Mapping social vulnerability to landfalling hurricanes in the Atlantic Basin

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ABSTRACT

Studies have shown that about 63% of deaths in the U.S. due to tropical cyclones between 1970-1999 occurred inland. The main cause of these deaths is freshwater flooding often associated with severe local storms spawned from the parent cyclone. In addition, these storms can produce numerous and widely scattered tornadoes, as evidenced by Hurricane Ivan (2004) that produced 117 tornadoes across eight states. Inland communities remain at risk, despite a steady decline of deaths in coastal communities. This research maps both the inland and coastal social vulnerability to hurricanes making landfall in the Atlantic Basin. Historical flood data and inland wind decay functions from tropical cyclones are used to identify hazard prone regions. Specific demographic factors are used on the county level to identify vulnerable communities and create a vulnerability index on a scale of 1-10. This builds on the existing Hurricane Disaster Risk Index by including the vulnerability of inland communities and their associated factors. The most vulnerable counties are located in Arkansas and the Carolinas with vulnerability values between 4.00-4.53. Counties in the southern Florida Peninsula are found to have high vulnerability due to their likelihood of flooding as a result of tropical cyclones with values at 4.80 and higher. The least vulnerable region is the D.C. area with vulnerability values as low as 2.67. The social vulnerability map produced may be used as a decision aid for emergency managers to assist with resource allocation and emergency response.

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1. Introduction

It is known by many the hazards hurricanes pose to communities (NOAA 2012, Davidson and Lambert 2002, Pomp and Haluska 2011). Figure 1 shows a decline in the number of fatalities by decade with some credit given to well-timed evacuations from storm surge flood zones (Rappaport 2000; Willoughby et al. 2007). Although great efforts have been made to decrease the lethality of hurricanes near landfall (Kunkel et al. 1999; Rappaport 2000; Sadowski and Sutter 2005; Baker et al. 2007), inland communities are still at risk. Strong winds, tornadoes and flooding rains accompany the tropical cyclone as it moves over land (Czajkowski and Kennedy 2010). The overall vulnerability of inland communities is difficult to assess due to the omission of fatalities due to freshwater flooding in the official statistics (Czajkowski et al. 2011). Despite this, research has shown that freshwater flooding is the cause of the majority of tropical cyclone related deaths. In fact, about 63% of deaths from 1970-99 have occurred inland and can occur hundreds of miles from the coast as described in Figure 2 from Rappaport 2000. Czajkowski and Kennedy (2010) also mention that when including the amount of inland deaths due to flooding, there is not a downward trend in the lethality of these tropical cyclones. Noticing the significant increase in hurricane losses, efforts to reduce these losses have also increased with the development of the Hurricane Disaster Risk Index (HDRI) (Davidson and Lambert 2002).

![Figure 1 Timeseries of tropical storm-related fatalities. Fatalities exceed 1000 in the first four decades of the twentieth century, and then gradually fall under about 200 until the 2000s. In 2005, hurricane Katrina noticeably reversed this downward trend. (Czajkowski et al. 2000; source Pielke et al. 2000; NHC annual summaries)](image_url)

Commonly after natural disasters, an assessment of the social vulnerability of the impacted communities is necessary to enhance the efficiency of emergency management capabilities. These assessments can also aid in identifying areas most at risk for natural hazards (Tapsell et al. 2010). Since the HDRI is limited to coastal hazards and there are clear indicators of increased losses of lives inland due to tropical cyclones, an additional index is needed that will include both inland and coastal vulnerabilities. Emergency managers and other officials will be able to use this resource to easily detect vulnerable areas, make long-term planning decisions, and allocate resources to these particular areas. This study will advance existing approaches by including social vulnerability of inland communities. More specifically the aim is to measure their vulnerability to freshwater flooding, storm surge, and wind, while strictly focusing on life loss rather than economic loss. A case study of Hurricane Ivan 2004 illustrates inland hurricane impacts including an analysis of hurricane spawned tornadoes and highlighting the need for inland vulnerability assessments.

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The definition and assessment of social vulnerability components to coastal and inland hurricane impacts will be discussed in section 2. The formula used to calculate social vulnerability and its uses will be described in section 3, followed by results in section 4, Case Study: Hurricane Ivan in section 5, and conclusions and discussion in section 6.

2. Approach to Assessing Social Vulnerability

a. Hazard, Exposure and Vulnerability

Hurricane impacts include three factors: hazard, exposure, and vulnerability. The properties of the hurricane (e.g. surge, wind, rainfall etc.) are considered the hazards. Exposure describes what is at risk (e.g. mobile homes and other poorly structured buildings, disabled populations, coastal communities, inland communities near flood zones etc.). Lastly, vulnerability is how exposure responds to the hazard. For example a mobile home is likely to suffer more damage than a well built home. Hazard and exposure have been the main focus in hurricane impacts studies, with little attention given to vulnerable areas.

An example of an index developed to map hurricane risk is the HDRI (Davidson and Lambert, 2002). Mentioned in section 1, the HDRI is a composite index created to compare the risk of hurricane disasters in U.S. coastal counties. It was designed to support local, state, and national agencies as they 1) make resource allocations and decisions 2) make high-level planning decisions and 3) raise public awareness of hurricane risks. The developers of HDRI identified the factors that contributed to economic and life loss during hurricanes in the United States such as a county’s location, topography, and socio economic status of its residents. Secondly measurable scalar indicators were chosen to represent each factor previously identified, based on their ability to be represented in the conceptual framework and on the availability of data in the U.S. After that, a mathematical index was developed to combine the indicators into two composite index values, one representing economic loss and the second representing life disaster risk. The four
factors that were included in the HDRI are: 1) hazard, 2) exposure, 3) vulnerability, and 4) emergency response and recovery capability (Davidson and Lambert 2002).

The approach for this study differs from the example above in that the focus will be solely on mapping social vulnerability (of both coastal and inland communities), and not economic losses. The first step is to identify these regions by using hurricane storm tracks, along with inland wind decay models and flood maps. The second step will be to explore the spatial variability of social vulnerability within these regions.

b. Determining Hurricane Impact Regions

Vickery (2005) found that modeling the decay of storms is a crucial process in accurately assessing the vulnerability to wind damage. Instead of modeling the decay of wind speed as seen in Kaplan and DeMaria (1995; 2001), we model the decay of central pressure. Vickery (2005) also noted that hurricane models that simulate decaying central pressure are also able to give a mathematical representation of the hurricane wind field using the gradient wind balance equation combined with information on the characteristics of tropical cyclones (translation speed, central pressure and radius to maximum winds). The steps to determine the inland extent of damaging tropical cyclone winds are as follows:

1) Obtain historical landfalling tropical cyclone track data from 1988-2010 using IBTrACS data (Knapp et al. 2010);
2) Extract storm variables (including pressure difference between the storm center and the environment, translation speed, and the radius of maximum winds) and calculate the storm decay rate \( a \), following Vickery (2005);

\[
a = a_0 + a_1 \left( \frac{\Delta p_v V_T}{RM_W} \right)
\]

where \( V_T \) is the translation speed and \( RM_W \) is the radius of maximum winds.
3) Plug the decay rate from Eqn.1 into the Vickery (2005) filling model. The filling model is in the form of an exponential decay function:

\[
\Delta p(t) = \Delta p_o \exp(-at)
\]

where \( \Delta p(t) \), is the central pressure difference in hPa between the storm center and the far field pressure (assumed to be a constant 1013mb) \( t \) hours after landfall. \( \Delta p_o \), also in hPa, is the pressure difference at the time the storm makes landfall. The specific models below will be used to calculate the filling constant in different regions following Vickery (2005):

Gulf Coast: \[ a = 0.0413 + 0.0018 (\Delta p_v V_T/RM_W) \]
Florida Peninsula Coast: \[ a = 0.0225 + 0.0017 (\Delta p_v V_T/RM_W) \]
Mid-Atlantic Coast: \[ a = 0.0364 + 0.0016 (\Delta p_v V_T/RM_W) \]
New England Coast: \[ a = 0.0034 + 0.0010 (\Delta p_v V_T/RM_W) \]

4) Convert the pressure decay to wind decay using gradient wind balance (see Holland et al., 2010 for details);
5) Bring winds down to the surface using a constant factor of 0.72 and account for wind gusts using a constant factor of 1.25, both following Vickery (2005), and convert winds from storm relative to ground relative by adding the storm translation speed;
6) Determine the farthest reach of 50kt wind speed from the historical storm dataset for each of the four regions of the US coast. The 50kt threshold was chosen because it is the magnitude of wind that is defined as severe. We find maximum inland extent of 50kt winds for the four regions between 930 and 2100 km reaching beyond the coast, well into the inland areas. The historical storms by region and 50kt wind maximum include:
   - New England: Hurricane Floyd 1999, 50kt winds 2100 km inland
   - Mid-Atlantic: Hurricane Hugo 1989, 50kt winds 1780 km inland
   - Florida Peninsula: Hurricane Gabrielle 2001, 50kt winds 990 km inland
   - Gulf Coast: Tropical Storm Opal 1995, 50 kt winds 930 km inland

Historical flood data are used to identify regions both inland and along the coast that are vulnerable to flooding due to hurricanes. For example, Villarini et al (2011) found that the majority of the flooding in Hurricane Ivan occurred well inland as a result of heavy rainfall far from the center of the track. The hazard domain showing the states affected by both wind decay and flooding is shown in Fig. 3. A climatology of tropical cyclone flooding based on historical tropical cyclones from Villarini et al. (2010) will also be added as a vulnerability factor and described later in Section 3.

![Historical Flooding due to Tropical Cyclones](image)

Figure 3. Hazard domain as defined by wind decay and historical flooding due to tropical cyclones. Colors indicate a measure of the likelihood of tropical cyclone flooding using historical streamflow data from Villarini et al (2011).

c. Assessing and Mapping Social Vulnerability

One can find many definitions of social vulnerability in the literature, but the following definitions apply most to the current study:

“The characteristics of a person or group and their situation that influence their capacity to anticipate, cope with, resist and recover from the impact of a natural hazard … It involves a combination of factors that determine the degree to which someone’s life, livelihood, property and other assets are put at risk by a discrete
and identifiable event … in nature and in society. (Wisner et al., 2004)"

“…social factors that place people in highly exposed areas, affect the sensitivity of people to that exposure, and influence their capacity to respond and adapt.” (Yarnal, 2007)

The former is a broader definition, whereas the latter is more specific to people and how society tends to place them in harm’s way.

The components of social vulnerability listed in Parker et al. (2009) and Tapsell et al. (2010), include security, economic, and social. Security includes the safety and stability of the built environment, along with effective response and minimal disruption in daily life. Economic refers to the access of resources available to communities that are considered socially vulnerable; conditions prior to a hazard have an effect the quality of life post hazard event. Lastly, social characteristics include demographic factors (age, gender, disability etc.) that influence the sensitivity of a communities risk to hazards.

d. Vulnerability factors and indicators

Most impacts indices have been developed using the “top down” approach which makes general assumptions for the whole; this is the approach used here. While it ignores small scale local drivers of vulnerability, factors are generally chosen to satisfy vulnerable populations within limitations posed by data restrictions and other factors. However, what one may hypothesize makes a community vulnerable may not necessarily be so. For example, a community with a large population over 65 may be deemed more vulnerable assuming that the majority are immobile and can not care for themselves. However, in the case of Hurricane Andrew, many elderly residents did not evacuate because of “familiarity” to hurricanes, not because they had no means of leaving (Peacock et al. 1997 pp. 66).

Despite this limitation, the top-down approach is used here to present a broad overview of social vulnerability although we caution against interpreting mechanisms of vulnerability from our results without first conducting complementary research using the bottom-up approach to examine and include the local drivers, of vulnerability.

3. Developing the Index:

The demographic factors discussed here and listed in Table 1 were chosen to be included in this study based on evidence from existing statistical and theoretical studies in the literature.

Age is one of the most commonly used vulnerability factors (Blaike et al. 1994; Davidson and Lambert 2002; Cutter, et al. 2000; O’Brien and Milet 1992; Hewitt 1997; Ngo 2001, Cutter et al. 2003). Infants defined as 0-5 yr olds, and elderly, defined as 64+, are more likely to be at risk during severe weather events. For example, 36.7% of Americans 65 and over are disabled compared to the 10% in the 18-64 brackets (2010 U.S. Census Bureau).

Gender plays a strong role in decision making responsibilities. If a woman is a single parent, she will probably take more precaution in determining evacuation decisions. Statistics show men are more likely to be killed in hazardous weather than women. In a study by Rappaport (2010) out of 392 fatalities due to freshwater flooding in which gender was known, 71% were men and
29% were women. The reasons for this difference are unknown but possibly include chivalry, or not perceiving a weather event as “high risk.”

Race/Ethnicity is a factor in vulnerability due to the level of diversity within the United States. Language barriers, cultural barriers, etc. exist. However it can’t be presumed a culture is more at risk just because it is different. For example some Native Americans are able to interpret weather events and based off their knowledge, make sound decisions for their community; this is not necessarily true for every culture. For instance, the majority of African Americans, make up the poorer demographic in the U.S. Census. Resources to evacuate and educate themselves on hazards are not always accessible. Another example is Hispanic populations; with the growing number of immigrant and migrant Hispanics near the Mexican border, there may exist a language barrier preventing them from fully understanding their risk in certain hazards.

Education is important and it can be presumed that the more “educated” communities are, the more likely they are able to understand warnings and can take action. It is also an indicator of wealth (U.S. 2010 Census), due to the high cost of private schooling and college. Personal wealth plays a role in many social issues. The wealthier you are, the more likely you are to build a quality home that can be considered “storm ready,” vice versa for poorer communities. Income also plays a role in the amount of resources available to you in the event of evacuating and is linked to education as previously stated.

Renters, apartments in particular, are vulnerable due to the lack of severe weather planning. To give a scenario, imagine you live in an apartment on the third floor; there is a tornado, where do you go? Or imagine you live on the first floor, where do you go? The same is true for a hurricanes, for which it may be possible that apartments are about as safe as mobile homes. Renters are also connected to the personal wealth factor. People who rent homes are probably less likely to be able to afford a home of their own and are also less likely to have home owners insurance. This puts them at risk of losing everything with no means of “bouncing back.”

Building codes will be assessed using the Building Code Effectiveness Grading Schedule (BCEGS). This is used to asse how well building codes are enforced on the community level. Mobile homes will also be a component of this factor due to their being the most vulnerable structures during weather events

Special needs are determined based off census data pertaining to disability and demographic type. For instance, disability based on blindness, hearing impaired, mental health, and mobility.

Emergency planning is assessed subjectively, in the absence of studies, through tests developed to determine the usability, available planning information, and length of time it took to find disaster such information in each state. Similar to Davidson and Lambert (2002) “public education factor,” this will determine how publically accessible information is, based off the aforementioned indicators. Population density will be an additional component to this factor as it relates to how many people are at risk, need to evacuate and may clog up roads during the evacuation process.

Each factor contains one or more indicator as shown in Table 1. Within each factor, the indicators are given equal weights in the absence of information to suggest unequal weighting. Each factor is then be scaled to a value between 0 and 1 by normalizing with the maximum value. The gender factor however was weighted differently with males weighing more than females. The reasoning behind this is research showing 71% of males as victims of tropical cyclone related fatalities (Rappaport 2000). In addition, the flood study by Villarini et al. (2011) was restricted to the eastern portion of the United States and Texas and since our study extends beyond these regions we scaled the flood data starting at 0.5 to 1 instead of starting at 0 and gave
the flood factor double weighting. Finally all factors are added together giving a total score of 1-10 with 10 being the most vulnerable.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Indicators</th>
<th>Data Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>0-5</td>
<td>U.S. Census</td>
</tr>
<tr>
<td></td>
<td>65+</td>
<td></td>
</tr>
<tr>
<td>Race/Ethnicity</td>
<td>Black or African American</td>
<td>U.S. Census</td>
</tr>
<tr>
<td></td>
<td>Native Americans</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hispanic-Latino</td>
<td></td>
</tr>
<tr>
<td>Gender</td>
<td>%male (accounts for female)</td>
<td>U.S. Census</td>
</tr>
<tr>
<td>Education</td>
<td>Pop 25 and older w/</td>
<td>U.S. Census</td>
</tr>
<tr>
<td></td>
<td>Less than 9th grade</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9-12 no diploma</td>
<td></td>
</tr>
<tr>
<td></td>
<td>H.S. Diploma</td>
<td></td>
</tr>
<tr>
<td>Personal Wealth</td>
<td>Below Poverty Level</td>
<td>U.S. Census</td>
</tr>
<tr>
<td>Disability</td>
<td>Hearing</td>
<td>U.S. Census</td>
</tr>
<tr>
<td></td>
<td>Ambulatory</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vision</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cognitive</td>
<td></td>
</tr>
<tr>
<td>Renter</td>
<td>Apartments</td>
<td>U.S. Census</td>
</tr>
<tr>
<td>Building Grade codes and Mobile Homes</td>
<td>%1-2</td>
<td>BCEG</td>
</tr>
<tr>
<td></td>
<td>%4-7</td>
<td>U.S. Census</td>
</tr>
<tr>
<td></td>
<td>%8-10</td>
<td></td>
</tr>
<tr>
<td></td>
<td>% Mobile Homes</td>
<td>BCEG</td>
</tr>
<tr>
<td>Emergency Planning and Population Density</td>
<td>Rate on accessibility</td>
<td>Survey</td>
</tr>
<tr>
<td>Historical Flood Data</td>
<td>Population Density</td>
<td>U.S. Census</td>
</tr>
<tr>
<td></td>
<td>Flood Likelihood</td>
<td>Villarini 2010</td>
</tr>
</tbody>
</table>

Table 1. List of indicators and associated contributing factors to social vulnerability.

4. Results

Examples of the indicators and their contributions to the index are shown in Figs. 4a-d. Note the use of different color scales to highlight the spatial variability of each indicator. For a given location, each indicator does not contribute equally to vulnerability; the contribution depends on the value of the indicator relative to the range of values of the indicator over all counties within the hazard prone region. For example, the Native American Population in our domain is less than the Black/African American population, so the Black/African American populations in areas where the contribution is highest will weigh more than Native Americans in the index.
Figure 4. Spatial distribution of the contributions to vulnerability from four example indicators: (a) Native American population, (b) Black/ African American population, (c) Education, and (d) Hispanic/Latino population.

A map of the social vulnerability index is shown in Figure 5. and is referred to as SVAH in the figures to follow. Southern Florida has the highest vulnerability because of the high likelihood of flooding due to tropical cyclones. In general, the southern portions of the United States (from Texas to the Carolinas) have high vulnerability, with Arkansas having the most counties with high vulnerability. This is a result of the large contributions from lack of emergency preparedness and the BCEG in Arkansas. There is also high vulnerability in west Texas and New Mexico, especially along the Mexican border due to high contributions from lack of education and large Hispanic populations; however, a correlation cannot be made between the two without further research.
5. Case Study: Hurricane Ivan

In this section we present a historical hurricane case study to explore the locations of the affected counties, the range of vulnerability, and breakdown of vulnerability factors. Hurricane Ivan made U.S. landfall as a category 3 hurricane and spun off 117 tornadoes along the eastern portion of the United States that killed 7 people and injured 17. Tornado and wind reports are shown in Figs 6a-b.

Tornadoes that spin off from hurricanes are an area of active research. In contrast to Ivan, it is more common to have only a few tornadoes during a tropical cyclone event. In relation to this study, tornadoes are also considered a hazard to inland communities who are often surprised by such events and have little lead time to seek shelter. Hurricane spawned tornadoes are commonly found on the outer rainbands, 200-400km from the cyclones center, but McCaul (1991) found that some tornadoes have formed within the eye wall and inner core. The favorable area for tornado development in TCs is the Right Front Quadrant (RFQ) of the TC since it is the area with the highest Bulk Richardson Number, shear and deep convection (McCaul, 1991; Verbout et al. 2007). TCs making landfall along the US Gulf coast are more likely to produce tornadoes since it is exposed to the RFQ longer than landfalling TCs in the Atlantic that strike the U.S. coast obliquely. Verbout et al. (2007) found that using TC curvature was a better indicator of tornado development. Using synoptic composites of TCs that re-curve verses the ones that don’t, the authors showed that mid latitude troughs provide additional deep-layer and low-layer vertical wind shear to re-curving TCs which favor mesocyclogenesis and tornadogenesis respectively. Other factors include landfalling TCs with significant dry air intrusions. (Belanger et al. 2009).

In the case of Ivan, the hazard extends well beyond tornadoes. The heavy rainfall swath associated with Hurricane Ivan extended far inland (Fig. 6d) and was heaviest not just at the point of landfall but also over the Appalachians associated with orographic uplift and also over
Pennsylvania associated with extratropical transition. There were a total of 25 deaths due to tornadoes (7), surge (5), flooding (4), wind (3), surf (2) and mudslides (4) (National Hurricane Center Tropical Cyclone Report 2012). The vulnerability of the counties affected by wind and tornadoes (presented in Fig. 6c) shows both the large inland extent of the hazards and also the range of vulnerability of the affected counties. These counties are next broken down by individual indicators, showing how each contributed to the total vulnerability for each county.

Figure 6. a. Social vulnerability index and tornado reports from Ivan; b. Social vulnerability index and wind reports from Ivan; c. Wind and tornado impacted counties from Ivan colored by the social vulnerability index; and d. Rainfall distribution from Ivan (Villarini et al. 2011).
Figure 7a-c. Vulnerability breakdown from Tornado and Wind impacted counties from Ivan

Taking a closer look at the vulnerability of the pairs of affected counties reveals some important differences in the dominant indicators. Dallas and Wilcox counties, Alabama (Fig. 7a), are in close proximity and have high vulnerability. The breakdown shows Dallas County has a higher contribution of all demographic indicators with the exception of sex, age, and mobile homes, compared to Wilcox County. Scotland County, North Carolina is also highly vulnerable but is located far apart from Dallas County. Comparing the two (Fig. 7b), Scotland County has a higher contribution of Native Americans and Hispanic/Latinos, but the main contributing factor is the fact that Scotland is more vulnerable to flooding due to tropical cyclones when compared to Dallas County. Fayette and Oconee Counties were affected counties in close proximity with lower vulnerability. Fayette county; however, has a higher likelihood of flooding from tropical cyclones (Fig. 7c). This breakdown of vulnerability, in combination with a quantitative look up table (see Table 2 for example) will be an important component of emergency planning and
response. This will enable an emergency manager or official to assess the specific needs of counties in the track of a hurricane and respond accordingly.

<table>
<thead>
<tr>
<th>County, ST Contribution</th>
<th>Dallas, AL</th>
<th>Wilcox, AL</th>
<th>Conecuh, AL</th>
<th>Monroe, AL</th>
<th>Fayette, GA</th>
<th>Oconee, GA</th>
<th>Clarke, GA</th>
<th>Johnston, NC</th>
<th>Harnette, NC</th>
<th>Scotland, NC</th>
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</thead>
<tbody>
<tr>
<td>Total Vulnerability</td>
<td>4.57</td>
<td>4.58</td>
<td>4.44</td>
<td>4.27</td>
<td>3.07</td>
<td>3.19</td>
<td>4.16</td>
<td>4.08</td>
<td>4.20</td>
<td>4.85</td>
</tr>
<tr>
<td>Age 0-5</td>
<td>0.26</td>
<td>0.22</td>
<td>0.21</td>
<td>0.22</td>
<td>0.17</td>
<td>0.21</td>
<td>0.22</td>
<td>0.27</td>
<td>0.29</td>
<td>0.25</td>
</tr>
<tr>
<td>Age 65+</td>
<td>0.12</td>
<td>0.13</td>
<td>0.16</td>
<td>0.14</td>
<td>0.10</td>
<td>0.08</td>
<td>0.06</td>
<td>0.08</td>
<td>0.08</td>
<td>0.12</td>
</tr>
<tr>
<td>Native American</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.03</td>
</tr>
<tr>
<td>Black</td>
<td>0.25</td>
<td>0.26</td>
<td>0.16</td>
<td>0.15</td>
<td>0.07</td>
<td>0.02</td>
<td>0.09</td>
<td>0.05</td>
<td>0.07</td>
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<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.02</td>
<td>0.01</td>
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<td>0.04</td>
<td>0.03</td>
<td>0.01</td>
</tr>
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<td>Female</td>
<td>0.57</td>
<td>0.55</td>
<td>0.52</td>
<td>0.53</td>
<td>0.53</td>
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<td>0.54</td>
<td>0.51</td>
<td>0.51</td>
<td>0.53</td>
</tr>
<tr>
<td>Male</td>
<td>0.16</td>
<td>0.22</td>
<td>0.29</td>
<td>0.27</td>
<td>0.28</td>
<td>0.30</td>
<td>0.23</td>
<td>0.33</td>
<td>0.31</td>
<td>0.28</td>
</tr>
<tr>
<td>Education</td>
<td>0.40</td>
<td>0.54</td>
<td>0.50</td>
<td>0.42</td>
<td>0.10</td>
<td>0.19</td>
<td>0.27</td>
<td>0.32</td>
<td>0.32</td>
<td>0.43</td>
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<tr>
<td>Poverty</td>
<td>0.45</td>
<td>0.54</td>
<td>0.43</td>
<td>0.36</td>
<td>0.07</td>
<td>0.10</td>
<td>0.47</td>
<td>0.21</td>
<td>0.23</td>
<td>0.41</td>
</tr>
<tr>
<td>Disabled</td>
<td>0.48</td>
<td>0.29</td>
<td>0.29</td>
<td>0.42</td>
<td>0.13</td>
<td>0.17</td>
<td>0.21</td>
<td>0.22</td>
<td>0.28</td>
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<tr>
<td>Renters</td>
<td>0.29</td>
<td>0.14</td>
<td>0.10</td>
<td>0.17</td>
<td>0.07</td>
<td>0.09</td>
<td>0.45</td>
<td>0.18</td>
<td>0.24</td>
<td>0.26</td>
</tr>
<tr>
<td>Mobile Homes</td>
<td>0.16</td>
<td>0.24</td>
<td>0.17</td>
<td>0.18</td>
<td>0.03</td>
<td>0.06</td>
<td>0.04</td>
<td>0.15</td>
<td>0.19</td>
<td>0.21</td>
</tr>
<tr>
<td>BCEG</td>
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<td>0.36</td>
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<td>0.36</td>
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<td>0.30</td>
<td>0.26</td>
<td>0.26</td>
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</tr>
<tr>
<td>Emergency Response</td>
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<td>0.12</td>
<td>0.12</td>
<td>0.12</td>
<td>0.00</td>
<td>0.00</td>
<td>0.10</td>
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<td>0.10</td>
</tr>
<tr>
<td>Pop. Density</td>
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<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
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<tr>
<td>Likely Flood</td>
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<td>0.96</td>
<td>1.12</td>
<td>0.93</td>
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<td>1.13</td>
<td>1.24</td>
<td>1.36</td>
<td>1.26</td>
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</table>

Table 2. Vulnerability and indicator contribution breakdown of example counties affected by wind and tornadoes from Hurricane Ivan 2004

6. Conclusions and Discussion

A social vulnerability index was developed in this study that includes both inland and coastal vulnerabilities to hurricanes making landfall in the Atlantic Basin. A major finding is that the most vulnerable communities are found inland, providing evidence that inland communities should be considered during planning in hurricane disaster prevention. It is found that the most vulnerable counties were located in portions of west Texas, New Mexico, Arkansas and the Carolinas. Counties in the southern Florida Peninsula were found to have high vulnerability due to their likelihood of flooding during tropical cyclones. The least vulnerable region was in the D.C. area. To truly reduce the lethality of hurricanes, a thorough assessment of the communities that will be impacted is necessary to reduce loss of life. Emergency managers use various tools to aid them in determining when and where to allocate funding and resources to prevent hurricane disaster. The vulnerability index developed in this study presents additional important information on all counties within the hazard prone regions, not just coastal communities.
Data Limitations

Limitations in the availability of data from both the physical and social sides presented numerous challenges to this study. Firstly to assess the physical hazards using flood data, the study by Villarini et al. (2011) is limited to the Eastern portion of the U.S. and Texas. Secondly, when looking for data for the building codes, some states did not participate in the survey so assumptions were made and states with missing values were assigned the mean value over all states. Native American populations were difficult to assess because all tribes are not federally recognized which means during disasters, they would not receive federal or state funding. Some tribes however, have signed treaties with certain states but this information would only be found by contacting each head tribal member (personal communication with Ma’Ko Qua Jones). For the emergency preparedness factor, there was little information that is available to the public about the preparedness of a particular state or county. Finally, the census data had percentage errors that were not accounted for in this study.

Future Work

There are several opportunities to expand on this research, which include addressing the limitations described above. Initial testing (not presented here) showed that different combinations of factors strongly influenced the overall vulnerability of a county. Therefore conducting comprehensive sensitivity tests would allow for a better understanding of detailed factors that increase social vulnerability. Developing a complete climatology of floods associated with tropical cyclones is also important to get the most accurate assessment of the hazard, especially for inland communities. It is also important to get a break down of the indicators even further that will pinpoint specific needs to specific demographics. Conducting more surveys to get a better analysis of emergency preparation for each county is needed because the surveys provided limited information and was on the state level. Finally a more integrated approach that will expand beyond the “top-down” approach would give more comprehensive vulnerability assessments and help communities prepare for disaster.

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