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Quantitating 3-Dimensional Geomorphological Terrain-Related Coefficients for Hydrodynamic Catchment Mapping Flood-Vulnerable Geo-referenceable Basins of High-Priority Hurricane Evacuation Routes, and Remotely-Identified Levee Construction Sites in Hillsborough County, Florida

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Abstract

Flood-vulnerability, disaster management, and the emergency evacuation strategy and arrangement in the event of a hurricane or severe tropical weather represent significant public health and legislative issues in coastal locations of humid subtropical climate, such as Florida. A cursory evaluation of current procedures and resources for hurricanes and flooding in Hillsborough County reveals an immediate necessity for improvement in evacuation prioritization and flood maps for the county. Data drawn from the 2010 Census estimate that there are approximately 1,862 persons per square mile inhabiting the city of Tampa, and 1,082 persons/mi^2 in Hillsborough County. As they currently stand, however, these population density estimates, when compared with Florida's overall estimation of 321 persons/mi^2, demonstrate how imperative it is to have proper protocols regarding natural disasters in place. Expanding upon what is already understood concerning important crisis regions will allow first responders, legislators and other stakeholders to make informed critical and time-sensitive decisions with potentially limited resources. Financial investment and time spent toward disaster mitigation and preparedness may significantly reduce injury, personal hardship and mortality, as well as property damage and economic strain in a potential disaster scenario.

Keywords: Natural disasters; Remote sensing; Geomorphology; Flood management

Introduction

Hillsborough County currently utilizes the Hurricane Evacuation Assessment Tool (HEAT) to view evacuation prioritization. This tool, updated last in 2002 and developed with the Federal Emergency Management Agency (FEMA), utilizes geographic information systems (GIS) technology only to a fraction of its prediction and spatial representation potential, applying only elevation and basic street-level maps to the decision-making process. In addition, HEAT does not take into consideration residential or commercial zoning when evaluating evacuation protocols. Misrepresentation of priority flood areas may lend a false sense of security in zones that are actually at a heightened risk, as well as less than judicious allocation of public funds to low-risk zones.

No study has yet been published, for Hillsborough or any of the surrounding counties in the Tampa Bay area that illustrates flooding and hurricane scenarios using updated GIS methods and three-dimensional modelling. Remotely sensed, 3-D, geomorphological models utilizing free, publicly available satellite imagery from the United States Geological Survey (USGS) can be used to forecast flood-vulnerable locations that go beyond the elevation-only models that are presently in use [1]. Municipality road class capacity data and census population density zones may be used to create models, which indicate priority areas for emergency management services and evacuation. In fact, many of these are already in use. However, combining these techniques may provide greater clarity with an overall picture of Hillsborough county vulnerability to flooding, and indicate the best intervention, or set of interventions, to lessen the scope of, or avert altogether, a probable disaster situation. The models in this study also exhibit the use of remote-sensing techniques to decide potential locations for levee construction and flood management.

These are powerful tools for planning evacuation routes, ensuring that these routes are clear in the event of a disaster, and averting property damage and loss of life. Updated 3D GIS models can be readily incorporated into the current systems that assist policy makers and emergency management personnel in the appropriate use of public funds, as well as fulfill FEMA mandates for disaster planning [2]. These models can also be expanded for use in countywide studies or, with high-resolution data, can be narrowed down to target specific neighborhoods and municipalities.

Methods

Resources

Landsat 8 TM30-meter satellite data were used for the base texture maps, and National Elevation Data (NED) >3 meter were used to create the digital elevation models used for this study. Both were obtained from the United States Geological Survey (USGS). The Landsat8 TM multispectral products with 16-bit pixel depth. The image analysis tool enables us to create a composite band with a TIF extension from the acquired multispectral bands. The near infrared (NIR) (0.76 to 0.90 μm) and Red (0.63 to 0.69 μm) spectral bands of the composite raster image were subsequently utilized in constructing the normalized different vegetation index (NDVI) model for HC (Figure 1). It suffices to say, that band 1 through band 6 is adequate for building NDVI and SAVI models. The following equation for NDVI was employed in the image analysis tool within ArcGIS. The following equations were derived in calculating NDVI:

$$\frac{P_{NIR}-P_R}{P_{NIR}+P_R} \qquad (1)$$

$$\mu_{cal}^2(NDVI) = \left(\frac{\partial NDVI}{\partial \rho_{NIR}}\right)^2 \mu_{cal}^2(\partial \rho_{NIR}) + \left(\frac{\partial NDVI}{\partial \rho_R}\right) \qquad (2)$$

$$\mu_{cal}^2(\partial P_R) + 2\frac{\partial NDVI}{\partial P_{NIR}}\frac{\partial NDVI}{\partial P_R}\mu_{cal}^2(P_{NIR}, P_R) \qquad (3)$$

$$\frac{\partial NDVI}{\partial P_{NIR}} = \frac{2\rho_R}{(\rho_{NIR}+P_R)^2} \qquad (4)$$

$$\frac{\partial NDVI}{\partial P_R} = \frac{-2\rho_{NIR}}{(\rho_{NIR}+P_R)^2} \qquad (5)$$

$$\frac{\partial NDVI}{\partial P_{NIR}}\frac{\partial NDVI}{\partial P_R} = \frac{-4\rho_{NIR}\rho_R}{(\rho_{NIR}+\rho_R)^2} \qquad (6)$$

NDVI is the ratio of the reflected radiance (difference between NIR and Red divided by its sum) required to normalize illumination and topographic variation within the model [2,3]. The value ranges from -1.0 to 1.0 form Landsat reflectance (ρ).

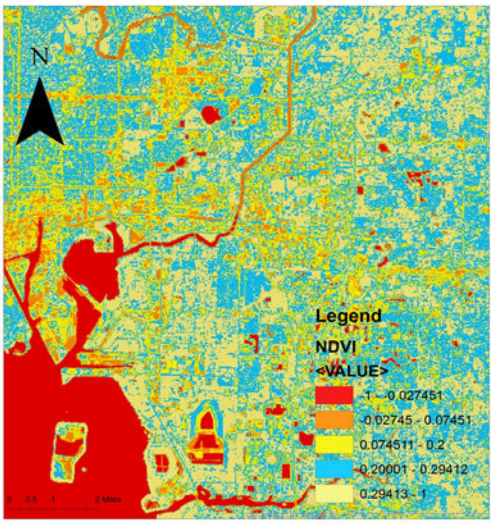

Figure 1: Normalized difference vegetation index for coastal Hillsborough County.

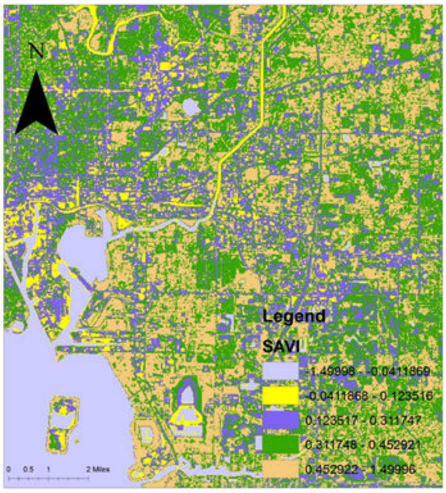

Figure 2: Soil-adjusted index for coastal Hillsborough County.

We corrected for the changes in soil brightness by calculating soil adjusted vegetation index (SAVI), applying an adjustment factor (L) of 0.5 commonly used in research. The adjustment factor L ranges from 0.0 to 1(where 0.0=high vegetation cover, 1.0=low vegetation cover) is necessary to remove soil background noise [1]. The equation of SAVI was expressed as:

$$\text{SAVI}=(1+\text{L})\frac{\rho_{NIR}-\rho_R}{\rho_{NIR}+\rho_R+L} \qquad (7)$$

$$\mu_{cal}^2(SAVI) = \left(\frac{\partial SAVI}{\partial \rho_{NIR}}\right)^2 \mu_{cal}^2(\rho_R) + \left(\frac{\partial SAVI}{\partial \rho_R}\right)^2 \qquad (8)$$

$$\mu_{cal}^2(\rho_R) + 2\frac{\partial SAVI}{\partial \rho_{NIR}}\frac{\partial SAVI}{\partial \rho_R} \cdot \mu_{cal}(P_{NIR}, P_R) \qquad (9)$$

Where

$$\frac{\partial SAVI}{\partial \rho_{NIR}} = (1+L)\frac{2\rho_R+L}{(\rho_{NIR}+\rho_R+L)^2} \qquad (10)$$

$$\frac{\partial SAVI}{\partial \rho_R} = (1+L)\frac{2\rho_R+L}{(\rho_{NIR}+\rho_R+L)^2} \qquad (11)$$

The road class shapes were obtained from the Diva-GIS online database. Census data was obtained from the United States Census Bureau. Comparison evacuation zone maps were obtained from Hillsborough county evacuation procedures publications. HC building layouts and zoning information were both obtained from the Hillsborough county ArcGIS database. All resources were last referenced in July 2015 (Figure 2).

Remote sensing techniques have been employed in flood vulnerable geographic landscapes. In our research, we compartmentalize Hillsborough County into a 5 km by 5 km grid in Arc map and subsequently overlaid on the Landsat8 imagery. Numeric place-markers/sampling points on the grid cells allowed for identification geo-sampled territories and also allow for assessment of potential flood damage [2].

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Population density model

Landsat 8 30-meter data were overlaid with the census bureau tracts. These residential tracts were scored based on their household density from low to high. The lowest tracts had a household density of 0 and were considered industrial or commercial tracts and therefore omitted from the recommendations. Tracts with density >0 were highlighted to display the residential zones, from green (low population density) to red (high population density). However, we utilized Hillsborough administrative shape files from Diva-GIS in constructing the population density maps (Figure 3).

Similarly, grid cells generated was used to quantitate the relationship between floodwater volumes and flood water level. Therefore, we designed the grid cells from low to high elevation: since, water gravitates towards a higher plain.

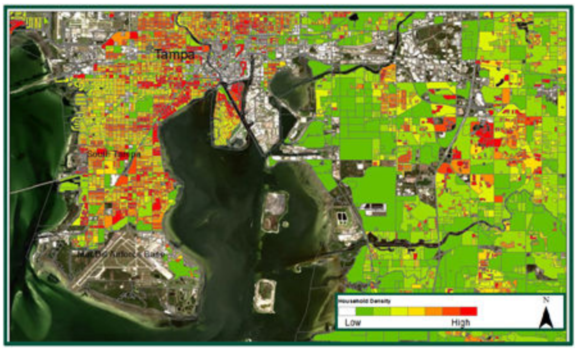

Figure 3: Household densities for Hillsborough County.

Digital 3D elevation model (road ranking)

DEM for HC was downloaded through GEOTIFF in Landsat 8 TM and subsequently processed as a layer when imported into ArcGIS. This was projected in the default coordinate system for ArcGIS (WGS 1984 UTM Zone 48N). Additionally, in order to be precise with our outcome, we compared DEMs generated from Landsat8 point for point in Google Earth TM and found them to similar (Figure 4). Similarly, these products were radio-metrically, and sensor corrected to minimize error.

NED >3 meter data were overlaid with the road plans for Hillsborough county and scored based on civil road planning capacity indicators. These "road class" indicators were used to isolate high-capacity roads available for evacuation out of high-priority evacuation zones. The indicators (in descending order) were 'freeway', 'freeway ramp', 'principal arterial', 'minor arterial', 'collector', and 'local' roads. A rasterization of the Hillsborough County DEM displays low elevation areas against road classes to illustrate potential problem areas in evacuation.

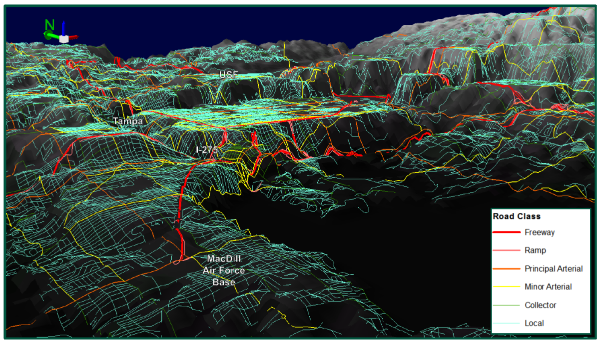

Figure 4: Digital 3D Elevation Model with Significance Road Design.

Digital 3D elevation model (Water swell indicators with and without Floor plans)

The Hillsborough county DEM and the road ranking dataset were floated in Arc-scene to generate a 3D elevation model. Likewise, the draped image over the terrain enabled us visualize the geomorphologic features and other causal parameters (i.e., elevations, slope gradients, curvatures and water swell) associated with flooding susceptibility in HC [3].

The aforementioned Hillsborough county DEM was exaggerated 40x employing 3D analyst tool in ArcGIS. The geographic landscapes were vertically exaggerated to show case some of the hidden features within the terrain. We observed like similar studies, that elevation levels and slopes are important variables for flood vulnerability [4]. Two sets of models were created, one with the geo-referenced floor plans for the entire county, and the other with roads only, both overlaid on the exaggerated DEM. Water swells were represented by extruding a calibrated 3D layer into the model. These water swell models were adjusted at different standardized heights, from 8 feet to 34 feet, according to guidelines already used in evacuation levels in HC and extended slightly to encompass swell heights recorded from New Orleans after Hurricane Katrina (33 feet to 34 feet).

Results

A comparison of Hillsborough county evacuation maps with the population density model created in this study indicates the need for a reevaluation of priority evacuation zones. The current maps indicate zones based on elevation and water swell levels only. Large swathes of the highest-priority evacuation zones are largely industrial or commercial zones, which bear a relatively small burden of evacuation priority in a real-life scenario. The typical hurricane evacuations, which have ample warning, take place from residences.

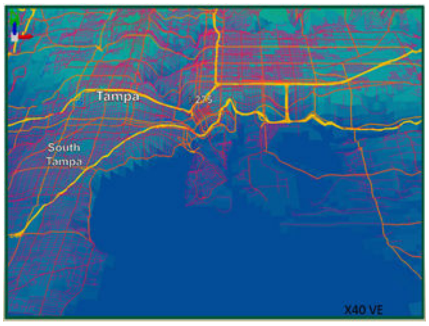

Figure 5: Vertically Exaggerated Digital Elevation Model by a factor of 40.

The Figures 5 and 6 were Digital Elevation Model Vertically Exaggerated by a factor of 40 and 80 respectively to demonstrate elevation and depression points on major evacuation routes. This model can be used to identify similar depression points and high-risk areas for water run-off accumulation

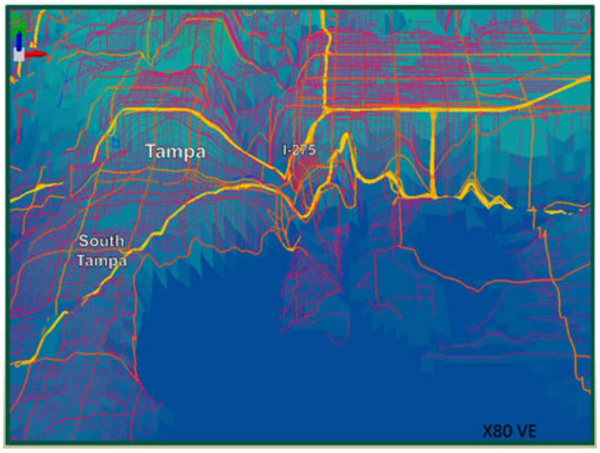

Figure 6: Vertically Exaggerated Digital Elevation Model by a factor of 80.

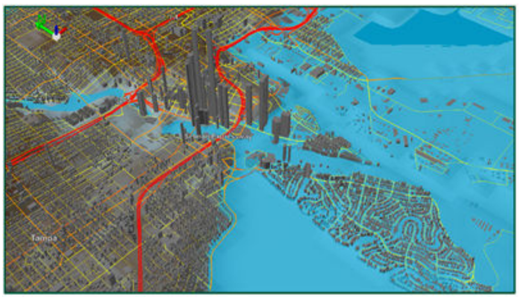

Figure 7: Digital 3D Remotely Sensed Levee Recommendations on Interstate 275.

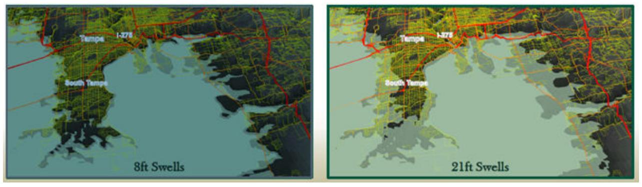

Figure 8: Digital 3D Elevation Models with major evacuation roads assuming 34 ft. (top), 8 ft. (bottom left), and 21 ft. (bottom right) swells.

The 3D models created provide an easy assessment of significant roads as well as locations of concern in a sizeable storm (Figures 7-10). The two major freeways out of Tampa (to be used by first responder vehicles and evacuees), are Interstate-275 and the Selmon Expressway. The models predict each to have portions of road with either ramps or parts of the roads at risk of flooding with swells as small as 8 feet.

Figure 9: Digital 3D Elevation Models with major evacuation roads in Hillsborough county.

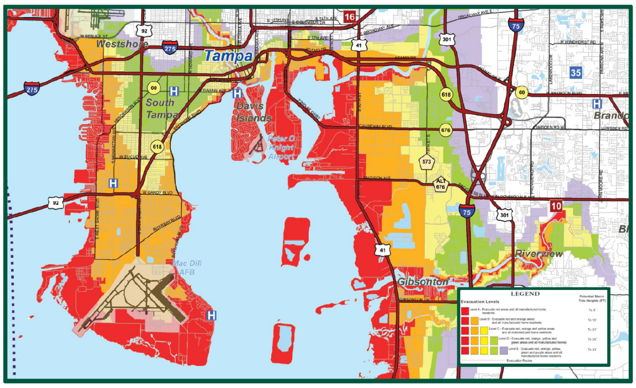

Figure 10: Prioritized areas for evacuation in the event of flooding in Hillsborough County.

Conclusion and Recommendations

Though often considered a "flat" area, Hillsborough County could benefit immensely from improvements to current evacuation planning maps that more thoroughly address regional population density and residential areas. Future protective developments, such as levees and other flood-preparation structures, may also be better specified using these models at high-risk sites, such as low elevation points on I-275 and the Selmon Expressway. Further modelling may be used to predict water runoff and high-risk flow accumulation within the county, as well.

The economic impact may seem obvious in commercial districts, but residential areas could also be negatively affected by flooding due to property damage. Prospective renters, as well as those considering investing in residential properties, may well avoid looking in areas negatively impacted by flooding, and these properties may be withdrawn from active listings by the sellers during the immediate aftermath of a disaster [5]. This could compound negative impacts on the commercial economy in these areas in the longer term.

The models created in this study represent the potential of ArcGIS to better illustrate possible weak points in infrastructure when preparing for disaster scenarios. With higher resolution data, these models can be made with high geo-specificity, allowing for a more rigorous evaluation of localized neighborhoods, as well as enabling procedural implementation to be communicated with precision.

Daily, or more frequent, maps of surface water have important applications in environmental and water resource management in Hillsborough County. In particular, surface water maps derived from remote sensing imagery can play a useful role in the derivation of spatial inundation patterns over time and in calibrating and validating eco-hydrological and eco-hydrodynamic models. While coarse resolution data can provide realistic means to achieve this, cloud cover often limits them during flooding events, and their spatial resolutions (e.g., 250-1000 m pixel) are not always suited to small river catchments. The Landsat TM data can provide daily 3-D surface water maps, both spatially and temporally, across a range of catchments. This study shows that Landsat TM data is suitable for capturing both medium and large flood events while cartographically detailing around the edge of a flood or along narrow water features where coarse resolution (MODIS) tends to underestimate water extent. Compared to a coarse resolution water map, the Landsat TM water maps can a strong-to-moderate statistical agreement between flood vulnerable geo-locations. Terrain–related geomorphological land cover can be mapped with moisture in the soil based on soil color. Flooding under dense vegetation is often invisible to MODIS or any other optical remote sensor [www.esri.com]. The view angle, or range distance from sensor to pixel, influences the amount of water that can be mapped, as is demonstrated with a permanent water body [2]. On a temporal scale, cloud cover often inhibits the use of MODIS imagery at the start and lead-up to the peak of a flood event. Landsat TM 3-D surface water maps are sensitive to the dynamics of water movement when compared to flow gauge data. Given their temporal and spatial characteristics, the Landsat TM sensors can provide useful information for eco-hydrodynamic modelling and do appear to be the best available product for mapping inundation extent and its change dynamics at large county-level/basin scales.

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