Assessing the Vulnerability of Coastal Buildings to Storm-Surge Flooding: Case Study - Southern Miami Beach, Florida

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ABSTRACT

Coastal regions are vulnerable to natural hazards such as storm surge flooding. Increased population growth and wealth in coastal areas have led to swelling costs associated with flood-related damages, as evidence in Miami-Dade County, Florida across the decades. While, various studies have assessed the flood hazard levels in the County, incorporating the FEMA Flood Insurance Rate Maps, no examination has been conducted to determine the vulnerability of individual buildings to storm surge flooding. Inferring from the concept of Papathoma Tsunami Vulnerability Assessment (or PTVA), which employed a multi-criteria evaluation method to assess the vulnerability of buildings to a tsunami in Australia, this study developed the Storm Surge Building Vulnerability (SSBV) model to assess the vulnerability of coastal buildings to storm surge flooding, and utilized Miami-Dade County sites, as case study areas. The study selected SSBV parameters based on FEMA's report of the observed damages to buildings caused by hurricanes and available literature. Input data included a Category 5 hurricane SLOSH model, GIS floodplains data, and building characteristics. The model was applied to a transversal section of buildings on Miami Beach, which included two historic districts. Validation was performed through a Synoptic Survey, Google Earth images, and existing GIS data. Out of the total of 297 buildings considered in the model, 101 evidenced moderate vulnerability, 73 high vulnerability, and six a very high vulnerability. Of the 79 buildings that exhibited a high and very high vulnerability, 55 (approximately 70%) of them are slab-on-grade buildings. Most of the very low and low vulnerability buildings are high-rise buildings and/or were located behind the tall dune. It can be concluded from this study that the vulnerability of buildings to storm surge flooding is dependent on the nature of the building's constructive features, its relation to the ground plane, and to contextual features in its immediate vicinity, as opposed to only the flood hazard present within zones.

INTRODUCTION

Low-lying coastal areas across the globe are increasingly challenged by stronger and more frequent climate-related extreme weather events and rising seas due to warmer and expanded ocean waters; aggravating existing economic, physical and social frailties. Coastal population, poverty and urbanization rates, patterns, and location (Neumann et al, 2015), as well as a misalignment of economic incentives (USACE, 2009), and building characteristics, increase exposure levels and amplify overall risks, as verified by the United Nation's Intergovernmental Panel on Climate Change (Pachauri et al., 2014). Miami-Dade County is among the most vulnerable locations along the seaboard due to its combination of aforementioned risk factors, sea-level rise (Wdowinski, 2016), geology, and geographic location (Solis, 2012). More intense and frequent weather events are expected over time, as are a rise of sea levels, dry-day flooding, and storm-surge activity (Leuttich, et al, 2014). Vulnerability to coastal flooding related to hurricanes is largely a consequence of storm-surge actions; generally, also expected to worsen due to climate changes (Parry et al., 2007). Modeling the impacts of storm-surge action on buildings, utilizing parameters that reflect the particularities of a given built and urban context, allows for a finer grain understanding of a community's overall risks, which can in turn better inform evolving disaster reduction strategies (Lloyd et al, 2016).

METHODOLOGY

STUDY AREA

Miami Beach comprises a chain of narrow low-lying, natural and artificial landmasses, along the Florida coastline, connected to the mainland through bridges and canals, each comprised of varying physical characteristics. Miami Beach is an urbanized barrier island, located along the eastern coast of Miami-Dade County in Florida, USA (Figure 1 and 1.a). In the initial phases of this study, consultations with the Miami Beach Office of Resilience, Planning Department, Emergency Management, and Preservation Division, facilitated the selection of a case study site. The chosen swath, traversing the Flamingo Park Historic District and Ocean Drive/Collins Avenue Historic District, sits along an east (ocean side) west (bayside) axis. It made possible analysis of a variety of adjoining urban intensities, building typologies, constructive types, and construction periods; a cross-section of the island possessing differing topography and contextual features, including a natural defense system along its eastern edge. The study 'transect' includes a range of spot elevations, from -1.5 ft., 2.5 ft., 4.8 ft., and 6.3 ft., with the highest elevation on the island reaching a height of 13.5 ft.

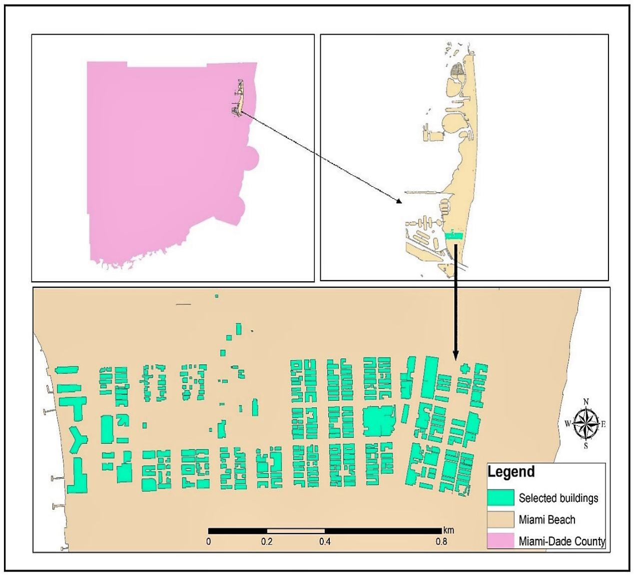

Figure 1. Map of the study area showing Miami-Dade County, Miami Beach and the buildings selected for the study. Chao and Ghansah..

above mean sea level (MSL), directly facing the ocean at the enhanced dune.

As a recreational, convention, and holiday destination, Miami Beach has a wide array of commercial and residential buildings. Within the study area, high-rise hotels and condominiums are concentrated along the eastern and western perimeters, mainly along West and Ocean Avenues; located closest to the two abutting water bodies. The neighborhood, between Alton Road and Collins Avenue, is the heart of the Flamingo Park Historic District, and residential and commercial buildings characterize it, the majority of which are between two and four stories. According to FEMA's Flood Insurance Rate Maps (FIRM), a significant percentage of Miami Beach lies in the AE flood hazard zone, with a Base Flood Elevation (BFE) of 8 ft. The AE flood insurance rate zone corresponds with flood depths greater than three feet and mandatory flood insurance purchase requirements apply. There is also a strip of the VE zone, occupying the land areas between the enhanced dune and the shore. The VE flood insurance rate zone corresponds to coastal areas that have additional hazards associated with storm waves. There is at least a one-in-four chance of flooding during a 30-year mortgage, and mandatory flood insurance requirements apply. Miami Beach's geographical location, its importance as a world tourist destination, its role as the leading economic engine for Miami-Dade County, and increasing exposure to higher storm surge flooding, especially in the era of climate change and sea-level rise, makes it an ideal area for assessing the storm surge flooding vulnerability of coastal buildings, located on a barrier island.

DATA

Various datasets were referenced in this study. GIS data, obtained from the University of Miami library, included numerous city infrastructure features, including shapefile of buildings, transportation infrastructure, parks and recreational areas, coastal and inland waterbodies, and other land use/ land cover (LULC) types. The data also included boundary shapefile of block groups, artificial reefs and FIRM zones. The main raster datasets were the DEM and SLOSH models. In addition, a Synoptic Survey was carried out to gather ground truth information of various datasets, as well as new ones. This intersection of quantitative and qualitative data allowed for a more accurate calibration of the SSBV modeling in the subsequent phase.

Within the selected cross-section of South Beach, all 297 buildings were included in this study. The selection was in consultation with the City of Miami Beach, and included areas with different urban intensities, building and structural typologies, and land-uses (RM-1, CD-2, RM-3, RS-4, GU, RO, MXE). They also included recreational infrastructures such as sports stands, monuments, security posts, and storage structures.

Each building shapefile contained an attribute table accessed using ArcGIS. Some of the attributes pertinent to the study were: Object ID for each building, address, year built, finished floor elevation, orientation of building, construction type, building use, base flood elevation, flood hazard zone, and description of the block group. In addition, the number of stories, presence of garden walls, and a standardized accounting of the finish floor elevations, were obtained from the Synoptic Survey. For this modeling process, the 297 structures were divided into two sets, in a ratio of 85% to 15%. The first set, the training set, was used for the modelling process and the second set, test set, was used for validation. The study used Microsoft Excel and the M-Macbeth software for the modeling process and displayed the results in ESRI ArcGIS.

PHYSICAL VULNERABILITY

Physical vulnerability assessment involved determining the nature of a building and its neighborhood characteristics that expose it to extreme storm surge flooding. Similar studies assessing the physical vulnerability of buildings used a multi-criteria decision making (MCDM) approach to evaluate the resultant impacts of conflicting criteria on the buildings, in the event of a hypothetical natural or human-made disaster (Dall'Osso, and Dominey-Howes, 2009). In most of these studies, the observed characteristics of the catastrophic phenomenon and the structural performance of the buildings were used to determine the parameters for assessing the vulnerability of buildings. A scaling and weighing system were then designed and applied to score each parameter, and the scores aggregated to obtain their resultant impact on vulnerability.

Figure 1.a Transect Map of Study Area. Google Earth Pro and Gridics, 2017.

In this study, the parameters selected for the vulnerability were fundamentally based on FEMA's ground truth observations of the characteristics and damage to buildings caused by historical storm surge flooding in the Eastern Seaboard of the US. In addition to observations from Hurricane Andrew (1992) (FEMA, 1992) and Hurricane Wilma (2005) (FEMA, 2006), FEMA's documentation of Hurricane Irma (2017) (FEMA, 2018) states that floodwater depth, distance from floodplain, nature of building design and construction, foundation type, age of building, manufactured housing or site built, were the prevailing determinants of the level of damage to buildings due to storm surge flooding. In addition, published literature on the characteristic effects of various storm surge flooding events on buildings helped to select the parameters for the multi-criteria evaluation. This confluence resulted in the selection of 6 parameters, grouped into two categories; Exposure Category: floodwater depth and distance from the floodplain, and, the Building Design Category: number of stories, construction type, finished floor elevation, and year built. The next sections outline these parameters.

FLOOD WATER DEPTH

Floodwater depth is the water level above ground at a specified location and is a function of the elevation and the storm surge at that point. It determines how high inundated water can rise in the vicinity of a building or within the building itself. Miami-Dade County is among the coastal areas within the US that have experienced high floodwaters due to storm surge from hurricanes. In 1992, floodwater depth from Hurricane Andrew (Category 5 storm) measured 7.8 ft above ground around Downtown Miami (Figure 2) and reached a peak height of 16.8 ft above ground around the Burger King Headquarters in Miami-Dade County (FEMA, 1992), where the eye of the storm passed through. Storm surge flooding from Hurricane Irma (Category 4 storm) ranged between 4.1 to 8 ft above ground in the Downtown area of the county (FEMA, 2018), although the eye of the storm was distant. The Category 5 Sea, Lake, and Overland Surge from Hurricanes (SLOSH) storm surge data used in this study estimated storm surge height between 3 ft (minimum) at West Avenue area and 9 ft (maximum) around the tall dune on the oceanside.

Floodwater depth was selected as the leading parameter in assessing the vulnerability of buildings due to its dominant role in causing damages to buildings during storm surge flooding (FEMA, 2017), thereby determining levels of exposure or hazard to a building. According to FEMA FIRMs, buildings within 3 ft and above of floodwaters are within moderate to high flood zones. This classification is pinned to the observed moderate to high damages that a building in such a zone will sustain (FEMA, 2019). The higher the floodwater, the more vulnerable the buildings are in that area. Creach et al. (2015) indicated that floodwater depth above 1.6 feet significantly impedes rescue operations, as rescue teams cannot use terrestrial vehicles. Also, it has been ascertained that a person in good health cannot move easily in water depth above 3 ft., moreover, that a ceiling will trap humans at a water depth of 6 ft in a single-story building (Creach et al., 2015) leading to probable fatalities. Thus, the

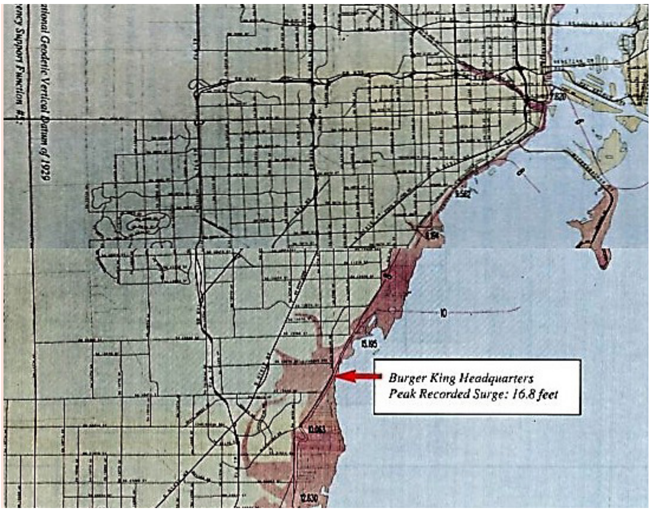

Figure 2. A section of Miami-Dade County showing the spot heights of floodwater during Hurricane Andrew in 1992. The image was extracted from the building performance report (FEMA, 1992).

relatively low elevation of the study area (average elevation of Miami-Dade is only 6 ft. above sea level) and the observed increase in the number of higher category hurricanes in recent years (Malmstadt et al., 2009) suggests increased exposure and damages to buildings due to floodwater depth.

FLOOD PLAIN

Floodplain criteria was selected as the second leading parameter for assessing the physical vulnerability of buildings to flooding. According to FEMA's reports cited above, buildings within the floodplain sustained a high level of damage during the various storm surges compared to those at distances from floodplains. This can be interpreted to be the result of increased exposure of floodplain buildings to higher floodwaters as well as other storm surge hazards. As the distance from floodplain increases, floodwater depth reduces and hazard levels to buildings diminish, and according to Brody et al. (2008), a floodplain is the second most significant factor after sea-level rise (floodwater) when evaluating physical vulnerability to climate change hazards. Floodplain is an essential factor in assessing the risk to buildings within Miami-Dade County due to various reasons. Firstly, due to Miami-Dade's southern location, across the area there are outlet for upstream rivers (Geology.com, 2019). Coupled with this are a significant number of natural and artificial reservoirs and drainage systems within the county, which adds to the number of floodplains (Cambridge Systematics, 2008). The relatively low elevation of the county and its coastal condition, characterized by bays, marinas, and canals, (Google Earth Images, 2019; Miami Beach Rising Above, 2019) mean that a significant proportion of buildings within the county are exposed to floodplain inundation. The topology of buildings to floodplains is thus critical when assessing the vulnerability of buildings to storm surge flooding. Xian et al. (2018) assessed the damages caused by Hurricane Irma in the Florida Keys and reported that the storm surges severely damaged buildings and other structures near the coastline and narrow channels. Satellite images and the modeled results from their study showed that buildings along coastal waterbodies and their channels sustained more serious damages as compared to those distant from the coast.

NUMBER OF STORIES

Available stories in a building can help prevent people from being trapped in a building when floodwater heights increase. Thus, an increased number of available floors augments the number of spaces that can be used as shelters above the level of storm surge waters. According to Dall'Osso et al., (2009), buildings with multiple stories have good structural resilience to the impact of natural disasters, including hurricanes. Because taller buildings must bear a more substantial weight, they are constructed to have a more resistant load-bearing capability than single-story buildings. More specifically, multi-story buildings and skyscrapers are stronger at the ground floor level, where the impact of storm surges are expected to be maximum (Sarà, 1993). Miami Beach's South Beach area, has a considerable number of residential and commercial multi-story buildings, often forming the frontline structures along the coastal waters and canals forming the Finished floor elevation

CONSTRUCTION TYPES

The Building Performance Survey report of Hurricane Andrew in Florida (FEMA, 1992) indicated that masonry/concrete buildings and wood-frame structures performed better against damage by the storm. Reese et al., (2006) and Rossetto et al., (2007) have all reported that in terms of protection against storm surges, concrete buildings are less vulnerable compared to wood-frame structures. Xian et al., (2018) indicated that 16% of the destroyed buildings in Marathon, Florida Keys, by Hurricane Irma were mobile homes. Reinforced concrete (RC) and reinforced wood frame (WD) are the primary building types within the study area, with very few wood-frame buildings.

FINISHED FLOOR ELEVATION

Finish Floor Elevation refers to the top of the structural slab and its elevation above sea level (NAIOP, 2015), in this case, linked to the first habitable floor. Research has indicated that in the case of a riverine or inland flood if the lowest floors of buildings are not elevated above the flood level, these buildings and their contents will be damaged or destroyed (FEMA Technical Fact Sheet, 2019). Destruction or damages to buildings and their content have been determined to be more severe in the case of coastal flooding where wave action causes even more damage, often destroying enclosed building areas below the flood level (FEMA Technical Fact Sheet, 2019). Three main types of FFE were observed within Miami-Dade County. These are: Slab on Grade (SG), with a Crawl Space (CS), and One Full floor above grade or more (OF). Prevatt et al. (2018)

and FEMA documentation including photographs of Hurricane Irma showed that SG buildings sustained more severe damage compared to other FFE building types (FEMA, 2018). In 1992, damages to interiors of SB constructions were extensive and resulted in many of the flood damage buildings being gutted entirely (FEMA, 1992). The report recommended that when re-constructing buildings that have been damaged by the floods, the lowest floor of the buildings should be elevated to or above the Base Floor Elevation (BFE).

YEAR BUILT

The year in which a building was constructed also influences its vulnerability. Buildings within Miami-Dade County were classified into three main year groups; before 1965, between 1965 and 1994, and after 1994. The historic preservation guidelines of the City of Miami (City of Miami, 2011) elaborates on the structural and architectural properties of the buildings within the county. Buildings constructed before 1965 are deemed to be of moderate strength to damage due to the characteristics of its foundations and the hardening of its Dade County Pine structural elements. The structural components of these buildings were tied and anchored utilizing construction methods more capable of withstanding environmental shocks such as high winds and storm surges. Though built prior to contemporary building codes, these buildings have been observed to moderately stand against recent prevailing hurricanes. This performance differential was observed in the aftermath of Hurricane Andrew. Masonry and wood-frame historic buildings in South Dade outperformed more recently built structures of the time in the Country Walk area, often characterized by poorly secured wood trussed roofs and plywood gabled ends, at times coupled with an inadequately secured second story wood framed envelop over its concrete block ground floor(CBS). The observed exceptions were commonly the result of fallen trees in the vicinity of the older buildings.

The demand for more homes after World War II, sparked the construction of numerous buildings in the county, with the principal objectives of providing homes for veterans and new settlers. Though these buildings (between 1965 and 1994) were constructed based on a series of improved buildings codes developed from observed impacts of hurricanes, the strength of these buildings was tested by Hurricane Andrew in 1992. Unfortunately, these buildings' failed!' (Dixon, 2009). The experience from Hurricane Andrew led to a 'major structural and building component upgrades in 1994' (Dixon, 2009) to develop building codes that have since become the reference documents for current building construction in Miami-Dade County. These newer buildings withstood the damages of Hurricane Irma (Pinelli, et al, 2018). Out of the 297 buildings considered in the study, 243 were constructed between 1920 and 1964, 43 buildings were constructed between 1965 and 1993, and 11 were constructed between 1994 and 2012.

	Very low	Low	Moderate	High	Very high	Reference(s) used
Floodwater depth	1 ft.	2 ft.	3 and 4 ft.	5 and 6 ft.	7 ft. and above	FEMA (2019), Miami Dade County - GIS (2019)
Floodplain	above 5km	3km -5 km	1km - 2km	300 m-1km	<300 m	Xian, et al, (2018), Google Earth Pro, (2019)
Number of stories	5 stories and above	4	3	2	0-1	Dall'Osso and Dominey-Howes, (2009)
Construction type	Reinforced concrete/ steel frame	other concrete	Reinforced wood	Wood masonry	Wood frame	Rossetto et al., (2006); Reese et al., (2007); Razorback Concrete, (2014)
Finished floor elevation	One floor off		Crawl space		Slab on grade	FEMA, (2019), FEMA (2018) Prevatt et al. (2018)
Year built	after 1992		before 1965		between 1965 and 1994	Pinelli, et al, (2018); Novaes, et al, (2011)

Table 1. Values assigned to the six factors influencing the vulnerability of a building. Chao and Ghansah.

CALCULATING BUILDING VULNERABILITY

The first step in calculating a building's vulnerability was the development of a scoring system to classify the values within the parameters according to their influence on vulnerability, and aggregate the parameters on a standard scale. According to the scoring system, the values in each parameter were scaled from 1 to 5, with 1 indicating a very low contribution to vulnerability and 5 indicating a very high contribution to vulnerability (Table 1). After assigning a score for each value, the parameters were aggregated algebraically. Weights were then applied according to their observed and perceived influence on vulnerability, as described above.

The Macbeth Software was employed to compute weights for each parameter. The M-Macbeth is a multicriteria value measurement decision support system, which converts qualitative judgment about the difference of influence between two factors at a time in order into quantitative scores (Ban e Costa (2004; Dall' Osso and Dominey-Howes, 2009). By rearranging the parameters in a matrix form, in terms of their relative importance, weights were generated for each parameter. For each building, the weight was multiplied by the proportional vulnerability in each parameter. The resultant value was normalized using the sum of the weights (equation 1). The resultant weighted values were then grouped based on their standard deviation (SD) from the mean (McIntyre, 1952). The grouped values were then classified into levels of vulnerability from 1, indicating very low vulnerability, to 5 indicating very high vulnerability. The result was then joined to the respective building shapefile in ArcMap using the ObjectID as the as the primary key. The data was displayed to depict the geographic patterns of physical vulnerability within Miami Beach's South Beach area.

Equation 1:

SSBV=WiXi/∑Wi .... (1)

Validation

The model was validated by running the weighted equation on the test set. In doing so the indicated vulnerability of each building was verified against the information gathered during the Synoptic Survey. Additional verification was done referencing some of the structures, using Google Earth Images.

Results and discussion

The weighting process resulted in the determination of robust numerical values as weights based on the importance between the different parameters. The exposure parameters carried the highest weights, followed by the parameters indicating the nature of the buildings. Applying the weights to the proportional parameters and normalizing them resulted in equation (2) which defines the vulnerability of buildings to storm surge flooding located within the study area.

Equation 2:

SSBV=[100x(FWD)+80.95x(FPD)+69.05x(NS)+61.90x(CT)+48.92 x(FFE)+29.18x(YB)]/390 (2)

Applying equation (2) to each building and displaying the results in ArcMap showed the spatial distribution of the vulnerability of buildings within the study area (Figure 3). The resulting map shows that vulnerability of buildings does not have a simple distribution pattern but rather depends on attributed parameters for each building. From the map, the western and eastern frontlines which are closest to water bodies and floodplains have very low and low vulnerabilities. The observation at the eastern end can be attributed to the locations of high-rise buildings there, at times with habitable floors located above one or more levels of open parking decks. There is also a tall dune running along the eastern edge of the barrier island, which adds to the protection of these structures. Most of the western buildings, facing the bay, are also high-rise structures; many are hotel/condominium buildings that are 20 stories and above. Though this area had the lowest elevation, and thus has the highest exposure compared to the other parts of the study area, the structural stability of the high-rise buildings, the presence of habitable floors again located more than one floor above the ground, similar to those facing the ocean, and the numerous habitable spaces, thanks to the multiple floors, that can provide safety for people and/or their properties, in like manner, resulted in these buildings demonstrating the attributes of very low and low vulnerability. In addition to the number of stories and habitable spaces located above parking decks, some building parcels are partially filled, thus located on a higher elevation relative to the other parts of the study area, explaining the cluster of very low and low vulnerability there. The high and very high vulnerabilities are located in the middle section of the case study site. Buildings in these areas are usually 2-4 stories high, and have either slab-on-grade or crawl space finished floor elevation. Commonly, buildings in this area were built prior to 1965 and between 1965 and 1992. Table 2 is the statistics for each vulnerability class.

Class	Number
Very low	33
Low	83
Moderate	101
High	73
Very High	6

Table 2 (Above) Statistics of building vulnerabiity

Figure 4 (Right) Storm Surge Building Vulnerability (SSBV) Results within the study area

CONCLUSION

In conclusion, the Storm Surge Building Vulnerability (SSBV) model assessed the vulnerability of coastal buildings to storm surge flooding, utilizing Miami-Dade County sites, as case study areas. The study selected SSBV parameters based on FEMA's report of the observed damages to buildings caused by hurricanes and available literature. Input data included a Category 5 hurricane SLOSH model, GIS data of floodplains, and the number of stories, construction type, foundation type, and the period of building construction. The model was applied to a transversal section of buildings on Miami Beach, which included two historic districts. Validation was performed through a Synoptic Survey, Google Earth images, and existing GIS data. Out of the total of 297 buildings considered in the model, 101 evidenced moderate vulnerability, 73 high vulnerability, and six a very high vulnerability. Of the 79 buildings that exhibited a high and very high vulnerability, 55 (approximately 70%) of them are slab-on-grade buildings with few stories. Most of the very low and low vulnerability buildings are high-rise buildings and/or where located behind the tall dune. It can be concluded from this study that the vulnerability of buildings to storm surge flooding is dependent on the nature of the building's constructive features, its relation to the ground plane, and to contextual features in its immediate vicinity, as opposed to only the flood hazard present within zones.

On the other hand, buildings' vulnerability to storm surge flooding in Miami-Dade County may also depend on other factors such as distance to evacuation facilities and emergency transportation routes, which were not included as parameters in this study. Potentially critical to post-storm habitability and fire hazards, but not considered in this study, is the location of building systems and equipment in relation to the BFE. Also, the design of this study addressed the vulnerability of a place, in this case Miami-Dade County and hence the model may not be robust across all coastal areas. Further research is needed to validate the performance of the model across the Eastern Seaboard if the model is to be used across other coastal cities in Southwest US. Also, comprehensive data may be required, and more iterations will be needed to build a single SSBV model across the Eastern Seaboard. Nonetheless, this study points to the need to define models at a 'hyper-local' level, in order to provide useful protocol to analyze and interpret the many variables of vulnerabilities of coastal buildings in hurricane situations.

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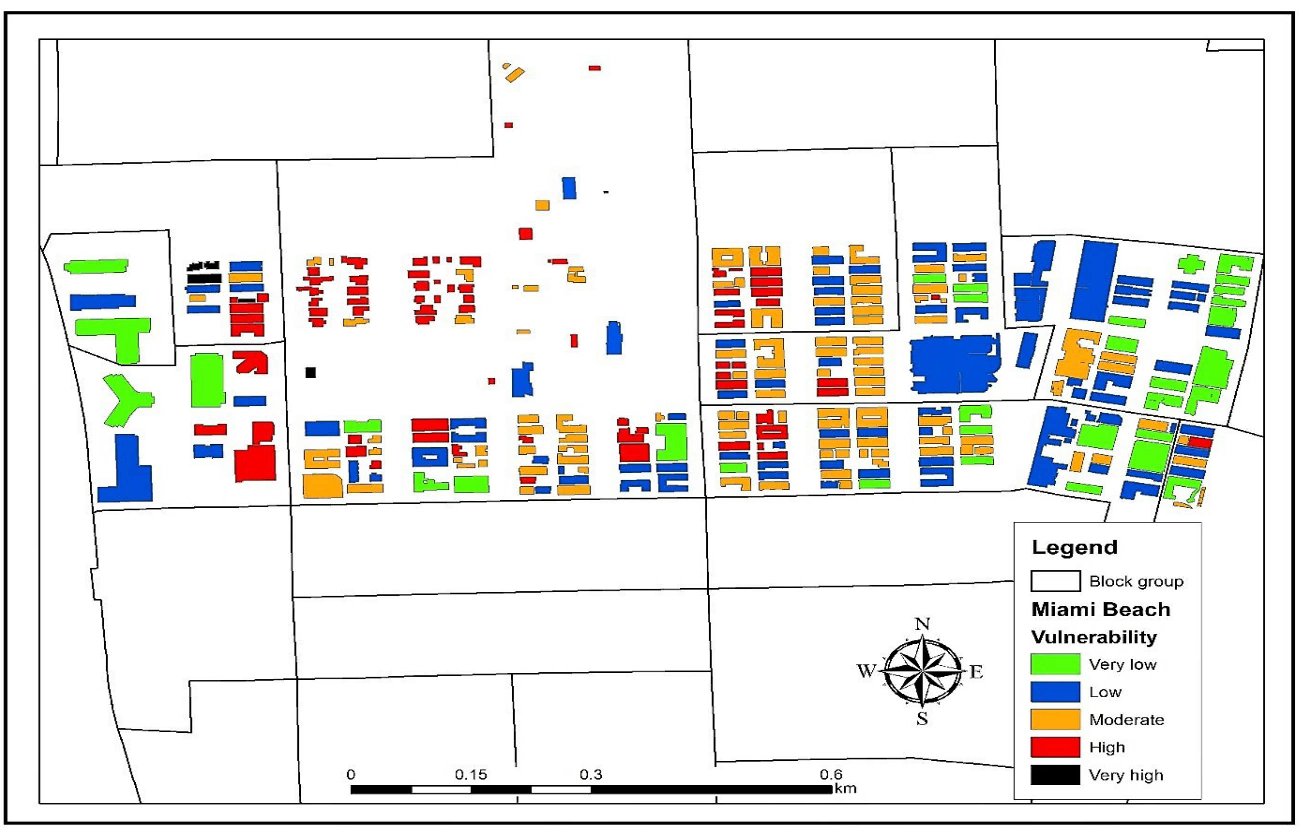

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