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16. Abstract

The increased frequency and intensity of hurricanes and the trajectory of urbanization within Florida have increased the exposure and vulnerability of coastal communities cascading into socio-economic disruption and challenging recovery. Although multiple approaches have been developed to quantify the impact of hurricane-induced flood loads on coastal communities, less focus has been spotted on the dynamic variability of hurricane risk on coastal communities due to the temporal change in hazard and exposure because of climate change and urbanization. Also, the complexity of the hurricane vulnerability component in terms of the socio-physical impacts on the built environment, including population, buildings, and infrastructure. In this project, a multi-hazard community-level hurricane risk assessment approach will be developed to assess the vulnerability of the built environment to hurricane-induced hazards. The impact of storm surge on buildings and population will be quantified in terms of the sustained damage. To extend the developed approach from building-level to community-level, a suite of building archetypes will be used to model the different building typologies within the community. Then, a fragility-based vulnerability function for each archetype will be used to quantify the level of vulnerability in terms of the exceedance probability of a set of prescribed damage states. The final impact of the built environment will inform a population impact analysis to identify the amount of population dislocation. The proposed approach will outline the first steps for a community resilience assessment against flood hazards. This approach can provide a robust tool for policymakers and stakeholders to make risk- and resilience-informed decisions for coastal communities.

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High-Resolution Approach for Socio-Physical Community-Level Hurricane Risk and Resilience Assessment in an Uncertain Climate

Final Report

May2024

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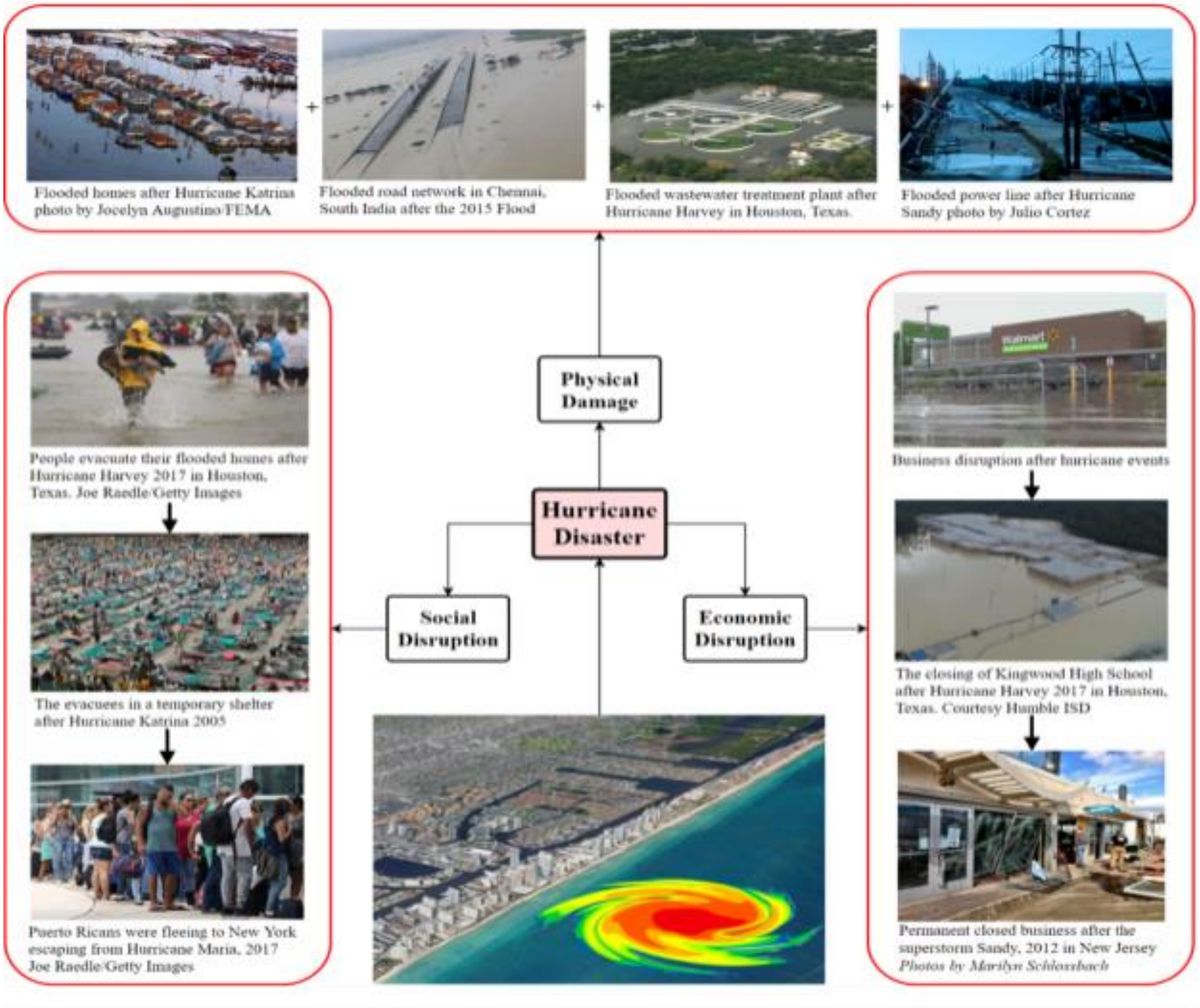
CHAPTER 1: INTRODUCTION

1.1. Project Motivation

Hurricane-induced hazards cause severe damage to the built environment cascading into major impacts on the socio-economic systems as shown in Fig 1. Most current hurricane risk assessment approaches investigate the impact of one or a combination of hurricane-induced hazards on the built environment. Recently, Hurricane Ian made landfall as a high-end Cat4 storm in Southwest Florida in September 2022 and was the third-costliest weather disaster on record with more than $50 billion in insured losses and the deadliest hurricane to strike the state of Florida since the 1935 Labor Day hurricane with more than 148 fatalities. Such extreme hurricane events highlight the significance of the impact of hurricane-induced hazards on coastal communities. Therefore, hurricane research has been evolving over the years to address the diverse aspects of hurricanes, including hazard, exposure, vulnerability, and risk. A number of researchers have investigated the modeling aspects of hurricane-induced wind loads (Guo and van de Lindt 2019; Vickery et al. 2006a, 2009), building performance (Aghababaei et al. 2018; He et al. 2017; Pita et al. 2012), and loss estimation (Kakareko et al. 2020; Khajwal and Noshadravan 2020; Li and Ellingwood 2006; Mishra et al. 2017; Vickery et al. 2006b). The combined impact of hurricane-induced wind loads and the wind-born debris has also be investigated in terms of the subsequent damage to buildings (Chung Yau et al. 2011; Grayson et al. 2013). On the other hand, the impact of hurricane-induced surge loads on buildings has also been investigated using component-based fragility approach (Hatzikyriakou et al. 2016). A stochastic model for the joint impact of wind and storm surge induced by hurricanes has been also developed (Bushra et al. 2019; Pei et al. 2013, 2014; Unnikrishnan and Barbato 2017). Assembly-based vulnerability models were also developed to account for the combined impact of wind, rainwater intrusion, and storm surge on buildings (Li et al. 2012; Park et al. 2013, 2014). Dietrich et al. developed an approach to account for the compound impact of waves and storm surge in terms of hazard modeling (Dietrich et al. 2011) and loss estimation (Do et al. 2020; Tomiczek et al. 2014, 2017). Several multi-hazard models were developed to account for the combined impacts of wind, wave, and storm surge on buildings to develop fragility functions for wood-frame structures (Masoomi et al. 2019; Massarra et al. 2019; Nofal et al. 2021a; b; Van Verseveld et al. 2015), and performance-based hurricane engineering models (Barbato et al. 2013; McCullough et al. 2013).

While these studies contributed significantly to the literature and advanced the conceptualization of hurricane hazard, exposure, and vulnerability, less focus was spotted on the impact of coastal flooding on socio-physical systems. Also, most of the available studies focus on the system- and building-level with less focus on the community-level. On the other hand, the trajectory of urbanization and climate change in terms of the increased intensities and frequencies of hurricane-induced hazards makes it a challenge to quantify the actual risk. Therefore, more models are required to capture the actual hurricane risk corresponding to different hurricane categories since the hazard and exposure components of risk keep changing over time with lots of epistemic uncertainties (systematic: such as the lack of data to provide better estimates of the random variables which are reducible with more data) and aleatoric uncertainties (statistical: such as the differences between numerical hazard model and natural phenomena which is irreducible).

Therefore, more studies are needed to capture the dynamic variability in the hurricane-induced flooding on coastal communities.



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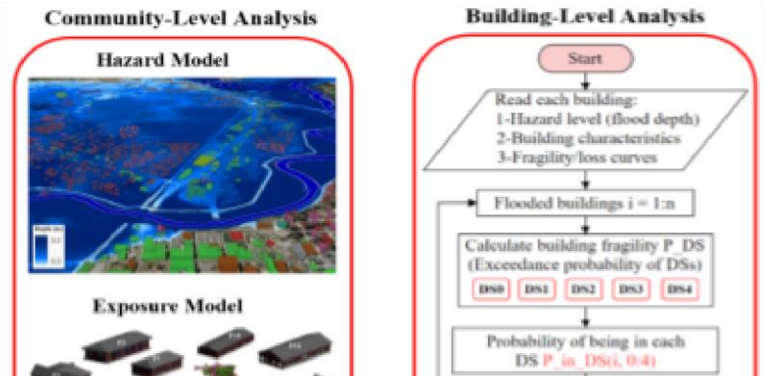
1.2. Research, Objectives, and Tasks

The main objective of this project is to probabilistically capture the performance of the built environment under extreme hurricane-induced coastal flooding hazards including the impact of storm surge on buildings. Therefore, in this project, a high-resolution flood risk assessment approach is proposed to account for the impact of storm surge on the built environment. This will be done by developing high-resolution models of the different risk components, including hazard, exposure, and vulnerability. This requires detailed discretization of the various social and physical



components of the community as shown schematically in Fig. 2. The proposed detailed community model will be linked with storm surge and wind hazard maps to identify the exposure of the buildings and physical infrastructure in terms of the hazards' intensities (surge height) at each exposed asset. The hazard intensity at each exposed assets will be used as an input for a multi-hazard hurricane vulnerability model to account for the compound impact of storm surge on buildings using the model developed by Nofal et al. (Nofal et al. 2021a) as shown in Fig. 2. The final damage will be in terms of the exceedance probability of the developed damage states which can then be converted into loss estimates. The main objective of the proposed approach is to allow hurricane risk assessment with a resolution enough to make riskand resilience-informed decisions efficiently with reasonable computational cost. To test the developed models, the proposed approach will be applied to Miami-Dade County as an example community. Miami-Dade County is one of the most hurricane-vulnerable locations in the US, which makes it a perfect case study for the proposed approach.

Summary of Project Activities

The proposed high-resolution community-level hurricane risk model will be done through a number of activities and research tasks. The project is divided into five main tasks connected through input-output data. Initiating each task can be independently conducted, but it requires the input data from previous task to be finalized. This will allow some overlap between tasks which will enable efficient analysis. Task 1 will initiate the community model to serve as the base for the exposure analysis by overlaying the hazard models developed from task 2. Then, Task 3 will initiate a detailed exposure analysis of each exposed asset in terms of the hazard intensities at each building and infrastructure system. Task 4 will use the outputs from the previous three tasks in terms of the exposed asset type and the exposure type and level to initiate a vulnerability analysis to identify the level of damage to each asset. Finally, Task 5 will take the damage output from Task 4 and use it to identify the potential disruption to the built environment in terms of population dislocation.

These objectives were accomplished through the following research tasks:

Task 1 – Collect the Data for the study area (Miami-Dade County) and develop the community model

Detailed building data was used to develop a community-level hurricane risk assessment model. The national structure inventory (NSI 2024) was used to collect detailed data about the buildings within Miami-Dade County. This data include occupancy, number of stories, first-floor elevation, foundation type, and roof shape, which is needed to model the physical characteristics of the building inventory. Also, this data include estimate for population corresponding to each building. The population data was used to identify the population dynamics corresponding to the level of damage to the residential buildings. Harnessing this information is essential to build the community model and identify the appropriate vulnerability function assigned to each corresponding building. This was done using a portfolio of building archetypes to model the different buildings typologies within the community. A mapping algorithm was used to map these archetypes to each building within the community using the provided information about each building as shown in Fig. 3 where buildings are color-coded based on their flood archetypes. More information about these archetypes can be found here (Nofal and van de Lindt 2020a). The proposed community-level computational environment discretizes the built environment by performing spatial analysis for buildings and population to identify the social and physical exposure of the community. It calculates the spatial distribution of hazard intensity across the community.

Task 2 – Develop hazard models for storm surge, waves, and wind

The first step to develop a hurricane risk model is to develop the hazard model of interest either for a specific hurricane scenario such as a 100-yr or a 500-yr storm or modeling a specific historic event such as Hurricane Andrew 1992 as shown in Fig. 4 for examples of historic hurricane storms. However, in this study the NOAA hurricane SLOSH model will be used to assess the vulnerability of the buildings to different hurricane categories.

Task 3 – Develop a community-level exposure model

The modeled community in Task 1 is then overlaid with the hazard layer from Task 2 to identify the hazard intensity (surge height) at each building location. Spatial analysis will be conducted to process the hazard and community data and extract the required information to be used as inputs for the next stage of the analysis. Two types of data will be used in this analysis. Vector data will be used to process the buildings data and raster data will be used to process the hazard data. Spatial extraction functions will be used to extract the hazard intensities from the raster data to store it in the vector data of the community model. Fig. 4 shows the example community from Fig. 3 overlaid with an example hazard model to show the variability of the hazard intensities across the community and the necessity to perform spatial analyses to conduct exposure analysis at the community-level.

Fig. 3 A sample building data for an example community showing 3D buildings color coded based on building use.

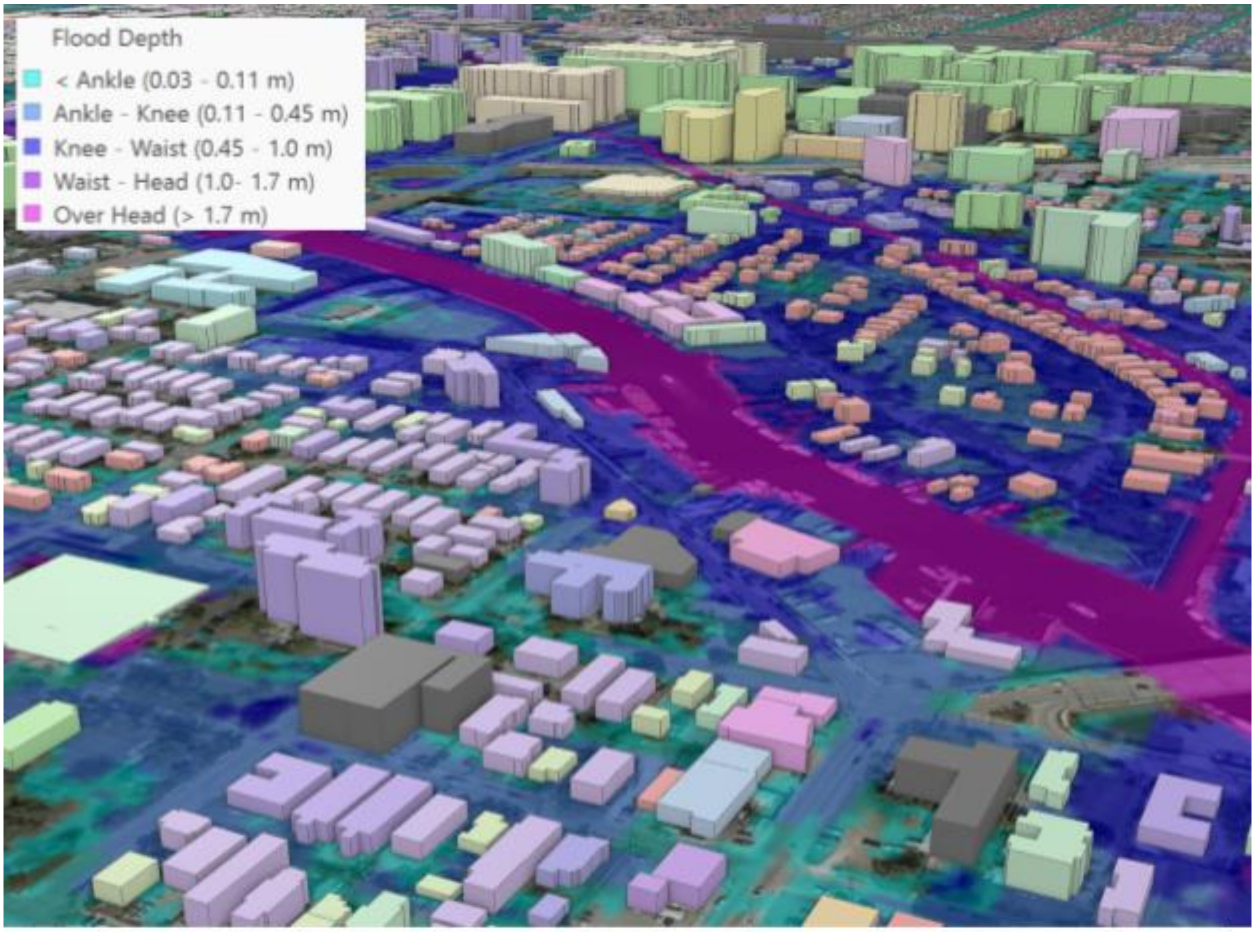


Fig. 4 The same sample of buildings data from Fig. 3 overlaid with 100-year flood hazard map showing the exposed assets and the level of exposure.

Task 4 – Develop the fragility-based community-level vulnerability model

The proposed socio-physical coastal flood risk model proposed herein will account for storm surge hazard, exposure (assets and population), and vulnerability (physical and social). For the building-level analysis, the proposed socio-physical vulnerability function will quantify the direct and indirect impacts of hurricane-induced hazards on physical assets and population. This will be done using fragility-based probabilistic vulnerability approach to propagate uncertainties in the susceptibility of the different components to hurricane-induced hazards (Nofal et al. 2021a). The flood fragility functions developed by Nofal and van de Lindt (2020b) will be used to capture the level of damage corresponding to the flood hazard intensity for each exposed building. For the community-level vulnerability analysis, a portfolio of vulnerability functions corresponding to each archetype will be used to model the vulnerability at the community level after representing the different exposed assets, as shown in Fig 5. An algorithm will be developed to use the detailed community-level exposure information from the previous task and run a vulnerability analysis building by building to identify the total damage for each exposed building. On the other hand, a simplified vulnerability model will be developed for the power and water network to identify the exposed power substations and water treatment plants. The HAZUS stage damage functions for such utilities will be used to quantify their functionality. Afterwards, the service area associated with each disrupted facility will be identified and linked with each corresponding building to identify the total functionality.

Fig. 5 A schematic representation of a mapped community using a portfolio building archetypes.

Task 5 – Quantify the potential disruption to the built environment

In this task, the potential disruption resulting from hurricanes on the built environment will be quantified in terms of physical damage to buildings and infrastructure and social disruption to the population socio-economic activity. This will be done by calculating building damage in terms of prescribed damage states (insignificant, slight, moderate, extensive, complete). For social impacts, population dislocation will be quantified for two age groups including under and over 65 years old. Also, the impact of flooding on schools and the dislocated students will be quantified.

Chapter 2. ANALYSIS RESULTS

2.1. Storm Surge Hazard Modeling

The NOAA SLOSH storm surge model was used to quantify the coastal flood exposure of Miami-Dade County. The NOAA SLOSH model provides surge hazard data in terms of flood depth corresponding to each the five different hurricane categories. These hazard maps were used to extract the flood depth at each building with Miami-Dade County. Fig. 6 shows the storm surge SLOSH hazard map for Miami-Dade County for a flooding event induced by Cat5 hurricane. The hazard map is available in a raster format that can be processed to identify the surge height at each building.

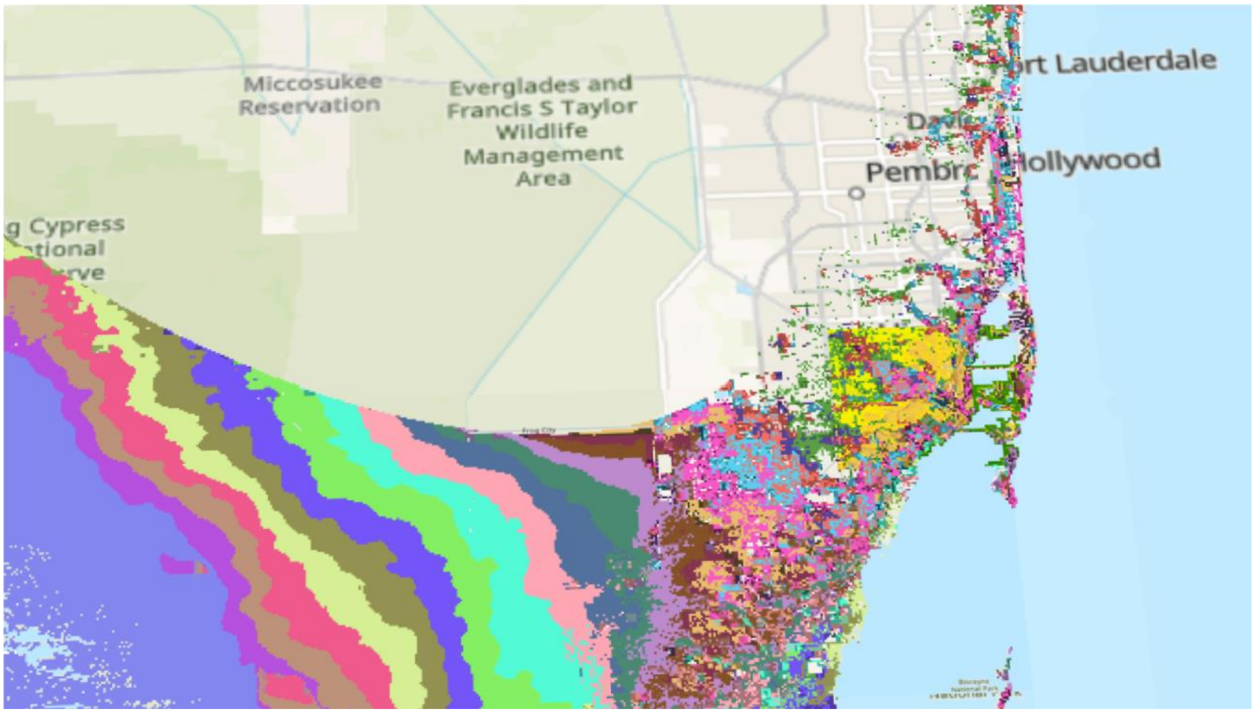


Fig. 6 The NOAA Cat 5 storm surge SLOSH model for Southern Florida.

2.2. Community Modeling

The national structure inventory (NSI) developed by the Army Corp. of Engineers was used to discretize the different building typologies within Miami-Dade County. This data includes detailed building data such as building occupancy, building construction material, foundation type, number of stories, first-floor elevation, etc. A mapping algorithm was developed to map a portfolio of 15 building archetypes along with their fragility functions to each building within the community. Table 1 provide a description of each building archetype. Fig. 7 shows a schematic 3D visualization of each one of these archetypes.

Table 1. The building archetypes description

Building archetype	Building description
F1	One-story single-family residential building on a crawlspace foundation
F2	One-story multi-family residential building on a slab-on-grade foundation
F3	Two-story single-family residential building on a crawlspace foundation
F4	Two-story multi-family residential building on a slab-on-grade foundation
F5	Small grocery store/Gas station with a convenience store
F6	Multi-unit retail building (strip mall)
F7	Small multi-unit commercial building
F8	Super retail center
F9	Industrial building

F10	One-story school
F11	Two-story school
F12	Hospital/Clinic
F13	Community center (place of worship)
F14	Office building
F15	Warehouse (small/large box)

Fig. 7 A schematic representation of a portfolio of 15 building a to be used to discretize the community.

2.3. Exposure Modeling

The adopted hazard models were overlaid with the developed community models in a GIS environment to identify the hazard intensities at each building. The flood depth and wind speed at each building was calculated based on the raster hazard maps corresponding to each hazard. Fig. 8a shows the flood exposure hazard map for south Florida under category 5 hurricane storm surge based on the NOAA SLOSH storm surge model. Fig. 8b shows color-coded map for the entire building inventory in Miami-Dade County (579,133 buildings).

2.4. Risk Modeling

A fragility-based flood vulnerability analysis was conducted to quantify the potential damage to the building inventory in Miami-Dade County corresponding each hurricane category. The final damage was calculated in term of the exceedance probability of a prescribed damage state (DS). Table 2 provide detailed description of each DS. The most probable damage was quantified for each building based on the maximum probability of being in each DS. An algorithm was developed to conduct vulnerability analysis at the community-level to identify the building damage for each building within the community. Table 3 provide a summary for the building damage corresponding to the storm surge resulting from Cat 5 hurricane in terms of the number of buildings designated by their most probable DS.

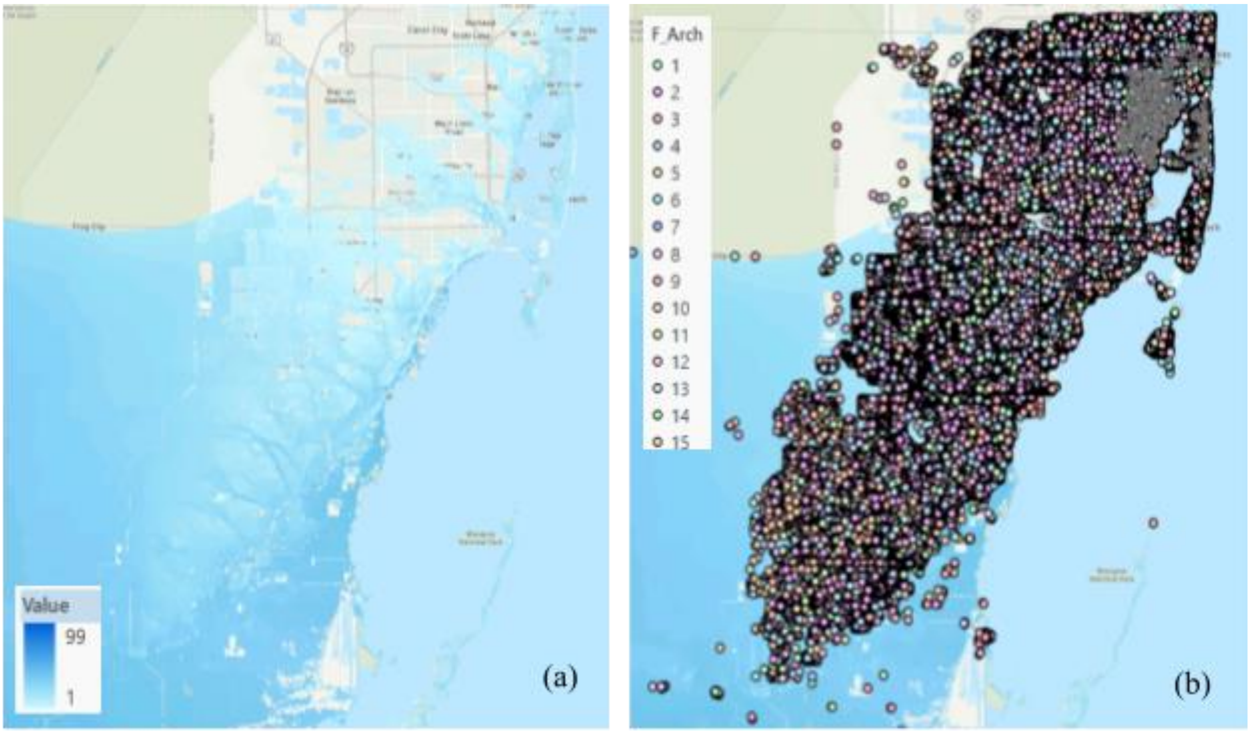


Fig. 8 The flood exposure of Miami-Dade County for Category 5 hurricane storm surge: (a) Storm Surge hazard map for Miami-Dade County; (b) Color-coded buildings overlaid with the flood hazard map.

Table 2 Damage states description

DS	Description
DS 0	Insignificant damage to components below first-floor elevation. Water enters crawlspace/basement and touches foundation (crawlspace or slab on grade). Damage to components within the crawlspace/basement including base insulation and stored inventory. Minor damage to garage interiors including drywall, cabinets, electrical outlets, wall insulation (Garage is below the first-flood elevation (FFE)). No sewer backup into the living area.
DS 1	Water touches floor joists up to minor water enters the building. Damage to carpets, pads, baseboards, flooring. Damage to the external AC unit (if the AC unit is not elevated) and the attached ductworks (if ductworks are in the crawlspace). Complete damage to the garage interior (if the garage is below FFE). No drywall damages with the potential of some mold on the subfloor above the crawlspace. Could have a minor sewer backup and/or minor mold issue.
DS 2	Partial damage to drywalls along with damage to electrical components (base-outlets), water heater, and furnace. Complete damage to major equipment, appliances, and furniture on the first floor. Damage to the lower bathroom and kitchen cabinets. Doors and windows may need replacement. Could have a major sewer backup and major mold issues.

DS 3	Damage to the non-structural components and interiors within the whole building including (but not limited) drywall damage to upper stories for multi-story buildings (e.g. attic, second story, etc.). Electrical switches and mid-outlets are destroyed. Damage to bathroom/kitchen upper cabinets, lighting fixtures on walls are destroyed with potential damage to ceiling lighting fixtures. Studs reusable: some may be damaged. Major sewer backup will happen along with major mold issues. Equipment, appliances, and furniture on the upper floors are also damaged (e.g., attic, second floor, etc.).
DS 4	Significant structural damage present (e.g. studs, trusses, joists, etc.). Non-structural components and interiors are destroyed including all drywall, appliances, cabinets, furniture, etc. Damage to rooftop units/components including roof insulation, sheathing, and electro-mechanical systems (rooftop AC units, electrical systems, cable railing, sound system, etc.). Foundation could be floated off. The building must be demolished or potentially replaced.

Fig. 9 shows the number of buildings designated by their most probable DS corresponding to each hurricane category. Table 3 provide detailed numbers of presented data in Fig. 9. The analysis results showed the number of buildings designated as DS0 (insignificant damage) decrease as the category of hurricane increases. This because much more buildings will get higher damage state which is explained by the increase in the number of buildings in DS1 to DS4. Also, it is obvious that the buildings designated as DS2 is much more than the other higher DSs. The flood damage analysis was conducted for the flooding events corresponding to the five-hurricane category. Full analysis results data is available under reasonable request. For the sake of space, the analysis results for Cat 5 hurricane are shown below. Fig. 10 and Fig. 11 shows color-coded map for the building inventory in Miami-Dade County based on the total losses as percentage of the building value and maximum probable DS with respect to a flooding event resulting from Cat 5 hurricane with close-up view on downtown Miami.

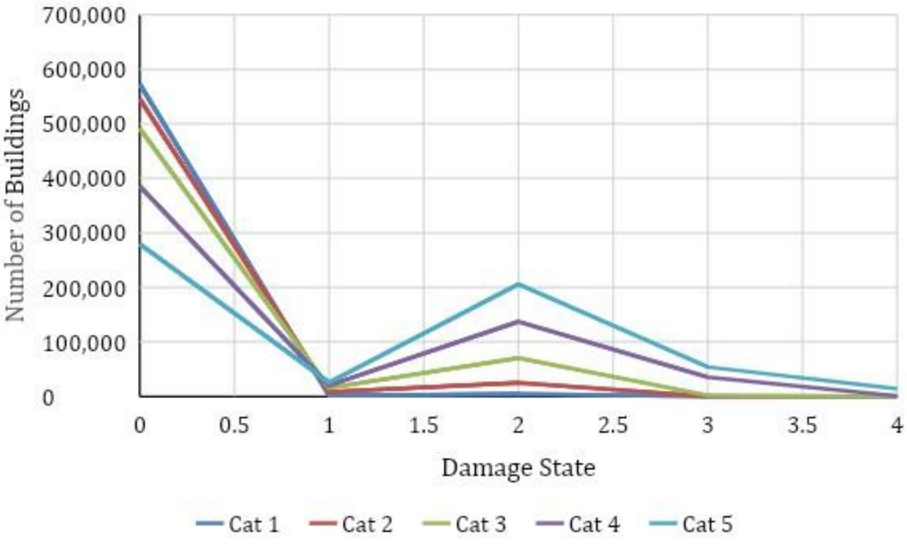


Fig. 9 The number of buildings designated by their most probable flood damage state corresponding to each hurricane category.

Table 3. The number of buildings within each probability range of exceedance of a functionality

state

Most Probable Flood DS per Hurricane Category	Number of buildings (Total=579,133)				
	DS0	DS1	DS2	DS3	DS4
Cat 1	572,891	1,537	4,703	2	0
Cat 2	545,742	8,420	24,828	143	0
Cat 3	491,431	15,595	70,111	1,995	1
Cat 4	385,247	20,337	137,195	35,292	1,062
Cat 5	279,336	25,610	206,073	54,025	14,089

Fig. 12 shows color-coded map for the flood impact resulting from the different hurricane categories at the same location which is close to the shoreline. The buildings are color coded based on their damage states from blue for DS0 to red for DS4. These figures show how the more buildings are turning from blue to red with the increased hurricane category reflecting the increased damage due to the increased flood depth. Detailed building vulnerability data for the entire Miami-Dade County is available for the different hurricane categories.

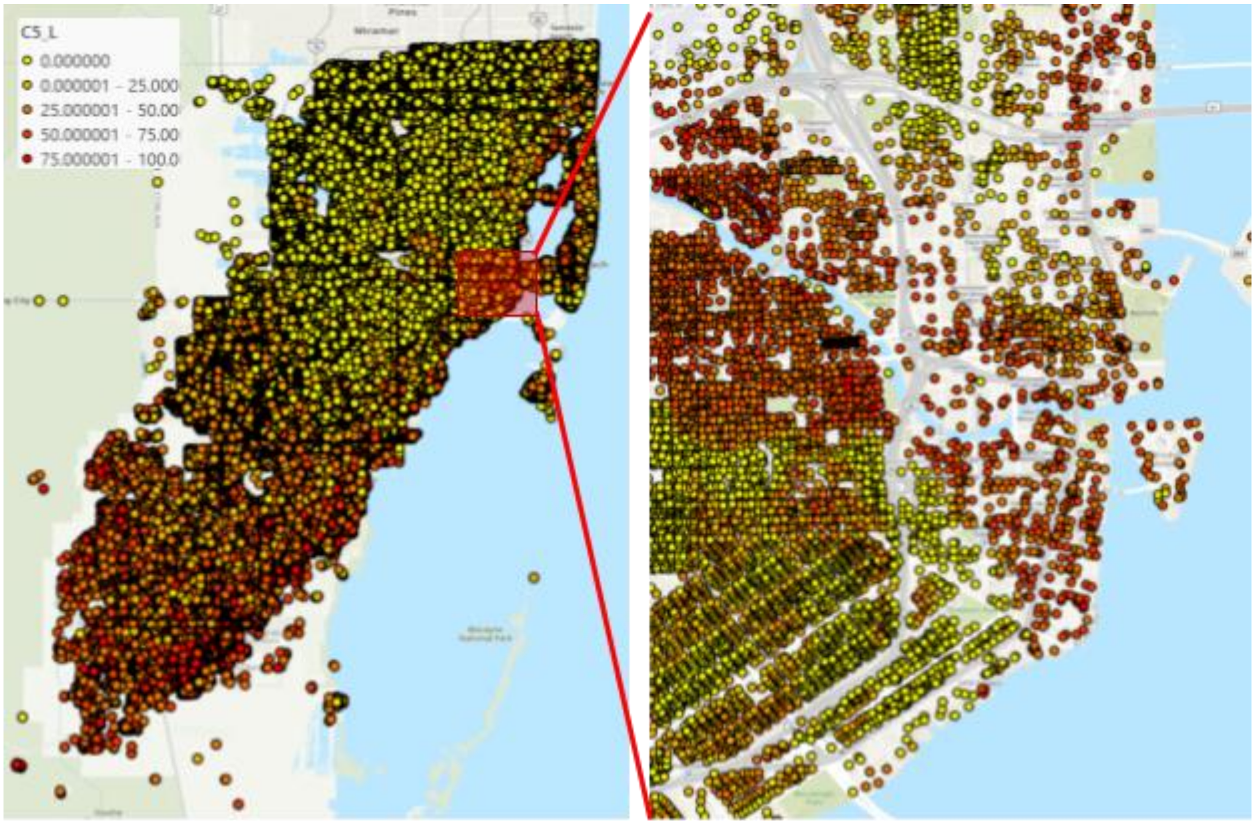


Fig. 10 Color-coded map for the building inventory in Miami-Dade County based on the total losses as percentage of the building value with respect to a flooding event resulting from Cat 5 hurricane with close-up view on downtown Miami.

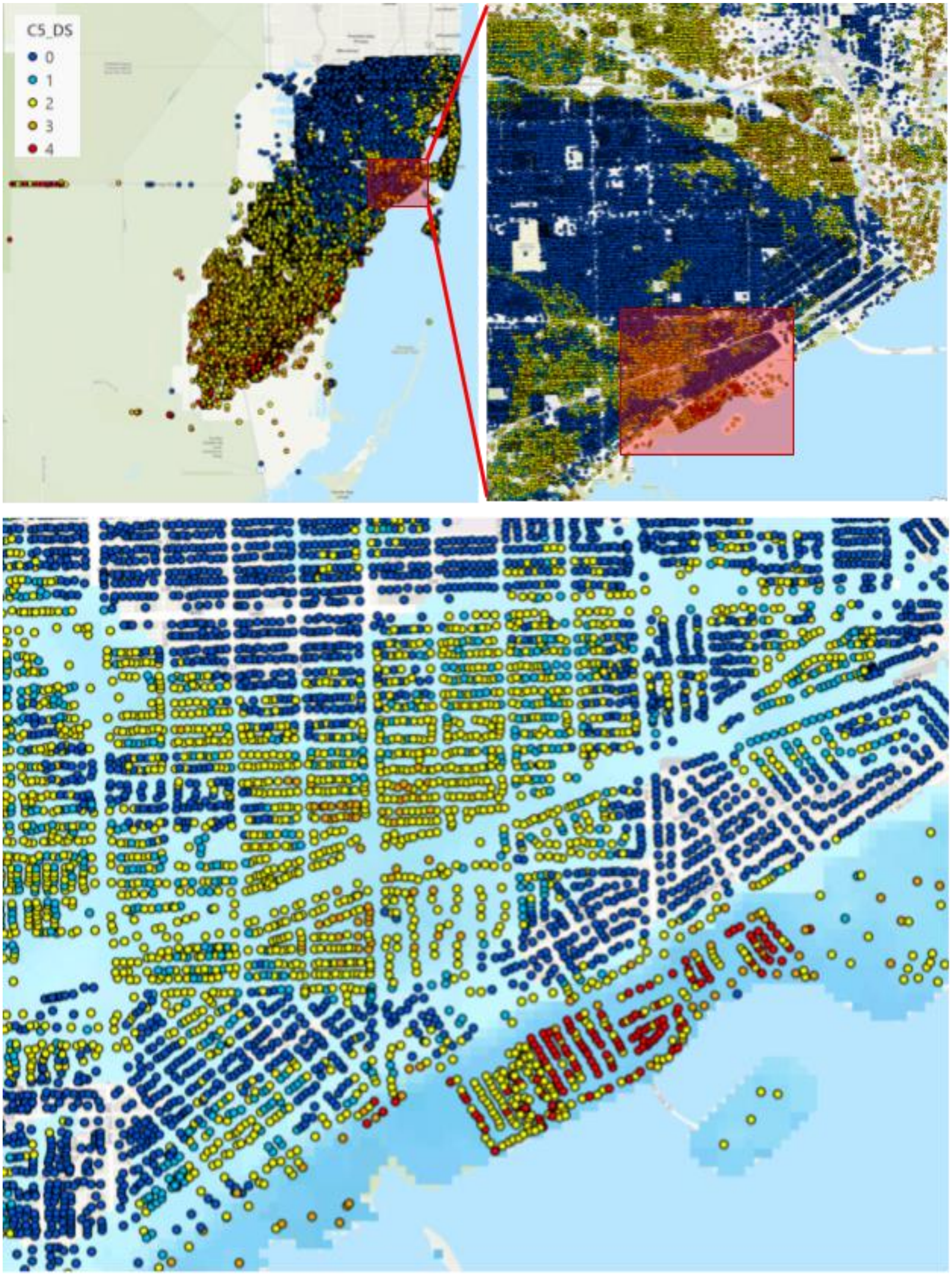


Fig. 11 Color-coded map for the building inventory in Miami-Dade County based on the maximum probable DS with respect to a flooding event resulting from Cat 5 hurricane with close-up view on downtown Miami.

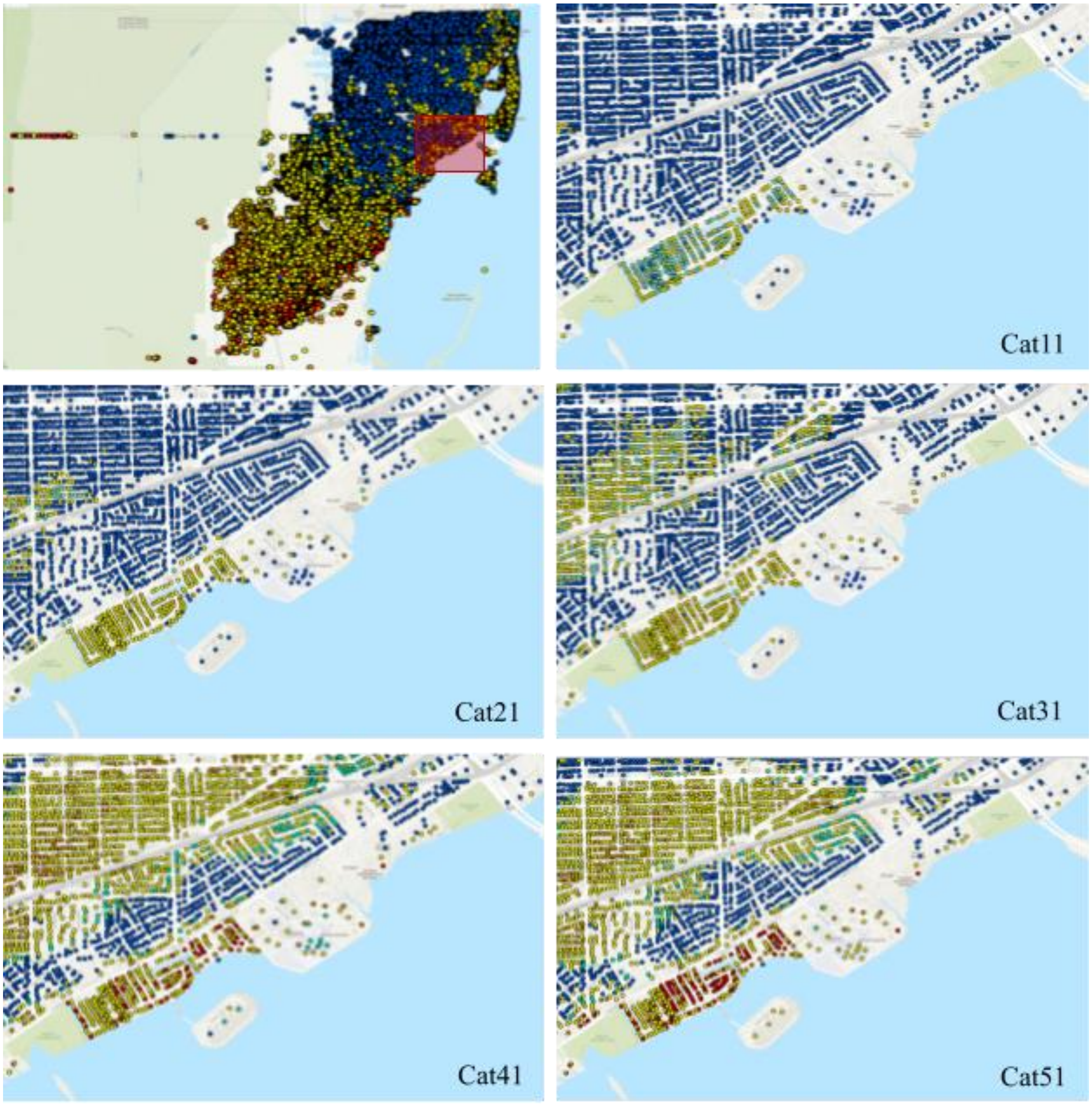


Fig. 12. Color-coded map for the coastal flood impact of different hurricane categories on the same neighborhood

2.5. Population Dislocation

The National Structure Inventory provide detailed information about the population within each building in terms of the population capacity within each building in the morning and night and if they are over 65 and under 65 years old and if they are disabled or not. To quantify the population dislocation, a conditional probability was used to account for the probability of dislocation given a specific damage state was exceeded. The best engineering judgment was used to provide estimates of these condition probabilities based on the description of each damage states and the potential dislocation corresponding to each one of them. The total population dislocation was calculated based on the population resides at home at night for over and under 65 years old. Also, the dislocation of disables population was calculated based on the same basis. Fig. 13 shows the number of dislocated populations over 65 and under 65 years old along with the number of dislocated students and Table 4 shows the exact number of dislocated populations corresponding to each hurricane category. Fig. 14 shows the building inventory in Miami-Dade County color-coded based on the number of dislocated people.

Fig. 13. Color-coded map for the flood impact of the different hurricane category on the same neighborhood

Table 4. The number of buildings within each probability range of exceedance of a functionality state

	Population Dislocation			
	over 65	under 65	Total (o65+u65)	Students
Cat 1	62,806	9,858	72,664	22,111
Cat 2	117,775	22,197	13,9972	29,833
Cat 3	245,105	52,628	29,7733	48,898
Cat 4	533,452	119,286	652,738	95,768
Cat 5	827,527	187,182	1,014,709	151,743
Total Population	2,209,370	451,532	2,660,902	408,171

Fig. 14. Color-coded map for Miami-Dade County buildings based on the number of dislocated people

Chapter 3. Conclusions and Recommendations

A detailed building-level flood risk assessment was conducted for entire Miami-Dade County which includes over 500k buildings. The NOAA SLOSH model was used to identify the hurricane-induced surge corresponding to the different hurricane categories for Miami-Dade County. The national structure inventory developed by the Army Corps of Engineers was used to model the entire community. A mapping algorithm was developed to map a portfolio of building archetypes along with their fragilities to each building within the community. This algorithm uses detailed building information (e.g., building occupancy, foundation type, number of stories, etc.) to assign the matchable archetype to each building. The fragility function corresponding to each archetype was used to quantify the potential amount of damage corresponding to each hurricane category. Population dislocation was calculated using the population information provided by the National Structure Inventory along with the conditional probability of population dislocation given that a specific damage already exceeded.

The developed approach is systematic and can be scaled to run analysis at much larger scale such as regional level. This approach is fully probabilistic and provide the damage in terms of exceedance probabilities of prescribed damage states. However, for decision making, the most probable damage state was used to designate buildings by just one quantity. The developed approach can also convert the calculated damage to losses by multiplying the probability of being in each DS by the replacement cost of each DS. This approach is more advanced than the HAZUS approach since HAZUS uses deterministic stage-damage functions that doesn’t account for the uncertainties in the demand and resistance parameters. Also, it can be extended to account for other hazards such as wind and waves impacts if the hazards and fragility data are available.

The flood risk analysis approach proposed in this study went beyond physical damage to quantify social disruption in terms of population dislocation. The developed approach uses the provided household and students' information provided by the NSI data to make estimates about population dynamics. The population dislocation was identified for different age groups including under and over 65 years. These results can leverage many social studies related to the coastal flooding impacts on elderly people along with their vulnerability to dislocation.

The developed research in this study can be extended to study the multi-hazard impacts pf hurricane-induced hazards on buildings by integrating flood damage with wind damage for content, structural, and non-structural components. Also, the impact of using a number of mitigation and adaptation strategies can be investigated including hazard mitigation sea wall, levees, and retention systems, exposure mitigation building elevation, buyout, managed retreat, and vulnerability mitigation such enhancing the structural system of buildings by using hurricane clips, more nails, and other better structural systems.

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