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Chapter 5

Visualization for Hurricane Storm Surge Risk Awareness and Emergency Communication

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1. Introduction

1.1. The impetus for hurricane storm surge visualization

Visualizations of storm surge forecasts offer opportunities to improve risk awareness and communication of impending disaster in emergency situations such as a hurricane evacuation. A continuum of potential visualizations ranges from static maps, animated model output, to 3-D, immersive, and multimedia. In addition to risk communication for the public high-quality photorealistic geovisualizations might allow managers to investigate and explore forecasted surges and could reveal vulnerabilities and improve preparedness and response. Visualization can reveal three-dimensional space-time dynamics and provide insights for practical applications [1,2]. Scientific and visual analytic applications, for example, might include representations of model uncertainty or instability, such as "quality flags" symbolized on the model mesh or grid. With a focus on spatial and specifically "place-based" site and situation, geovisualization encourages analysis for multiple purposes and users, for interpreting spatial patterns, and using new multimedia and communications in a broader, informed way among academics, government managers, and stakeholders [3]. Hence, the challenge is to develop accessible technology that will provide proven and robust improvements to risk awareness and communication.

This chapter aims to evaluate existing storm surge models such as Sea, Lake, and Overland Surges from Hurricanes (SLOSH) and ADvanced CIRCulation (ADCIRC) models (described below) in order to identify constraints to their application for risk communication and to explore their potential for diverse forms of geovisualization. This chapter reviews some of the physical and computational limitations of surge models, the factors inhibiting spatial repre-

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sentation and visualization, and the applications of and hurdles for GIS post-processing and cartographic analysis and communication. A subset of computational techniques and geovisualizations are demonstrated that could improve upon the limitations inherent in the status quo approaches to representing surge and inundation model output. Applications and case studies that employ enhanced spatial resolution (down-scaled) grid output, enforcement of hydrologic connectivity in spatial models of inundation, and web-based, interactive cartography (2-D and 3-D) and 3-D, animated, and interactive-immersive geovisualization are described. Enhanced visualizations that provide better "on the ground" resolution of potential flooding events play an increasingly critical role in surge management and response, particularly in urban centers with dense population and infrastructure. While storm tracks, intensity forecasts, and tabular metrics have become ubiquitous, they do little to convey the highly localized effects of potential flooding at municipal or facility scales. The chapter concludes with a case study, reflects upon the constraints and limitations, and makes suggestions for avenues of future research.

1.2. General approaches to modeling water surfaces

Users of storm surge model output should realize that the surface of the storm tide is not flat. It has relief. In addition, local short-term variation in sea surface height results mostly from tidal forces and atmospheric conditions and is less influenced by large-scale ocean and estuarine circulation, or even gravitational anomalies. NOAA has defined three broad categories within which most storm surge models may be classified: modeled water surfaces, interpolated water surfaces, and single-value water surfaces [4].

Modeled water surfaces typically comprise inundation grids that are based on output from either a single hydrodynamic model, or a combination of hydrodynamic and wave models. Both the SLOSH and ADCIRC models provide modeled water-surface outputs. Water surface models may consider variables such as winds, atmospheric pressure, tides, storm duration, basin circulation, terrestrial obstructions, and other factors. Increased output accuracy of modeled water surfaces is the primary benefit that results from accounting for this diversity of variables. However, the models used to produce these surfaces require significant amounts of *a priori* information and often require expert-level knowledge of one or more modeling applications.

Interpolated water surfaces may be preferred when only a few water level observations exist for an area of interest. In such cases, the modeler must interpolate water level values between actual water level measurements within the study area. This method is often used and best employed for post-event analysis when modelers employ observed high-water data (e.g., high water marks or tide gauges) to reconstruct flood levels for a storm. This approach for predictive surge modeling may have limited value due to the need for observational input. Input of a relatively small set of observational data may also result in a coarse resolution representation of the water surface height that does not adequately reflect variations due to terrestrial topography and other factors. However, the variety and complexity of interpolation methods benefits greatly from analyst experience in spatial statistical techniques.

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Single-value water surface models create water surfaces representations based on a single numerical water level value that is draped over a study area. These models are often known as "bathtub" models as they simply raise the water surface evenly and consistently over an entire region. Single-value water surface models may be the best alternative where only one water level observation is available and other modeling techniques are impractical [4]. Static models such as these are also frequently developed as second-tier models that use the output from modeled water surfaces (SLOSH, ADCIRC) as input parameters. The case study explored later in this chapter makes use of this technique. Single-value models require minimal modeling expertise and for this reason are often employed by small organizations with limited resources. NOAA suggests that modeled and interpolated surfaces are generally preferred to the single-value method for better accuracy and more realistic depictions [4].

2. Spatial modeling of hurricane surge inundation

Storm surge models are often developed by coastal modelers who only give secondary consideration to visualization or the potential for integration into GIS and other decision-support systems. There are many advantages to incorporation of such model output into decision-support systems. Other data layers, such as evacuation routes, critical infrastructure, and vulnerable populations, can be analyzed in conjunction with the model results. The SLOSH model is the model that most emergency managers use for evacuation decision-making as well as for post-landfall guidance regarding the areas of likely inundation impacts and for disaster-response planning [5]. The model output is spatially coarse and provides limited assistance to site-specific operational preparedness, but rather produces a first-order estimate of storm surge potential.

A GIS model has been created to downscale the resolution of the SLOSH output, and to provide a more representative estimation of inundation. The downscaling of the SLOSH output uses a variety of elevation layers to illustrate the model's flexibility. The downscaled SLOSH outputs, shown in experimental form throughout this chapter, are compared to the other currently available SLOSH data products available in the State of North Carolina's geospatial clearinghouse, NC OneMap [6], to determine the best mapping, interpolation, and visualization techniques to represent a slow-moving Saffir-Simpson category 3 storm. Other comparisons that will be discussed include the areal extent of inundation produced by each model, the discrepancies of impacted critical infrastructure in the output and the measures of size and vulnerabilities of affected at-risk populations based on coarse- and fine-scale data.

2.1. Slosh

The SLOSH model was originally developed by the Techniques Development Laboratory of the National Weather Service (NWS) as a real-time operational surge forecast that could be run once the appropriate tropical cyclone track and pressure data became available. The networks of grid points comprising model domains are called SLOSH basins, and have been created for the Atlantic coast, Gulf Coast, Bahamas, Virgin Islands, Puerto Rico, as well as for parts of China and India. Each grid cell in a SLOSH basin has either topographic or bathymetric data associated with it. Updates are released as new elevation and bathymetry data for particular basins are provided by the U.S. Geological Survey (USGS) and the National Geophysical Data Center (NGDC). SLOSH basins are individually designed for the geography of a given coastal segment. Depending on the size and location of the particular area of interest, one might choose from an assortment of telescoping grids. The telescoping grid allows for higher resolution in coastal areas and less detail of open ocean. This reduces computing requirements compared to structured grids with uniform cells across a model's domain.

To obtain the surge levels, the SLOSH model requires several fairly simple meteorological parameters, at specified time intervals. The calculations use the latitude and longitude of the storm's eye, central atmospheric pressure, the radius of the maximum winds (RMW), storm track and speed [7]. Surface wind speed is not an input parameter in the SLOSH model [8], but rather "water levels are forced by an idealized wind field that depends upon the pressure deficit (Δp) and the radius of maximum wind (RMW) from the storm center" [5]. Houston and Powell [5] note that the calculations consider topography and bathymetry, but not astronomical tides, waves or rainfall flooding.

Every model, whether forecast model or numerical model, requires assumptions. Different models are designed to operate and handle these inaccuracies and assumptions in different ways depending on the end-product and the end-user. SLOSH has its own series of issues and limitations. One issue relevant to local application stems from the grid structure and basin formation. While the telescoping grids are efficient with regard to computational resources, they can fall short of local managers' desires when used to model inundation and surge to inform decision-making. For example, if the area of interest is a section of hurricane-prone Dare County, North Carolina, USA, the size of the cell is often too coarse to distinguish either surge on sound-side or back-barrier sites versus open-ocean shorelines, or the direction and interaction of both source area surges. Coarse resolution in this region occurs as a result of distance from the central arc of the SLOSH grid origin. Figure 1 illustrates how the cell size increases with the distance along an axis of the telescoping grid for an area of the Pamlico Sound SLOSH basin, and shows ambiguities of source-cell inundation (shown in hachures of selected grid cells overlaid on a greyscale of Light Detection and Ranging (LiDAR) elevation grids for the peninsular mainland and Outer Banks barrier islands). One solution for disambiguating the potential surge for finer-scale, local hurricane emergency management is to downscale the SLOSH surge forecast and incorporate finer elevation data and hydrologic modeling techniques in a GIS. To do so opens up a new set of issues and subject matter for research and geovisualization, but also new concerns for miscommunication and the mistaken assumption of precision as opposed to model forecast accuracy.

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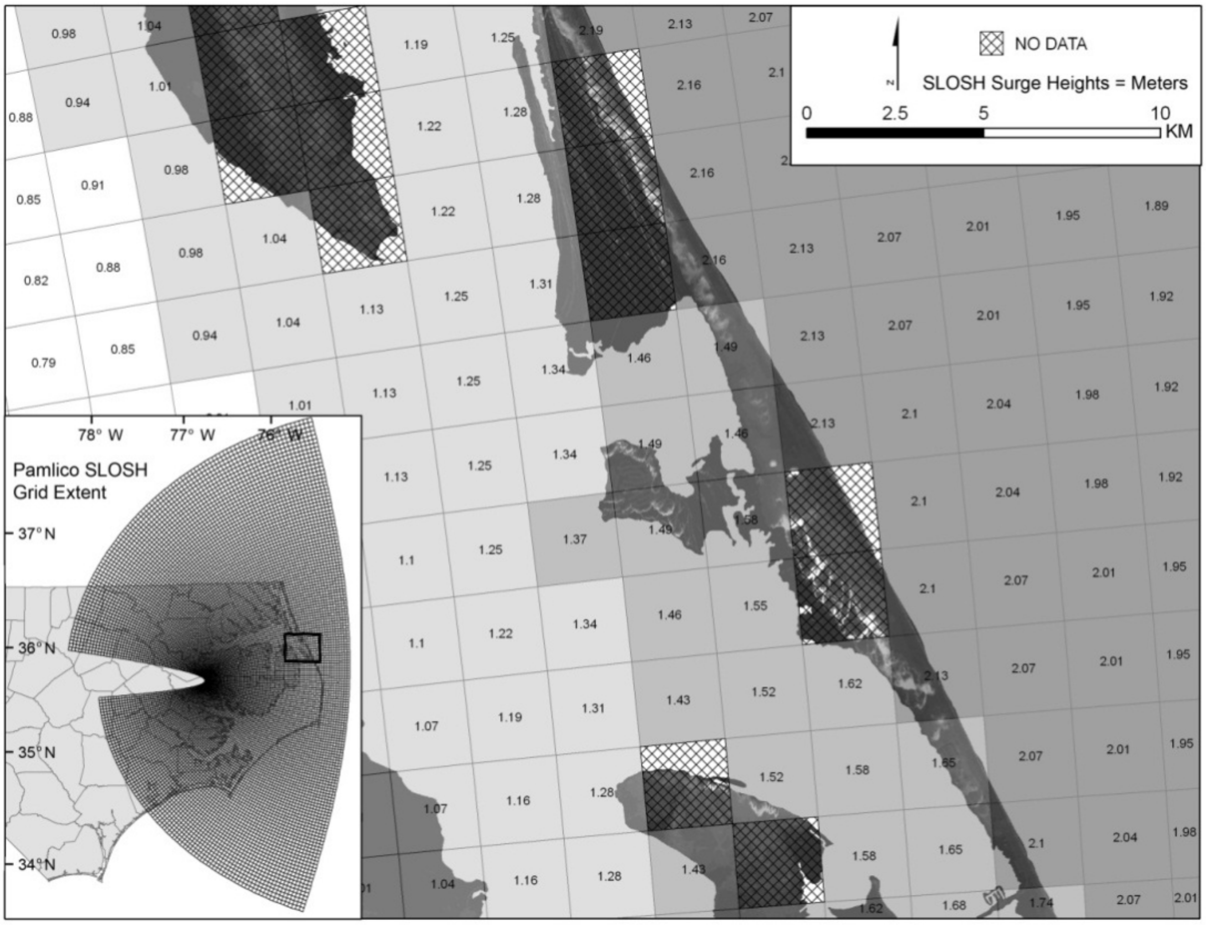

Figure 1. SLOSH surge model grid for Pamlico Sound Basin, North Carolina (inset) and a subset of the northern Outer Banks, illustrating telescoping grid scale, overlapping sound and ocean cells. Background shading of elevation corresponds to high resolution airborne LiDAR elevation values. Grid cells symbolize SLOSH forecast surge heights (meters) for a Category 2 slow-moving storm (Maximum-of-Maximums scenario) with hachured grid cells denoting ambiguities of source inundation (ocean vs. estuarine grid cells).

2.2. Surge visualization for emergency management

Coastal emergency managers have begun using visualizations in graphical programs to portray potential changes of ground-level inundation from floods and surges with photorealism and software applications such as *CanVis* [9,10]. Technologies such as webmap services and GIS portals are now ubiquitous and able to distribute storm surge models such as ADCIRC output and related maps and animations produced using real-time forecasting [11]. The Louisiana Geographic Information Center's 2009 Hurricane Response Mapping is one example that has linked the National Hurricane Center (NHC) products with custom-developed Internet map servers [12], while the NC Coastal Hazards Portal (NC COHAZ) is an experimental platform that integrates multiple hazard layers in separate thematic map interfaces (e.g., coastal erosion, surges, and real-time hazards) [13]. In addition, local emergency managers have GIS resources and personnel who can employ the GIS products like SLOSH from the NHC. Some may already be using GIS software, such as FEMA HAZUS for loss estimation, in their operations [14]. Output generated by HAZUS may include coastal flood models corresponding to 100-year return interval flood events, based on FEMA flood modeling. These output data can be rendered in a desktop GIS and even draped onto high resolution LiDAR DEMs with building footprints rendered in 3-D (Figure 2). The outputs of generic inundation or hydrologic models are often erroneously applied to a specific, approaching hurricane to meet the desire of emergency management officials for data and forecasts specific to the potential track, intensity, and other factors of their storm. The result can be very inaccurate and grossly erroneous visuals. Therefore, anyone desiring to visualize forecast surges from hydrodynamic models must first select the most appropriate surge model output data and cross-reference this to the spatial context, resolution, and time-delimited needs of emergency managers. SLOSH Maximum Envelope of Water (MEOW) and Maximum of Maximum (MOM) of MEOW files are provided with the SLOSH Display System [15] and are exportable to ESRI shapefile format for GIS analysis. The SLOSH Display System provides access to a library of pre-run simulations, including a graphical user interface (GUI) to query and extract appropriate MEOW or MOM files. The system can be used as a stand-alone decision support tool or in conjunction with other software (such as FEMA's HAZUS-MH [16], Sea Island Software and FEMA-funded HURREVAC [17], PC Weather Products' HURRTRAK tracking software [18], or within a GIS). In general, the MOMs provide forecast guidance for up to 5 days of pre-landfall operations and decision-making. MEOW surge files, depending upon the local evacuation dimensions, routing issues, and congestion factors, can be used to guide decision-making closer to the actual critical decision time. A minimum clearance time of 24 to 48 hours is typically desired, and this often prompts the use of MOM and MEOW surge estimates for guidance. Prior to landfall, hurricane track and intensity forecasts are usually inadequate to judiciously postpone a decision, unless tropical storm-force winds arrive during an evacuation. Furthermore, antecedent rainfall and forecasts from the NWS's Hydrometeorological Prediction Center [19], time of day, tides, and local logistical factors are also used in response decisions and the selection of surge guidance.

The MEOW output characterizes maximum surge level associated with a hypothetical storm at any time for every grid cell in a SLOSH Basin. The MEOW represents the worst-case flooding scenario possible from a threatening hurricane of a given category, size, and particular track direction [20]. MEOW files do not directly incorporate tidal conditions, but these may be generalized and either added or subtracted in software like the SLOSH Display System.

A MOM is the maximum of a set of MEOWs, forming a composite of the maximum water levels at every grid cell for all hurricanes of a given category and for water from all directions. There are only 5 MOMs for each SLOSH model basin, each representing a single storm category. As with MEOWs, the MOM does not factor in tides. However, the SLOSH Display System provides easy access to the library of pre-run simulations, and to a GUI to query and extract appropriate MEOW or MOM files and to incorporate approximate tidal conditions at landfall (low, mean, or high).

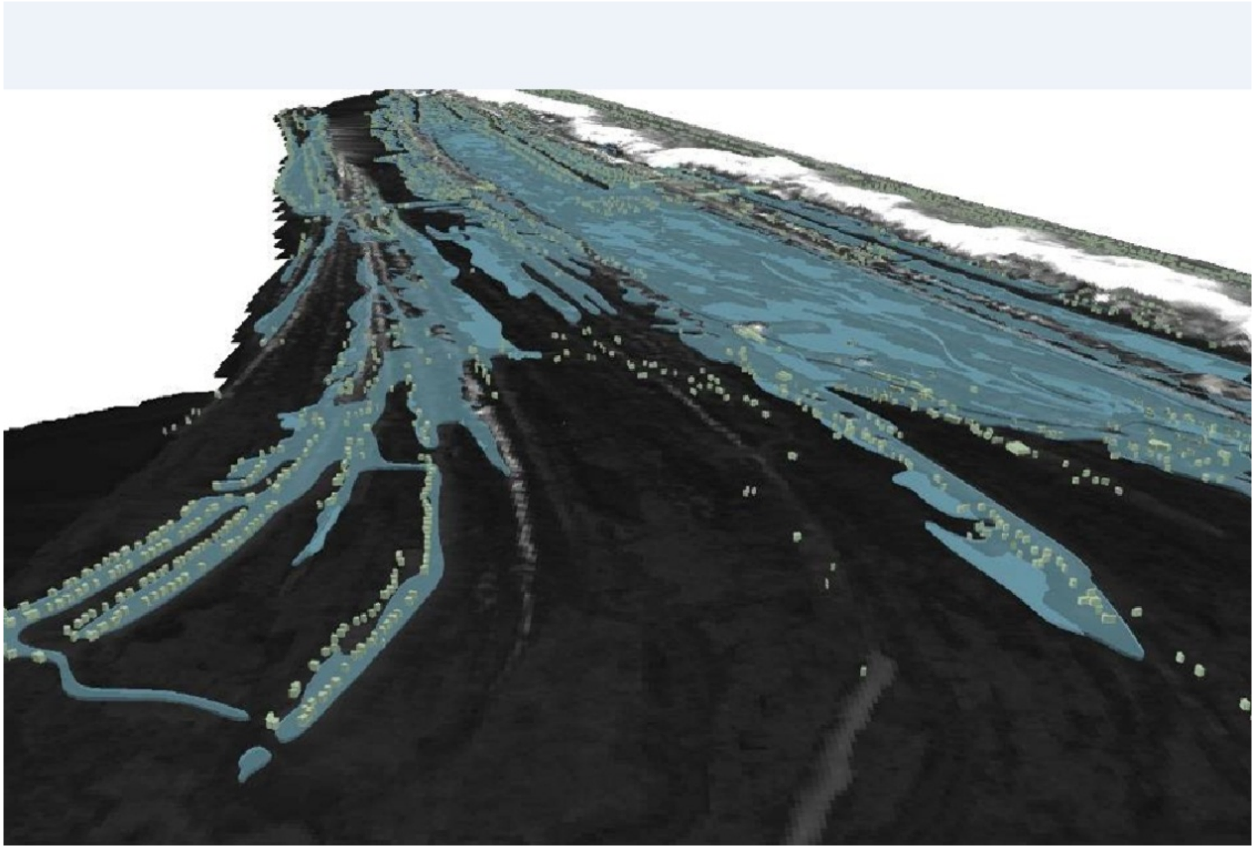

Figure 2. Orthoperspective of SLOSH surge model for northern Outer Banks (Kitty Hawk, Southern Shores, and Duck) illustrating digitized inundation contours for a SLOSH MOM category 2 slow-moving storm, superimposed over elevation with building model footprints extruded in 3-D. Lighter tones on the background DEM depict high dunes (upper right) and beach ridges for the relict Kitty Hawk Woods coastal spit (foreground.)

2.3. Surge modeling limitations

Every model, whether forecast model or numerical model, produces errors, uncertainties, and contains assumptions. Models are designed to handle some of these factors in different ways that depend upon the end-product and the end-user. SLOSH is no exception to this. It has its own series of issues and limitations. The limitations of concern here are primarily associated with grid-type, basin, and environmental parameters.

2.3.1. Grid spatial resolution

The first issue to be addressed is grid-type and basin geography. While the telescoping grids are designed to limit computational resources needed to run the model, they can fall short for surge inundation visualization. For example, if the area of interest is a section of Dare County, North Carolina, a highly hurricane-prone area, the size of the native SLOSH cell is too coarse for a site-specific visualization of surge, primarily because cell size increases with distance from the central arc of the origin of the grid. This limits the effectiveness of inundation forecasts for an emergency manager depending upon SLOSH output to identify problem areas, site vulnerabilities, relief staging areas, evacuation orders, shelters of last resort, or rapid response, reentry, and recovery operations. Later in this chapter, a method to down-scale and visualize some of these sensitivities is evaluated.

2.3.2. Forecast storm track uncertainty, waves, and tides

Limitations of the model remain a concern, particularly of concern is the need to simultaneously account for wave heights, astronomical tides and the forcings created by river-water levels that are not included in the model. Nonetheless, a set of MEOW grids are derived from hundreds of storm-track scenarios (based on varying the direction of landfall), forward-speed scenarios and tides scenarios (mean and high). Forward-speed scenarios predict surge variation according to increments of 5, 10, or 15 mph (8, 16, or 24 kph), which improves the earlier "slow" (<18mph, 29kph) and "fast" (>18mph or 29kph) scenarios. Emergency planning also benefits from the simpler derivation of MOM files, which characterize the maximum of MEOWs and provide a consistent worst-case picture of storm surges at specific intensities (Saffir-Simpson category 1-2, 3, and 4-5 are aggregated in traditional inundation contour maps), notwithstanding the limitations of antecedent precipitation and river-flow input, astronomical tides and waves.

Physical processes are fully represented in SLOSH. Temporal considerations dictate the use of pre-run models for 'worst case' estimates or reliance on single-run deterministic track runs (dependent and highly sensitive to track or intensity forecast errors). Thus, while SLOSH remains the NWS's *de facto* standard and operational model, it is also more often used in conjunction with forecasts from ADCIRC based on deterministic runs within approximately 24 hours of hurricane landfall. The model's limitations remain a concern. Nonetheless, a set of MEOWs output grids are derived from hundreds of storm-track, forward-speeds and tidal scenarios.

2.3.3. Currency and near-real-time utility

Real-time wind-field predictions or measurements are also lacking in SLOSH output. The wind models used by SLOSH can vary greatly from a storm's actual wind field in time, space, and magnitude. This was the case for hurricane Emily in 1993 when the eye wall crossed eastern Pamlico Sound in North Carolina causing very strong surface winds, and the SLOSH model "…significantly underestimated the surface winds and resulting storm surge observed on the Pamlico Sound side of Cape Hatteras" [5]. In further comparisons of SLOSH-model wind fields with observed winds, it was concluded that the use of the NOAA Hurricane Research Division's real-time wind-field data could be used to improve the SLOSH model's estimated values.

2.3.4. Surge uncertainty and elevation

The accuracy of SLOSH is also limited by elevation data accuracy and resolution. Surge heights are represented by a +/- 20% accuracy of predicted maximum surge height [21]. For instance, a prediction of 15-foot surge (4.57 m) might actually produce a range of prediction from only 8 to 12 feet (2.44 to 3.66 m). Since SLOSH computes storm tide elevations in National Geodetic Vertical Datum 1929, it is at least cumbersome to recalculate values to match extensive LiDAR DEMs in vertical meters and North American Vertical Datum 1988 (feet or meters). By design, SLOSH does not incorporate fine-scale landform features and potential inundation thresholds (such as the breaching of inlets in barrier islands, dunes, or engineered features such as levee). The grid resolution of SLOSH is variable and relatively coarse scale, with most cells on the order of 1 mile x 1 mile (1.6 km x 1.6 km). Elevations for grid cells are based on the averages of underlying DEMs, so the actual cell may really possess a non-normal distribution of elevation. Levee areas or areas protected by natural ridges may be overgeneralized. Furthermore, flooding in SLOSH cells is considered aspatially, wherein each cell is flooded as if it was inundated irrespective of the direction of flooding.

To assess the impacts of errors in elevation models as they relate to downscaling of SLOSH values to a finer grid, a Monte Carlo simulation was conducted. The primary goal of the downscaling model is to predict the area of inundation by utilizing the SLOSH model output and a DEM. The degree of positional error is related to the uncertainty in vertical and horizontal measurements and issues surrounding datum conversion, projections, and interpolation methods. If using high resolution airborne LiDAR, the dense sampling of LiDAR points reduces projection and interpolation errors to practically negligible for shorelines [22]. Airborne topographic LiDAR is increasingly available with a horizontal accuracy of +/- 2.0 m and a vertical accuracy of +/-0.30 m (even as fine as +/- 5 to 10 cm). This amount of potential error may cause the position of the inundation zone to fluctuate either landward or seaward, but far less than any other modeling approach. Liu et al. [22] note that “the error inflation factor is determined by the foreshore slope. For each beach with a gentle surface slope, a slight vertical error will be amplified and translated to a larger error” [22]. Nonetheless, larger spatial error could result in poor decision making in the face of an extreme coastal event. The Norfolk, Virginia case study provides some insight into urban facility managers’ concerns and the possible ramifications of error.

3. Geovisualization

The experimental demonstrations below primarily analyzed SLOSH and North Carolina LiDAR elevation data. The SLOSH data were obtained from two sources, the SLOSH Display Package [15] distributed by NOAA NHC and the NC Center for Geographic Information and Analysis (NCCGIA) data from NC OneMap online GIS repository [6]. The SLOSH data from NOAA are used in the downscaling model, and input as either MEOW or MOM file. The SLOSH MOM data are a “worst case” scenario, in which multiple hurricane tracks are used and landfall can occur from multiple directions for a given storm category and speed [15]. Elevation data were obtained from the North Carolina Flood Plain Mapping program in a variety of spatial resolutions (NC Floodplain Mapping Program uses 50 feet (15.24 m), 20 feet (6.1 m), and 10 feet (3.0 m) resampled elevation grids).

3.1. Downscaling and spatial analysis

The spatial modeling methods employed here include a combination of vector- and raster-based analysis, as well as automation using ArcGIS Model Builder. The downscaling model has the flexibility of incorporating a user-defined elevation grid and allows future iterations of the model to estimate inundation as new data become available. This is a substantial improvement over the traditional method of producing downscaled inundation maps, which were created with hand- digitized USGS topographic maps. The model also allows for the input of deterministic SLOSH model output from the NHC in the event of an actual storm, giving emergency managers more accurate predictions of area inundation, the affected populations and evacuations routes.

Most inundation models allow for the flooding of interior sections of land as water levels rise, that are, in reality, disconnected from water sources (either a bay or the ocean), an issue known as hydro-connectivity. This is typically referred to as a “bathtub model” and provides inaccurate representations. Hydro-connectivity is established in the model applied here by using a cost-distance function that allows inundation only from a source raster of water (i.e., a bay or the ocean). This generates better results than those produced using single-pixel or contour-based bathtub inundation.

The output from the SLOSH downscaling model is a raster grid. Once the downscaling has been computed, map algebra calculations are used to compare differences in inundation between the three elevation resolutions, and ultimately to a rasterized NCCGIA data. The analysis will be conducted for Dare County, North Carolina, with a special focus on Roanoke Island and the city of Nags Head. In subsequent geovisualization techniques, the LiDAR-based and SLOSH-downscaled surge inundation calculations are used.

3.2. 3-D Geovisualization

In addition to official updates from the NWS, other groups have worked with model output to refine the resolution for better visualization and more accurate representation of inundation. The size of the cells to the south of Kitty Hawk, North Carolina, for example, is not always appropriate for visualization. Figure 1 shows that single SLOSH cells may cover an entire swath of barrier island and in the current example (SLOSH category 2, fast-moving MOM) that stretch of barrier island would be inundated with between 1 and 2 meters of water.

The NCCGIA inundation and SLOSH inundation polygons are aggregated using the available 1:24,000 USGS topographic maps (approximately 5-foot or 1.5-meter contour interval). Areal interpolation was used to create an overlay to delimit inundation according to lumped categories 1 and 2, category 3, and categories 4 and 5 hurricanes. The result was a polygon file that exhibits inundation with relatively fine detail (Figure 2). These elevation data, however, have been vastly eclipsed by LiDAR bare-earth models with 15-cm vertical accuracy and 5- to 20-m spatial resolution.

3.3. Monte Carlo error modeling

The procedure used in the assessment of accuracy errors in the prediction of inundation area was similar to those used by Liu. First, the levels of error and uncertainty (bound of potential error) of the source elevation model were determined. Then using a pseudo-random number generator and the bound of potential error, 30 random permutations were created. All 30 had similar means and standard deviations and were therefore determined to be within the realm of possible error. The inundation model was run on each permutation and their differences were recorded.

3.4. Case study: Hurricane Irene 2011 urban storm surge in Norfolk, Virginia, USA

In August 2011, Hurricane Irene drew close to the southeastern U.S. coast (Figure 3), eventually making landfall at Cape Lookout, North Carolina at 8 a.m. EDT, August 25, 2011 as a category one hurricane with maximum sustained winds near 85 mph. The storm moved more slowly than expected over North Carolina, with its center crossing over Norfolk and southeastern Virginia on August 27.

The path of Hurricane Irene was accurately predicted more than four days in advance by NOAA's NHC [23]. As the storm approached, the Emergency Management team at Old Dominion University (ODU) in Norfolk, Virginia began creating impact scenarios and making contingency plans. Potential flooding was of critical concern for a number of reasons. The university's population of 25,000 students has become more residential over the last few years and includes a large number of international students that have no other permanent U.S. residences to serve as temporary shelter. ODU is in a highly urbanized, mixed-use setting within Norfolk, is adjacent to several tidally influenced surge-prone water bodies (Chesapeake Bay, the Elizabeth River, and the Lafayette River) and has restricted transportation routes and limited evacuation corridors. A 2007 surge study in Norfolk revealed that census blocks near the university had some of the highest vulnerability to hurricane storm surge in the region [24].

The inherent challenges related to impending surge from an oncoming storm were exacerbated by Irene's timing as she was expected to pass over ODU during the "move-in" weekend for residential students. University administrators were faced with decisions such as: *Should students be allowed to move in prior to the storm? Do we evacuate residents and, if so, to where? What critical infrastructure is likely to be exposed to flooding? Should assets be relocated to mitigate damage? Which areas require temporary storm protection (sand bagging, etc.)? Which areas may be isolated during the flooding?* The best available information regarding potential storm surge flooding was required to confidently answer these questions. In June 2011, the Hampton Roads Planning District Commission (HRPDC) had compiled a report addressing storm-surge vulnerability in southeastern Virginia [25]. While this report estimated that over 100,000 people may be displaced by a Category 1 storm, regional surge maps were not of sufficient resolution to be useful at neighborhood or facility scales. To remedy this scale issue, independent GIS modeling and analysis of the surge potential associated with Irene was performed at the university.

Figure 3. NOAA GOES-13 satellite showing Hurricane Irene on August 25, 2011 at 10:10 a.m. EDT.

Localized surge inundation models were created for the ODU campus following three basic steps outlined by NOAA: 1) obtain and prepare elevation data, 2) determine water levels, 3) create MEOW inundation maps for the study area from the SLOSH display package. At the time of Irene's approach, ODU already possessed the best available high resolution (1-foot or 0.3-m grid) LiDAR-derived elevation data having an accuracy of +/-.30 m, referenced to the National Geodetic Vertical Datum 1929 (NAVD29). Horizontal and vertical datums (reference heights) must match when creating and overlaying elevation surfaces. If they do not, error will be introduced into the flood model elevation surface [4].

Since its inception, the SLOSH model has been used successfully by numerous emergency management agencies and forecasters to predict storm surge and assess flood potential [26]. Given the longevity and widespread use of the SLOSH model, ODU elected to use SLOSH model water level output and to evaluate the probabilistic SLOSH forecasts [27] for a "bathtub" campus flooding model. In this hybrid approach, iterative flood surfaces were developed from the most current storm track and intensity forecasts provided the NWS and NHC. Immediately prior to Irene's landfall, the most likely storm parameters were: a category 2 storm bearing NNE at 14 mph (22.5 kph) during mid-tide with the tide rising. Thus, this case using SLOSH, local LiDAR and 3-D GIS data provides insight into fine-resolution, urban applications of these modeling and geovisualization techniques.

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4. Results and discussion

4.1. Downscaling and spatial analysis

To exploit the available LiDAR DEMs, the model used accepts either raw MEOW/MOM data or deterministic runs when available and it outputs similar results. This dataset adds the option of including high accuracy LIDAR DEMs as they become available and using deterministic runs when they are made available by the NWS. The model inputs SLOSH, LiDAR DEMs, and water raster data and computes a cost-distance function with enforced hydro-connectivity to the bay or the ocean. The inundation can only originate from open-water sources and this eliminates the non-connected inundation polygons associated with "bathtub" models. Model output from three different elevation grids (2.4, 6.1, and 3.0 m resolution) generated similar results. The inundation grids from the 20-foot resolution (6.0 m) downscaled inundation model were overlaid with the NCCGIA interpolated contour-based flood prediction (Figure 4). The contour-based surge model expects more inundation on the Outer Banks relative to data indicated in LiDAR DEMs.

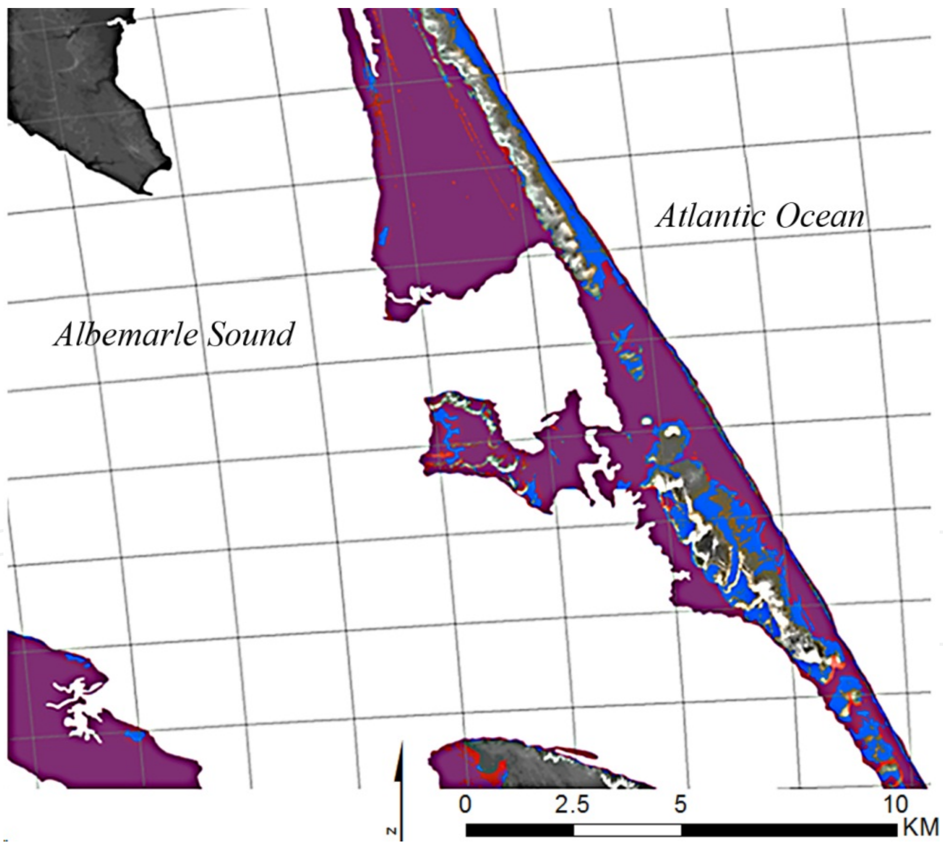

Figure 4. The comparison of results of inundation grids from the 20-foot resolution (6.0 m) downscaled inundation model and the NCCGIA interpolated contour-based flood prediction model from USGS 30 m DEMs (red-only), areas of agreement (purple), and areas of LiDAR-based potential inundation (blue-only) for a subset area of the Outer Banks and northern tip of Roanoke Island (at bottom). Shades of light grey surrounded by surge areas are relict medaño dunes and, in Jockey's Ridge State Park, a star dune.

4.2. Geovisualization

An experimental program to visualize and communicate storm surge risk and raise awareness to the hazard prompted the development of 3-D models and a series of photorealistic, interactive, and animated geovisualizations. In cooperation with Dare County (North Carolina) Office of Emergency Management, the Renaissance Computing Institute (RENCI) East Carolina Engagement Center [28] developed 3-D building models using Google Sketchup software. Seventeen prominent landmarks were selected in consultation with the emergency manager and community leaders. In addition, building footprints and heights were incorporated within surrounding 1-km buffers of the landmarks from the county's GIS database and extruded in 3-D using ESRI ArcScene software. SLOSH MOMs were also incorporated and matched to the elevation datum used in Google Earth. All landmarks were evaluated for availability on the Google 3-D Community Warehouse so that users examining existing building models would see the correct objects. For each focal landmark, a visualization was created and included: 1) a 3-D ortho-perspective view for use as representative graphic in presentations and briefings; 2) prerecorded video for download or playback on the Internet (e.g., a Windows Media Player (.wmv) file or FLASH); and 3) an interactive, downloadable master Keyhole Markup Language (.kmz) file with embedded 3-D inundation, landmark and building objects. All data were organized into a library hosted on the RENCI SurgeViz 2010 website [29].

These products were used in diverse venues, displayed to different audiences and employed in several activities which enabled a qualitative evaluation of their utility. Presentations and interactive educational use was facilitated in public school presentations to elementary, middle- and high school students on the Outer Banks to inform them of their local storm-surge potential. The library of graphics was compiled into a set of Microsoft Office Powerpoint slide presentations for use by emergency managers and forecasters for briefings and training exercises. These presentation graphics are organized by SLOSH MOM category and geography allowing for quick selection of appropriate surge levels and for specific sites during an emergency. Animations of short 3-D fly-throughs for each location and each MOM category provide snapshots of potential inundation regionally and are useful for risk communication. Finally, the interactive 3-D content of the.kmz files enabled public download and private exploration. All of these products could also be used in hurricane exercises and drills, and in June 2010 each product was demonstrated in a mock "tabletop" exercise for the Dare County Control Board using a hypothetical Hurricane Felix, a MOM category 2, fast-moving storm striking near the North Carolina-Virginia border. Each of these uses was deemed successful by their audiences (Figure 5).

Although qualitative successes of these geovisualization applications are difficult to quantify, particularly in a real emergency, it is possible to identify several problems that occurred in their production and delivery. First, the integration of local building data, storm surges, Google imagery and elevation data created some asynchrony and error. For instance, a custom building model in Sketchup was incorrectly located on the Google Imagery on a street opposite its true location. The model was submitted to the Google 3-D Warehouse and accepted, eventually also appearing in Google's building database for Google Earth users.

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However, the placement error was only discovered later and took some months to correct. Additionally, very high spatial resolution aerial imagery in the Google Earth image database sometimes did not coincide with building footprints and surge data. In some cases, dynamic changes (e.g., dune construction or destruction) on the barrier island actually altered potential surge patterns. In other cases, edges and misalignments between the aerial imagery and building data were revealed that may indicate that there was either geometric error in the aerial data or positioning error in the mapped buildings. Nonetheless, the graphics seldom failed to impress emergency managers and oftentimes generated requests for similar products for other municipalities.

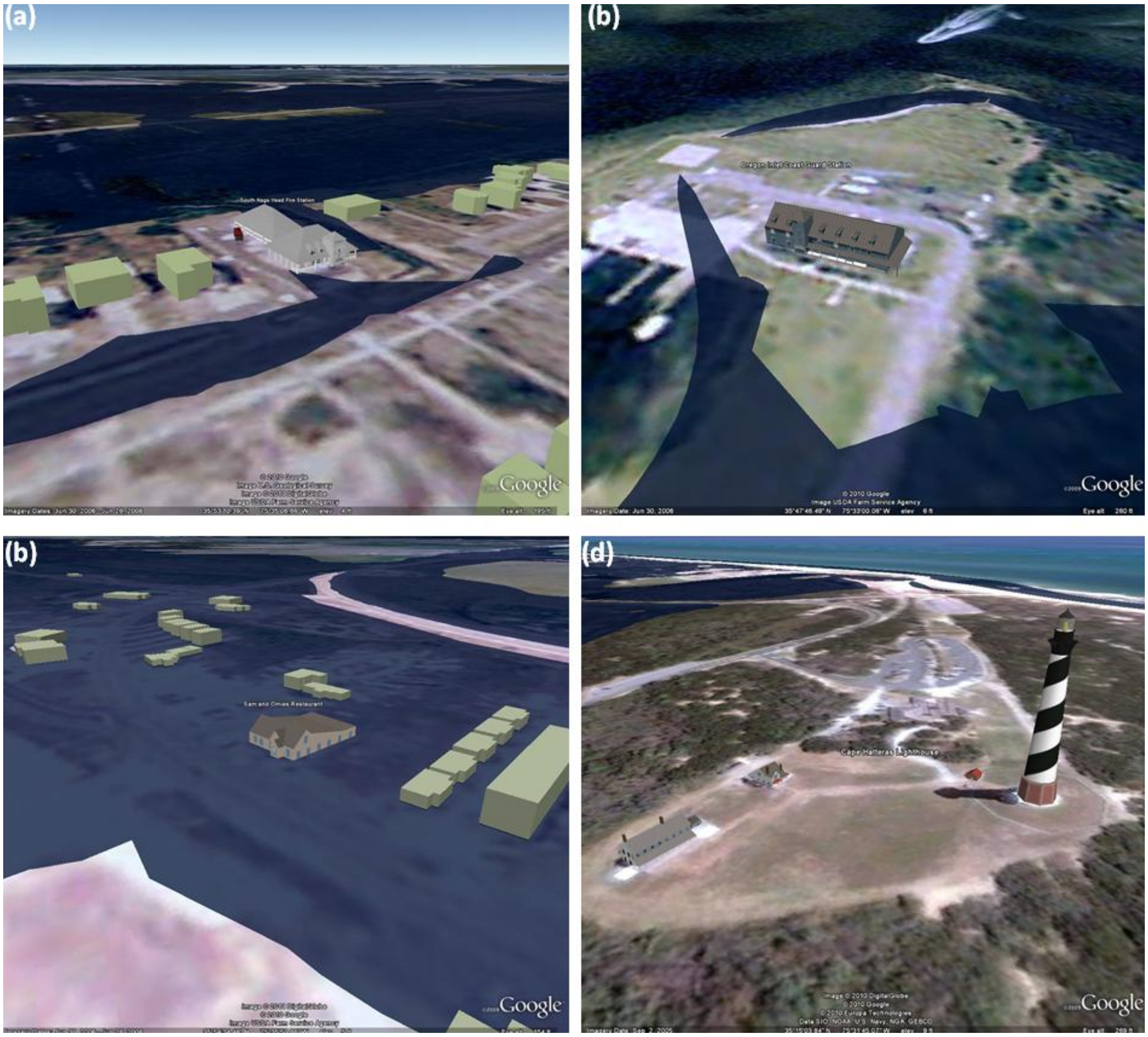

Figure 5. Screenshots of customized.kmz files with building footprint models, landmark 3-D buildings, and SLOSH MOM output storm surge inundation layers superimposed over Google imagery for a category 2 storm affecting the Outer Banks, North Carolina, (a) South Nags Head fire station, (b) US Coast Guard Oregon Inlet station, (c) Sam & Omie's Restaurant at Whalebone Junction, South Nags Head, and (d) Cape Hatteras Lighthouse, Buxton.

The static, apparently non-destructive impact of surges evident in the geovisualizations generated suggestions for future improvements to reinforce that these are downscaled surge models and only approximations of potential worst-case scenarios of SLOSH MOMs. They may not occur at all of these locations and they also carry the limitations of the SLOSH model with respect to accuracy and accurate portrayal of wave energy impacts. To scientifically and visually evaluate the potential error also found in the elevation data, a Monte Carlo error model was also applied.

4.3. Monte Carlo error modeling

The initial Monte Carlo simulation of error in the DEM focused on results around the Town of Manteo, Roanoke Island (Figure 6). Individual cells of the DEM were randomly perturbed by error following the Gaussian error distribution for +/-15 cm vertical error. For each new DEM, the downscaled SLOSH inundation model was run to delineate possible alternative inundation zones. The analysis reveals that in a minority of cases in the simulation, a depression in the study area is inundated (that is *not* delineated in the original DEM.) This result prompted further analysis and exploration of cartographic representation.)

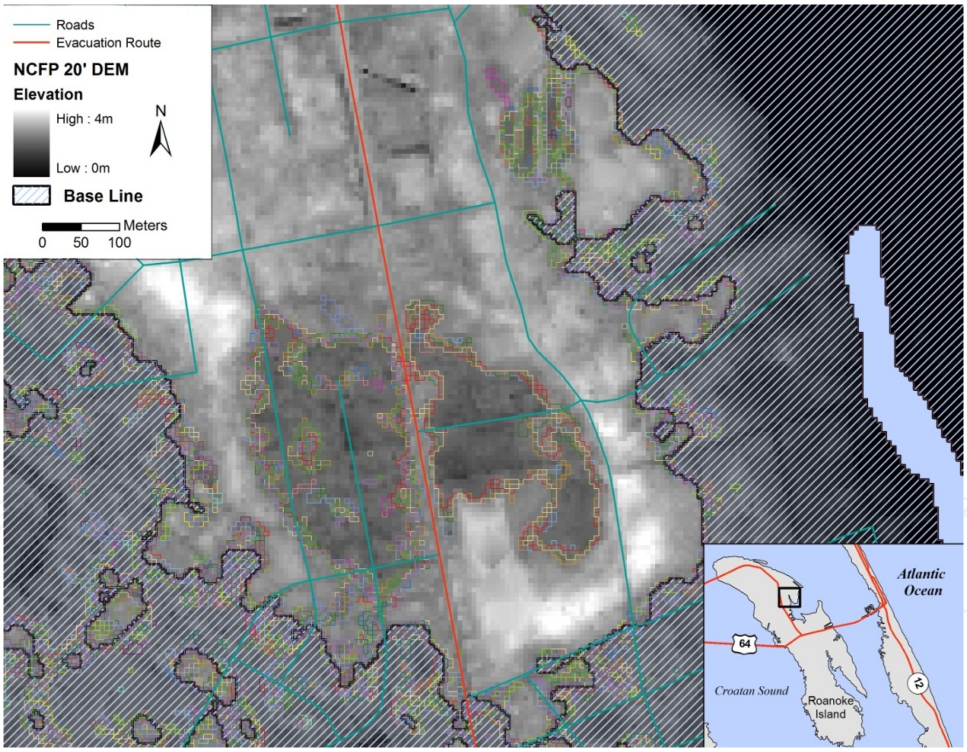

Figure 6. Prototype of Monte Carlo simulation analysis of inundation sensitivity, showing original storm surge inundation model with existing 20-foot (6-m) DEM (hachures and bold boundary line) and iterative results from the perturbed error modeling in alternate color polylines for an intensive study area of the Town of Manteo, North Carolina. This shows 30 possible inundation zones, each is shown in a different color (and the original outline in bold with a hachured inundation zone). The dark tone area of the DEM at center illustrates a low zone, bisected by a major road, of low-lying ground that the current DEM does not inundate but that several runs of the Monte Carlo simulation found to be inundated.

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To further evaluate the technique for evaluating sensitivity of inundation confidence, the analysis applied variable transparency and shading to more precisely identify uncertain areas in the DEM in a low-lying shore area (Figure 7) and on a barrier island segment (Figure 8). The cumulative confidence of inundation for 30 simulations was calculated by tallying the number of runs that resulted in each cell being inundated. The cells were shaded in proportion to the number of simulations that produced flooding. Results of this symbolization allow more precise delineation of potential DEM error and flood vulnerability. On the island, there seemed to be more inundation agreement, except in the boundaries around dunes and the upper beach berm zone. However, the zone of inundation appearing over water (in the later orthophoto) also underscores the potential for temporal asynchrony (the DEM for Figure 8 is from 2002 whereas the aerial orthophoto is from 2010) or error. Beach erosion at this location is not reflected in either the DEM or in the downscaling inundation model.

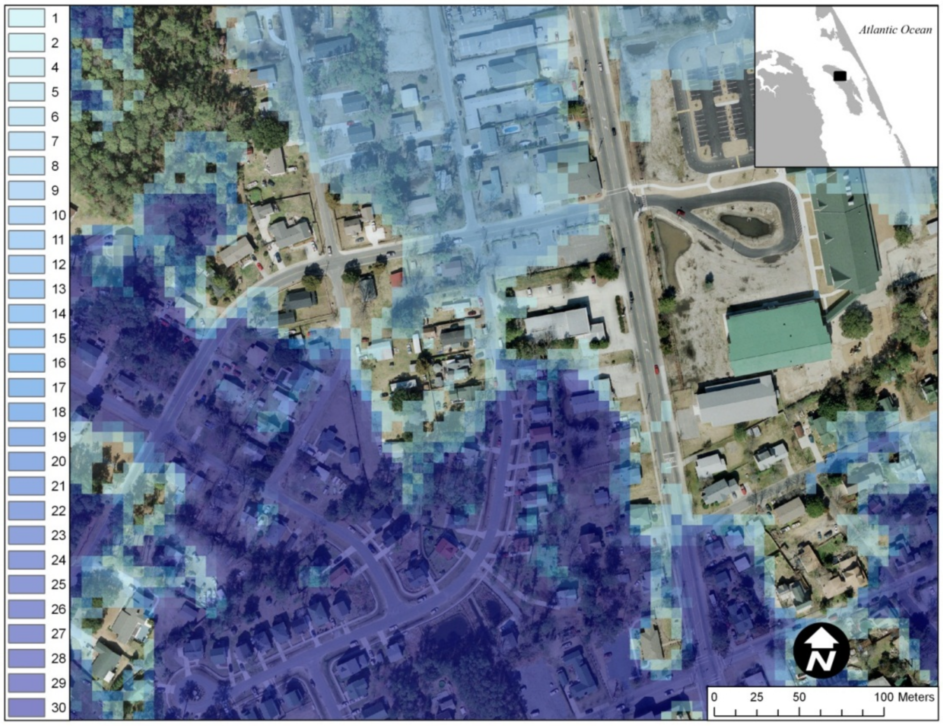

Figure 7. Sensitivity analysis of DEM inundation potential for a category 2 SLOSH MOM surge in Manteo by tallying inundation of Monte Carlo simulation runs. Transparency and saturation are proportionately modulated to the number of model runs that predicted flooding.

Over most of the tested portions of Roanoke Island and Cape Hatteras, there is marginal spatial variation in the inundation area. However, some surprising patterns are evident where there is likely to be an underlying representation limit. In low-relief coastal plain landscapes and barrier islands, features such as salt marshes, shrub and maritime forests, canals and drainage ditches and narrow features such as dune crests impart variable elevation error, even in LiDAR DEMs, and these may restrict the accuracy of inundation models of any kind. In our study area, one area exhibited a drastically different inundation zonation in the simulation. In Manteo (Figure 7), an extensive area was predicted to flood in several simulation runs but not based on the original DEM. This highlights the need for future floodplain-delineation sensitivity research and a need to better understand downscaling and surge inundation modeling error to address the propagation of inherent versus processing error.

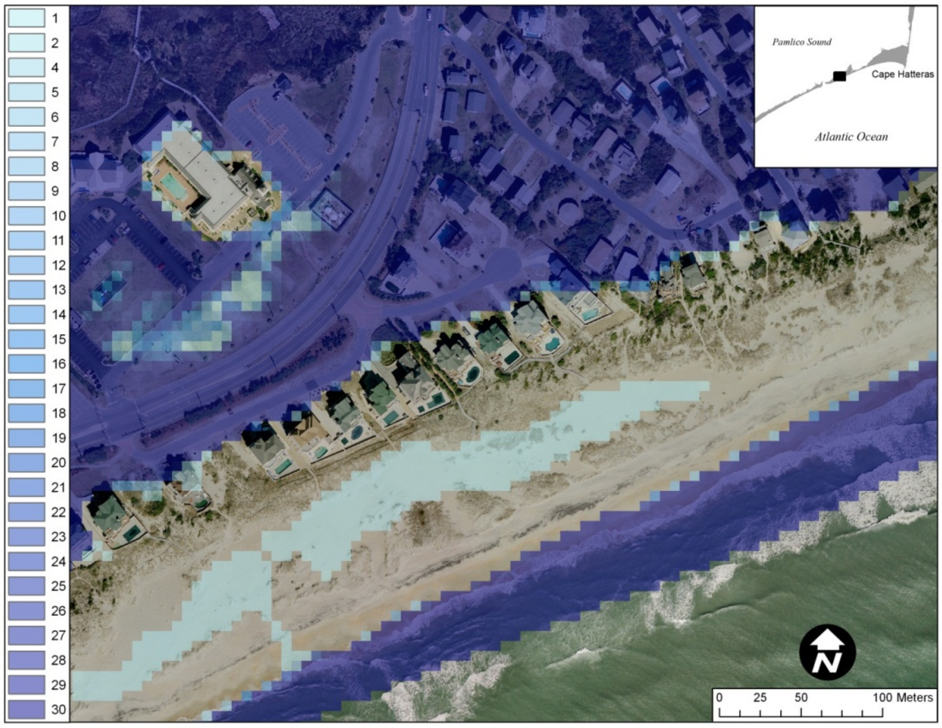

Figure 8. Results for Monte Carlo error analysis for a SLOSH category 2 MOM surge potential for southern Hatteras Island.

4.4. Hurricane Irene in Norfolk case study

The SLOSH model was run using these inputs to create a modeled water surface for the operational analysis of impacts from Hurricane Irene (Figure 9). SLOSH model runs predicted a storm surge of approximately 6.4 feet (2 m), referenced to NGVD29 vertical datum. However, the SLOSH model does not include precipitation, wave action, and the effects of tidal phases (spring/neap), each of which can have a significant impact on flooding. As Irene's landfall coincided with a spring tide and heavy rains were expected, 1.5 feet (0.5 m) of additional urban flooding was added evenly across the modeled surface. A raster surface approximating an 8-foot (2.4-m) water level was draped uniformly upon both 2-D and 3-D representations of ODU. Two-dimensional maps, graphics and GIS overlay-analysis proved valuable for determining the buildings and assets that required the most pre-storm intervention and flood-mitigation effort.

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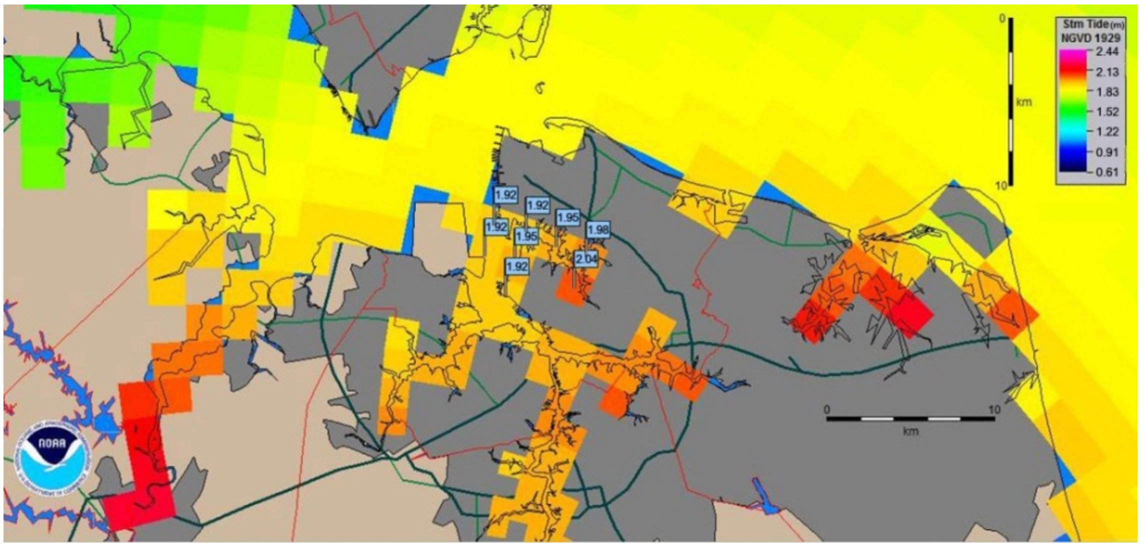

Figure 9. SLOSH model for Hurricane Irene with storm surge values flagged near ODU campus.

The 2-D portrayal of LiDAR estimated inundation reveals the surge following the low topography of an historic creek through the middle of campus (Figure 10). Water backing up the tributary is forced overbank onto streets, in many instances using streets as flood channels. Figure 10 also demonstrates the simultaneous, multivariate mapping of flood inundation depth (level of water above the ground surface) and the heights of the bases of building, important for protecting facilities and planning for emergency services. Flooded streets and impediments to vehicular or pedestrian traffic are also incorporated into this cartography. Three-dimensional visualizations employing enhanced cartographic techniques were more instructive to emergency management personnel for visualization of potential high-flood storm conditions (Figures 11 and 12).

Based upon the flood surfaces depicted in these visualizations, emergency management and facilities staff at the university were able to prioritize their efforts, spending time and resources more effectively. Non-fixed assets in the two residence halls predicted to be most severely impacted by flooding were relocated or elevated. Sand bags were deployed at critical seepage points for several structures. Several parking lots were also cleared based on the indication that they would experience flooding of 2 feet (0.6 m) or more. Ultimately, Irene weakened and turned towards the northwest as it passed through the Norfolk area, resulting in flood heights of approximately 2 to 3 feet (0.6 to 0.9 m) which was lower than predicted by all surge forecasts.

With all storms, the amount of flooding depends on hurricane intensity, tidal phase, rainfall, wind-driven waves, storm speed and duration, prior precipitation, and other factors [21]. ODU and southeastern Virginia were fortunate, as the northeast quadrant of the storm which always has stronger winds and higher surge, moved off the coast rather than inland. Despite the discrepancy between predicted and actual flooding, ODU's modeling and visualization of Irene's surge potential are viewed as having been a valuable resource and is now incorporated as standard operating procedure for future hurricanes.

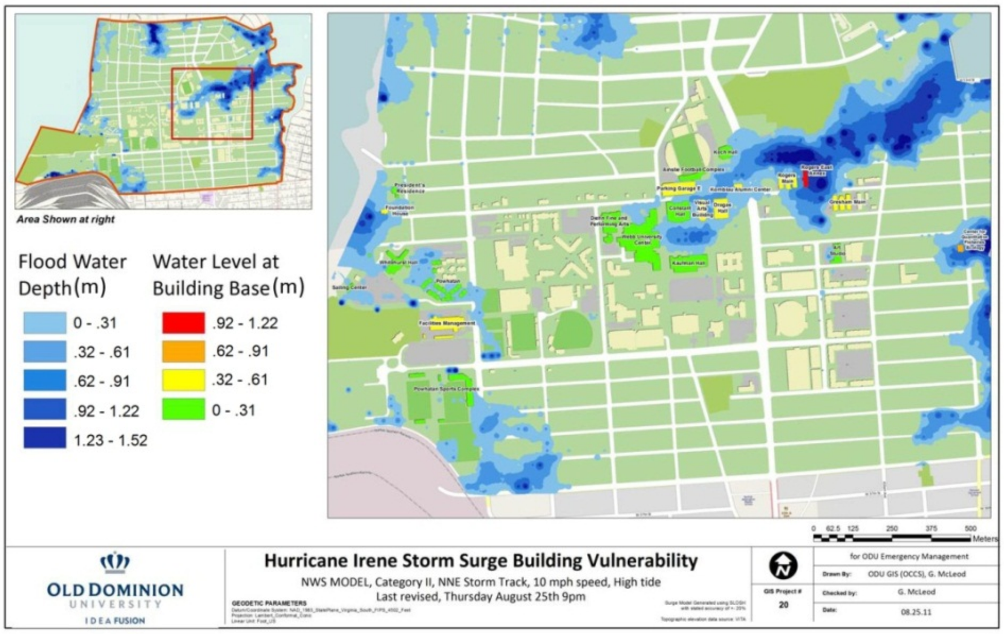

Figure 10. Map of depths of flooding encroaching on campus from the Lafayette River based on maximum storm tide for SLOSH MEOW scenario for Hurricane Irene, with depths of inundation based on cell by cell calculation from LiDAR DEM data for high tide.

Figure 11. A 3-D ortho-perspective of Hurricane Irene maximum flooding at ODU campus. Map depicts inundation depth superimposed over 3-D buildings and orthophotography draped on a LiDAR DEM. View north toward Lafayette River at top and Elizabeth River at left. Inundated areas shown in blue shades connote inundation depths (as described in Figure 5). Building hues denote water level at first floor base height of building.

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Figure 12. D ortho-perspective of Irene-generated flooding focused on ODU with 3-D building models extruded for perspective. Blue shades depict inundation depth (as described in Figure 5).

5. Conclusion

This review and exploratory geovisualization research found variable results when comparing traditional coastal elevation to modern LiDAR DEM elevation and in residual fine-scale error in digital inundation models. Discrepancies in inundation predictions when using traditional contour-based surge maps compared to contemporary digital LiDAR-based inundation models were significant, highlighting the underestimation of potential surges in coarser coastal topographic data. Forecasters and emergency managers should be aware of their data sources and the potential error in maps used to make decisions. Incorrect results are produced not only by operational and observational errors in computer models but also by ignoring the errors inherent in elevation data sources. Future accuracy assessments should be made for downscaled inundation models to increase realistic representation of the extent of flooding. Even though the agreement of the areas of inundation produced by the two models is close to 95%, three main advantages of the more recent GIS-based model have been identified, all relate to model flexibility. The downscaling and fine-resolution error modeling of the Monte Carlo simulation methods also highlight the existence of error even in our modern, fine-scale LiDAR DEMs. Simulation runs showed that there is spatial variation in DEM error that may propagate underestimates of areal flooding in surges. Thus, floodplain mapping and emergency managers should cautiously interpret single inundation models, as underlying error in fine-scale topographic features (a levee, for instance) could mask the potential in some likely to be surge-affected areas. Cartographic techniques such as transparency and variable shading demonstrated in our chapter could also illuminate such weaknesses and errors in the DEMs or downscaled inundation model maps.

In the event of an actual hurricane landfall, the SLOSH deterministic runs could be input to the model resulting in a more realistic representation, rather than using inundation zones generated by the SLOSH MOM output. Doing this would provide a clear advantage over a static, "worst case" scenario map, and would allow emergency managers to pinpoint areas and infrastructure that would be effected in the event of specific storm parameters and track. Another advantage of the GIS-based model is its easy incorporation of newly available elevation data. In addition, digital elevation models do not typically incorporate features such as ditches and water-control canals that can greatly alter the spatial patterns of inundation, so DEM-processing techniques such as "stream burning" or "hydro-correction" to improve and enforce hydrologic representation in both runoff and inundation would help to improve the accuracy of surge visualizations.

This chapter also focused on the use of SLOSH model MEOW and MOM data for the time-delimited preparedness and response operations (particularly evacuation) of emergency management. In the future, the ability for modeling to produce a variety of inundation model output will expand and reduce uncertainty. Experimental runs are being conducted to make use of output from the ADCIRC model, and these will be enhanced by improvement of storm-track and intensity forecasts within the closing hours of landfall. The ADCIRC model is better than the SLOSH model in many ways, but still has some of the same visualization issues. In sum, the downscaling GIS SLOSH model produces results similar to previous contouring and manual-digitizing techniques but has better accuracy and tends to not overgeneralize. Although Monte Carlo analysis of inundation variability using error modeling suggests broad fidelity of inundation zones, there are still areas of moderate uncertainty. More work is needed to assess the accuracy of these downscaling models using actual storm data and hind-casting. Nonetheless, the GIS model has many advantages; they are primarily the model's flexible acceptance of inputs and its cartography. With more work, emergency managers and the public will be able to improve risk awareness and risk communication.

The array of geovisual products developed for education, public awareness, and emergency exercises have been welcomed by communities to whom they have been presented. Photorealism and 3-D building models are demonstrably versatile, providing visual communication in static graphics, libraries of surge visualizations, animated fly-throughs, and interactive 3-D digital globe data (such as Google Earth). The algorithms to downscale and visualize SLOSH or other surge model forecasts at the neighborhood or finer scale have fulfilled a need in local emergency management. The ODU case study demonstrated the integration of surge forecast inundation, fine-scale orthophotography and cartographic symbolization of building planimetrics, and accessibility for operational use during an emergency. Such applications require cautious and informed use of disparate data (meteorological, geospatial, and infrastructural). The spatial accuracy, scale, and temporal and physical uncertainties of a phenomenon as complex as storm surge suggest the need for advanced training and judicious exercising of the use of GIS and geovisualization. Hence, academics and practitioner communities comprising geographers, coastal modelers and engineers, emergency managers, and decision-makers must continue to collaborate in the development of scientific approaches and robust tools to further refine and expand these advances for coastal disaster management.

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