DEVELOPING A NEW ARCGIS TOOL TO QUANTIFY BUILDING-CONTENT VULNERABILITY FROM STORM-SURGE INUNDATION

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ABSTRACT

A storm surge that accompanies a hurricane creates a major threat to humans and the near-shore built environment. Improving the analysis and identification of risk to vulnerable communities from storm-surge damage is crucial for risk-reduction policy making in coastal cities and towns. Storm surges can damage buildings' structures and their contents; however, content-damage assessment methodologies are not well studied. This study developed and implemented a conceptual framework to estimate flood-damage vulnerability to building contents. We achieved our goal by developing a new hypothetical-damage function and a damage-assessment algorithm, which was implemented in the ArcGIS environment which permits database and spatial object manipulation routines through scripting, and the development of customized tools. Python was used as the main scripting language because it is open source, object oriented, and one of the core programming languages capable of handling ArcObjects. The Town of Groton, a Connecticut coastal town, was used to test the damage-assessment tool. A digital elevation model (DEM) of the study area was derived from high resolution LIght Detection And Ranging (LIDAR) data. The FEMA/USACE/NWS Sea, Lake, Overland Surge from Hurricanes (SLOSH) model was used to simulate surge heights. Twenty-seven damage scenarios were simulated based on the flood rasters created from the DEM and the SLOSH-derived surge heights. This study demonstrated that combining the spatial analysis capabilities of a GIS with the modeling capabilities of a programming language can produce a useful, general-purpose tool that helps decision makers assess vulnerability of flood-prone areas.

INTRODUCTION

Coastal communities in many parts of the world are vulnerable to tropical cyclones, known as hurricanes in the Atlantic and Eastern Pacific, typhoons in the Western Pacific, and cyclones in the Indian Ocean (Lindell and Parter, 2007). The storm surge that accompanies a hurricane causes major damage. A storm surge is a rise in sea-level elevation caused by high winds and a sudden change in air pressure (Simpson and Riehl, 1981, Lowe *et al*., 2001). Storm-surge disasters are ranked the top among all natural disasters in the world (Fenge and Hong, 2007). To manage the risk to costal communities, disaster managers have a range of short- and long-term mitigation measures available. Some of these include emergency evacuation, establishing real-time monitoring and warning systems, developing deterministic flood models to predict likely inundations, establishing risk management standards, and applying geographic information systems (GIS) to natural hazard risk management (Apel *et al*., 2009, Zerger and Smith, 2003). Prior to implementing either short- or long-term mitigation measures, the risk on the human environment must be quantified with respect to different storm-surge inundation scenarios.

Hurricanes have the greatest destructive potential of all natural disasters in Connecticut. The population growth along the coast leads to increased vulnerability to coastal flooding events resulting from hurricanes. Today, significant portions of infrastructure facilities – such as transportation, telecommunication and power distribution networks – remain vulnerable, and many thousands of new homes have been constructed in vulnerable areas (Witharana, 2009). Thus, improving the analysis and identification of storm-surge damage risk is crucial to provide the information needed for risk-reduction policy-making and to help prioritize risk reduction investments along the Connecticut's coast. According to United Nations International Strategy for Disaster Reduction (UNISDR, 2004), "risk is the expected loss of lives, people injured, property, livelihoods, economic activity disrupted resulting from interactions between natural or human induced hazards and vulnerable conditions." Developing a robust tool to asses the risk on the built environment, mainly residential, commercial, and industrial building, is vital for assessing the risk on human life. Such a tool will facilitate local planners to quantify the risk (or the expected damage) on buildings for different inundation scenarios along Connecticut's coast.

A storm-surge can damage buildings' structures and contents. In the literature, structural damage-assessment methods are well addressed but the methods that estimate damage to building-content are rarely found (Witharana, 2009). It is important to assess the damage on building contents due to several reasons. In reality, it is unlikely to observe high magnitude flooding events and expect total or partial damage to building structures at all times. At lower flood heights, building structures could retain intact; however, building contents might suffer considerable damage by getting wet. In general, valuable items in buildings are usually located close to the floor. For example, in a house, electronics, furniture and other valuable household items are located either on the floor or approximately one meter above the floor. Therefore, only a few centimeters of flooding can inflict significant damage to a building's contents, and the building's structure remains relatively unharmed. We developed a hypothetical-damage function (depth-damage function) to estimate damage to building contents. We integrated Python scripts into the ArcGIS developer environment to develop a new ArcGIS tool that implements our new hypothetical-damage function for a given storm-surge scenario. The proposed GIS methodology aims to be generic and practical to facilitate its use by other coastal towns along Connecticut's coast that are also vulnerable to damage from future storm surges. We anticipate that the proposed approach will be adaptable for other flooding events such as river flooding and tsunamis.

Storm-Surge Modeling

The SLOSH model (Jelesnianski *et al*., 1992), developed by the Techniques Development Laboratory of the National Weather Service (NWS), provides the primary guidance used by emergency management officials to develop and execute coastal evacuation plans. SLOSH is a two-dimensional, numerical-dynamical, tropical storm-surge model that enables real-time forecasting of hurricane storm surges on continental shelves, across inland water bodies, along coast lines, and for inland routing of water either from sea or from inland water bodies (Jelesnianski *et al*., 1992 and FEMA, 2003). The National Hurricane Center (NHC) uses SLOSH to estimate storm-surge heights and winds resulting from historical, hypothetical, or predicted hurricanes by accounting for pressure, size, forward speed, track and winds. Even though SLOSH accounts for astronomical tides, it does not include rainfall, river flow, or wind-driven waves (NOAA, 2009). The point of a hurricane's landfall is a crucial factor in determining which areas will be inundated by the storm surge, so SLOSH considers that as a major input parameter. Therefore, inaccurate forecasting of a hurricane's track will degrade the accuracy of SLOSH's predictions. SLOSH, therefore, is best used for defining the potential maximum surge for a location (NOAA, 2009), which makes it ideally suited for this study. We ran SLOSH to simulate a full range of surge scenarios for the study area.

Hazard and Vulnerability

A hazard is defined as a physical event, phenomenon, or human activity that has potential for causing damage to society (UNISDR, 2004). Depending on the nature of the hazard, indicators describing the hazard intensity or duration specify the hazard event as well as the condition of the location, which is described by indicators like soil type, surface height or slope (Taubenböck *et al*., 2008). This study focuses on coastal flood hazards (storm surge) posed by hurricanes. Flood hazards, both inland and coastal, are often quantified by a measurable parameter, such as depth, extent, or flow velocity (Wenzel *et al*., 2007, Lotto and Testa, 2000). Probabilities of exceeding a specific value of this hazard parameter in any given time are determined through observation, experimentation, modeling, or a combination. In this study, projected surge heights (hazard parameter) were modeled using SLOSH for different hurricane categories with varying landfall velocities and directions.

Vulnerability refers to the degree of loss due to a given element at risk, or set of such elements, resulting from the occurrence of a natural phenomenon of a given magnitude and expressed on a scale from 0 (no damage) to 1 (total loss) or in percent of the new replacement value in the case of damage to property (UNDHA, 1992). The elements at risk are defined as population, buildings, civil engineering works, economic activities, public services, and infrastructure exposed to hazard (Zerger, 1998 and Granger, 2003).

Damage Risk Assessment and GIS

Risk is defined as the probability of the adverse effects caused by a natural process such as a storm surge with a certain magnitude (intensity) from which certain damages and losses occur (vulnerability) (Granger, 2003 and Crichton, 1999). In damage risk assessment, hazard must first be determined, which incorporates a frequency analysis of the intensity of the threatening occurrence (Lindenschmidt *et al*., 2006). In this study, the occurrence is a storm surge and the intensity is measured by the depth and extent of the flooding. Damage occurs as a result of flooding and it increases with the intensity of the event (Lotto and Testa, 2000). The probability of exceedance along with the intensity of the event (flood depth) establishes the hazard induced by the surge event (Lindenschmidt *et al*., 2006 and Wenzel *et al*., 2007). The vulnerability of elements that are exposed to a given inundation scenario can be assessed using damage costs as function of water depth (surge height). A fundamental principle of damage-risk assessment is that risk due to natural disaster is location dependent, and that the risk can be assessed within an acceptable range of uncertainty if reliable historical and location specific data are available (Lavakare, 1998 and Zeger, 1998). GIS integrates hardware, software, and data for capturing, storing, checking, integrating, analyzing and displaying spatially referenced data (Longley *et al*., 2005). Manipulation, analysis, and graphical presentation of the risk and hazard data can be done within a GIS, and, because these data have associated location information that are also stored within the GIS, their spatial interrelationships can be determined and used in computer-based risk assessment models (Lavakare, 1998, Cova *et al*., 1997, and Zeger, 2002). Damage due to coastal flooding depends on several factors, such as water depth, duration of inundation, flow velocity, sediment concentration and pollution. However, this study focused only on the possible damage associated with flooding depth.

DATA AND METHODOLOGY

Study Area

The Town of Groton, located within the coastal zone Connecticut, was the study area (Figure 1). The southern and western boarders of Groton are mainly bounded by the Long Island Sound (LIS) and the Thames River, respectively. The eastern and northern boarders are bounded by the Mystic River and the town of Ledyard, respectively. Groton is the largest municipality between New Haven, Connecticut, and the cities surrounding Providence, Rhode Island. Groton has a total area of 117 km^2, of which 82 km^2 are land and 36 km^2 are marine. According to the Census of 2000, there were 39,907 people, 15,473 households, and 9,980 families residing in the Town. The population density was 490 people per square kilometer. Many of Connecticut's focal points (industrial, educational, and military) are located along the coastal stretch of Groton. These include a U.S. Naval submarine base, submarine construction facilities of the Electric Boat division of General Dynamics, Global Research and Development campus of Pfizer Inc. and, the University of Connecticut Avery Point Campus.

Geospatial Data and Software

We created a digital elevation model (DEM) of the study area from high-resolution, Light Detection And Ranging (LIDAR) data that were acquired in December 2006 during leaf off, before snow, and at low-tide conditions. The LIDAR data cover a narrow swath running parallel to the shore line covering the hundred-year flood zone demarcated by Federal Emergency Management Agency (FEMA). The average spacing of the LIDAR postings is 1 m, and the LIDAR returns are classified into ground and nonground classes. The quality-assurance and quality-control reports for these data (Dewberry, 2007) state that this LIDAR dataset is of "outstanding quality" and meets the needs of FEMA and FEMA contractors for flood mapping. The raw LIDAR data were in Log ASCII Standard (LAS) format version 1.0. Horizontal and vertical coordinates refer to the North American Datum of 1983 (NAD 83) and the North American Vertical Datum of 1988 (NAVD 88), respectively. Building foot prints and land parcels, attributed with building value, property value and building type, were obtained from the GIS unit of the Town of Groton, Connecticut. Street network, hydrography, administrative divisions and other salient vector-data layers were obtained from the Connecticut Department of Environmental Protection (www.ct.gov/dep).The online data base of the Center for Land use Education And Research (http://clear.uconn.edu/) of the University of Connecticut was used to download raster layers such as a state-wide mosaic (2004) of orthoimages (30cm resolution) and ADS40 true color images (50cm resolution). A set of National Geodetic Survey (NGS) survey markers that fall within the LIDAR coverage were used to assess the accuracy of the DEM. A real time network (RTN) GPS survey was performed to acquire horizontal coordinates of bench marks and vertical coordinates of horizontal marks because horizontal coordinates of bench marks and orthometric heights of horizontal makers are scaled in National Geodetic Survey (NGS) data sheets. Data sheets from the NGS were used to recover the survey makers and obtain published values for vertical and horizontal coordinates.

The ArcGIS 9.3 software system was used to perform all the GIS analyses. Python IDLE 2.5.1 was used to code the damage assessment-algorithm script. We also used LP360 software to convert LAS LIDAR point files into ArcGIS shape files.

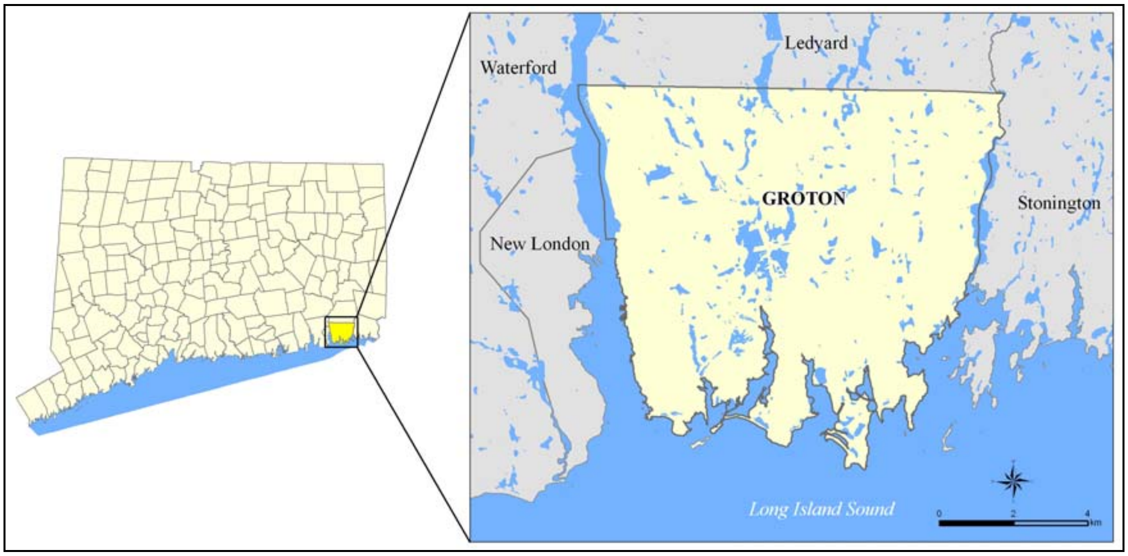


Figure 1. Geographical setting of the study area.

Data Processing

The ground LIDAR points that fell within the study area were used to derive a high resolution DEM. A software program called LP360 was used to convert LAS LIDAR point files into ArcGIS shape files. The ArcGIS 9.3 interpolating spline method was used to interpolate the point cloud. Spline interpolation ensures a smooth surface while imposing two conditions on the interpolant: 1) the surface must pass exactly through the data points, and 2) the surface must have minimum curvature (Dierckx, 1995). Ground LIDAR points in each tile were merged to make a single shape file containing all points. A 30-meterbuffer was created around each tile and the buffered tile was used to clip points from the mass point cloud. This procedure was repeated for all tiles falling within the study area. This set overlapping points in neighboring tiles and minimized the edge effect during the interpolation (seamless raster). Prior to final interpolation, the bare-earth LIDAR cloud was inspected to identify remaining missclassified ground points (e.g., ground points on bridges). Bridges must be removed before the interpolation because they act as dams to the flooding algorithm. The Connecticut statewide mosaic (2004) of orthoimages (30 cm resolution) and the ADS40 true color images (50cm resolution) were used to identify bridges. The LIDAR point cloud and the street network were overlain on orthoimages, and the remaining ground LIDAR points on bridges were removed manually. Each buffered tile was then interpolated using the spline method. A horizontal resolution of 1m was chosen for the output raster grid, comparable to the spacing of the LIDAR postings. Each individual LIDAR raster grid was mosaicked to provide a DEM for the entire study area, and the erroneous surface values were clipped to avoid areas of no data. Figure 3 shows the DEM and the ground control points that were used to assess the accuracy of the DEM.

Several standard methods were used to assess the accuracy of the DEM. A visual inspection process was performed to identify artifacts and other processing errors . In order to perform a ground validation of the DEM, the quantitative validation method entailed comparing the real time network (RTN) observations at NGS survey markers with the DEM derived from the nonground LIDAR data. The accuracy assessment followed the guidelines from the American Society for Photogrammetry (ASPRS) and the National Digital Elevation Program (NDEP). With the National Standard for Spatial Data Accuracy (NSSDA), the vertical accuracy of a data set is defined by the root mean square error (RMSE) of the elevation data, in feet or meters, at ground scale. FEMA follows the NSSDA guidelines to assess the accuracy of LIDAR data and expects a RMSE error of 20 cm (0.66 ft) for a LIDAR point cloud capable of deriving 0.6m (2ft) interval contours (Dewberry, 2007). Our LIDAR data are suitable for the creation of 0.6 m (2 ft) interval contours. Therefore, we used the RMSE method to assess the accuracy of the DEM.

The RTN-GPS heights at ground control points were converted from ellipsoid heights to orthometric heights so that comparisons could be done between the RTN orthometric heights and the LIDAR-derived DEM orthometric heights. The survey markers were overlain on the DEM surface in a GIS. The orthometric heights for the DEM and the RTN-GPS measurements were used to calculate the difference and the absolute difference in elevation for each point. A RMSE was calculated as the square root of the average of all the difference values.

Vulnerability Assessment

Vulnerability can be conceptualized as a function that gives the percentage of the value of a property that could be lost as a function of event intensity. Vulnerability functions are normally deduced from records of past events. Vulnerability functions model the vulnerability of buildings and their contents as a function of water depth, type of building, and construction material. The intensity of the surge can be determined by considering the maximum water depth and the maximum water velocity. Because the present study does not take into account hydrodynamics, only maximum water depth was considered during the damage assessment process.

A hypothetical-damage function (depth-damage function) was developed to estimate possible damage on building contents. In flood-damage assessment, building height is important because damages are mostly related to water depth. Our function uses surge height (water depth), building height, and number of stories as input parameters to estimate possible damage. The proposed damage function does not take into account the types of construction materials. A plot of the hypothetical damage function is shown in Figures 2 and 3.

Hypothetical-Damage Function

Following formula is our hypothetical-damage function. It returns a damage value between 0 and 1 as a function of surge height. The damage (*D*) is zero when the flood-water depth (*d*) inside the building is zero. The maximum damage of 1 is attained when the flood-water depth exceeds the height of the building. The equation's exponential component controls the gradient of the function and returns damage values between 0 and 1. The floor operator models multiple-story buildings. The floor operator replicates damage across multiple stories. The damage function is

$$D = \lfloor S_n(d) \rfloor + 1 - e^{-5 Mod[S_n(d), 1]}$$

$$S_n(d) = Min(d/m, n)$$

where

- D damage (unitless),
- d flood-water depth inside the building (m),
- m average floor height of the building (m),
- n number of floors in the building (unitless),
- e the base of the natural logarithm, and
- $\lfloor . \rfloor$ floor operator

Figures 2 and 3 depict the hypothetical-damage function applied to single-story and three-story buildings, respectively. The *y*-axis depicts the expected damage and from 0 to 1. The *x*-axis depicts flood-water depth inside the building. In Figure 3, floor height was selected as 3 m, and the building has three stories. Because the flood-water depth (> 9 m) is greater than the total height of the building (9 m), the building is totally under water incurring maximum damage (nominal damage =1).

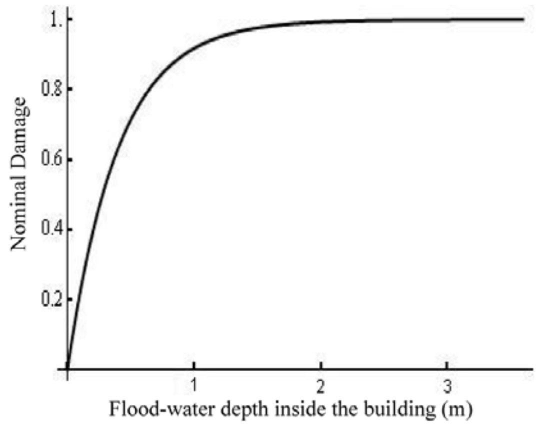


Figure 2. Hypothetical-damage function for a single story building.

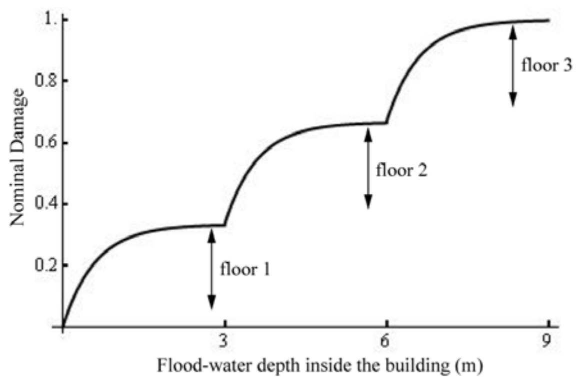


Figure 3. Hypothetical-damage function for a three story building.

Developing a New ArcGIS Tool

Damage Assessment Algorithm. An algorithm was developed to estimate possible damage to buildings and implemented in Python. Shaded boxes in Figure 4 depict the user inputs. The algorithm starts with a building footprint selected from the building footprint vector layer. In the next step, the selected building footprint is used as a mask to extract raster values from the flooding raster. The flooding raster, which is a binary raster, depicts the extent of the flooding; flooded cells have the value of 1 and not-flooded cells have the value of 0. If the selected building footprint includes at least one flooded cell, that building is considered as a flooded building. Otherwise the building is considered as a not-flooded building and the algorithm loops back to the first step. If the building is identified as a flooded building, the foundation elevation of the building is extracted from the DEM and the average roof elevation is computed from non-ground LIDAR points that fall within the extent of the building foot print. Subsequently, the height of the building and number of floors are estimated based upon roof elevation, foundation elevation, and user-defined floor height. Flood-water depth inside the building is calculated by using foundation's elevation and surge height. In the final step, the hypothetical-damage function is evaluated with flood-water depth, floor height and number of floors, which were estimated in previous steps. Subsequently, the attribute table of the input building foot print layer is updated with estimated-damage values in a new field.

Programming in Python. A new ArcGIS tool was developed to automate the damage assessment on vulnerable buildings in the study area. The hypothetical-damage function was implemented in the tool. With the introduction of ArcGIS 9 and Python support, it is now possible to access the software through scripting and develop customize tools (ESRI, 2009). Further, it is possible to write stand-alone applications in Python that use the geoprocessing functionality in ArcGIS. Python was used as the main scripting language because it is one of the core programming languages capable of handling ArcObjects. Python is a general-purpose programming language that is often applied in scripting tasks. Python has many advantages including: it is open-source, object-oriented, cross-platform, can access the ArcGIS Integrated Development Environment (IDLE), and there is a wealth of scripts and libraries to extend its functionality (Lutz and Ascher, 2004). Python IDLE 2.5.1 was used to code the damage assessment-algorithm script. A new toolbox was created inside the ArcGIS 9.3 toolbox, and the debugged script was exported into the newly created toolbox. A user interface for the tool was developed, and the tool was documented for the convenience of the end user.

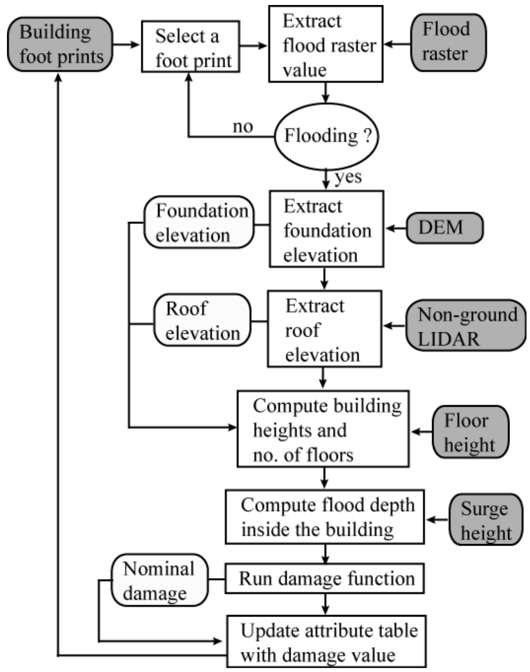


Figure 4 Simplified schematic of building damage assessment algorithm.

Simulating Storm Surges. Different inundation scenarios for the study area were generated from SLOSH. The maximum envelop of water (MEOW) surge heights were obtained for each hurricane category, and a total of 243 surge heights resulted based on velocity, direction and tide condition (low/high) for all hurricane categories. We selected a set of surge heights that depict worst and best scenarios based on maximum and minimum wind directions and wind velocities and on tide condition (high tide). The worst scenario came from maximum wind velocity under high tide condition where as best scenario came from minimum wind velocity under a low tide condition. A total of 27 representative scenarios were selected after an analysis of all possible surge heights. The minimum surge height was 0.6 m (2.0 ft) and maximum was 5.0 m (16.0 ft).

Flood Extent. Flooding rasters were derived from the DEM to delineate the flooding extent for each flooding scenario (surge height). Flooding rasters define how far water will extend inland. These layers were derived by separating the DEM into regions below and above the flood level. This procedure could have been accomplished using the level slicing method in the ArcGIS, which computes new raster grid values defining all the regions that would be flooded by the flood level and all regions not affected. However, the method selects all values that are below the flood level, including low lying areas inland that are not connected to the water source, and hence does not address the connectivity issue of flood modeling. In order to overcome the connectivity issue, a different Python script, which takes into account cell connectivity, was used to create flooding rasters for candidate flooding scenarios.

Damage to Building Content. Approximately 7600 building footprints were found to be in the study area by clipping them from the building foot print vector layer. The newly developed ArcGIS tool was used to estimate damage buildings in the study area, and 27 damage scenarios were simulated. Building damage maps were created for the study area.

RESULTS AND DISCUSSION

The New ArcGIS Tool

Figure 5 shows the user interface of the new ArcGIS tool. The interface accepts these parameters: 1) the DEM of the area interest; 2) the flooding raster, which depicts the extent of flooding for a given surge height; 3) the nonground LIDAR point file; 4) the building vector layer; 5) the average floor height of the buildings; and 6) the SLOSH-derived surge height.

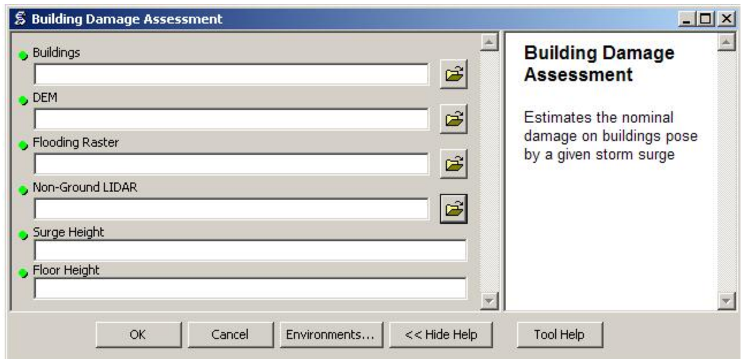


Figure 5. User-interface of the damage assessment tool.

Building Damage Results

Table 1 summarizes the damage results obtained by running the damage assessment tool for the 27 flooding scenarios. The estimated damage is quantified as the “Nominal Damage (ND)” and varies between 0 and 1. The table shows the total number of damaged buildings (ND > 0) expressed as a percentage of the total number of buildings (~ 7600). The damaged buildings are further classified based on the extent of damage (*i.e.* ND = 1, 0.5 < ND < 1 and 0 < ND < 0.5). Tables 2.a and 2.bgiver summarized versions of detailed damage statistics. These tables show the estimated damage to different types of buildings (residential, commercial, industrial, and unclassified). In each category, the estimated damage was further classified based on the nominal damage (ND) as ND =1, 0.5 < ND < 1, and ND < 0.5. We refer the reader to Witharana (2009) for detailed damage results obtained for 27 flooding scenarios.

Table 1 Summary of estimated damage on vulnerable buildings.

Hurricane Category	Total no. of damaged buildings (ND > 0)	% of vulnerable building damage	No. of buildings (ND = 1)	No. of buildings (0.5>ND>0)	No. of buildings (1>ND>0.5)
I	513	6.8	0	436	77
II	1173	15.4	0	951	222
III	1909	25.1	41	1429	463
IV	2713	35.7	833	1298	1223

Table 2.a. Summary of estimated damage to different types of buildings.

Hurricane Category	Residential				Commercial			
	total	ND = 1	1>ND>0.5	0.5>ND>0	total	ND = 1	1>ND>0.5	0.5>ND>0
I	444	0	67	377	56	0	6	50
II	978	0	180	798	142	0	27	115
III	1616	12	402	1202	203	2	40	161
IV	2315	156	1074	1085	262	27	91	144

Table 2.b. Summary of estimated damage to different types of buildings.

Hurricane Category	Industrial				Unclassified			
	total	ND = 1	1>ND>0.5	0.5>ND>0	total	ND = 1	1>ND>0.5	0.5>ND>0
I	0	0	0	0	14	0	4	10
II	33	0	6	27	20	0	7	13
III	66	0	15	51	24	3	6	12
IV	105	4	44	57	29	5	14	10

Visualizing the Damage to Building-Contents

Figures 5.a, 5.b, and 5.c depict three different damage scenarios for flood heights of 1.2 m (4.0 ft), 3.0 m (10.0 ft), and 4.8m (16.0 ft), respectively. In each 3-D perspective, a true-color orthoimage was draped over the DEM, and the 3-D building layer and flood surface was overlain on the draped image The color ramp indicates the value of the nominal damage on each building. Orange indicates total damage, and yellow indicates no damage.

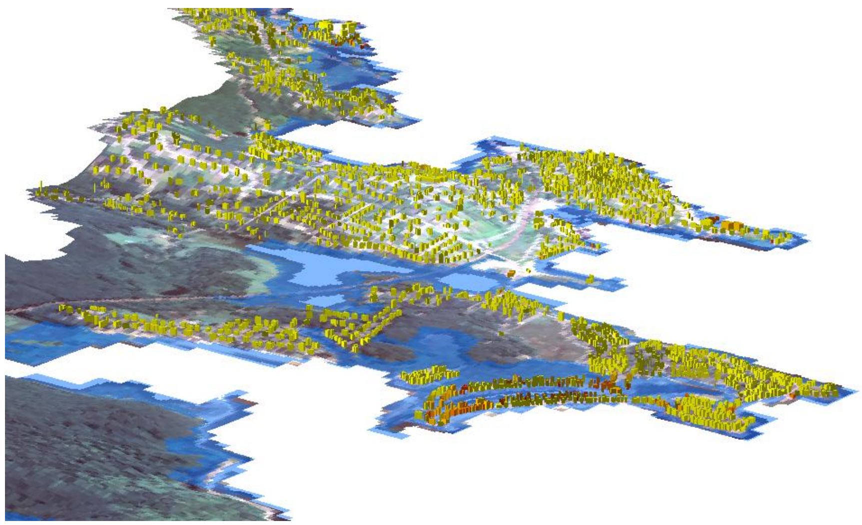
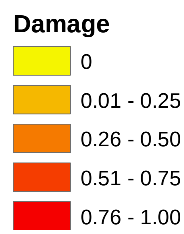


Figure 6.a. Damage for the 1.5 m surge scenario.



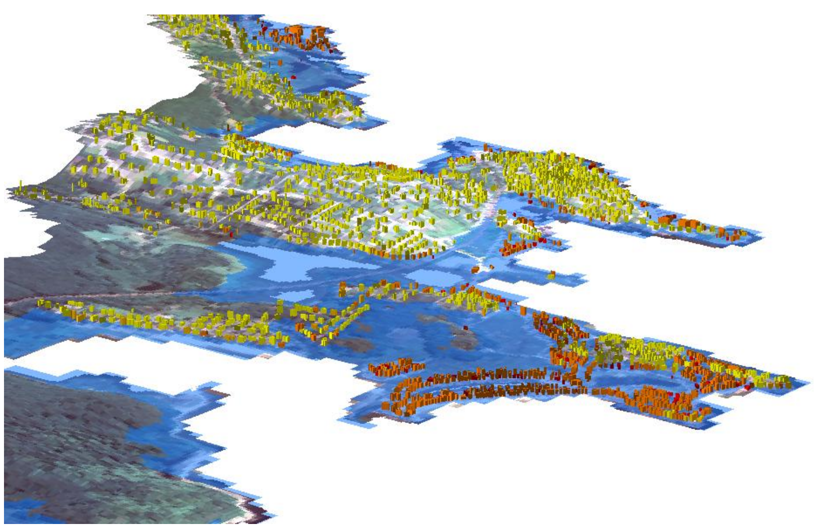


Figure 6.b. Damage for the 3 m surge scenario.

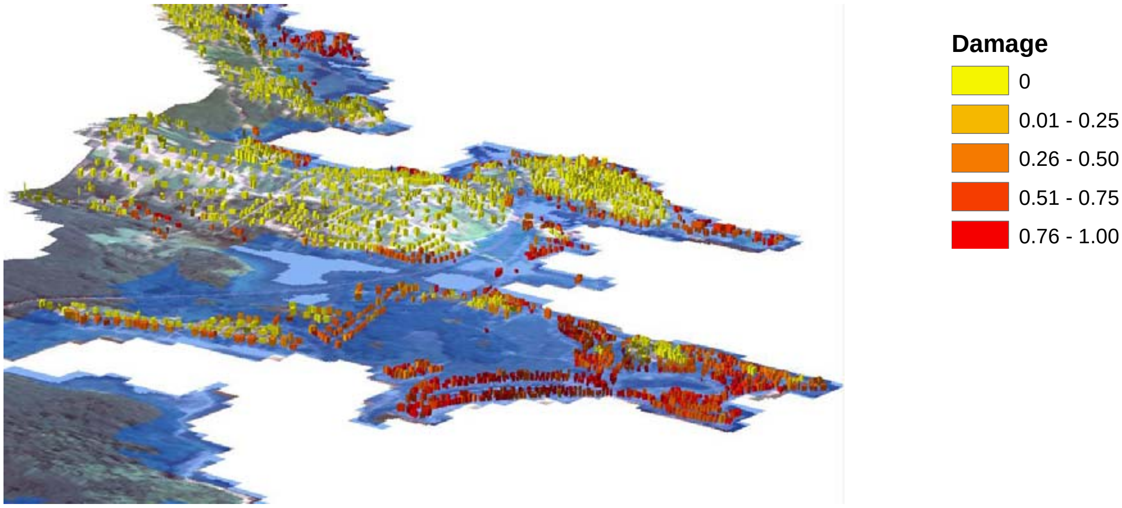


Figure 6.c. Damage for the 5 m surge scenario.

Damage Function and ArcGIS Tool

Most flood-vulnerability functions in the literature focus on building structural damage caused by a flooding event, but it is also important to assess the damage on building contents, as well. Most valuable items in buildings are usually located close to the floor. For example, in a house, electronics, furniture and other valuable household items are located either on the floor or approximately one meter above the floor. Therefore, only a few centimeters of flooding can inflict significant damage to a building's contents. Our damage function has an asymptote at nominal damage = 1, but this does not mean that the building has incurred total structural damage. Instead, this is a projection of total damage to building contents. The shape of the damage curve was chosen so that the gradient of the curve reflects the damage expected in a real flooding scenario: the curve has high gradient at low inundation levels because greater damage will be incurred by low flood-water depths; and after an approximately-50 cm depth limit, the curve grows with a low gradient, approaching an asymptote indicating total damage to the building content. The damage curve estimates the damage to multiple-story buildings by applying this damage function sequentially to each story. The accuracy of this hypothetical-damage function could not be assessed because we do not have actual damage data.

Flood-water velocity should have been included as a variable in the damage function, because water velocity is as important as water depth. However, the scenarios in this study are based on a 'still-water model,' which ignores flood-water velocity. Ignoring flood-water velocity makes this model conservative, but still allows, correctly, for total damage to a building.

Building construction materials should have also been introduced to the damage assessment although we do not assess the structural damage. The type of construction material can affect the degree of damage to the building content. For example, a higher damage can be expected for wooden floors compare to cement floors. Further, wooden structures are comparatively vulnerable for partial or total collapse at low flood water depths compare to other construction materials. Therefore, collapsing of building structure could lead to a total destruction of building content.

The damage function takes flood-water depth inside the building, floor height, and number of floors to project the damage to a building as input parameters. Flood-water depth and number of floors must be derived from the available data. The Python script calculates flood-water depth and number of floors, and then estimates damage. The script should be enhanced further to accept multiple surge heights and corresponding flooding rasters, because the user will then be able to estimate damages for multiple flooding scenarios with a single simulation. An optional input parameter, a digital surface model (DSM) as an alternative to non-ground LIDAR, can be introduced to the tool so that the user has a freedom to use either non-ground LIDAR or DSM.

The ArcGIS tool is not limited to assessing flood damages posed by storm surges, because the damage function running inside the tool takes into account flood-water depth. Therefore, this tool can be used in other flood-damage assessments as well as assuming a 'still water model.'

Estimated Damage Results

For all the flooding scenarios, the estimated damages were expressed as nominal damage that varied between 0 and 1. Damage would be more meaningful if expressed in U.S. dollars. However, the building layer did not contain any attributes indicating either structure values or property values. If the structure values had been given, the projected damage could have been converted into U.S. dollars and could directly express the damage on building contents, because U.S. Army Corp Engineers have tabulated the mean values of building contents as a function of structure values based on building use such as residential, commercial, and industrial (USACE, 1998).

The number of damaged buildings rapidly increases with the increasing surge height. The results showed that total damage (ND=1) occurs only in surges heights greater than 2.8 m. Of these, the number of totally damaged buildings suddenly leaps to more than 100 after a 4 m surge height. The values in Table 2.a indicate that greater damage occurs with residential buildings compared to other building categories. This is mainly due to concentration of residential areas close to the coast. A Category I hurricane (surge 0.6-1.2 m) can cause considerable damage on the coastal communities of Groton. Approximately 500 building were projected to be damaged, of which nearly 450 building are residential. A Category II hurricane (surge 1.8-2.4 m) was projected to damage nearly 1200 buildings, of which nearly 950 buildings are residential. Category I and Category II hurricanes are incapable of creating surges that inflict total damage. Category III (surge 2.7-3.6 m) and Category IV (surge > 3.6 m) hurricanes have to greatest impact on buildings. Our projections suggest Category IV hurricanes are capable of damaging more than 2000 buildings.

CONCLUSIONS

A new mathematical expression was derived to estimate the possible damage to building content. This vulnerability function estimates the degree of damage (from 0 – 1) resulting from storm-surge inundation. This function differs from others in that this one specifically focused damage on building contents. This function takes into account the number of floors in a building as a variable in addition to flood-water depth in the building for assessing damage. The proposed damage function can be enhanced by validating it with actual building damage data. This study demonstrated that combining the spatial analysis capabilities of a GIS with the modeling capabilities of a programming language can produce a useful, general-purpose tool that helps decision makers assess vulnerability of flood-prone areas. The outcomes of this research can be adopted in flood risk mapping activities in coastal cities and towns throughout the United States.

REFERENCES

Apel, H., B. Merz, and A. H. Thieken, 2009. Influence of dike breaches on flood frequency estimation, *Computers & Geosciences*, 35, 907-923.

Crichton, D., 1999. *The Risk Triangle*, J. Ingleton ed., Tudor Rose, London.

Cova, T. J., and R.L. Church, 1997. Modeling Community Evacuation Vulnerability Using GIS, *International Journal of Geographical Information Science*, 11, 763-784.

Dewberry, 2007. LiDAR QA/QC - Quantitative and Qualitative Assessment report, Dewberry, Virgina.

Dierckx, P., 1993. Curve and Surface Fitting with Splines, Oxford University Press.

ESRI, 2009. ArcGIS 9.3 Desktop Help, Accessed on January.

FEMA, 2003. SLOSH Training, Federal Emergency Management Agency, 2003, http://www.fema.gov/pdf/plan/prevent/nhp/slosh_display_training.pdf>. Accessed on January 2009.

Fenge, L. H., and W. Hong, 2007. A quantitative expression for the magnitude and intensity of disaster of storm surges, *Natural Hazards*, 45, 11-18.

Granger, K., 2003. Quantifying Storm Tide Risk in Cairns, *Natural Hazards*, 30, 165-185.

Jelesnianski, C. P., J. Chen, and W.A. Shaffer, 1992. SLOSH: Sea, lake, and overland surges from hurricanes, NOAA, Technical Report NWS.

Lavakare, A., 1998. GIS and Risk Assessment, GISdevelopment, <http://www.gisdevelopment.net/application/miscellaneous/misc010.htm>, Accessed on January 2009.

Lindell, M. K., and C.S. Prater, 2007. A hurricane evacuation management decision support system (EMDSS), *Natural Hazards*, 40, 627-634.

Lindenschidt, K. E., U. Herrmann, I. Pech, U. Suhr, H. Apel, and A. Thieken, 2006. Risk assessment and mapping of extreme floods in non-dyked communities along the Elbe and Mulde Rivers, *Advanced Geosciences*, 9, 15-23.

Longley, P., M.F. Goodchild, D.J. Maguire, and D.W. Rhind, 2005. *Geographical Information Systems and Science*, 2 ed., Wiley, Chichester.

Lotto, P. D., and G. Testa, 2000. Risk Assessment: A Simplified approach of flood damage evaluation with the use of GIS, Interpraevent 2000 - Villach/Osterreich, Italy.

Lowe, J. A., J.M. Gregory, and R.A. Flather, 2001. Changes in the occurrence of storm surges around the United Kingdom under a future climate scenario using a dynamic storm surge model driven by the Hadley Centre climate models, *Climate Dynamics*, 18, 179-188.

Lutz, M., and D. Ascher, 2003. *Learning Python*, 2 ed., O'Reilly Media, Sebastopol.

NOAA, 2009. Storm Surge, <http://www.nhc.noaa.gov/HAW2/english/storm_surge.shtml>, Accessed on Janaury2009.

Taubenbock, H., J. Post, A. Roth, K. Zosseder, G. Strunz, and S, Dech, 2008. A conceptual vulnerability and risk framework as outline to identify capabilities of remote sensing, *Natural Hazards and Earth System Sciences*, 8, 409-420, 2008.

UNDHA, 1992. Internationally Agreed Glossary of Basic Terms Related to Disaster Management, UNDHA (United Nations Department of Humanitarian Affairs), Geneva.

UNISDR, 2004. Terminology: Basic terms of disaster risk reduction, UNISDR (United Nations International Stratergy for Disaster Risk Reduction), <http://www.unisdr.org/eng/terminology/terminology-2004-eng.html>, Accessed on January 2009.

USACE, 1998. National economic development procedures manual-Urban flood damage, U.S. Army Corps of Engineers, Water Resources Support Center, Institute for Water Resources, Virginia.

Wenzel, F., A. Thieken, H. Kreibich, P. Köhler, M. Müller, G. Grünthal, P. Heneka, T. Hofherr, R. Wahlström, L. Kleist, B. Büchele, A. Kron, S. Tyagunov, J. Wächter, B. Merz, C. Kottmeier, B. Ruck, F. Nestmann, L. Stempniewski, and J. Zschau, 2007. Center for Disaster Management and Risk Reduction Technology (CEDIM) – Results and Perspectives, Disaster Reduction in Climate Change.

Witharana, C., 2009. A GIS Approach to Estimate Storm Surge Damage Risk to Buildings in Groton, Connecticut, M.S, Center for Integrative Geosciences, University of Connecticut, Storrs.

Zerger, A. Z., 1998. Cyclone inundation risk mapping, Ph.D, Centre for Resource and Environmental Studies, Australian National University, Canberra.

Zerger, A. Z., and D.I. Smith, 2003. Impediments to using GIS for real-time disaster decision support, *Computers, Environment and Urban Systems*, 27, 123-141.

Zerger, A.Z.., 2002. Examining GIS decision utility for natural hazard risk modelling, *Environmental Modelling & Software*, 17, 282-294.