Development of a spatially explicit vulnerability-resilience model for community level hazard mitigation enhancement

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Abstract

Community vulnerability to coastal hazards can be difficult to analyze at a local level without proper modeling techniques. Societal assets and human populations are dispersed unequally across landscapes, causing vulnerability to vary from one community to another. A common method of quantifying vulnerability has developed in the form of vulnerability indexes, typically conducted at the county scale. These indexes attempt to measure community vulnerability by assessing exposure of traditional vulnerability indicators. Sensitivity and adaptive capacity analyses are excluded from these assessments, creating a less than holistic vulnerability analysis. Traditional vulnerability assessments also neglect the inclusion of place-specific differentially weighted indicators, and the effects of spatial autocorrelation. These limitations make indexes less effective for community level analysis. In response to these challenges, a resilience index that incorporates place, spatial, and scale specific indicators that are more appropriate for community level analysis was developed. The model developed in this research determines varying distributions of vulnerability across the study region using several socioeconomic, spatial and place specific indicators. Spatial statistics (such as spatial autocorrelation techniques) and multivariate techniques (such as factor analysis) were employed to determine the differential influence of each vulnerability and adaptive capacity indicator. The results of the model enable decision makers to target mitigation efforts toward place-specific, differentially weighted indicators that most impact vulnerability at the community level. The model also depicts that traditional vulnerability indicators are differentially impactful at varying spatial scales.
Keywords: vulnerability, resilience, coastal hazards, disaster management.

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1 Introduction

The intersection of natural hazards and human populations results in natural disasters that can cause significant damage to human lives and property. Coastal communities are vulnerable to many natural hazards, including hurricanes, tropical storms, coastal erosion, tsunamis, flooding, and climate change-related hazards influenced by sea-level rise (SLR) [1–4]. To increase the effectiveness of hazard mitigation and comprehensive planning for these and other hazards, it is important to assess vulnerability at the community level so as to provide more detail on local level vulnerability and better target limited mitigation resources. Traditionally, mitigation strategies are chosen and implemented based on perceived mitigation needs, risk tolerance and available funding [5, 6]. These strategies are commonly structural in nature or address the possibility of shaping development patterns, but they often do not consider targeting socioeconomic factors as a way to facilitate recovery while also assisting in resilience enhancement [7–9]. Vulnerability is the potential for loss [10–13]. Vulnerability is a function of exposure, sensitivity, and adaptive capacity. Exposure is the proximity of a community to a hazard, sensitivity is the degree to which a community is affected by a hazard, and adaptive capacity is the ability of the community to adapt and cope with hazard impacts [13, 14]. Resilience is a function of a community's ability to respond to a disaster with minimal help from outside [11, 15, 16]. The understanding of a community's resilience level can aid greatly in post- disaster recovery and estimation of potential losses [16].

Due to uneven distribution of vulnerability indicators within a given area, vulnerability is variable across the landscape including at the sub-county scale. Because societal assets dispersed throughout a community have variable vulnerability to hazards, it is important to identify their differential spatial distribution throughout the community [11, 17]. If reducing local vulnerability is a goal, then hazard mitigation strategies should be targeted at areas within the community with the highest vulnerability. However, many communities often lack the financial resources or expertise to compile hazard analysis on their own, forcing communities to rely on analyses from external consultants or government agencies. External analyses often lack a focus on local hazards, may not adequately consider community nuances, and may not have been conducted at a spatial scale most appropriate for local hazard mitigation [9].

Even though higher spatial resolution for hazard modeling often allows communities to better target mitigation resources, there are several problems associated with conducting spatial analysis at varied spatial scales. Due to data aggregation used in vulnerability and resilience research, it is possible that the reliability of certain analytical methods can be biased based on the way the areal units are defined [18]. For example, the US Census Bureau uses varying levels of spatial aggregation to describe the distribution of the population within the United States. These enumeration units, such as census tracts and blocks, are created based on areas that have mostly homogenous population characteristics, visible boundaries and economic status [19]. This means that the area of each of these blocks will vary based on the population characteristics within them. As

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the level of analysis is aggregated from census block to census tract and upward, the amount of bias increases as well. Aggregation bias creates another reason for the importance of incorporating community scale, locally derived factors, rather than relying solely on nationally collected data when conducting vulnerability assessments. The inclusion of sub-county scale factors is an important component for measuring community vulnerability and resilience because of factor variation inside and across communities within a county [4, 20–22].

This paper presents research conducted through a case study of Sarasota County, Florida that is used to identify and examine place-specific vulnerability indicators for the Spatially Explicit Resilience-Vulnerability (SERV) model. Although Sarasota County serves as a case study for this research, this methodology is applicable to any community or jurisdictional unit, no matter the spatial scale. The second section of the paper provides a brief background on existing limitations of current hazard vulnerability assessments. The methods section briefly discusses the theoretical framework for the SERV model, but predominantly focuses on the identification and classification of mitigation strategies implemented in the county. The results sections details the findings of the analysis as it relates to hazard mitigation decisions. Finally, the discussion and conclusions sections demonstrates the societal relevance of this research as it pertains to a need for multiscalar vulnerability assessments for enhancing community hazard mitigation planning.

2 Background

Mitigation and adaptation policies and plans help reduce coastal community vulnerability to hazard impacts, as well as minimize the cost of recovery from disasters. Hazard mitigation practices include planning, hazard identification and profiling, vulnerability and risk assessments, and implementation of mitigation actions [23–29]. Hazard planning consists of both structural and non-structural actions designed to reduce the potential loss of property or human life in the event of a natural disaster [23, 28–30]. To determine vulnerability to certain hazards, decision makers often conduct vulnerability assessments and incorporate the results into hazard mitigation plans (HMPs). Hazard vulnerability assessments essentially occur at three different levels of evaluation: 1) hazard identification, 2) vulnerability analysis, and 3) risk analysis. Hazard identification defines where the hazard is likely to transpire and calculates the probability of its occurrence. Vulnerability analyses determine which factors cause populations to experience increased or decreased vulnerability to hazards in certain places. Risk analysis calculates probabilities of a hazard occurring and determines probabilities of the levels of damage or injuries that could occur in specific areas [26]. A complete vulnerability assessment includes all three of these levels of hazard assessments. Most vulnerability assessments, however, are often limited to just the hazard identification, the vulnerability analysis, or a combination of both. Vulnerability analyses are included more often than risk assessments, but it is not a common practice for them to be included in mitigation plans. It is also rare for a socioeconomic vulnerability assessment to be present in most HMPs. Hazard assessments generally do not include risk assessments [26]. Risk assessments utilize probabilistic modeling techniques to illustrate the varying probability of occurrence for coastal hazards across a given spatial scale and to provide a greater understanding of not only the extent of the hazard, but where hazards are more likely to occur and which areas might suffer more/less damage [26, 31]. Possession of this information is important for local decision makers and planners if their goal is to efficiently allocate funds for hazard mitigation to areas within the community that contain the highest vulnerability.

For this reason, this research developed the Spatially Explicit Resilience-Vulnerability (SERV) model to help better determine community scale vulnerability and resilience using differentially weighted place-specific, spatial, and temporal vulnerability indicators. The SERV model is a function of exposure, sensitivity, and adaptive capacity, where the components of the model will be determined using the created hazard layers and socioeconomic factors resulting from the vulnerability index. This research uses Sarasota County, Florida as a case study whereby understanding the county's community vulnerability, a measure of community resilience can then be determined using place-specific, spatial and temporal resilience indicators. The results of the analysis are then compared to mitigation strategies that are currently in progress within the county to determine if mitigation is occurring in areas where exposure or vulnerability are highest.

2.1 Study area

Sarasota County, Florida (Fig. 1) lies along the western coast of the Florida peninsula. The county has approximately 35 miles of shoreline and a low average elevation, which makes it susceptible to coastal hazard inundation impacts, such as storm surge inundation and inland precipitation flooding. Much of the county is located at or near sea level, and its highest point of elevation is located further inland in the far north-eastern corner of the county. Low average elevation and central location along the coast makes the county especially vulnerable to coastal hazards and climate change effects such as sea level rise. The county's Comprehensive Emergency Management Plan (CEMP) states that 45% of the county lies within the 100-year floodplain. This increases the county's vulnerability to not only storm surge from hurricanes, but inland precipitation from other coastal storms as well. The county has experienced significant population growth within the last decade and is highly developed along the lower elevations that will likely continue due to the location of current infrastructure and an urban service boundary that essentially limits development to areas more proximal to the coast.

3 Methods

Researchers reviewed the Comprehensive Emergency Management Plan (CEMP) and the county's Unified Local Mitigation Strategy (ULMS) to identify what mitigation strategies are in progress or completed and where they are being implemented within the county. While the CEMP generally describes policies that are in place within the county, location specific mitigation strategies are not explicitly listed. Examples of general mitigation strategies include the mapping of critical and essential infrastructure across the county, identifying Memorandums of Understanding's with other counties and support agencies' responsibilities for disaster relief. In order to determine the location of specific mitigation strategies, the ULMS plan was reviewed. This plan was created in response to the Disaster Mitigation Act of 2000 (DMA 2000), which requires local jurisdictions to prepare and implement a local natural hazard mitigation plan as a condition for receiving mitigation grant funding [29]. DMA Local mitigation plans serve as a guide for decision makers to reduce the effects of natural hazards on local jurisdictions. The Sarasota County ULMS plan specifically identifies hazards and mitigation strategies implemented at the local level within the county. Mitigation strategies that included some spatial reference were georeferenced to map the locations of each strategy.

To determine place-specific, spatial sensitivity and adaptive capacity indicators for Sarasota County, researchers conducted two principal components analyses (PCA), a data-reduction technique that identifies groups of inter-correlated variables, on the two lists of compiled sensitivity and adaptive capacity indicators [32]. The sensitivity variables were aggregated to the census block level and the adaptive capacity variables were aggregated to the census tract level because those were the smallest geographic areal unit of analysis with available data. To determine average level of spatial autocorrelation between the variables, a Moran's I was conducted for each indicator in both indexes. To conduct the PCAs for sensitivity and adaptive capacity researchers used the following parameters: maximum of 20 components, Kaiser Criterion (eigenvalues ≥ 1), and a Gamma rotation based on the level of spatial autocorrelation within the datasets to account for spatial autocorrelation. Gamma rotations assign factors to sets of already inter-correlated indicators, which corrects for spatial autocorrelation in the data [33]. Variables that described $< 5\%$ of the total population were considered to be non-significant and were either aggregated into a composite variable or were removed from the PCA. Subsequent PCA analyses were conducted using the same parameters to determine the final set of principal components within the sensitivity and adaptive capacity datasets. Sensitivity variables with component loadings ≤ -0.45 or ≥ 0.45 (to identify weaker variables traditionally found in vulnerability theory) and adaptive capacity variables with component loadings ≤ -0.5 or ≥ 0.5 are statistically significant to the final index. Block vulnerability scores were calculated using the following static vulnerability equation:

$$V = [E + S] - AC$$ (where V= vulnerability, E= exposure, S= sensitivity and AC= adaptive capacity)

The scores for each of the equation components (exposure, sensitivity and adaptive capacity) are calculated using existing methods and methods developed in this research. Overlay analysis using deterministic inundation extents, including hurricane storm surge, developed in Frazier *et al.* [4] were utilized to

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determine exposure. Inundation extents also were calculated to include inland precipitation. Sensitivity and adaptive capacity scores were determined by calculating the percentage of each variable within a block. This illustrates which blocks hold the greatest presence of each vulnerability indicator. Researchers assigned directionality to each component loading based on whether the indicator traditionally has a positive or negative influence on vulnerability [20, 27]. Weighted scores were calculated based on the varying influence of each indicator and its factor on sensitivity or adaptive capacity. The final weighted values for each indicator were then summed to create the raw scores for sensitivity and adaptive capacity components. Once the raw scores were determined for each component, the scores were converted to z-scores to prevent any errors that might results from the aggregation of variables. The composite scores were then applied to the vulnerability equation to calculate block level vulnerability scores for Sarasota County, Florida. Once the vulnerability scores were determined, the results were overlayed with georeferenced locations of the current mitigation projects occurring within the county. This was done to determine the relationship of the implementation of mitigation strategies to levels of exposure and vulnerability within the county.

4 Results

The resulting exposure scores were mapped to illustrate areas of exposure from inundation impacts of inland precipitation and sea level rise enhanced storm surge. Fig. 1 symbolizes the distribution of the exposure scoring for a Category 3 storm with 4 inches of inland precipitation.

Results indicate that exposure is greatest along the coast and inland waterways (due to presence of storm surge), but there are also blocks further inland that have high levels of exposure due to inland precipitation. This pattern also indicates that the addition of inland precipitation inundation behaviour to overall hurricane inundation increases the total percentage of exposure.

The results of the sensitivity index PCA also identified the following contributing factors that explain 72.8% of the variance: base population, business and development, traditionally vulnerable populations, critical and medical facilities, low to medium development, income and economic base, and tourism and agriculture. Results indicate that sensitivity is highest in main population zones with areas along the coast predominately containing the highest sensitivity scores. Positive scores indicate higher vulnerability (in red), while negative scores indicate lower vulnerability (in blue). For the adaptive capacity index, the PCA identified the following factors that explain 82.7% of the variance: age and employment, population and utilities, economic base, social services and infrastructure, traditionally vulnerable populations and housing capital, and higher education and equality. The vulnerability scoring results were mapped to illustrate the distribution of community vulnerability within the county (Fig. 2). Positive scores indicate higher vulnerability (in red), while negative scores indicate lower vulnerability (in blue).

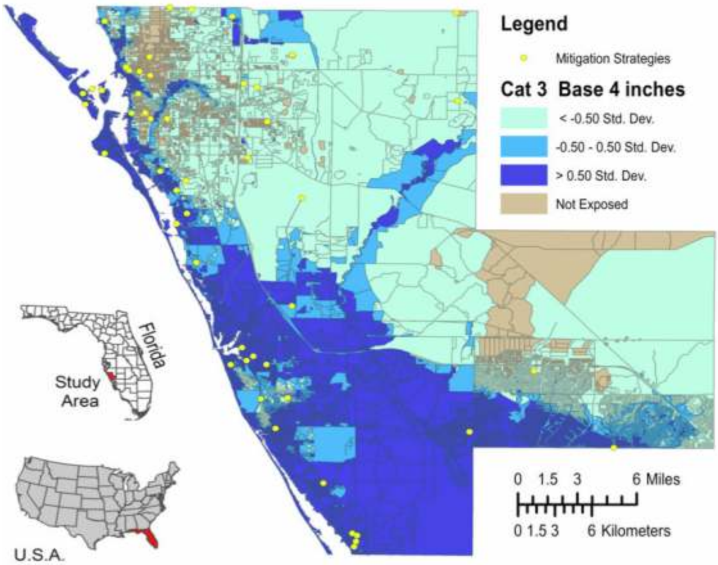

Figure 1: Block exposure scores with mitigation strategies – Category 3 Base 4 inches storm scenario.

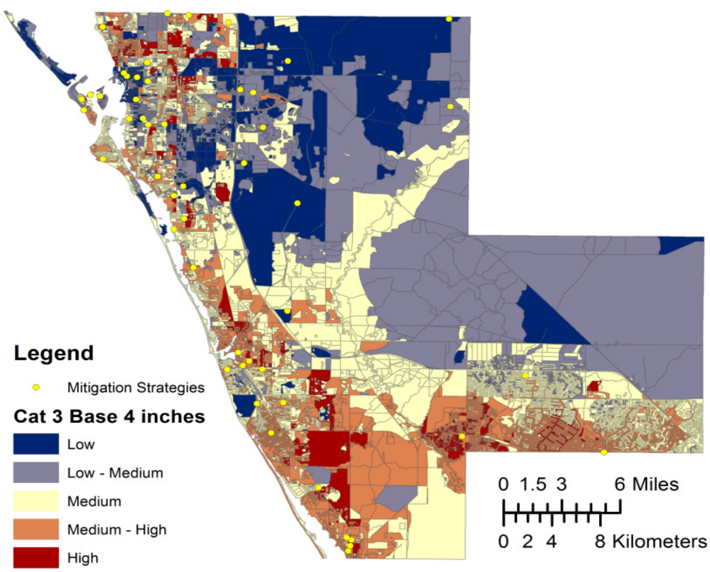

Figure 2: Block vulnerability scores with mitigation strategies – Category 3 Base 4 inches storm scenario.

These results symbolize vulnerability during a Category 3 storm with 4 inches of inland precipitation. The map indicates that communities along the coast and

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in the southern part of the county experience higher vulnerability than the mean. In addition, the vulnerability scores for these areas increase from the mean as exposure increases by storm category. The results of the geospatial analysis of overlayed exposure and vulnerability scoring with the locations of mitigation strategies found in the plan reviews indicate that county mitigation strategies are predominately directed by exposure alone and not based on total vulnerability scores. Results of the plan review also indicate that many of the mitigation strategies within Sarasota County are mostly structural in nature (i.e. relocate fire stations out of floodplain) in areas where exposure to storm surge or inland precipitation is highest.

5 Discussion

Vulnerability assessments that incorporate place specific indicators and consider all three components (exposure, sensitivity and adaptive capacity) provide more holistic information about its assessment. This information can help to determine where short-term disaster mitigation strategies are more cost-effective and serve to better guide the implementation of long-term mitigation and adaptation practices. Local agencies and communities with limited financial resources or expertise to compile hazard analysis often contract out their plan. This often leads to ineffective HMPs that fail to or only marginally enhance local community resilience [29]. Local communities also are usually forced to rely on county, regional, or state level assessments conducted at larger spatial scales that ignore place-specific indicators, which are often too general or unspecific for local level hazard mitigation practices thus hindering the enhancement of local community resilience [9]. Conducting vulnerability analyses at a county scale or higher makes it difficult to place the appropriate amount of emphasis on community level vulnerability indicators, particularly considering the need to consider the spatial relationship of these indicators. Traditional vulnerability assessments only include hazard exposure and do not consider the influence of sensitivity and adaptive capacity on vulnerability [22, 27, 34, 35].

The exposure scoring results indicate that hazard exposure is greatest along the coast and inland waterways as higher elevations impede the ability of storm surge to move further inland. As such, a majority of the implemented county mitigation strategies (predominantly structural in nature) lie along the coast, in areas within the 100-year floodplain and along inland waterways. Inland areas within the 100-year flood plain also experience exacerbated exposure because limited barriers slow inundation flowing further inland. The county’s urban service boundary limits development to areas along the coast, where exposure is greatest also contributing to the pattern of mitigation strategies predominantly being in areas where exposure is high. Understanding where exposure is greatest can help local communities to mitigate against further structural losses in the future, but is often done at the expense of mitigation for specifically targeted socioeconomically vulnerable population groups. Socioeconomic factors (such as poverty or age) influence overall vulnerability but mitigation for them is often not specifically assessed or addressed by local communities.

There is often a disconnection between mitigation strategies and overall vulnerability. Some of the mitigation strategies chosen by Sarasota County are located in areas of lower vulnerability, with only a few located in places where vulnerability is considered high. This occurs because these areas have high exposure, but experience lowered sensitivity and higher adaptive capacity. In addition, there are also areas of medium and moderate vulnerability where mitigation strategies (either structural or non-structural) are not being implemented. An issue associated with targeting mitigation to exposed areas is that long-term comprehensive and mitigation planning only considers contemporary hazards. Hazard exposure is likely to change in the future due to climate change enhanced hazards, such as sea level rise or increased storm precipitation. Therefore, targeting mitigation in areas exposed to contemporary hazards in long-range plans might overlook areas where exposure will likely increase as a result of climate change enhanced hazards [4].

The sensitivity scoring results indicate that populated areas along the coast contain the highest sensitivity scores. This might occur because there is a higher population density, larger minority and dependent populations, and a greater amount on infrastructure present in these areas. The adaptive capacity results identify several tracts in the northern and southern part of the county as having lowered adaptive capacity. This could be due to a larger amount of impoverished or dependent populations that have less access to resources. Conversely, several census tracts along the coast and on barrier islands have higher adaptive capacity, despite the higher hazard exposure levels likely due to a greater presence of populations with greater access to resources.

The vulnerability analysis results indicate that areas experiencing high sensitivity and low adaptive capacity have higher vulnerability scores despite their level of exposure. Exposure can indicate areas where greater amounts of damage will occur, but it does not indicate the level of hazard sensitivity of individuals or societal assets. Traditional capital coupled with private insurance, serves to enhance access to resources in many coastal communities thus facilitating post disaster recovery and contributing to lower sensitivity scores. Conversely, impoverished populations, which rely more on social capital and state and federal social programs, are more sensitive to hazard impacts. Thus, simply targeting structural mitigation areas does not necessarily account for or reduce the impact of other indicators on overall vulnerability.

While a majority of the georeferenced mitigation strategies fell within areas exposed to coastal storm inundation hazards, these strategies were not necessarily located in areas where overall vulnerability was greatest. Ten of the 143 listed mitigation strategies in the ULMS plan were non-structural in nature (i.e. public education and outreach and evacuation warning systems) and only two of these strategies were given specific geographic location references. From this, we can conclude that mitigation strategies that target specific vulnerability indicators are not being addressed explicitly within the hazard mitigation planning process. This could occur because decision makers are not aware of socioeconomic marginality in certain areas that can increase vulnerability in part due to the deficiencies in traditional vulnerability assessments. Existing research commonly generalizes vulnerability results to the county level, which does not provide information about what areas within the county are most vulnerable. A more detailed analysis is needed to effectively target mitigation at the sub-county level. It is also possible that socioeconomic factors that can increase vulnerability are not being considered or targeted when mitigation strategies are chosen or implemented at the local level for political, financial or otherwise unlisted reasons. This provides insight as to why the mitigation strategies more coincide with areas of greatest exposure as it is often easier to generate political and financial support for more exposed areas regardless of overall vulnerability. This is likely due to limited knowledge concerning the differential spatial spread of vulnerability indicators across the landscape. This produces general results that can cause mitigation practices to be uniform across the county. Unfortunately, mitigation practices distributed uniformly across a county does not necessarily lead to uniform vulnerability reduction.

6 Conclusions

Vulnerability is variable throughout a community due to a differential distribution of factors that influence vulnerability. Recognizing the uneven distribution of socioeconomic factors and how they intersect with physical hazards is important for effective community-level hazard mitigation and efficient allocation of limited resources. While many existing studies measure vulnerability through vulnerability indexes, they are not conducted at the sub-county level and disregard weighted-place and scale-specific indicators in vulnerability assessments. These issues often lead to incomplete vulnerability assessments and can result in the implementation of uniform mitigation practices across the county. Uniform mitigation practices do not translate to uniform vulnerability reduction and may result in mitigation practices that focus resources on areas that are not as vulnerable.

Including information about the distribution of place-specific, local vulnerability indicators helps planners target non-structural hazard mitigation strategies and response planning to more vulnerable areas. The overlay of current mitigation strategies within Sarasota County and the results of the SERV model illustrate that mitigation strategies are mostly structural in nature and are implemented in more exposed areas, not necessarily areas of high vulnerability. Implementation of mitigation strategies specifically targeted at areas within the community to socioeconomic factors that contribute to overall vulnerability should be addressed if community resilience enhancement is a goal.

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