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MULTI-HAZARD HURRICANE VULNERABILITY MODEL TO ENABLE RESILIENCE-INFORMED DECISION

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Hurricanes or typhoons are multi-hazard events that usually result in strong winds, storm surge, waves, and debris flow. A community-level multi-hazard hurricane risk analysis approach is proposed herein to account for the combined impacts of hazards driven by hurricanes including surge, wave, and wind. A tightly coupled ADCIRC and SWAN model is used to account for the surge and wave hazard. Community-level exposure analysis is conducted using a portfolio of building archetypes associated with each hazard. A building-level hurricane vulnerability model is developed using fragility functions to account for content, building envelope, and structural damage. These fragility functions calculate the exceedance probability of predefined damage states associated with each hazard. Then, a building damage state is calculated based on the maximum probability of being in each damage state corresponding to each hazard. The proposed hurricane risk model is then applied to Waveland, Mississippi, a community that was severely impacted by Hurricane Katrina in 2005. The main contribution of this research is modeling the community-level hurricane vulnerability in terms of damage to the building envelope and interior contents driven by surge, wave, and wind using fragility functions to provide a comprehensive model for resilience-informed decision-making.

Keywords: Hurricane surge, Hurricane waves, Hurricane risk, Hurricane damage, Hurricane losses, Community resilience.

1 INTRODUCTION

Hurricane-induced hazards have resulted in devastation to coastal communities across sectors and networks from physical infrastructure to local institutions. Hurricane damage results from storm surge, wave, and wind. Additionally, the torrential rains induced by hurricanes drive fluvial (riverine) and pluvial (rainfall) flooding for inland communities. Together, these damages impact communities' social, economic, infrastructure, environmental, and cultural systems. The focus of this study is on coastal communities' vulnerability to compound hurricane-induced hazards. There is a substantial body of research related to hurricane-induced hazards and their impacts on the built environment. For example, hurricane wind loads models were recently improved (Guo and van de Lindt 2019) along with their associated damage and loss models (e.g. Mishra *et al*. 2017). Additionally, improvements have been made to hurricane storm surge and wave comprehensive hazard models (e.g. Dietrich *et al*. 2011), building damage prediction (Masoomi *et al*. 2019), fragility functions (Do *et al*. 2020), and loss analysis (Li *et al*. 2012). Furthermore, different hurricane multi-hazard vulnerability models were developed including performance-based hurricane engineering models (Barbato *et al*. 2013) and time-dependent fragility functions (Masoomi *et al*. 2019). Developing probabilistic vulnerability models for hurricane-induced hazards has been the focus of the literature over the last two decades (Li and Ellingwood 2006).

Despite the recent advances in developing vulnerability functions for the multiple loadings produced by hurricanes, a comprehensive vulnerability function that accounts for the compound impacts of these hazards on the community-level has not yet been developed. This is partly because the spatiotemporal variation of hurricane-induced hazards across coastal communities makes it a challenge to develop a community-level hurricane risk model. Additionally, most of the current vulnerability methods only account for damage to the building envelope and structural system with less focus on content damage, i.e. often relying on approximations and broad assumptions. Therefore, a community-level multi-hazard hurricane risk analysis methodology is presented herein to account for content, building envelope, and structural damage. Current building-level hurricane risk analysis is extended to a community-level analysis using the concept of the building portfolio to model the vulnerability of coastal communities to hurricane-induced hazards. The vulnerability of each building within a community to the hazards driven by hurricanes is calculated using the state-of-the-art for fragility functions for the multiple loadings produced by hurricanes (surge, waves, and wind are all considered herein). These fragility functions are combined in a way that enables the calculation of both building envelope and interior content damage. Then, the hazard, exposure, and vulnerability models are overlaid together in a Geographic Information Systems (GIS) environment to account for the spatial distribution of hurricane damage. The resulting damage is calculated as the exceedance probability of pre-defined damage states (DSs). A DS is assigned to each building based on the maximum probability of being in a DS and fragility-based loss function is used to account for building losses as a percentage of market value.

2 METHODOLOGY

A novel high-resolution approach is presented in this paper to capture the community-level hurricane risk components, namely, the hazard, exposure, and vulnerability. The impact of three major loadings produced by hurricanes is considered including surge, wave, and wind with Hurricane Katrina in 2005 used as the scenario to illustrate the approach. The wind hazard is modeled using a combination of the National Oceanic and Atmospheric Administration (NOAA) hurricane research division wind analysis system and an interactive objective kinematic wind analysis model (Powell *et al*. 2010). The surge and wave hazards are modeled using a tightly coupled ADCIRC and SWAN model (Dietrich *et al*. 2012). Community-level vulnerability models are developed using building archetype portfolios. For wind hazard, a portfolio of 19 building archetypes developed by Memari *et al*. (2018) was used, and for combined surge and wave hazards, a residential building archetype developed by Do *et al*. (2020) was used. For static flooding resulting from hurricane surge, a portfolio of 15 building archetypes developed by Nofal and van de Lindt (2020) is used. Building data for a small coastal community including building occupancy, archetype, ground elevation (GE), and first-floor elevation (FFE) was collected by navigating the buildings within the community using Google Street Map View. The fragility functions associated with each building portfolio corresponding to each hazard are assigned to each building within the example community of Waveland, Mississippi to model their multi-hazard vulnerability. Figure 1 shows a schematic representation of the proposed hurricane risk components including hazard, exposure, and vulnerability models. This approach calculates structural damage separately from content damage. The surge-wave fragility surfaces along with the wind fragility curves only account for the damage to the building envelope and structural system. Therefore, the static flood fragility surfaces are designed to account for content damage from DS0 up to DS3 and structural damage only included in DS4. Therefore, they are used to only account for building content damage resulting from flood depth and flood duration.

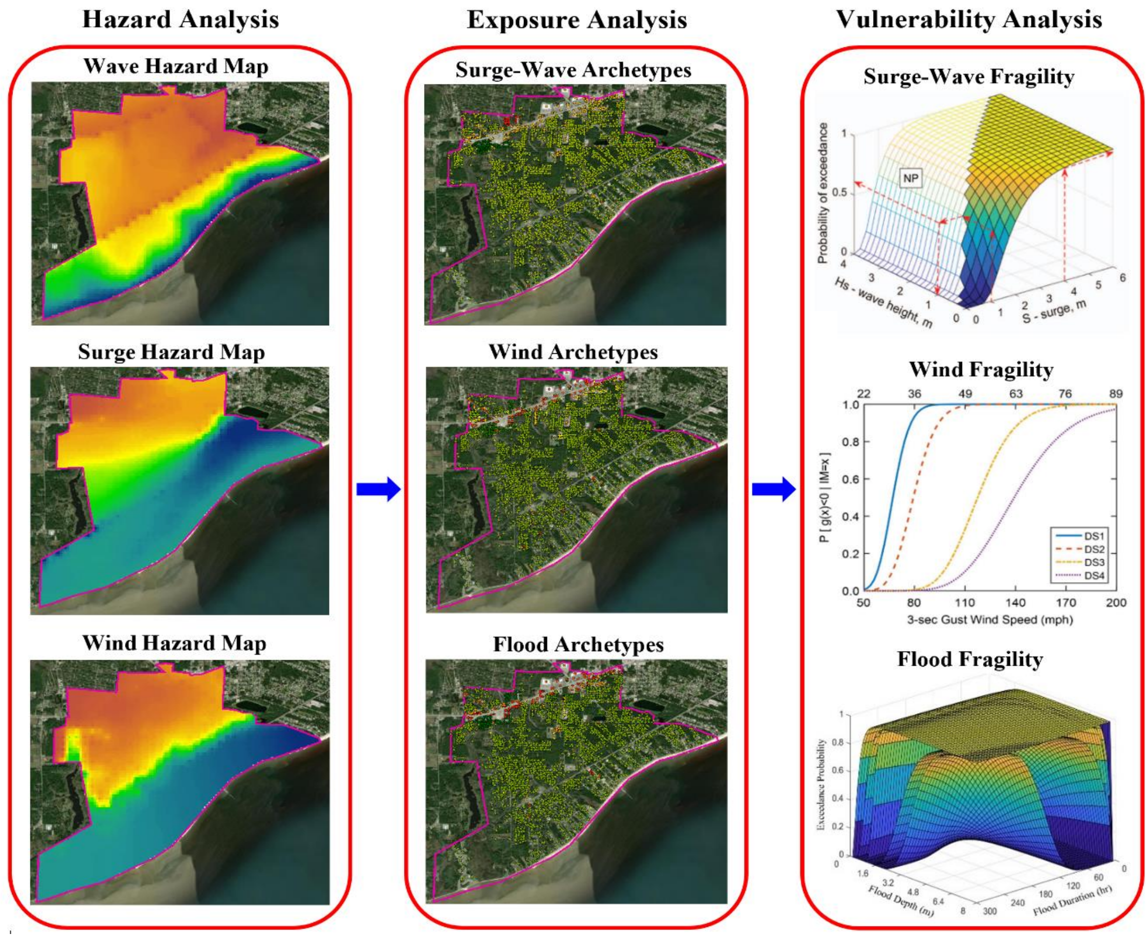

Figure 1. A schematic representation of the proposed community-level hurricane multi-hazard risk analysis framework.

The intensity of each hazard (surge, wave, and wind) was extracted for each building within the example community. An algorithm was then developed to relate the archetype of each building with its corresponding fragility functions. Afterwards, the exceedance probability of each DS corresponding to each hazard intensity is calculated. A single DS is assigned to each building based on the maximum probability of being in each DS calculated from each fragility function corresponding to each hazard. Finally, fragility-based losses were calculated by multiplying the probability of being in each DS by the replacement cost associated with each DS using Eq. (1). This was done by dividing building damage into content and structure damage. Then, the structural damage was further divided into damage caused by wind loads and damage caused by surge-wave loads. Finally, damage and loss results are mapped to the buildings to account for the spatial damage distribution across the community.

$$L_f\,(IM=x)=\sum_{i=0}^{4}\Big[P\big(DS_i\big|IM=x\big)-P\big(DS_{i+1}\big|IM=x\big)\Big]\times Lr_{ci}.V_t \tag{1}$$

where $L_f(IM=x)$ = total building fragility-based losses in monetary terms at $IM=x$ (replacement or repair cost), $P(DS_i \mid IM=x)$ = exceedance probability of DS_i at $IM=x$, $P(DS_{i+1})$ = exceedance probability of DS_{i+1} at $IM=x$, Lr_{ci} = cumulative replacement cost ratio corresponding to DS_i, and V_t = total building cost (replacement cost).

3 EXAMPLE COMMUNITY: WAVELAND, MISSISSIPPI

The coastal community of Waveland, Mississippi, was used to illustrate the framework developed in this paper. Waveland is a small coastal community located in Hancock County, Mississippi with a population of only 6300 people and 2700 buildings. Figure 2 shows the spatial location of Waveland within the state of Mississippi in the southern part of the U.S. with a closeup view of the city's location. Most of the buildings in Waveland are single-family dwellings with some multi-family and commercial buildings in the northern part of the community. Waveland was selected as an example community herein because of the repeated impacts of hurricane hazards including Hurricane Camille in August 1969 and Hurricane Katrina in August 2005.

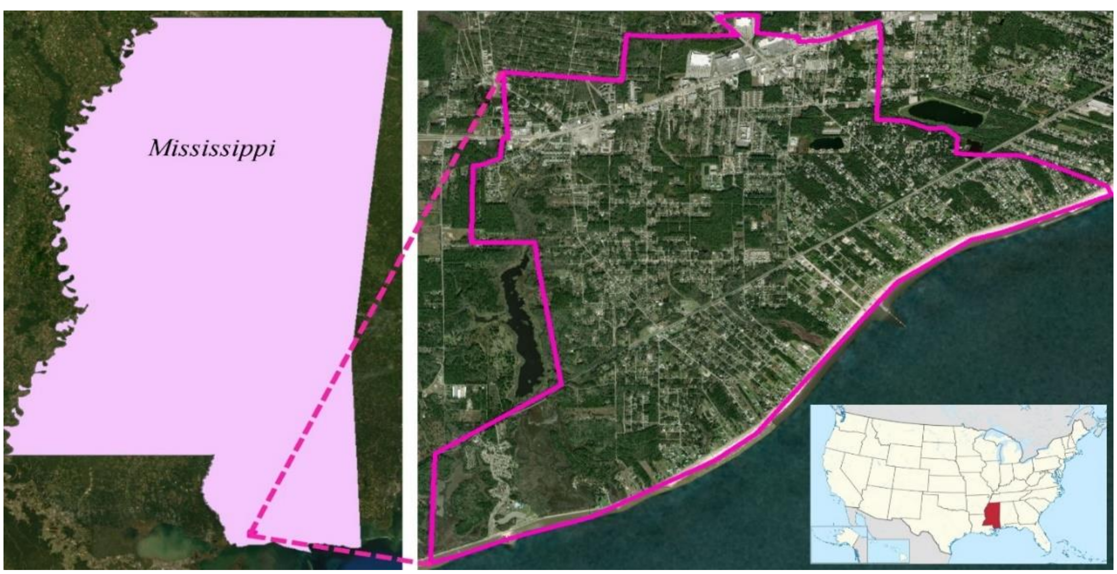

Figure 2. The spatial location of Waveland city within Mississippi state.

4 RESULTS

The damage analysis showed that most of the buildings experienced a DS4 level for surge-wave loads, with a few buildings designated as DS3. This is because of the high surge and waves driven by the Hurricane Katrina simulation, with surge heights exceeding 7.0 m and wave heights of more than 3.0 m, which when combined are easily enough to cause DS4 even for elevated buildings. For wind loads, most of the buildings were characterized as DS1 since the maximum wind speed was 44 m/s (wind speeds are not the full marine strength, but rather have been reduced due to canopy and overland roughness), which typically only causes damage to the building envelope. Thus, as was observed in Katrina, the surge-wave hazard was the dominant cause of building damage. In terms of content damage, most of the buildings were characterized as DS3, or complete damage to the building content. Finally, assigning the maximum DS from surge-wave, wind, and static flooding results in characterizing most of the buildings as DS4 with losses ranging from 75-100% of the buildings' market value, as shown in Figure 3.

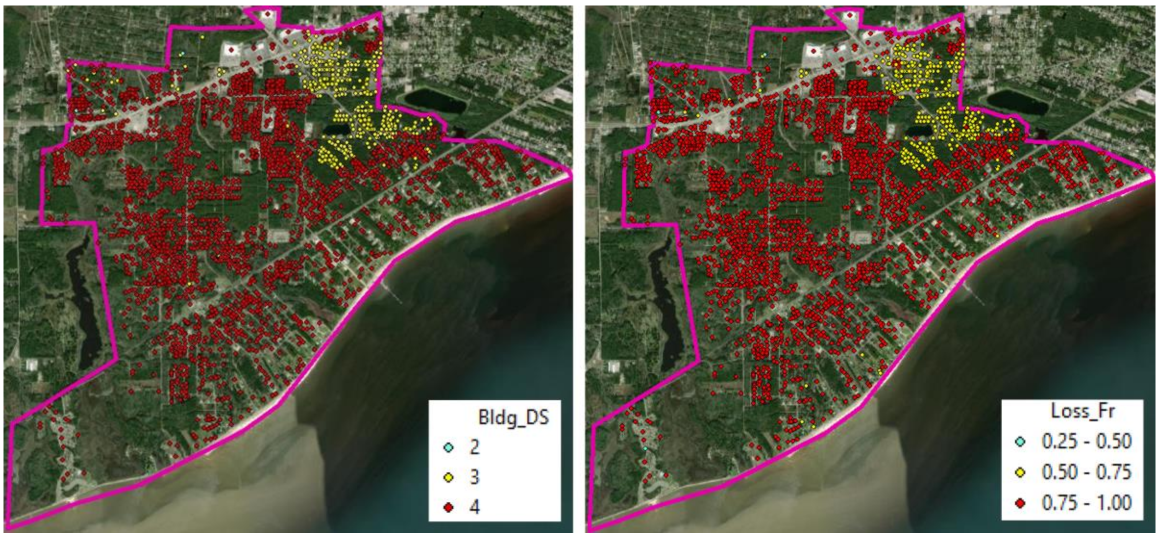

Figure 3. Color-coded map for the spatial distribution of damage/loss across the example community: (a) Building DS; (b) Building loss ratio.

5 SUMMARY AND CONCLUSIONS

A high-resolution multi-hazard hurricane risk assessment methodology was summarized herein to capture the impact of hurricane-induced hazards including wind, surge, and wave on structures and content damage across coastal communities. The high-resolution hurricane risk assessment model developed in this research will enable communities to investigate mitigation scenarios at the building- and community-level including policy decisions, which has not been possible for low resolution or aggregated models. Finally, the damage prediction model presented herein set the initial condition for community resilience analysis which can span multiple disciplines such as social science and economics.

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