Journal of
Geography & Natural Disasters

Tate and Frazier, J Geogr Nat Disast 2013, S1
DOI: 10.4172/2167-0587.S1-001

Research Article Open Access

A GIS Methodology to Assess Exposure of Coastal Infrastructure to Storm Surge & Sea-Level Rise: A Case Study of Sarasota County, Florida

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Abstract

Storm surge is the leading cause of loss of life and property from hurricanes. Recent research using geographical information system (GIS) technology has demonstrated sea level rise (SLR) will increase storm surge inundation zones. While effective and accepted GIS models exist for framing surge inundation there is a lack of depth information and consideration of SLR that may be critical for examining the exposure of coastal assets to current and future storm surge hazards. There is a need for a methodology that relates depth to inundation and asset exposure, and is supported by recent hazard vulnerability and resilience literature. Furthermore, new data has been collected that facilitates more detailed SLR modelling than available in previous research. Researchers provide a framework for GIS depth modelling of contemporary and SLR enhanced storm surge that is superior to two-dimensional inundation modelling for examining exposure of societal assets to storm surge and SLR in Sarasota County, Florida. The effectiveness of this framework is demonstrated in a GIS by comparing inundation modelling, depth modelling, and SLR modelling as applied to the exposure of flood-depth sensitive infrastructure in Sarasota County, Florida.

Keywords: Sea level rise; Infrastructure; Storm surge; GIS; Resilience; Conditional exposure

Introduction

During the 20th Century flooding caused more damage to life and property in the United States than any other natural disaster [1]. National Flood Insurance Program (NFIP) data demonstrates that the cost of flood damage to property increases with depth of flood water exposure [2]. Coastal communities in regions prone to hurricanes are at risk of storm surge flooding. Hurricane Katrina's nearly 8.53 m (28ft) peak surge height above sea level, recorded at Pass Christian, Mississippi [3] demonstrates the potential destructive impact of this hazard along the Southeast coastline. The devastation along the Louisiana, Mississippi, and Alabama coasts from Hurricane Katrina confirmed that coastal communities are vulnerable (vulnerability is used here as the 'susceptibility to be harmed' [4]) to storm surge exposure. The risk is not to property alone. Despite Federal Emergency Management Administration (FEMA) mandated risk assessment plans and early warning systems, storm surge causes 90 percent of hurricane fatalities [1].

Sea-level rise (SLR) is a key manifestation of climate change that is affecting the low-lying coastal communities of the Southeast United States today [5,6], and is expected to threaten these communities centuries into the future [6-8]. The biggest threats of SLR to these coastal communities include enhanced flooding (both permanent and episodic), accelerated erosion and land loss, ecosystem and habitat degradation, impeded land drainage, and saline intrusion into rivers, estuaries, and coastal aquifers [5,6,9]. Especially worrisome is the prospect of future hurricane storm surge. The literature supports that these factors are anticipated to impact the exposure, thus vulnerability [10,11], of coastal communities to hurricane flood effects: sea-level rise [12-16], new trends in storm strength and frequency due to climate change [17,18], shifts or trends in demographics, wealth, population [10,19,20], and mitigation and/or adaptive or resiliency planning [15,21-23]. Sea-level rise increases potential community storm surge exposure by increasing potential storm surge inundation and flooding [15].

Infrastructure and urban development

Infrastructure is a critical component of economic growth, sustainability, national security, and public health [24, 25]. Because urban development in the United States has typically been located adjacent to transit corridors, utility infrastructure has historically been located along these corridors and right of ways. Development of coastal communities in the Southeast United States has been enhanced by amenities such as favourable climate and public policies that promote tourism and attract retiree population settlement. A secondary cause of population influx in these regions is the demand to maintain the service sector needed to accommodate growth. The growth of critical infrastructure to support urban development must meet the demand fostered by increased population in the region. This growth has paid limited attention to the interconnectivity of infrastructure, especially considering the implications of single system failure that may result in multiple system failures. For example, if a storm surge caused a local disruption of service by interrupting several local substations, and that cascaded to a larger disruption within the region, this could affect the power supply to freshwater public supply pumps and the efficiency of communication services within and adjacent to the disaster area. This scenario suggests that the effects of the storm surge might expand beyond the zone of inundation and complicate recovery efforts. This would indicate heightened regional sensitivity to storm surge and be a concern when considering a real disaster resiliency [26-31].

Because critical infrastructure and urban development are

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Received March 14, 2013; **Accepted** April 26, 2013; **Published** May 01, 2013

Citation: Tate CA, Frazier TG (2013) A GIS Methodology to Assess Exposure of Coastal Infrastructure to Storm Surge & Sea-Level Rise: A Case Study of Sarasota County, Florida. J Geogr Nat Disast S1:001 doi:10.4172/2167-0587.S1-001

connected, the examination of surge exposure has implications that extend to social capital, health, community resilience, and disaster mitigation [32]. Effective planning strategies might be enhanced by investigating existing infrastructure vulnerability to current and climate change enhanced storm surge exposure scenarios to facilitate more resilient (the ability of a system to return to normal function after exposure to perturbations [33]) infrastructure upgrade and future location decisions.

Importance of modelling storm surge depth

Examining the depth of storm surge inundation (flooding) is crucial in determining the degree of exposure for current and future societal assets in coastal communities. Although previous research in Sarasota County has demonstrated storm surge zones size will increase with SLR [15], past research was not sufficiently complex to model the depth of storm surge inundation. The electrical utility provider in Sarasota County, Florida, the case study area, estimates nine months repair or replacement time for individual substations damaged by potential storm surge inundation. Electrical substations operated in Sarasota County can, however, operate in up to 1.83 m (6 ft) of water (Florida Power & Light personal communication, 2009). After shelter, potable water is the primary resource required for post-disaster survival, and the availability of this resource is an indicator of resilience [31, 34]. As SLR increases surge inundation zones, researchers expect to find an increasing amount of the public supply water source from freshwater wells at risk of over-the-top saline intrusion from exposure. Public supply freshwater wellheads are mandated to be 0.61m (2ft) above grade in Sarasota County (Sarasota County Department of Health, personal Communication, 2011). Over-the-top saline intrusion may contaminate these freshwater wells. It is therefore critical to determine for each hurricane category the location of critical infrastructure at probable risk of exposure based on resulting levels of storm surge inundation.

The role of planning

Global reinsurance data indicates concentrations of population and infrastructure in hazard prone areas are the main factors of an increasing cost of catastrophes [35]. Planning has proven to be the most effective tool for minimizing losses stemming from natural hazards—including hazards related to climate change—and consequently for increasing resilience, reducing vulnerability, and building more sustainable communities[15,36,37]. Informed planning is critical in areas prone to climate hazards where high population density exists and areas projected for population growth and economic development to reduce future exposure by steering development towards areas less prone to flooding [36].

SLOSH and depth

The Sea, Lake, and Overland Surge from Hurricanes (SLOSH) model [37] is widely used by planners for disaster policy decisions. Outputs are freely available to the general public through the SLOSH Display program that can be downloaded from The National Hurricane Center (NHC), which administers SLOSH. These outputs can be exported as *.shp (shape) files that can be incorporated into most GIS. Unfortunately SLOSH shape files only account for two dimensional inundation of contemporary storm surge. They lack flood depth information and SLR variability. By applying depth to SLOSH storm surge shape files and utilizing SLR enhanced storm surge scenarios, planners would be enabled to expand disaster policy decisions beyond what is reflected by two dimensional inundation modelling.

Although progressive local governments account for hurricane storm surge in their planning, many do not account for SLR nor plan on the timescales of SLR projections. A prerequisite of this study is that data and methodology to model storm surge depth and SLR be practical and available to local planners with modest resources. Modest resources indicate user access to data and a GIS, and some technical understanding of how to implement input and interpret output from a GIS.

Because of the threat of SLR and the importance of planning to preserve life and property, a framework for examining the depth of contemporary and future storm surge inundation is needed to better guide mitigation, adaptation, and resilience enhancement efforts. Furthermore, this framework should be within reach of communities with limited budgets or technical resources, and at the highest resolution possible. This research utilizes recently released high resolution Light Detection and Ranging (LiDAR) data and SLOSH to determine the depth of contemporary and SLR enhanced storm surge inundation for Sarasota County, Florida at the highest resolution possible considering data limitations. This flood depth modelling framework is applied to the exposure of two flood depth sensitive critical infrastructures: electrical substations, and public supply freshwater wells.

Methods

NOTE: Point data representing infrastructure within this document have been intentionally generalized. Due to the sensitive nature of critical infrastructure and potential threats to security, researchers elected not to publish this data at a resolution or scale that would explicitly compromise local efforts to preserve the integrity of the critical infrastructures addressed in this study.

For this study 'inundation' is the modelled two-dimensional description [38] of storm surge landward extent. 'Flooding' in this text implies the degree of exposure of a specific located unit to inundation considering the depth of water. 'Flooded' in tables and maps indicates infrastructure flood exposure beyond the range that the unit could be expected to function.

A case study: Sarasota County, Florida

Data collected by the Atlantic Oceanographic and Meteorological Laboratory (AOML) shows that Florida has the greatest frequency of hurricane exposure in the United States [39]. Sarasota County, Florida is situated south of Tampa Bay on the west coast of the Florida Peninsula, adjacent to the Gulf of Mexico, and is at risk of exposure to hurricanes and storm surge. Development in Sarasota County, as in much of the United States, has progressed along common right-of-ways and transit corridors. Much of the traditional infrastructure in Sarasota County is located near the coast where development is most concentrated, and potential exposure to storm surge the greatest [15] (Figure 1).

Researchers chose Sarasota County as a study area because of the risk of storm surge exposure, the availability of high-quality data for the area, and for the benefit of analysis by comparison to previous research in this county that did not include a depth component for storm surge or SLR exposure.

Background

Four storm surge models were considered for this study: The Arbiter of Storms (TAOS) model by Kinetic Analysis Corporation; the Semi-implicit Eulerian-Lagrangian Finite-Element (SELFE) model developed at and distributed by the Center for Costal Marine

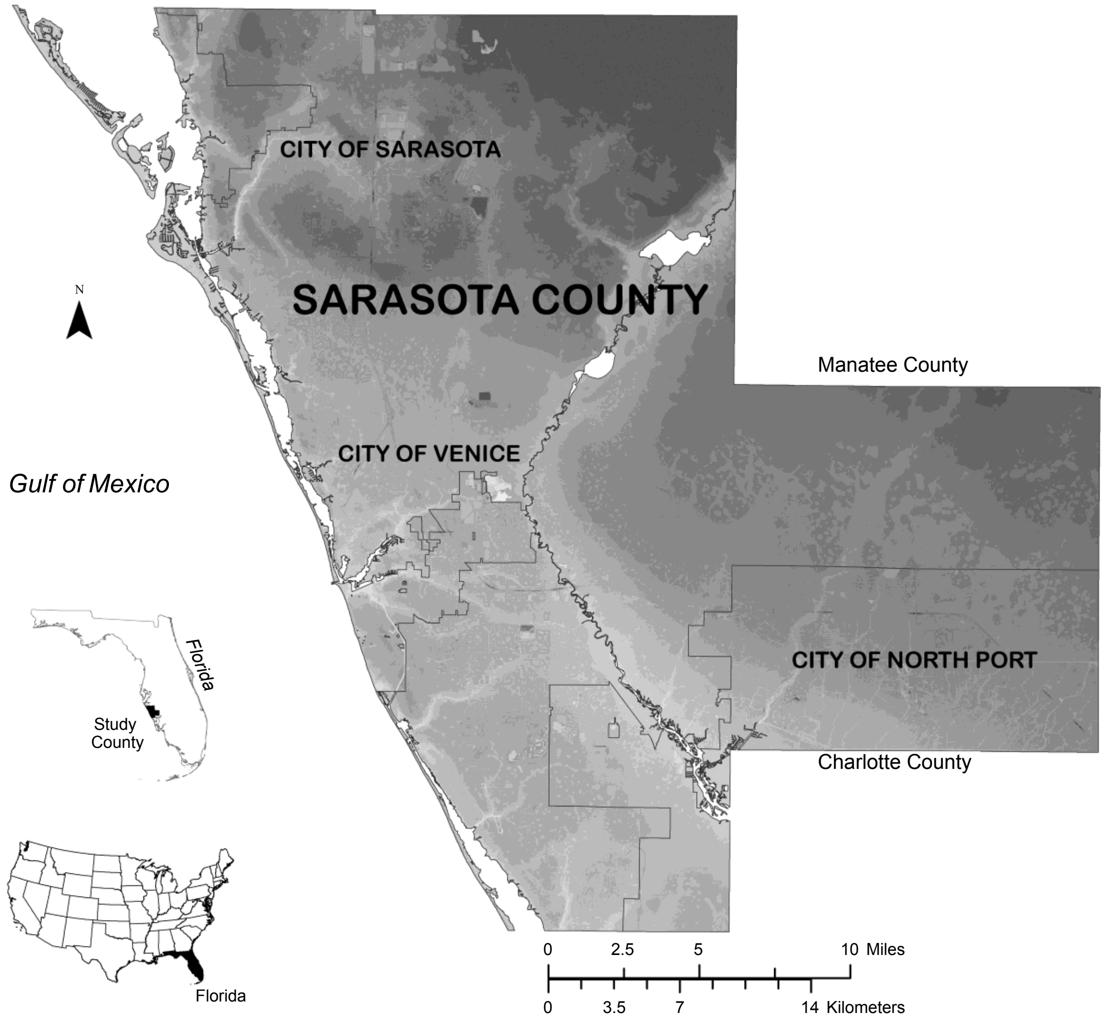

Figure 1: Study Area: Sarasota County, Florida.

Observation & Prediction at the Oregon Health and Science University; the HAZUS model administered by FEMA; and the SLOSH model used by NHC.

The researches rejected TAOS because of cost, and the difficulty of independently verifying the algorithms that generated the results obtained from the for-profit model. The SELFE model was attractive because it is free to download and license, open-source, robust, has flexibility of resolution, a depth component, and the ability to model SLR. Developer and user community support for SELFE is excellent. However, it is labor intensive to construct the unstructured grids that SLEFE uses, and SELFE's complexity and high computation cost puts the model out of reach of local planning agencies with modest resources. HAZUS was rejected because there may be difficulties in local application due to redundancy and data availability and/or inadequate data. HAZUS utilizes SLOSH for its storm surge output, but requires ancillary input that renders the model inappropriate for our targeted application by the necessity for architectural and other data sources that may be underdeveloped in some communities.

Researchers elected to use SLOSH because it is commonly used by policy-makers in disaster planning, is cost free and readily available to the public, and the wind driven wave computations are delivered with the SLOSH Display software. SLOSH Display and the SLOSH model should not be confused. The SLOSH model generates the outputs bundled in the SLOSH Display program, so users are not required to have access to the time and computational resources needed to complete multiple SLOSH runs. However, data exported from SLOSH Display describes surge inundation and does not have the depth component required for this study. SLOSH Display also lacks an input for SLR scenarios.

The SLOSH model uses a SLOSH basin and *.trk (track) files for input to create Maximum Envelope of Water (MEOW) outputs [40]. Track files are text files that specify local tide, storm trajectory and forward speed, storm intensity (as wind speed –Table 1), and storm circumference. The Saffir-Simpson scale is dependent on measured hurricane wind speeds that are sustained for at least one minute [41] (Table 1).

Basins are created by choosing an initial point of origin and developing one of three types of grids: polar, elliptical, or hyperbolic. Basins utilize digital bathymetry and land elevation maps to populate the grid cells with elevation data. All three grids types are generated from the initial point outwards, creating grid cells of increasing dimension the further from point of origin. This has the net effect of

Category	Wind Speed
Category 1	119 – 153 km/hr (74 – 95 mph)
Category 2	154 – 177 km/hr (96 – 110 mph)
Category 3	178 – 209 km/hr (111 – 130 mph)
Category 4	210 – 249 km/hr (131 – 155 mph)
Category 5	> 249 km/hr (> 155 mph)

Table 1: The Saffir-Simpson Scale.

coarser inundation data resolution compared to bathymetry or land elevation data the further a given SLOSH cell is from the point of origin. A time series output is generated using physics algorithms that represent surface stress and atmospheric pressure [42]. The NHC uses specialized software and manual determinations of how water direction and velocity will influence adjacent cells depending upon land cover and other factors (such as grid extent) that are not strictly elevation.

Of the three SLOSH approaches, the Composite Approach is 'regarded by the NHC as the best approach for determining storm surge vulnerability for an area because it takes into account forecast uncertainty' and 'play[s] an integral role in emergency management' [43]. To develop a Composite Approach, Maximum Envelope of Water (MEOW) inundation data are modelled by running several thousand storm scenarios with different tides, trajectories, and landfalls related to the point of origin, and retaining the outputs for each storm category. MOM (Maximum of Maximums, or Maximum of MEOW) are worst case storm surge scenarios modelled by using MEOW outputs for each category storm. This study uses MOM shape files provided by Sarasota County. SLOSH modelled inundation accuracy is described to be +/- 20% [44] of historical storm surge measurement.

Data, hardware, and software used

Three primary forms of data were acquired: (1) SLOSH MOM inundation polygons for category 1 through category 5 hurricanes for the Fort Meyers basin provided by Sarasota County, (2) a bare-ground digital elevation map (DEM) of the study area referenced to the North American Vertical Datum of 1988 (NAVD 88) prepared by Woolpert, Inc. of Orlando, Florida and provided by Sarasota County, and (3) point data representing critical infrastructure provided by local utility companies and the Sarasota County Department of Health (DOH). Wool pert data was provided in units of US Survey feet. Accuracy of the LiDAR Control Points for the DEM was average 1.22 cm (.04 ft) horizontally and 3.52 cm (.11 ft) vertically at a 95% confidence level [45,46]. Raster cell size of the DEM represent 1.52 m by 1.52 m (5 ft by 5 ft) horizontal ground surface (Sarasota County GIS personal communication, 2011). The machine used for analysis was limited to an Intel Pentium Dual Core Central Processing Unit (CPU) and 8 gigabytes (GB) of random access memory, an internal Integrated Drive Electronics (IDE) hard drive with 500 GB of storage, and a 2.0 Universal Serial Bus (USB) 1 terabyte hard drive for back up. A Windows 7 operating system (OS) and ArcGIS ArcMap 10.0 with a Spatial Analyst license were installed and used for this study.

Modelling depth and SLR from SLOSH

SLOSH shape files for category 1 through category 5 storms were converted to raster format and integrated with the DEM in a GIS to derive contemporary and SLR storm surge inundation zones. Figure 2 shows SLOSH inundation zones by hurricane categories 1 through 5, and generalized locations of the two types of infrastructure examined.

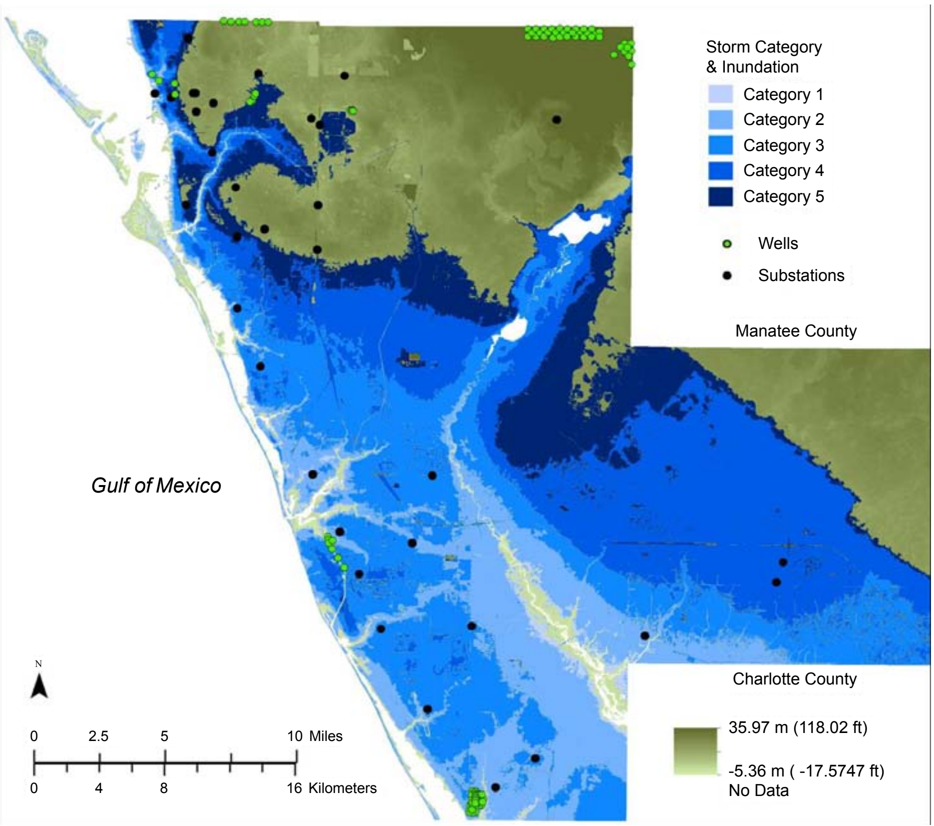

Figure 2: SLOSH category 1-5 inundation zones with generalized substation and wellhead locations.

By converting SLOSH vector output to raster format, calculations were less computationally intensive for the machine employed, reliable, and much faster than the vector format. With raster format some GIS functionality was limited, but for the purpose of this research that loss of functionality was acceptable. These inundation zones were layered with infrastructure point data and spatially referenced to NAD 1983 HARN State Plane Florida West FIPS 0902 Feet. A survey was conducted to extract elevation values of DEM raster cells that were 'dry' and adjacent to cells that were 'wet' on landward SLOSH inundation fronts. By this method, the maximum elevation of the DEM at the extent of SLOSH modelled inundation was extracted. The extracted elevation value was subtracted from the DEM's datum to create new layers in the GIS representing depth-associated inundation. This was done for each of the five Saffir-Simpson hurricane categories, resulting in negative elevation values that represented flooded raster cells according to SLOSH. These layers were compared to the original SLOSH shape files to verify congruity. Figure 3 shows the depth flood framework at a contemporary category 5 hurricane, and generalized locations of substation and wellhead point data. (Figures 2 and 3)

SLR scenario values of 0.3 m, 0.6 m, 0.9 m, and 1.2 m were chosen to be flood depth modelled because of a call for this scale by the IPCC and in previous research [15]. These values were subtracted from each of the five depth outputs resulting in a total of 24 flood depth associated DEMs.

The Fort Meyers basin uses an elliptical grid, therefore the SLOSH cells that indicate storm surge exposure are never at a scale consistent with the cell dimensions of the Sarasota County DEM. Also, at the time of this study, SLOSH does not account for localized wave effects. For this reason a range of flood depth values representing expected infrastructure exposure was adopted. Researchers classified exposure for contemporary and SLR surge scenarios for both types of infrastructure as a percentage of infrastructure in a category over total infrastructure points in the county. Categories were defined as: Wet (exposed but not expected to be compromised), Critical (exposed and expected to be compromised), and Flooded (exposed and considered to be compromised).

Modelling substation risk to exposure

Substation point data was overlaid on the depth model outputs and spatially referenced. Elevations were extracted for the substation point data for each DEM layer. Within the model the substations were classified by risk of exposure to storm surge based on elevation, hurricane category, and SLR scenarios. Substations not exposed to any flood event were classified as dry. A critical depth range of 1.52 m (5 ft) to 2.13 m (7 ft) below modelled high flood depth was established to represent a tolerance for substation critical risk of exposure flood depth. This range is based on the 1.83 m (6 ft) known substation failure sensitivity to flood exposure. Exposed substations not flooded to this

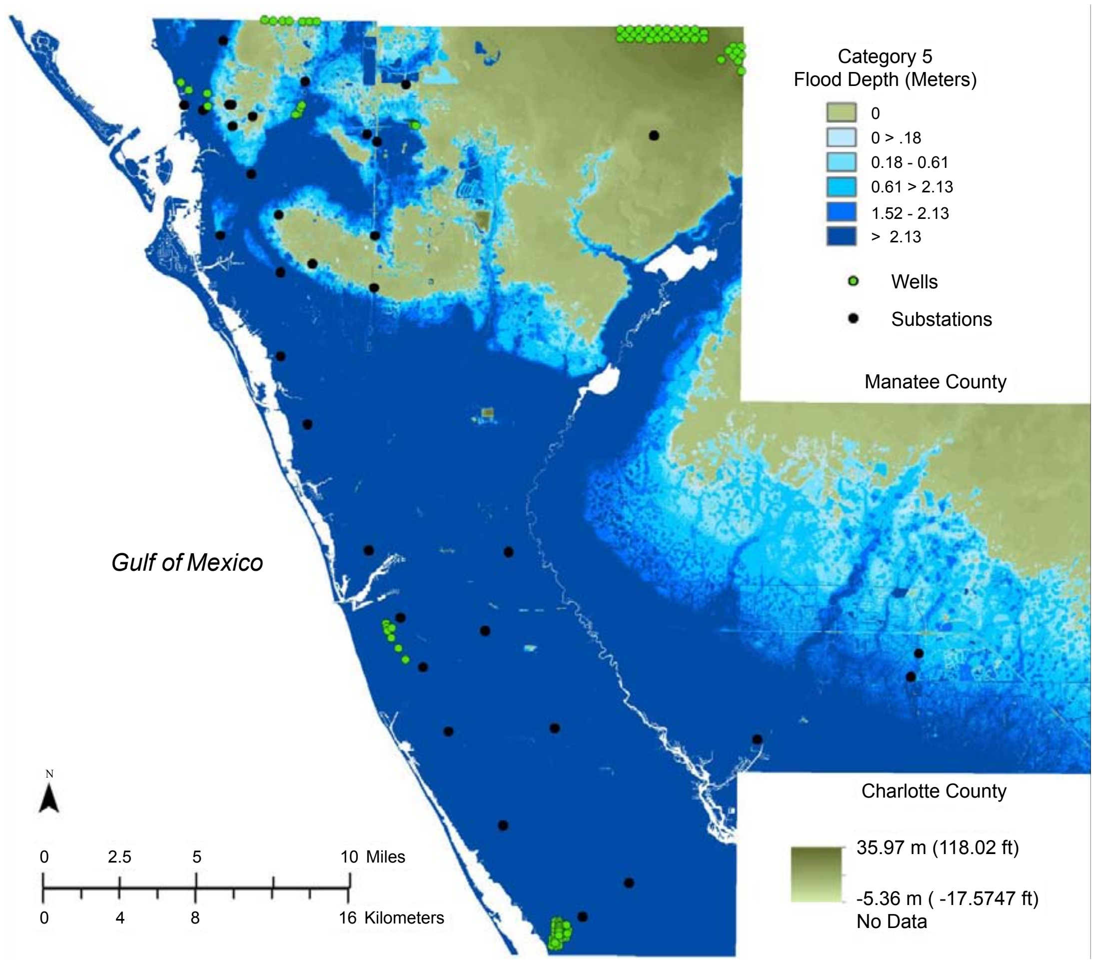

Figure 3: Depth category 5 contemporary storm surge with generalized substation and wellhead locat.

	Substation Flood Depth
Dry	–
Wet	<1.52 m (5 ft)
Critical	1.52 m (5 ft) – 2.13 m (7 ft)
Flooded	> 2.13 m (7 ft)
	Calibrated Wellhead Flood Depth at top of Wellhead
Dry	-
Wet	Grade > and < - .3048 m (1 ft)
Critical	- .3048 m (1 ft) to .3048 m (1 ft)
Flooded	>.3048 m (1 ft)

Table 2: Categories of Infrastructure Exposure.

critical range were classified as Wet. Substations flooded beyond this critical range were classified as Flooded (Table 2). Figure 4 shows the degree of exposure for substations at a contemporary category 5 hurricane.

Modelling wellhead exposure

Wellhead modelling was limited to community supply wells. According to an interview with the Sarasota County Department of Health in 2011, these wellheads are mandated to be 0.669 m (2 ft) above grade. Private wellheads were not subject to the same mandate prior to 1983. Some landowners have modified privately owned wellheads after initial county inspection to ease lawn maintenance by cutting the casings to be at or below grade. Because of the difficulty of ground-truthing the thousands of known private wells in Sarasota County, they were excluded from this study. Encapsulation or other protection that might influence the exposure of community supply wellheads to storm surge was not considered.

There are over ten thousand known freshwater wells existing in Sarasota County. Most are private and some of these are defunct. The industrial and commercial sector has a large number of wells used for a variety of purposes. In addition to the ninety eight wells that are classified as 'public supply' by the DOH, Sarasota County supplements this supply by purchasing water from adjacent counties. This water is stored in open reservoirs that are near treatment facilities and adjacent to urban areas. Fluctuations in water demand, usage, and source make it difficult if not impossible to determine what percent of the population is being served with potable water from a particular public supply well. Though researchers requested data about maximum output capacity of the individual wells, it could not be provided. The overall vulnerability of Sarasota County water supply is beyond the scope of this study.

Wellhead point data was overlaid on the original bare-ground DEM, spatially referenced, and elevation values established. We added 0.6096 m (2 ft) to the elevation of the wellhead points to calibrate for the county-mandated height above grade. This adjusted elevation layer was applied to the depth model outputs to indicate flooding. Wellheads

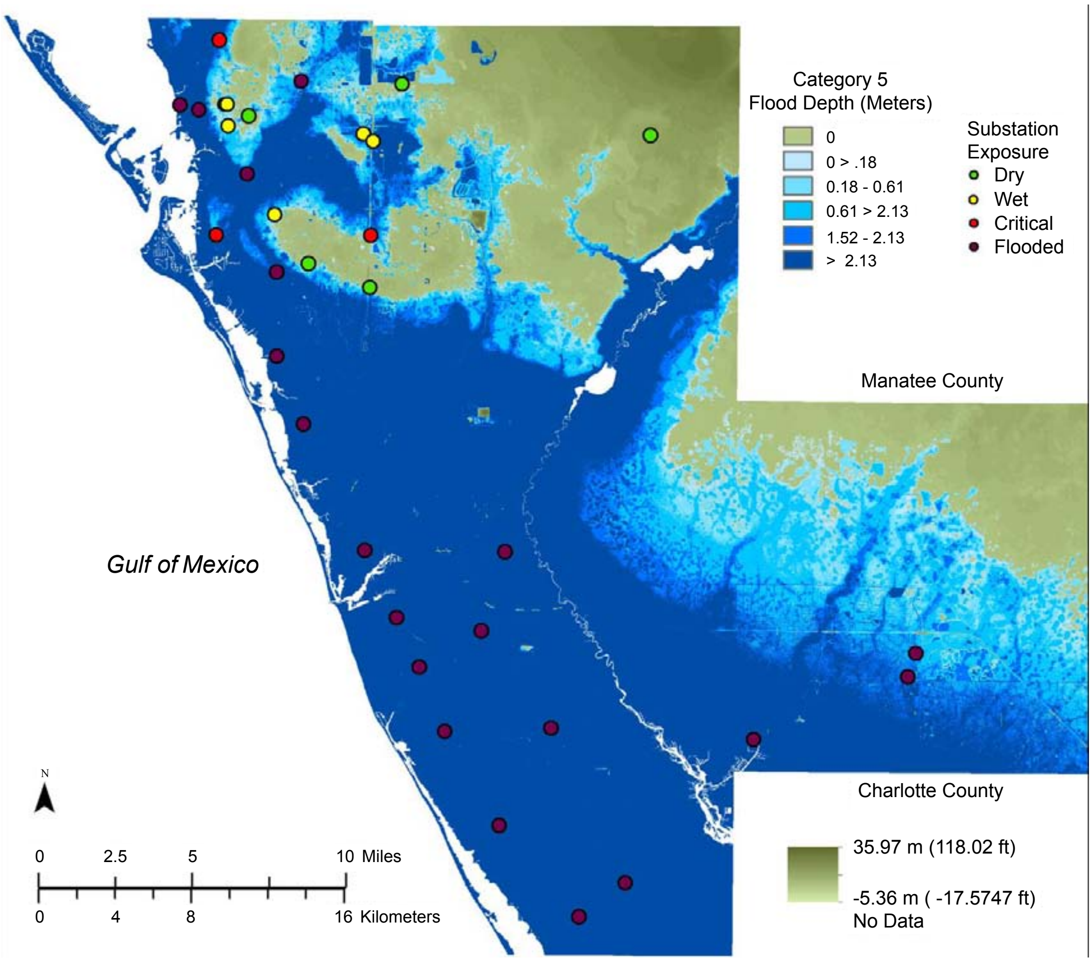

Figure 4: Depth category 5 contemporary storm surge exposure of substations.

outside of flood events were classified as dry. A critical range was adopted +/- 0.3048 m (1 ft) of the top of wellheads to indicate critical exposure. Wellheads experiencing less flooding than this critical range were classified as Wet, and wellheads experiencing flooding greater than this critical range were classified as Flooded (Table 2). Figure 5 shows the exposure of wellheads for a contemporary category 5 hurricane.

A proportional 'headcount' vulnerability indicator was used [4] to indicate exposure for analyses of SLOSH inundation to base hurricane category (contemporary) storm surge depth exposure (Table 2 and Figures 4 and 5).

Results

Substations

None of the 35 substations located in the study area were shown to be affected by a category 1 hurricane surge by SLOSH, the flood depth framework, or the SLR scenarios. Table 3 shows substation exposure to storm surge inundation demonstrated by the SLOSH model.

Because SLOSH output is two dimensional, sensitivity of substations cannot be represented here. Table 4 is the output of the flood depth framework for substation flood exposure to contemporary and SLR enhanced storm surge.

	Actual Dry	Actual Inundated	Percent Exposed
Category 1	98	0	-
Category 2	64	35	35.71
Category 3	56	42	42.86
Category 4	45	42	42.86
Category 5	42	49	50.00

Table 3: Wellhead Exposure per SLOSH.

For a Category 1 hurricane, both tables indicate that none of the 35 substations are at risk from exposure. The Category 2 hurricane shows four exposed substations compared to three per the inundation model, indicating that the depth framework is showing more overall exposure than SLOSH. However, the substations exposed to inundation from a Category 2 storm surge are not indicated to be in danger of failure from flooding. Category 3 demonstrates a similar pattern with SLOSH showing thirteen exposed substations, and the depth framework showing fourteen, but only one substation is in the Critical range. In a worst case scenario one substation out of fourteen is at a known risk of failure from flooding from a contemporary Category 3 storm surge. At Category 5 the results are more disparate, with SLOSH showing fifteen dry substations and twenty inundated, while the depth framework shows only six dry substations and 20 flooded substations. According to depth, four substations are flooded at the range of expected failure (Critical), and twenty beyond the point of expected failure (Flooded).

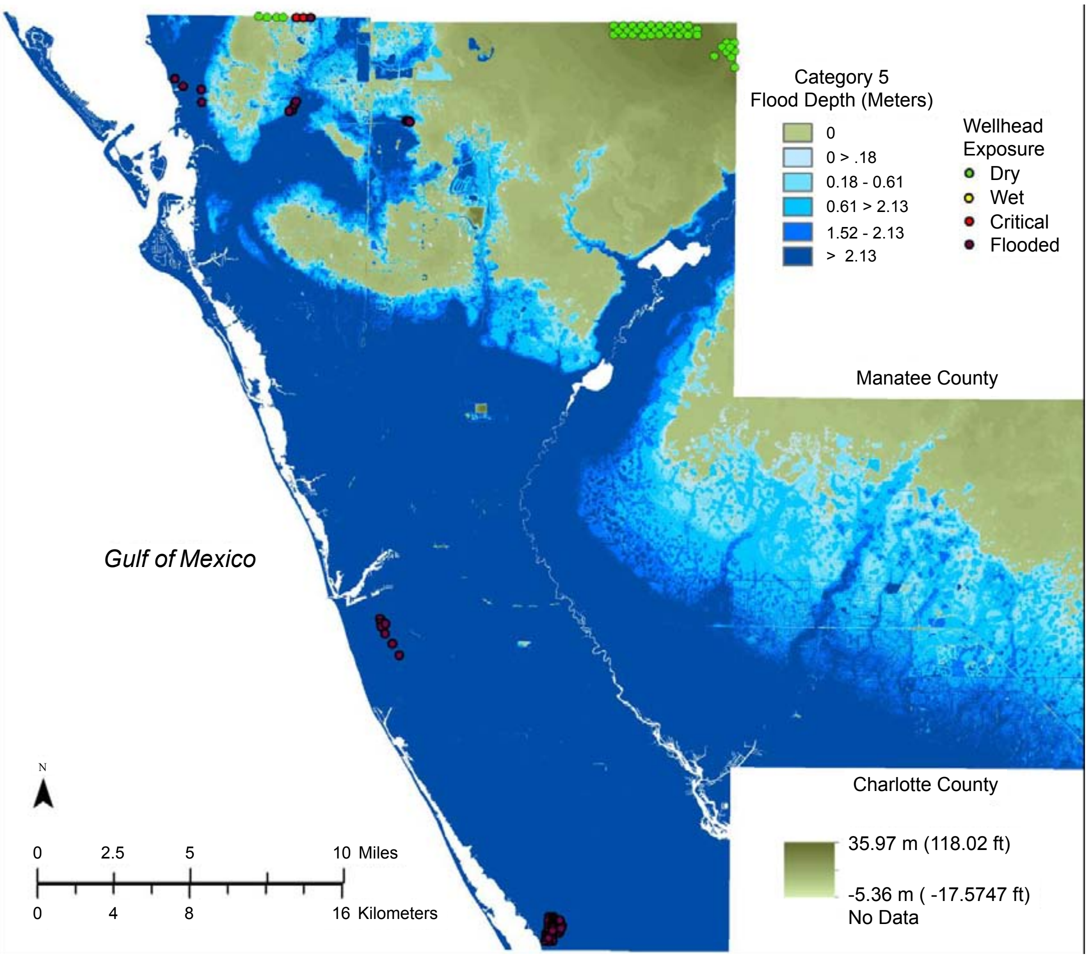

Figure 5: Depth category 5 contemporary storm surge exposure of wellheads.

Category x_SLR m	Actual Dry	Actual Wet	Percent Exposed Wet	Actual Critical	Percent Exposed Critical	Actual Flooded	Percent Exposed Flooded
Category 1_1.2 m	35	-	-	-	-	-	-
Category 2_0.0 m	31	4	11.43	-	-	-	-
Category 2_0.3 m	25	10	28.57	-	-	-	-
Category 2_0.6 m	24	11	31.43	-	-	-	-
Category 2_0.9 m	23	12	34.29	-	-	-	-
Category 2_1.2 m	22	13	37.14	-	-	-	-
Category 3_0.0 m	21	13	37.14	1	2.86	-	-
Category 3_0.3 m	21	10	28.57	4	11.43	-	-
Category 3_0.6 m	21	5	14.29	9	25.71	-	-
Category 3_0.9 m	20	4	11.43	7	20	4	11.43
Category 3_1.2 m	20	3	8.57	2	5.71	10	28.57
Category 4_0.0 m	9	9	25.71	2	5.71	15	42.86
Category 4_0.3 m	8	9	25.71	2	5.71	16	45.71
Category 4_0.6 m	8	7	20	3	8.57	17	48.57
Category 4_0.9 m	8	5	14.29	4	11.43	18	51.43
Category 4_1.2 m	6	5	14.29	4	11.43	20	57.14
Category 5_0.0 m	6	5	14.29	4	11.43	20	57.14
Category 5_0.3 m	5	5	14.29	5	14.29	22	62.86
Category 5_0.6 m	3	5	14.29	5	14.29	24	68.57
Category 5_0.9 m	3	6	17.14	6	17.14	25	71.43
Category 5_1.2 m	3	6	17.14	6	17.14	27	77.14

Table 4: Substation Exposure: Contemporary and SLR Storm Surge Scenarios per Depth Framework.

	Dry	Inundated	Exposed
Category 1	98	0	-
Category 2	64	35	35.71 %
Category 3	56	42	42.86 %
Category 4	45	42	42.86 %
Category 5	42	49	50.00 %

Table 5: Wellhead Exposure per SLOSH.

Category x_SLR m	Actual Dry	Actual Wet	Percent Exposed Wet	Actual Critical	Percent Exposed Critical	Actual Flooded	Percent Exposed Flooded
Category 1_0.0 m	98	-	-	-	-	-	-
Category 1_0.3 m	98	-	-	-	-	-	-
Category 1_0.6 m	98	-	-	-	-	-	-
Category 1_0.9 m	95	1	1.02	1	1.02	1	1.02
Category 1_1.2 m	87	6	6.12	3	3.06	2	2.04
Category 2_0.0 m	64	11	11.22	17	17.35	6	6.12
Category 2_0.3 m	62	2	2.04	22	22.45	12	12.25
Category 2_0.6 m	61	2	2.04	12	12.25	23	23.47
Category 2_0.9 m	57	3	3.06	4	4.08	34	34.69
Category 2_1.2 m	56	1	1.02	5	5.1	36	36.73
Category 3_0.0 m	56	1	1.02	5	5.1	32	32.65
Category 3_0.3 m	55	1	1.02	4	4.08	38	38.78
Category 3_0.6 m	54	1	1.02	2	2.04	41	41.84
Category 3_0.9 m	54	0	-	2	2.04	42	42.86
Category 3_1.2 m	54	0	-	1	1.02	43	43.88
Category 4_0.0 m	45	3	3.06	2	2.04	48	48.98
Category 4_0.3 m	44	0	-	4	4.08	50	51.02
Category 4_0.6 m	43	1	1.02	3	3.06	51	52.04
Category 4_0.9 m	42	1	1.02	1	1.02	54	55.1
Category 4_1.2 m	42	0	-	2	2.04	54	55.1
Category 5_0.0 m	42	0	-	2	2.04	54	55.1
Category 5_0.3 m	42	0	-	1	1.02	55	56.12
Category 5_0.6 m	42	0	-	0	-	56	57.14
Category 5_0.9 m	41	1	1.02	0	-	56	57.14
Category 5_1.2 m	38	3	3.06	1	1.02	56	57.14

Table 6: Wellhead Exposure: Contemporary and SLR Storm Surge Scenarios per Depth Framework.

Five substations are in the Wet category. Again, the depth framework describes more exposed substations than SLOSH.

Adding 1.2 m SLR to a base Category 2 does not cause any substations to be classified as Critical or Flooded. All Category 1 hurricane scenarios are indicated as Dry. As expected, exposure increases with storm strength and SLR.

Wellheads

Community supply freshwater wells are clustered near areas of urban development except for an array in the northeast corner of the county (Figure 5). This corner has the highest land elevation. None of the 98 community supply freshwater wells were in the contemporary SLOSH Category 1 hurricane inundation zone. Table 5 shows community water supply wellhead exposure demonstrated by SLOSH.

The calibrated depth framework did not show wells in inundation zones until the Category 1_0.9 m of SLR scenario (Table 6). Table 6 shows the output of the calibrated depth model framework for wellhead flood exposure to contemporary and SLR enhanced storm surge.

Though the exposed wellhead counts designated as Wet, Percent Exposed Wet, Critical, and Percent Exposed Critical fluctuate beyond a Category 2_0.3 m storm, there is an overall increase in exposure as depth of water increases. This is evident by comparing the Dry column to the flooded column in Table 6. Table 6 also shows the output of the calibrated depth model framework for wellhead exposure to the SLR scenarios. The difference in exposure from Category to Category considering SLR shows a greater degree of increase for smaller storms. Category 1_0.0 m to Category 2_0.0 m demonstrates the greatest overall increase of flooded wellheads, yet shows a net reduction of exposure between Category 2_1.2 m and a Category 3_0.0 m storm. There is also a net reduction between Category 3_1.2 m and Category 4_0.0 m. However, examination of the tables shows a trend of increasing exposure for increased storm strength, and an increase of exposure within each storm category for increased SLR scenarios. The only exception is Category 5_0.6 m to Category 5_0.9 m, where Critical and Flooded categories are static.

Comparison of depth and inundation modelling

Table 7 shows the differential exposure of infrastructure points located in depth model contemporary storm surge and SLOSH inundation zones for substations.

The depth framework shows more exposure than inundation for Categories 2-5, with Categories 4 and 5 having a difference of nine

	Substations	
	Depth	SLOSH
Category 1	0	0
Category 2	4	3
Category 3	14	13
Category 4	26	17
Category 5	29	20
	Wellheads	
	Depth	SLOSH
Category 1	0	0
Category 2	34	35
Category 3	42*	42*
Category 4	53	42
Category 5	56	49

Table 7: Differential Exposure – Substations & Wellheads.

exposed substations. Table 7 also examines the calibrated wellhead depth exposure and SLOSH inundation exposure.

(* The SLOSH model and depth framework each showed a unique exposed well that the other did not, creating an offset for Category 3.)

Here the disparity between the depth framework and SLOSH is less than for substations and SLOSH, except for Category 4 wellhead exposure.

Discussion

The graphical information generated by this study best represents the spatial contrasts between depth and inundation. Due to limitations of space these cannot be fully reproduced or discussed here, though these spatial contrasts are represented in the tables. There is an interesting contrast between the developed infrastructures in this study. Sarasota County has utilized an Urban Growth Boundary to encourage residential and commercial development towards the coastal areas which are at highest risk of storm surge exposure, while preserving inland natural habitat and rural development outside of the boundary. Historically the high-risk areas have been the most desirable for residential and economical development (i.e. coastline proximity amenities, land speculation, and tourism). Infrastructure developed to support and service this pattern of urban development. Though electrical substations and public supply wells service the same population they maintain spatial patterns characteristic of distance decay effects that are weighted by economy of distribution for the commodity provided. The locations of these infrastructures ensure delivery of consistent service demanded by use and efficiency of delivery. A significant number of wellheads are located in the high elevation northeast section of the county, are impervious to flooding by the bounds of storm surge effects in this study, but in an area that has little population. Substations are located according to population density. Both commodities are largely sourced out of county. The different spatial distributions in relationship to elevation and total infrastructure points accounts for exposure disparities between the two infrastructures at all storm category and SLR scenarios.

This study largely supports the findings of Frazier et al. 2010 [15] that describe an increased exposure of socioeconomic assets and vulnerability of Sarasota County, using substations and community supply wellheads as a proxy, for a land falling hurricane when storm intensity and/or SLR conditions increase. However, Frazier et al. 2010 [15] did not examine conditional exposure of assets to flooding, or specific infrastructure, so a direct comparison is not possible. This study indicates that sea level rise may not have 'the equivalent effect on storm surge risk of increasing the intensity of contemporary hurricanes by one Saffir-Simpson category' [15]. Researchers suggest that spatial distribution and conditional vulnerability of assets cannot be ignored when examining potential exposure from contemporary storm surge and storm surge enhanced by SLR.

While this research is concerned specifically with storm surge and SLR, the concept of examining conditional exposure could categorically benefit hazards resilience and vulnerability research. For instance, applying conditional exposure to the Cutter et al. 2008 DROP model [30] might reveal skewed results from a stochastic application of exposure and the resultant effect when considering social vulnerability. It may also influence research where stakeholder perceptions and interactions are fundamental to studying the dynamics of developing risk management policies, such as demonstrated in Frazier et al. 2009 [36].

Budget complexities combined with population growth, historical development, and climate change does not allow coastal communities to mitigate for every eventuality. Utilizing a flood depth framework for flood modelling allows an examination of exposure of societal assets at a three dimensional scale that is not possible using SLOSH Display output. This can be used to target infrastructure at greater risk of exposure, or determine when it would be more resilient to focus on response and recovery methods rather than mitigation.

The resilience of the electrical grid infrastructure in Sarasota County can be expressed, in part, as the vulnerability of its substations to exposure from storm surge events. By employing a flood depth framework post-disaster site planning for new substations could focus on areas within acceptable risk and exposure tolerance. Substations are vulnerable to the effect of functional degradation over time and require replacement. As an adaptive strategy, substations that need to be replaced under a maintenance plan could use surge depth modelling to increase grid resilience by site relocation or by re-engineering the site location to survive storm surge events. The flood depth framework may be used to determine if and how high levees should be constructed around existing substations. The ability to consider multiple SLR surge scenarios enhances the adaptive potential within the planning process.

The depth framework could be used to examine the exposure vulnerability of freshwater resources and the potential availability of potable water post-disaster. This could lead to community supply well relocation adaptive strategies, and securing holding structures in areas of acceptable risk and exposure tolerance.

Examining current and future infrastructure exposure in context of infrastructure interconnectivity and network dynamics may influence future development and disaster planning. This influence might enhance community resilience by relocating current or locating future assets in areas within an acceptable margin of risk and exposure tolerance or securing alternate sources of service outside potential disaster zones.

Other depth-sensitive critical infrastructure, such as evacuation/resupply routes for developed urban areas, might be examined for storm surge exposure vulnerability. Evacuation shelters could be examined for spatial and vertical location in context of proximity to population and accessibility for resilience. The results of this use of the methodology can inform planning in the face of increased risk of exposure to storm surge due to climate change effects.

This method demonstrates that calibration of the flood depth model framework can be applied to infrastructure that is not adequately represented by grade-level elevation. Processing of LiDAR data to acquire bare ground DEM's results in the loss of some elevation information. Calibration could be applied to compensate for that loss. For instance, many state and interstate highways are elevated above grade to be more resilient to flooding events. By calibrating road infrastructure critical elevation, a more accurate representation of exposure might be obtained.

According to the Director of NHC, hundreds of requests for SLOSH output utilizing higher resolution basin grids and/or higher resolution land data are received by NHC every year. NHC lacks the resources to grant these requests (Personal Contact, Jamie Rhome, 2011). An increasing number of coastal areas are LiDAR surveyed therefore more DEMs are available at higher resolutions than utilized by SLOSH. Custom SLOSH runs are labor and resource intensive, and require software and methods not generally available to the public.

Conclusions

Examination of the exposure of coastal infrastructure in Sarasota County, Florida to storm surge is enhanced by modelling the depth of flood exposure as opposed to two-dimensional inundation modelling. Depth modelling shows that infrastructure sensitivity to exposure increases with depth of flooding, and inundation modelling does not necessarily represent a degree of exposure that might cause disruption in a particular infrastructure system. Yet the failure or partial failure of a system can cause failure in another system. This study supports recent research that SLR will increase storm surge exposure to coastal assets. It also brings to question some methodology in current research.

This methodology demonstrates calibration of exposure to flooding that may be extended to model variant depth-sensitive infrastructures. By calibrating, modelling, and examining the sensitivity of societal assets to contemporary and future storm surge scenarios, stakeholders may have an impetus to adopt adaptive measures that can increase community resilience. Not everything that is exposed can be mitigated. This research could be applied towards a goal of multi-scalar resilience planning by using targeted mitigation and adaptation strategies. The use of higher resolution data not available for previous research has facilitated extending the functionality of infrastructure exposure to storm surge analysis in Sarasota County, Florida. It has been demonstrated that exposure may be conditional, and that this conditionality should be considered when modelling the physical environment as part of a 'best practices' planning or modelling strategy. Researchers demonstrated that this methodology can be accomplished using modest resources with publicly available data.

Limitations, advantages, and further research

By creating a custom SLOSH grid using the DEM in this study, and track files with a modified tide, it might be possible to use SLOSH to model SLR scenarios. This may require modifying grids to accommodate inland extents of SLR enhanced storm surge. A comparison of exposure from the framework outlined here would be useful. Researchers would like to generate MEOWs and MOMs from a custom SLOSH run that:

- Incorporated SLR scenarios
- Utilized highest possible resolution land and bathymetry DEM data
- Benefited from a higher resolution and expanded SLOSH grid that emphasized resolution over areas of high population density, and encompassed all potentially inundated cells considering SLR.
- Would be designed and implemented to NHC standards to be included in the SLOSH Display program.
- Use the depth framework on the MOM outputs to contradict or validate the bathtub method of modelling depth from contemporary SLOSH zones.

Because the depth model is derived from the highest elevation at inland surge extent, it is less conservative than SLOSH. The depth model can extend beyond the SLOSH model grid and areas behind boundaries that could inhibit surge flow, resulting in some non-contiguous representation of flooding and contiguous inundation beyond what SLOSH represents as likely by wind-driven waves. Using a vector format might mitigate some of these anomalies by the availability of methods that cannot be applied to the raster format. However, because the depth framework is based on a DEM that is at finer resolution than the SLOSH grid, it may be able to depict potential flooding that SLOSH cannot. Creating a SLOSH output at a resolution approaching that of the DEM used in this study, accounted for SLR, and extended over the entire study area would facilitate a more detailed examination of storm surge depth exposure.

Since SLOSH cannot account for localized wave crests or water piling dynamics on structures above grade, a range of critical values was adopted in the depth model framework. Ground-truthing and potentially adjusting these ranges might improve the accuracy of the model. Also, comparing calibrated infrastructure depth and SLOSH inundation might be deceptive. This is demonstrated in Table 7 by the disparity between exposures for Category 2 and the push at Category 3.

Saline intrusion into aquifers is a concern for low lying coastal communities [47-49]. Potential saline intrusion of freshwater wells by permeation-effect through local geological strata and over the top contamination, in consideration of SLR, is a subject of further research in the study area.

Work is being done to create a module for ESRI's ArcGIS v. 10 to 'toolbox' SLOSH output and the methodology outlined in this paper for demonstrating storm surge depth and SLR scenarios.

Developing functionality for SLR in the SLOSH Display Program, which is readily available to stakeholders with limited computer resources, should be considered for enhancing adaptive coastal disaster management policy and coastal community resilience and adaptive planning.

Acknowledgements

Funding for this research was provided by the Idaho Experimental Program to Stimulate Competitive Research (Idaho EPSCoR) through the National Science Foundation (NSF) by a Research Experience for Undergraduates (REU) grant, the University of Idaho McNair Achievement Program, and Dr. Brian and Gayle Hill of Portland, Oregon through a grant awarded by the Hill Undergrad Research Fellowship. Special thanks to Althea Sheets of Idaho EPSCoR, Vicki Trier of University of Idaho McNair Achievement Program, and Dr. Brian and

Gayle Hill. Thanks to Florida Power & Light for substation point data, the Sarasota County Department of Health for wellhead data and support, and the Sarasota County GIS data repository. The authors thank the University of Idaho Hazards Research Group (UIHRG) for preliminary reviews. Distinguished thanks go to Courtney Thompson of the UIHRG for her insight and inspiration, and her cartographic assistance with the figures.

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