

Investigation of the Wind-borne Debris Regions in ASCE 7-22, Phase II

Draft Final Report

Florida Department of Business and Professional Regulation

Florida Building Commission

and

Engineering School of Sustainable Infrastructure and Environment (ESSIE)

University of Florida (UF)

Project Leader: Jennifer A. Bridge, Ph.D.

jennifer.bridge@essie.ufl.edu

May 22, 2026

Executive Summary

The Florida Building Commission initiated this study to inform potential refinements to the Wind-Borne Debris Region (WBDR) definition for consideration in future revisions of the Florida Building Code (FBC). The study seeks to determine whether inland residential areas adjacent to large open-water bodies that produce Exposure D wind conditions should be designated as WBDRs when basic design wind speeds range from 130 to 139 mph, and, if so, the inland distance over which such designation should apply. Because WBDR designation triggers enhanced building-envelope protection requirements, any modification to WBDR boundaries must be supported by technically defensible evidence demonstrating comparable WBD risk.

This investigation was conducted by the University of Florida in collaboration with Applied Research Associates, Inc. (ARA). Phase I assessed relative WBD risk through literature review, historical storm damage data, and physics-based simulation of debris generation and impacts within representative residential neighborhoods.

Hurricane damage assessment reports demonstrate that WBD damage occurs at wind speeds well below 140 mph, regardless of exposure conditions and distances from the coast. Based on the widespread WBD damage observed following Hurricane Charley (2004), the FEMA Mitigation Assessment Team report recommended that 120 mph would be an appropriate threshold wind speed for the designation of WBDRs. Observations of WBD damage following Hurricane Michael (2018) highlighted that it can occur well beyond one mile of the coast, indicating that wind speed is a dominant factor in the generation of damaging WBD. These damage assessments support lowering the WBDR threshold wind speed below the current ASCE 7 level of 140 mph, and removing proximity to the coast (or any large water body creating an Exposure D condition) as a factor in the designation.

Design-level hurricane events are, by definition, rare. For a 700-year mean recurrence interval (the basis for the design wind speed maps for Risk Category II buildings) there is less than a 7% probability that one will occur over 50 sequential years. There has been only one event approaching design level in the central region of Florida with wind speeds between 130 and 139 mph in over 100 years. As a result, simulation using a validated model produced by ARA was used to compare the risk for WBD damage when houses are subject to wind speeds from 130 to 139 mph and have terrain exposures associated with proximity to large water bodies to the risk for WBD damage in conditions that are already accepted in ASCE 7 to designate WBDR: 140 mph wind in Exposure B conditions.

The simulation-informed findings of Phase I indicated that debris-impact risk under Exposure D at 130–139 mph is approximately equivalent to the WBDR benchmark (140 mph in Exposure B), when buildings are located within 3,000 ft from the water line in both exposure conditions. These findings were based on an idealized neighborhood representation and limited observational data, necessitating further analysis to support potential code decisions.

Phase II built upon Phase I analytical framework by incorporating improved neighborhood representation and refined modeling to provide a more robust technical basis for evaluating inland WBDR designation. The HURMis model, a validated, physics-based debris simulation model, was

applied to a 1,000 ft-by-1,000 ft parcel-level representation of the residential neighborhood surrounding Lake Louisa to establish a baseline methodology for consistent application across the additional neighborhoods identified in Phase I of the project. The modeling incorporates realistic building spacing, construction characteristics, and directionally dependent terrain roughness derived from land-cover data.

When neighborhoods are adjacent to large bodies of water that create Exposure D conditions (>5,000 ft of fetch in the upwind direction), the smoother terrain results in higher wind speeds that can impact the generation and transport of WBD. As the distance from the Exposure D condition increases, the terrain roughness increases and wind speeds are reduced. The terrain conditions surrounding 30 Florida neighborhoods located on large inland and coastal water bodies were evaluated to assess the difference between coastal, inland bay, and inland lake proximity. When the direction of the smoothest upwind condition is considered, there are no noticeable differences in the surface roughness controlling wind design between inland and coastal neighborhoods. Furthermore, the terrain roughness increases similarly with distance from the waterline for both coastal and inland neighborhoods. The resulting conclusion is that the distinction of a “coastal” condition should not be used in the definition of a WBDR.

The HURMis model was employed to determine the distance from the waterline that the risk for WBD damage was equivalent to the accepted WBDR with 140 mph Exposure B conditions. This risk equivalency approach was used to determine the appropriate WBDR boundary from large water bodies that create Exposure D conditions. The simulation approach specific to Phase II is summarized as follows:

- Model a 1,000 ft x 1,000 ft neighborhood on Lake Louisa with 81 relatively densely spaced houses, featuring a mix of one- and two-story homes and various roof types.
- Use a larger neighborhood (195 houses) to generate debris (from failing upwind houses), while still only counting debris hits in the central 81-house neighborhood.
- Screen the debris hits to only count those that result in glazing and door damage and scale the results by the fraction of the wall area associated with fenestration to get a more accurate count of damaging WBD hits.
- Place the neighborhood at different distances from the water in each of the 30 neighborhood locations (i.e. creating varying surface roughness conditions) and subject it to 130 mph and 139 mph winds at three different wind angles.
- Extract the mean of the window-breaking hits for each location and wind angle.
- Divide the mean window-breaking hits for each subject location and wind angle by the mean window-breaking hits for the neighborhood subject to 140 mph, Exposure B conditions at three different wind angles.
- Use the ratio of subject-to-threshold mean window-breaking hits to evaluate WBD risk equivalency: A ratio > 1 means the condition (wind speed, surface roughness, and wind angle) results in risk higher than the accepted WBDR threshold.
- Determine the distance from the water at which most of the conditions result in a ratio < 1 and use this distance to establish the WBDR boundary from the waterline.

- Evaluate how this WBDR boundary changes for different neighborhood housing characteristics (e.g., roof material, roof shape, and density) to determine if the WBDR boundary changes.

The result of this modeling process confirmed that an appropriate boundary for designating WBDR in proximity to large water bodies creating an Exposure D condition is 3,000 ft when design wind speeds range from 130 – 139 mph. This modeling also demonstrated that the coastal versus inland variants of Exposure D designation is not a meaningful distinguishing factor in WBD damage risk. Additional conclusions demonstrate that while roof type, roof shape, and housing density all impact WBD risk, when normalized by the amount of potential WBD damage in the same neighborhood configuration subject to 140 mph Exposure B, the differences become negligible at the 3,000-ft boundary.

An analysis of all 30 neighborhoods in this study shows that there are small differences in the house spacing, roof material, and number of stories between coastal and inland neighborhoods when evaluated in aggregate, but not of a magnitude or consistency to warrant their consideration in the evaluation of relative WBD damage risk. This is especially true given that the relative risk for WBD damage becomes negligible at the 3,000 feet boundary for all neighborhood housing characteristics.

The recommendations based on the results of both phases of this study are:

- Based on evidence and recommendations from hurricane damage assessments, consider a blanket WBDR threshold of 130 mph.
- If there is a preference to use the current WBDR definition to establish acceptable WBD damage risk, then regions within 3,000 ft of a body of water creating an Exposure D condition should be designated as WBDR when the basic wind speeds are between 130 and 139 mph.
- Regardless of the threshold established for designating a WBDR, it should not be specifically referenced to the coast but rather to exposure conditions.
- Additional research in the form of targeted WBD hurricane damage assessments, wind tunnel studies to evaluate the impact of terrain transitions on wind loads, and advanced modeling to evaluate absolute WBD risk is recommended.

Table of Contents

Executive Summary	ii
Table of Contents	v
1 Introduction.....	1
1.1 Background.....	1
1.2 Tasks and Objectives.....	2
2 Historical Storm Data	2
2.1 Design Level Windspeed, Exposure, Mean Recurrence Interval (MRI)	2
2.2 Historical Storm Reports.....	5
2.2.1 Hurricane Charley (2004)	6
2.2.2 Hurricane Harvey (2017)	7
2.2.3 Hurricane Michael (2018).....	8
2.2.4 Hurricane Ian (2022).....	9
2.3 Imagery Analysis	10
3 Debris Modeling	13
3.1 HURMis Model	13
3.1.1 Description.....	13
3.1.2 Modeled Wind Loads.....	14
3.1.3 Missile Transport Model	17
3.1.4 Validation	17
3.1.5 Model Improvements Validation.....	21
3.2 Overview of Phase I Modeling	22
3.2.1 Florida Neighborhoods	23
3.2.2 Directional Z0	23
3.2.3 Modeled Neighborhood	24
3.2.4 Summary of Phase I Results	25
3.3 Phase II Modeling	26
3.3.1 Neighborhood Characteristics.....	26
3.3.2 Analysis of WBD Risk.....	33
3.3.3 Neighborhood Modeling.....	36
3.4 Analysis Results.....	42
3.4.1 Coastal vs. Inland Comparisons: Similar Relative Risks.....	44

3.4.2	Sensitivities	49
4	Impact of Neighborhood Characteristics	71
5	Conclusions and Recommendations	71
5.1	Recommendations.....	73
6	References.....	74
7	Appendix A: Representativeness Analysis.....	77

List of Figures

Figure 1. Estimated extent of WBDR in ASCE 7-22. Light blue represents areas between the 130 and 140 mph contours estimated by ARA to be within the WBDR as defined in ASCE 7-22.....	4
Figure 2. Tracks of hurricanes with maximum winds exceeding Category 3 that have passed through the lake region in central Florida in the past 105 years. The ASCE 7-22 Risk Category II wind map contours for 130 and 140 mph, respectively, are as indicated. (NOAA Historical Hurricane Tracks)	5
Figure 3. Windows damaged by aggregate at a hospital in Arcadia (inland). Estimated wind speeds between 110-120 mph. (FEMA, 2005)	7
Figure 4. Missile impact damage to roll down shutter, located on an inland bay 10 miles from the coast (left) and glazing damage 5 miles from the coast on inland bay. The estimated wind speed was 120 mph (Exposure C). (FEMA, 2019).....	8
Figure 5. Bank in Panama City with extensive glazing damage. The estimated wind speed was 126 mph. (FEMA 2020).....	8
Figure 6. WBD damage to windows in houses in Panama City. The estimated wind speeds were 128 mph (left) and 134 mph (right). (FEMA, 2020).....	9
Figure 7. WBD damage to glazing in St. James City (on an inner barrier island in Lee County). The estimated wind speed was 114 mph. (FEMA, 2023).....	9
Figure 8. Low resolution post-storm aerial imagery showing residential building damage and scattered debris. (NOAA National Geodetic Survey, 2017)	10
Figure 9. Low resolution pre (left) and post-storm (right) satellite imagery showing damage to buildings near inland water bodies with scattered debris. (NASA Earth Observatory, 2004)	11
Figure 10. Post-storm aerial imagery with debris obscuration caused by complex background surface conditions. (Li et al., 2024)	11
Figure 11. Visual occlusions from streetscape elements. (Li et al., 2024).....	12
Figure 12. Schematic of HURMis model	14
Figure 13. Roof zones for wind loads for gable roof.....	15
Figure 14. Roof zones for wind loads for hip roof	16

Figure 15. Roof GCp as a function of wind direction and roof zone for gable roofed buildings with a slope of 4:12.....	16
Figure 16. Roof GCp as a function of wind direction and roof zone for hip roofed buildings with a slope of 4:12.....	17
Figure 17. Missile characteristics and source location for case 2.....	20
Figure 18. Experimental configuration for shingle and tile experiments at UWO (ARA, 2008).	22
Figure 19. Comparison simulated shingle debris for shingle and tile experiments at UWO (ARA, 2008)	22
Figure 20. Cumulative distribution of minimum average directional surface roughness length, Z0. ASCE 7-22 , Z0 ranges are shaded for reference.	24
Figure 21. Plan view of the phase I modeled neighborhood.....	25
Figure 22. Roof material type distribution for the coastal neighborhoods	28
Figure 23. Roof material type distribution for the inland neighborhoods	28
Figure 24. Average of roof material type for coastal and inland neighborhoods.....	29
Figure 25. Story distribution for the coastal neighborhoods.....	29
Figure 26. Story distribution for inland neighborhoods.....	30
Figure 27. Average number of story distribution for coastal vs inland neighborhoods	30
Figure 28. Nearest neighbor edge-to-edge spacing between building footprints for coastal neighborhoods.....	31
Figure 29. Nearest neighbor edge-to-edge building spacing for inland neighborhoods.....	32
Figure 30. Impact of impact energy screening on the CDF relative mean hits at origin and offset distances for 30 locations based on 130 mph reference wind speed.....	35
Figure 31. Impact of impact energy screening on the CDF relative mean hits at origin and offset distances for 30 locations based on 139 mph reference wind speed.....	36
Figure 32. Google Map view of Lake Louisa neighborhood.....	37
Figure 33. 2D representation of the Lake Louisa model	38
Figure 34. 2D Lake Louisa expansion neighborhood sensitivities models	39
Figure 35. $\bar{\lambda}w$ for expanded neighborhood compared to $\bar{\lambda}w$ for the base neighborhood	40
Figure 36. Relative $\bar{\lambda}w$ compared to the next smallest neighborhood.....	41
Figure 37. Final modeled Lake Louisa neighborhood with expansion 2 WBD sources	42

Figure 38. CDF of λ_R at origin and offset distances for 30 locations with reference windspeed 130 mph.	43
Figure 39. CDF of λ_R at origin and offset distances for 30 locations with reference windspeed 139 mph.	44
Figure 40. Reclassified neighborhood locations from coastal to inland.....	45
Figure 41. CDF of λ_R at origin and offset distances based on 130-mph design wind speed for coastal locations.....	46
Figure 42. CDF of λ_R at origin and offset distances based on 130-mph design wind speed for inland locations.....	47
Figure 43. CDF of λ_R at origin and offset distances based on 139-mph design wind speed for coastal locations.....	48
Figure 44. CDF of λ_R at origin and offset distances based on 139-mph design wind speed for inland locations.....	49
Figure 45. Comparison of λ_R at origin and offset distances for 30 locations for 130 mph design wind speed for tile and shingle roof coverings.....	51
Figure 46. Comparison of λ_R at origin and offset distances for 30 locations for 139 mph design wind speed for tile and shingle roof coverings.....	51
Figure 47. λ_R versus Z_0 for 130 mph design wind speed.....	53
Figure 48. λ_R versus Z_0 for 139 mph design wind speed.....	54
Figure 49. CDF of λ_R at origin and offset distances based on 130-mph design wind speed for inland locations.....	55
Figure 50. CDF of λ_R at origin and offset distances based on 130-mph design wind speed for coastal locations.....	55
Figure 51. CDF of λ_R at origin and offset distances based on 130-mph design wind speed for inland locations.....	56
Figure 52. CDF of λ_R at origin and offset distances based on 139 mph design wind speed for coastal locations.....	57
Figure 53. CDF of λ_R at origin and offset distances based on 139 mph design wind speed for inland locations.....	58
Figure 54. Sensitivity neighborhoods.....	59

Figure 55. Comparison of λ_w for Mexico Beach by relative wind direction for three distances moving inland from the origin	61
Figure 56. Comparison of λ_R for Mexico Beach by relative wind direction for three distances moving inland from the origin	62
Figure 57. Ratio of gable λ_R to hip λ_R at the origin for a reference wind speed of 139-mph for the selected neighborhoods	63
Figure 58. Ratio of gable λ_R to hip λ_R at 3,000 ft offset from the origin for a reference wind speed of 139-mph for the selected neighborhoods.....	63
Figure 59. Low density model house layout.....	66
Figure 60. Expanded neighborhood for the low-density model.	67
Figure 61. Comparison of λ_w for Mexico Beach by relative wind direction for 3 distances moving inland from the origin for housing density	68
Figure 62. Comparison of λ_R for Mexico Beach by relative wind direction for 3 distances moving Inland from the origin for housing density	69
Figure 63. Ratio of high density λ_R to low density λ_R at the origin for a reference wind speed of 139-mph for the selected neighborhoods.....	70
Figure 64. Ratio of high density λ_R to low density λ_R at 4,000 foot offset from the origin for a reference wind speed of 139-mph for the selected neighborhoods.....	70
Figure 65 - One-mile study buffer for Lake Louisa with residential building polygons (yellow) and spatial quadrants (Q1–Q4) used in the representativeness analysis.....	78
Figure 66 - Percentage missing data for all neighborhoods.....	81
Figure 67 - Representativeness spider plot for all study neighborhoods showing standardized bias indicators.....	81
Figure 68 - Overall representative flag for the neighborhoods.....	82

1 Introduction

1.1 Background

In 2024, the Florida Building Commission initiated an evaluation to support potential refinements to the definition of wind-borne debris region (WBDR) for adoption in the 2026 Florida Building Code (FBC). The central question is whether inland areas adjacent to large lakes that create Exposure D wind conditions should be designated as WBDRs for basic design wind speeds of 130–139 mph, and if so, how far inland that designation should extend. Because WBDR designation requires enhanced building-envelope protection, including impact-resistant glazing or protective systems for exterior openings, any change to WBDR boundaries must be supported by technically defensible evidence showing that inland Exposure D regions pose a wind-borne debris (WBD) risk comparable to the established American Society of Civil Engineering (ASCE) statewide WBDR threshold.

In response to this regulatory need, a team from the University of Florida (UF) and Applied Research Associates, Inc. (ARA) conducted a multi-phase study to evaluate WBD risk in inland regions adjacent to large water bodies subject to Exposure D conditions and design wind speeds between 130 and 139 mph. Phase I evaluated WBD risk through a combination of literature review, historical storm damage assessments, and numerical simulation of debris impacts within representative residential neighborhoods. Results from this initial phase indicated that residential structures located near large inland water bodies under Exposure D conditions may experience WBD risk comparable to that associated with the established WBDR threshold of 140-mph design wind speed under Exposure B conditions. Initial simulation comparisons suggested that this equivalency occurs when homes are located within approximately 3,000 ft of the shoreline, providing a preliminary basis for considering inland WBDR designation and setback distance. In addition, when the upwind direction with the lowest surface roughness is considered for a building site, the risk for impacts from WBD are the same for coastal and inland regions.

The second phase of this research was initiated to further establish the scientific basis for WBDR definitions in Florida, with a focus on a more in-depth analysis of observational evidence of inland WBD damage following design-level storm events, and a more refined and representative modeling framework that accounts for a range of neighborhood characteristics. The objective of Phase II is to provide a more robust analysis to determine whether inland Exposure D conditions produce WBD risk equivalent to that associated with the established 140-mph WBDR threshold defined in ASCE 7-22 and to inform potential decisions regarding inland WBDR designation and appropriate setback distances from large inland water bodies. To achieve this objective, Phase II work was structured into the tasks and deliverables described in section 1.2.

1.2 Tasks and Objectives

- Task 1: Data Collection and Analysis

The objective of Task 1 is to collect data from published, post-storm imagery to assess the generation and transportation of WBD relative to wind field and upwind terrain conditions for storm events with overland wind speeds between 130 and 140 mph.

- Task 2: Damage Assessment

The objective of Task 2 is to assess WBD generation and resulting damage in neighborhoods adjacent to Exposure D conditions following a hurricane and to document the distances from the waterline over which debris damage is observed.

- Task 3: WBD modelling

The objective of Task 3 is to refine the stochastic WBD model developed in the first phase of this research to account for variation in neighborhood makeup and to validate simulation results with debris damage observations.

2 Historical Storm Data

Several agencies, including the Federal Emergency Management Agency (FEMA) and the National Oceanic and Atmospheric Administration (NOAA), document hurricanes that make landfall in the United States. Although many of these storms produce damaging winds, relatively few generate wind speeds that approach or exceed ASCE 7 design-level wind speeds at the locations where damage is assessed.

Although design-level events are rare, historical storm events for which damage was documented provide the opportunity to correlate observed damage with the wind speeds measured or estimated at the same location. For this project, the objective of reviewing historical damage reports was to evaluate the wind speeds at which WBD damage is observed and, if possible, assess whether inland regions near bays and lakes have a higher risk for WBD damage than areas with less open exposure. Historical storm events were selected for review based on their relevance to current inland WBDR design considerations, with emphasis on storms that produced estimated wind speeds in the 130–140 mph range. This range closely aligns with the regulatory threshold being evaluated for potential inland WBDR designation. The following subsections discuss design-level wind speeds and their statistical likelihood of occurrence, summarize historical storms that reached or exceeded design-level conditions, and discuss the limitations of using post-storm imagery to trace WBD from source locations to points of impact.

2.1 Design Level Windspeed, Exposure, Mean Recurrence Interval (MRI)

According to ASCE 7 (ASCE, 2022), design-level wind speed refers to the basic wind speed used for determining wind loads on buildings and other structures. It is a probabilistic wind hazard parameter expressed as a 3-second gust 33 ft above ground in Exposure C terrain, rather than a direct measure of hurricane sustained wind speed at landfall.

The effect of terrain on design wind speeds and resulting pressures is represented in ASCE 7 by Surface Roughness categories (Table 1), which are, in turn, used to determine the Exposure Category (Table 2). Lower surface roughness is represented by lower roughness length values (Z_0) and results in higher wind loads.

Table 1. ASCE 7-22 Surface roughness categories

Surface Roughness	ASCE 7-22 Description
B	Urban and suburban areas, wooded areas, or other terrain with closely spaced obstructions that have the size of single-family dwellings or larger
C	Open terrain with scattered obstructions that have heights generally less than 30 ft. Includes flat, open country and grasslands.
D	Flat, unobstructed areas and water surfaces. Includes smooth mud flats, salt flats, and unbroken ice.

Table 2. ASCE 7-22 Exposure categories

Exposure Category	Abbreviated ASCE 7-22 Description	ASCE 7-22 Roughness Length, Z_0 (m) range
B	Surface Roughness B prevails in the upwind direction for at least 1,500 ft.	0.15 – 0.7
C	Where Exposure B and D do not apply	0.01 – 0.15
D	Surface Roughness D prevails in the upwind direction for at least 5,000 ft.	< 0.01

Figure 1 shows the basic wind speed map adapted from ASCE 7-22 for Risk Category II. In both ASCE 7 and FBC 2026, any region with basic wind speeds above 140 mph are designated as WBDR and are shown shaded in blue. Between the contours that bound the 130-139 mph design wind speeds, the inland WBDR resulting from the definition in ASCE 7-22 are indicated. These are regions within one mile of Exposure D condition.

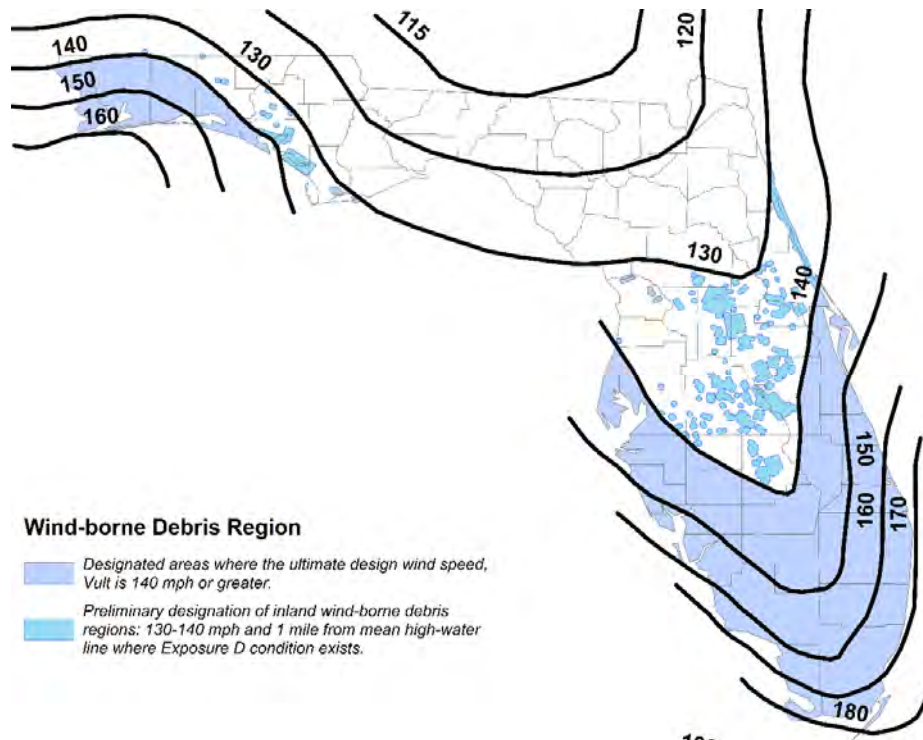


Figure 1. Estimated extent of WBDR in ASCE 7-22. Light blue represents areas between the 130 and 140 mph contours estimated by ARA to be within the WBDR as defined in ASCE 7-22.

The statistical basis for the basic wind speeds is the Mean Recurrence Interval (MRI). For ordinary buildings (e.g. residential) classified as Risk Category II, ASCE 7 uses a 700-year recurrence interval wind speed. Lower-risk structures use a 300-year wind speed, while higher-consequence structures use longer return periods of 1700 years for Risk Category III and 3000 years for Risk Category IV. An MRI does not mean that the wind event will occur exactly once every 700 years. Rather, it means that, in any given year, there is approximately a 1/700 probability, or approximately 0.14% annual chance, that the mapped design wind speed will be exceeded. Over a typical 50-year residential building life, this corresponds to roughly 6.9% chance of exceedance. This probability illustrates that design-level wind speeds represent rare, high-consequence wind events rather than routinely observed storm conditions. Consequently, only a small subset of historical hurricanes is expected to produce winds that approach or exceed these design-level values at a given location.

Figure 2 shows the tracks of major hurricanes that have passed over central Florida in the last 105 years. Only Hurricane Charley (2004) had estimated wind speeds that even approached design levels (e.g., the high estimate near Zolfo Springs for Exposure C was 130 mph (FEMA, 2005)). No other recorded storms reached ASCE 7-22 design wind speeds for Risk Category II buildings between the 130 and 140 mph contours.

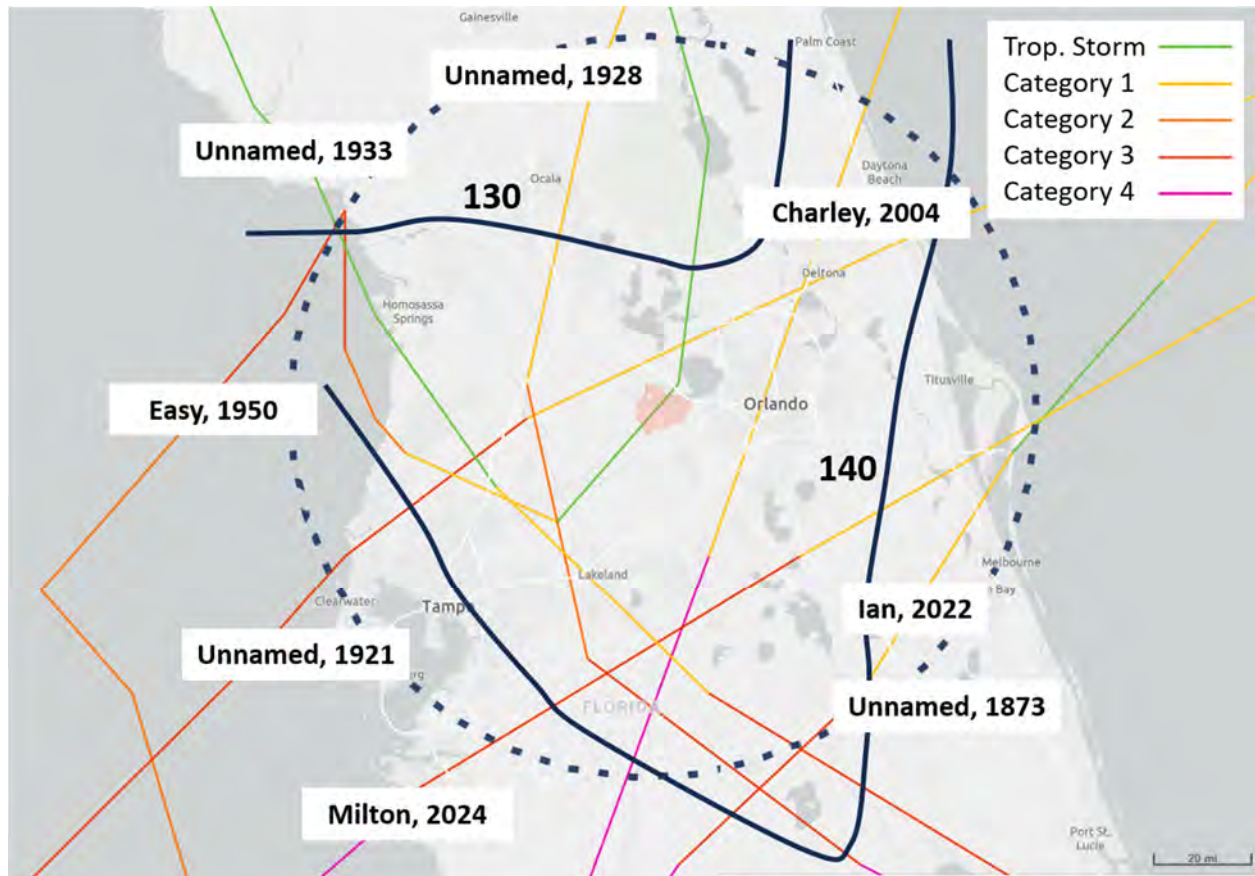


Figure 2. Tracks of hurricanes with maximum winds exceeding Category 3 that have passed through the lake region in central Florida in the past 105 years. The ASCE 7-22 Risk Category II wind map contours for 130 and 140 mph, respectively, are as indicated. (NOAA Historical Hurricane Tracks)

2.2 Historical Storm Reports

Historical storm observations provide useful evidence that WBD damage is governed by wind intensity, terrain exposure, debris availability, and building vulnerability, rather than by distance from a coastal or inland Exposure D boundary alone. Post-hurricane damage assessments have shown that debris-related glazing damage can occur well beyond conventional WBDR limits when local wind speeds and at wind speeds as low as 115 mph.

Because design-level wind speeds correspond to rare, low-probability events, as discussed in Section 2.1, only a limited number of historical storms are expected to produce conditions severe enough to generate comparable WBD damage at a specific inland lake location. We have not identified post-storm reports documenting WBD damage during design-level wind events in inland areas with lake-related Exposure D conditions and wind speeds between 130 and 139 mph, as there has only been one event in over 100 years that generated winds approaching 130 mph in the region (Hurricane Charley in 2004). Damage assessments are generally intended to provide representative observations of building performance rather than comprehensive documentation of all affected

locations, and they are often prioritized toward coastal landfall areas, heavily damaged regions, infrastructure impacts, or broad building-performance patterns. As a result, available reports do not provide the detailed information needed to isolate lake-related WBD effects, including debris source, debris path, opening type, site-specific exposure, distance from the water body, and local wind speed at the damaged structure. Therefore, the absence of extensive lake-adjacent WBD observations should not be interpreted as evidence of negligible hazard; rather, it reflects both the low likelihood of observing design-level wind conditions at a specific inland lake location and the limited scope of available post-storm documentation.

While WBD damage data adjacent to lakes during design level wind events is not available, historical storm reports do provide evidence of the wind speeds at which such damage occurs, in coastal regions and inland, across a range of Exposure Categories. Damage assessment reports from four hurricanes demonstrate that WBD damage to glazing occurs when wind speeds are lower than 140 mph.

2.2.1 Hurricane Charley (2004)

Estimated wind speeds from Hurricane Charley at different locations as the storm moved inland are shown in Table 3 (FEMA, 2005).

Table 3. Estimated wind speeds during Hurricane Charley as it travelled across Florida in the northeast direction (FEMA, 2005)

Location	Estimated Wind Speeds (mph)			
	Exp. B		Exp. C	
	Low	High	Low	High
Port Charlotte	125	140	140	160
Arcadia	110	120	125	140
Zolpho Springs	100	115	115	130
Lake Wales	95	110	110	125
Orlando	90	105	105	120

WBD damage was documented by the FEMA Mitigation Assessment Team (MAT) as far as 40 miles inland, in Arcadia, where 3-second gust wind speeds in Exposure B conditions were estimated at 110-120 mph (Figure 3). (FEMA, 2005).



Figure 3. Windows damaged by aggregate at a hospital in Arcadia (inland). Estimated wind speeds between 110-120 mph. (FEMA, 2005)

The FEMA MAT report for this storm noted:

“In addition, windborne debris caused significant envelope damage (and virtually all of the glazing damage) that the MAT observed where wind speeds from the event were thought to be 120 mph 3-second peak gust and greater.... Many homes and businesses that experienced only contents damage could have prevented these losses if their openings had been protected. Success in designing the structural frame to resist wind loads and internal pressures was negated by significant losses to building interiors and contents.” (FEMA, 2005).

2.2.2 Hurricane Harvey (2017)

WBD damage was reported following Hurricane Harvey from 120 mph gusts (Exposure C) on the coast as well as on the inland side of the bay (5-10 miles from the coast). While impact resistant windows and shutters mitigated some glazing damage, evidence of debris impacts to opening protections was still observed (Figure 4) (FEMA, 2019).



Figure 4. Missile impact damage to roll down shutter, located on an inland bay 10 miles from the coast (left) and glazing damage 5 miles from the coast on inland bay. The estimated wind speed was 120 mph (Exposure C). (FEMA, 2019)

2.2.3 Hurricane Michael (2018)

Extensive WBD damage was observed following Hurricane Micheal. In Panama City, a bank and several homes suffered significant glazing damage due to debris at wind speeds between 126 and 134 mph (Figure 5 and Figure 6). Notably, Panama City is located on the inland side of St. Andrew's Bay and therefore not directly on the coast. (FEMA, 2020).



Figure 5. Bank in Panama City with extensive glazing damage. The estimated wind speed was 126 mph. (FEMA 2020).



Figure 6. WBD damage to windows in houses in Panama City. The estimated wind speeds were 128 mph (left) and 134 mph (right). (FEMA, 2020)

The FEMA MAT report for Hurricane Michael concluded that: “*Damage to glazing is not limited to within the 1-mile area of the coast and can occur much farther inland.*” (FEMA, 2020).

2.2.4 Hurricane Ian (2022)

Hurricane Ian impacted southwest Florida near Fort Myers. While the coastal region impacted is in an established WBDR with a design wind speed of 160 mph, the measured and estimated wind speeds provide insight to the conditions that can result in WBD damage. Homes in this area are required to have opening protections; however, damage to glazing attributed to WBD was still observed, notably at an estimated wind speed of 114 mph. (FEMA, 2023)



Figure 7. WBD damage to glazing in St. James City (on an inner barrier island in Lee County). The estimated wind speed was 114 mph. (FEMA, 2023)

This field evidence from these four hurricanes indicates that WBD risk should not be evaluated solely as a function of distance from a coastline or inland water body. Factors such as wind speed, terrain exposure, debris-source characteristics, and the vulnerability of glazed openings can

influence debris risk. The results of these damage assessment reports support designating WBDRs where the basic wind speed is greater than 120 mph, regardless of Exposure category.

2.3 Imagery Analysis

The research team investigated image analysis methods that may provide further insights on the generation, trajectory, and impact of WBD to inform risk characterization. However, imagery analysis was limited by several constraints that reduced the chances of identifying and tracking WBD at the building scale. These constraints include the following:

- Image resolution, typically 15–30 cm ground sampling distance at zoom levels 19–20, was too low to reliably detect most building-scale WBD. Although these zoom levels (scale at which objects are viewed) allow roads, intersections, and medium-sized buildings to be viewed, they generally do not provide enough detail to identify smaller debris objects. As a result, observations were largely limited to larger debris, approximately 1–3 m in size or greater (See Figure 8-9).
- In urban environments, complex background surfaces such as pavement and vegetation reduce image contrast, while trees and other vegetation can physically obscure debris, making WBD difficult or impossible to distinguish from surrounding surfaces in aerial imagery (see Figure 10).
- Aerial images mostly show roofs and horizontal surfaces, while walls, windows, and areas under overhangs are hidden, making it difficult to see debris or resulting damage on buildings or areas beneath overhangs.
- Some images are restricted by maximum zoom levels set by original sensor resolution, reducing access to fine spatial detail.
- Discontinuity and temporal gaps in available imagery, hindering the ability to establish a continuous sequence linking debris generation, transport, and resulting damage.



Figure 8. Low resolution post-storm aerial imagery showing residential building damage and scattered debris. (NOAA National Geodetic Survey, 2017)



Figure 9. Low resolution pre (left) and post-storm (right) satellite imagery showing damage to buildings near inland water bodies with scattered debris. (NASA Earth Observatory, 2004)



Figure 10. Post-storm aerial imagery with debris obscuration caused by complex background surface conditions. (Li et al., 2024)

Prior studies incorporating machine learning and aerial imagery for debris assessment indicate that such imagery is generally more reliable for identifying debris zones or accumulation areas than for detecting and tracking individual debris objects, particularly smaller items at the building scale

(Jiang and Friedland, 2016; Womble et al., 2008; Cheng et al., 2024). Limitations related to spatial resolution, roof-dominant viewing angles, background complexity, and temporal gaps between image captures further constrain the ability to establish direct source-to-impact relationships linking debris generation, transport, and façade-level damage (Ghaffarian and Kerle, 2019; Winans et al., 2023).

Key constraints in street view images include the following:

- Street-level, post-storm imagery predominantly documents the street-facing elevations; consequently, damage on side and rear façades, where WBD impacts may also occur, are frequently unobserved.
- Visual occlusions from vegetation, parked vehicles, fencing, and other streetscape elements routinely obscure openings and potential debris sources, making it difficult to track WBD damage (see Figure 11)
- Image acquisition is restricted to roads that remain accessible following the event, resulting in uneven spatial coverage and the potential omission of critical WBD indicators in inaccessible blocks, dead-end streets, and interior parcels.



Figure 11. Visual occlusions from streetscape elements. (Li et al., 2024)

Some of these limitations are also acknowledged in prior research. For example, Zhai and Peng (2020) used Google Street View (GSV) imagery to assess damage from Hurricane Michael in Mexico Beach, Florida, following the 2018 landfall. They note that imagery is only available where Street View coverage exists and where roads remain accessible after an event, which can produce uneven spatial coverage and lead to omission of damage in areas that cannot be reached. Other limitations encountered in our study include rapid post-landfall debris removal and cleanup operations, which often eliminated physical evidence of WBD before ground-based documentation could be collected. In addition, available post-storm imagery was not taken with the intent to capture WBD; therefore, details needed for WBD identification or tracking were inadequately captured. Collectively, these limitations restrict the extent to which available post-storm imagery alone can be used to quantify WBD generation and transport and highlight the need for complementary approaches.

3 Debris Modeling

Validated simulation tools and statistical models are widely used to explore the likelihood and potential impacts of rare and extreme natural hazard events. Such tools underpin design standards and building codes and inform the insurance industry and policy making. In this project, modeling is used to evaluate the risk for WBD damage under a range of scenarios related to wind speed, terrain conditions, and neighborhood characteristics. The ability to comprehensively explore these scenarios when observational data is limited—as is the case with hurricane data—enables the development of rigorous conclusions on the risk of WBD damage.

The objective of the modeling was not to evaluate the general conditions that result in the generation of damaging WBD. Rather the objective was to evaluate the risk of WBD damage for houses near large water bodies (coast, lakes, inland bays) subject to 130 and 139 mph wind speeds *relative* to houses subject to the conditions in accepted WBDRs: 140 mph wind in Exposure B conditions. All conclusions of the simulations are provided within this relative risk framework.

The following sections provide a description of the modeling tool used in this research, an overview of the modeling objectives and results from the first phase of this research, and a detailed description of the modeling improvements and results from the second phase of this research.

3.1 HURMis Model

3.1.1 *Description*

The HURMis modeling tool was developed by ARA in the 1990s and early 2000s to simulate WBD trajectories and impacts in residential neighborhoods during hurricane events. The model uses a three-dimensional, physics-based simulation framework in which debris missiles generated from failed components of upstream structures are individually tracked by integrating their equations of motion. The resulting trajectories, impact locations, and impact characteristics are then evaluated for building envelopes and glazed openings. A schematic of the HURMis Model components is shown in Figure 12.

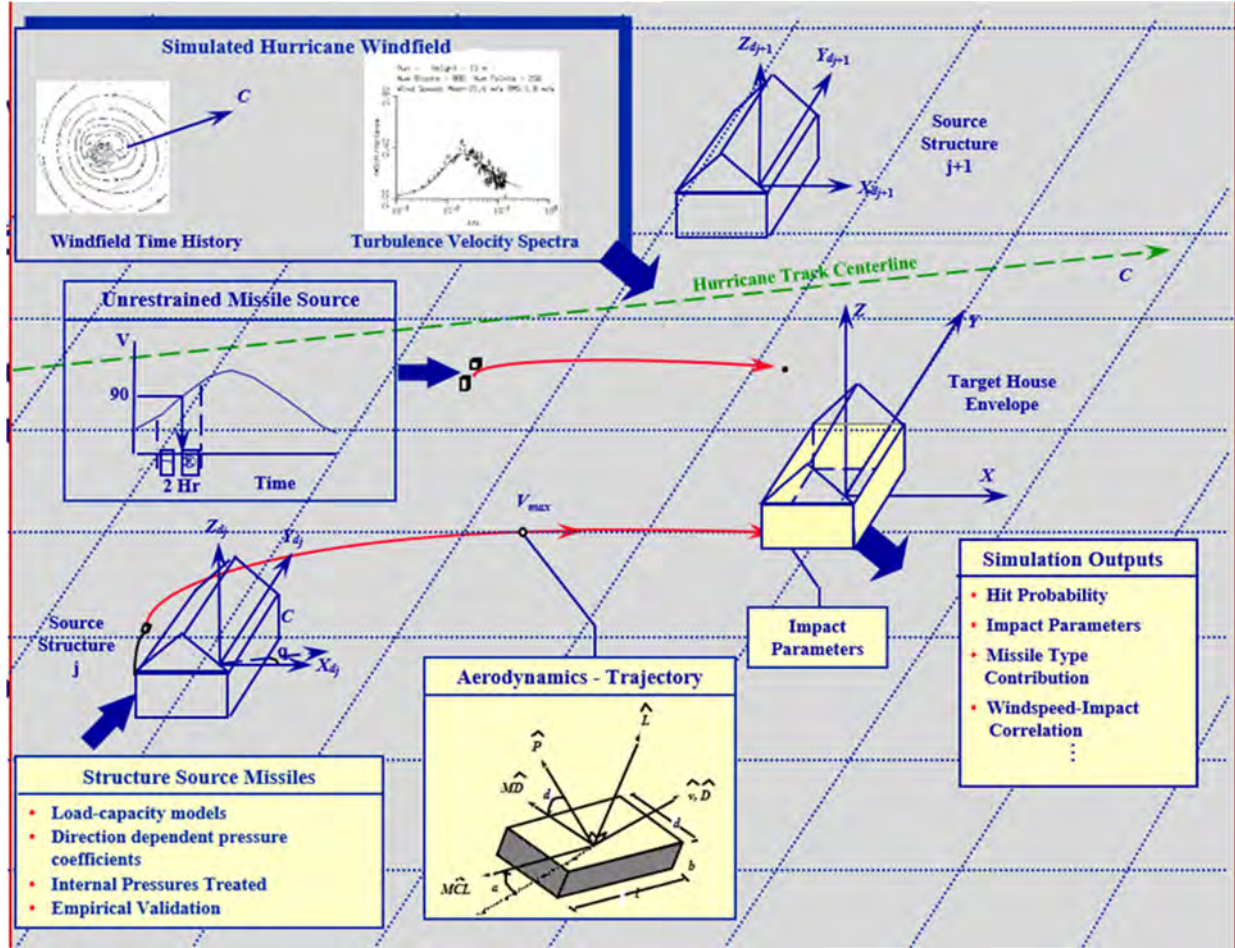


Figure 12. Schematic of HURMis model

3.1.2 Modeled Wind Loads

3.1.2.1 Mean Velocity Profile and Turbulence Modeling

In HURMis, the boundary layer wind field (in hurricane and straight-line winds) was modeled using established boundary layer formulations based on Engineering Sciences Data Unit (ESDU) methods. The approach assumes that, near the ground, the wind flow characteristics are primarily governed by the local surface roughness. For homogeneous terrain, the mean wind speed profile varies with height as a function of friction velocity and surface roughness length.

The turbulence characteristics were also modeled as height-dependent quantities. The longitudinal turbulence intensity was defined based on the mean wind speed, friction velocity, surface roughness, height above ground, and the Coriolis parameter. The vertical turbulence component was related to the longitudinal component, and the Reynolds stress parameter was evaluated using the turbulence components and boundary layer height. In addition to defining the vertical variation of mean wind speed and turbulence intensity, the simulation of boundary layer wind speed time histories requires a representation of the frequency content and spatial correlation of turbulence. These characteristics were incorporated through auto-spectral and cross-spectral density functions.

The spectral formulations used in the model were based on ESDU (1974a, 1974b) guidance and provide the necessary information to simulate correlated turbulent wind components for boundary layer flow.

3.1.2.2 Roof Pressure Coefficients

The pressure-coefficient models used in HURMis to model load for roof components are shown in Figures 13 to 16. Figures 13 and 14 show the roof zones for wind loads for gable and hip roofs respectively. Figures 15 and 16 show the roof pressure coefficient as a function of wind direction for one quadrant of a given roof shape for gable and hip roofs respectively. The roof zones and pressure-coefficient were developed using data from wind tunnel testing conducted at the University of Western Ontario (UWO). For gable-roof buildings, the GC_p values were derived using a combination of data reported in Stathopoulos (1979) and the methodology described in Vickery, Kopp, and Twisdale (2011). For hip-roof buildings, the GC_p values were developed using data from Meecham (1988), also following the procedures outlined in Vickery, Kopp, and Twisdale (2011).

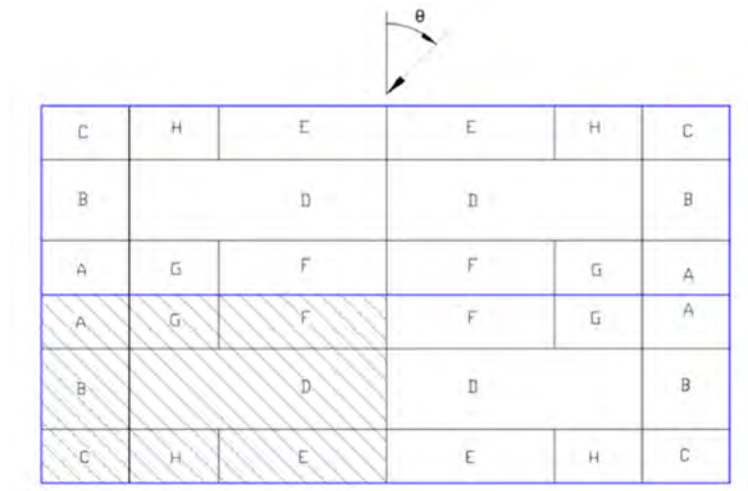


Figure 13. Roof zones for wind loads for gable roof

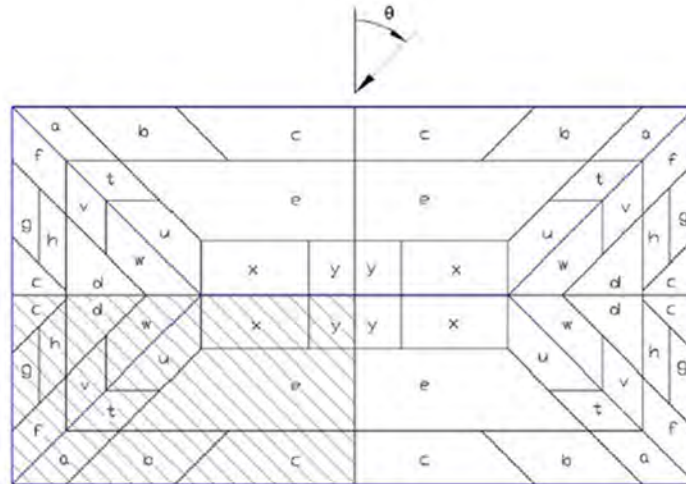


Figure 14. Roof zones for wind loads for hip roof

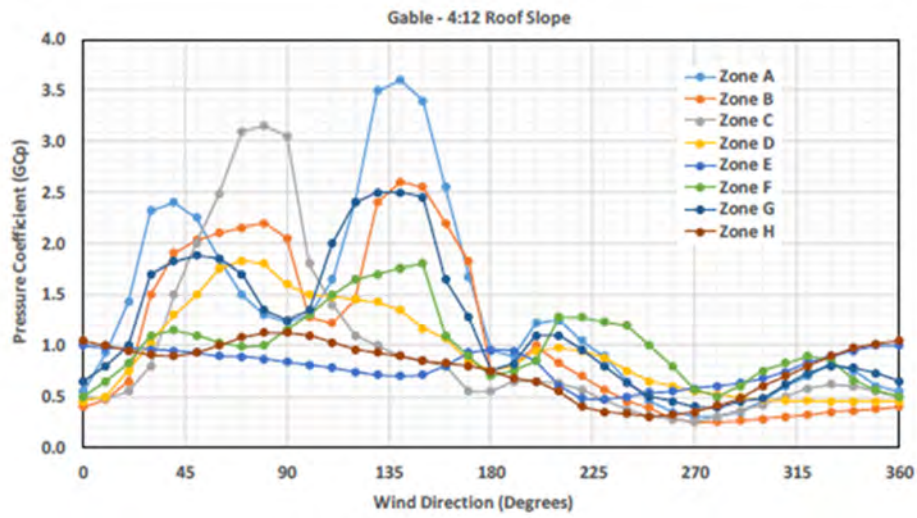


Figure 15. Roof GCp as a function of wind direction and roof zone for gable roofed buildings with a slope of 4:12

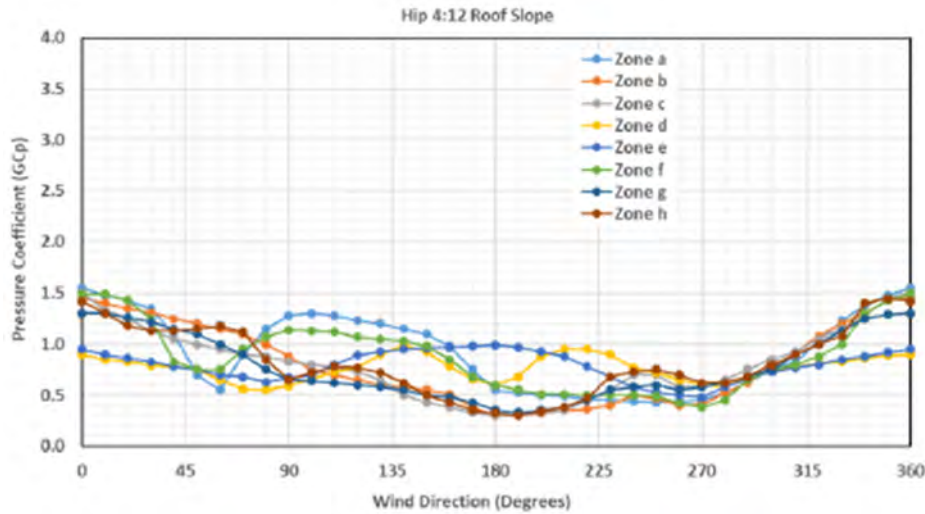


Figure 16. Roof GCp as a function of wind direction and roof zone for hip roofed buildings with a slope of 4:12

3.1.3 Missile Transport Model

The missile transport methodology consists of two main components: a missile trajectory model and a missile interaction model. The trajectory model uses the missile release or injection conditions as initial inputs, including the time of release, position, orientation, and initial velocity. Missile geometry and mass are also included as key input parameters. The trajectory model describes the free-flight motion of windborne debris using aerodynamic models, dynamic and kinematic equations, and numerical solution procedures. For a given set of initial conditions, the equations of motion are integrated over time to predict the missile flight path, impact location, impact conditions and density of impacts. The overall transport process begins with missile release or injection, which may involve restrained missiles such as those from house components or unrestrained missiles such as accessories and miscellaneous debris. The missile trajectory model then combines the wind field model with the missile's dynamic, kinematic, and aerodynamic behavior to generate a flight time history. The missile interaction model evaluates whether the missile is lofted, what it impacts, and the resulting impact conditions. It also accounts for ground interaction behavior, where heavier or low length-to-diameter missiles may roll or slide after ground contact, while slender missiles generally have limited ground rolling or sliding. The basic model and the data were described in Twisdale (1979, 1981 and 1984).

3.1.4 Validation

This section summarizes validation studies performed for the HURMis debris generation and transport models. These validations were described in an ARA report on WBD impact risk for residential structures (ARA, 1996) and in subsequent briefings to the Florida Building Commission Hurricane Research Advisory Council in 2006 and 2008.

The development of a reliable WBD risk model requires validation against observed field data to confirm that the underlying physical assumptions and computational formulations reasonably

represent real-world behavior. In ARA (1996), the validation effort focused on two primary components of the modeling framework: (1) the debris generation model, which predicts the quantity and characteristics of debris produced by damaged structures; and (2) the debris trajectory model, which simulates the transport, impact location, and impact momentum of WBD.

Validation was performed by comparing model predictions with documented damage and debris transport observations from Hurricane Andrew in 1992 and Hurricane Erin in 1995. Post-storm damage surveys conducted by ARA engineers provided detailed datasets of residential building damage and debris fields, including roof sheathing loss, structural failures, and measured debris weight and transport distances. These datasets allowed the model to be evaluated for its ability to reproduce both the initiation of debris sources and the subsequent transport of debris under high-wind conditions.

The validation approach considered model performance in two stages. First, the debris generation model was evaluated by comparing simulated damage states and failure mechanisms with observed roof damage patterns for different residential building configurations. Second, the trajectory model was evaluated by comparing predicted debris transport distances, distributions, and variability with field measurements for representative debris types, including roof sheathing panels, roof tiles, and framing members. These comparisons provided insight into both the average transport distances and the variability of modeled debris behavior relative to the observed data.

The following subsections summarize the validation of the debris generation and trajectory models, identify areas of agreement and discrepancy, and discuss the implications of these findings for the reliability and applicability of the modeling framework.

3.1.4.1 Debris Generation Model Validation

The debris generation model was validated by comparing simulated roof sheathing damage states with observed field data from post-hurricane damage surveys.

3.1.4.1.1 Hurricane Erin

Observations of WBD debris data collected during field surveys after Hurricane Erin indicated that roof components were the largest single contributor to the debris inventory. Therefore, the damage survey focused primarily on roof sheathing performance for hip and gable roof houses, with particular attention given to building orientation relative to the shoreline.

Table 4. Comparison of observed and simulated roof sheathing failures from Hurricane Erin

Case	No. of Structures	Observed No. with Failures	Simulated Mean No. with Failures	Observed % with Failures	Simulated % with Failures
One-story gable roof, oriented parallel to beach	10	0	0	0	5.7
One-story gable roof, oriented perpendicular to beach	5	0	0	0	0
Two-story gable roof, oriented parallel to beach	56	12	10	21	18.1
Two-story gable roof, oriented perpendicular to beach	20	0	2	0	13.3
Hip roof houses	43	0	1	0	3.7

3.1.4.1.2 Hurricane Andrew

Following Hurricane Andrew, a total of 466 homes were surveyed across nine neighborhoods that experienced high levels of damage. Building damage was categorized into four damage states: no damage, minor damage, moderate damage, and severe damage. ARA obtained detailed house-by-house survey results, including information on roof sheathing loss and structural damage. Table 5 summarizes a comparison of observed and simulated damage fractions for one of the surveyed neighborhoods.

Table 5. Comparison of observed and simulated damage states for Hurricane Andrew

Damage State	Description	Observed Fraction	Model Range
1	No sheathing loss	~0.34	0.06-0.37
2	One or more panels lost	~0.25	0.44-0.67
3	Structural damage	~0.41	0.05-0.50

The results indicate that the model captured the general damage trends observed in the field. However, the comparison also suggests some overprediction of moderate damage, particularly for cases involving one or more lost roof sheathing panels. These differences may reflect uncertainties

in construction quality, local wind exposure, field classification of damage states, and limitations in representing structural failure mechanisms within the model.

3.1.4.2 Trajectory Model Validation

The debris trajectory model was validated by comparing simulated and observed debris transport distances for different debris types. The validation used field observations from Hurricane Erin and compared measured debris transport distances with corresponding simulated transport distances. Table 6 summarizes the statistics of observed and simulated transport distances for the four individual test cases, as well as for a combined dataset that includes all four cases. 17 shows the missile characteristics and corresponding source locations for Case 2.

Table 6. Comparison of observed and simulated debris transport distances from Hurricane Erin

Case	No. of Missiles	Observed Mean (ft)	Observed Std. Dev. (ft)	Observed Maximum (ft)	Simulated Mean (ft)	Simulated Std. Dev. (ft)	Simulated Maximum (ft)
1	3	42	42	90	68	58	240
2	4	80	33	120	113	89	400
3	4	130	81	200	68	73	330
4	8	68	26	91	72	81	508
Combined	19	79	50	200	80	80	508

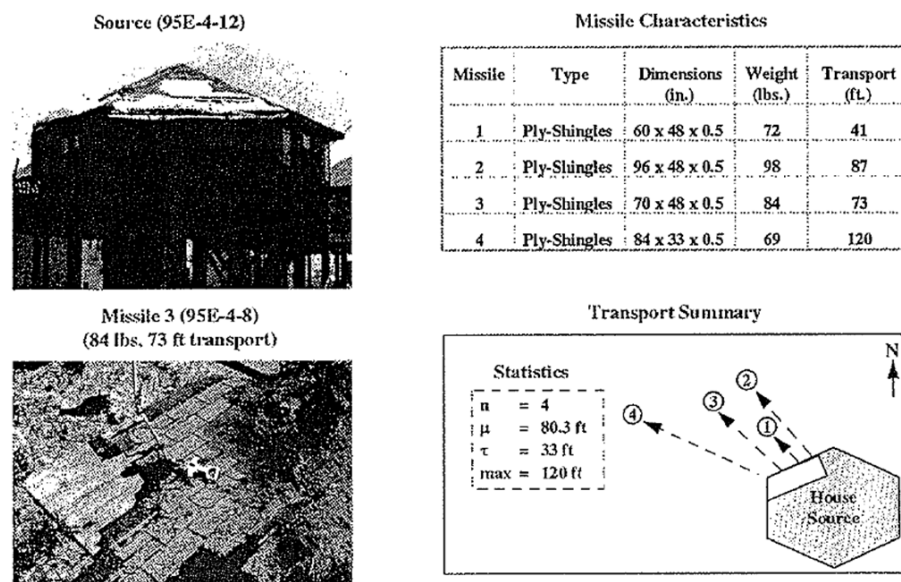


Figure 17. Missile characteristics and source location for case 2

The comparison shows that the model predicted the combined mean debris transport distance very well, with an observed mean of 79 ft and a simulated mean of 80 ft. However, the model tended to predict greater variability in transport distances, as indicated by the higher simulated standard

deviation and maximum transport distance. This suggests that the model reasonably captured the average transport behavior but may overestimate the upper-tail variability of debris travel distances.

It is recognized that uncertainties exist in both field data and modeling assumptions. These include variability in construction quality, incomplete documentation of debris inventories, uncertainty in the original debris source locations, and simplifications in aerodynamic and structural modeling. Therefore, the objective of the validation was not to achieve exact agreement with observations, but to demonstrate that the model captures the dominant physical and statistical characteristics of debris generation and transport with sufficient accuracy for engineering risk assessment applications. Overall, the validation cases indicate that the model predictions of component failures and debris transport distances are reasonable.

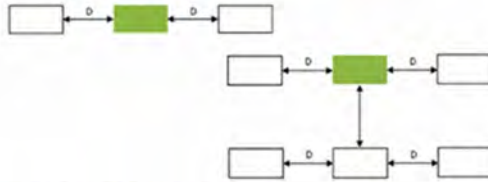
3.1.5 Model Improvements Validation

The missile simulation model used in the Hurricane Erin and Hurricane Andrew validation studies was subsequently improved by incorporating experimental data from the Boundary Layer Wind Tunnel Laboratory (BLWTL) at the University of Western Ontario (UWO). The testing program was conducted as part of a research collaboration between UWO and ARA. The experiments included shingle and tile debris tests, which provided additional information on debris aerodynamic behavior, flight characteristics, and transport distances. The results of these model improvements were presented to the Florida Building Commission, Hurricane Research Advisory Committee in 2008. Figure 18 shows the experimental setup at UWO, and Figure 19 presents a representative model validation case comparing simulated debris transport results with data from the corresponding UWO experiment. Overall, the model predictions of mean debris travel distance and the variability of landing locations were found to compare reasonably well with the experimental data.

UWO Experiments

■ Two subdivision configurations

➤ Single- and two-row houses



➤ 3 and 6.5 houses/acre

■ 16 cases for shingle and 12 cases for tile (30 tests were conducted in each case)

■ Six roof locations to release debris (Zones A, B, C, D, E, F)

■ Two wind directions (0° and 45°)

■ Open country ($z_o=0.01m$)

■ Mean of peak failure wind speeds

➤ Range from 57 to 149 mph

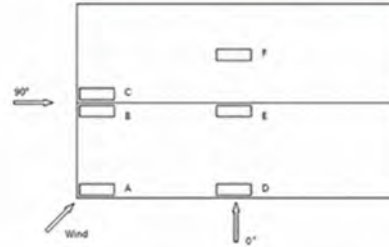
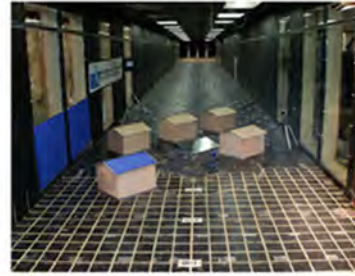
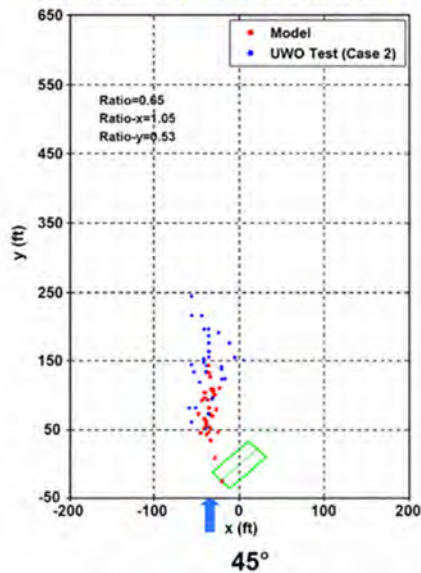


Figure 18. Experimental configuration for shingle and tile experiments at UWO (ARA, 2008)

■ Zone B (ridge corner) in 1-row house subdivision and 6.5



■ Zone B (ridge corner) in 2-row house subdivision and 6.5

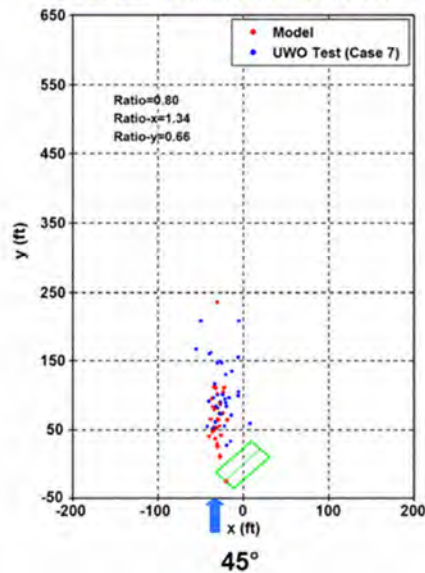


Figure 19. Comparison simulated shingle debris for shingle and tile experiments at UWO (ARA, 2008)

3.2 Overview of Phase I Modeling

Phase I of the study evaluated WBD risk for neighborhoods located near large water bodies in Florida, focusing on regions within the 130–139 mph design wind-speed contours. The primary objective was to determine how proximity to open water, directional terrain exposure, and wind

direction influence debris impact risk relative to the pre-ASCE 7-22 WBDR minimum risk threshold (140 mph, Exposure B). A uniform modeling framework was employed to isolate terrain-driven effects, utilizing the HURMis debris simulation tool to quantify debris generation, transport, and wall impacts across a residential neighborhood. The results of this phase established the baseline for evaluating inland vs. coastal debris hazards and inform risk-equivalent boundary distances.

The stochastic WBD simulation framework developed by ARA, HURMis, was applied to a single prototype neighborhood subject to the terrain conditions of 30 representative Florida neighborhoods located near large inland and coastal water bodies. The modeling approach compared “subject” cases, representing terrain conditions near large bodies of water in the 130–139 mph wind-speed band, against a “reference” case representing the established WBDR threshold of 140 mph in Exposure B terrain. Results were expressed using a relative hit metric, defined as the ratio of debris impact on walls in the subject case to debris impact on walls in the reference case. A relative hit value of 1.0 therefore represents equivalent WBD risk to the reference WBDR condition, while values above or below 1.0 indicate higher or lower relative risk, respectively.

3.2.1 Florida Neighborhoods

A total of 30 Florida neighborhoods were selected for analysis in Phase I—23 inland lake or bay locations and seven coastal locations—all situated within the 130–139 mph design wind-speed band defined by ASCE 7-22 and within one mile of a large waterbody (inland lake, bay or coastal) with at least 5,000 ft of upwind open-water fetch consistent with Exposure D conditions. The neighborhoods were chosen to provide broad representation of Florida's inland and coastal water-adjacent residential development patterns. Across all 30 locations, the only site-specific characteristics incorporated into the modeling effort were the directionally dependent surface roughness lengths (Z_0) extracted from NLCD land-use data; all other neighborhood features—including housing layout, construction type, and building spacing—were held constant, enabling an unbiased evaluation of how directional terrain variations influence WBD exposure under ASCE 7-22 criteria.

3.2.2 Directional Z_0

Directional surface roughness length (Z_0) was characterized for each neighborhood to quantify the effect of terrain on the near-surface wind field. Z_0 was computed across 36 wind directions in 10-degree increments using a 5,000-ft upstream fetch, selected based on ASCE 7 exposure guidelines and a sensitivity analysis that identified the 1,500-m fetch as most appropriate for capturing extended open-water influence. Values were derived from NLCD 2019 land-cover data mapped to roughness lengths following FEMA Hazus methodology, and evaluated at six inland offset distances (0, 1,000, 2,000, 3,000, 4,000, and 5,000 ft). For directions crossing large water bodies, Z_0 typically falls below 0.03 m, consistent with the lower bound of Exposure C in ASCE 7-22, while inland directions reflect higher roughness from suburban or vegetated land cover. At each location and offset, the minimum directional Z_0 was used as the controlling upwind condition —

a conservative choice since smoother terrain produces higher wind speeds and greater debris transport potential. These directional roughness profiles form the basis for the subsequent debris-risk calculations.

Figure 20 shows the cumulative distribution of the minimum directional surface roughness values for each neighborhood assessed in this study as the offset distance increases. The results demonstrate that inland and coastal neighborhoods have similar surface roughness conditions.

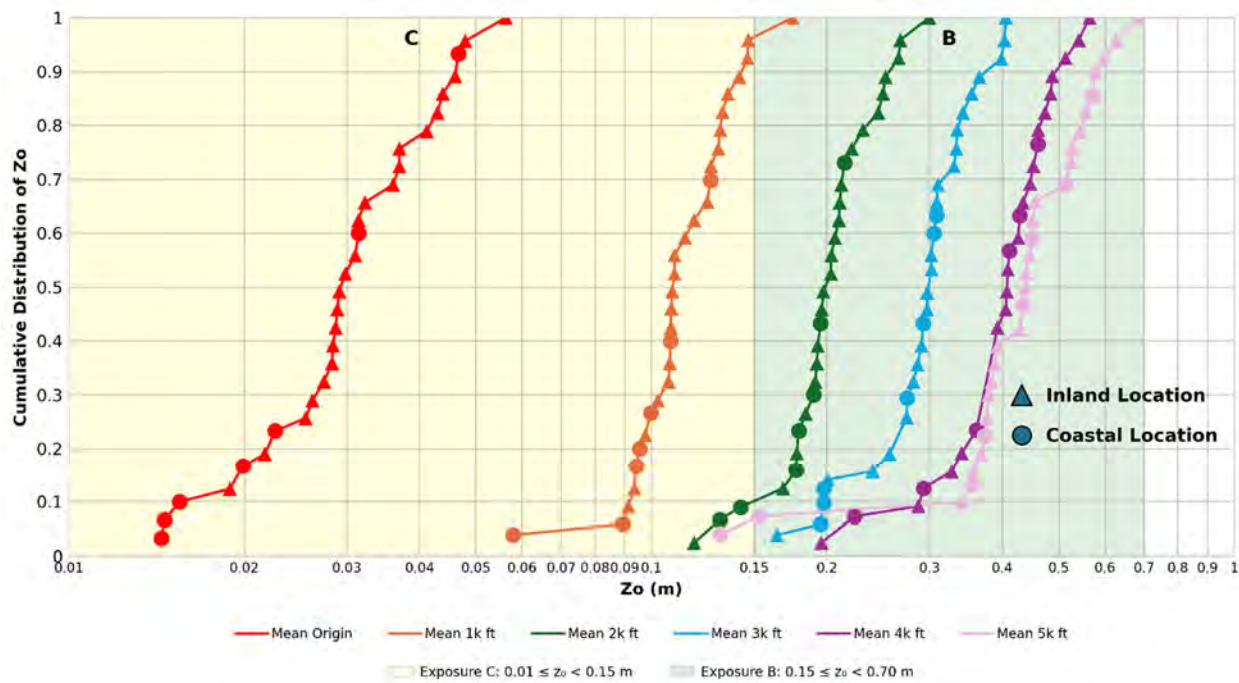


Figure 20. Cumulative distribution of minimum average directional surface roughness length, Z_0 . ASCE 7-22, Z_0 ranges are shaded for reference.

3.2.3 Modeled Neighborhood

Phase I WBD simulations were conducted within the HURMis modeling framework using a generic, idealized 1,000 ft × 1,000 ft residential grid containing 84 identical one-story wood-frame homes arranged in seven rows and twelve columns (see Figure 21). Buildings were treated as both debris sources and impact targets, with discrete missiles generated from failed roof cover, sheathing, and framing components. This controlled uniform layout was intentional — it isolated the effects of terrain exposure, wind speed, wind direction, and distance from the waterline across all 30 neighborhoods without introducing variability from site-specific building characteristics.

Simulations were run at straight-line wind speeds of 130 and 139 mph for three wind orientations relative to the direction of minimum Z_0 (0° , 215° , and 270°), capturing the most critical open-water-fetch exposures. Each scenario was evaluated at six offset distances from the waterline (0, 1,000, 2,000, 3,000, 4,000, and 5,000 ft), with ten stochastic runs per scenario and wall impacts averaged across the modeled neighborhood.

The principal output metric is the mean number of wall impacts per structure, normalized against a 140 mph Exposure B reference condition consistent with pre-ASCE 7-22 WBDR criteria. A normalized value greater than 1.0 indicates higher debris risk than the reference; a value less than 1.0 indicates lower risk. This relative hit metric forms the basis for determining the inland distances at which debris risk is equivalent to the pre-ASCE 7-22 coastal WBDR definition. While the idealized neighborhood enabled consistent cross-site comparisons, it also motivated the Phase II analysis, which replaces the generic layout with realistic neighborhood-specific building spacing and construction characteristics.

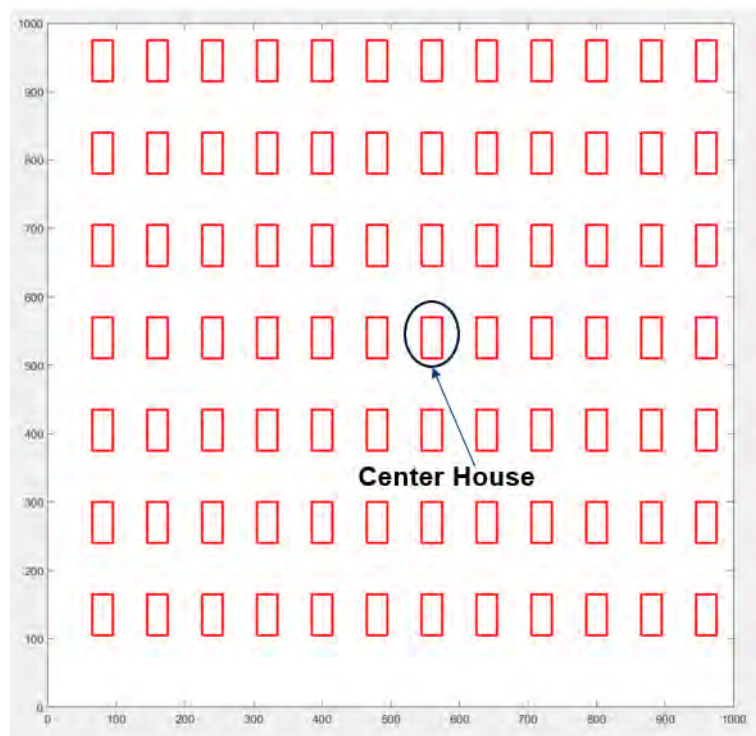


Figure 21. Plan view of the phase I modeled neighborhood.

3.2.4 Summary of Phase I Results

Phase I modeling demonstrated several key trends relevant to inland WBDR designation:

- Risk decreases with distance from open water: For nearly all neighborhoods and wind orientations, relative hit values decline consistently as offset distance increases. This reflects the influence of rising Z_0 and the shielding effect of inland terrain.
- A ~3000 ft distance represents risk equivalence to WBDR thresholds: For 130 mph within 2,000 ft, and 139 mph analyses, within 3000 ft of open water, approximately 50% of neighborhoods produce relative hits greater than or equal to 1.0, indicating risk comparable to the 140 mph Exposure B WBDR. Beyond 3000 ft, the proportion of cases exceeding

relative hit equal to 1.0 drops sharply. By 5000 ft, approximately 90% of cases show risk below the 140 mph Exposure B reference.

- Inland and coastal neighborhoods behave similarly under Exposure D: When directional roughness conditions are equivalent, inland lake communities exhibit debris risks comparable to coastal sites. Geography (coast vs. inland) is not a reliable predictor of WBD hazard, terrain exposure and open-water fetch dominate the risk profile.
- Implications for ASCE 7-22 WBDR boundaries: Findings suggest that the 1-mile WBDR buffer is conservative in inland locations and that a 3,000-ft boundary more accurately represents equivalent WBD risk. This evidence supports refining exposure-based criteria in future code updates.

3.3 Phase II Modeling

In Phase II, a more realistic neighborhood was used in place of the idealized model used in Phase I. The goal was to model actual construction practices in residential neighborhoods located near large open water bodies, where Exposure D conditions exist, and the design wind speeds range from 130 mph to 139 mph. The Phase II model represents an actual inland lake neighborhood identified in Phase I study that includes a mix of one- and two-story houses with hip and gable shaped roofs. The Phase II study evaluates the same 30 representative locations as used in Phase I across central Florida and the Florida panhandle area, including both coastal and inland sites. Directional surface roughness lengths (Z_0) calculated in Phase I for the 30 locations were used in this analysis. The HURMis modeling tool was used to simulate debris generation, transport, and impact frequencies across a modeled single-family residential neighborhood.

The simulations incorporate directionally dependent, Z_0 values, directional straight wind trace with turbulence characteristics, and detailed component-level failure modeling for typical residential construction. For each site, simulations were conducted across multiple relative wind directions and at offset distances ranging from 0 to 5,000 ft inland from the Exposure D condition, to capture the influence of surface roughness gradients on WBD risk. Debris impact results were normalized against a benchmark Exposure B scenario at 140 mph, producing “relative risk” metrics that quantify WBD risk on a consistent basis across locations. The modeling framework and detailed analysis results are presented in the following sections.

3.3.1 Neighborhood Characteristics

The Phase I analysis showed that many inland neighborhoods adjacent to large lakes exhibited surface roughness conditions similar to those observed in coastal neighborhoods. This finding suggests that from an exposure standpoint, some inland lake-adjacent neighborhoods may experience wind field characteristics comparable to a coastal environment. However, WBD generation is not controlled by terrain exposure alone. Building and neighborhood characteristics, including spacing between houses, roof material type, and the number of stories, can also influence debris generation, transport, and impact potential.

To extend the Phase I exposure-based comparison, we compare the neighborhood characteristics of inland lakes to coastal neighborhoods. The objective is to determine if there are any differences in neighborhood characteristics that may affect WBD generation and transport behavior.

The comparisons provided in the subsequent sections use an updated classification of which of the 30 neighborhoods are coastal and which are considered inland. This reclassification is discussed further in Section 3.4.1 and results in only five neighborhoods with direct coastal exposure; neighborhoods located on inland bays and inland waterways are grouped with the inland neighborhoods.

3.3.1.1 Extracting Neighborhood Characteristics

To support the analysis, tabular housing-characteristics data from the Zillow Transaction and Assessment Database (ZTRAX) (Zillow, 2026) database were joined to Florida statewide parcel geometries in ArcGIS Pro. Shoreline baselines were delineated for each study neighborhood using the neighborhood area bounding extents established in Phase I. From each shoreline baseline, a one-mile inland buffer was generated to define the neighborhood study area. The one-mile distance was selected to maintain consistency with the wind exposure considerations used in ASCE 7.

Within each one-mile buffer, residential parcels were extracted and screened using Florida Department of Revenue (FDOR) land-use classifications. The analysis focused on single-family and mobile-home parcels because these building types are most relevant to residential WBD generation. The extracted dataset was used to evaluate roof material type and number of stories.

Given that several study areas contained incomplete ZTRAX attributes records, a representativeness analysis was conducted before comparing housing characteristics. This step was necessary to determine whether the subset parcels with usable housing-attribute data were reasonably representative of the full-parcel population within each neighborhood. The representative analysis results showed that the parcels with data for all the neighborhoods were representative except Lake Tibet, Panasoffkee, Lake Butler, and Lake Down. See details of methodology in Appendix A.

3.3.1.2 Roof Material Type

The roof material types were aggregated into six broader categories that capture the dominant roof construction material. The results are shown in Figure 22-24.

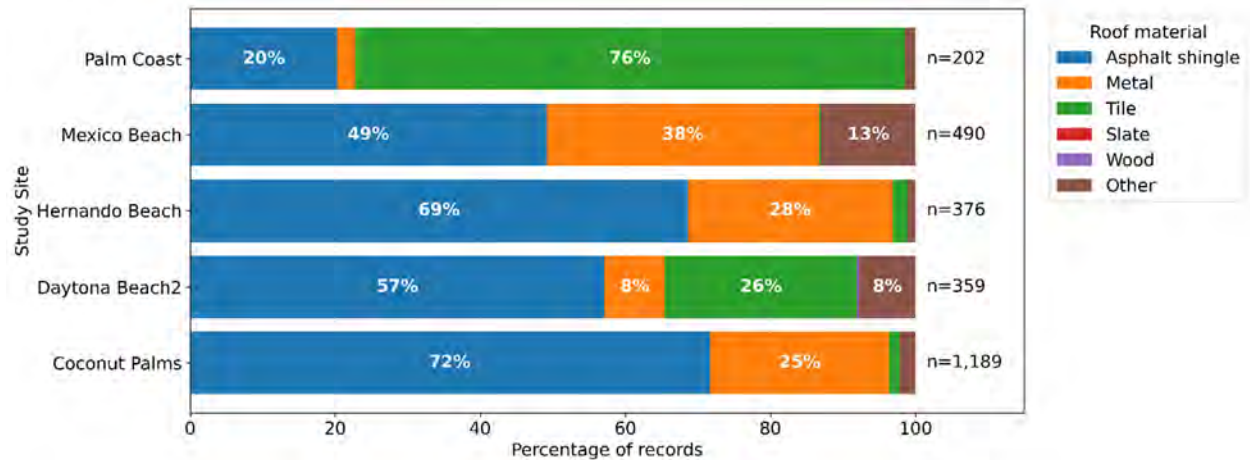


Figure 22. Roof material type distribution for the coastal neighborhoods

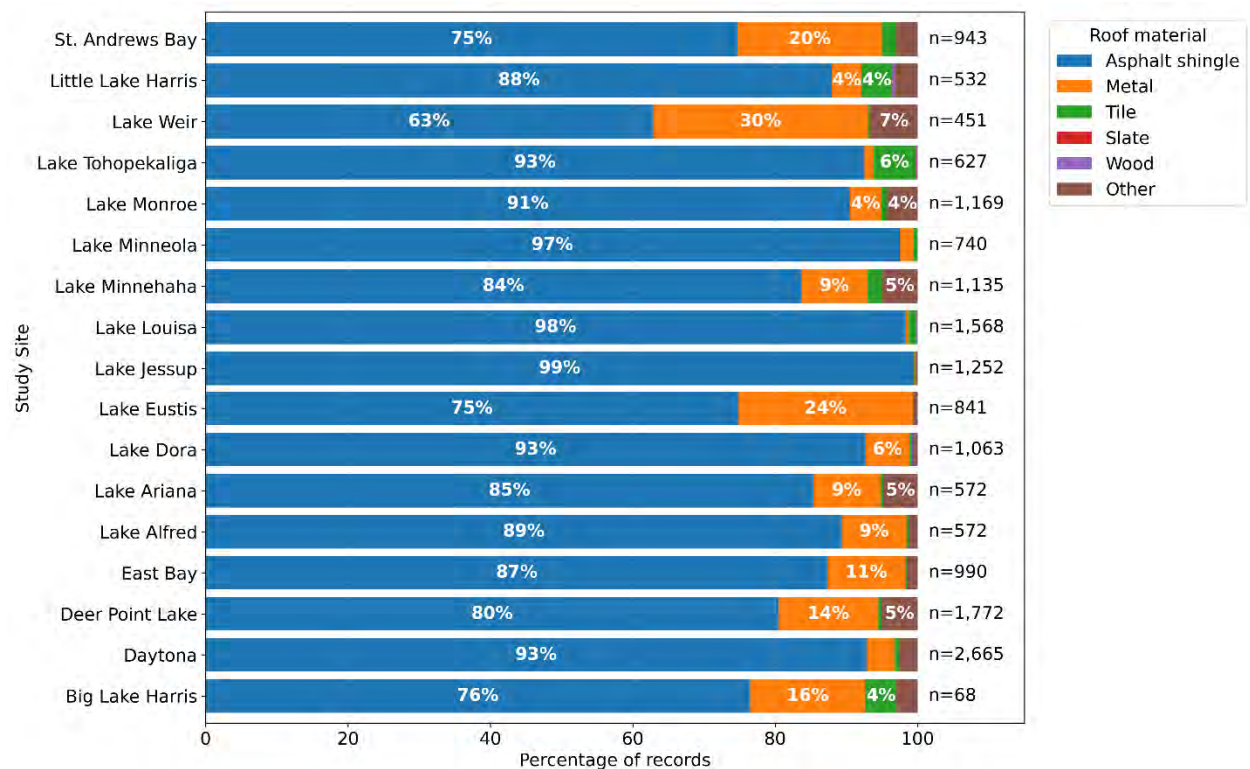


Figure 23. Roof material type distribution for the inland neighborhoods

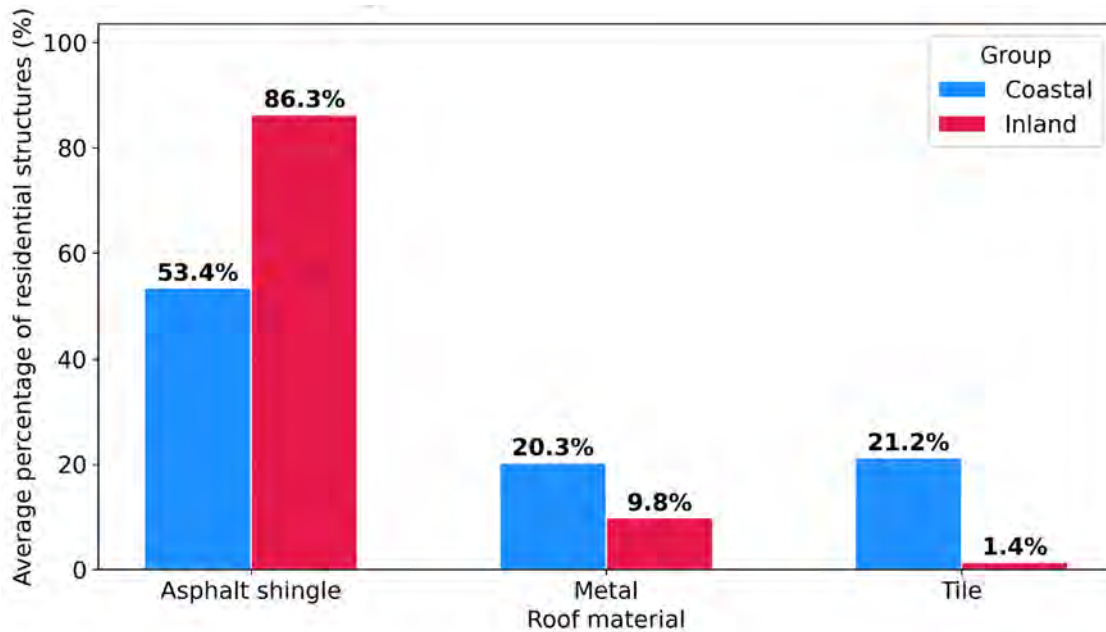


Figure 24. Average of roof material type for coastal and inland neighborhoods

The roof material comparison shows that asphalt shingles are the dominant roofing material type across both coastal and inland neighborhoods. Although some coastal neighborhoods contain notable fractions of tile and metal roofing (Mexico Beach, Hernando Beach, and Coconut Palms), asphalt shingles remain the majority material in most coastal sites and are the dominant material at every inland site, suggesting that that roof material composition is broadly similar across the two study domains.

3.3.1.3 Number of Stories

For the 30 neighborhoods, the story type for residential houses in the coastal neighborhoods were compared with that of the inland neighborhoods. The results as shown in Figure 25-27.

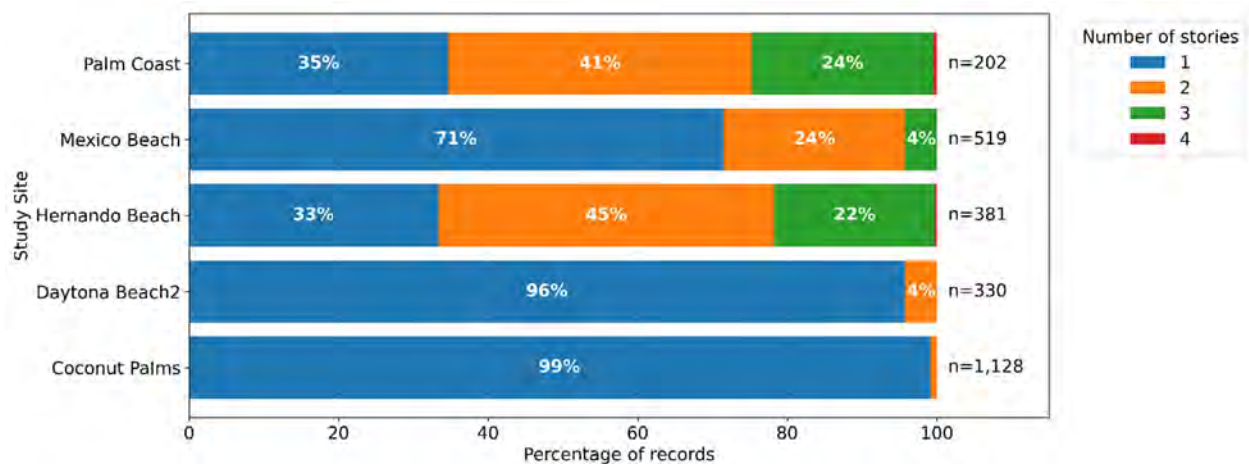


Figure 25. Story distribution for the coastal neighborhoods

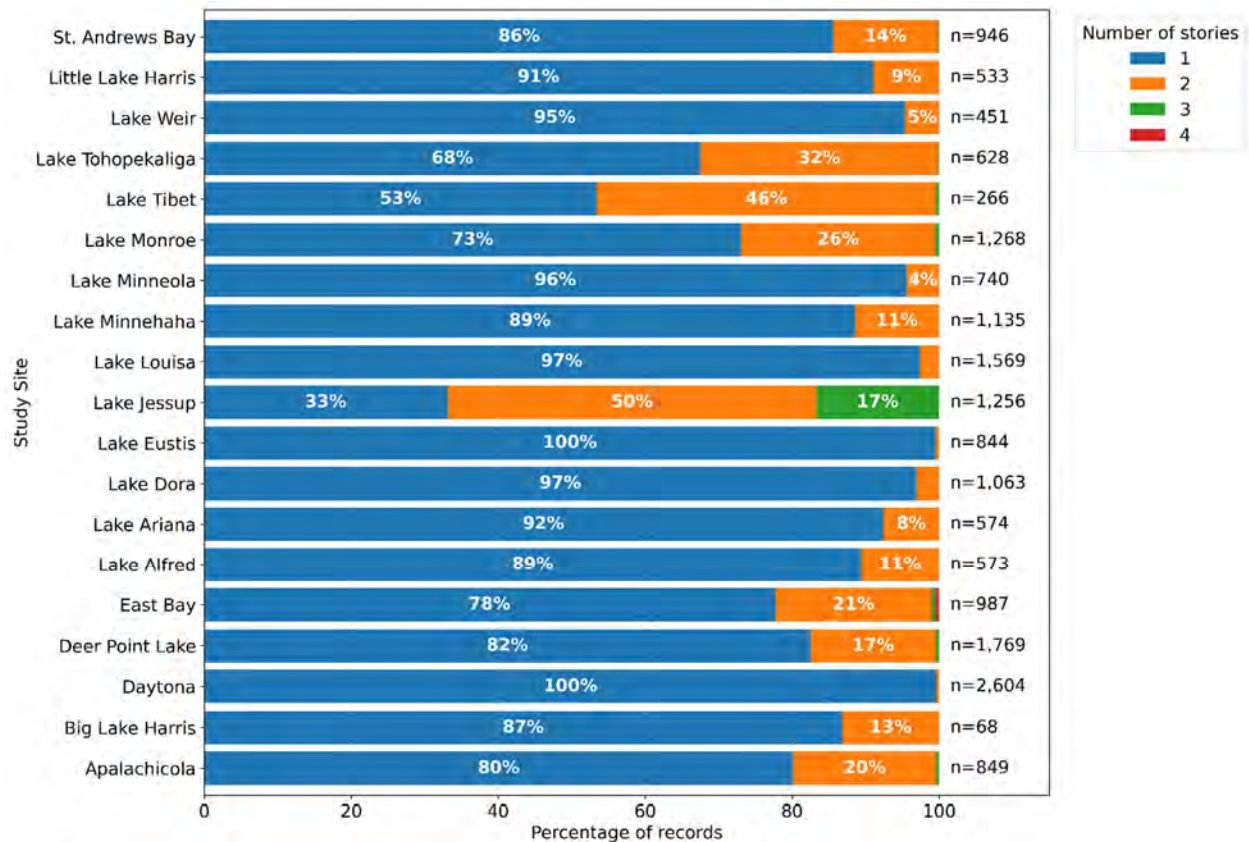


Figure 26. Story distribution for inland neighborhoods

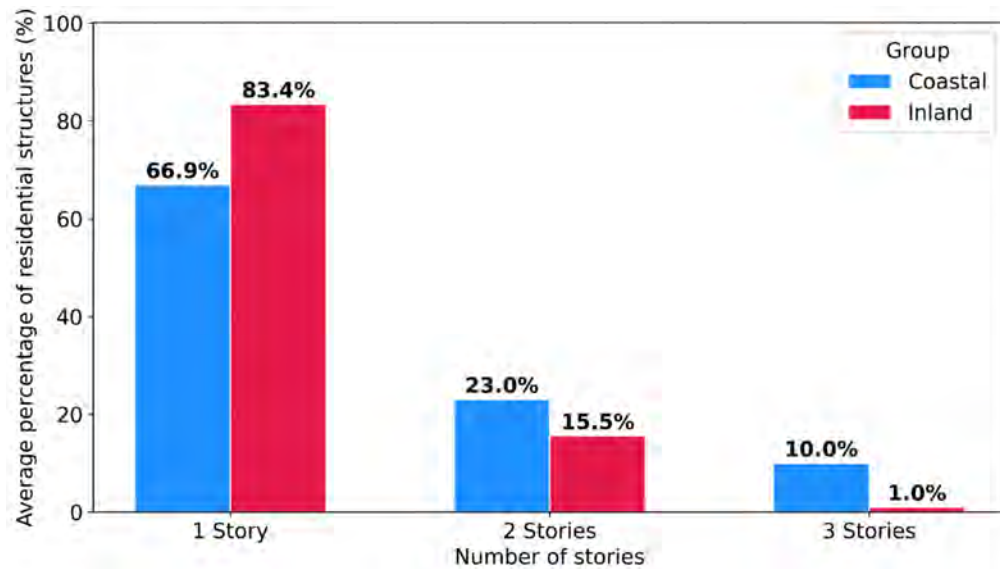


Figure 27. Average number of story distribution for coastal vs inland neighborhoods

The comparison shows that inland neighborhoods are overwhelmingly single-story. Most inland sites contain roughly 80–100% one-story houses with only a few inland exceptions exhibiting

appreciable two-story shares. Coastal neighborhoods are more heterogeneous: some coastal sites are almost entirely one story, while others contain substantial proportions of two- and three-story buildings. This difference implies inland areas have a lower vertical profile than coastal areas. From WBD perspective, differences in building height may affect debris source height, exposure, shielding, and potential debris trajectories.

3.3.1.4 Neighborhood Spacing

House spacing was evaluated using nearest-neighbor edge-to-edge distances between residential building polygons within each one-mile buffer.

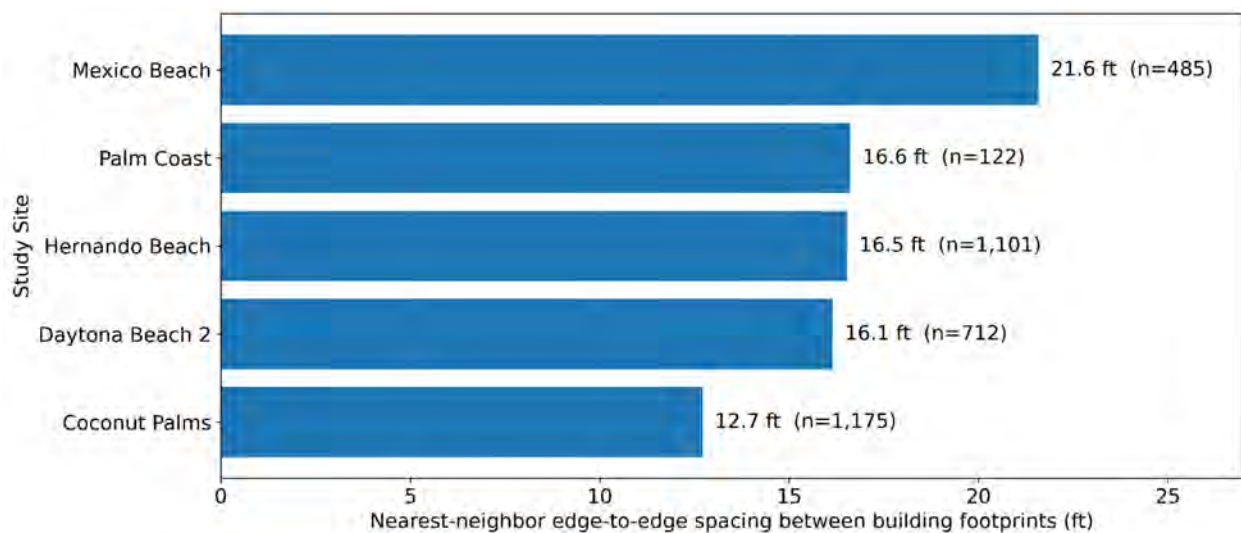


Figure 28. Nearest neighbor edge-to-edge spacing between building footprints for coastal neighborhoods

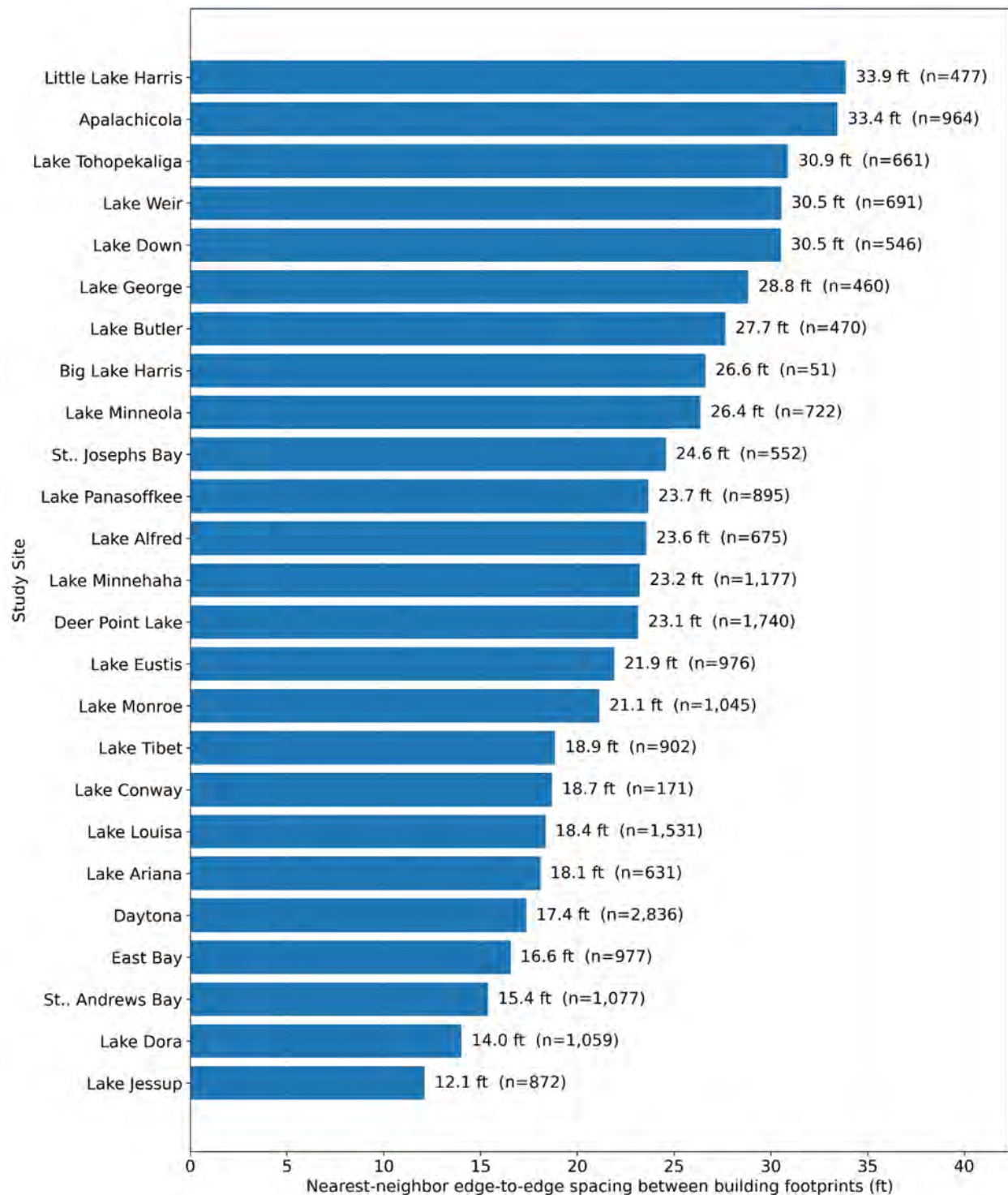


Figure 29. Nearest neighbor edge-to-edge building spacing for inland neighborhoods

Coastal neighborhoods are marginally more compact than inland neighborhoods, with a median nearest-neighbor edge-to-edge spacing of approximately 16 ft for coastal sites compared to approximately 23 ft for inland sites, a relatively modest difference suggesting broadly comparable

residential densities across both groups. Closer or small house spacing increases the likelihood of neighbor-to-neighbor debris interactions and cascading damage pathways, whereas larger spacing reduces direct house-to-house impact but changes exposure patterns (e.g., more open fetch for debris trajectories and different shielding effects).

3.3.1.5 Summary of Neighborhood Characteristics

Overall, the analysis shows that inland lake- and bay-adjacent neighborhoods and coastal neighborhoods share several important housing characteristic similarities, particularly in roof-material composition. Asphalt shingles dominate both groups (86.3% for inland and 53.4% for coastal), suggesting that roof-cover material alone may not strongly distinguish inland and coastal residential debris-source conditions.

While some differences were observed in building height distribution and neighborhood spacing, these distinctions are modest and unlikely to materially alter overall WBD risk assessments. Inland neighborhoods are predominantly one story and exhibit relatively uniform spacing, with a median nearest-neighbor center-to-center spacing of approximately 23 ft across most inland sites. Coastal neighborhoods display greater variability in building height and are marginally more compact, with median spacings approximately 16 ft—a difference that, while measurable, is not substantial enough to warrant a fundamentally different treatment of WBD risk beyond what is already captured by design wind speed and exposure category. Taken together, the housing characteristics across coastal and inland neighborhoods are sufficiently similar that design wind speed and terrain exposure remain the primary drivers of differential WBD risk between the two groups.

3.3.2 Analysis of WBD Risk

In Phase II, HURMis simulations were performed similar to the Phase I approach. For each of the 30 neighborhoods and associated offset points, all applicable roughness lengths (Z_0) were evaluated under three wind directions: 0°, 215°, and 270°. These directions represent winds parallel, oblique, and perpendicular, respectively, to the neighborhood's north-south axis, measured clockwise from neighborhood north. For each offset position, a single Z_0 value was used consistently across all three wind directions. The Z_0 values for each location are given in the Phase I report.

In Phase I, the “relative risk” or relative hit metric was defined by computing normalized mean wall impacts for each neighborhood at the offset locations identified. The relative hits were used to develop directional relative hits metric to provide a comparative index of debris risk under local exposure conditions relative to standard WBDR criteria. This metric is defined as the ratio of the mean wall impacts at reference wind speeds of 130 mph and 139 mph using the minimum directional Z_0 identified in Phase I, to the corresponding mean wall impacts at a reference wind speed of 140 mph in Exposure B terrain ($Z_0 = 0.35$ m). For reference, this relative hit metric is denoted as λ_{R-I} .

In Phase II, the relative hit metric developed in Phase I was further refined to quantify mean window and door breaking impacts. This updated metric considers the impacts that will likely cause damage to the vulnerable wall area, rather than counting all wall impacts as a measure of risk. The revised criterion for calculating mean window-breaking impacts is shown in Equation 1:

$$\bar{\lambda}_w = \frac{\sum_{i=1}^n \frac{\lambda_i}{N_{Sim}} * q_n}{n} \quad (1)$$

where, $\bar{\lambda}_w$ = mean window-breaking impacts; n = number of structures within the 1,000 ft × 1,000 ft base neighborhood; λ_i = number of wall impacts that exceed the impact energy in i^{th} structure; N_{Sim} = number of simulations; q_n = fenestration area fraction (window, door, and garage door area divided by total wall area) for structure n .

The $\bar{\lambda}_w$ uses the energy imparted by missiles on wall surfaces and screens impacts using the impact energy required to break annealed glass (18 ft-lb). Consistent with ARA (1996), missile hits are assumed to be uniformly distributed on the wall surfaces, the fenestration fraction q_n reduces the total impact count to those likely to strike windows, doors, or garage doors. The number of structures considers all structures within a base neighborhood size of 1,000' x 1,000' area that was used in Phase I.

To compute the relative mean window-breaking impacts, $\bar{\lambda}_w$, values for windspeeds in the 130–139 mph range are divided by the corresponding value at 140 mph with Exposure B conditions, $\lambda_{w \text{ WBDR}}$, evaluated separately for each of the three wind directions analyzed in Phase I. This produces a dimensionless comparison metric in which values greater than 1 indicate a higher mean number of damaging window impacts than would be expected for a neighborhood located in an accepted WBDR. Equation 2 presents the formulation of this ratio in terms of $\bar{\lambda}_w$ for the 130-mph wind speed.

$$\text{Relative mean window damaging impacts, } \lambda_R = \frac{\bar{\lambda}_{w130 \text{ mph}}}{\bar{\lambda}_{w \text{ WBDR}}} \quad (2)$$

Where; $\bar{\lambda}_{w \text{ WBDR}}$ = mean window-breaking impacts for the accepted WBDR; $\bar{\lambda}_{w130 \text{ mph}}$ = mean window-breaking impacts for 130-mph reference windspeed. For the 139-mph wind speeds the numerator would be replaced with $\bar{\lambda}_{w139 \text{ mph}}$.

The influence of impact energy screening on the Phase I results is illustrated in Figure 30 and Figure 31 for reference wind speeds of 130 mph and 139 mph, respectively. In both wind speed scenarios, the resulting cumulative distribution function (CDF) of the relative hit shifts higher with respect to the Phase I results for the first three offset locations (origin, 1000 ft, and 2000 ft). This increase in the relative hit metric is caused by lower impact energies observed for missiles simulated under Exposure B conditions at 140 mph than those observed for lower reference wind speeds with smoother terrains. In contrast, the Phase I approach counted all missile strikes on

building walls, including those associated with very low impact energies. Consequently, the refined approach better differentiates between low-energy, non-damaging and damaging impacts.

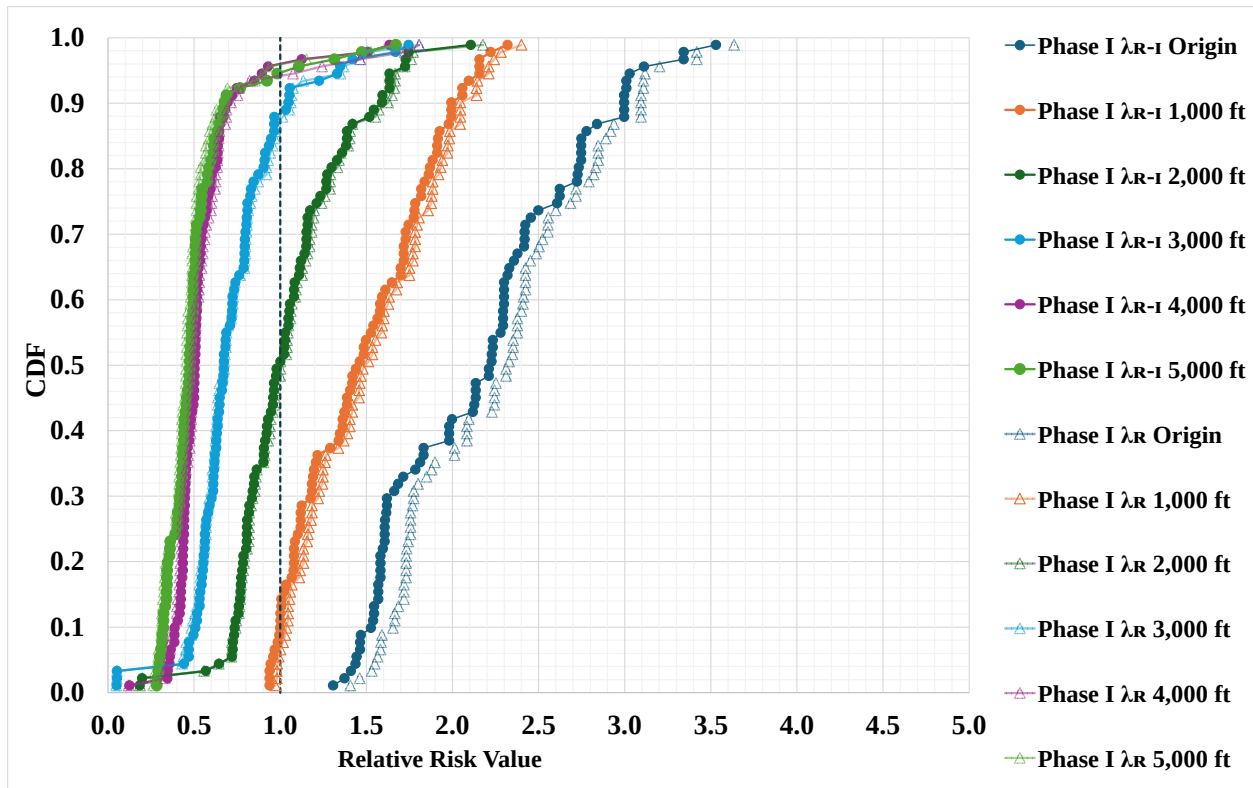


Figure 30. Impact of impact energy screening on the CDF relative mean hits at origin and offset distances for 30 locations based on 130 mph reference wind speed

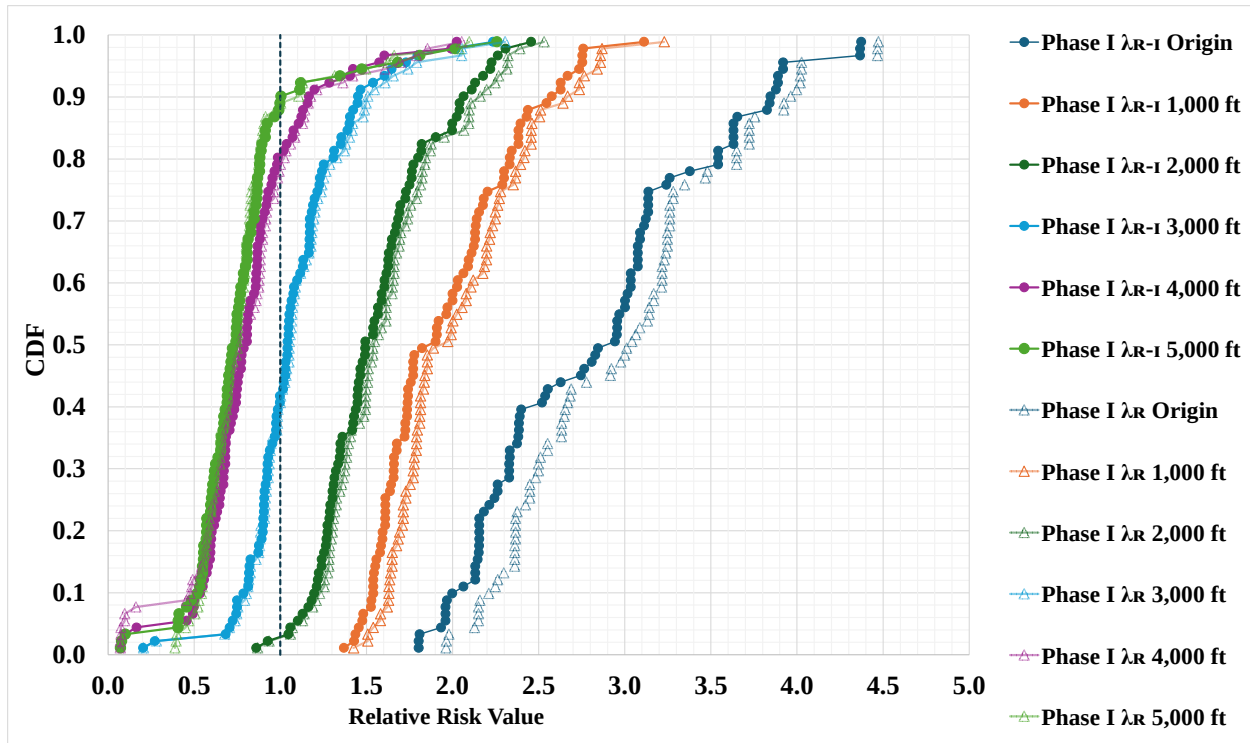


Figure 31. Impact of impact energy screening on the CDF relative mean hits at origin and offset distances for 30 locations based on 139 mph reference wind speed

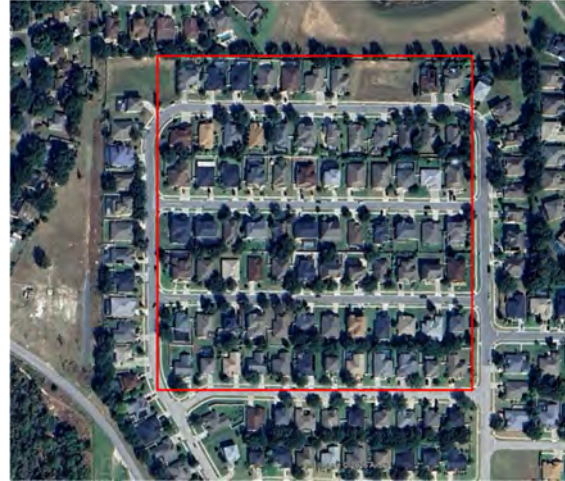
In Phase II, the number of straight-wind simulations per direction, per neighborhood, and for each offset case was increased from 10 (used in Phase I) to 30. This increase provides a larger sample size that reduces variance in the estimated mean number of hits while maintaining a reasonable balance with the added computational time and cost.

3.3.3 Neighborhood Modeling

For Phase II, housing characteristics described in Section 3.3.1 were used in the development of a more realistic neighborhood model, replacing the generic neighborhood representation used in the Phase I HURMIS simulations. The Lake Louisa neighborhood shown in Figure 32 was selected because it represents a post FBC construction neighborhood along an inland lake characterized by Exposure D conditions on its southern side. Since the focus of this project is on FBC requirements, the simulation assumed post-FBC construction. Figure 32 shows an overview of the Lake Louisa Neighborhood with the modeled neighborhood inside a red square.



(a) Overview



(b) Modeled Section

Figure 32. Google Map view of Lake Louisa neighborhood

The Lake Louisa neighborhood consists of 81 houses within an approximately 1,000 ft $\times$ 1,000 ft area, including 79 houses with hip roofs and two houses with gable roofs. Of these, 55 are one-story houses and 26 are two-story houses. Three representative house models were used in HURMis to model the Lake Louisa neighborhood: a one-story gable-roof house, a one-story hip-roof house, and a two-story hip-roof house. The characteristics assigned to these representative house models are summarized in Table 7. For all houses in the neighborhood, the roof system was modeled as an average-quality FBC asphalt shingle roof covering installed over plywood roof deck panels. The roof deck panels were assumed to be attached to the roof framing using 8d nails with 6 in./12 in. edge/interior spacing. Windows, garage doors, and entry doors were assumed to be non-impact resistant.

Only roof-related components, including the roof covering, roof deck panels, and roof framing members, were considered as potential sources of WBD debris. Figure 33 shows the two-dimensional modeled layout of the neighborhood and the locations of the representative house types. Although the actual neighborhood occupies an approximately 1,000 ft by 1,000 ft area, the modeled neighborhood covers an 800 ft by 900 ft area. This adjustment was made because the representative modeled structures have, on average, footprints approximately 950 ft² smaller than the actual houses in the Lake Louisa neighborhood. However, the on-center spacing between structures was preserved to maintain representative debris flight distances between neighboring houses. The preserved spacings include approximately 70 ft in the X-direction, 170 ft in the Y-direction across the street, and 120 ft in the Y-direction along the same side of the street.

Table 7. Lake Louisa house model characteristics

House Model	House Dimensions (ft x ft)	Number of Modeled Structures	Stories	Mean Modeled Roof Height (ft)	Roof Shape	Roof Material	Number of Shingles	Number of Modeled Roof Deck Panels	Wall Area (ft ²)	Window Area	Number of Modeled Windows	Number of Modeled Doors	Number of Modeled Garage Doors
GR1	60 x 30	2	1	12	Gable	FBC Shingle	1920	64	2011	261.4	27	2	1
HR1	60 x 30	53	1	12	Hip	FBC Shingle	2024	84	1710	256.5	27	2	1
HR2	60 x 30	26	2	21.5	Hip	FBC Shingle	2024	84	3420	444.6	54	2	1

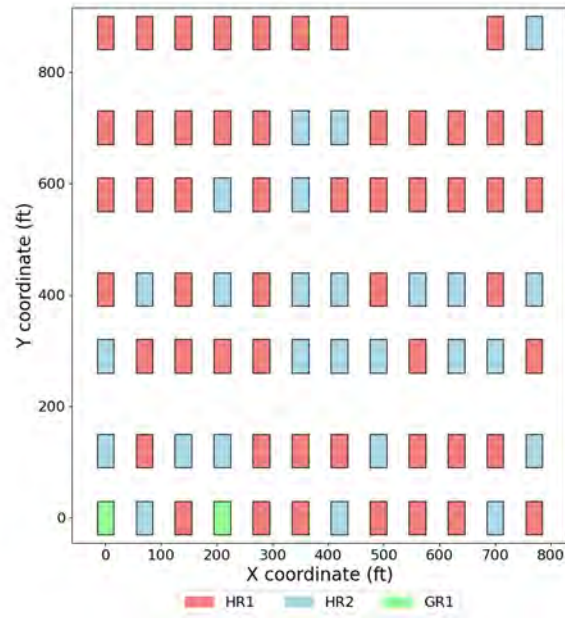


Figure 33. 2D representation of the Lake Louisa model

In the neighborhood model, the houses are oriented such that the long axis of each structure is either 90° or 270° relative to the east, matching the predominant orientation of homes within the neighborhood. Each of the 81 houses serves as both a potential source of windborne debris and a potential debris target. When damage occurs and debris is generated, its trajectory is tracked, and all resulting impacts on exterior wall surfaces are recorded and screened as described in Section 3.3.2.

3.3.3.1 Neighborhood Expansion

The base neighborhood, represented by the 81 houses of Lake Louisa described above, is used to score λ_R . As part of Phase II, the potential influence of additional WBD debris sources, such as surrounding neighborhood structures, was evaluated. This assessment was carried out through a series of sensitivity simulations. In these simulations, houses were incrementally added around the base neighborhood to determine how much surrounding development is required to adequately capture the effects of externally generated window-damaging debris. Four additional neighborhood sizes were considered in this sensitivity as pictured in Figure 34. Table 8.

Neighborhood sizes for expansion sensitivity Table 8 summarizes the total number of houses modeled for each case and the corresponding overall neighborhood footprint.

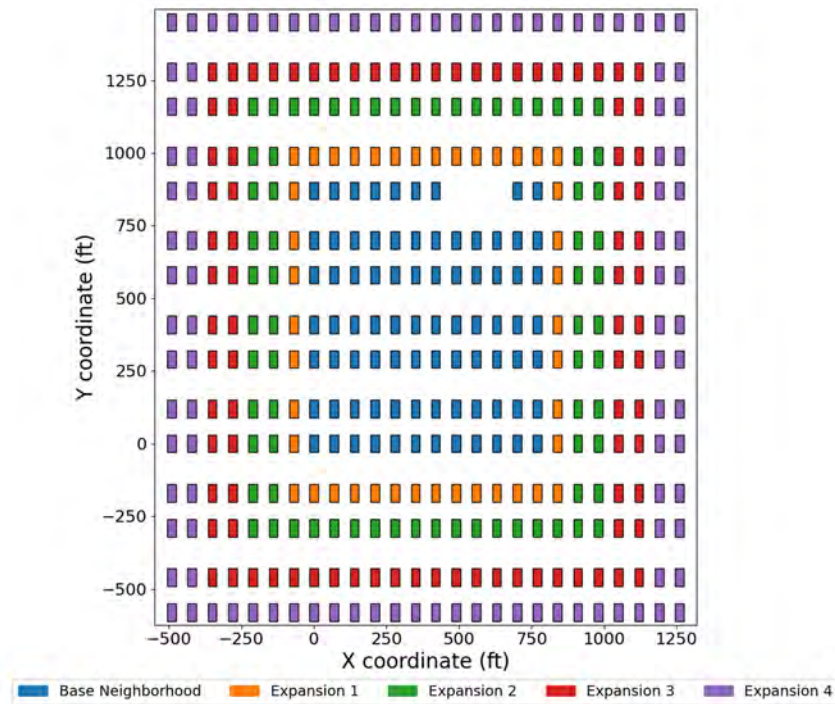


Figure 34. 2D Lake Louisa expansion neighborhood sensitivities models

Table 8. Neighborhood sizes for expansion sensitivity

Model	Total Houses	Neighborhood Footprint (ft ²)
Base Neighborhood	81	800 x 900
Expansion 1	123	940 x 1,220
Expansion 2	195	1,220 x 1,510
Expansion 3	283	1,500 x 1,800
Expansion 4	387	1,780 x 2,090

To determine the amount of additional surrounding housing needed to adequately represent external debris sources, each expanded neighborhood model was simulated for the origin Z_0 value of 0.037 at 130 mph for each of the three wind directions used in Phase I. The $\bar{\lambda}_w$ was calculated for the 81 structures in the core neighborhood regardless of the expansion size. This approach was used because only the houses in the base neighborhood were considered in the window damage calculations, while the added houses in the expanded neighborhoods were included solely as additional sources of WBD. All additional houses in these models were modeled as HR1 structures based on the characteristics in Table 7. Modeling the added structures as one-story houses allows a greater number of missiles to pass over the surrounding structures, reducing shielding or

interception effects from the expansion houses and providing a more direct estimate of debris impacts on the base neighborhood.

The ratio of $\bar{\lambda}_w$ for a given neighborhood size to the $\bar{\lambda}_w$ for the base neighborhood evaluated at 130 mph was calculated to quantify the relative increase in impacts over the base neighborhood size. The results indicate a general increase in the λ_R compared with the base neighborhood, as expected. However, the incremental increase diminishes as the neighborhood expansion extends farther from the core area. Among the three wind directions evaluated, the largest and continued increase was observed for the 215° wind direction, as shown in Figure 35.

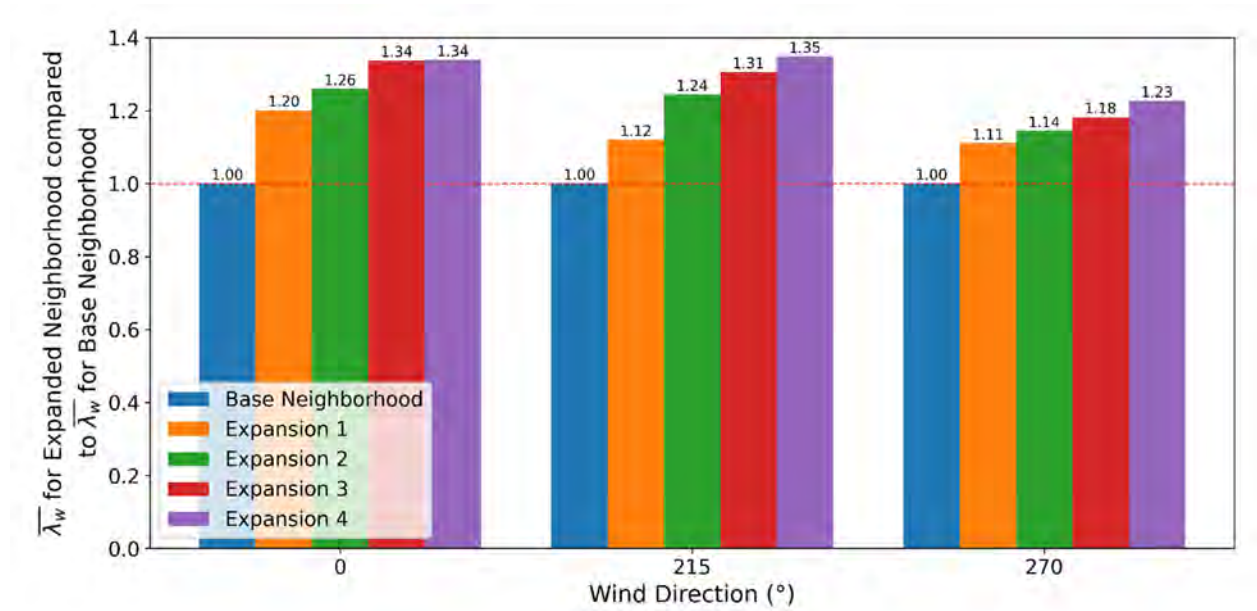


Figure 35. $\bar{\lambda}_w$ for expanded neighborhood compared to $\bar{\lambda}_w$ for the base neighborhood

A second relative comparison was performed by calculating a relative $\bar{\lambda}_w$ to quantify the incremental increase in risk associated with each additional neighborhood expansion. The results shown in Figure 36, indicate that after the second neighborhood expansion size, the relative increase in the relative $\bar{\lambda}_w$ becomes negligible. The 215° wind direction, which showed the largest and most sustained increase in Figure 35, also exhibits a noticeable drop-off at Expansion 3 when the relative increase in relative $\bar{\lambda}_w$ is compared with the Expansion 2 neighborhood.

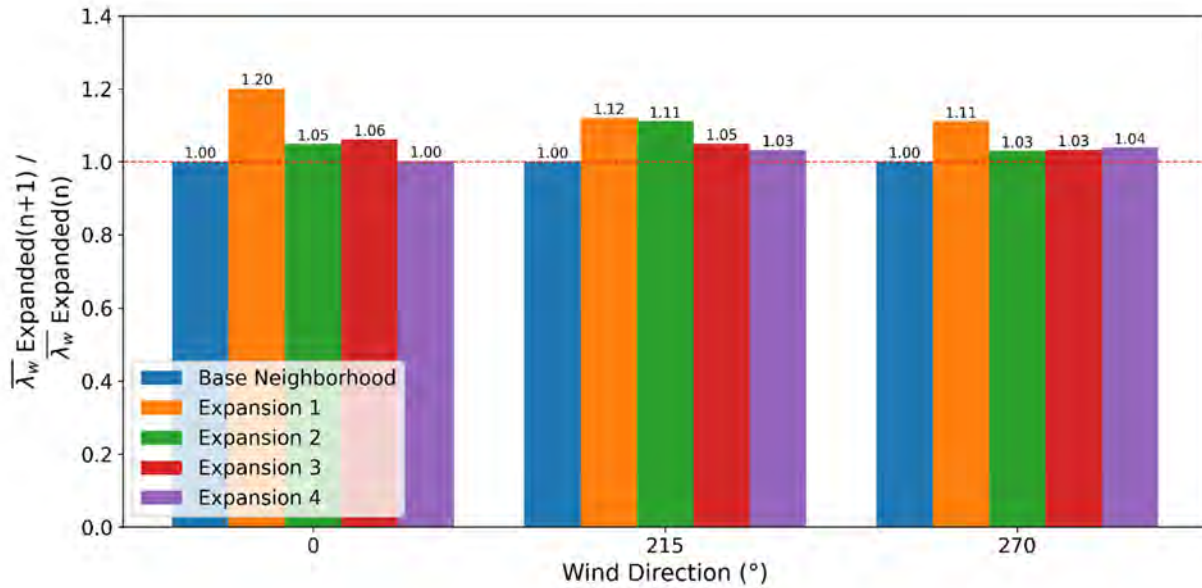


Figure 36. Relative $\bar{\lambda}_w$ compared to the next smallest neighborhood

For the remaining models and discussion in this report, all results are based on the Expansion 2 neighborhood size as shown in Figure 37. This neighborhood size was selected because further expansion produced only a marginal increase in relative $\bar{\lambda}_w$ compared with the next smallest neighborhood size. Expansion 2 was also preferred to maintain reasonable computational run times. The typical runtime for this model was approximately 16 hours, whereas the runtime for the Expansion 4 model approached 72 hours. Subsequent sensitivity analyses described in Section 3.4.2 further increased runtimes, with FBC tile roof simulations requiring approximately 48 hours for Expansion 2 and more than a week for Expansion 4.

Expanding the missile sources as described above also accounts for missile impacts on structures on the perimeter of the base neighborhood. The maximum mean flight distance at the 139-mph reference wind speed for shingles by distance from origin is presented in Table 9. Given the overall maximum mean flight distance is 243 ft for the origin in the 0° relative wind direction, size of the neighborhood footprint of Expansion 2 adequately covers the region in which these additional missiles would spawn from neighboring structures. Note that the mean flight distance is based on the entire neighborhood simulation and does not capture the flight of an unobstructed missiles which would fly further. However, given the study is observing WBDR missile hits, this reduced distance was deemed acceptable.

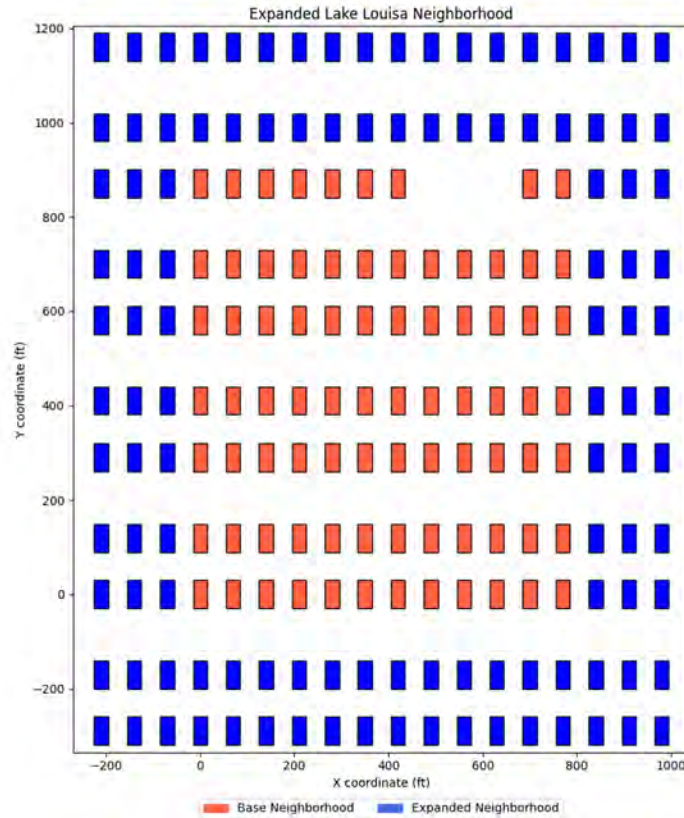


Figure 37. Final modeled Lake Louisa neighborhood with expansion 2 WBD sources

Table 9. Maximum mean flight distance by wind direction and distance from origin

Relative Wind Direction (°)	Maximum Mean Flight Distance by Distance from Origin (ft)					
	Origin	1,000 ft	2,000 ft	3,000 ft	4,000 ft	5,000 ft
0	243	197	177	166	165	151
215	216	176	158	148	148	136
270	214	174	156	147	147	133

3.4 Results

Figures 38 and 39 present simulation results for all 30 neighborhoods and all three wind directions, for reference wind speeds of 130 mph and 139 mph respectively. Each value in the CDF represents λ_R . A λ_R value of one indicates that the risk of WBD hits is the same as the neighborhood in an established WBDR.

For a reference wind speed of 130 mph, approximately 40 percent of the 90 simulation cases at the origin fall below the WBDR threshold (i.e., $\lambda_R \leq 1$). By 1,000 ft from the origin, 100 percent of the simulated cases indicate conditions less severe than the established WBDR criteria. For a reference wind speed of 139 mph, approximately 50 percent of the simulation cases fall below the 140-mph

Exposure B WBDR risk level at an offset distance of 3,000 ft. At the 4,000-ft offset distance, approximately 90 percent of the cases fall below the same risk threshold.

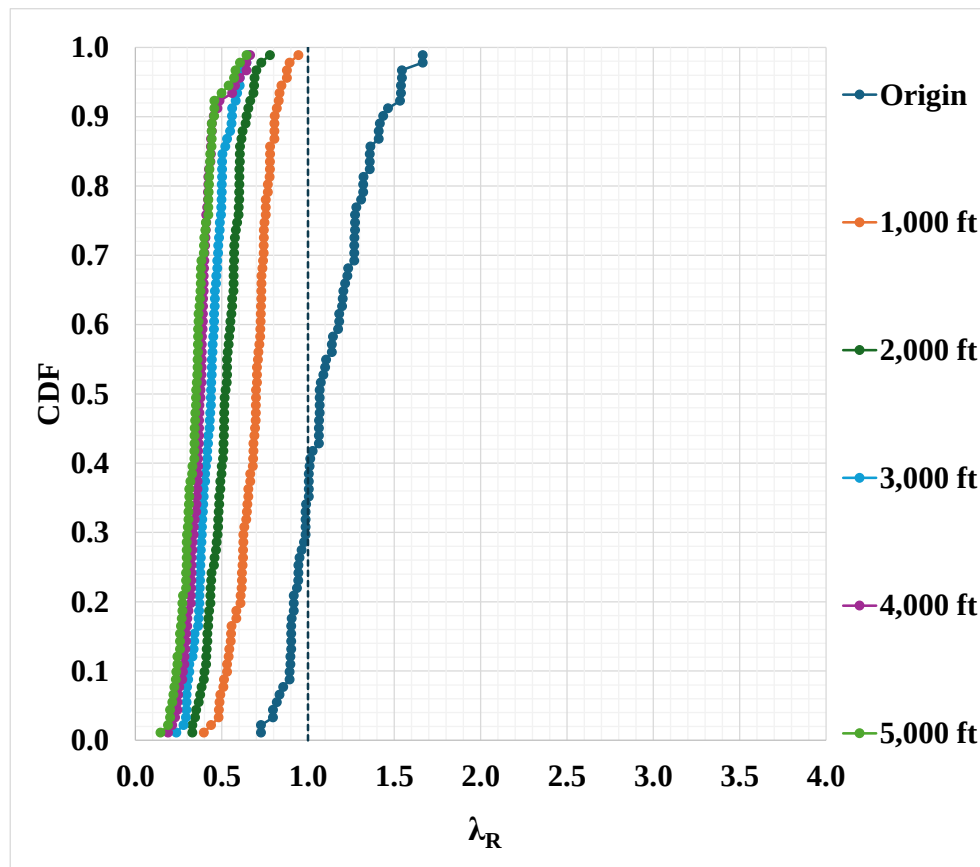


Figure 38. CDF of λ_R at origin and offset distances for 30 locations with reference windspeed 130 mph.

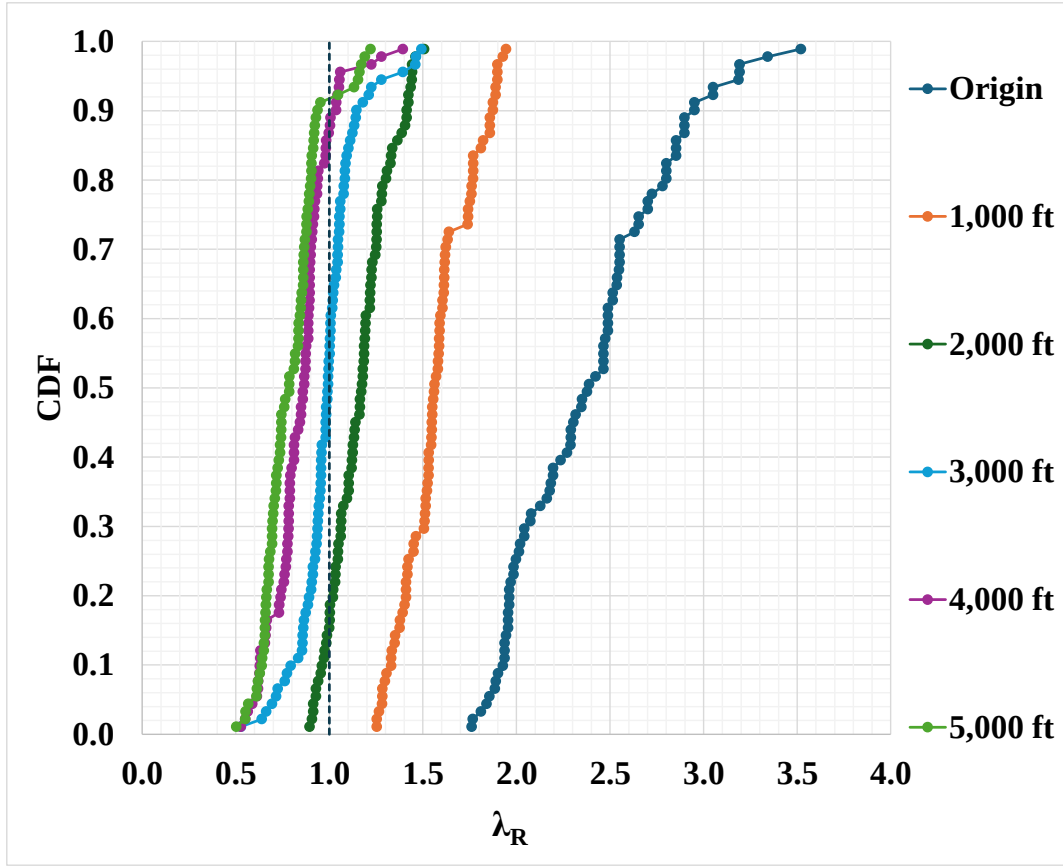
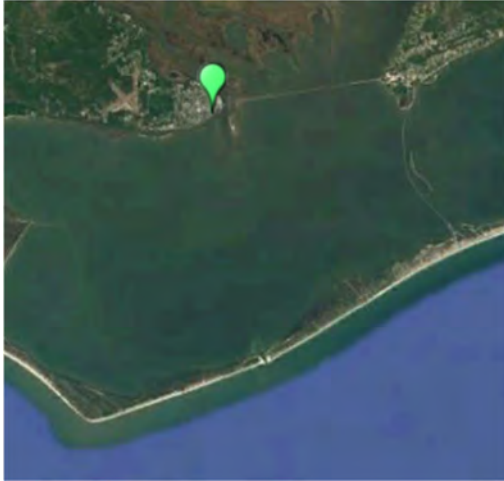


Figure 39. CDF of λ_R at origin and offset distances for 30 locations with reference windspeed 139 mph.

3.4.1 Coastal vs. Inland Comparisons: Similar Relative Risks

Phase II also reclassified two neighborhood locations from coastal to inland. The Apalachicola and Daytona Beach sites were situated on the landward side of barrier islands and intracoastal waterways. Because these locations are shielded from direct ocean exposure by intervening landmasses in all directions, they were reclassified as inland for the Phase II analysis. Figure 40 shows the two reclassified neighborhoods, shown as green pins on Google Earth images. In Figure 40 (b), the blue pin denotes the Daytona 2 site, which remains classified as coastal, while the Daytona neighborhood located West of the intracoastal waterway has been reclassified as inland.



(a) Apalachicola



(b) Daytona

Figure 40. Reclassified neighborhood locations from coastal to inland

To compare coastal and inland debris risk, the data in Figure 38 was filtered by coastal vs. inland location. Figure 41 presents the CDFs of relative WBD risk for the five coastal locations while Figure 42 presents corresponding CDFs of the twenty-five inland locations, all evaluated using a reference wind speed of 130-mph. The results indicate that, beyond an offset distance of 1,000 ft from the water body, all modeled coastal locations exhibit relative risk values below 1.0. This indicates a lower WBD risk than the baseline 140-mph Exposure B condition, a trend observed for both coastal and inland sites. For inland locations, approximately 40 percent of the sites at the origin fall below the 140-mph Exposure B baseline.

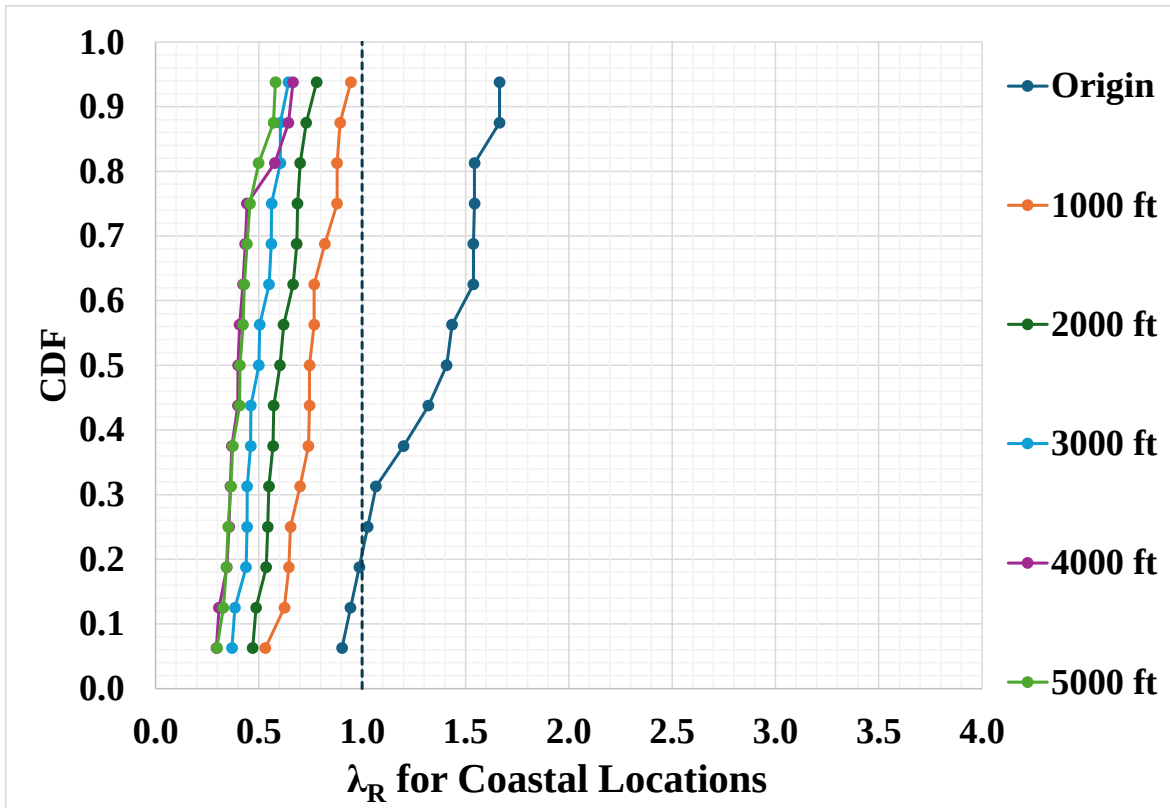


Figure 41. . CDF of λ_R at origin and offset distances based on 130-mph design wind speed for coastal locations

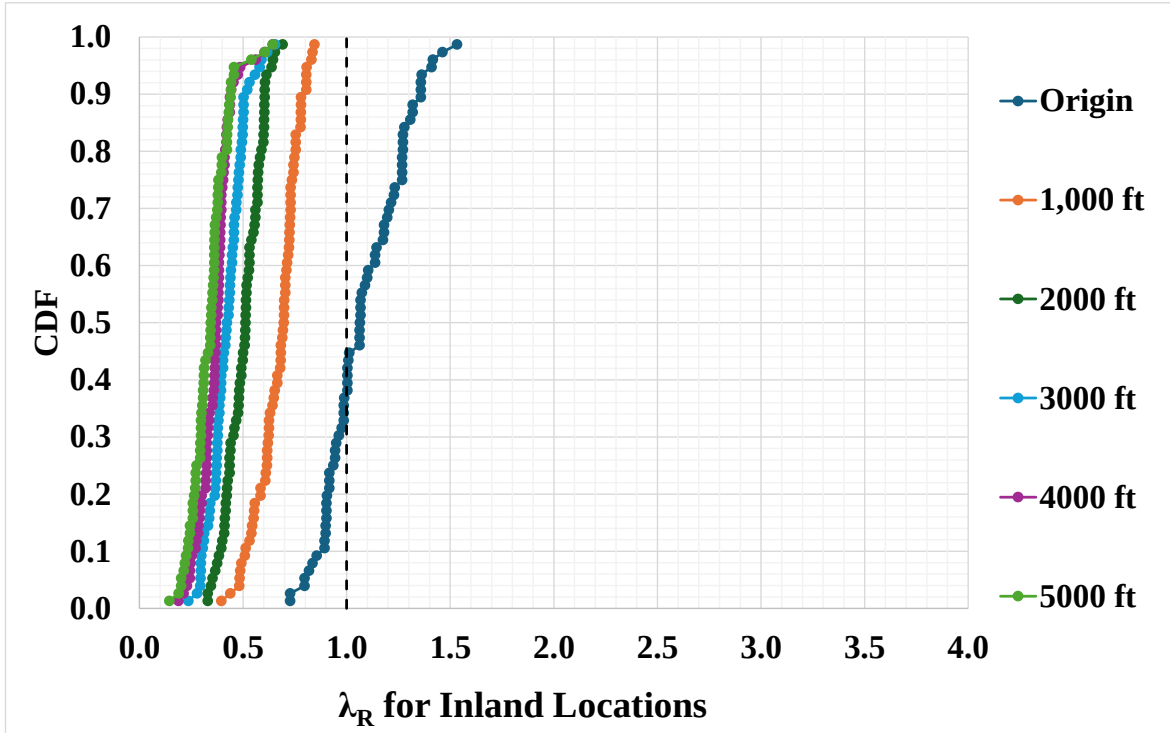


Figure 42. CDF of λ_R at origin and offset distances based on 130-mph design wind speed for inland locations

Figures 43 and 44 present the corresponding CDFs for the same locations under a 139-mph wind condition for coastal and inland locations respectively. In this case, beyond an offset distance of 3,000 ft, approximately 40% of coastal and 55% of inland simulation cases show λ_R values below 1.0.

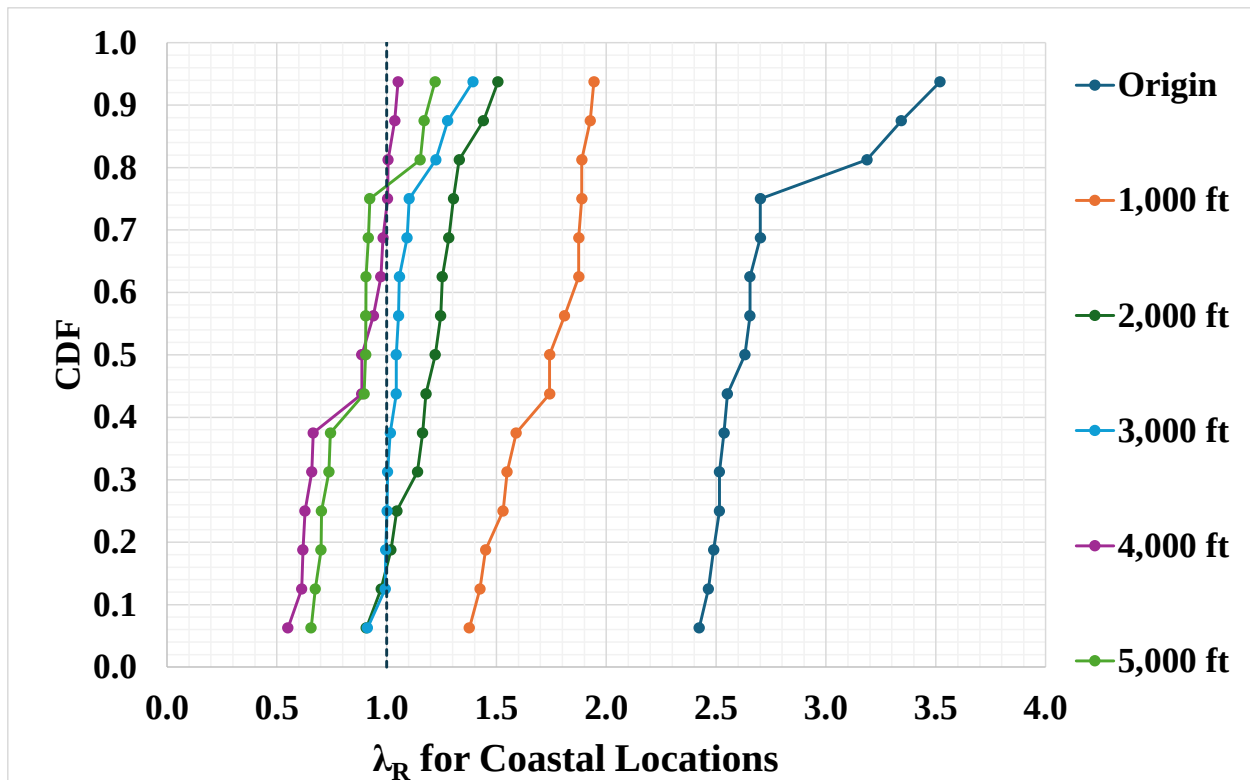


Figure 43. CDF of λ_R at origin and offset distances based on 139-mph design wind speed for coastal locations.

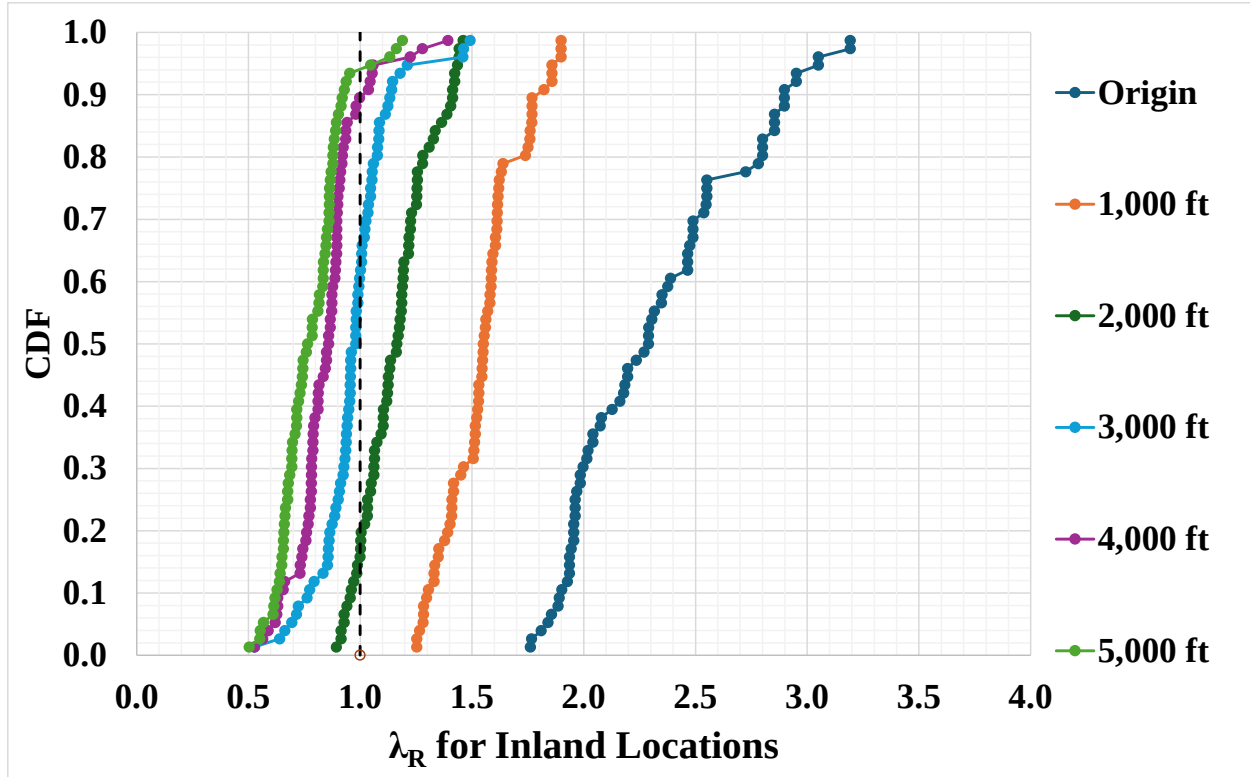


Figure 44. CDF of λ_R at origin and offset distances based on 139-mph design wind speed for inland locations.

The relative risk metric, λ_R , demonstrated similar directional trends and magnitudes across both coastal and inland neighborhoods, indicating that geographic classification (coastal versus inland) is not necessarily a meaningful predictor of debris risk when terrain exposure is comparable. These results support the removal of the “coastal” designation in ASCE 7-22 and reinforce the shift toward criteria based on terrain roughness and exposure conditions.

As the distance between the neighborhood and the edge of the open water body increases, λ_R consistently decreases, particularly where the upstream terrain transitions from open-water exposure to more suburban conditions. This behavior was observed across both inland and coastal neighborhoods.

3.4.2 Sensitivities

Several sensitivity analyses were performed to evaluate the effects of construction characteristics on λ_R as summarized in Table 10.

Table 10. Sensitivity cases

Sensitivity Case	Variable	Comparison
Case A	Roof Material	FBC Shingle versus FBC Tile
Case B	Roof Shape	Hip Roof versus Gable Roof
Case C	House Density	High Density versus Low Density Neighborhoods

3.4.2.1 Case A: FBC Shingle vs. FBC Tile

For this sensitivity, the same Expanded Lake Louisa neighborhood model was used, however the FBC shingle roof covering for every house was replaced with average-quality FBC villa tiles. Sensitivity simulations were performed for all thirty neighborhood locations using corresponding z_o values at each origin and offset points, and for the three wind directions examined in the study. The objective was to evaluate the effect of tile roofing, relative to asphalt shingles, on the frequency of window-breaking debris impacts.

Figure 45 compares the results of simulation presented in Section 0 for FBC asphalt shingle roofing with the FBC villa tile roofing with all other housing characteristics and simulation criteria remaining constant for the 130-mph wind reference speed. The results demonstrate that, for tile roofing, approximately 50% of the 1 simulations at the 1,000 ft offset result in λ_R values greater than one compared to approximately 1% of that for shingles. As such, tile roofs substantially increase debris generation and associated WBD risk at locations closer to open-water/Exposure D conditions. At the 3,000-ft offset, the distribution of λ_R for the two roof types are comparable, and at locations further inland, a reversal occurs in which tile roofs having slightly lower debris-impact rates relative to shingles.

Figure 46 presents the same comparison for the 139-mph reference wind speed. Approximately 50% of tile and shingle simulations at 3,000 ft from origin have a λ_R value greater than one. Similar to the 130-mph results, impacts at the 3,000-ft offset are comparable for the two roof types, and further inland, tile roofs again show slightly reduced debris-impact potential relative to shingles.

Table 11 and Table 12 provide percentile values corresponding to the CDFs in Figure 45 and Figure 46, respectively. Cells highlighted in red in these tables indicate λ_R values greater than 1.0.

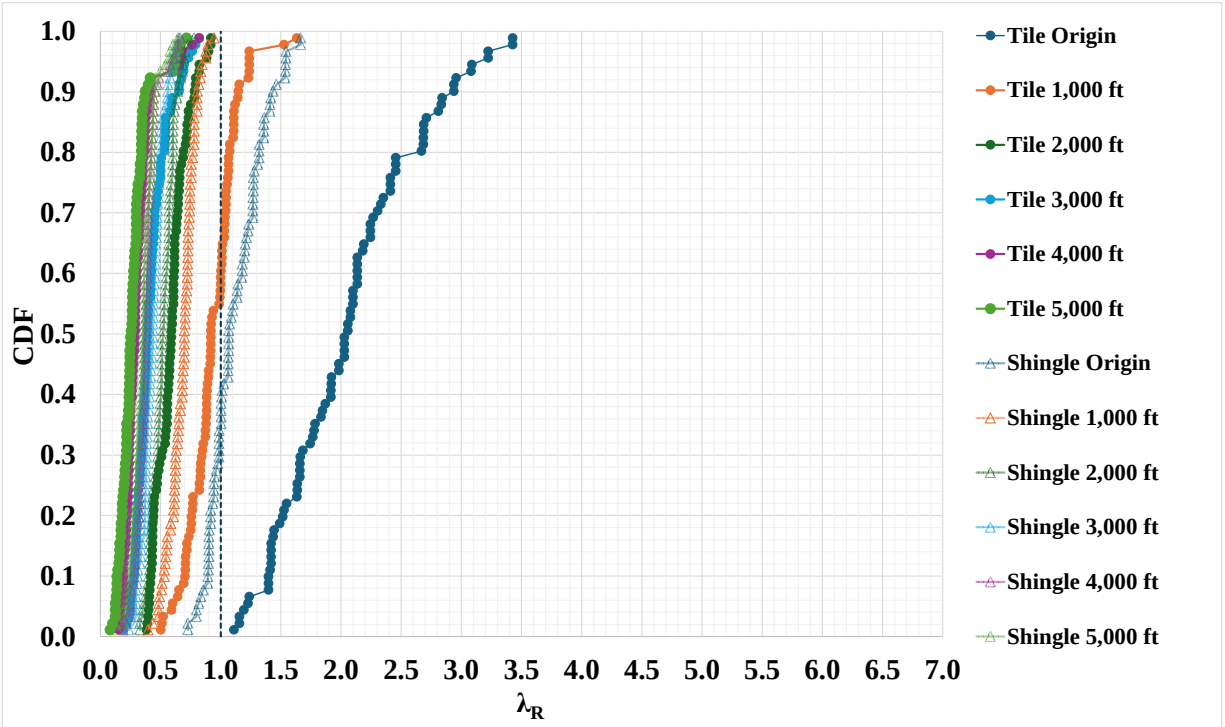


Figure 45. Comparison of λ_R at origin and offset distances for 30 locations for 130 mph design wind speed for tile and shingle roof coverings

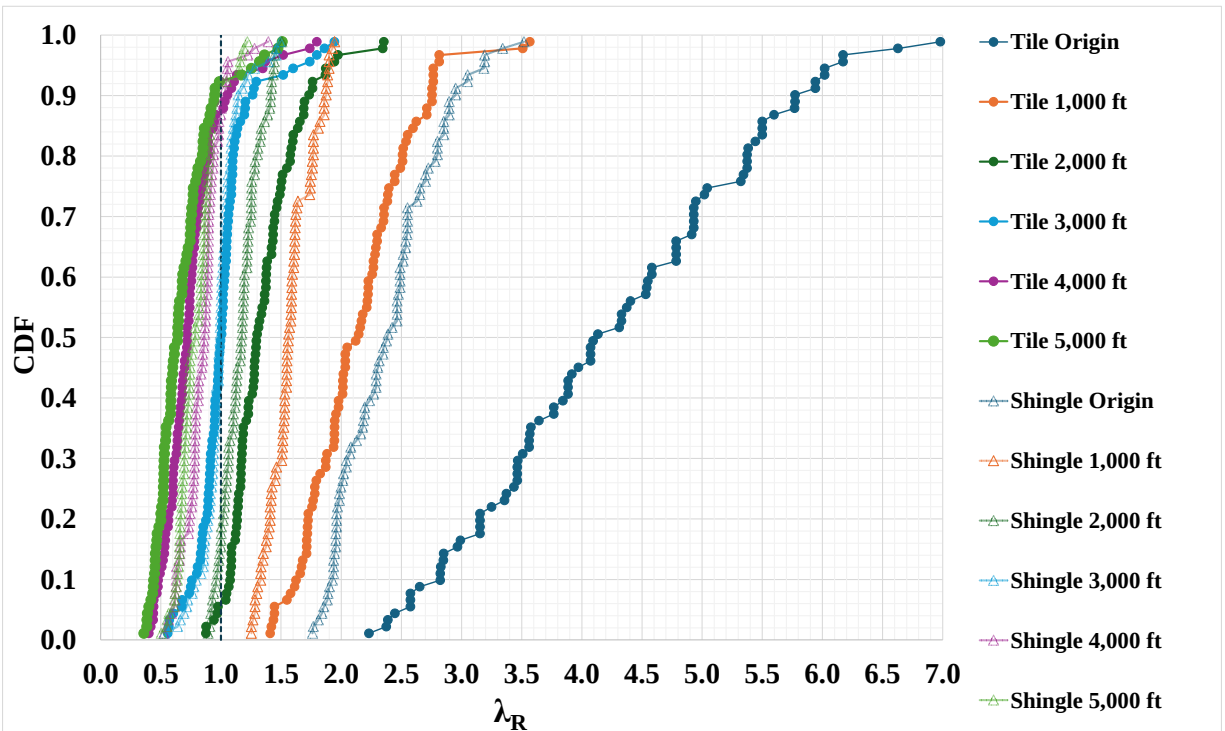


Figure 46. Comparison of λ_R at origin and offset distances for 30 locations for 139 mph design wind speed for tile and shingle roof coverings

Table 11. λ_R percentiles for 130mph based on roof material and offset distance

Percentile	Tile						Shingle					
	Origin	1,000 ft	2,000 ft	3,000 ft	4,000 ft	5,000 ft	Origin	1,000 ft	2,000 ft	3,000 ft	4,000 ft	5,000 ft
5	1.21	0.60	0.40	0.25	0.18	0.13	0.81	0.49	0.36	0.30	0.24	0.21
25	1.64	0.82	0.47	0.32	0.23	0.20	0.94	0.62	0.45	0.38	0.33	0.30
50	2.04	0.92	0.59	0.39	0.29	0.25	1.07	0.70	0.52	0.44	0.38	0.35
75	2.41	1.05	0.66	0.49	0.35	0.32	1.27	0.75	0.59	0.49	0.41	0.41
95	3.15	1.24	0.85	0.71	0.66	0.62	1.54	0.86	0.69	0.60	0.59	0.55

Table 12. λ_R percentiles for 139mph based on roof material and offset distance

Percentile	Tile						Shingle					
	Origin	1,000 ft	2,000 ft	3,000 ft	4,000 ft	5,000 ft	Origin	1,000 ft	2,000 ft	3,000 ft	4,000 ft	5,000 ft
5	2.52	1.44	0.97	0.64	0.44	0.40	1.85	1.28	0.92	0.71	0.60	0.59
25	3.42	1.78	1.16	0.90	0.60	0.52	1.99	1.42	1.04	0.92	0.77	0.68
50	4.11	2.13	1.30	1.00	0.72	0.64	2.38	1.56	1.17	0.99	0.86	0.79
75	5.11	2.41	1.50	1.09	0.84	0.78	2.67	1.74	1.26	1.06	0.92	0.88
95	6.09	2.79	1.90	1.66	1.36	1.28	3.19	1.90	1.44	1.33	1.06	1.16

To further assess the influence of roof-covering material on λ_R , the values from all offsets in Figure 45 were aggregated for both shingle and tile roofs. The same aggregation was performed for the results shown in Figure 46. The combined λ_R values were then plotted as a function of Z_0 for each roof-covering type. Figure 47 presents the resulting λ_R – Z_0 relationship for the 130-mph reference wind speed, and Figure 48 presents the corresponding relationship for the 139-mph reference wind speed. In both cases, the variation of λ_R with Z_0 is well described by a power-law curve. The fitted relationships indicate the approximate Z_0 level at which λ_R decreases below one, marking the transition to debris-impact conditions less severe than those associated with Exposure B at 140 mph. These figures indicate that while tiles have larger effect on WBD risk for smoother terrains, that effect is erased as surface roughness increases toward an exposure B condition (i.e., $Z_0 = 0.35$).

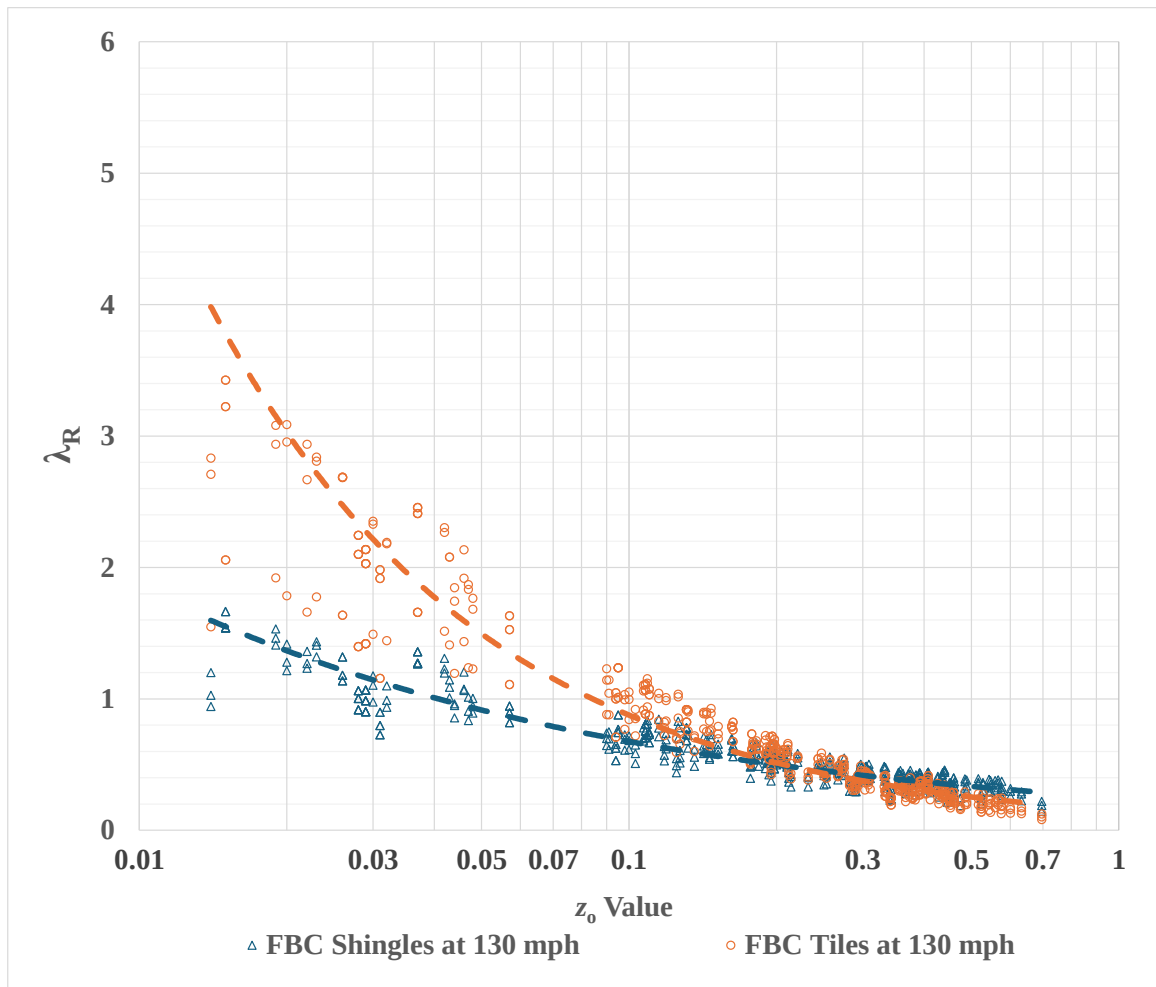


Figure 47. λ_R versus Z_0 for 130 mph design wind speed

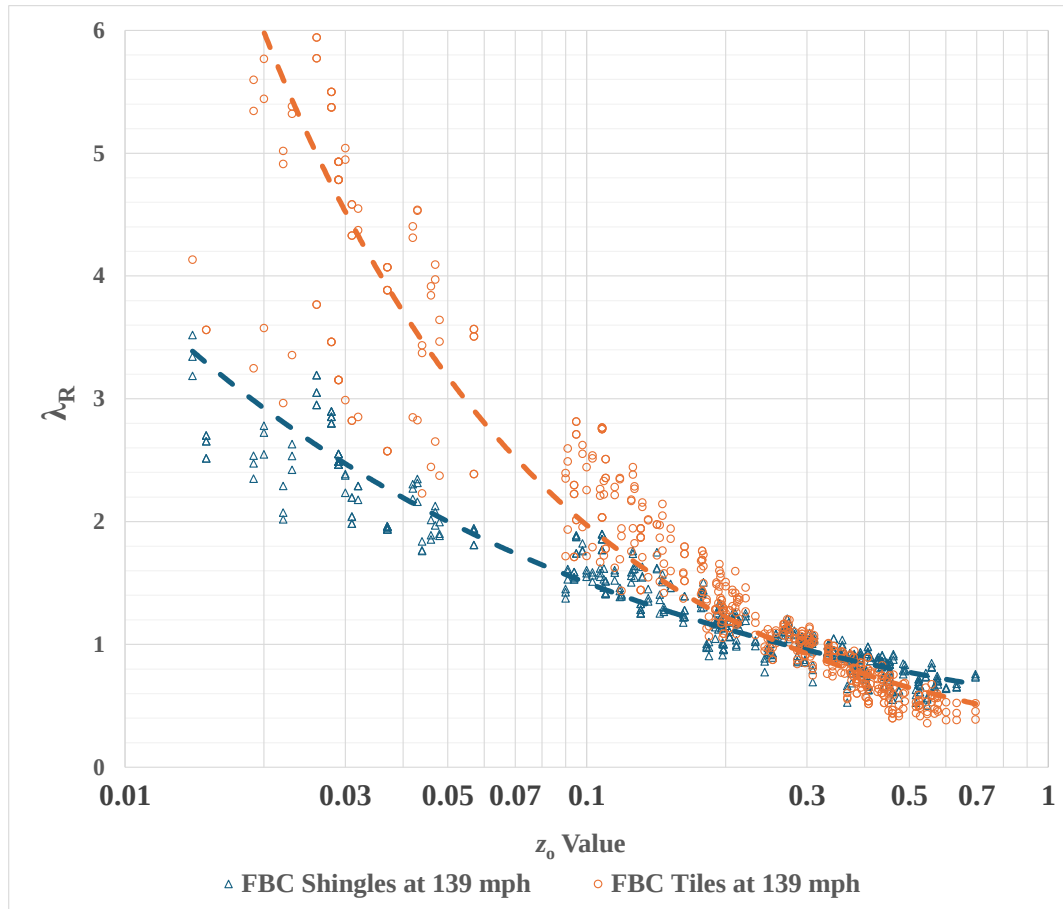


Figure 48. λ_R versus Z_0 for 139 mph design wind speed

3.4.2.1.1 Coastal versus Inland Comparisons: Similar Relative Risks

The comparison between coastal and inland neighborhoods was performed for the FBC villa tile construction case in the same method as the FBC asphalt shingle case. To compare coastal vs inland risk, the data in Figure 50 was divided into coastal and inland locations. CDFs of relative WBD risk for the five coastal and 25 inland locations are presented in Figure 50 and Figure 51, respectively, for the 130-mph reference wind speed. The results show that, beyond an offset distance of 2,000 ft from the water body, all the modeled coastal simulation cases yield relative risk values below 1.0 indicating a lower WBD risk than the baseline Exposure B condition at 140 mph for both coastal and inland sites. For Inland sites approximately 40% of the simulations at the origin are below the baseline Exposure B condition at 140 mph.

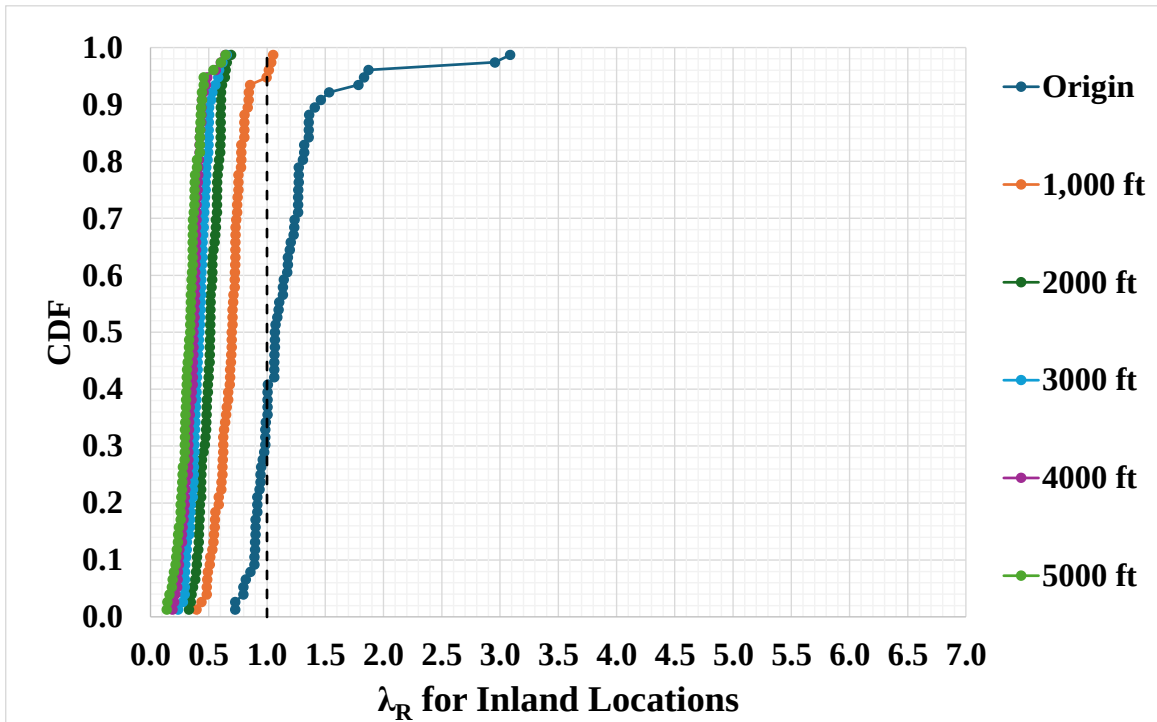


Figure 49. CDF of λ_R at origin and offset distances based on 130-mph design wind speed for inland locations

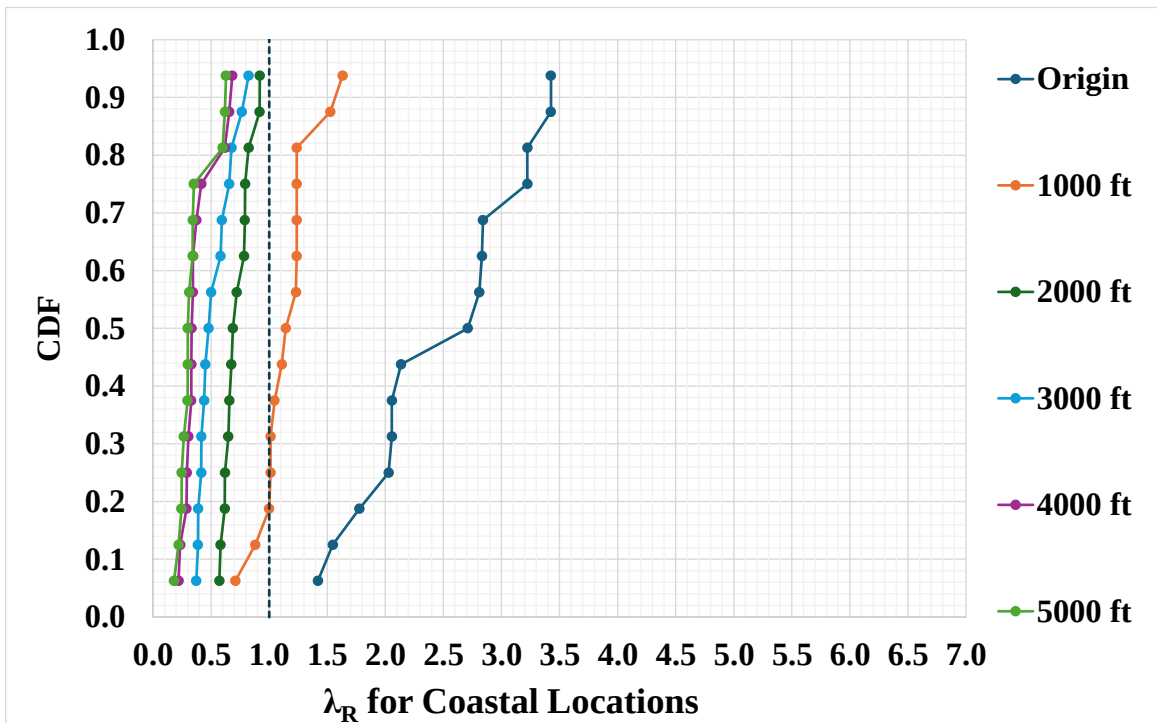


Figure 50. CDF of λ_R at origin and offset distances based on 130-mph design wind speed for coastal locations

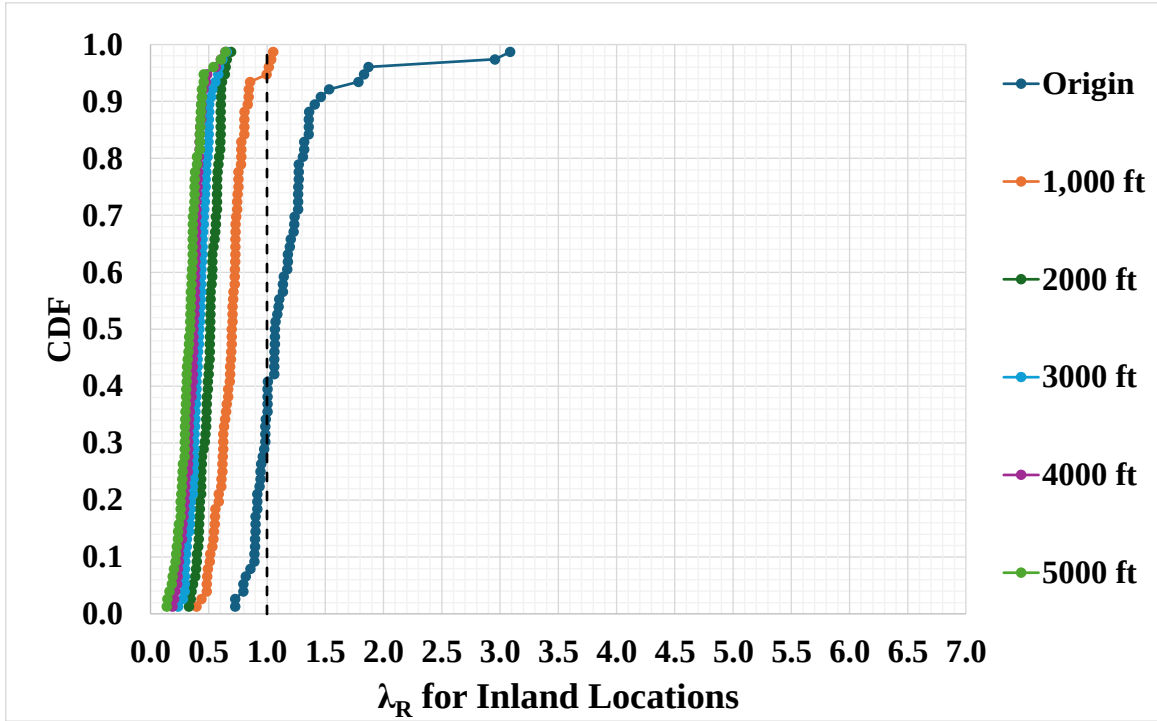


Figure 51. CDF of λ_R at origin and offset distances based on 130-mph design wind speed for inland locations

Figure 52 and Figure 53 present the corresponding CDFs for the same locations under for the 139-mph reference wind speed for coastal and inland neighborhoods respectively. In this case, beyond an offset distance of 3,000 ft, approximately 60% of the inland and 10% of the coastal simulation cases show relative risk values below one.

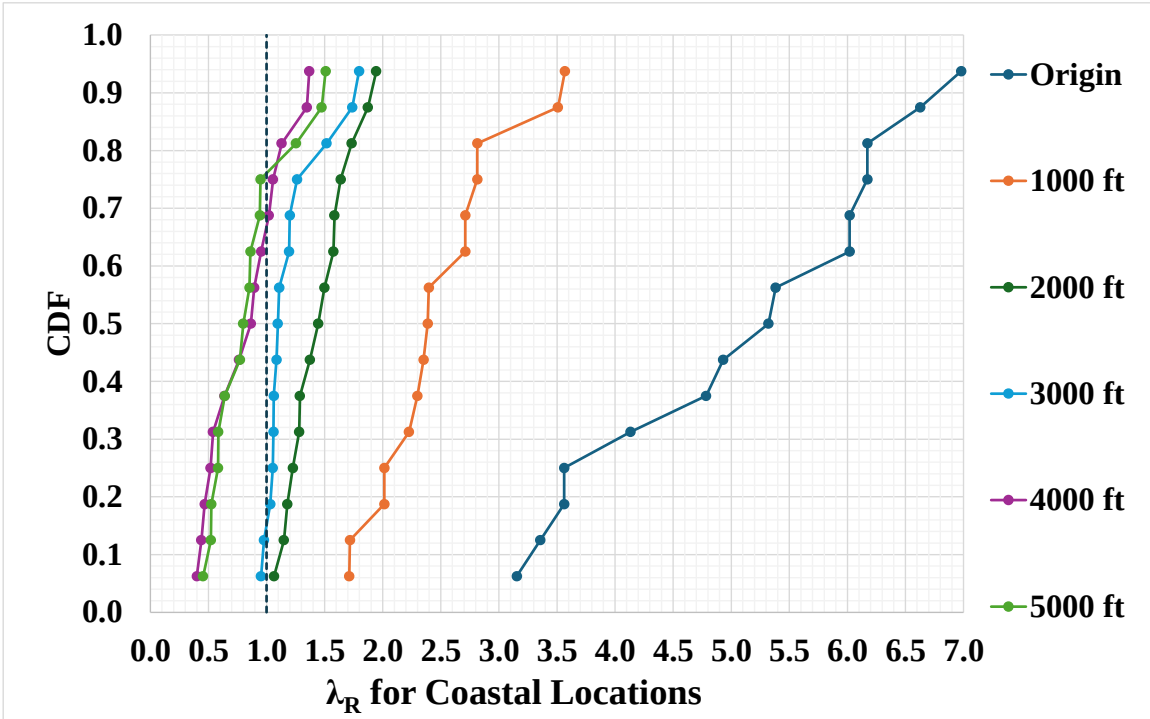


Figure 52. CDF of λ_R at origin and offset distances based on 139 mph design wind speed for coastal locations

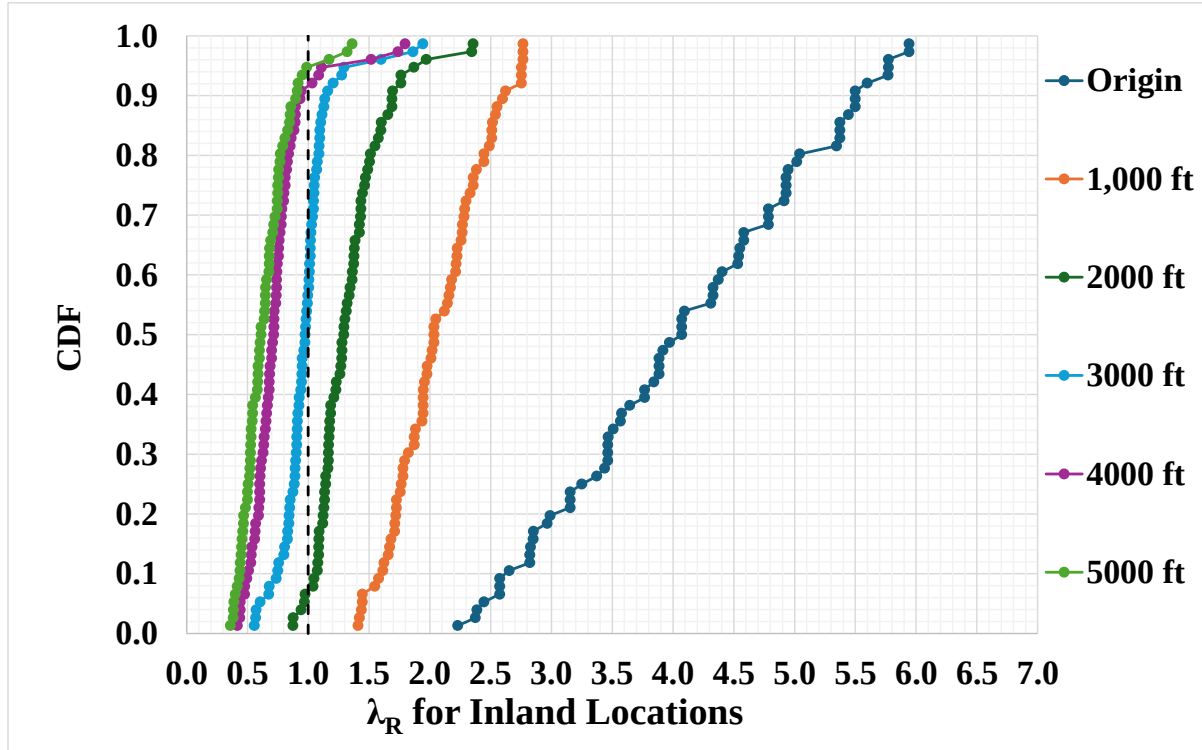


Figure 53. CDF of λ_R at origin and offset distances based on 139 mph design wind speed for inland locations.

λ_R values in both groups follow similar directional patterns and magnitudes, reinforcing that geographic location (coastal vs. inland) is not a meaningful indicator of debris risk when terrain exposure is equivalent. This finding supports the removal of the “coastal” reference in ASCE 7-22 and a shift toward terrain- and exposure-based criteria.

3.4.2.2 Case B: Hip vs Gable Roof Shape

The base neighborhood model used for calculating all $\bar{\lambda}_w$ values contains 81 houses, of which only two have gable roofs. To evaluate the influence of roof shape on debris generation and window-damage potential, a sensitivity analysis was conducted in which all structures retained their original number of stories but were modeled with gable roof shapes while maintaining FBC-compliant asphalt shingle roofs. To examine the effects across a representative range of conditions, a subset of neighborhoods was selected based on the maximum and minimum λ_R from the 139-mph CDF at origin locations.

Mexico Beach exhibits the highest λ_R value across all neighborhoods, independent of wind direction, whereas Lake Dora exhibits the lowest. To evaluate behavior in coastal and inland settings, the maximum and minimum λ_R neighborhoods were also identified within each classification. Lake Dora and Palm Coast represent the minimum λ_R cases for inland and coastal neighborhoods, respectively, while Lake Tibet and Mexico Beach represent the maximum cases

for inland and coastal areas. Figure 54 shows Google Earth imagery for each of the selected neighborhoods for this sensitivity analysis.



Figure 54. Sensitivity neighborhoods

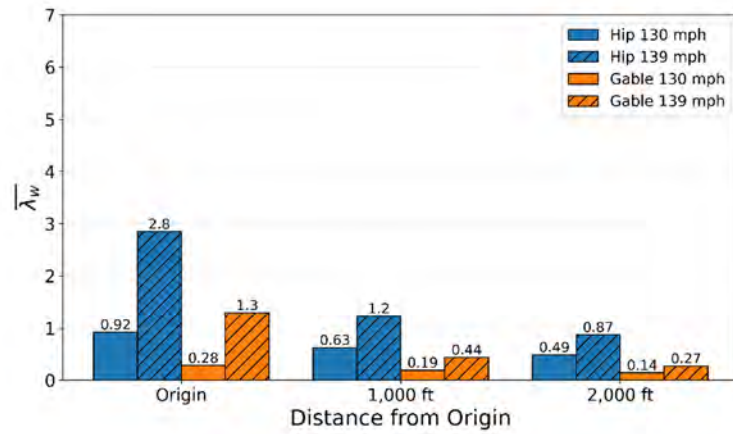
Figure 55 presents $\bar{\lambda}_w$ for Mexico Beach at the first three offset distances (origin, 1,000 ft, and 2,000 ft). The results show that, for wind directions of 215° and 270° relative to the neighborhood's north-south orientation, neighborhoods composed entirely of gable-roof structures produce substantially higher mean impact counts than the corresponding hip-roof configuration, in contrast to the 0° wind direction. This pattern is consistent with the wind-pressure coefficients shown in Figures 4 and 5. For winds approaching from 0°, the pressure coefficients for gable roofs are lower than those for hip roofs, resulting in reduced debris generation for that wind direction. For the other wind directions evaluated, the pressure loads on gable roofs exceed those on hip roofs, producing higher debris-generation rates and, consequently, higher damaging-impact counts for gable-roof neighborhoods.

Figure 56 presents λ_R values for both gable-roof and hip-roof cases at reference wind speeds of 130 mph and 139 mph, for all three wind directions, at the three offset distances evaluated for the Mexico Beach neighborhood. Figure 56 (a) shows the effect of the roof pressure coefficients for gable roof structures for the 0° wind direction is not as pronounced as it appears in Figure 55 when comparing $\bar{\lambda}_w$ values directly. All the λ_R values for both roof types move closer to one as the offset distance from the origin increases, indicating that the effect of roof shape on λ_R diminishes with increasing distance from the open-water boundary.

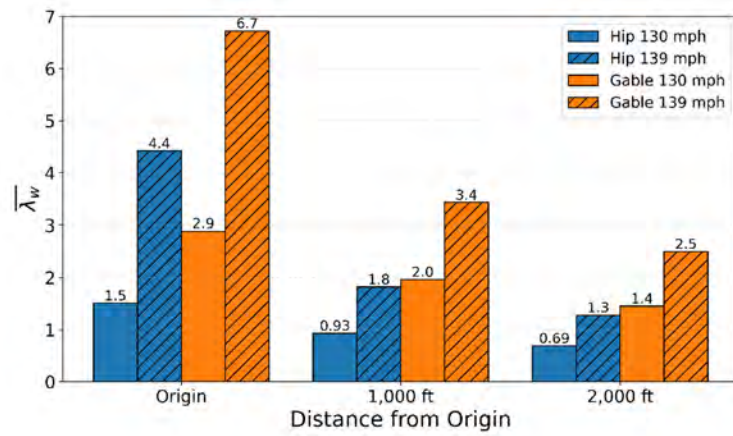
To further illustrate the influence of roof shape on λ_R , the ratio of the λ_R values for gable-roof cases to those for hip-roof cases was computed for the three wind directions at the origin location for all neighborhoods selected in the Case B sensitivity analysis. The resulting comparisons are presented in

Figure 57. A ratio of 1 indicates that roof shape has little to no effect on WBD risk. The 0° wind direction shows a higher λ_R ratio for gable structures due to the normalization applied to the λ_R values prior to computing the ratio with the corresponding hip-roof results. Lake Dora shows the least sensitivity to roof-shape differences at the origin location. Overall, the variation in ratios among the four sensitivity neighborhoods does not indicate a systematic difference between coastal and inland sites when comparing the neighborhoods associated with the maximum and minimum λ_R values.

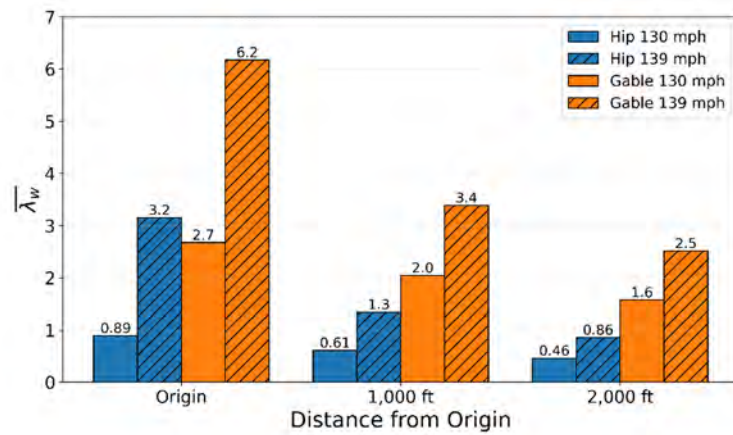
Figure 53 shows that for the 3,000 ft offset, all locations exhibit little sensitivity to roof shape for WBD risk for any of the selected neighborhoods. Since the effect of roof shape is shown to be minimal for the 3,000 ft offset case and 139-mph reference wind speed, we conclude that choice of roof shape does not have a significant impact on this report's conclusions.



(a) 0° Relative Wind Direction

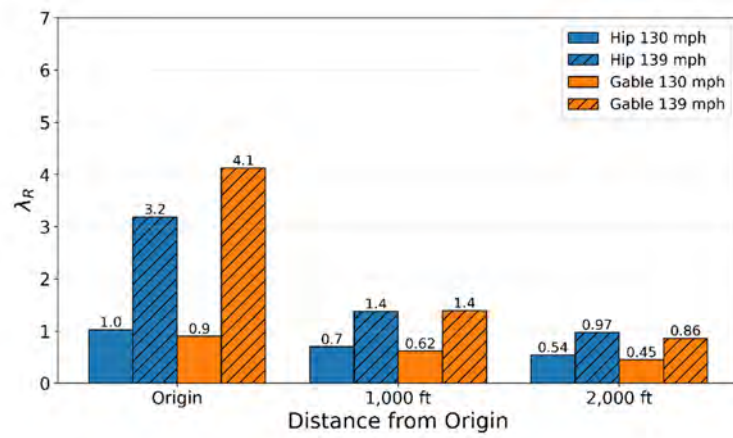


(b) 215° Relative Wind Direction

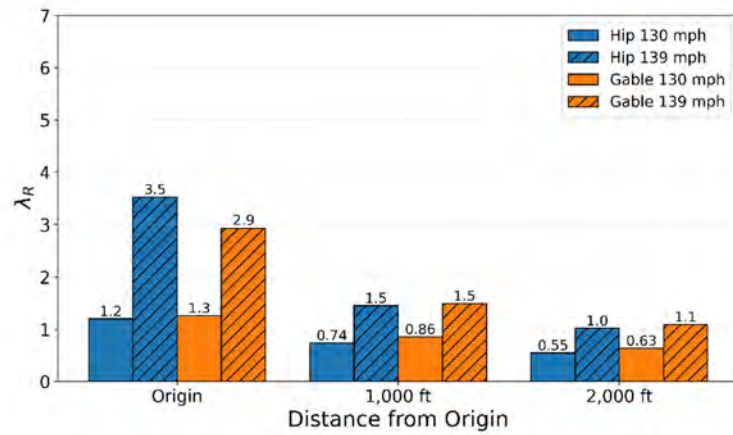


(c) 270° Relative Wind Direction

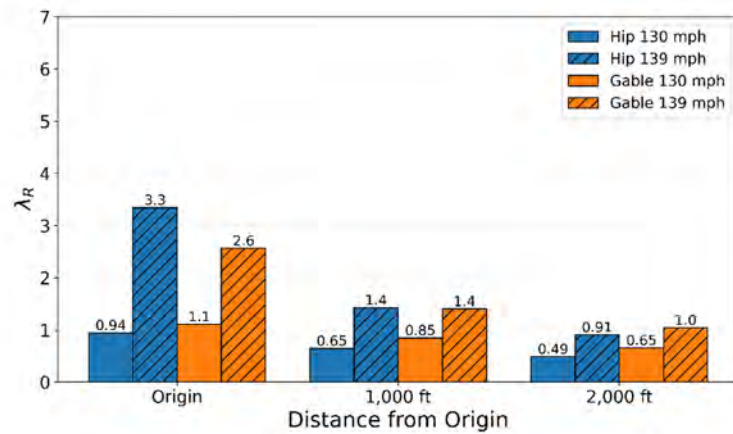
Figure 55. Comparison of $\overline{\lambda_w}$ for Mexico Beach by relative wind direction for three distances moving inland from the origin



(a) 0° Relative Wind Direction



(b) 215° Relative Wind Direction



(c) 270° Relative Wind Direction

Figure 56. Comparison of λ_R for Mexico Beach by relative wind direction for three distances moving inland from the origin

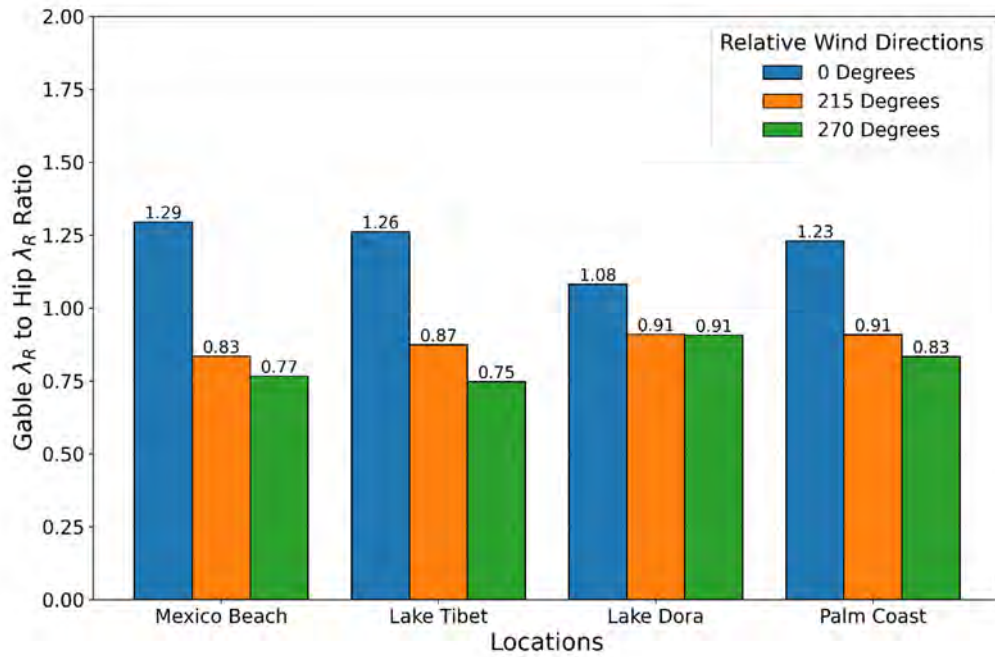


Figure 57. Ratio of gable λ_R to hip λ_R at the origin for a reference wind speed of 139-mph for the selected neighborhoods

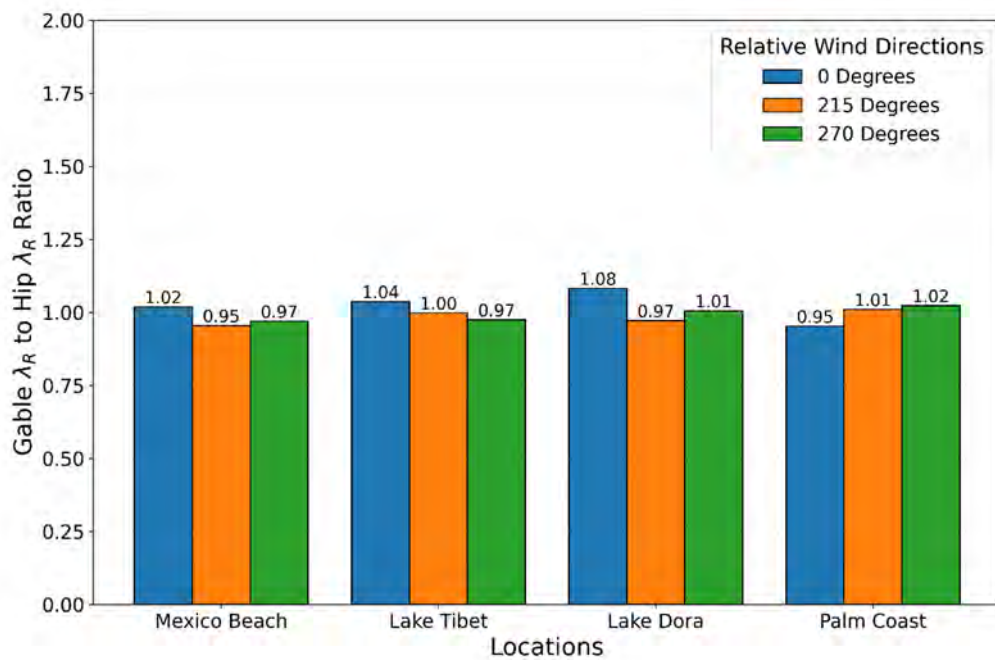


Figure 58. Ratio of gable λ_R to hip λ_R at 3,000 ft offset from the origin for a reference wind speed of 139-mph for the selected neighborhoods

3.4.2.3 Case C: High Building Density versus Low Building Density Neighborhoods

A sensitivity analysis was conducted to evaluate the influence of neighborhood housing density on damaging window impacts. Housing densities for Florida neighborhoods were characterized using a houses-per-acre metric. These densities were derived by identifying neighborhood center points and counting residential structures within polygonal regions that excluded large water bodies and vegetated areas to avoid underestimating density. Using this method, the neighborhood densities ranged from 0.90 houses per acre at Lake Down to 4.16 houses per acre at Lake Jessup. The Lake Louisa neighborhood has a measured housing density of 3.47 houses per acre.

The modeled Lake Louisa neighborhood, however, exhibits a higher density of 4.74 houses per acre, exceeding all neighborhood densities listed in the table, and is therefore classified as a high-density case. This discrepancy arises because the modeled homes have smaller footprints than the actual homes in Lake Louisa by approximately 950 ft², while maintaining the original on-center spacing. As a result, more buildings fit within the same neighborhood footprint, increasing the modeled housing density relative to real development. To create a low-density model, the low bound of 0.90 houses per acre for Lake Down was applied to the neighborhood area of Lake Louisa resulting in what should be 15.37 houses which was rounded up to 16 houses. The houses were assigned building types matching the relative proportional amounts in the Lake Louisa Neighborhood model as shown in

Table 14. To maintain the houses per acre the houses were all spaced equally within the neighborhood as shown in Figure 59.

Table 13. House densities for Florida

Neighborhood	Neighborhood Area (acres)	Total no. of houses	Houses/acre
Lake Down	31.04	28	0.90
Lake Tibet	58.67	54	0.92
Lake Butler	80.78	79	0.98
Lake Tohopekaliga	61.29	66	1.08
Lake Weir	25.44	31	1.22
Hernando beach	62.35	101	1.62
Little lake harris	26.57	50	1.88
Lake Panasoffkee	41.46	83	2.00
Deer point Lake	41.87	84	2.01
Apalachicola	32.77	67	2.04
Lake Alfred	21.93	46	2.10
Lake Apopka	43.08	91	2.11
St. Joseph's Bay	49.04	107	2.18
Lake Minnehaha	19.1	42	2.20
Daytona beach	47.59	105	2.21
Lake Eustis	40.48	90	2.22
Lake Conway	23.36	54	2.31
St. Andrew bay	42.43	106	2.50
Lake Monroe	40.8	102	2.50
East bay	19.11	49	2.56
Palm Coast	96.78	259	2.68
Big Lake Harris	17.37	47	2.71
Lake Ariana	32.84	89	2.71
John's Lake	29.29	80	2.73
Daytona beach 2	25.97	75	2.89
Lake Minneola	31.52	94	2.98
Mexico beach	67.98	204	3.00
Lake Dora	28.04	93	3.32
Lake George	24.51	83	3.39
Lake Louisa	23.339	81	3.47
Coconut palms	16.99	62	3.65
Lake Jessup	24.527	102	4.16

Figure 60 shows the low-density model with an expanded neighborhood with two rows of additional housing following the earlier analysis. The additional houses were added to the low-density model based on the two rows of additional housing added to the base Lake Louisa model in the Y-axis as pictured in Figure 37. In line with the Expanded Lake Louisa Neighborhood model, the 48 additional houses were modeled using the HR1 building characteristics.

Table 14. Housing comparison between base neighborhood and low-density neighborhood

Model	House Model	House Count	House Percentage of Neighborhood
Base Neighborhood	HR1	53	65%
	HR2	26	32%
	GR1	2	2%
Low Density Neighborhood	HR1	10	63%
	HR2	5	31%
	GR1	1	6%

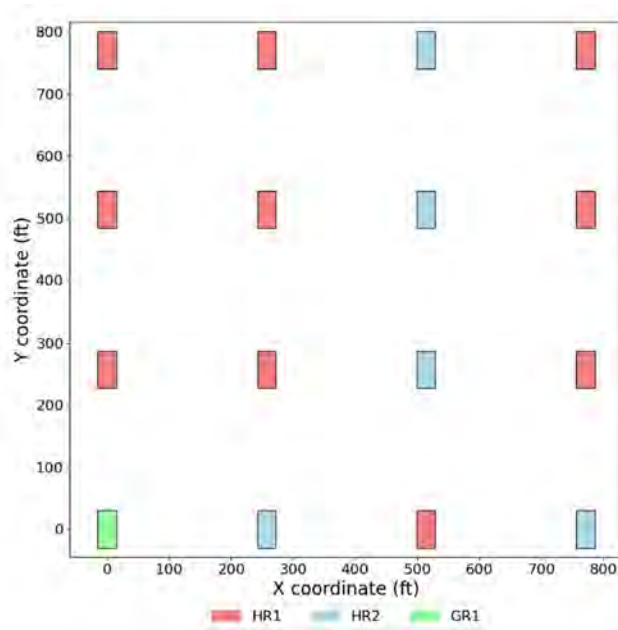


Figure 59. Low density model house layout.

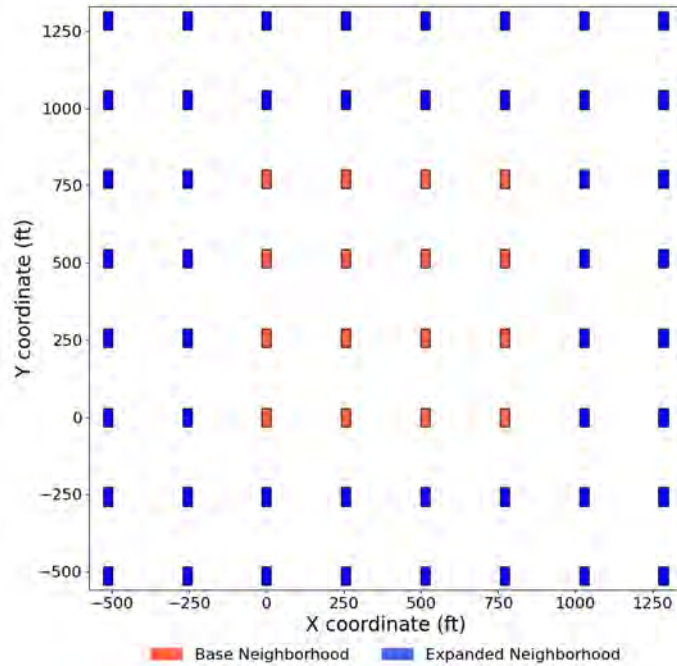
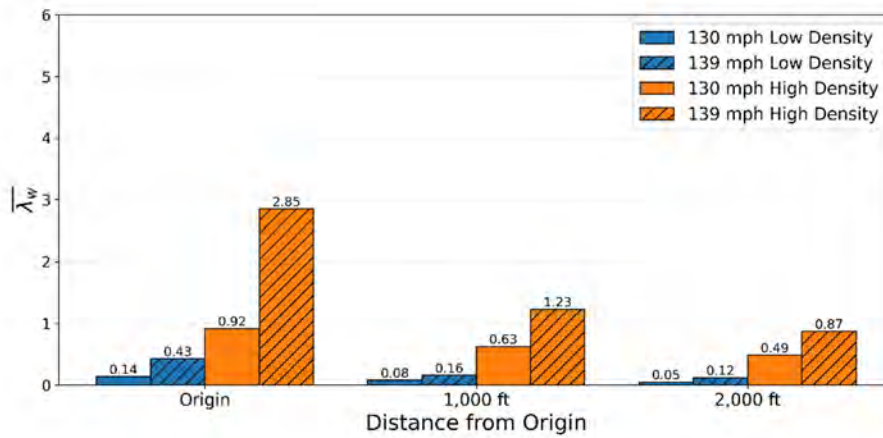


Figure 60. Expanded neighborhood for the low-density model.

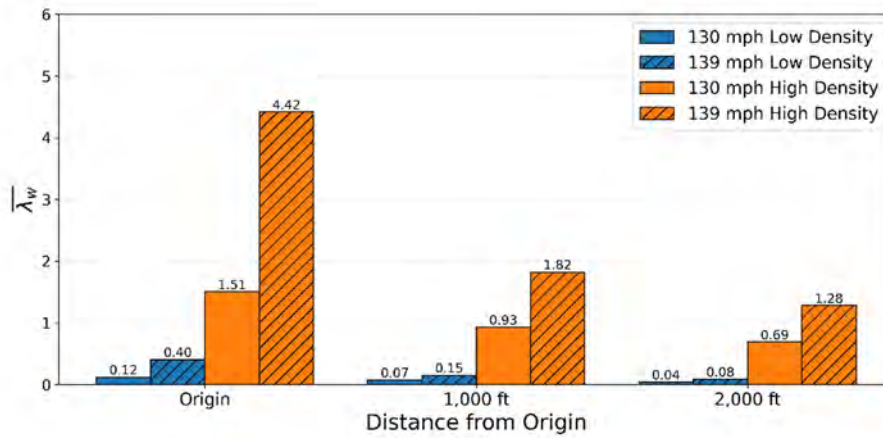
As with the roof shape sensitivity analysis, the same four neighborhoods were evaluated using their corresponding Z_0 values and to compare results from the Lake Louisa (high-density) model to those from the low-density configuration. Figure 61 and Figure 62 show $\bar{\lambda}_w$ and λ_R , respectively, for the Mexico Beach neighborhood. Figure 61 shows that $\bar{\lambda}_w$ s are approximately 6 to 11 times higher for the high-density neighborhood at the origin across all wind directions at 139 mph. Similarly, Figure 62 demonstrates an increase in λ_R for high-density relative low-density neighborhoods at 139 mph for most cases. This indicates that the WBD risk generally elevated in high-density areas, such as the Lake Louisa neighborhood.

Figure 63 presents the ratio of λ_R between high- and low-density neighborhoods at 4,000 ft offset from the origin for all locations analyzed. A ratio of 1 indicates that housing density has little effect on WBD risk. All locations show ratios higher than 1 in 0° and 215° relative wind directions and less than 1 for 270° wind directions. The similarity in ratios across the four sensitivity neighborhoods indicates limited sensitivity to coastal versus inland conditions when examining the maximum and minimum λ_R locations at the origin.

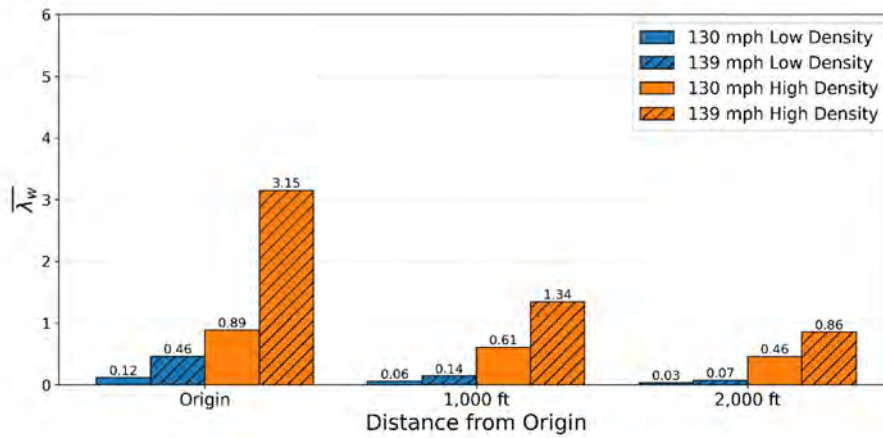
Figure 64 shows the ratio of λ_R between high and low density neighborhoods at 4,000 ft from the origin for all locations analyzed. All cases demonstrate an increase in λ_R with higher housing density, confirming that increased neighborhood density elevates WBD risk. This observed trend supports the conclusion that the selection of the Lake Louisa neighborhood (representing a high-density configuration) was a conservative choice for this analysis.



(a) 0° Relative Wind Direction

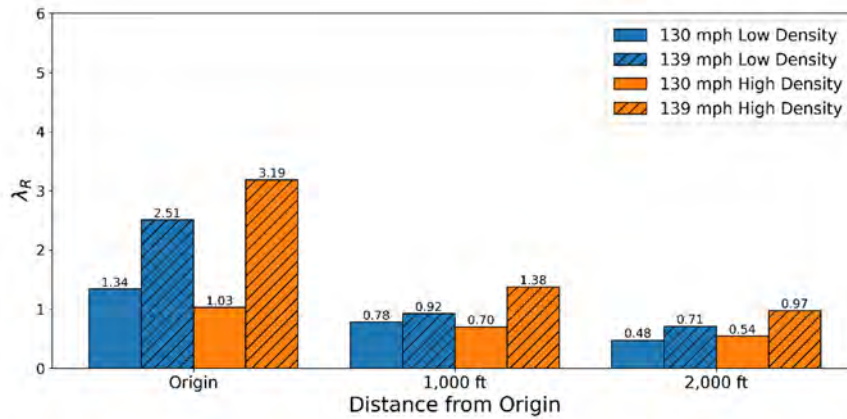


(b) 215° Relative Wind Direction

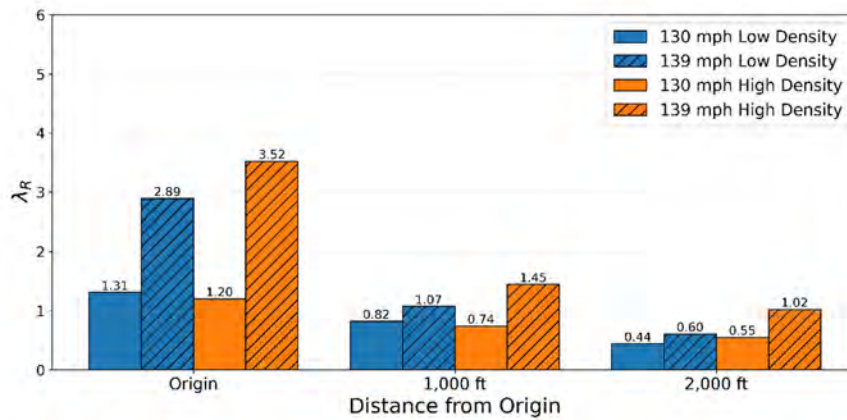


(c) 270° Relative Wind Direction

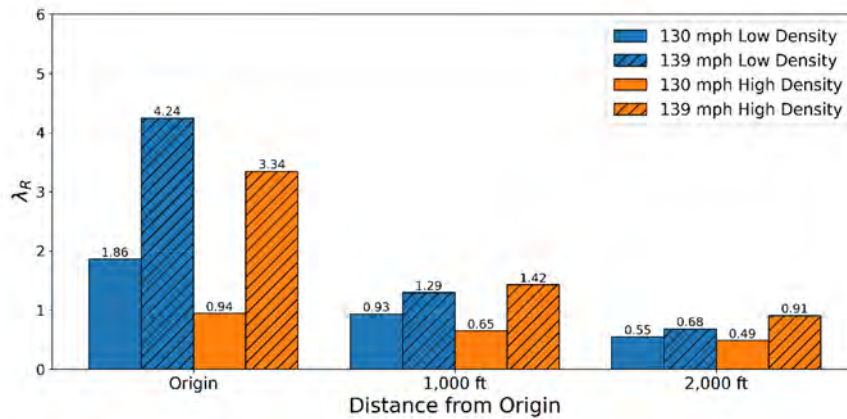
Figure 61. Comparison of $\overline{\lambda_w}$ for Mexico Beach by relative wind direction for 3 distances moving inland from the origin for housing density



(a) 0° Relative Wind Direction



(b) 215° Relative Wind Direction



(c) 270° Relative Wind Direction

Figure 62. Comparison of λ_R for Mexico Beach by relative wind direction for 3 distances moving Inland from the origin for housing density

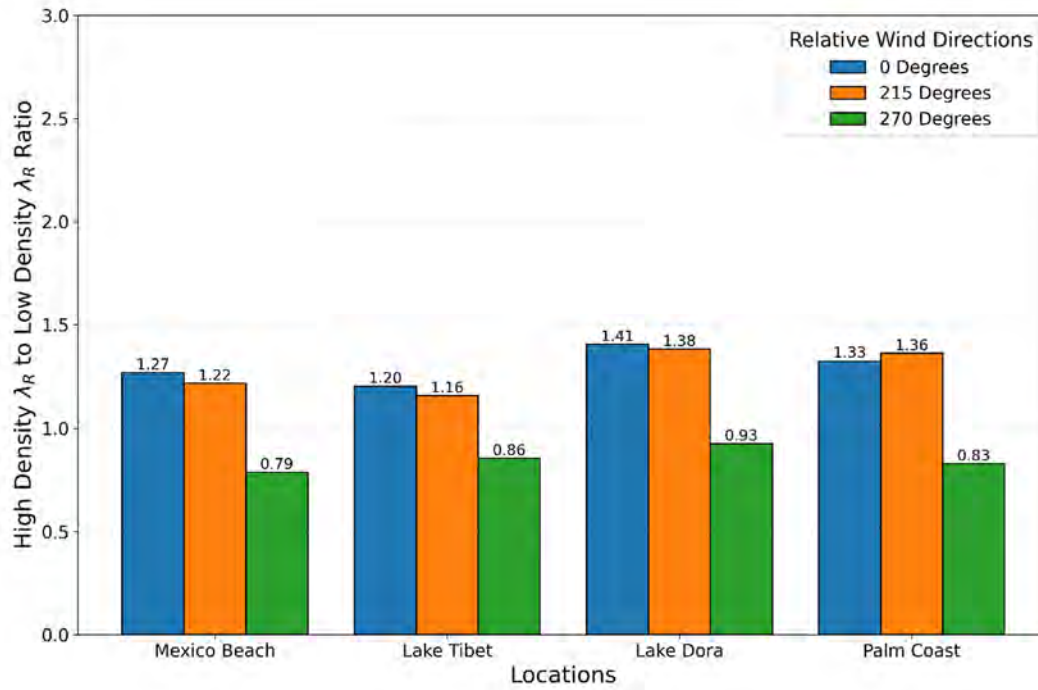


Figure 63. Ratio of high density λ_R to low density λ_R at the origin for a reference wind speed of 139-mph for the selected neighborhoods

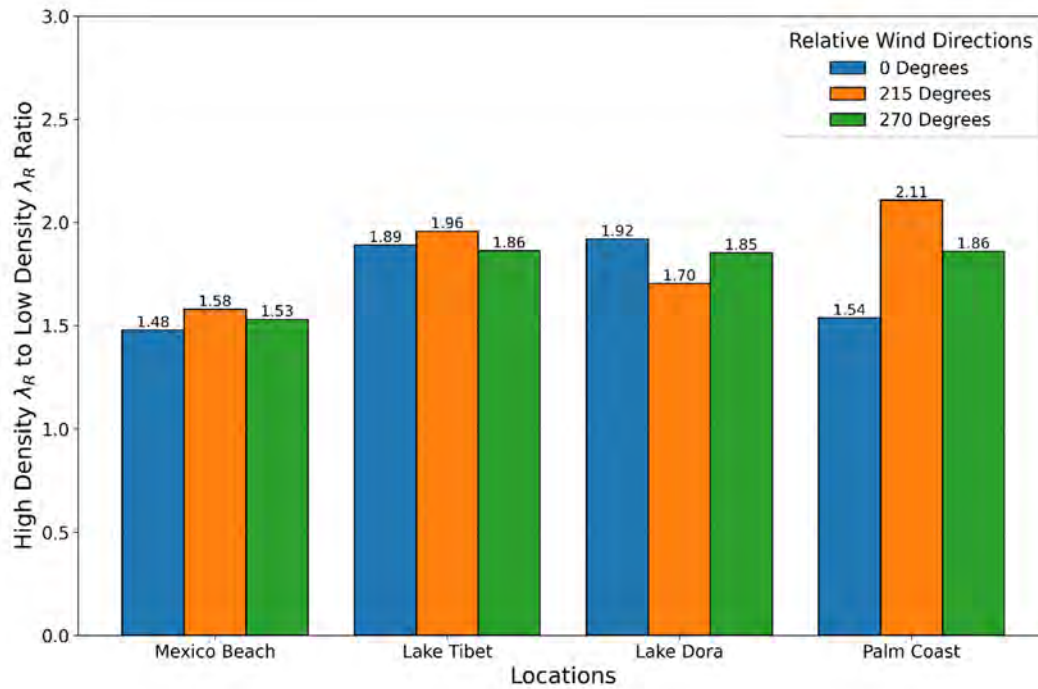


Figure 64. Ratio of high density λ_R to low density λ_R at 4,000 foot offset from the origin for a reference wind speed of 139-mph for the selected neighborhoods

4 Impact of Neighborhood Characteristics

The Phase II analysis provides a more realistic evaluation of WBD risk by incorporating detailed residential construction characteristics and refined λ_R definition. Compared with the idealized Phase I model, the Phase II framework indicates that:

- ***Distance from open water remains the dominant predictor of debris risk.*** Across all neighborhoods, λ_R decreases steadily with inland distance. For typical Florida inland-lake and coastal sites, WBD risk generally falls below the ASCE 7 Exposure B at 140-mph reference condition by approximately 3,000 ft from open water for both 130-mph and 139-mph reference wind speeds.
- ***Coastal versus inland geographic classification is not a meaningful distinguishing factor.*** When adjusted for directional terrain roughness and fetch, coastal and inland locations exhibit comparable WBD risk profiles. This is consistent with the directional Z_0 -based analysis in Phase II and supports the ASCE 7-22 decision to remove the “coastal” designation for WBDRs.
- ***Roof covering type substantially affects debris risk near open water.*** Tile roofing produces markedly more debris than shingles in smoother terrain conditions. Differences diminish with increasing roughness and are nearly erased at Exposure B ($Z_0 = 0.35$).
- ***Roof shape effects are directional and diminish inland.*** Gable roofs produce more debris than hip roofs for wind directions associated with higher roof pressure coefficients; however, λ_R differences become negligible by the 3,000-ft offset for all sensitivity neighborhoods.
- ***Neighborhood housing density significantly influences debris production.*** High-density neighborhoods exhibit $\bar{\lambda}_w$ values 6 to 11 times higher than low-density neighborhoods under 139-mph winds, and λ_R values consistently higher at both origin and inland offsets. This indicates that Phase II results using the Lake Louisa (high-density) base case represent a conservative estimate of WBD risk.

Overall, these findings support a terrain- and distance-based approach to WBDR designation and indicate that the current one-mile criterion is conservative for inland-lake and coastal settings.

5 Conclusions and Recommendations

The results presented in this report provide an assessment of the risk for WBD damage in Florida as a function of terrain-dependent exposure for buildings subject to wind speeds below 140 mph. Hurricane damage assessment reports observe that WBD damage occurs at wind speeds well below 140 mph, regardless of exposure conditions and distances from the coast. Based on the widespread WBD damage observed following Hurricane Charley (2004) the FEMA MAT team recommended that 120 mph would be an appropriate threshold wind speed for the designation of WBDRs. Observations of WBD damage following Hurricane Michael (2018) highlighted that it can occur well beyond one mile of the coast, indicating that wind speed is a dominant factor in the generation of damaging WBD. These damage assessments support lowering the WBDR

threshold wind speed below the current ASCE 7 level of 140 mph and removing proximity to the coast (or any large water body creating an Exposure D condition) as a factor in the designation.

Design-level hurricane events are, by definition, rare. For a 700-year mean recurrence interval (used for the design wind speed maps for Risk Category II buildings) there is less than a 7% probability that one will occur over 50 sequential years, and there has been only one event approaching design-level in the central region of Florida with wind speeds between 130 and 139 mph in over 100 years. As a result, simulation was used to compare the risk for WBD damage when houses are subject to wind speeds from 130 to 139 mph and have terrain exposures associated with proximity to large water bodies to the risk for WBD damage in conditions that are already accepted in ASCE 7 to designate WBDR: 140 mph wind in Exposure B conditions.

When neighborhoods are adjacent to large bodies of water that create Exposure D conditions (>5,000 ft of fetch into the upwind direction), the smoother terrain results in higher wind speeds that can impact the generation and transport of WBD. As the distance from the Exposure D condition increases, the terrain roughness increases and wind speeds are reduced. The terrain conditions surrounding 30 Florida neighborhoods located on large inland and coastal water bodies were evaluated to assess the difference between coastal, inland bay, and inland lake proximity. When the direction of the smoothest upwind condition is considered, there are no appreciable differences in the surface roughness controlling wind design between inland and coastal neighborhoods. Furthermore, the terrain roughness increases similarly with distance from the waterline for both coastal and inland neighborhoods. The resulting conclusion is that the distinction of a “coastal” condition should not be used in defining a WBDR in ASCE 7-22.

The HURMis model simulates WBD trajectories and impacts in residential neighborhoods during hurricane events. The model has been validated with damage and debris flight observations from Hurricanes Erin and Andrew and further refined and calibrated against wind tunnel experiments. HURMis was employed to determine the distance from the waterline that the risk for WBD damage was equivalent to the accepted WBDR with 140 mph Exposure B conditions. This risk equivalency approach was used to determine the appropriate WBDR boundary from large water bodies that create Exposure D conditions.

The simulation results determined that an appropriate boundary for designating WBDR in proximity to large water bodies creating an Exposure D condition is 3,000 ft when design wind speeds range from 130 – 139 mph. This modeling also demonstrated that the coastal vs. inland variants of Exposure D designation is not a meaningful distinguishing factor in WBD damage risk. Additional conclusions demonstrate that while roof type, roof shape, and housing density all impact WBD risk, when normalized by the amount of potential WBD damage in the same neighborhood configuration subject to 140 mph Exposure B, the differences become negligible at the 3,000-ft boundary.

An analysis of all 30 neighborhoods in this study shows that there are small differences in the house spacing, roof material, and number of stories between coastal and inland neighborhoods when evaluated in aggregate, but not of a magnitude or consistency to warrant their consideration in the evaluation of relative WBD damage risk. This is especially true given that

the relative risk for WBD damage becomes negligible at the 3,000 feet boundary for all neighborhood housing characteristics.

5.1 Recommendations

- Based on evidence and recommendations from hurricane damage assessments, consider a blanket WBDR threshold of 130 mph.
- If there is a preference to use the current WBDR definition to establish acceptable WBD damage risk, then regions within 3,000 ft of a body of water creating an Exposure D condition should be designated as WBDR when the basic wind speeds are between 130 and 139 mph.
- Regardless of the threshold established for designating a WBDR, it should not be specifically referenced to the coast but rather to exposure conditions.
- Additional research in the form of targeted WBD hurricane damage assessments, wind tunnel studies to evaluate the impact of terrain transitions on wind loads, and advanced modeling to evaluate absolute WBD risk is recommended.

6 References

- American Society of Civil Engineers (2022). *Minimum Design Loads and Associated Criteria for Buildings and Other Structures*. ASCE Standards ASCE/SEI 7-22.
- ARA (1996). Analysis of Hurricane Windborne Debris Impact Risk for Residential Structures. Report prepared for State Farm Mutual Automobile Insurance Company.
- ARA (2008). Wind Borne Debris/Terrain Research. Presented to Florida Building Commission, Hurricane Research Advisory Committee, December 2008
- E.S.D.U.((1974a) Characteristics of Atmospheric Turbulence near the Ground — I. Definitions and General Information. Data Item 74030
- E.S.D.U.((1974b) Characteristics of Atmospheric Turbulence near the Ground — 2. Single Point Data for Strong Winds (Neutral Atmosphere). Data Item 74031.
- Federal Emergency Management Agency (2023)., *Mitigation Assessment Team report: Hurricane Ian in Florida: Building Performance Observations, Recommendations, and Technical Guidance* (FEMA P-2342). U.S. Department of Homeland Security
- Federal Emergency Management Agency. (2005). *Mitigation Assessment Team report: Hurricane Charley in Florida: Observations, recommendations, and technical guidance* (FEMA Report No. 488). U.S. Department of Homeland Security.
- Federal Emergency Management Agency. (2019). *Mitigation Assessment Team report: Hurricane Harvey in Texas: Building Performance Observations, Recommendations, and Technical Guidance* (FEMA P-2022). U.S. Department of Homeland Security.
- Federal Emergency Management Agency. (2020). *Mitigation Assessment Team report: Hurricane Michael in Florida: Building Performance Observations, Recommendations, and Technical Guidance* (FEMA P-2077). U.S. Department of Homeland Security.
- Ghaffarian, S., & Kerle, N. (2019). TOWARDS POST-DISASTER DEBRIS IDENTIFICATION FOR PRECISE DAMAGE AND RECOVERY ASSESSMENTS FROM UAV AND SATELLITE IMAGES. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLII-2/W13, 297–302. <https://doi.org/10.5194/isprs-archives-XLII-2-W13-297-2019W>
- Gurley, K. and Masters, F. (2011), *Post 2004 Hurricane Field Survey of Residential Building Performance*. ASCE Natural Hazards Review, 12(4): 177-183.
- Jiang, S., & Friedland, C. J. (2016). Automatic urban debris zone extraction from post-hurricane very high-resolution satellite and aerial imagery. *Geomatics, Natural Hazards and Risk*, 7(3), 933–952. <https://doi.org/10.1080/19475705.2014.1003417>

- Joshua S. Graff Zivin and Gregor Singer, "Disparities in Pollution Capitalization Rates: The Role of Direct & Systemic Discrimination," NBER Working Paper 30814 (2022), <https://doi.org/10.3386/w30814>.
- Li, Hao; Deuser, Fabian; Yin, Wenping; Luo, Xuanshu; Walther, Paul; Mai, Gengchen; Huang, Wei; Werner, Martin. (2024). *CVIAN: Cross-View Geolocalization and Disaster Mapping with Street-View and VHR Satellite Imagery for Hurricane IAN* [Dataset]. <https://doi.org/10.14459/2024MP1749324>
- Meecham, D. (1988). "Wind Action on Low-Rise Buildings," M.E.Sc. Thesis, The University of Western Ontario, London, ON, Canada.
- NASA Earth Observatory. (2004, August 14). *Florida After Hurricane Charley*. NASA. NASA Earth Observatory. <https://earthobservatory.nasa.gov/images/4751/florida-after-hurricane-charley>
- NOAA National Geodetic Survey. (2017, August). *Hurricane Harvey Emergency Response Imagery*. National Oceanic and Atmospheric Administration (NOAA) / National Geodetic Survey (NGS). NOAA National Geodetic Survey (NGS) Storm Imagery. <https://storms.ngs.noaa.gov/storms/harvey/index.html>
- Stathopoulos, T. (1979). "Turbulent wind action on low-rise buildings." Ph.D. thesis, Univ. of Western Ontario, London, ON, Canada.
- Structural Extreme Event Reconnaissance Network. (2018). *Hurricane Michael preliminary virtual assessment team (P-VAT) report*. (NHERI DesignSafe Project ID: PRJ-2112) Structural Extreme Event Reconnaissance Network.
- Twisdale, L. A., Dunn, W. L., and Davis, T.L. (1979), "Tornado Missile Transport Analysis," *Nuclear Engineering and Design*, Vol. 51, 1979.
- Twisdale, L. A., Dunn, W. L., Lew, S. T., David, T. L., Hsu, J. C., and Lee, S. T. (1978), *Tornado Missile Risk Analysis*, Electric Power Research Institute, EPRI NP-768 and NP-769 (Appendixes), Palo, Alto, CA, May.
- Twisdale, L.A. Dunn, W. L., Lew, S. T., David, T. L., Hsu, J. C., and Lee, S. T. (1981). *Tornado Missile Simulation and Design Methodology*, EPRI NP-2005, Volumes 1 and 2, Electric Power Research Institute, Palo Alto, CA, August.
- Twisdale, L.A. et al., (2002). *Development of Loss Relativities for Wind Resistive Features of Residential Structures*, prepared for Florida Department of Community Affairs, Tallahassee, FL, March.
- Vickery, P. J., G. A. Kopp and L. A. Twisdale, Jr. (2011). "Component and Cladding Wind Pressures on Hip and Gable Roofs: Comparisons to the US Wind Loading Provisions," *13th International Conference on Wind Engineering*, Amsterdam, The Netherlands.

- Vickery, P. J., Skerlj, P. F., Lin, J., Twisdale, L. A., Jr., Young, M. A., & Lavelle, F. M. (2006). *HAZUS-MH Hurricane Model Methodology. II: Damage and Loss Estimation*. In *Natural Hazards Review* (Vol. 7, Issue 2, pp. 94–103). American Society of Civil Engineers (ASCE). [https://doi.org/10.1061/\(asce\)1527-6988\(2006\)7:2\(94\)](https://doi.org/10.1061/(asce)1527-6988(2006)7:2(94))
- Winans, W. R., Chen, Q., Qiang, Y., & Franklin, E. C. (2023). Large-area automatic detection of shoreline stranded marine debris using deep learning. *International Journal of Applied Earth Observation and Geoinformation*, 124, 103515. <https://doi.org/10.1016/j.jag.2023.103515>
- Womble, J. A., Adams, B. J., Ghosh, S., & Friedland, C. J. (2008). Remote Sensing and Field Reconnaissance for Rapid Damage Detection in Hurricane Katrina. *Structures Congress 2008*, 1–10. [https://doi.org/10.1061/41016\(314\)264](https://doi.org/10.1061/41016(314)264)
- Zhai, Wei, and Zhong-Ren Peng. “Damage Assessment Using Google Street View: Evidence from Hurricane Michael in Mexico Beach, Florida.” *Applied Geography* 123 (October 2020): 102252. <https://doi.org/10.1016/j.apgeog.2020.102252>.
- Zillow. (2026). *Zillow Transaction and Assessment Database (ZTRAX), United States, 1940-2020* [Dataset]. Inter-university Consortium for Political and Social Research [distributor]. <https://doi.org/10.3886/ICPSR39652.v2>

7 Appendix A: Representativeness Analysis

7.1 Data Representativeness Analysis

A representativeness analysis was conducted to determine whether parcels with usable building-attribute data were similar to the residential parcel dataset within the 1-mile buffer of each neighborhood. The analysis focused on whether complete-data parcels were spatially and geometrically comparable to all residential parcels in the neighborhood.

The representative analysis used three screening metrics: spatial quadrant distribution difference, spatial centroid offset, and parcel-area difference. Data completeness was reported separately for transparency but was not used to determine the final representative flag.

7.1.1 Spatial Quadrant Distribution (*SpatialQuadTVD*)

The Spatial Quadrant Total Variation Distance (TVD) evaluates whether complete/partial data parcels are spatially distributed in a manner consistent with all the residential parcels. Each neighborhood was divided into four spatial quadrants (see Figure 65). The percentage of all complete/partial data parcels in each quadrant was then compared with the percentage of all residential parcels in each quadrant.

To spatial quadrant difference was also quantified using the TVD:

$$spatialQuadTVD = \frac{1}{2} \sum_{q=1}^4 |P_{partial,q} - P_{all,q}| \quad (4)$$

Where $P_{partial}$ is the proportion of partial data parcels in quadrant q , and $P_{all,q}$ is the proportion of all residential parcels in that quadrant.

This calculation was performed separately for each housing attribute (roof material type, number of stories and building size). To provide a conservative neighborhood-level assessment, the maximum *SpatialQuadTVD* across the attributes was retained for the final comparison. A threshold of 25% was used to flag possible spatial bias. An illustrative example of this process for Lake Louisa is presented in Table 15.

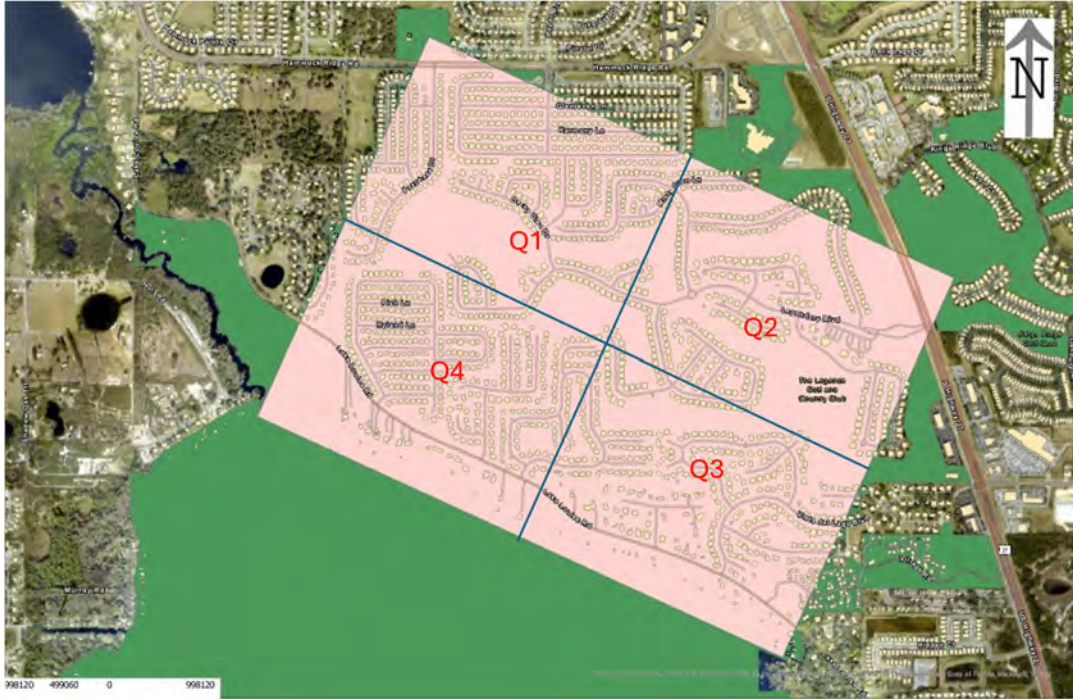


Figure 65 - One-mile study buffer for Lake Louisa with residential building polygons (yellow) and spatial quadrants (Q1–Q4) used in the representativeness analysis

Table 15 - Quadrant distribution of all residential parcels and incomplete-data parcels across Q1–Q4 with absolute percentage differences used to compute the spatial TVD for Lake Louisa

Group	Q1 %	Q2 %	Q3 %	Q4 %
All Parcels	35.946	19.949	22.753	21.351
Incomplete-data Parcels	35.969	19.962	22.768	21.301
Absolute Difference %	0.023	0.013	0.015	0.05

The Spatial Quadrant TVD is calculated as half the sum of the absolute percentage differences across all quadrants as shown in the equation above. In this example, the resulting TVD is 0.05%. To facilitate uniform comparison on the diagnostic spider plot, this metric is normalized against the 25% concern threshold (i.e., $[0.05\%/25\%] \times 100 = 0.2\%$). This normalized value indicates that the observed spatial discrepancy reaches only 0.2% of the critical threshold limit. Because the spatial deviation between the complete-data subset and the overarching residential baseline is exceptionally small, we can conclude that no meaningful spatial bias is present.

7.1.2 Maximum spatial Offset Percentage

The Spatial-Centroid Offset measures whether the center of partial data parcels is displaced from the center of all residential parcels within the one-mile buffer for each study neighborhood. First, the mean spatial centroid of all residential parcels inside the 1-mile buffer was first calculated. Then, the mean spatial center of the partial-data parcels is calculated for each housing attribute (roof material type, story levels and building size).

The straight-line distance (d) between these two centers was calculated and normalized by the diagonal length of the neighborhood bounding box:

$$Offset\% = d/L \times 100 \quad (5)$$

Where d is the distance between the residential parcel center and the partial-data parcel center, and L is the diagonal length of the neighborhood 1-mile buffer box.

Normalization by the diagonal allows the offset to be interpreted relative to the size of each neighborhood. A small offset percentage indicates that partial-data parcels are centered near the full residential parcel population and vice versa. A threshold of 20% was adopted as a screening criterion.

7.1.3 Parcel Area Difference

The parcel-area difference evaluates whether the parcels with usable building-attribute data (roof material, number of stories, or building area) are similar in size to all the full residential parcel population. For each attribute-specific subset, the mean parcel area, $\bar{A}_{partial}$ was compared with the mean parcel area of all residential parcels within the one-mile buffer, $\bar{A}_{all}$:

$$Area\ Diff\ (\%) = \left| \frac{\bar{A}_{partial} - \bar{A}_{all}}{\bar{A}_{all}} \right| \times 100 \quad (6)$$

A threshold of 50 % was adopted. Values exceeding 50 % indicate that the parcels with building attribute data are larger or smaller than the typical residential parcel and therefore may not be a good representation of the houses within the neighborhood.

7.1.4 Standardization for Spider Plots

Because the representativeness metrics have different units and concern thresholds, the raw values were standardized before being displayed on the spider plots. Each metric was divided by its corresponding threshold and multiplied by 100:

$$Standardized\ Score = \frac{raw\ metric}{threshold} \times 100 \quad (7)$$

Under this standardization, a value of 100 represents the concern threshold for every metric. Values below 100 indicate that the metric is within the acceptable screening range, while values above 100 indicate that the metric exceeds the concern threshold. This allows the spider plots to compare the relative severity of different bias indicators on a common scale.

7.1.5 Overall Representativeness Flag (OverallRepFlag)

The Overall representativeness (OverallRepFlag) was determined using a bias-only decision rule that evaluates the three spatial-bias metrics described previously (spatial-quadrant total-variation distance, centroid offset, and mean parcel-area difference). Although the completeness of the ZTRAX attributes is reported for transparency, it does not influence the flag assignment.

For each neighborhood the bias indicators are compared against their prespecified concern thresholds (25 % for spatial-quadrant TVD, 20 % for centroid offset, and 50 % for mean parcel-area difference). The flag is then assigned according to the following hierarchy:

- “Likely representative” – none of the three bias indicators exceed their thresholds.
- “Usable with caution” – a single bias indicator exceeds its threshold, suggesting a modest, localized deviation that warrants careful interpretation.
- “Potential bias – review before use” – two or more bias indicators exceed their thresholds, indicating that the available data may be skewed and that substantive validation is required before the neighborhood can be used to draw conclusions or make inferences.

The flag was used as a screening tool to determine whether each neighborhood’s housing-characteristic data were suitable for comparison between coastal and inland areas. Figure 66 - 68 illustrates the outcome of this representativeness assessment across all study neighborhoods, showing the distribution of the three flag categories and the corresponding standardized bias values on the spider plots.

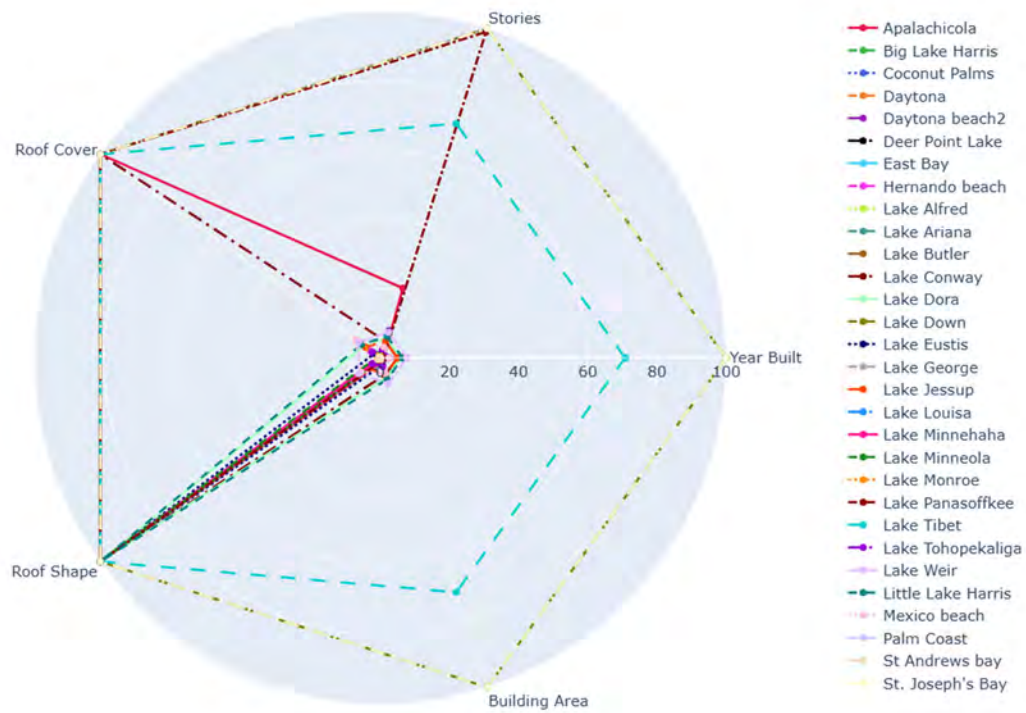


Figure 66 - Percentage missing data for all neighborhoods

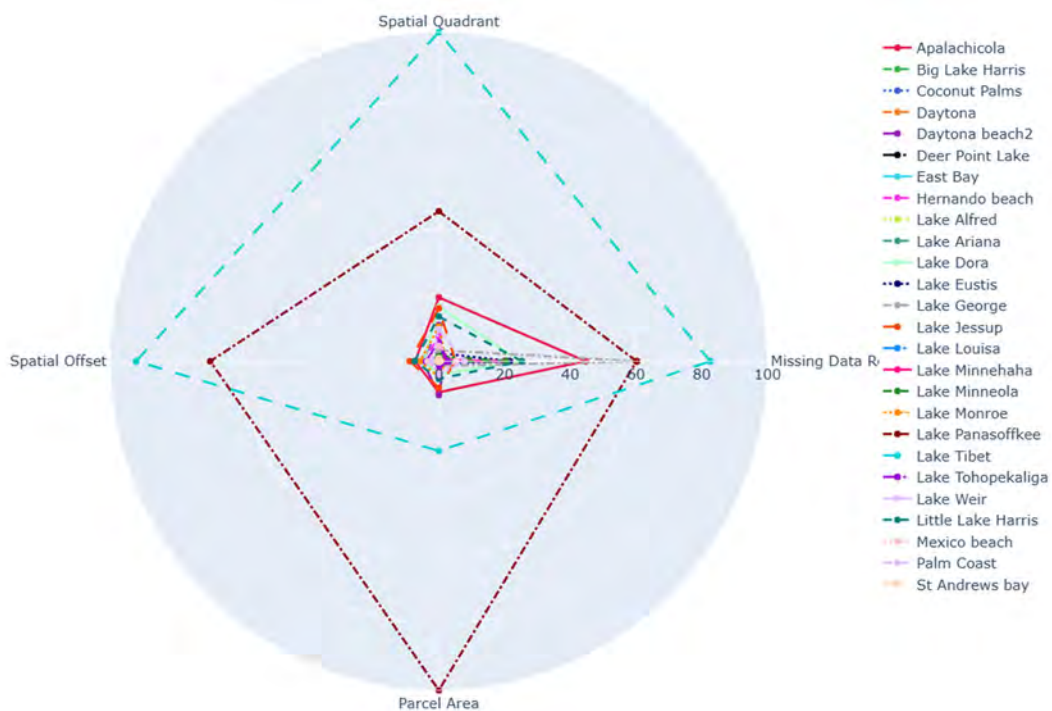


Figure 67 - Representativeness spider plot for all study neighborhoods showing standardized bias indicators

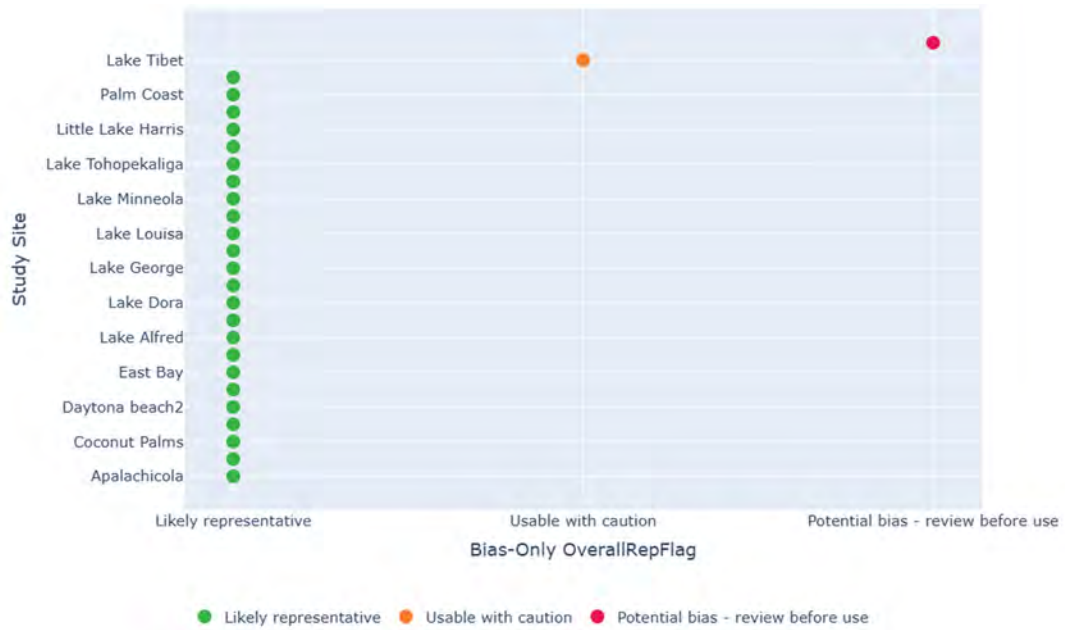


Figure 68 - Overall representative flag for the neighborhoods

Lake Butler, Lake Down, St. Joseph and Lake Conway had no data and so was not considered in the representative analysis.