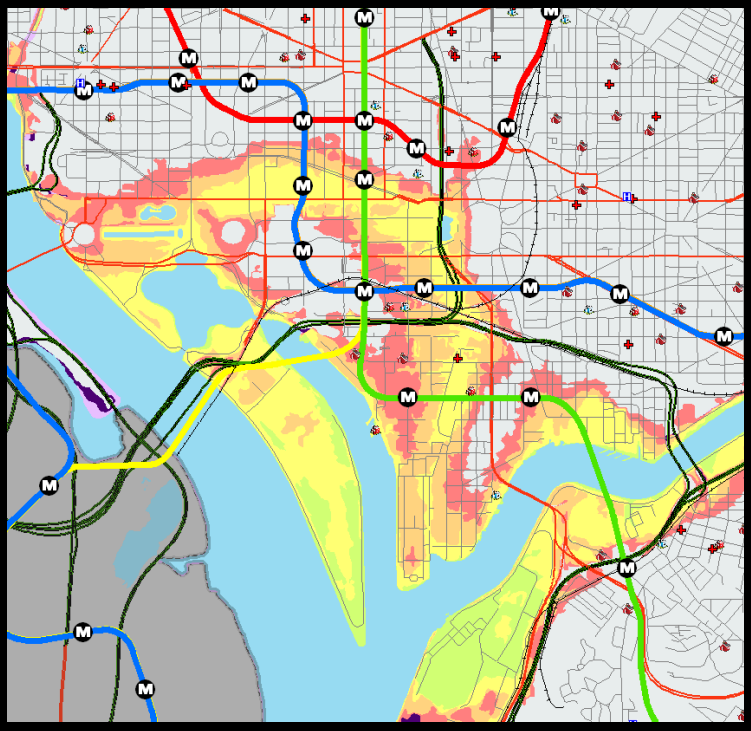

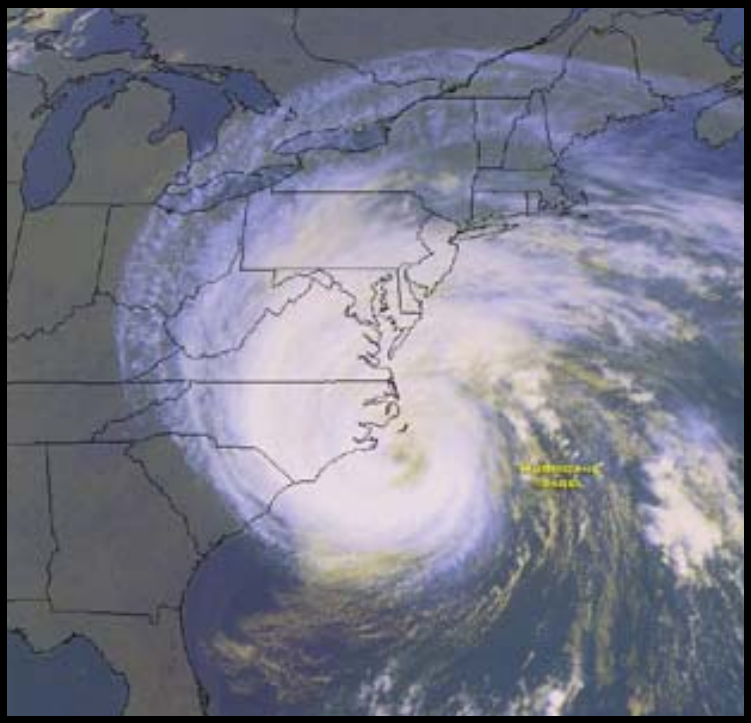

Washington, DC Metropolitan Area Hurricane Storm Surge Mapping

FINAL REPORT

FEMA

Prepared by:

National Planning Center of Expertise
for Coastal Storm Damage Reduction
USACE National Hurricane Program Office
North Atlantic Division/Baltimore District

June 2009

WASHINGTON, DC METROPOLITAN AREA
Hurricane Storm Surge Mapping

Prepared for

Federal Emergency Management Agency
National Hurricane Program

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1 INTRODUCTION

The National Hurricane Program (NHP) has conducted Hurricane Evacuation Studies (HESs) for most of the coastal communities impacted by Tropical Storms for the past 27 years. Two on-going HESs in the mid-Atlantic region, the Maryland Western Shore HES and the Virginia HES, will be completed in Spring 2009. As identified in Figure 1-1, the study area for the Maryland Western Shore HES includes eight jurisdictions (seven counties and one city) ranging from Harford County to the north to St. Mary's County to the south. The Virginia HES includes 18 jurisdictions (10 counties and eight cities) ranging from Westmoreland County to the north to the City of Virginia Beach to the south.

The geographical area between these two study boundaries includes the District of Columbia, Arlington County, City of Alexandria, Fairfax County, Prince William County, Stafford County, and King George County. These seven geographical jurisdictions were not part of the Maryland Western Shore nor the Virginia HES. In 2003, Hurricane Isabel demonstrated that these areas around our Nation's Capital are vulnerable to hurricanes and the various devastating impacts that are associated with these tropical storm systems. As a result, the NHP funded the initial phase of a HES, a Hazards Analysis for the District of Columbia and Northern Virginia region. Depending on the results of the Hazards Analysis, the NHP with input from the Commonwealth of Virginia and the District of Columbia will assess the need for a full HES for the District of Columbia and Northern Virginia area.

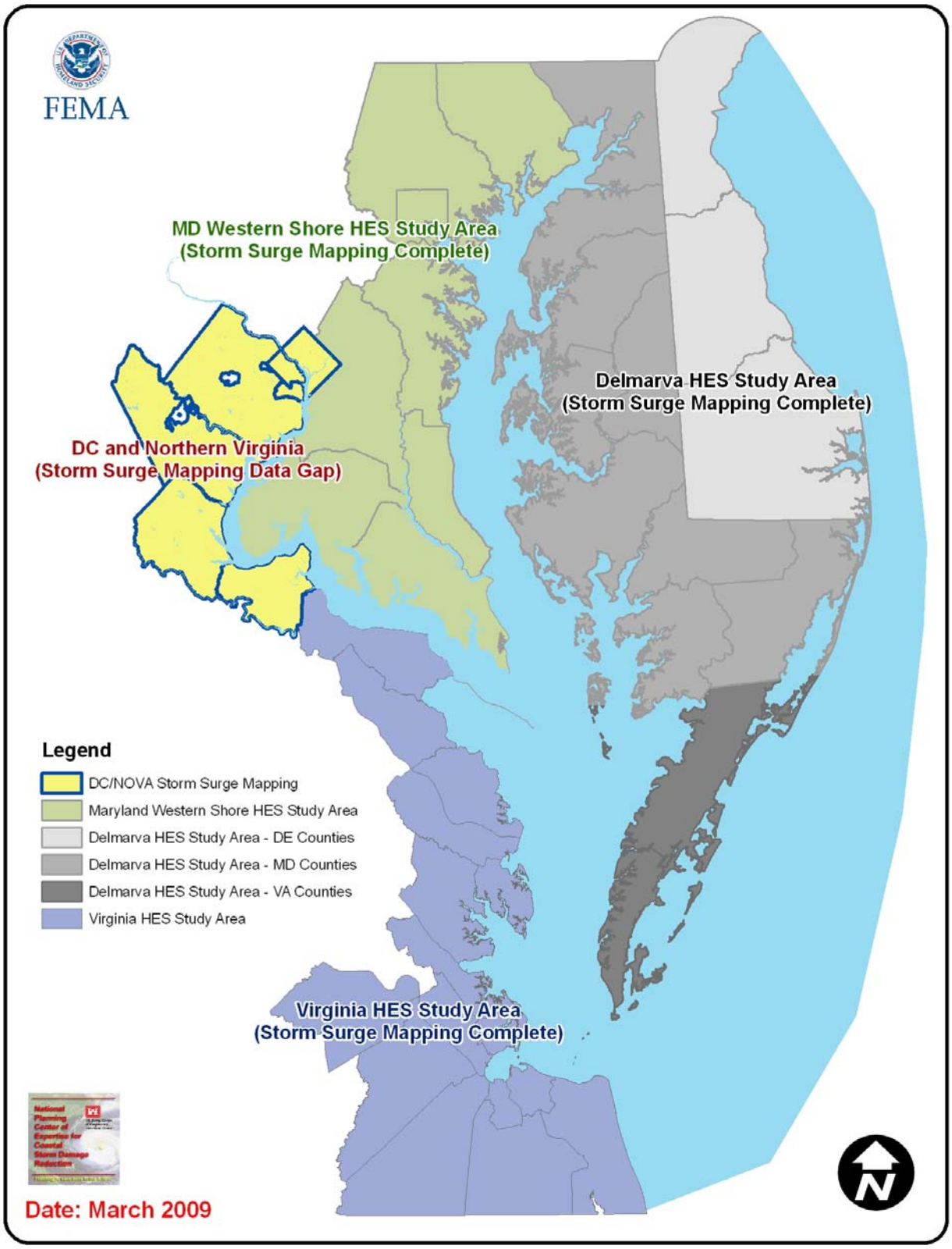
The primary objective of this Hazards Analysis is to determine the probable worst-case (peak) storm surge from the various intensities of hurricanes that could strike the region. The end product of this analysis includes worst-case scenario storm surge mapping for each category hurricane (i.e., categories 1, 2, 3, and 4). Categories 1 through 4 refer to the Saffir-Simpson scale of hurricane intensity. Using the National Oceanic and Atmospheric Administration's (NOAA) Sea, Lake and Overland Surges from Hurricanes (SLOSH) model, the storm surge elevations used for the mapping presents "worst-case" combinations of direction, forward speed, landfall point, and astronomical tide for each Saffir-Simpson scale of hurricane category. A detailed description of the SLOSH model is presented in Section 2 – Storm Surge Mapping Methodology.

The following major tasks, which are defined in Section 2 – Storm Surge Mapping Methodology, were completed under this project:

1. Data Collection
2. Data Analysis and Interpolation
3. Geographical Information System Storm Surge Mapping Analysis and Data Creation
4. Storm Surge Map Production

This project produces two deliverables: 1) a hardcopy storm surge map for each county/jurisdiction in the study area and 2) a GIS storm surge inundation data layer for each county/jurisdiction.

Figure 1-1: Maryland Western Shore and Virginia HES Study Area and the DC and Northern Virginia Hazards Analysis Study Area.



2 STORM SURGE MAPPING METHODOLOGY

2.1 STORM SURGE

Storm surge is the abnormal rise in water level caused by extreme wind and pressure forces. Various storm events can cause storm surge, but it is generally the result of a very large scale meteorological disturbance. Along the mid-Atlantic seaboard, extra-tropical storms known as "nor'easters" have produced some of the highest storm surges and resultant damages in recent history. However, hurricanes, because of their vast energy and relative compactness, have the potential to produce much higher storm surges. Storm surges can affect a shoreline over distances of more than 100 miles; however, there may be significant spatial variations in the magnitude of the surge due to local bathymetric (water depth) and topographic features. Wind is the primary cause of storm surge. Wind blowing over the surface of the water exerts a horizontal force that induces a surface current in the general direction of the wind. The surface current, in turn, forms currents in subsurface water. In the case of a hurricane, the depth affected by this process of current creation depends upon the intensity and forward motion of the storm. For example, a fast-moving hurricane of moderate intensity may only induce currents to a depth of a hundred feet, whereas a slow moving hurricane of the same intensity might induce currents to several hundred feet. As the hurricane approaches the coastline, these horizontal currents are impeded by a sloping continental shelf, thereby causing the water level to rise. The amount of rise increases shoreward to a maximum level that is often inland from the usual coastline.

Factors Affecting Surge Height

The elevation reached by the storm surge depends upon the meteorological parameters of the hurricane and the physical characteristics along the coastline. The meteorological parameters affecting the height of the storm surge include the intensity of the hurricane, measured by the storm-center sea-level pressure, track (path) of the storm, forward speed, and radius of maximum winds. This radius, which is measured from the center of the hurricane eye to the location of the highest wind speeds within the storm, can vary from as little as 4 miles to greater than 50 miles. Due to the complementary effects of forward motion and the counterclockwise rotation of the wind field (in the northern hemisphere), highest surges from a hurricane usually occur on the right side of the storm's track in the region of the radius of maximum winds. Peak storm surge may vary drastically within a relatively short distance along the coastline, depending on the radius of maximum winds and the point of hurricane eye landfall. The geophysical characteristics that influence the surge heights include the basin bathymetry, roughness of the continental shelf, configuration of the coastline, and natural or man-made barriers. A wide, gently sloping continental shelf or a large bay may produce particularly large storm surges.

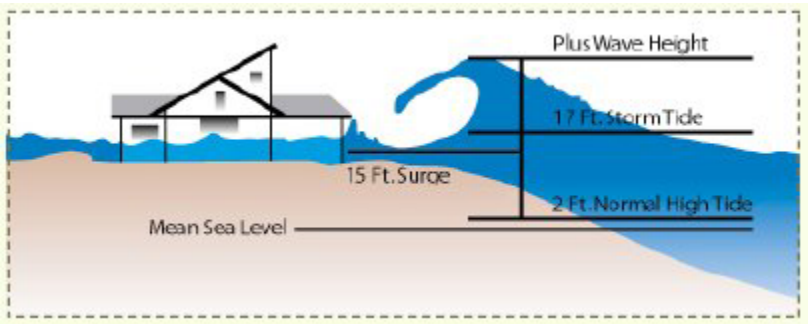
Total Flood Elevation

Other factors that contribute to the total flood elevation, or storm tide, are the initial water level within the basin at the time the hurricane strikes, and wave effects. Since storm surge increases the water level above the normal astronomical tide, a low-tide event is the best possible timing for landfall, while a high-tide event is the worst. The timing of the arrival of storm surge relative to the astronomical tide cycle is very important in that the difference in total flood elevation can be as much as 3 to 4 feet in the District of Columbia and Northern Virginia area of the Potomac River.

Another contributing factor to storm tide is the height of the waves themselves. The NOAA Sea, Lake and Overland Surges from Hurricanes (SLOSH) model does not provide data concerning the additional heights of waves generated on top of the still-water storm surge. Since near-shore wave phenomena under hurricane conditions are not well understood, it is assumed that for the open coast or shoreline, maximum theoretical wave heights occur near the time of landfall. Immediately along the coastline or the shorelines of very large sounds and estuaries, wave crests can increase the expected still-water depth above the terrain by one-third, thus greatly increasing the hazard. Due to the presence of barriers such as structures, dunes, or vegetation, the waves break and dissipate a tremendous amount of energy within a few hundred yards of the coastline. Buildings within that zone that are not specifically designed to withstand the forces of wave action are often heavily damaged or destroyed.

Figure 1-2 illustrates the relationship of astronomical tide, storm surge, storm tide and wave height.

Figure 1-2: Surge Model



2.2 DATA COLLECTION

To create storm surge maps for hurricane evacuation planning, two pieces of data, specifically GIS data, are required, which include 1) Topography Data and 2) NOAA SLOSH data. The following describes the topography and the SLOSH data that was collected to create the District of Columbia and Northern Virginia Storm Surge Maps.

Topography Data (Light Detection and Ranging (LiDAR))

Topography data for the District of Columbia, Arlington County, City of Alexandria, Fairfax County, Prince William County and the majority of Stafford County was provided by the Army Geospatial Center Imagery Office. The data is from 2004 at a 1-meter resolution in a bare earth grid format. The vertical datum is NAVD88.

Topography for King George County, dated 2006, was obtained from the Virginia Geographic Information Network (VGIN). This data was obtained in a TIN GIS file format and the vertical datum is NAVD88.

Topography for Stafford County was also derived from VGIN data created for the county in 2006 and 2007 as contours, with NAVD88 vertical datum. Figure 2-1 illustrates the extents of the elevation data collected. It should be noted that the topography for Stafford County was only

utilized in the southernmost areas of the county, where the 1-meter resolution grid supplied by the Army Geospatial Center Imagery office was not available (see Figure 2-1).

Sea, Lake and Overland Surges from Hurricanes (SLOSH)

SLOSH data, most recently updated in 2008, for the Chesapeake Bay Basin was supplied by NOAA. The SLOSH numerical storm surge model was developed by the National Weather Service to calculate potential surge heights from hurricanes. The SLOSH model was first conceived for real-time forecasting of surges from approaching hurricanes. In addition to computing surge heights for the open coast, the SLOSH model has the added capability to simulate the routing of storm surge into sounds, bays, estuaries, and coastal river basins, as well as calculating surge heights for overland locations.

Geophysical characteristics of an area covered by a SLOSH model are constructed as input data within the model. These characteristics include the topography of inland areas; river basins and waterways; bathymetry of near-shore areas, sounds, bays, and large inland water-bodies; significant natural and manmade barriers such as barrier islands, dunes, roads, levees, etc.; and a segment of the continental shelf. The SLOSH model simulates inland flooding from storm surge and permits flow through barrier gaps and barrier overtopping.

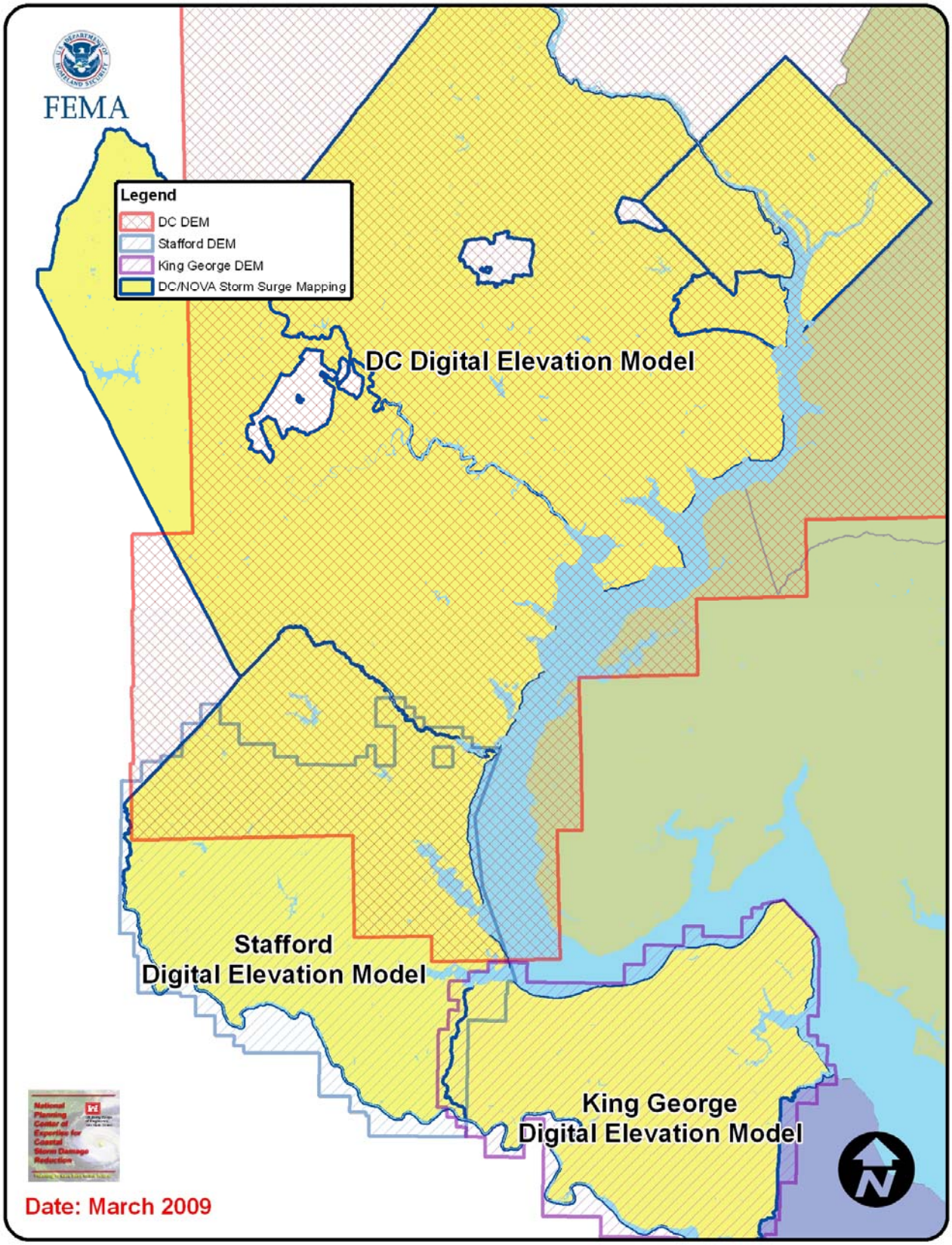
The SLOSH model uses time-dependent meteorological data to determine the driving forces of a simulated storm. These data are as follows:

1. Central barometric pressure at 6-hour intervals.
2. Latitude and longitude of storm positions at 6-hour intervals.
3. The storm size measured by the radius of maximum winds. Wind speed is not an input parameter, since the model calculates a wind-field for the modeled storm based on meteorological input parameters.

The height of the water surface well before the storm directly affects the area of interest and is also required. This initial height is the observed water surface elevation occurring about 2 days before storm arrival. In addition to mean tide, astronomical high tide was also set in the model.

The Chesapeake Bay SLOSH model was used for the District of Columbia and Northern Virginia Storm Surge Mapping. After initialization with observed geophysical values (depths of water and heights of terrain and barriers), the SLOSH model output provides heights of storm surge for various combinations of hurricane strength, forward speed, and approach direction. Storm strength is modeled using the minimum central pressure and radius of maximum winds for four of the five categories of storm intensity. Because of their extremely low chance of occurrence, Category 5 hurricanes were not modeled for the Chesapeake Bay SLOSH basin.

Figure 2-1: Topographic Data Used in the DC & Northern Virginia Storm Surge Mapping



After a SLOSH model has been constructed for a coastal basin, verification is conducted as real-time operational runs in which available meteorological data from historical storms are input into the model. The computed surge heights are compared with those measured from the historical storms and, if necessary, adjustments are made to the input or basin data. These adjustments are not made to force agreements between computed and measured surge heights from historical storms but to more accurately represent the basin characteristics or historical storm parameters. In instances where the model has given realistic results in one area of a basin, but not in another, closer examination has often revealed inaccuracies in the representation of barrier heights or missing values in bathymetric or topographic data.

The SLOSH model output for a modeled storm consists of envelopes of high water, and contains the maximum surge height values calculated for each grid point in the model. Maximum surges along the coastline do not necessarily occur at the same time. The time of the maximum surge for one location may differ by several hours from the maximum surge that occurs at another location. Therefore, at each grid point, the water height value shown is the maximum that was computed at that point during the 72 hours of model time, irrespective of the time during the simulation that the maximum surge height occurred.

Over 3,000 hypothetical hurricanes were modeled for the Chesapeake Bay basin at both mean and high tide. The characteristics of the simulated hurricanes were determined from an analysis of historical hurricanes that have occurred within the study area. The parameters selected for the modeled storms were the intensities, forward speeds, approach directions, and radii of maximum winds that are considered to have the highest meteorological probability of occurrence within the Chesapeake Bay Basin. Additionally, the SLOSH model for the storm surge in the Chesapeake Bay basin was updated post Hurricane Isabel due to inaccuracies in the model that were discovered in the Post Storm Assessment for Hurricane Isabel.

Maximum Envelopes of Water (MEOWS)

The highest surges reached at all locations within the affected area of the coastline during the passage of a hurricane are called the maximum surges for those locations; the highest maximum surge in the affected area is called the peak surge. The location of the peak surge depends on where the eye of a hurricane crosses the coastline, hurricane intensity, basin bathymetry, configuration of the coastline, approach direction, and radius of maximum winds. The peak surge from a hurricane usually occurs to the right of the storm path and within a few miles of the radius of maximum winds.

Due to the National Hurricane Center's (NHC) inability to precisely forecast the landfall locations of hurricanes, the NHC Storm Surge Group developed the Maximum Envelopes of Water (MEOWs). MEOWs determine the potential peak surge at every location within the SLOSH basin. For example, if there were two storms, identical in every respect and they followed parallel tracks separated by 50 miles, then very likely there would be locations having markedly different surge values resulting from the two storms. This dependency of surge height on storm track can be troublesome in evacuation planning. Accordingly, MEOWs were produced by running the SLOSH model to create a group of storms, all having the same characteristics, but with parallel tracks 10 miles apart. At each grid square, the maximum surge value that was calculated was saved. The result was a "maximum envelope of water." Thus the MEOW is the "worst case" surge that could be produced at any location by a storm with a particular

combination of approach direction, forward speed, and intensity, regardless of where landfall may have occurred. Since the MEOW is the "worst case" at all locations, no one storm can duplicate the flooding depicted by a MEOW.

Maximum of the MEOWS (MOMs)

The results of the 248 MEOWs were analyzed to determine which changes in storm parameters (i.e., intensity, approach speed, and approach direction) resulted in the greatest differences in the values of the peak surges for all locations, and those that could reasonably be combined to facilitate evacuation decision-making. Changes in storm category accounted for the greatest change in peak surge heights. Careful consideration was given to the impacts of various combinations of storm parameters on hurricane evacuation planning and decision-making. To simplify these processes, the NHC was asked to compile additional MEOWs.

The NHC subsequently combined MEOWs to create MOMs (Maximums of the MEOWs), eliminating consideration of hurricane approach speed and direction, but maintaining the separation of categories 1, 2, 3, and 4. It was from those MOMs that the storm surge maps were developed for the District of Columbia and Northern Virginia area using high tide conditions.

The storm surge heights that result from the SLOSH model for the Chesapeake Bay basin are referenced to the NGVD29 vertical datum. Figure 2-2 illustrates the SLOSH MOM output for a category 2 hurricane at high tide for the Chesapeake Bay basin in a polygon GIS format.

Hurricane evacuation decision-makers should keep in mind that the SLOSH model is a mathematical model and does not always produce perfect results. Based on the results of the statistical analysis conducted by the National Weather Service, a +20 percent adjustment to the SLOSH values would eliminate nearly all of the potential negative errors occurring from the model. However, such an adjustment would also add additional surge height to those values that already contain positive errors, possibly endangering the credibility of the SLOSH results. Therefore, a general adjustment was not made to the computed surge heights. Evacuation planners should remain cognizant of the potential 20 percent underestimate of some SLOSH surge values.

2.3 DATA ANALYSIS AND INTERPOLATION

SLOSH data, in a polygon GIS shapefile format, is converted into a point GIS shapefile format as illustrated in Figure 2-3. The points represent centroids of each polygon in the Chesapeake Bay basin grid. This information is exported to a spreadsheet format and imported into the Corpscon software in order to convert values from NGVD29 to NAVD88. The updated spreadsheet is then imported into GIS and converted to a point shapefile and exported to a geodatabase. HUC12 data, which represents watershed boundaries, is also imported into the same geodatabase. A terrain is built for each category hurricane (1-4). Figure 2-4 illustrates the terrain built for a category 2 hurricane. The SLOSH MOM point data is utilized as the source of the heights, while the watershed boundaries are used as a hard value fill in creating the terrain. The terrain, which is similar to a TIN, is then exported to a grid format for each category hurricane. This results in the creation of four grids, each representing the MOM storm height for the 4 distinct categories of hurricanes.

Figure 2-2: SLOSH MOM Output for a Category 2 Hurricane

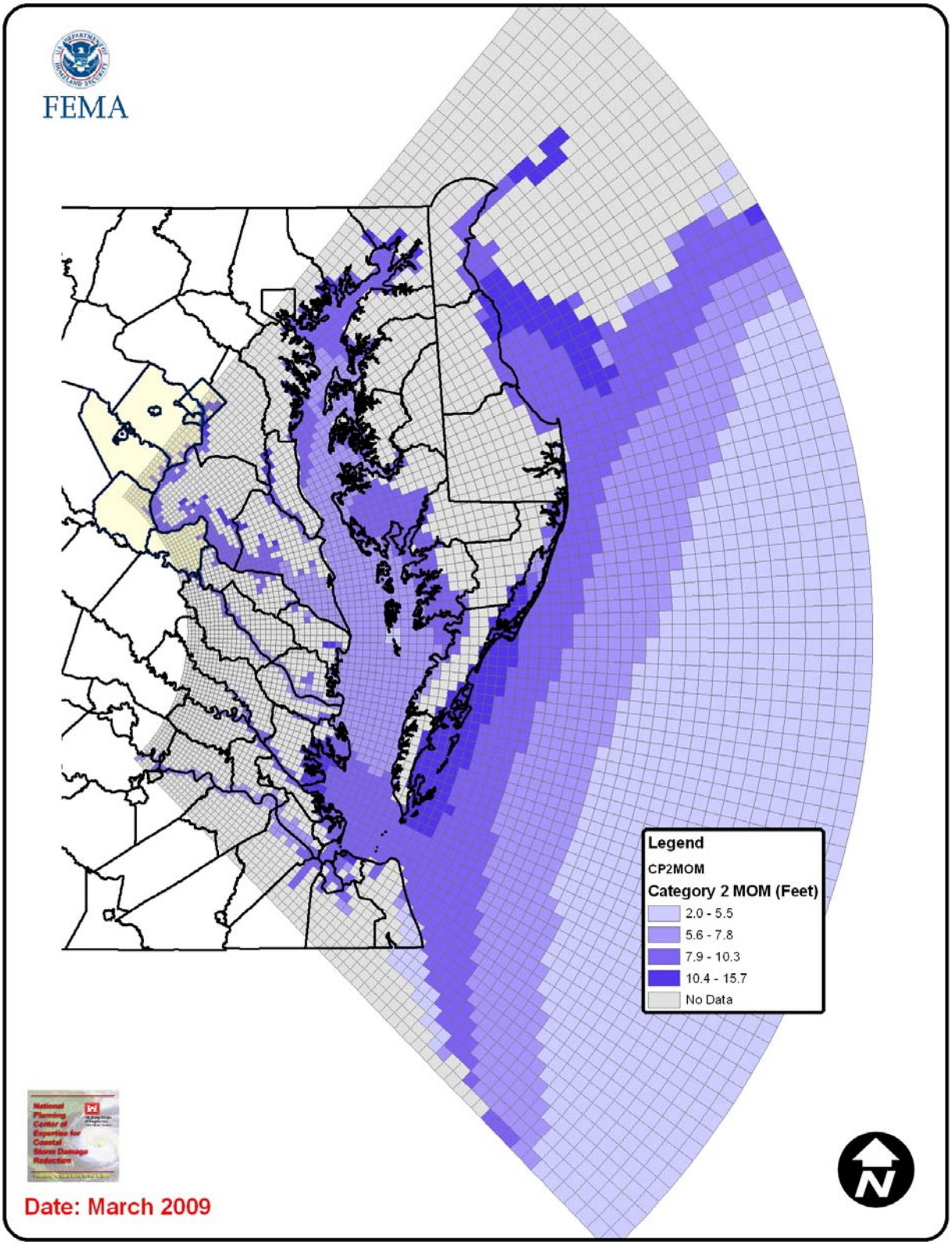


Figure 2-3: SLOSH Data Converted into a Point GIS Shapefile Format

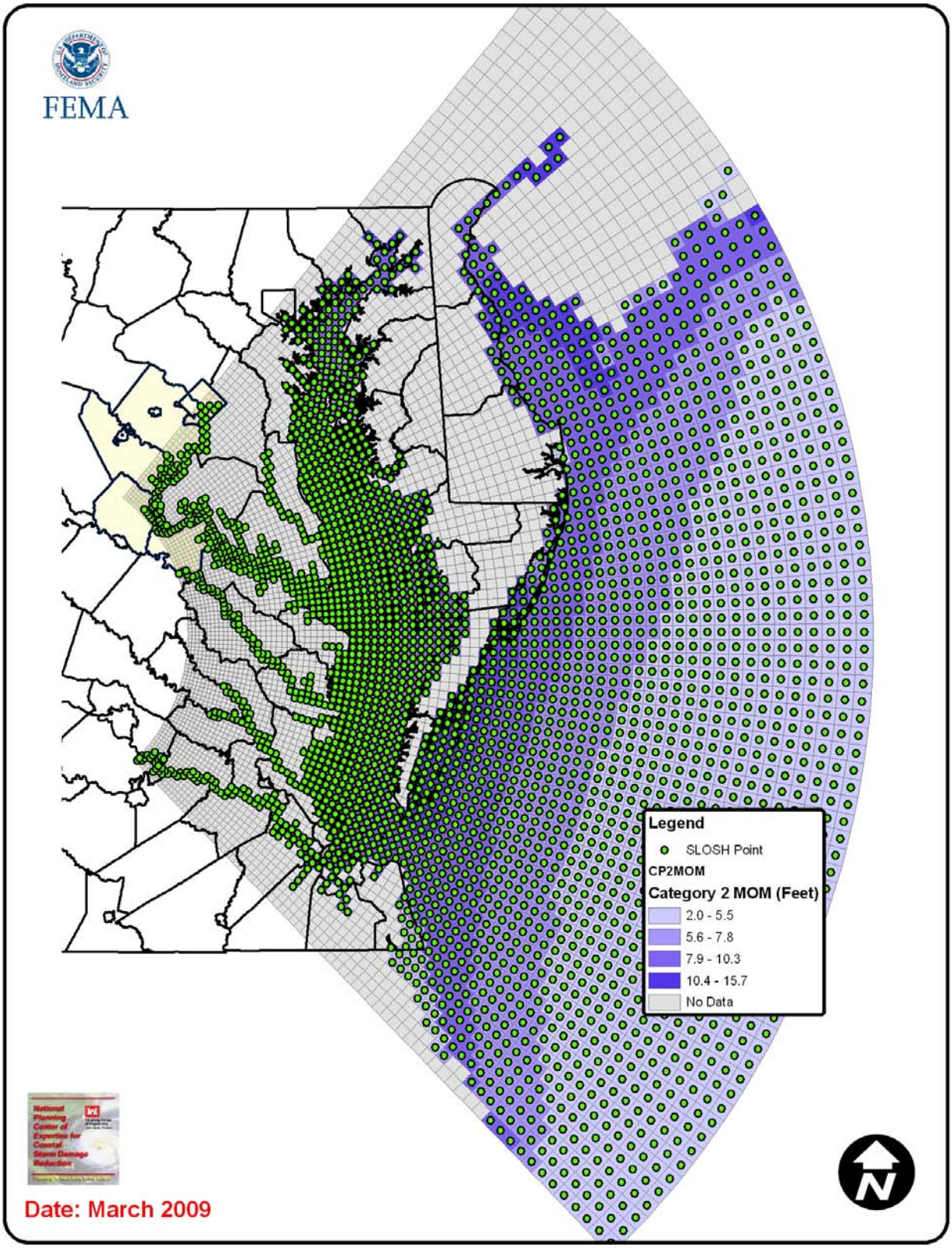
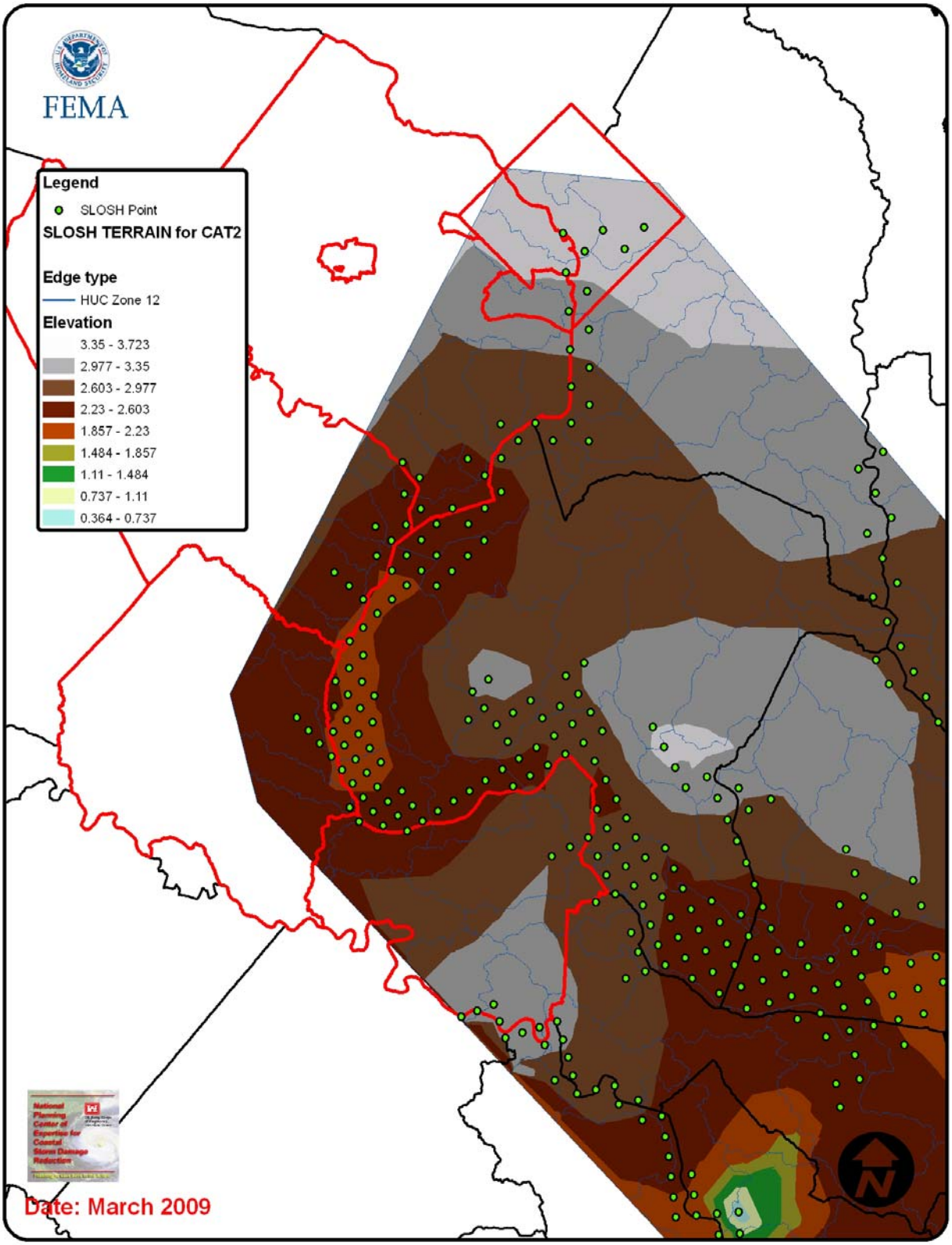


Figure 2-4: SLOSH Terrain, Created within a Geodatabase



After the interpolation of the SLOSH MOM data has been completed, then the collection topography data, if needed, is converted into grid format to match the grid format of the created SLOSH MOM grid. Topography data supplied by the Army Geospatial Center is in grid format, so no conversion was necessary. However, the topography data for King George and Stafford Counties required conversion from their original format into a grid format. The data for King George County was exported from TIN to a 3-meter resolution grid within ArcGIS. Data for Stafford County was imported as contours into a geodatabase. This data was then imported into a terrain, which was exported to a 3-meter resolution grid.

2.4 GEOGRAPHICAL INFORMATION SYSTEM STORM SURGE MAPPING ANALYSIS AND DATA CREATION

USACE has developed a hurricane storm surge GIS mapping process within the ModelBuilder environment of ArcGIS. This mapping process calculates the difference between the interpolated SLOSH MOM grids (Storm Surge Heights) and the collected digital elevation grids (Land Topography Values). The final product of this model is a raster, with values indicating which category hurricane would inundate an area (see Figure 2-5). A smoothing model using ArcGIS is then applied to this data. Figure 2-6 shows the final output of this model. Contours are created for each category hurricane; these contours are then imported into a geodatabase. Within the geodatabase, a topology is built and a polygon feature class is created. The contours are then used to build this polygon, with the final product being a single polygon GIS file that represents the extents of inundation for all categories of hurricanes. Within this polygon, the field "HES_Zone" is populated with values of 1,2,3,4 or 99. "1" indicates the area is inundated by a Category 1 hurricane, "2" indicating that an area is inundated by a category 2 hurricane, and so on. The value "99" indicates that an area is not going to be inundated in any storm.

2.5 STORM SURGE MAPS

As previously stated, this project produced two deliverables for the emergency management community in District of Columbia and Northern Virginia. The first end product is a hardcopy storm surge map for each county/jurisdiction that overlays the worst possible storm surge (peak surge) for each category hurricane with roadways, populated places, and other points of interests (i.e., police stations, fire stations, hospitals, nursing homes, and schools), if the data was available. These hardcopy maps are located in Appendix A. Additionally, PDF files for each storm surge map are located on the compact disc in Appendix B.

The second deliverable for this project is an ArcGIS geodatabase that contains the storm surge inundation data clipped for each county/jurisdiction and one storm surge GIS data layer for the entire study area. The geographical projection for all the storm surge GIS data is in North American Datum (NAD) 1983 State Plane Virginia North. All GIS storm surge data is located on the compact disc in Appendix B.

Figure 2-5: Hurricane Storm Surge Model Output as a Raster

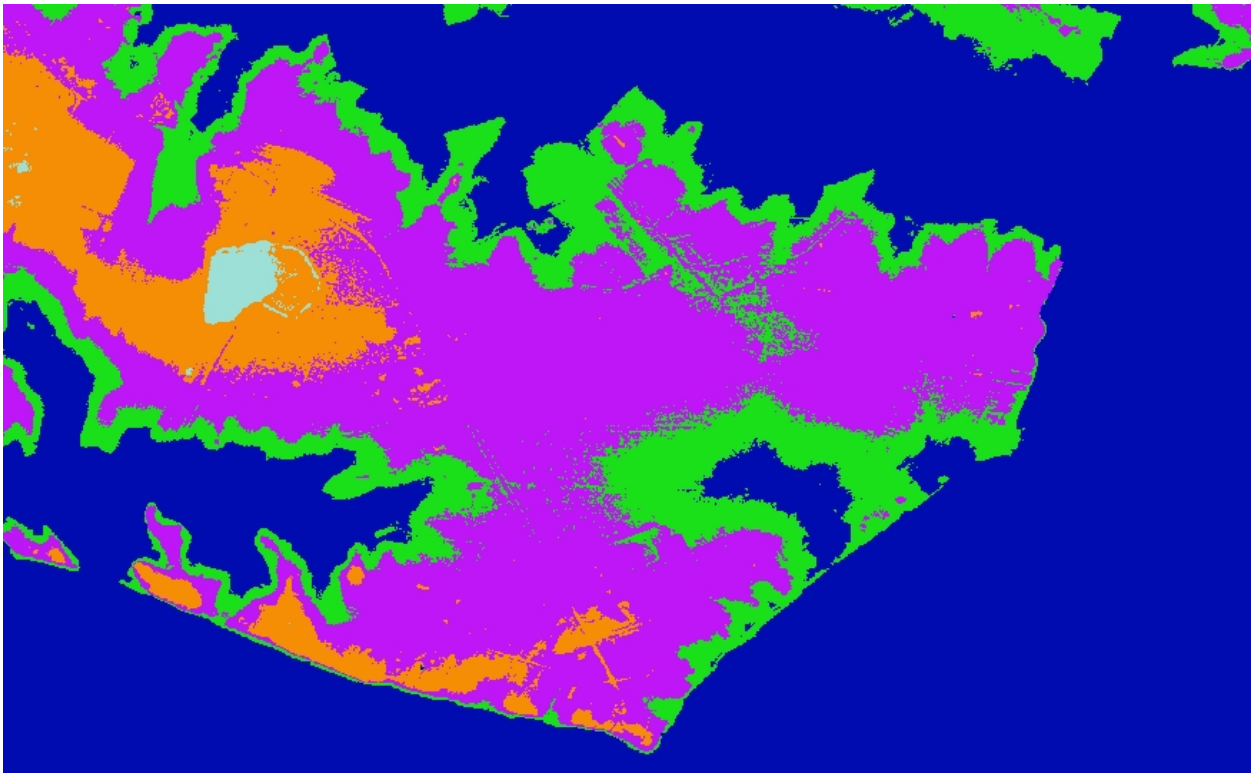


Figure 2-6: Smoothing Model Output using the Storm Surge Model Output

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3 RECOMMENDATIONS

The NHP develops storm surge inundation mapping to assist the State and local emergency managers with the development of hurricane emergency management plans. It is important to note that these inundation maps are for planning purposes only and should not be used for the design and construction of site-specific mitigation projects (i.e., levees). The storm surge mapping represents the worst cast scenario or peak storm surge for a category 1, 2, 3, and 4 hurricane based on an interpolation of NOAA's SLOSH model, which can contain a 20 percent +/- error. Based on the level of detail for this storm surge mapping product, the following table (Table 3-1) lists tasks that could be completed using the created storm surge data.

Table 3-1: Recommended Use for the GIS Storm Surge Data

Tasks	Name	Description
Task 1	Evacuation Zone Development	As part of the Hurricane Evacuation Study (HES) process, the next step is to use the storm surge maps to work with the local and State emergency management community to identify hurricane evacuation zones and develop GIS data layer for the identified evacuation zones.
Task 2	Vulnerability Analysis	Using GIS technology, a vulnerability analysis could be completed to identify vulnerable population that could be potential impacted by storm surge flooding. The following GIS data would be used to complete this analysis: storm surge, evacuation zones, census data or tax parcel data.
Task 3	Critical Facility Impact Analysis	Compare location of critical facilities (i.e., schools, hospitals, fire stations, shelters, major utilities, etc.) with location of the identified peak storm surge for category 1 through 4 hurricanes.
Task 4	Roadway Impact Analysis	Compare identified evacuation routes and major roads of egress and ingress for emergency vehicles with location of the identified peak storm surge for category 1 through 4 hurricanes.
Task 5	Federal Facility Impact Analysis	Using the storm surge mapping data, complete an analysis of the impact of storm surge flooding on federal facilities within the District of Columbia and Northern Virginia.

The NHP is near the completion of the Maryland Western Shore, Delmarva, and the Virginia HESs. The final product of the HESs includes the determination of transportation hurricane evacuation clearance times that are used by state and local emergency managers in making evacuation decisions. The hurricane evacuation clearance times for the Delmarva and Virginia HES have been loaded into HURREVAC, an evacuation decision assistance tool used by thousands of emergency managers and planners throughout the coastal community. The target date for loading the Western Maryland Shore clearance times into HURREVAC is prior to the start of the 2009 Hurricane Season.

The Hazard Analysis, which is the creation of the storm surge mapping, as previously stated, is the first phase of the HES process. The District of Columbia and the Commonwealth of Virginia, in coordination with the local Virginia communities, should discuss whether continuing the HES would provide information beneficial to their hurricane evacuation planning and if so, make a formal request to the NHP. The recently completed hurricane evacuation clearance times for the Maryland Western Shore, Delmarva, and Virginia could be used to assist the completion of a regional hurricane evacuation transportation study for the Maryland, Virginia, and the District of Columbia. However, in order to complete a regional hurricane evacuation transportation study, the recommended tasks outlined in Table 3-1 would need to be completed. NHP funding is limited and there is no guarantee that sufficient funds would be available to continue the study with next fiscal year funds without leveraging funds from other federal agencies and potential state contributions.

Appendix A – Hardcopy County Storm Surge Maps

Appendix B – CD with Storm Surge Mapping GIS Shapefiles and PDF Maps