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# A Multi-Hazard Community Risk Assessment Framework for Hurricanes Considering Wind-Water Interaction and Building-Specific Characteristics

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**SUMMARY**

Existing community-level hurricane risk assessments often evaluate wind and water hazards independently or depend on generalized fragility curves, which can overlook building-specific geometry, proximity effects, and hazard interaction. This study proposes a high-fidelity, coupled wind–water risk assessment framework for community-scale applications. A realistic 3D model of the target community is constructed to represent building geometries and spatial arrangement. The wind field is simulated using LES-based CFD, while storm surge and flooding are modeled using a hydrodynamic solver to quantify time-varying wind and water pressures on building components under specified hurricane scenarios. By deriving joint loading effects directly from physics-based simulations, the framework addresses limitations of applying separate fragility models to each hazard. Finally, stratified sampling is employed to improve computational efficiency and enable robust estimation of building- and community-level risk.

***Keywords:*** *Hurricane; Community risk; Multi-hazards; CFD; Hydrodynamic simulation, Stratified sampling*

## 1. INTRODUCTION

Hurricanes pose severe threats to coastal communities through the concurrent actions of extreme winds and storm surges. Accurate risk assessment is essential for guiding resilient design, retrofit prioritization, and mitigation planning. Yet many community-scale approaches still treat wind and water hazards independently, estimating damage probabilities for each hazard separately. Although recent studies have begun to address multi-hazard resilience by considering the joint occurrence of hazards (Nofal et al., 2021), several limitations remain when high-fidelity, building-specific damage estimation is required.

A central limitation is the widespread reliance on generalized fragility-curve databases. These curves are typically developed for broad building classes and may not represent the vulnerability of individual structures within real neighborhoods. Building geometry and spatial configuration can significantly alter local wind pressures through shielding, channeling, and turbulence, producing demands that differ from those implied by database-driven methods (Kim et al., 2024; Abdelhady et al., 2020). Moreover, applying separate fragility functions for wind and flood neglects physical interactions between hazards. Simultaneous wind loading and hydrodynamic actions can trigger coupled failure mechanisms—such as envelope breaches that change internal pressurization or accelerate water ingress—that are not captured when hazards are assessed in isolation (Masoomi et al., 2020).

To address these gaps, this study proposes a high-fidelity, community-scale multi-hazard risk assessment framework that couples wind and water effects at both the loading and damage-evolution levels. A realistic 3D model of the target community is constructed to capture building-specific geometric characteristics and proximity. Large Eddy Simulation (LES)-based computational fluid dynamics (CFD) is used to resolve complex urban wind flows, while hydrodynamic simulations quantify storm-surge and flooding actions. Together, these simulations provide time-dependent wind and water pressures on building components, enabling direct evaluation of coupled loading effects. Finally, a stratified-sampling strategy is employed to propagate uncertainty efficiently across hurricane scenarios, producing rigorous probabilistic estimates of building- and community-level risk with manageable computational cost.

## 2. METHODOLOGY

The proposed multi-hazard risk assessment framework integrates data-driven community modeling with high-fidelity physics-based simulations to evaluate the combined effects of wind and water hazards on coastal communities. As illustrated in Figure 1, the workflow consists of three primary stages: (1) high-resolution 3D community modeling, (2) micro-scale multi-hazard simulation driven by macro-scale hurricane scenarios, and (3) component-level damage assessment considering hazard interactions.

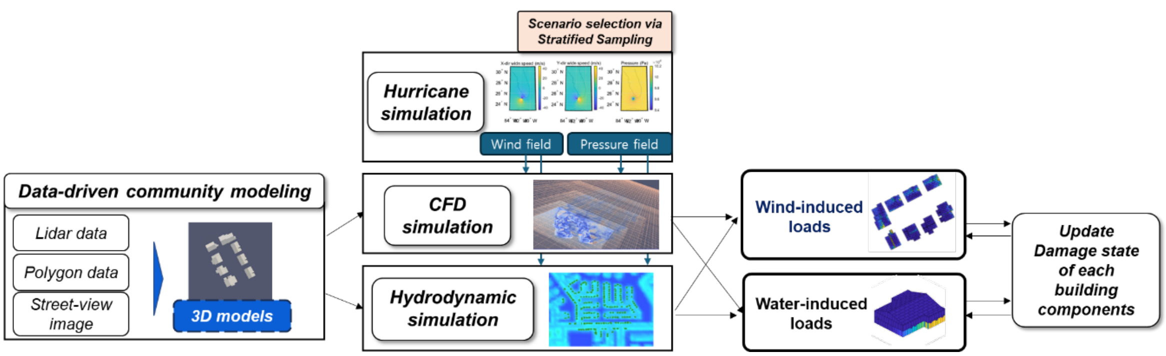


Figure 1. Proposed high-fidelity multi-hazard risk assessment framework.

### 2.1. Data-driven community modeling

To address the limitations of generalized fragility curves which often neglect building-specific geometric characteristics and shielding effects, a high-fidelity 3D model of the target community is constructed. Lidar point cloud data and GIS polygon data are utilized to extract precise building footprints and heights. Furthermore, street-view imagery is processed to identify detailed features such as shape and location of windows and doors. This detailed geometric representation is crucial for capturing the complex aerodynamic wake interference and local channeling effects of floodwaters that occur in dense residential areas.

### 2.2. Hazard simulation

To balance fidelity and computational cost, wind and water hazards are modeled using different strategies. For wind, running LES-CFD at every hurricane time step is prohibitive, so an aerodynamic database is constructed: high-fidelity LES is performed for representative wind directions (e.g., 15°–30° intervals) to obtain surface pressure coefficients $C_p$ for all buildings. Time histories of wind loads are then synthesized by combining these $C_p$ fields with the time-varying wind speed and direction from the macro-scale hurricane wind model. For water, scenario-specific high-resolution hydrodynamic simulations are conducted to resolve surge propagation and provide time-dependent water levels and velocities for computing hydrostatic and hydrodynamic loads.

### 2.3. Multi-hazard interaction and risk assessment

Multi-hazard interaction is modeled dynamically at the component level. The framework tracks how the relative contribution of wind and water loads changes with the instantaneous submerged ratio (flood depth) of each building. Component failure caused by either hazard can create openings, which immediately cause internal pressurization and water ingress. These couplings require a time-stepping scheme in which component damage states are updated at each step and fed back into the load calculations for the next step.

Community risk is quantified within an enhanced stratified sampling framework. Hurricane scenarios are divided into $m$ strata, $S_k$ for $k = 1,\ldots,m$, with probabilities $P(S_k)$, and $N$ samples are generated per stratum. For building $i$ and component $q$, damage occurrence in sample $j$ of stratum $k$ is represented by an indicator $D_{kj}^{iq}$ (1 if damage occurs, 0 otherwise). The component failure probability is estimated as:

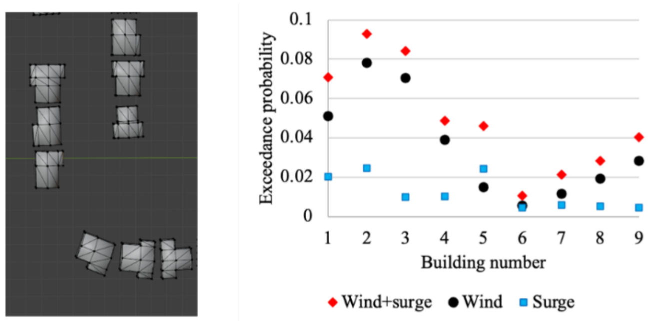
$$p_f^{iq} = \sum_{k=1}^{m} \left( \frac{1}{N} \sum_{j=1}^{N} D_{kj}^{iq} \right) P(S_k) \tag{1}$$

Aggregating component outcomes yields building- and community-level risk metrics.

## 3. APPLICATION STUDY

The proposed multi-hazard risk assessment framework was applied to a case study in Marco Island, Florida (FL), a coastal community highly exposed to hurricane winds and storm-surge flooding. The modeled domain covers an approximately 1 km radius and includes more than 100 residential buildings. Nine representative buildings near the center of the domain were selected as the primary targets for detailed assessment. The remaining buildings were retained to represent proximity effects (e.g., aerodynamic interference and flow diversion) and potential sources of wind-borne debris. Figure 2(a) presents the 3D geometric models of the nine target buildings, emphasizing the building-specific geometry and spacing that influence local hazard intensity and loading.

Figure 2(b) compares the building-level exceedance probability of Damage State 3 (DS3) across the nine buildings under the probabilistic hurricane scenarios considered, reporting results for wind-only, surge-only, and coupled wind and surge assessments. Two key observations emerge. First, the DS3 exceedance probability varies substantially by building, indicating pronounced spatial heterogeneity in damage risk even within a compact neighborhood. This variability is attributed to proximity effects that modify local wind pressures and surge propagation, as well as differences in relative elevation and exposure that influence the balance between wind- and inundation-driven demands. Second, the coupled wind and surge case yields markedly different results from those obtained by considering wind or surge in isolation. In most buildings, the coupled assessment produces higher DS3 exceedance probabilities than either single-hazard case, highlighting that independent evaluations can underestimate damage likelihood when hazards co-occur and interact. Overall, the case study demonstrates that explicitly resolving geometry, proximity, and coupled wind–water loading is essential for producing physically realistic building-level damage exceedance estimates and credible community-scale risk metrics.




(a) (b)

Figure 2. Wind- and water-driven component failure probabilities for nine buildings.

## 4. CONCULSIONS

This study proposed a high-fidelity, community-scale hurricane risk assessment framework that explicitly couples wind and storm-surge hazards at the building-component level. A realistic 3D community model was used to capture geometry and neighborhood proximity effects, while wind demands were synthesized from an LES-based aerodynamic database and water demands were obtained from scenario-specific hydrodynamic simulations. A time-stepping damage-update scheme enabled interaction effects, allowing damage evolution to feed back into subsequent load calculations. Stratified sampling provided computationally efficient probabilistic risk estimation and supported loss exceedance metrics. The application study showed strong building-to-building variability in DS3 exceedance driven by location, exposure, and proximity, and demonstrated that coupled wind and surge assessment can differ substantially from single-hazard results. Overall, the framework improves physical realism and interpretability for resilience planning.

**ACKNOWLEDGEMENTS**

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