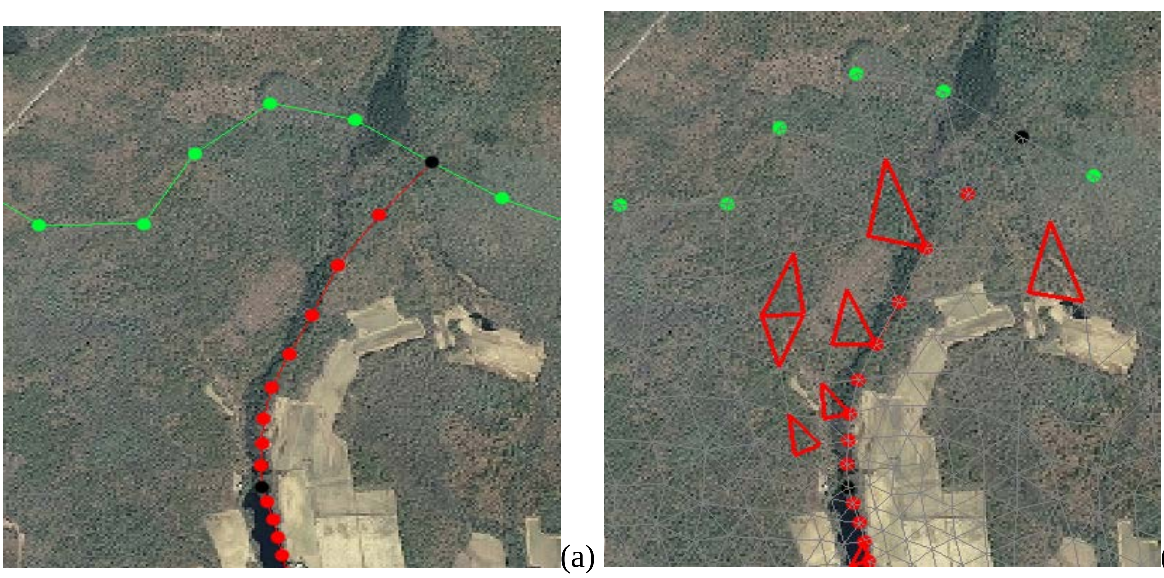
2.1.7.2 Connection of Upland Rivers to the Inland Boundary

In areas where river boundaries intersected or ended near the inland boundary, a discrepancy in the boundary spacing sometimes occurred. In some instances, where the upland boundary was very near the coastline, the inland boundary spacing was dense (following the guidance for the shoreline boundary as discussed in section 2.1.3) and matched the desired spacing along the river arc. If the inland boundary was far from the ocean boundary and the spacing had been set near the maximum of 1,640 feet, the node spacing along an intersecting river arc would differ greatly from the node spacing along the inland boundary. Although not all feature arcs had to be connected, it was necessary in some cases to connect the arcs to ensure a stable mesh transition from one resolution level to another. Figure 21 (a) shows a dense riverine feature arc ending near a coarsely spaced boundary feature arc. There is not enough space for a smooth transition from the dense spacing along the river boundary to the coarse spacing at the inland boundary. The resulting mesh shown in Figure 21 (b) has many mesh problems, as signaled by red triangles (indicating interior angle problems) and blue lines (indicating element area problems). The solution involved extending the river feature arc to meet the inland boundary and redistributing the nodes with a spacing that transitions from dense to coarse, as shown in Figure 22 (a). The resulting mesh still needs refining (as indicated by the red triangles), but the area change problems were eliminated (as indicated by the lack of blue lines) as shown in Figure 22 (b).



(a) (b)

Figure 21. (a) Sample arcs and (b) resulting mesh with no connection or transition between node spacing



(a) (b)

Figure 22. (a) Sample arcs and (b) resulting mesh with connection and transition

To determine when to begin transitioning the node spacing along the river feature arc to the node spacing along the interior boundary, the mesh developer used the 15-foot NAVD88 contour as a guideline. In Figure 23, the same area is shown with the 15-foot NAVD88 contour marked with a red arrow. Beginning there, the node spacing along the river arc was transitioned to match the inland boundary node spacing.

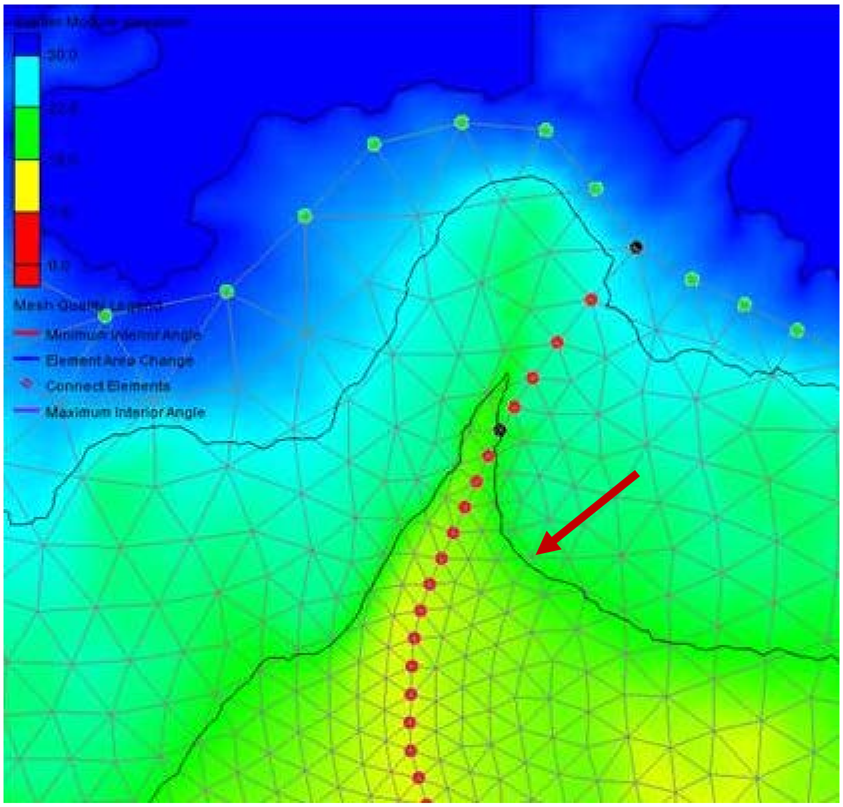


Figure 23. Area showing transition from recommended riverine spacing to recommended inland boundary spacing along the riverine feature arc; 15-foot NAVD88 contour marked by an arrow

2.1.8 Upland Valleys

Many of the upland valleys were broad and needed no special consideration, because normal mesh development methods would facilitate appropriate representation in the final mesh. However, a few relatively narrow valleys with relatively steep sided slopes do exist in the study area. Valleys with widths of 1,000 feet or less were treated the same way as narrow water bodies (discussed in Section 2.1.7.1), except that the submerged areas shown in Figure 18 would represent the valley floor. An example of a narrow valley (about 1,000 feet wide) is shown in Figure 24.

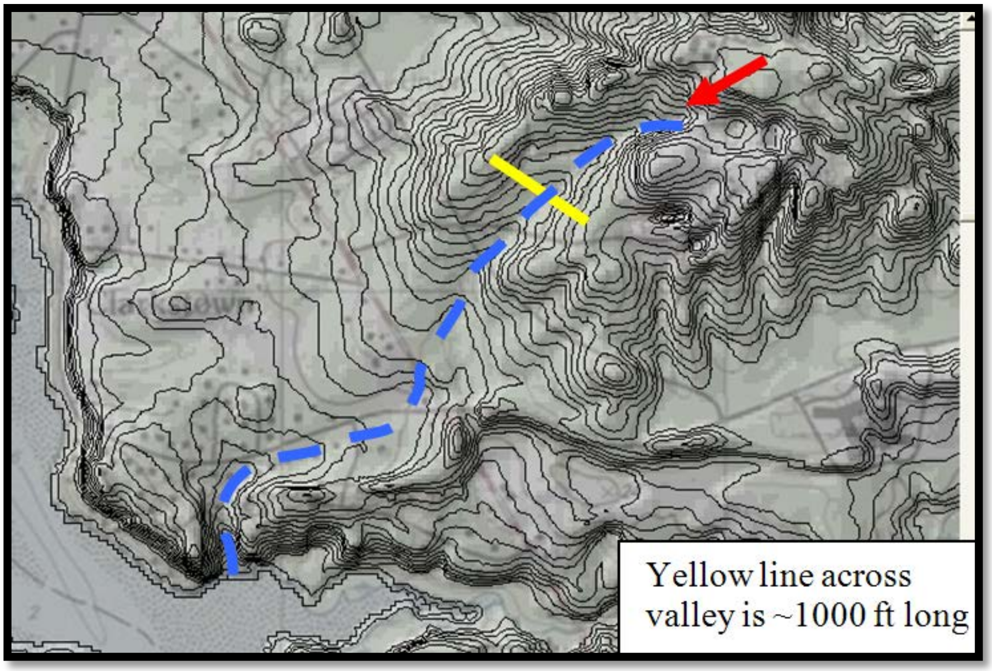


Figure 24. Example of an upland valley area

2.1.9 Marshes

Marshes are generally flat areas that flood during high tide. Often many narrow channels course through the marshes that were too detailed to be captured by the minimum resolution used for this project. Instead of modeling the channels explicitly (i.e., creating two to three wet nodes across the channel), the centerlines of major streams were followed with a single feature arc. This created a v-notch channel (as discussed in section 2.1.7.1), but because the surrounding elevation was close to the high tide elevation, the v-notch channel and surrounding marsh remained wet throughout a storm surge run and did not cause model instability. The node spacing throughout the marsh was set to the range of 500 to 650 feet.

2.1.10 Islands

2.1.10.1 Offshore Islands

For ocean boundaries that were part of an offshore island or peninsula, the node spacing depended on the width of the island. The goal was to have at least three dry mesh nodes across the width (i.e., one node at the ocean boundary, one on the interior, and one at the bay side of the island). The mesh developer aimed for 500- to 650-foot spacing (which was possible if the island was 1,000 to 1,300 feet wide). Three nodes were placed with a minimum spacing of 260 feet on a 500-foot-wide island. If the island was narrower, the mesh developer attempted to place two nodes across the island; one on the ocean side and one on the back-bay side. If the island was even narrower, a row of nodes was placed along the highest point of the island. An idealized island with ideal mesh node spacing is shown in Figure 25.

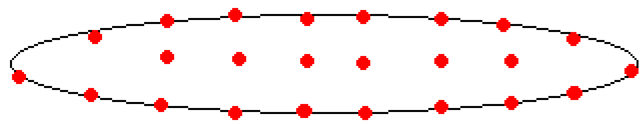


Figure 25. Simplified island (black) with mesh nodes (red)

2.1.10.2 Islands in Rivers

If islands existed in the middle of river channels, several factors were examined. The mesh developers viewed the islands and nearshore areas in aerial photographs to spot buildings and other development. Preference was given to representing populated areas in the mesh. Another factor was the width of the river channel. Per the guidelines given in Section 2.1.7 for rivers and streams, any channel narrower than 225 feet was ignored, and the island was treated as an extension of the land (Figure 26). For streams wider than 225 feet, preference was given to modeling a stream with at least two wet mesh nodes. Also, the topographic elevation of the island was considered. If the elevation of the island was within a few feet of the 0-foot NAVD88 contour, capturing the island in the mesh was less important, because any amount of storm surge would likely overtop it. Some examples and specific guidance are given below.

Figure 26 shows an area where the channels between the islands and the mainland are narrower than 225 feet, and the shoreline feature arc was extended around the islands. The channels were not represented because they were smaller than the minimum element size. Additional feature arcs were used along the channel edge to ensure that mesh nodes fell within the channel, just as occurred for streams narrower than 225 feet.

Figure 26. Islands included as mainland without channels

Figure 27 shows an example where the main channel to the left of the island is approximately 700 feet wide, and the smaller channel to the right of the island is only 300 feet wide. Since both channels are wider than 225 feet, they were both included using the guidelines for rivers and streams explained in Section 2.1.7.

Figure 27. Sample area with unpopulated island dividing the river channel

In some cases, such as the one shown in Figure 28, the channels indicated by red arrows are close to 225 feet wide. In this example, it is clear that the channels provide an important flow path and must be included in the model. Feature arcs were placed along the island and shoreline to allow the channel to be captured in the mesh.

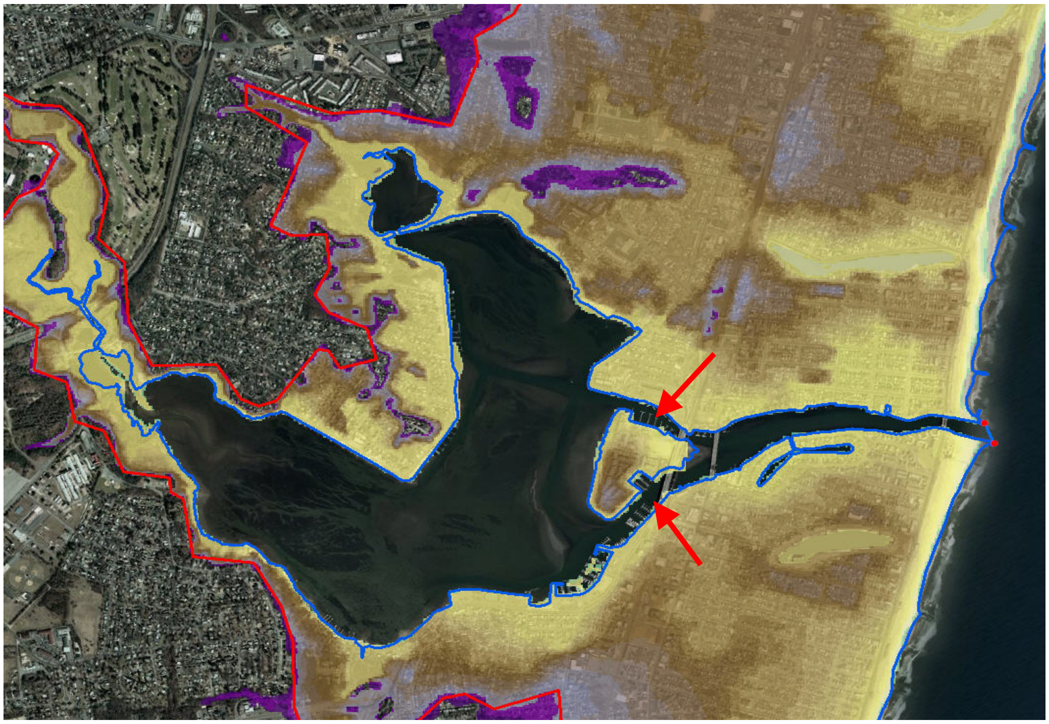


Figure 28. Sample area with channels approximately 225 feet wide

Some islands in the mesh were best represented by combining several nearby islands into one. Figure 29 shows an example where the islands within the red oval were combined into one island in the mesh. Feature arcs were placed just inside the land/water interface to capture the island size and shape as closely as possible.

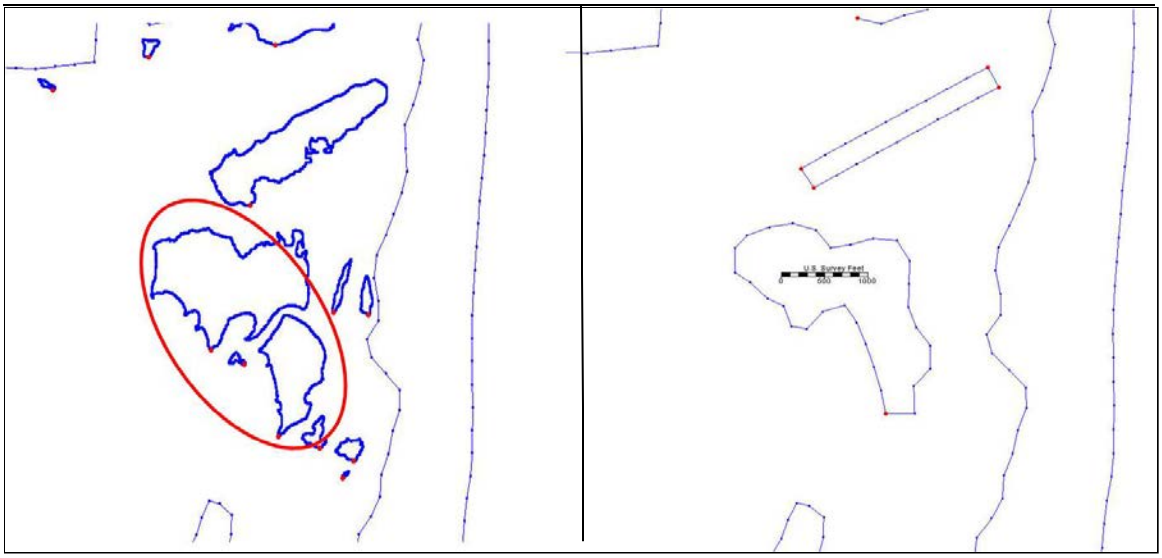


Figure 29. Example of islands combined into one

Some narrow islands were represented in the mesh by a single arc, as shown in Figure 30. The feature arc was placed at the island's highest possible elevation. The resulting mesh appeared similar to that shown in Figure 31. The three nodes represented by green triangles are dry mesh nodes at a higher elevation than the surrounding wet mesh nodes.

Figure 30. Narrow island represented by a single arc

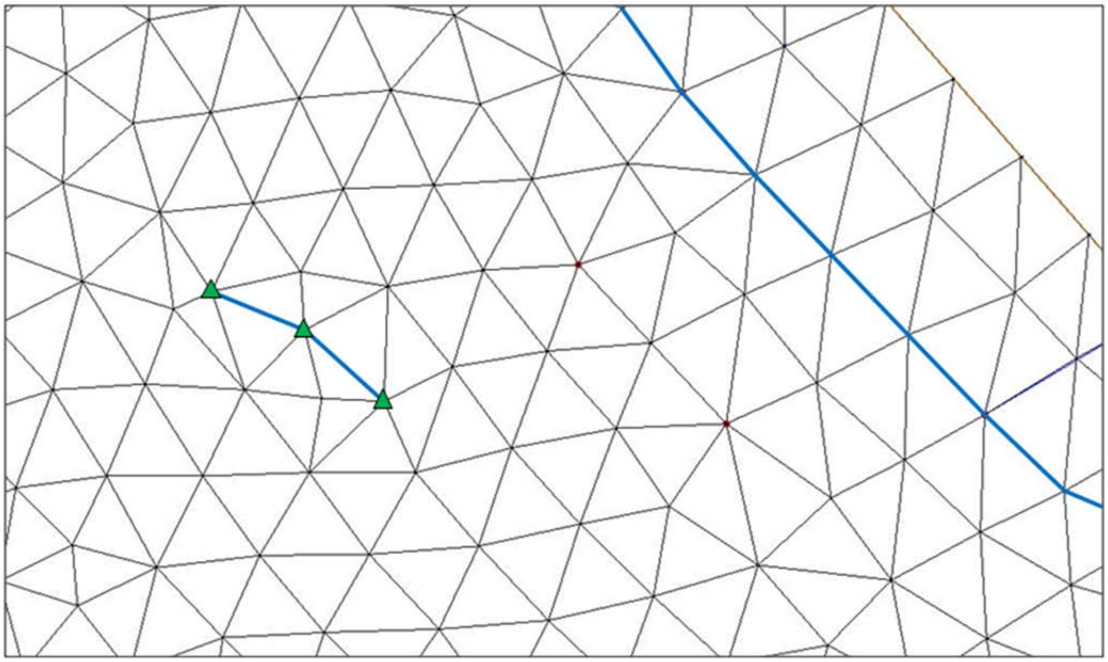


Figure 31. Sample mesh for a narrow island represented by a single arc

2.1.11 Boardwalks

Boardwalks were included in the topographic data. Boardwalk locations were visible in aerial photographs, and the mesh developer examined photographs from online mapping services and from the field reconnaissance trip to determine how to build the mesh in this area.

For areas where the sand was packed tightly below the boardwalk, the mesh nodes were placed along the boardwalk and the elevation data were not changed.

For areas where the sand was well below the boardwalk and water could flow freely underneath the structure, the boardwalk was eliminated from the mesh. Because removing the boardwalk from the topographic data would be cumbersome, the mesh developer placed a guiding arc seaward of the structure so that during the interpolation of the seamless DEM, the mesh nodes would be aligned with the lower elevation of the beach. Another arc landward of the boardwalk was placed to pick up the lower elevation on the other side.

For areas where the sand was well below the boardwalk, but where there was a retaining wall or some other structure that would impede the flow of water into the domain, the elevation at the mesh node matched the elevation of the top of the boardwalk.

If there was no photographic evidence from field reconnaissance notes and photographs, or from online street-view mapping services to determine whether water could pass under the boardwalk, mesh nodes were placed along the top of the boardwalk, and the elevation from the seamless DEM was used (i.e., with the mesh node elevation matching the elevation of the top of the boardwalk).

2.1.12 Linear Element Detection (LED) Tool and LED Tool Output

The RAMPP study team developed a feature extraction tool, the Linear Element Detection (LED) Tool, to aid in the location of flow barriers. Instead of depending exclusively on the mesh development team to select these features, the LED Tool automatically finds features like railroad beds and roadway bases, which may have a relief of only 2 to 3 feet above the ground surface. Figure 32 (a) shows an example of an area that could serve as a flow barrier, and Figure 32 (b) shows the output of the LED Tool delineating this feature.

(a) (b)

Figure 32. Example of (a) a ridge feature that could serve as a flow barrier and (b) the ridge as detected by the LED Tool

The output of the LED Tool included long, positive relief features. The output arcs along these features included the elevation information at the nodes. The LED Tool was set up to find narrow features (on the order of 15 feet wide) or intermediate features (up to 300 feet wide). The Tool did not necessarily identify all features, so the mesh developers reviewed other resources to be sure that all significant flow-retarding linear features were included in the mesh.

The LED Tool used an underlying DEM that was more detailed than the DEM used for mesh layout and creation. For most areas, this detailed DEM had 6-foot (1.8-m) cells, while the same area for mesh development had 33-foot (10-m) cells. The Tool identified features with widths on the order of the minimum spacing of the underlying detailed DEM (i.e., 6 feet (1.8 m) in most cases, but 33 feet (10 m) in the case of Atlantic, Ocean and portions of Monmouth Counties. The output from the LED Tool produced shapefiles that were input into SMS and converted to feature arcs. The nodes along the feature arcs were then redistributed to match the node spacing guidelines of nearby features, as discussed in the sections above. Details on how the LED Tool works can be found in Appendix A.

An example of an LED Tool output arc near the shoreline is shown in yellow in Figure 33. In this case, the node spacing used along the coastline (shown in green in Figure 33) was used along the LED Tool feature arc.

Figure 33. Example of nearby feature determining the spacing along LED Tool feature arc

In areas where the LED Tool arcs intersected with existing boundaries, adjustments were necessary to avoid a sharp angle at the intersection of these lines. These sharp angles in the mesh can affect model stability when the interior angle of an element was less than 35 degrees; it was flagged for further review. Section 3 details the mesh quality checks performed to avoid these issues. Figure 34 shows an example of (a) the feature arc as output from the LED Tool (in yellow), and (b) the adjustment to the inland boundary (in green) to eliminate the sharp angle between these lines.


(a) (b)

Figure 34. Example of a sharp angle at the intersection of the LED Tool arc with an interior boundary arc (a) and adjusted boundary (b)

Adjustments were made to avoid tight spaces between the end of an LED Tool arc and another boundary. Figure 35 shows where the LED arc stops short of the inland boundary by a distance of less than the minimum node spacing. Generally, the arcs were joined, although in some cases it was important to preserve the elevation "gap" between the LED arc and the boundary.

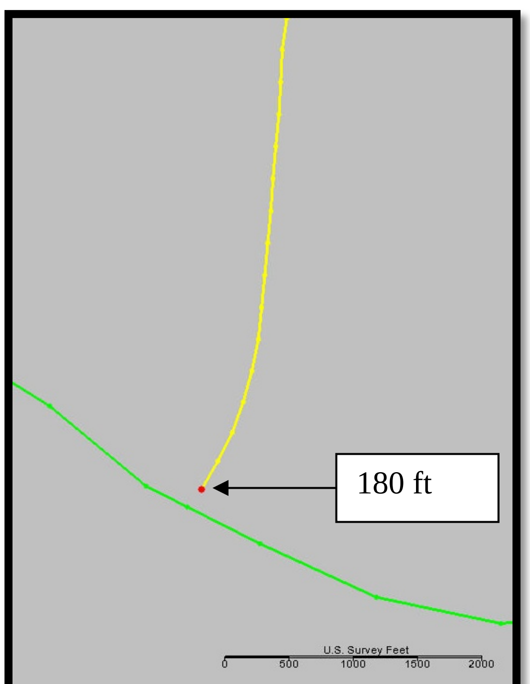


Figure 35. Example of an LED arc (yellow) ending near a boundary arc (green)

Although the LED output data went through a QC check, the mesh developer was responsible for checking the output to ensure there were not more LED arcs than could be reasonably modeled, and also determining whether the tool failed to detect any major barriers to flow.

In some locations, multiple LED arcs were tightly spaced. In this case, the highest elevation LED arc was kept and other arcs eliminated (especially when the space between the arcs was smaller than the minimum element size). An example of a highway overpass area is shown in Figure 36. Figure 37 shows this area with a hill shade representation of the topography data after the highest arc has been singled out.

Figure 36. Sample of area with multiple nearby LED arcs

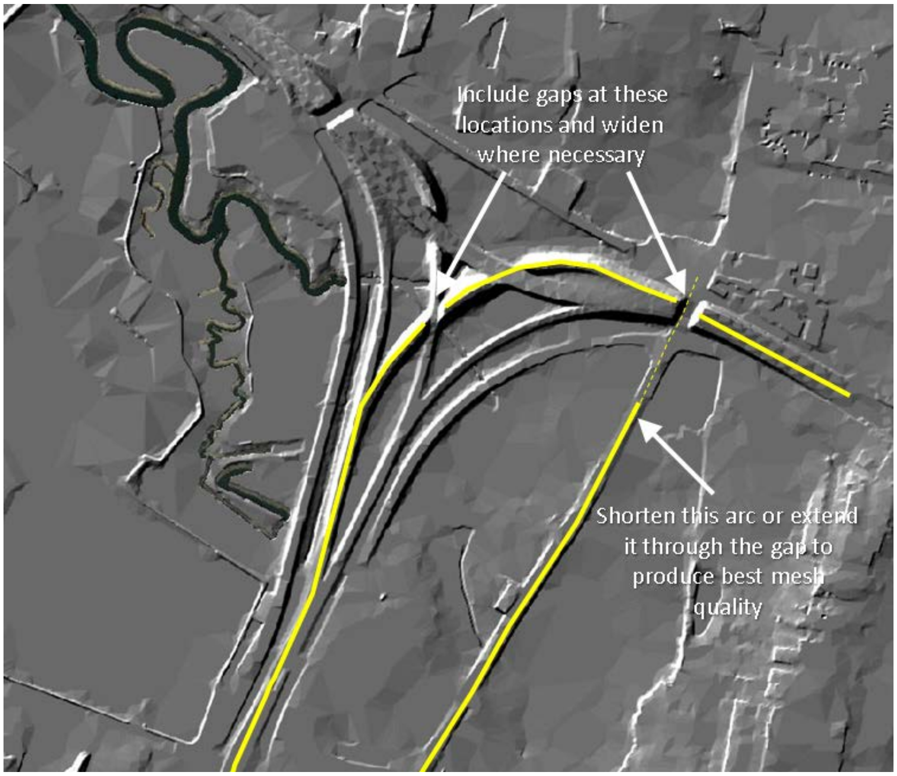


Figure 37. Image of final LED arcs

In other cases, there were multiple, short LED arcs that did not represent the dominant features. In Figure 38, several shorter arcs (shown inside the red boundary) were eliminated, and the main elevated roadway feature (yellow line) was extended (dashed yellow line) because it was a major flow barrier and the main feature in this area. Several tests were conducted to determine the minimum flow barrier that would affect the path of flow. Details of this study are listed in Appendix B. As a result of these tests, arcs shorter than 0.5 mile (that were not part of a major flow barrier) were removed.

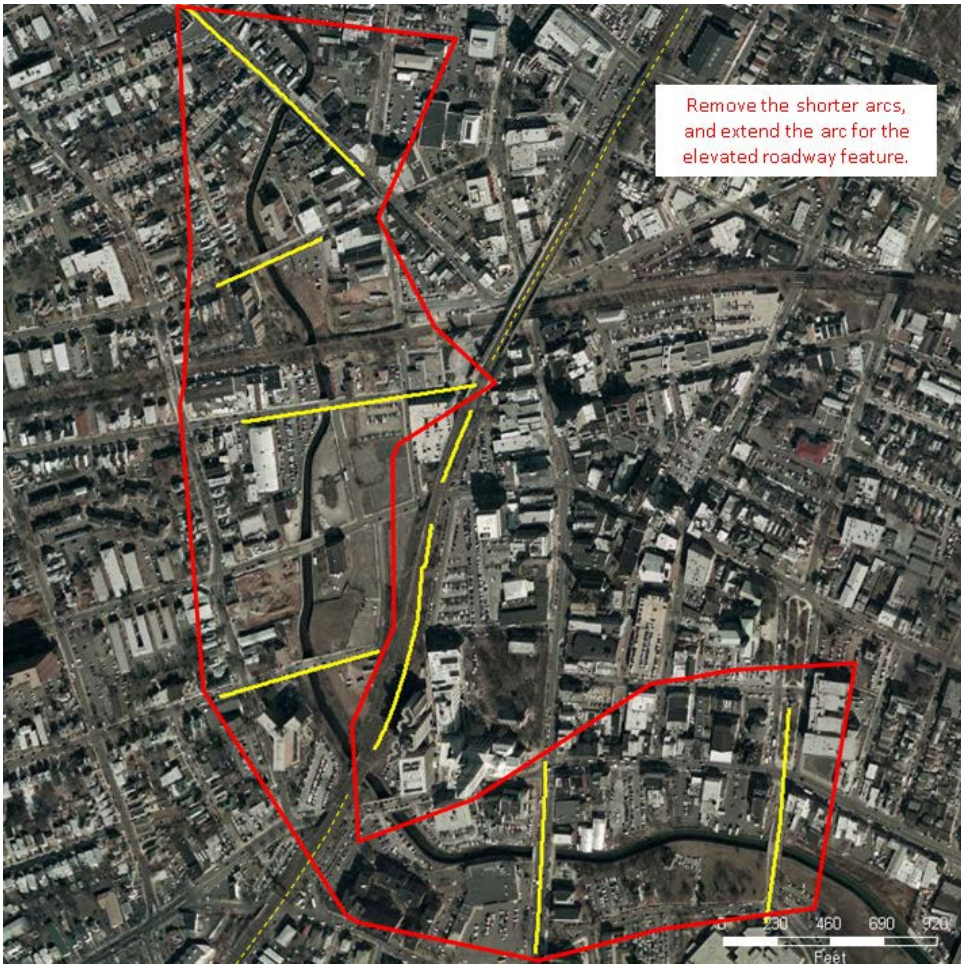


Figure 38. Area with extra LED arcs to be eliminated (inside red outline) and major feature to be extended (yellow line and dashed yellow line outside red outline)

2.1.13 Topography Changes

Across areas of steep topography change, it was important to model the major slope changes as accurately as possible. The mesh developers were restricted by the minimum element size, but where possible, additional feature arcs were used to follow topography changes. This technique was not used everywhere because increasing the number of feature arcs increased the constraints for SMS, and this would result in meshes with many triangular elements that did not meet the mesh quality guidance. This technique was often employed around peaks and ridges, such as those from the LED Tool output.

For ridges with a peaked top and a steep side slope followed by a more gradual slope, the mesh developers placed nodes at the major slope changes, as shown in Figure 39. The figure shows the node locations and the resulting elevation in the mesh compared with the “true profile” of the more detailed DEM data.

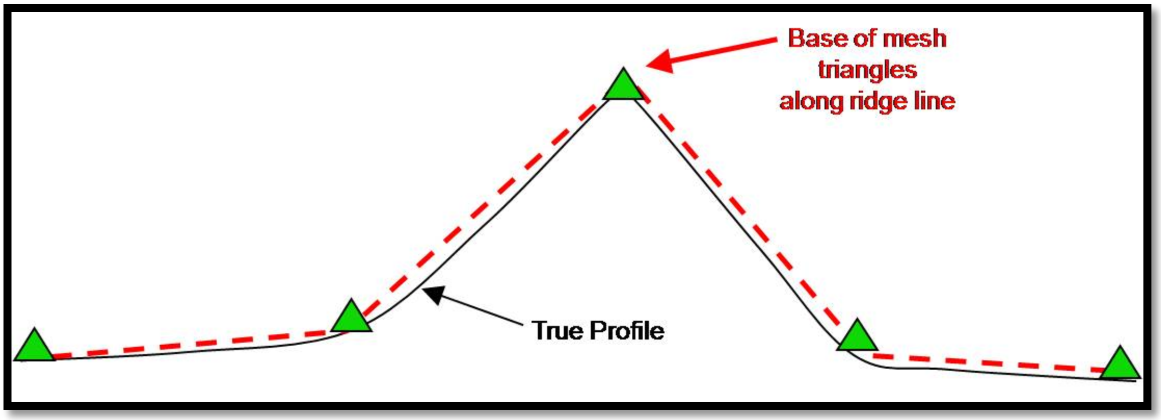


Figure 39. Profile of a peaked ridge feature

For ridges with a broad, smooth top, two nodes were placed on either side of the ridge instead of one node on the center to better represent the major slope changes, as shown in Figure 40.

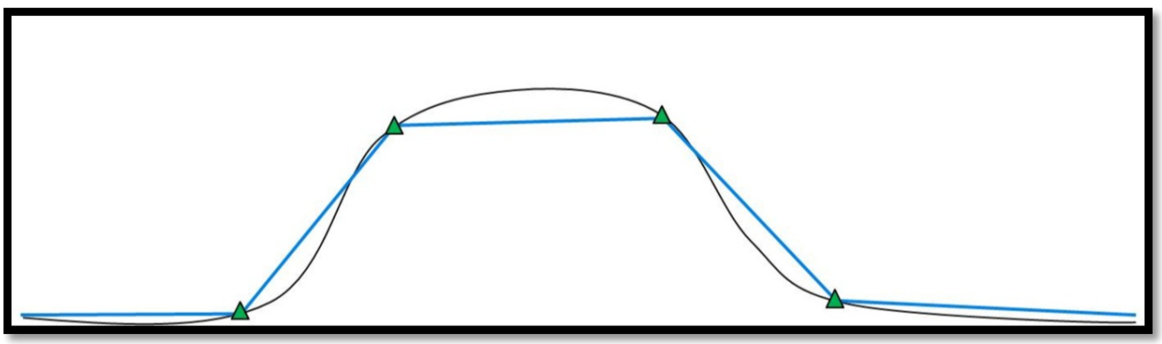


Figure 40. Profile of a broad, smooth-topped ridge feature

Sometimes the distance between the ridge peak and the major slope change location varied along a ridge line. In this case, additional feature arcs were placed along the slope change point as the line extended farther from the ridge peak. Figure 41 shows an example of changes in node spacing along the ridge line to better capture the slope change locations. In this example, the base of the ridge was wider on the north and south sections and narrower in the middle.

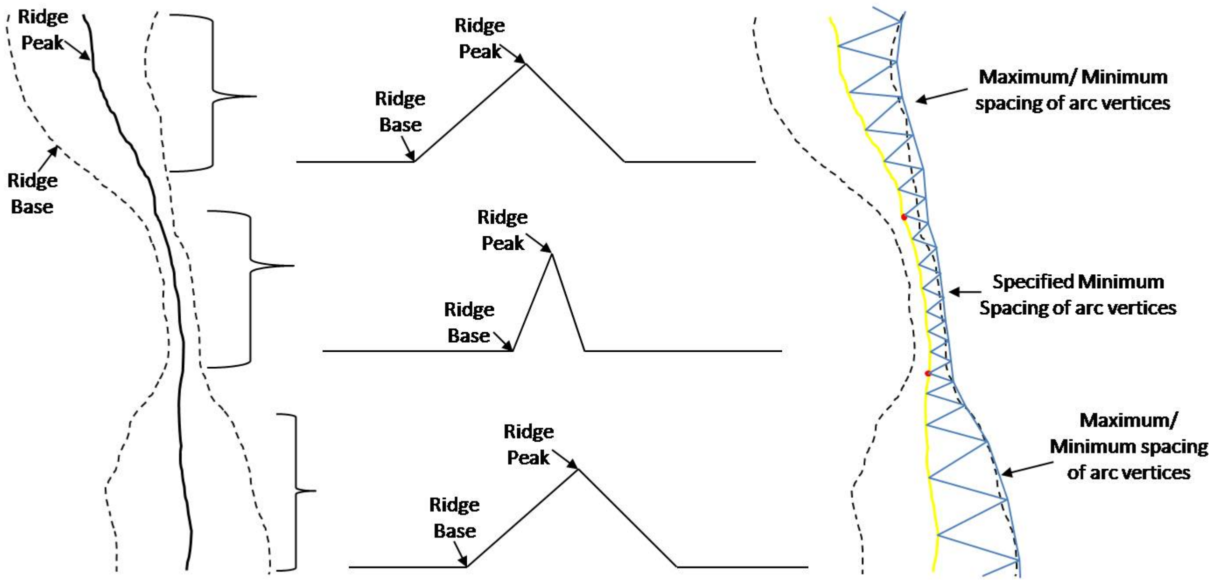


Figure 41. LED Tool arc split into multiple arcs

In some cases, the limit of the minimum element size necessitated distortion of the underlying geometry. Figure 42 shows a sharp feature (for example, an embankment or a wall) where the feature's width is less than the minimum allowed by the mesh nodes. These features were retained in the mesh and shown by the mesh nodes along the ridgeline, even though the next mesh nodes had to be located in such a way that the true slope was significantly distorted.

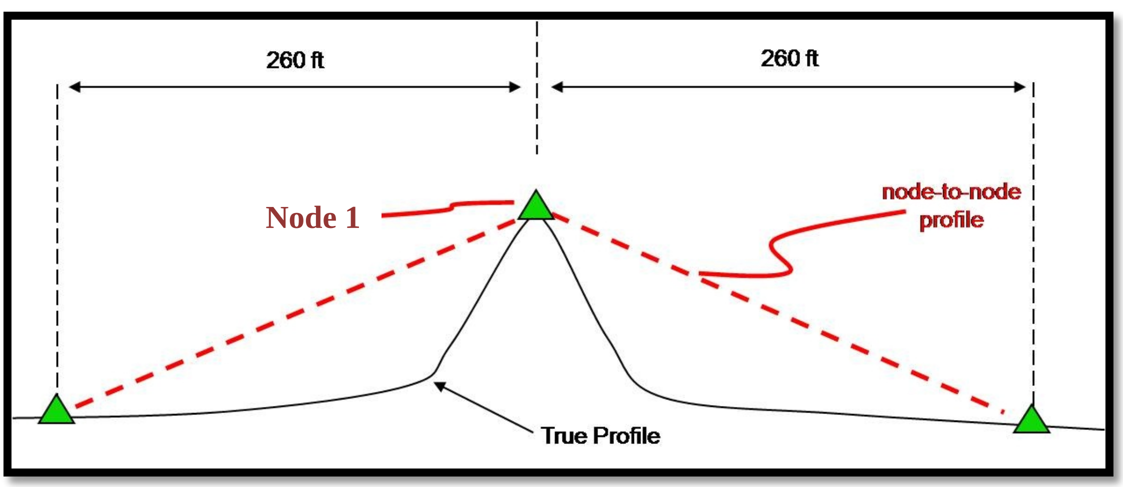


Figure 42. Narrow linear feature

2.1.14 Gaps in Ridge Features

Many ridge features (modeled with the LED arcs) had physical gaps at places like railroad underpasses that were large enough to allow storm surge waters to pass through. These gaps presented a number of challenges during mesh development. Many gaps were narrower than the minimum element size. Even some that were wider would have required distortions in the mesh to allow the computed flow to pass through while maintaining both the minimum element size and acceptable mesh element geometry. Figure 43 shows three cases that were most frequently found during mesh development. In Case I, the gap was significantly wider than the 260-foot dimension of the minimum element. In Case Ia, more than one node was positioned within the gap, but the sharp slope of the embankment to either side had to be distorted by showing the top dimension of the gap to be of greater width than in the true profile. Case Ib shows an alternative where a larger node spacing was used along the bottom of the gap, and again the side slopes were distorted. Case II shows an example where the gap was at (or very near) the minimum node spacing. Again the side slopes were distorted. Finally, Case III required the whole gap to be represented as a wider feature than in reality.

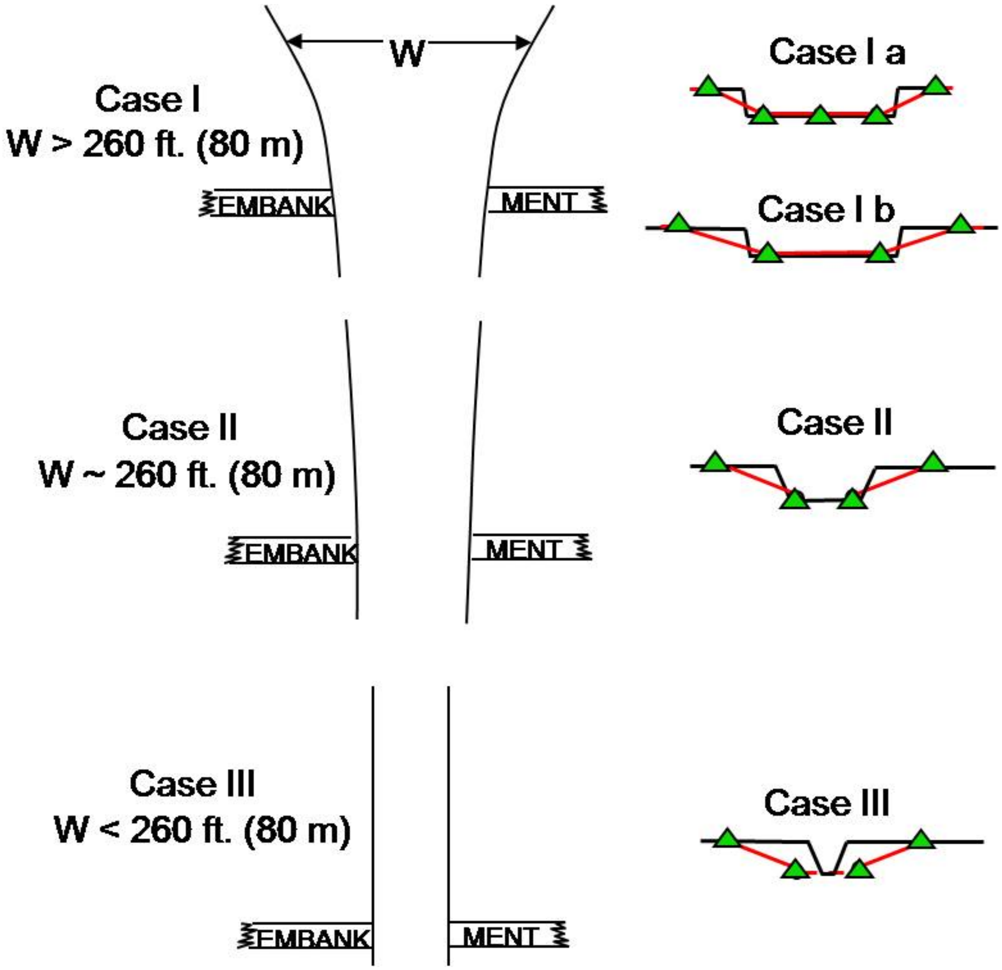


Figure 43. Schematics for mesh layout at gaps of different sizes

Some specific examples are outlined below. An example of a Case where the LED arc intersected a river that was wider than 260 feet, is shown in Figure 44. The feature arc design for this area is shown in Figure 45. The LED arcs were snapped to the guiding riverine arcs. The final mesh for this area is shown in Figure 46.

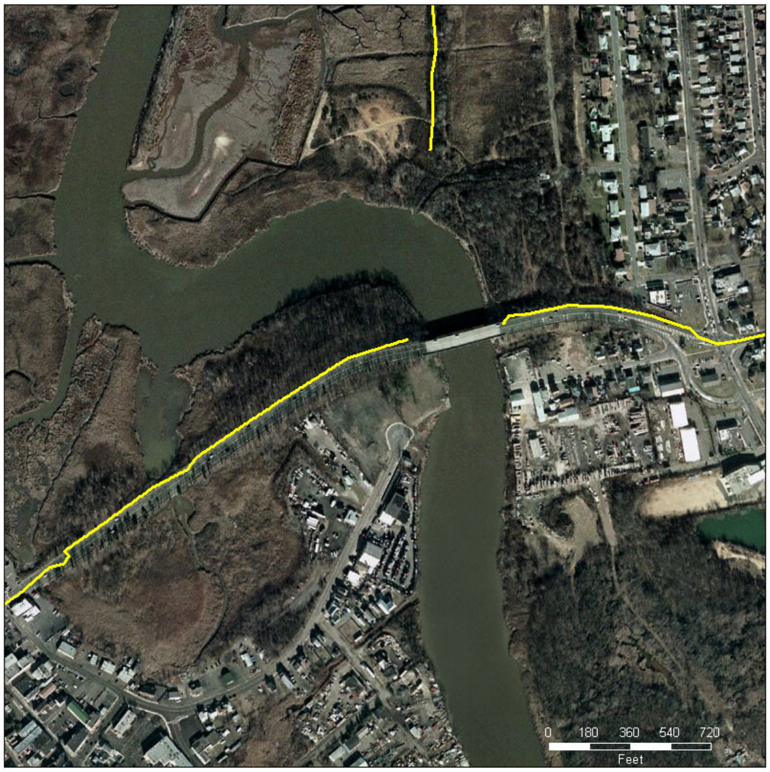


Figure 44. Sample area of Case I, where LED arc intersects with a river more than 260 feet wide

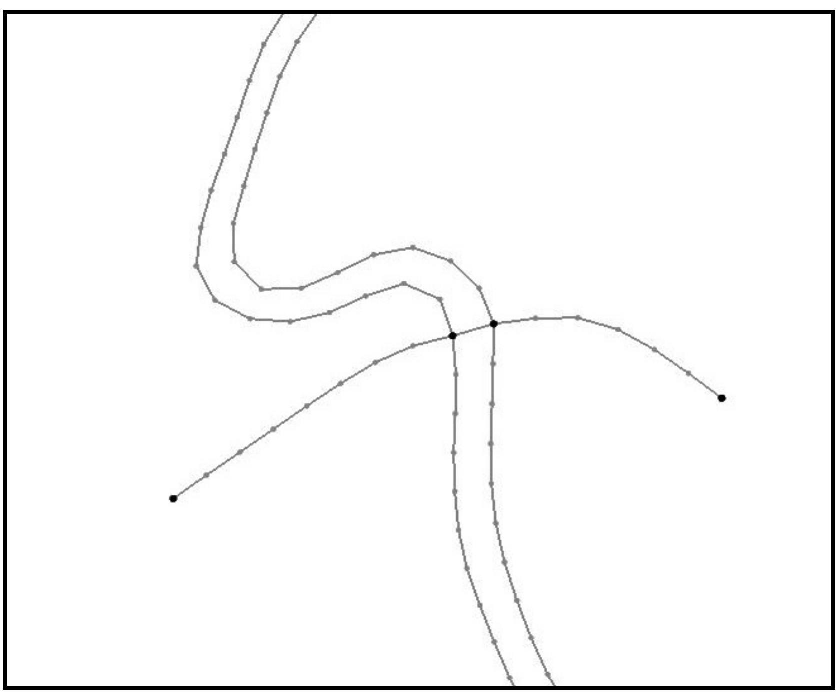


Figure 45. Sample riverine and LED arcs based on region shown in Figure 44

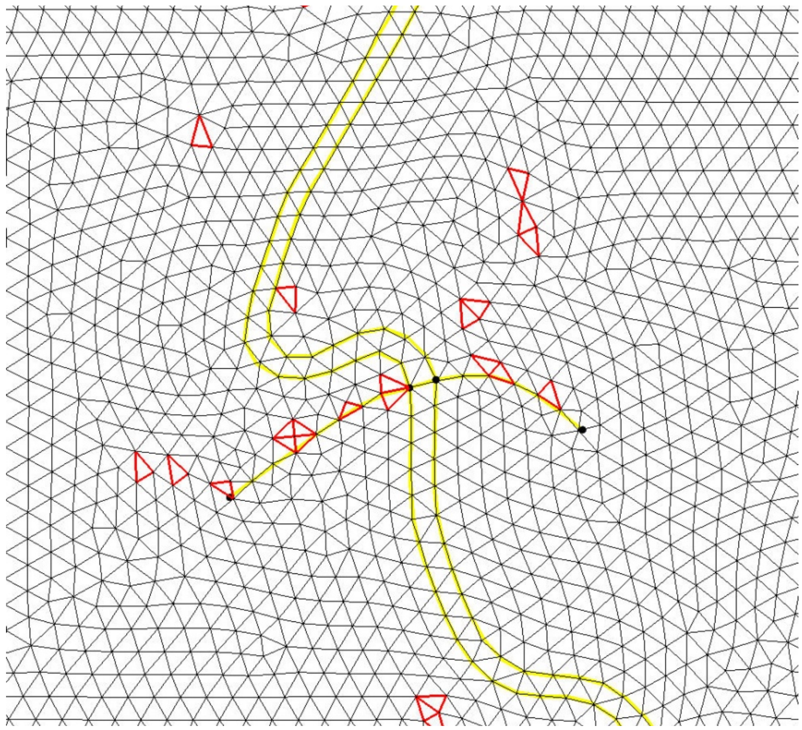


Figure 46. Sample mesh generated using arcs in Figure 45

For areas where the riverine opening was less than 260 feet (Case III), the gap was widened and the elevations adjusted on the end nodes in the gap to reflect the surrounding area of lower elevation. Figure 47 (a) shows an area with a small stream creating a gap in an LED arc, and Figure 47 (b) shows the same area with a wider opening. This was necessary to allow the minimum node spacing between the gap. The elevation of the nodes at the end of the LED arc was manually adjusted to reflect the elevation of the lower ground surrounding this area.

Figure 47. Example of LED arc intersecting a river less than 260 feet wide

2.1.15 Features with Many Gaps

Some LED arcs had many gaps, and the feature appeared almost as a dashed line. When these gaps appeared at regular intervals, the mesh developer determined where the main flow paths were and then concatenated the smaller LED arcs, creating fewer gaps. The goal was to make the arcs at least 3,000 feet in length. This length was determined by a sensitivity study, the details of which can be found in Appendix B. An example LED output with multiple gaps is shown in Figure 48 (a) and the concatenated version in Figure 48 (b).


(a)

(b)

Figure 48. Sample area where (a) multiple LED arcs are (b) combined to result in fewer gaps with longer LED arcs

2.2 POLYGONS AND MESH GENERATION

After the mesh boundaries were laid out, the mesh developers used SMS to create polygons. The polygons were then attributed in the 2D (two dimensional) Mesh Polygon Properties dialog box. The SMS program has several types of mesh generation techniques. For the overland mesh sections, two different meshing techniques were used. Figure 49 shows an example of the two main types of polygons the mesh developers used and the meshing technique associated with each. One polygon has four sides, and the sides opposite each other have the same number of nodes. This type of polygon was meshed using the “patch” mesh type. An example of a patch mesh type is shown in Figure 50. The other polygon either has fewer than four sides or has more than four sides and varying numbers of nodes along the arcs. These polygons were meshed using the “paving” mesh type, and the bias (or growth rate) could be adjusted manually so that elements within the polygon did not grow too quickly or too slowly. An example mesh for the paving polygon is shown in Figure 51.

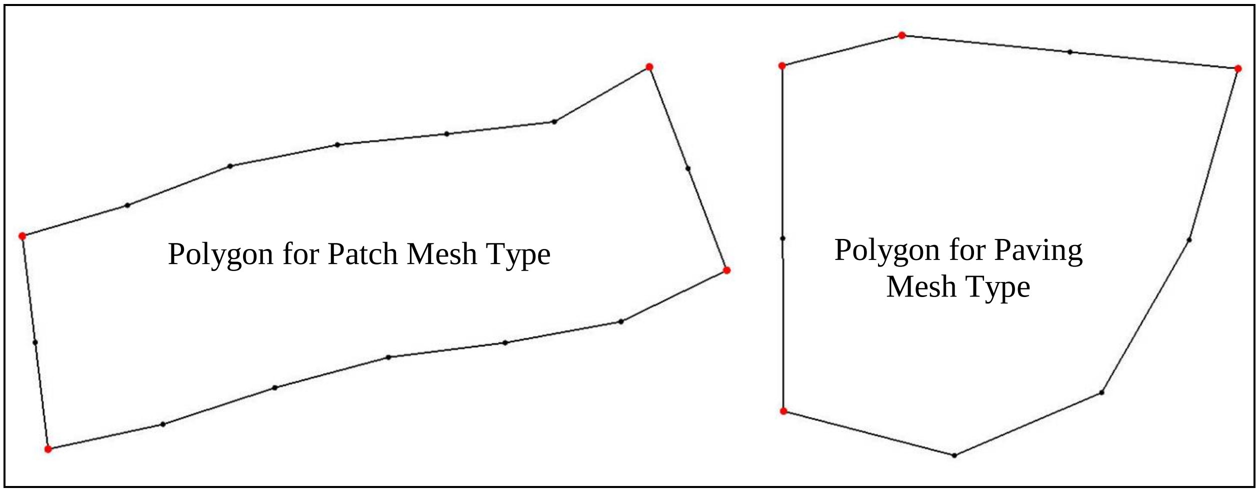


Figure 49. Two polygon types

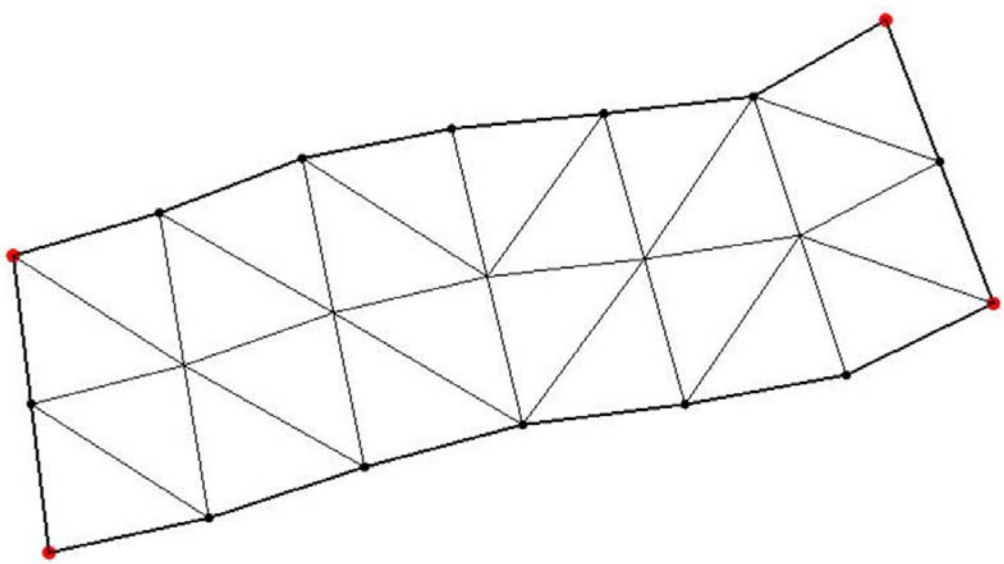


Figure 50. Example of patch mesh section

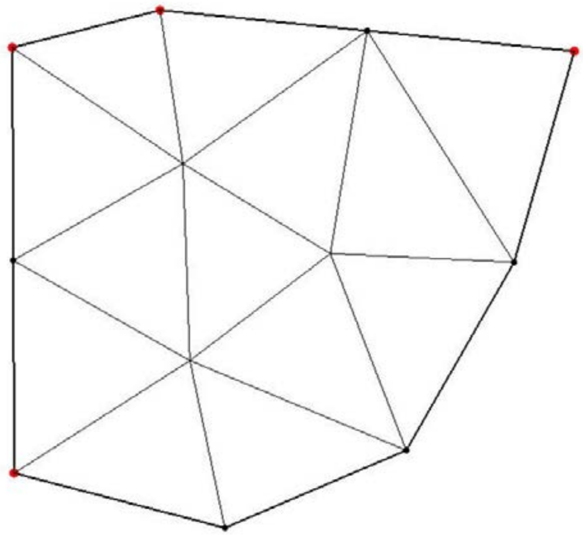


Figure 51. Example of paved mesh

For the offshore area, the Linear Truncation Error Analysis (LTEA) function in SMS was used to generate the mesh (instead of the paving and patching techniques described above). This method is beneficial for offshore submerged areas of the mesh where feature arcs are not required because the mesh resolution is analyzed and determined from the underlying bathymetry.

An outer boundary was selected to match the resolution of the Eastcoast 1995 mesh in the North Atlantic Ocean. The shoreline boundaries for each overland mesh section were merged and joined to the outer boundary to create one polygon. Because of limitations in computer memory, this was further subdivided into smaller, workable sections for processing. The LTEA process requires an input bathymetry dataset. The process begins with the generation of a basic mesh using the paving technique on which a linear ADCIRC run is conducted with the principal lunar semidiurnal (or M2) tidal constituent and a harmonic analysis is performed on the results. The truncation error is estimated and the LTEA algorithm calculates the relative error from node spacing. The algorithm then computes a size guideline for generating a new mesh.

From this information, SMS generates a revised mesh that generally has a higher resolution of the mesh nodes along features with sharp bathymetric changes (such as the continental shelf break), and has lower resolution in areas with smooth bathymetry. This process optimizes the resolution throughout the mesh to provide increased model efficiency.

SECTION THREE QUALITY CONTROL

The RAMPP Quality Management Plan (QMP) prescribes QA protocols to build quality into all products. The QA activities include training, process definition, knowledge management, and proactive measures to encourage an environment for the creation of high-quality products. The QC activities described in the RAMPP QMP are intended to validate that the QA infrastructure is effective and to inspect specific products to check compliance with the quality standards. For the mesh development activity, the RAMPP study team followed the QMP standards and conducted extensive checks of the mesh.

The first step in the process began with the mesh developers, who used the SMS mesh quality standards. The tools showed areas where the interior angle of the elements was less than 35 degrees and the change in element area between adjacent elements was more than 50 percent. Where these errors were found, the mesh developers adjusted the nodes and elements to bring the mesh within the acceptable tolerance.

After the initial check by the mesh developers, a detail check was conducted on each section of the mesh. The detail check reviewer looked for the same mesh quality issues discussed above. In addition, the reviewer ensured that the mesh conformed to the guidance discussed in Section 2.1 and checked the interpolated bathymetric/topographic elevation data at the mesh nodes.

Two independent technical reviews (ITRs) were conducted. The first compared the mesh for Monmouth and Ocean Counties because these mesh sections were developed by people in different work locations. After the mesh sections were merged, another ITR was conducted on the complete mesh. A final audit was conducted of the completed mesh and of the QA files.

SECTION FOUR FINAL MESH DETAILS

In creating the final mesh, individual mesh sections were first projected to geographic coordinates and merged. Transforming the horizontal datum from the State Plane coordinate system to geographic coordinates was accomplished using the SMS software. The final ADCIRC mesh has 604,790 nodes and 1,188,640 elements. The complete mesh is shown in Figure 52. The high-resolution portion of the mesh includes Delaware Bay, New Jersey; the Hudson River Valley up to Troy, New York; New York City; Long Island Sound; and Long Island. Rough county boundaries and the detailed portion of the mesh are shown in Figure 53. A zoomed view of lower Monmouth County with aerial imagery is shown in Figure 54. The final mesh is in Geographic Coordinate System (i.e., longitude and latitude) for the horizontal datum and MSL meters for the vertical datum.

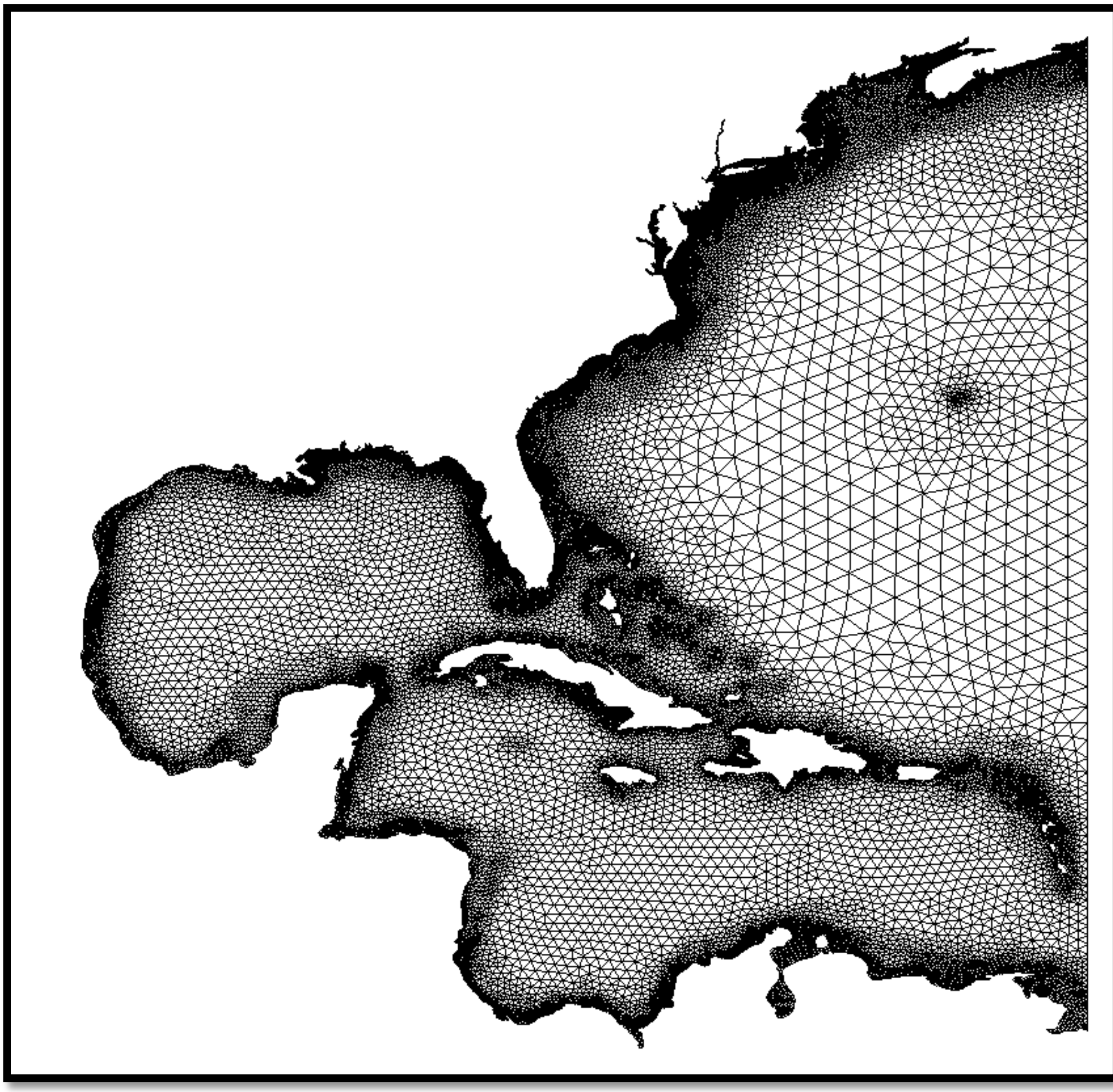


Figure 52. Final ADCIRC mesh

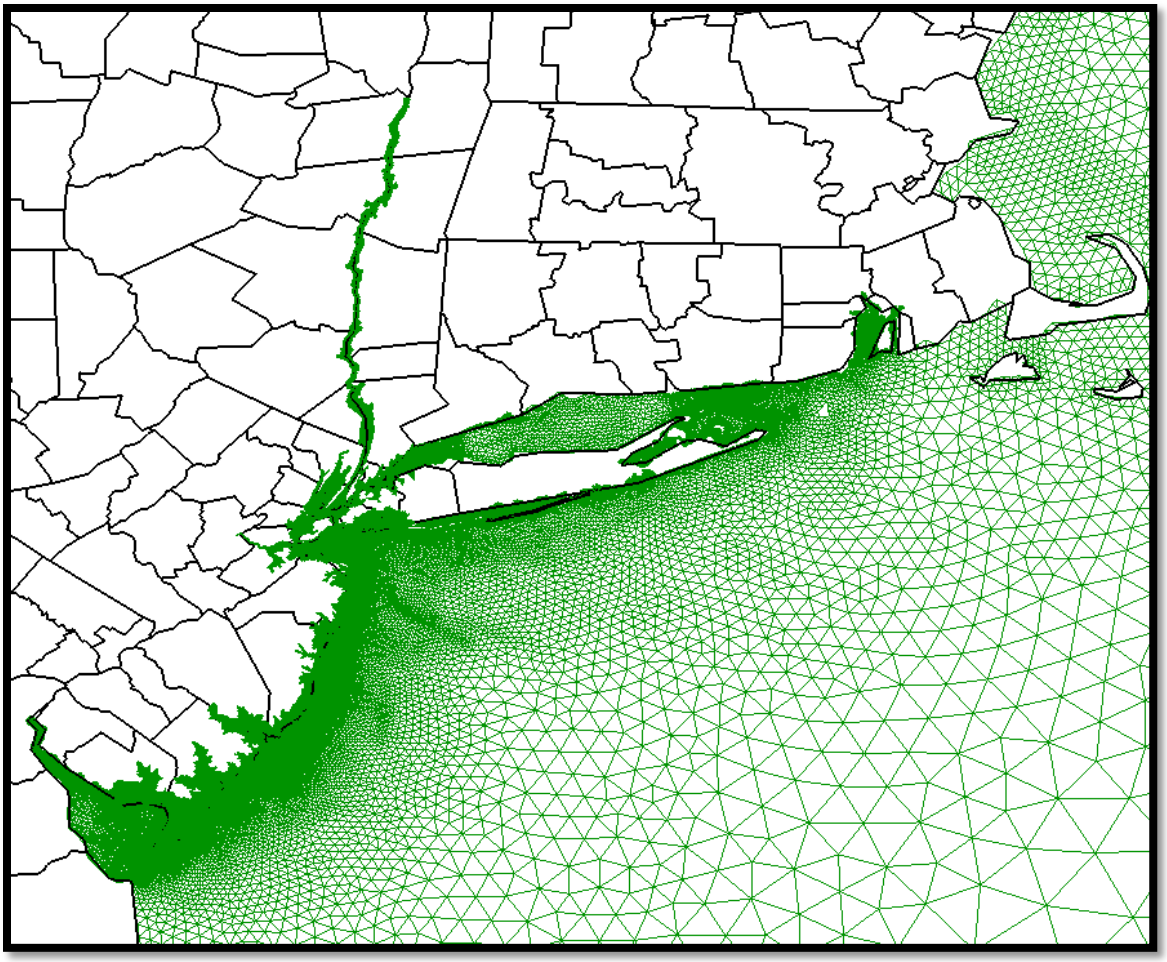


Figure 53. Detailed section of ADCIRC mesh and rough county boundary outlines

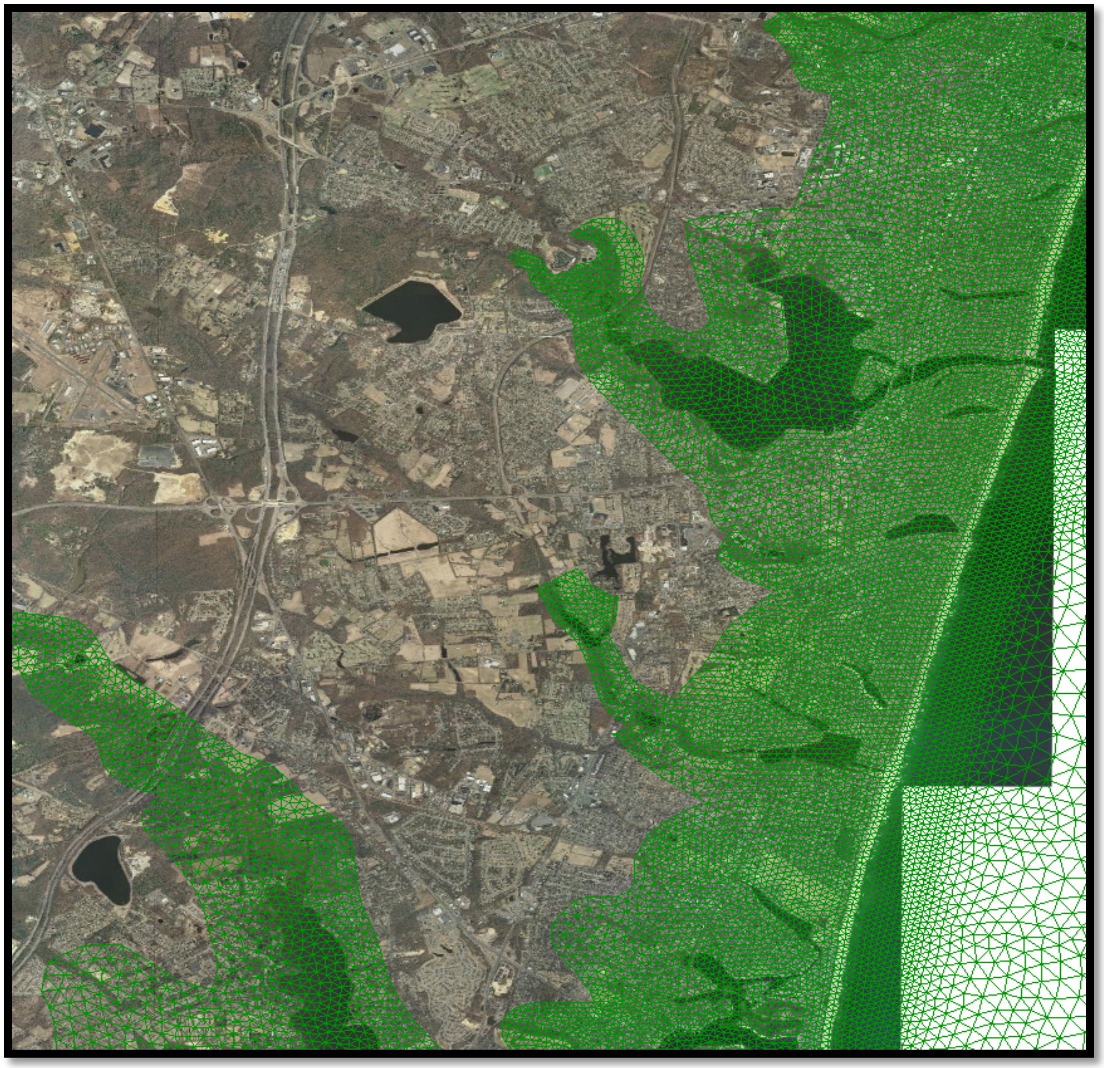


Figure 54. View of ADCIRC mesh in lower Monmouth County with background aerial imagery

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Mukai A.Y., J.J. Westerink, R.A. Luettich Jr., and D. Mark, 2002, Eastcoast 2001: a tidal constituent database for the western North Atlantic, Gulf of Mexico and Caribbean Sea, U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Technical Report, ERDC/CHL TR-02-24, September 2002, 201 pp.

Westerink, J.J., R.A. Luettich, and J.C. Muccino, Modeling tides in the Western North Atlantic using unstructured graded grids, Tellus, 46A, 1994, pp. 178-199.

APPENDIX A

Linear Element Detection Tool

INTRODUCTION

This appendix describes the steps to process and analyze DEMs to identify significantly high and long ridges that may have been missed in the normal model mesh development and add them to the storm surge models. This procedure utilizes Environmental Systems Research Institute (ESRI) software and DEMs of the New Jersey and New York Atlantic shoreline counties. The Linear Element Detection (LED) Tool was developed in ArcGIS by the RAMPP team and utilizes some ArcHydro tools.. This appendix describes the output of the LED Tool and application to the ADCIRC mesh development.

STEP 1: ACQUIRE AND PROCESS DEM/GRID DATA

Each county has one master GRID elevation dataset. The terms DEM and GRID are interchangeable throughout this appendix. GRID refers to the ESRI raster format and is used to represent single-band elevation datasets for this project. Elevations in this project are referenced to NAVD88. The source data were provided by county for the New Jersey and New York shoreline areas within the project boundary. It was necessary to clip the DEMs into smaller datasets for processing watershed delineations. The size depended on the number of cells in the GRID, with 1×10^8 cells being a reasonable size. After the subsections were developed, the bathymetry data were removed from the dataset.

Next, actual land elevations were extracted into a subset GRID for basin delineation. During the basin delineation, ArcHydro tools were used to build streams and delineate the basins. After the streams were delineated, the catchment GRID delineation was run for each stream segment to define the basins. The boundaries of the basins (or catchments) are the high ridge features. These features were converted into arcs and prepared for processing with the LED Tool.

STEP 2: LINEAR ELEMENT DETECTION TOOL

Step 2 in the linear extraction procedure consisted of testing the identified arcs and removing those that did not represent significant ridges. The testing method determined the steepness and height of each ridge section based on user defined parameters. Arcs that passed the testing criteria were written to a new output set of shapefiles.

The basic test attempts to estimate the difference in height between the ridge and the area surrounding the ridge. The height difference is calculated at user-specified distances from the arc, which identifies the steepness (i.e., height/distance).

The method for applying the height difference test is shown in Figure A-1.

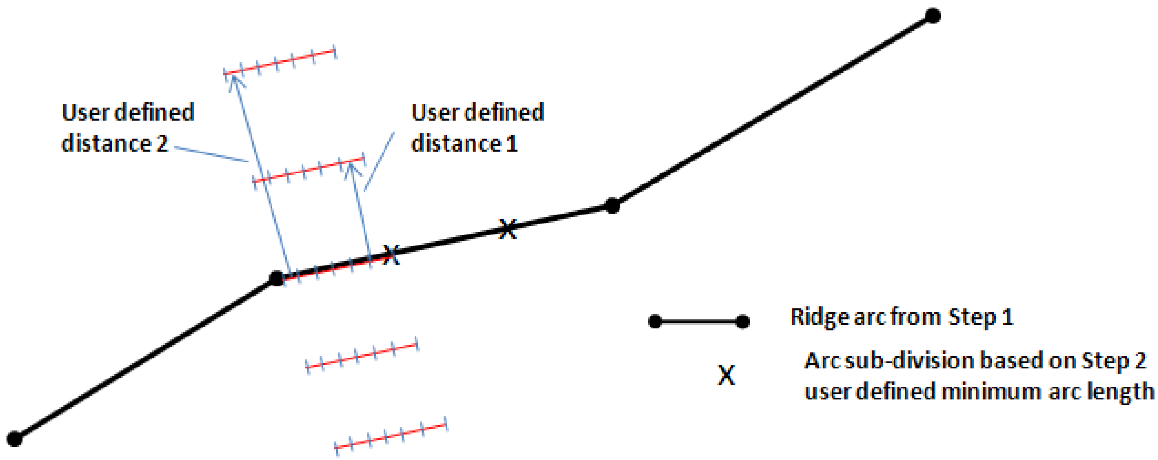

Figure A-1. Schematic showing details of test method

With this method, the arc segment is first draped over the elevation model, which inserts new nodes for each change in height along the arc segment; the new spacing is on the order of the grid cell size of the elevation model. The individual segments are tested by offsetting them on both sides of, and parallel to, the line at the distances specified (Figure A-1 shows offset sub-segments at user defined distances from the main arc segment). The average heights of the offset lines are determined by averaging the elevation values along the offset lines as pulled from the underlying elevation model. The height of the candidate ridge (i.e., the original arc segment) must be at least H units higher than the offset line to pass the test, where H is the height parameter at a user-specified distance.

The ***maximum number of failed segments*** parameter allows the model to retain arc segments that may have failed the test, but are bounded by arc segments that passed. For instance, consider the case where the ***maximum number of failed segments*** parameter is set to 3. As the testing progresses along the arc, if one arc segment fails, it is temporarily retained. If the next arc segment fails, it is also temporarily retained. If the third arc segment fails, then all three arc segments are permanently removed. However, if the third arc segment passes, then all three arc segments are permanently retained. If the maximum number of failed segments is set to 1, then any arc segments that fail are removed. (The ***maximum number of failed segments*** cannot be set to 0.)

Table A-1 shows the rules the system uses, as of LED version 1.2, when flagging the status of a candidate ridge.

Table A-1. Status Field Values

Condition	Status Field Value
Passes all tests, on both sides of the line, at all offset distances	Passed all tests
Passed one pair of tests on both sides of the line at one or more offset distances, but not all (i.e., at least one test failed)	Passed at least one, but not all tests
Passed at least one test on the left side of the line, and one test on the right side of the line, but not at a single distance (e.g., pass on left at first distance, but fail on right, and pass on right at second distance, but fail on left)	Passed asymmetrically

Condition	Status Field Value
Failed all tests at all distances	Fail
If an error occurs during processing, "with error" is appended to one of the above status messages.	… with error

The elevations of candidate ridge arc segments and their offset lines are computed by draping the segment over the elevation model, which then breaks the segment into sub-segments at each change in elevation, and assigns Z (elevation) values to the from and to nodes of the sub-segment. The average elevation is computed by weighting the average of the from/to node elevations by the length of the sub-segment.

$$\text{Average Elevation} = \frac{\sum_{o..x} (((\text{FromNodeElev} + \text{ToNodeElev}) / 2) * \text{SubSegmentLength})}{\text{TotalSegmentLength}}$$

The user interface allows for manual entry of the following parameters:

<u>Offset Distances:</u> a set of ***distances*** for specifying the testing locations, in map units (e.g., if the coordinate system of the input data is based on State Plane feet, the units for the offset distances field will be feet). At least one distance must be prescribed, but the user may enter as many as desired. The smallest distance needs to be at least the length of the underlying grid cell size. If more than one test at multiple distances is desired, enter individual numbers separated by commas (e.g., "30,60,90").

<u>Height Parameters</u>: a set of ***height difference*** values, in map units, one for each distance entered in the previous field. The height difference specified is the difference in height between the candidate ridge arc segment and the test locations at the offset distances.

<u>Maximum Segment Length</u>: the ***maximum length*** of an input arc segment. If an input arc is longer than this value, that arc will be subdivided into segments no longer than the ***maximum length.***

<u>Can Skip a Maximum of ____ Failed Segments</u>: the ***maximum number of failed segments*** between segments that pass that can be included in the output. This value can be used to chain together longer output arcs with short internal segments that do not meet the criteria.

The application generates a shapefile storing polylines (including Z values) with the following attributes:

FID: System-generated unique identifier of a feature.

Status: The result of the test, as described in Table A-1.

ErrMsg: If an error occurs during processing (as indicated by "…with error" in the Status field), a description of the error appears here.

SrcFID: Refers to the feature ID of the input catchment boundary arc.

Segment: The segment of the input arc feature (from 0 to the total number of segments for the input arc feature-1).

Rslt_#L and **Rslt_#R**: For each offset distance (where # is 1 to the total number of offset distances-1), a pair of fields is created to indicate whether the test on this side (L for left, R for right) passed ("P") or failed ("F") at the indicated distance.

Ht_#L and **Ht_#R**: For each offset distance (where # is 1 to the total number of offset distances-1), a pair of fields is created to store the average height difference between the candidate ridge arc segment and the offset line. Positive values indicate that the candidate ridge is at a higher elevation than the offset.

AvgElev: stores the average elevation of the candidate ridge arc segment.

If the **Save Output Points** option is selected, the application will also create a point shapefile storing the nodes of the output lines. The point shapefile contains the following attributes:

FID: System-generated unique identifier of a feature.

Elev: Elevation of node based on the elevation model.

Also included with the output shape file is a text document that lists the user-entered input parameters.

APPENDIX B

Model Tests Supporting Mesh Development Guidance

For the uniform development of the ADCIRC bathymetric/topographic model grid, it was necessary to provide the RAMPP study team with guidance on how best to represent segmented linear features such as natural dune ridges and highway or railroad embankments. To properly represent these features in an open mesh grid with a minimum 260 feet (approximately 80 m), it is necessary to have some sense of how they influence a storm surge flow of realistic heights and durations. The questions asked included:

1) at what length does a positive linear feature cause a significant blockage to the inland propagation of the surge? and

2) what is an appropriate way to represent a positive linear relief feature that is segmented by gaps?

To address these issues, the CMS-Flow hydrodynamic model, developed and supported by the U.S. Army Corps of Engineers Coastal Inlet Research Program, was used. This is a straightforward 2D (depth-averaged) finite difference model that supports a moving boundary representing the progression of inland flooding from storm surge. More information about this model is available in Buttolph et al., 2006.

To answer the question regarding the interaction of linear positive relief features and the storm surge, a schematic model domain was created. This rectangular domain had the dimensions of 7 kilometers by 7 kilometers. A flat plane with a gentle slope of 1/35 percent extended across the domain. The initial shoreline was located at the edge of the domain at the bottom of this slope.

A positive relief feature in the form of a ridge 50 meters wide and 0.9 meter high was located 3.5 kilometers upslope from this initial shoreline. The length of this ridge varied between 500 meters and 1,500 meters. The model surge was created by increasing the water level at the model boundary. The surge duration at the boundary was 18 hours. In each series, the hydrograph was controlled by a sine function. The surge height was adjusted so that for one subset of runs no overtopping occurred (Subset A), and for a second subset (Subset B), there was shallow overtopping.

Three pairs of output points were distributed so that one member of each pair was behind the middle of the ridge and its corresponding member was 2,000 meters from the side boundary; these provided a reference data set for the surge level unaffected by the ridge. The other members of the pairs were located at distances of 100, 400, and 750 meters behind the middle of the ridge. This represented the maximum distortion of the surge level caused by the ridge. This configuration of the model domain is shown on Figure B-1.

The results of the model runs are shown in Figure B-2 and B-3. The difference in maximum surge level between the adjacent output point pairs is plotted for different lengths of the ridge. With Subset A, the surge did not propagate far enough to reach pair 2 and pair 3. In all examples, the maximum differences were found at the output point just behind the ridge. The surge height difference diminished progressively with distance behind the ridge.

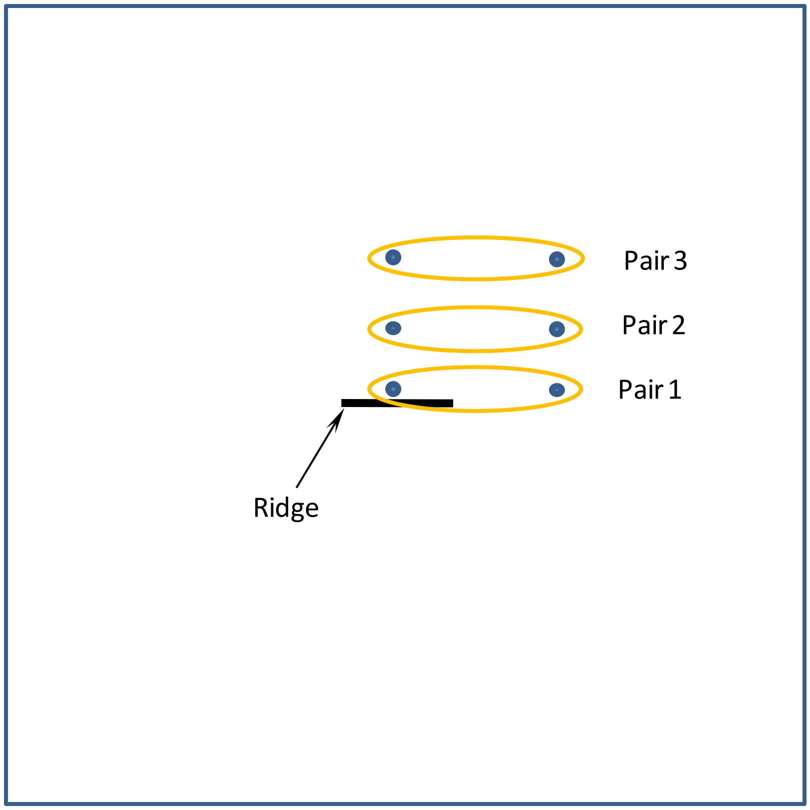

Figure B-1. CMS-Flow model domain (7,000 x 7,000 m)

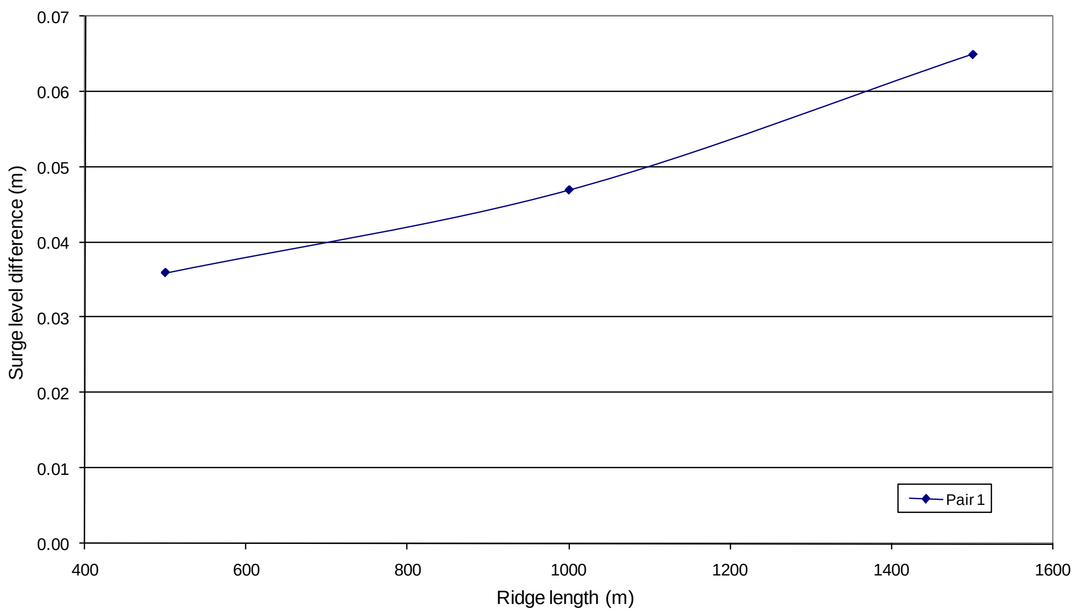

Figure B-2. Surge level difference with ridge length (0.3 m above base of ridge)

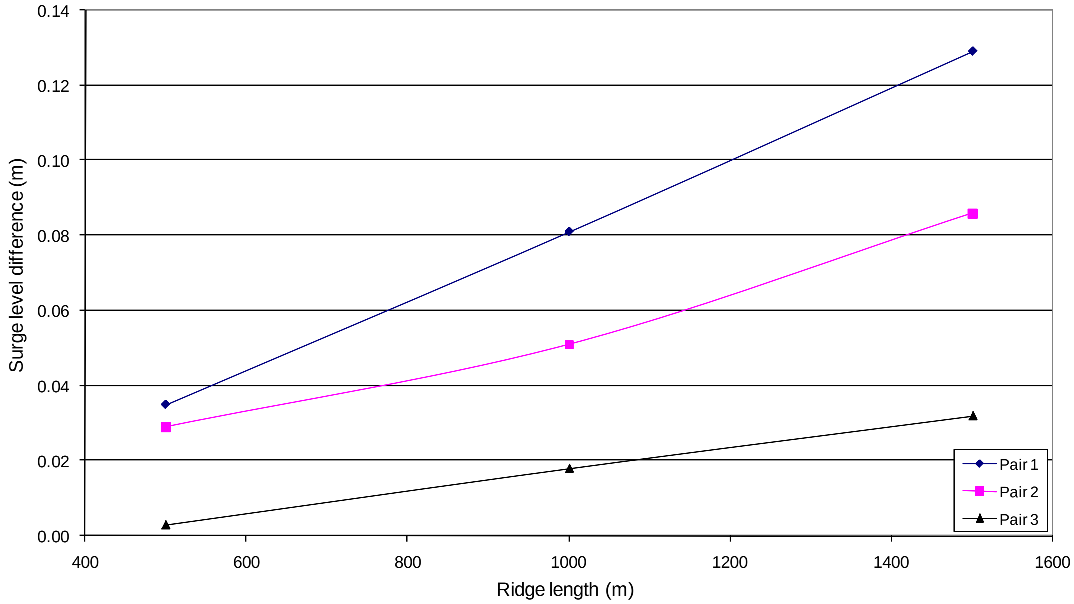

Figure B-3. Surge level difference with ridge length (0.95 m above the base of ridge)

Table B-1 shows the results of all four sets of model runs.

Table B-1. CMS-Flow Model Run Results

Subset	Ridge (m)	Surge Duration (hrs)	Max. Surge at Ridge Base (m)	Difference Pair 1 (m)	Difference Pair 2 (m)	Difference Pair 3 (m)
A	500	18	0.30	0.036	-	-
	1000	18	0.30	0.047	-	-
	1500	18	0.30	0.065	-	-
B	500	18	0.95	0.035	0.020	0.003
	1000	18	0.95	0.081	0.051	0.018
	1500	18	0.95	0.129	0.086	0.032

From these tests it was concluded that the differences caused by ridges less than 800 meters (about ½ mile) long were not significant. It was therefore recommended that ridges shorter than 800 meters not be represented in the ADCIRC model grid. Also, where positive linear relief features were segmented by gaps, only those spaced farther than ½ mile apart would need to be represented.

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