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

Interim Report

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Florida Department of Business and Professional Regulation
Florida Building Commission

and

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Executive Summary

The ASCE 7-22 definition of wind-borne debris regions (WBDR) was updated for areas with design wind speeds between 130 and 140 mph. Previously, in this wind speed range, buildings within one mile of the coast were in a WBDR. The update in ASCE 7-22 removed the word "coastal" and replaced it with an Exposure D condition at the water line. This exposure condition is met when there is at least 5,000 feet of water in the upwind direction from the water line, regardless of proximity to the coastline of Florida. The change created inland regions adjacent to large lakes and inland bays meeting the new definition. The adoption of this definition change in the 8th edition of the Florida Building Code resulted in new glazing protection requirements for buildings adjacent to inland bodies of water in portions of central Florida and the panhandle.

ASCE 7 introduced provisions for design against wind-borne debris in 1995, triggered by a single wind speed. Subsequent cycles of ASCE 7 increased the trigger wind speed while retaining the lower wind speed trigger for buildings within one mile of the coast. The one-mile distance was based on anecdotal observations from post-hurricane damage assessments; however, this distance has not been validated through scientific methods. In ASCE 7-22, the updated definition that replaced reference to the "coast" with an Exposure D condition at the water line was viewed by the ASCE 7 Wind Loads Subcommittee as a correction and a simplification that removed the challenge of consistently defining the location of the coastline.

This interim report includes a review of historical information, literature, and hurricane damage assessment reports. Thus far this effort confirms the need for a more rigorous scientific investigation to quantify the wind-borne debris risk in regions that are adjacent to Exposure D conditions, whether coastal or a large inland body of water.

A comprehensive review of post-hurricane damage assessments revealed two storms that resulted in wind-borne debris damage from wind speeds between 125 and 140 mph in regions adjacent to coastal Exposure D conditions. After Hurricane Charley (2004) wind-borne debris damage was noted in several locations more than three miles from the coast. Wind-borne debris damage was also noted after Hurricane Michael (2018), in this case more than three miles from an inland bay. These observations demonstrate the need to evaluate the one-mile distance with respect to wind-borne debris damage risk, and that the risk does exist when the closest body of water is not the direct coastline. We have not identified reports of damage during design wind speed events in inland areas with Exposure D conditions from lakes with design wind speeds between 130 and 140 mph. This is likely due to the limited number of design level wind events in these inland regions. Post-storm damage assessments are intended to provide a representative sampling rather comprehensive documentation and are typically prioritized to coastal regions due to relatively higher damage levels, so a dearth of observations does not preclude that such damage occurs.

A review of wind-borne debris research reveals that there have not been specific studies to guide the designation of wind-borne debris regions relative to upwind terrain conditions or how the risk for wind-borne debris damage varies with distance from terrain transitions. While some limited research has demonstrated how transition between terrain conditions impact wind loads, this research has not yet been extended to the impact on debris generation, transport, and damage.

1 Introduction and Background

1.1 Background

Damage to the windward facing envelope of buildings from the impact of wind-borne debris (WBD) can result in damaging water entry and increased internal pressures that can lead to failure of the primary structural system. Buildings in designated wind-born debris regions (WBDR) require higher levels of protection from debris impact. Prior to 2022, American Society of Civil Engineers (ASCE) 7, designated WBDRs as those where design wind speeds are above 140 mph or those between 130 and 140 mph and within one mile of the coast (coastal mean high-water line) (ASCE 7-16). The definition of WBDRs for design wind speeds between 130 and 140 mph was updated in ASCE 7-22 to remove the word "coastal" and add that an Exposure D condition must exist at the water line. An Exposure D condition is a site exposed to water surfaces in the upwind direction with a fetch of at least 5,000 ft. The result of this definition change is the designation of inland WBDRs where lakes and inland waterways provide at least 5,000 ft of fetch in the upwind direction where design wind speeds are between 130 and 140 mph; design wind speeds above 140 mph in hurricane prone regions are designated WBDR regardless of adjacent exposure conditions.

1.2 Project objectives and scope

The objective of this study is to provide the Florida Building Commission with a science-based analysis on the appropriateness of inland regions being designated as WBDRs that require increased protection for buildings. In particular, the study will seek to evaluate the differences between coastal and inland WBDRs across a number of contributing factors (e.g. exposure, land coverage, and development trends). The objectives will be achieved through an investigation into the origin of the language change (i.e. the removal of the requirement for the region to be coastal) in ASCE 7-22, a review of all relevant literature related to the designation of WBDRs, a comprehensive evaluation of available damage assessments conducted in the coastal and proposed inland WBDRs, and an analysis of debris generating potential and building damage vulnerability in the proposed regions through modeling and analysis. In addition, this study will conduct a cost analysis to estimate the difference in cost of construction to meet the design requirements for WBDRs.

The scope of work for this project consists of five tasks and accompanying deliverables:

- Task 1: Background and Literature Review
- Task 2: Data Acquisition and Analysis
- Task 3: Modeling
- Task 4: Cost Benefit Analysis
- Task 5: Reporting and Recommendations

As of this interim report, Task 1 is complete, Task 2 is near completion, Task 3 has been initiated, and Tasks 4 and 5 have yet to be started. This report provides the progress and relevant outcomes for the project to date.

2 Standard and Code Definitions

2.1 ASCE 7 and Florida Building Code

ASCE 7 provides the minimum design loads for buildings and other structures, and since 1995 it has included provisions related to the design for wind-borne debris. The Florida Building Code has largely adopted ASCE 7 standards since its first edition (FBC 2001). The historical WBDR definitions in the Florida Building Code and corresponding ASCE 7 references are summarized in Table 1.

Table 1. Summary of WBDR Definitions in Florida Building Code editions (adapted from ARA Wind-loss Mitigation Study, 2024).

Building Code(s)	ASCE Map	WBDR Definitions
FBC 2001, 2004, 2007	7-98, 7-02, 7-05	≥120 mph ≥110 mph w/in 1 mi. of coast
FBC 2010, 2014, 2017, 2020	7-10, 7-16	≥140 mph ≥130 mph w/in 1 mi. of coast
FBC 2023	7-22	≥140 mph ≥130 mph w/in 1 mi. mean water line where Exp. D exists

The 7th Ed. (2020) of the Florida Building Code for residential buildings (FBC(R), 2020) references the ASCE 7-16 WBDR definition, which are areas in hurricane-prone regions that are one of the following:

1. Within 1 mi (1.6 km) of the coastal mean high water line where the basic wind speed is equal to or greater than 130 mi/h (58 m/s), or
2. In areas where the basic wind speed is equal to or greater than 140 mi/h (63 m/s).

FBC(R) 8th Ed. (2023) references the WBDR definition in ASCE 7-22, which are areas within hurricane-prone regions located in accordance with one of the following:

1. Within 1 mile (1.61 km) of the mean high water line where an Exposure D condition exists upwind at the waterline and the ultimate design wind speed, V_{ult}, is 130 mph (58 m/s) or greater.
2. In areas where the ultimate design wind speed, V_{ult}, is 140 mph (63.6 m/s) or greater; or Hawaii.

An Exposure D condition occurs where Surface Roughness D (flat terrain and water) prevails in the upwind direction for a distance of at least 5,000 ft.

FBC(R) requires that buildings located in WBDRs provide protection for exterior glazed openings (meeting specific ASTM requirements). The result of the updated definition of WBDR in ASCE 7-22/FBC(R) 2023 is that inland regions in central Florida and the panhandle adjacent to large lakes or inland bays with design wind speeds between 130 and 140 mph will now also require buildings to have opening protections. There are stakeholders within Florida that are interested in reverting the 9th Ed. FBC(R) to the WBDR definition in the 7th Ed. based on ASCE 7-16.

Figure 1 shows the results of a preliminary analysis conducted by project research partner, Applied Research Associates, Inc. (ARA), superimposed over the ASCE 7-22 wind speed map for Florida. The highlighted inland regions in the 130-140 mph wind speed band are within one mile of the water line of lakes and inland waterways with at least 5,000 ft of fetch in the upwind direction. Figure 2 shows a detailed view of these regions in central Florida and Figure 3 shows a detailed view of these regions in the Florida panhandle.

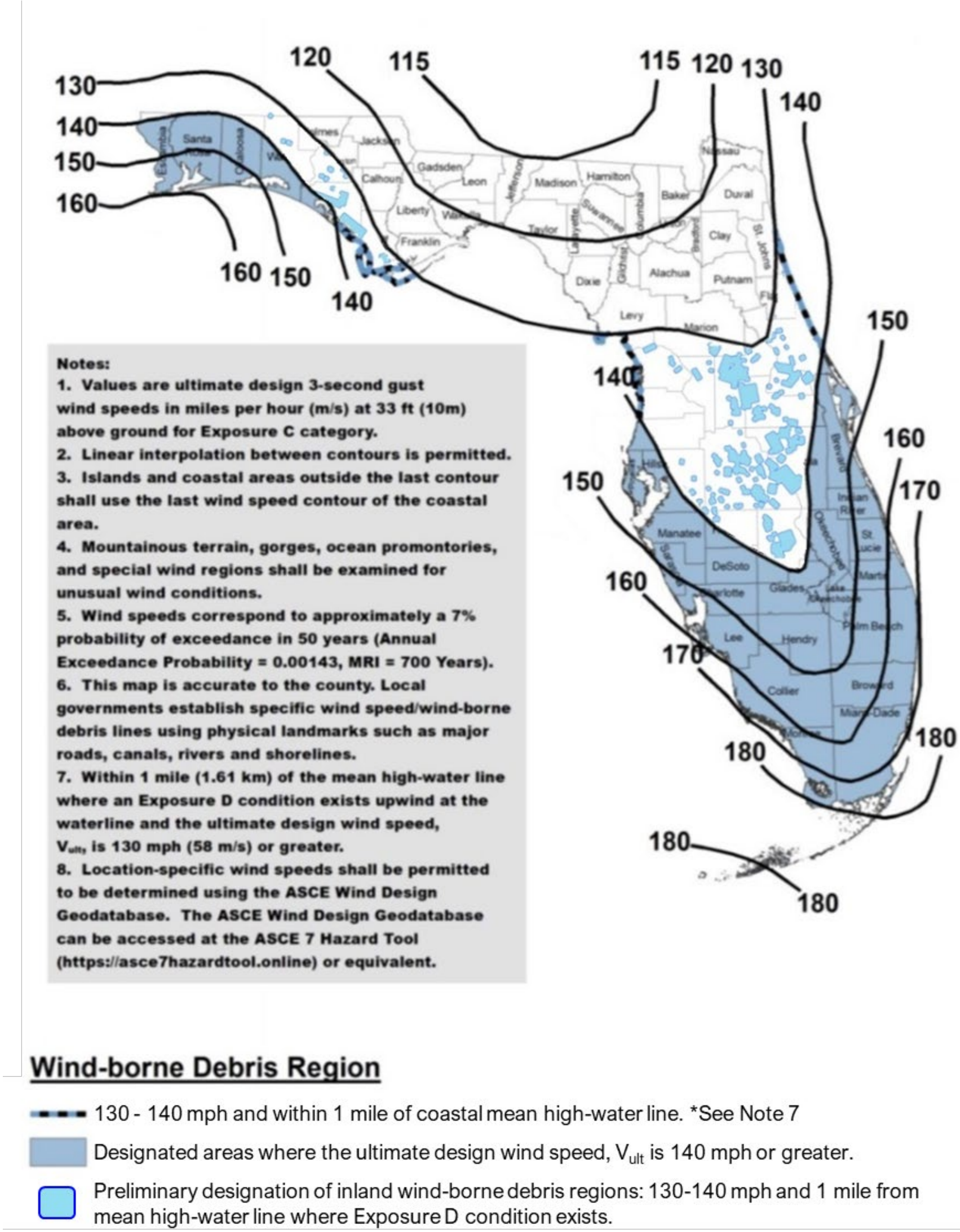

Figure 1. Designation of inland wind-born debris regions on ASCE 7-22 Wind Speed Map.

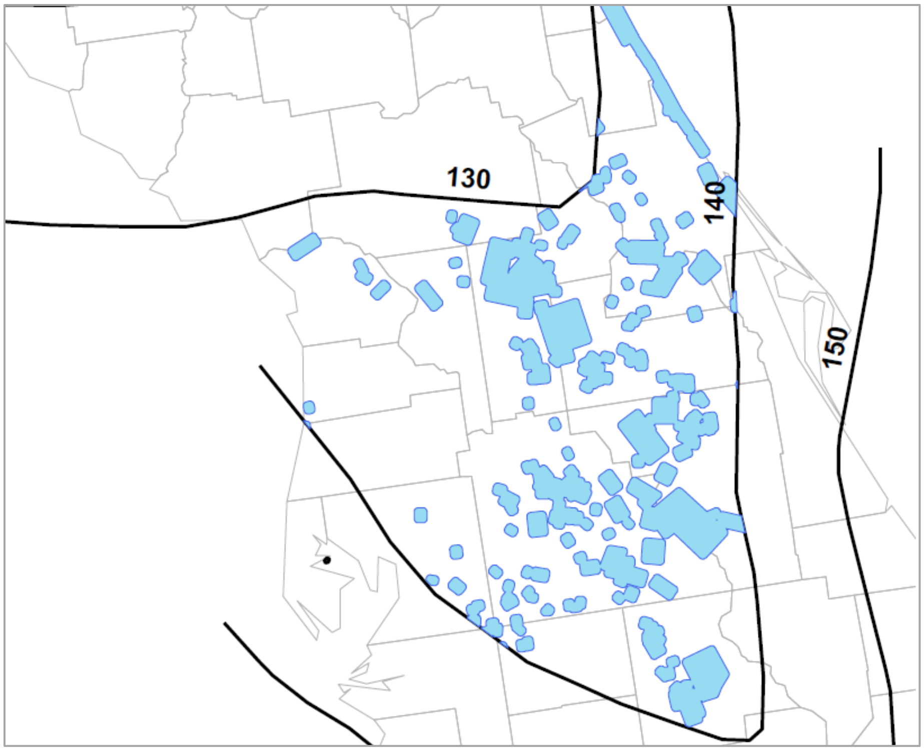

Figure 2. Detail of preliminary designation of inland WBDR in central Florida (courtesy of ARA).

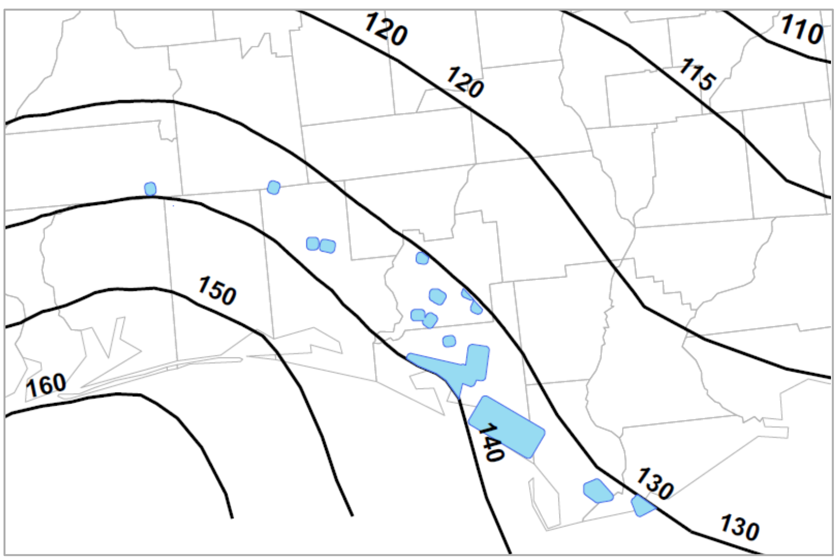

Figure 3. Detail of preliminary designation of inland WBDR in Florida panhandle (courtesy of ARA).

2.2 History of WBDR in ASCE 7

To understand the reasoning behind the WBDR definition in ASCE 7-22, it is important to review the history of WBD provisions in ASCE 7. This summary is drawn from conversations with members of the Wind Loads Subcommittee of ASCE 7 who have had first-hand experience, researching, developing, and updating the provisions[1].

Researchers began documenting damage from WBD during windstorms (primarily tornadoes) as early as the 1970s, which resulted in several unsuccessful proposals to include WBD criteria in ASCE 7. As a result of the observation of extensive glazing damage during Hurricanes Alicia (1983), Hugo (1989), and Andrew (1992), the ASCE Task Committee on Wind Loads again sought to include WBD design criteria to ASCE 7. The initial rationale for this update was to protect the building envelope from breaches to avoid damage to nonstructural elements. At the time, the glazing industry was only in early phases of developing impact resistant products, though since it has matured significantly.

In 1995 the first requirement for design for WBD was incorporated into ASCE 7, triggered only by a 110 mph (49 m/s) wind speed, based on a load factor of 1.6. In ASCE 7-98, the WBD windspeed trigger was increased to 120 mph, except for regions within one mile of the coast with wind speeds greater than 110 mph. This reduction in the WBDRs was driven primarily by resistance from building officials and authority having jurisdictions to adopt the previous designation, and not on new research or observations. The Committee's criteria for using the one-mile distance was based largely on anecdotal evidence from damage assessments; no specific research had been conducted to inform the selection of this specific distance.

Starting with ASCE 7-10, the windspeed trigger for WBDRs was increased to 140 mph with a load factor of 1.0, and 130 mph within one mile of the coast. During subsequent standard cycles, the ASCE 7 Wind Loads Subcommittee began considering removing "coastal" for the 130 mph regions. There was a recognition that an Exposure D condition is likely to occur regardless of whether the large body of water (at least 5,000 ft of fetch) is coastal or inland (i.e. "the wind can't tell the difference"). The fact that the word "coastal" was ever included was thought to be in error and an artifact of the damage assessments after Hurricanes Andrew and Hugo that drove the initial adoption of WBD criteria. These events largely produced reported damage in coastal regions and the priority for damage assessments was driven by damage severity.

Another issue with the coastal designation was confusion in how to define the coastline. The term "mean high water level" does not have a clear definition; as a result, the definition of the coast was left up to the local authority having jurisdiction to determine. An official inquiry by a building official for clarification on this definition prompted the Committee to further consider the removal of the word "coastal". To avoid confusion, ASCE 7-22 opted to make the designation based on an Exposure D condition, without reference to the coast.

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[1] The history of WBDR designations in ASCE presented in this report is synthesized from personal communication with Mr. Don Scott (past chair of the ASCE 7 Wind Loads Subcommittee) and Mr. Tom Smith (Consultant and member, ASCE 7 Wind Loads Subcommittee with extensive post-disaster investigation experience).

3 Literature Review

This section provides an overview of research studies on the generation, transport, and impacts of wind-borne debris, including experimental and numerical studies. Much of the research summarized is general in nature; there are limited numbers of studies focused specifically on the designation of WBDRs, how transitions between terrain exposures impacts debris risk, how the risk of wind-borne debris damage varies between inland and coastal regions, and how the risk decreases with increasing distance from the shoreline.

3.1 Overview

Wind-borne debris is a critical factor in structural damage during extreme wind events such as hurricanes and tornadoes. Generated and propelled by strong winds, wind-borne debris imposes impact loads on building envelopes, leading to structural failures and further debris generation. High-velocity debris can breach walls, windows, and roofs, allowing wind and rain to infiltrate, which increases internal pressure and can significantly increase the net load on structures, often culminating in catastrophic failures (Lin, 2005; Wills et al., 2002). The unpredictable nature of wind-borne debris, including its variability in size, shape, and velocity, complicates efforts to mitigate its effects. Understanding wind-borne debris behavior and its impacts on structures is therefore essential for minimizing damage and economic losses.

The economic implications of wind-borne debris during wind events are profound, with losses often amounting to billions of dollars. Dr. Joseph Minor’s investigations, starting in 1972, identified wind-borne debris as a primary cause of building envelope failure and subsequent economic loss. His analysis of wind events, including Hurricanes Alicia (1983), Hugo (1989), and Andrew (1992), demonstrated the role of wind-borne debris in widespread structural damage and underscored the need for more resilient building designs (Minor, 2005; Minor et al., 1972).

In urban areas, the risks posed by wind-borne debris are heightened due to the density of buildings and infrastructure with debris generating capability. Minor et al. (1978) explored the sources of urban debris and the severe damage these items can inflict when airborne. Breaches in building envelopes caused by debris can lead to internal pressurization, amplifying structural damage and increasing the likelihood of collapse. The study emphasized the necessity of robust risk assessment methodologies and mitigation strategies tailored to urban environments. These include impact-resistant materials such as laminated glass, reinforced wall systems, and secure roofing designs to reduce debris generation. Advances in urban planning, such as wind-tunnel studies and strategic placement of structures, also help mitigate exposure to debris.

Minor’s later work (2005) further highlighted the vulnerabilities of building materials to debris impact during windstorms. For instance, roof gravel or wood fragments can breach tempered glass and other commonly used materials which were previously deemed durable. These findings have prompted significant updates to building codes in hurricane-prone areas, requiring materials and designs capable of withstanding debris impacts. Modern testing protocols now evaluate both impact resistance and the ability to endure fluctuating wind pressures. Innovations such as laminated glass systems, which maintain structural integrity even after cracking, and advanced glass anchoring techniques, which prevent dislodgment under extreme conditions, reflect a shift toward ensuring functionality after impact.

The research emphasizes that improving the resilience of building materials, enhancing urban planning, and updating building codes are crucial steps in reducing the risks associated with wind-borne debris. By addressing these challenges through engineering and policy measures, the destructive effects of wind-borne debris during extreme wind events can be significantly mitigated.

3.2 Numerical simulations of wind-borne debris

Numerical simulations play a critical role in understanding and predicting the behavior of wind-borne debris during extreme wind events. These studies often categorize wind-borne debris into compact, sheet, and rod types based on shape, with compact types receiving particular attention due to their simpler geometry. Various analytical and numerical methods have been employed to model wind-borne debris motion, treating debris either as particles or fluids. These approaches utilize differential equations and multi-species fluid dynamics models to simulate trajectories (Holmes, 2004; Lin, 2005; Dowell et al., 2005; Moghim & Caracoglia, 2012). Model-scale experiments have validated these simulations, and empirical equations have been developed to approximate wind-borne debris behavior (Lin & Vanmarcke, 2010; Bourriez et al., 2020).

Twisdale et al. (1996) introduced a six-degree random orientation (RO 6-D) model to simulate three-dimensional debris flight trajectories, incorporating drag, lift, and side forces. Their results, compared with post-damage hurricane survey data, demonstrated the model's efficacy. Holmes (2004), Holmes et al. (2006), and Lin et al. (2007) focused on two-dimensional simulations of various debris types, using quasi-steady force coefficients derived from wind tunnel experiments and validating results with observed trajectories. Baker (2007) proposed an alternative non-dimensional scheme to Tachikawa's (1983) model and investigated numerical solutions for debris motion equations. Richards et al. (2008) extended this work by simulating the three-dimensional motion of plate- and rod-type debris. They observed that roofing sheets released at varying angles of attack exhibited nearly circular distributions in a vertical plane downstream, aligning with Tachikawa's (1988) wind-tunnel findings.

Probabilistic trajectory models have emerged as essential tools for predicting wind-borne debris behavior under turbulent wind conditions. These models, such as those developed by Wang et al. (2023), integrate randomness in wind fields and debris properties to simulate outcomes like impact locations and velocities. Techniques like Monte Carlo simulations assess multiple scenarios by sampling debris characteristics and wind conditions. Aerodynamic effects, including the Magnus phenomenon and Tachikawa number, are incorporated to enhance accuracy for complex debris types like plates (Wang et al., 2023). Validated through wind tunnel experiments, these models provide valuable insights for use in risk assessments and the development of protective measures for buildings and infrastructure.

Abdelhady et. All (2022) presents a framework to determine the necessary extent of surrounding buildings to include in simulations for accurately modeling hurricane-induced damage. Exogenous wind-borne debris, originating from neighboring subdivisions, is a significant factor in hurricane damage. Traditional models often underestimate damage by neglecting these external influences. The authors use a simulation-based iterative approach to define the radius of neighboring areas needed to account for wind-borne debris. The methodology begins with a single-building analysis and generalizes the results to larger, arbitrarily shaped neighborhoods. Some of the factors influencing the radius of neighboring areas are the maximum wind speeds, the density of the neighborhoods, and the building strength. The study highlights the importance of accounting for exogenous debris in damage models and offers a scalable, computationally efficient framework for integrating these effects.

Computational Fluid Dynamics (CFD) simulations have advanced the understanding of wind-borne debris dynamics by modeling complex aerodynamic behaviors during flight. These simulations compute critical forces such as drag, lift, and rotational moments acting on debris, particularly plate-like objects, which exhibit phenomena like vortex shedding and lift hysteresis (Kakimpa et al., 2010). Three-dimensional CFD models enhance accuracy by capturing intricate flow structures, such as ring vortices, that are less detailed in 2D simulations. High-fidelity turbulence models, such as Realizable $k-\varepsilon$ and Large Eddy Simulation (LES), further refine predictions by resolving unsteady flow effects like separation and reattachment. Studies validate CFD outputs against experimental data, providing a reliable tool for understanding debris motion and informing mitigation strategies. Insights from CFD simulations have guided the design of hurricane-resistant structures and protective barriers by predicting how debris interacts with wind fields.

3.3 Experimental studies

Experimental approaches often use wind tunnels and laboratory equipment to simulate wind-borne debris motion and its structural impacts, as full-scale tests are typically cost-prohibitive. These experiments are useful in improving and validating numerical models used in debris damage risk assessment. Model-scale experiments are commonly employed, with normalized variables used to extrapolate results. Lin (2005) conducted wind tunnel and aircraft-generated wind experiments, developing empirical equations to estimate wind-borne debris trajectories and impact speeds. Kordi and Kopp (2011) examined initial wind-borne debris conditions and identified flight behaviors such as "3-D spinning" and "no flight," influenced by local wind dynamics. Experimental studies, such as those by Crawford (2012), validated numerical models for compact and rod wind-borne debris trajectories in tornadic wind fields.

Tachikawa (1983, 1988) pioneered experiments on plate and prism debris in boundary-layer wind tunnels, establishing non-dimensional equations of debris motion and introducing the "Tachikawa Number," a parameter describing debris flight behavior (Holmes et al., 2006). Lin et al. (2006, 2007) expanded on these findings by conducting extensive wind-tunnel experiments to study three generic debris types, deriving non-dimensional empirical relationships for flight distance and speed as functions of the Tachikawa Number. Visscher and Kopp (2007) further examined roof sheathing panel trajectories in wind tunnel experiments, noting higher variability and sensitivity to flight conditions compared to earlier studies by Tachikawa (1983) and Lin et al. (2006, 2007).

It is noteworthy that none of the wind tunnel tests on debris transport involved study of the impact of upwind exposure and exposure transitions.

3.4 Impact of terrain transitions on wind loads

The interaction between wind and the built environment is a complex phenomenon that significantly influences the design and safety of low-rise buildings. Understanding how surrounding conditions, terrain transitions, topography, and wind loads effect wind-borne debris behavior is crucial for developing accurate predictive models and effective building codes. Variability in wind pressures caused by nearby structures, changes in terrain, and the generation and transport of debris can lead to critical fluctuations in building performance, especially in urban, suburban, and inland contexts. Compounding these challenges is the limited research on wind-borne debris impacts over inland exposure conditions, leaving significant gaps in understanding the mechanisms of damage in these regions.

Topography plays a key role in influencing wind behavior, often leading to the strongest winds flowing over relatively smooth areas such as large bodies of water (resulting in Exposure D condition defined in ASCE 7). This smooth terrain allows the mean flow to accelerate relative to upstream overland exposures, creating localized zones of amplified wind speeds and increased turbulence as the flow transitions from water to land. Such conditions are particularly concerning in inland regions with large lakes or inland bays, where this acceleration effect can amplify wind loads on structures near the body of water. However, these dynamics are often underrepresented in studies, which focus primarily on coastal or urban settings.

Previous research has emphasized the effects of surrounding structures and terrain transitions on wind loads. For example, studies by Ho et al. (1991) and Kim et al. (2024) have demonstrated how the alignment and proximity of buildings or the presence of suburban patches can significantly influence wind flow patterns and pressure distributions. These factors often result in amplified wind loads or localized pressure peaks, particularly at vulnerable areas like roof edges and building corners. Yet, such investigations have primarily focused on wind pressure effects, with limited attention given to the interaction between wind-borne debris and exposure transitions, especially in inland regions where smooth water surfaces can intensify mean wind speeds.

Ho et al. (1991) investigated the influence of surrounding conditions on wind loads acting on low-rise buildings. This research focused on quantifying the variability of wind loads caused by different configurations of nearby structures and obstacles, providing critical insights for accurate wind load predictions. The immediate surroundings, including the proximity, size, and alignment of adjacent buildings, significantly alter wind flow patterns, leading to notable variability in pressure distributions on roofs and walls. Surrounding structures can either shield the building or amplify wind loads, depending on their geometry and orientation relative to the wind. This influence is particularly pronounced in urban environments, where complex interactions such as turbulence, flow separations, and vortex shedding occur. Critical areas like roof edges and corners are especially sensitive to these effects. The study underscores the need to account for surrounding conditions in wind tunnel testing and computational models, as simplified design codes may fail to accurately represent these influences, potentially resulting in under- or over-engineered structures.

Kim et al. (2024) explored the impact of upwind terrain transitions, from open to suburban, on wind pressures and forces acting on low-rise buildings. Wind tunnel experiments were conducted to analyze how the distance and size of the terrain transition patch affect wind dynamics and pressure distribution. The presence of an upwind suburban patch consistently reduces mean wind speeds, leading to decreased mean pressures on building surfaces. This reduction is more significant when the patch is closer to the building or when the patch is larger. Turbulence intensity increases due to the upwind transition, resulting in greater fluctuations in wind pressures. Transition zones caused amplified wind loads on specific zones of the building, such as windward edges and corners, with peak pressures increasing. Negative pressure effects were particularly pronounced at these locations. Localized intensifications in wind pressures near upwind transitions can have critical design implications for structural integrity and safety. The study recommends accounting for these effects in building codes and design practices, even for short suburban patches.

Research on wind-borne debris has predominantly addressed coastal and urban environments, where debris sources and wind intensities are well-documented. In contrast, inland areas, where terrain transitions and exposure shifts (e.g., from open water to suburban zones) play a critical role in debris dynamics, remain underexplored. This gap in understanding limits the ability to accurately model wind-borne debris generation, transport, and impact under inland exposure conditions. Moreover, the amplification of wind speeds over large bodies of water in these regions further complicates predictive modeling and risk assessment.

By integrating the effects of topography, surrounding conditions, terrain transitions, and wind-borne debris dynamics, researchers can develop more comprehensive models to assess structural risks. Addressing the gaps in inland exposure studies is vital for enhancing building codes and design practices to ensure resilience against extreme wind events and associated debris impacts across diverse exposure zones.

3.5 Vulnerability and risk assessment

Statistical approaches are essential in analyzing the dynamics of wind-borne debris during extreme wind events, focusing on risk models to evaluate the threats to building components. These models incorporate stochastic methods to estimate the trajectory and impact probabilities of wind-borne debris, with probabilistic trajectory models accounting for uncertainties such as turbulence and wind flow variability, which significantly influence the flight and impact energy of debris (Grayson, 2011; Karimpour & Kaye, 2012). Including these uncertainties is crucial for accurate assessments of flight distances and impact energies.

There is limited research on debris-damage risk assessment, with one of the earliest models developed by Twisdale et al. (1996), who proposed a probabilistic model to estimate the mean debris-damage risk in residential areas. This model assumes that impact parameters, such as the number of impacts and momentum, are identically distributed across all debris types and houses in the area. Twisdale's model also assumes that the total number of debris impacts follows a Poisson distribution. Lin and Vanmarcke (2008) later refined this model by showing that the number of objects of each type of debris generated from a building can also follow a Poisson distribution, which helps to better estimate over threshold impacts. This method links the stochastic processes of debris generation, flight, and impact, improving the ability to predict damage and avoid the common assumption of uniform risk across buildings.

Twisdale's model has been applied in vulnerability analysis for residential buildings, where it has been used to estimate the debris risk parameters for typical residential subdivisions. These analyses contributed to the ASTM recommendations for debris-impact risk analysis (ASTM E1886-05 2005) and informed the FEMA HAZUS-MH Hurricane Model (Vickery et al., 2006) for estimating hurricane damage and losses. Additionally, the Florida Public Hurricane Loss Projection (FPHLP) model (Gurley et al., 2005) used a simplified debris risk model based on exponential distribution for structural vulnerability analysis. Although similar to the models of Twisdale et al. (1996) and Lin and Vanmarcke (2008), this approach lacked empirical data or numerical simulations, simplifying the estimation of parameters.

Wind-borne debris significantly increases the risk of building envelope failures during hurricanes, with vulnerabilities found in windows, walls, and roofs. Analytical models such as those developed by Lin and Vanmarcke (2010) employ probabilistic methods using Poisson distributions to estimate the frequency of impacts and exceedance of structural resistance thresholds, providing valuable tools for assessing structural vulnerability. Component-specific studies have identified critical weak points, particularly in residential windows, where lightweight debris poses a significant threat, underscoring the need for reinforced designs (Lin & Vanmarcke, 2010). Protective systems, like hurricane shutters, have proven effective in mitigating damage, especially from roof tile impacts.

3.6 Literature review summary

While significant progress has been made in understanding wind-borne debris through numerical simulations and experimental studies, substantial gaps remain, particularly regarding inland exposure conditions and over-water scenarios. Most existing research focuses on urban and suburban settings, with limited attention to transitional zones between water and land, or regions categorized as Exposure D. These areas are critically underrepresented, despite the unique challenges posed by increased turbulence and wind amplification over water bodies.

Research into wind-borne debris under inland exposure conditions, especially in transition zones, is essential for accurately modeling hurricane-induced damage and improving building codes. Studies should examine how changes in exposure conditions influence debris generation, flight trajectories, and impact probabilities. Such research would help address the existing knowledge gap, providing an assessment of the relative risk of wind-borne debris generation and damage between inland and coastal regions and how the risk decreases with distance from the smooth to rough exposure transition.

Further investigation should also explore the interaction between wind-borne debris and evolving urbanization patterns. Understanding how surrounding structures and water bodies contribute to wind-borne debris dynamics can lead to more insightful models that can improve mitigation strategies. By prioritizing these under-researched aspects, future work can offer critical insights into reducing damage and economic loss from wind-borne debris during extreme wind events.

4 Damage Reports

This review focuses on damage assessment reports of hurricanes affecting areas where design wind speeds, as specified by current ASCE 7 standards, range between 130 and 140 mph. Special attention is given to regions with unique geographic features, such as inland water bodies, which may influence the generation and impact of wind-borne debris. By analyzing historical hurricane data and the imagery of the damage assessment reports, this study aims to find evidence of wind-borne debris damage, particularly in inland areas adjacent to large water bodies.

4.1 Methodology

The methodology for this review focused on selecting hurricanes that closely align with current design wind speeds for inland WBDRs with the potential to generate wind-borne debris. Storms were chosen based on four primary criteria: wind speeds within the 130–140 mph range as defined by current standards, their geographic impact on both coastal and inland areas, the presence of water bodies such as lakes or inland bays along their paths, and storm intensity, specifically those impacting areas with observed wind speeds near the design threshold.

A comprehensive list of storms considered in this review, along with their main observations, is shown in Figure 4 and detailed in Table 2.

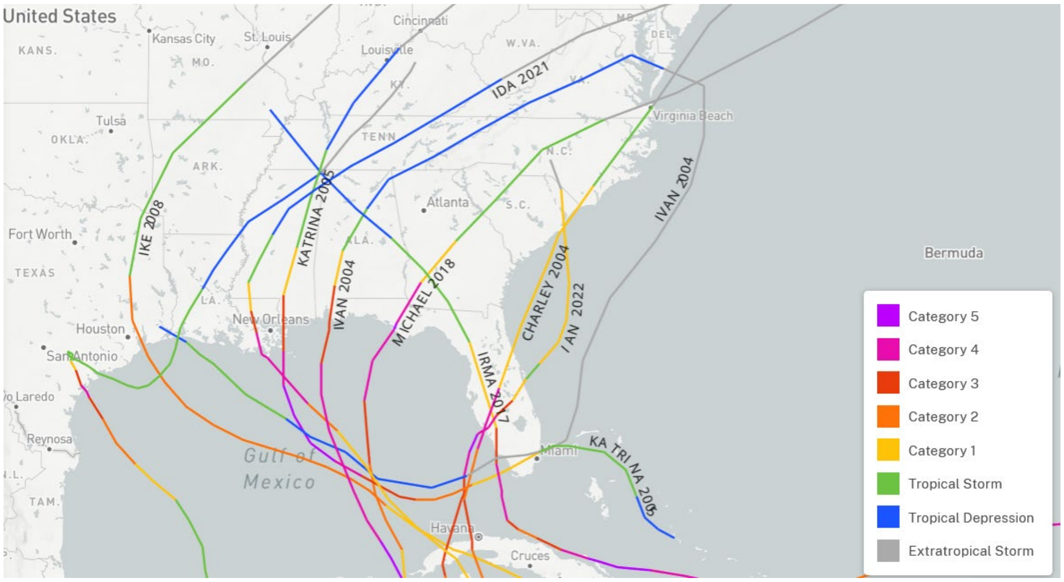

Figure 4. Storms that have made landfall in the United States as hurricanes between 2004 and 2022.

Two primary regions where the design wind speeds, as specified by ASCE 7, range between 130 and 140 mph are Central Florida and the Florida Panhandle. These regions also feature water bodies, such as lakes or inland bays, that might contribute to generating Exposure D condition. Hurricanes Charley (2004), Irma (2017), Michael (2018), and Ian (2022) were identified as significant events that impacted these areas. According to damage assessment reports, most hurricanes making landfall in these regions did not exceed the design wind speeds.

Following the selection of storms, publicly available damage assessment reports were extensively reviewed to identify evidence of wind-borne debris damage, particularly in inland areas. Notably, hurricanes Charley and Michael provided limited but significant evidence of wind-borne debris damage. These hurricanes are highlighted in green in Table 2, as their reports confirmed debris impacts, even in inland locations. Both affected areas are as WBDRs in ASCE 7-22.

Table 2. Landfalling hurricanes on the Atlantic Coast of U.S between 2004 and 2022.

Hurricane	Year	Primary Observations
Charley	2004	Affected Punta Gorda, FL. Estimated wind speeds exceeded design levels (at landfall). Classified as WBDR. Evidence of wind-borne debris damage, including some inland areas.
Ivan	2004	Affected Pensacola, FL. Estimated wind speeds were below design levels. Pensacola is classified as WBDR.
Katrina	2005	Affected Mississippi, Louisiana, and Alabama. Estimated wind speeds were below design levels. Imagery focused on structural failures due to storm surge; no wind-borne debris evidence.
Ike	2008	Affected Texas. Estimated wind speeds were below design levels.
Harvey	2017	Affected Texas. Estimated wind speeds were below design levels.
Irma	2017	Affected Florida. Estimated wind speeds were below design levels. Classified as WBDR.
Michael	2018	Affected Florida Panhandle. Estimated wind speeds exceeded design levels in some areas. Significant evidence of wind-borne debris damage, but no evidence in inland areas.
Ian	2022	Affected Punta Gorda, FL. Estimated wind speeds below design levels. Classified as WBDR. Imagery focused on structural damage with limited documentation of wind-borne debris.

4.2 Limitations

The damage assessments review faced several limitations for the purposes of this study. Most damage assessment reports and imagery prioritized and focused on the most severely impacted areas at landfall, particularly along shorelines, providing minimal data on wind-borne debris impacts in inland areas near lakes or other water bodies. Research teams' investigations were constrained to accessible locations, often overlooking areas near inland water bodies. Additionally, there was a significant lack of very specific investigations into wind-borne debris effects in inland regions, leaving critical data gaps that limit comprehensive analysis. The absence of this data in these reports does not preclude the occurrence of debris damage in areas outside the assessment regions.

4.3 Summary of damage assessment findings

A summary of critical findings from each storm is presented in Table 3, followed by detailed analyses in subsequent sections. Inland wind-borne debris damage was noted after Hurricane Charley (with wind speeds recorded between 125 and 130 mph) in buildings over three miles from the coast, potentially warranting more investigation into the one-mile distance for WBDR designation in that wind speed range. After Hurricane Michael, wind-borne debris damage was noted over three miles inland from St. Andrew Bay in Panama City (designated as WBDR in ASCE 7-22) for wind speeds between 125 and 140 mph, indicating the potential for wind-borne debris damage at these wind speeds in regions adjacent to inland bays. These findings underscore the need for targeted research into inland wind-borne debris impacts to inform future code updates and mitigation strategies.

Table 3. Summary of the damage assessments observed for the hurricanes impacting the Atlantic coast of the U.S (2004 – 2022).

Hurricane	Year	Type of location	Location	Wind speed recorded	Design Wind Speed	Main Observations
Charley	2004	Charlotte Harbor	Mangrove Point, just southwest of Punta Gorda, Florida.	125-130 mph	140-150 mph (current code)	The wind speed observed exceeded the design wind speeds. Extensive wind-borne debris damaged observed in Punta Gorda, however Punta Gorda is currently considered within the wind-borne debris due to the being located between 140 - 150 mph design wind speed. Some damage was observed in Orlando and Pine Island. Some wind-borne debris damage was observed in Acadia; however, this specific place located further than 1 mile from Exposure D condition.
Ivan	2004	Inland Bay	Pensacola, FL area	95-120 mph	150-160 mph	Hurricane Ivan did not exceed the design wind speeds. There is no evidence in the Mitigation Assessment Team Report from FEMA and in the wind investigation report from RICOWI of wind-borne debris damage.
Katrina	2005	Coastal	Mississippi: from Pascagoula westward to Ocean Springs. Mississippi Coast. Biloxi, D'Iberville, and Gulfport, Mississippi.	90-120 mph. 120-130 mph. 120-130 mph	140-150 mph	Hurricane Katrina did not exceed the design wind speeds. There is no evidence of wind-borne debris damage in the wind investigation report from RICOWI.
Ike	2008	Galveston Bay	Houston, Friendswood, Webster, Anahuac, Stowell, Liberty and Winnie, Texas. Deer Park, Friendswood, Cooper Field, Houston and Pasadena.	90 mph. 100-110 mph	Anahuac and Stowel: 140 - 150 mph. All others: 130-140 mph	RICOWI, Inc. released a wind investigation report on Hurricane Ike's impact across Galveston Bay, Texas. Recorded wind speeds ranged from 90 to 110 mph, falling below the design wind speeds of 130 to 150 mph. There is no information or images that could provide evidence of wind-borne debris.
Harvey	2017	Aransas Bay, Copano Bay. Port Aransas South: Coastal	Rockport Northwest, TX. Port Aransas South, TX. Holiday Beach, TX. Rockport Southeast, TX.	120- 130 mph. 120- 130 mph. 120- 130 mph. 130- 140 mph.	Port Aransas South: 160 - 170 mph. All others: 150-160 mph	Hurricane Harvey did not exceed the design wind speeds according to the IBHS damage investigation report. There are only comparative images of the behavior of older and newer constructions.

Hurricane	Year	Type of location	Location	Wind speed recorded	Design Wind Speed	Main Observations
Irma	2017	Coastal (WBDR)	Naples, Marco Island, Goodland, Everglade City, Ponte Vedra Beach, St. Augustine, Miami, Marathon, Cudjoe Key, Key West. Collier, Lee, Miami-Dade, and Monroe Counties.	60-120 mph	Naples: 160-170 mph. Marco Island: 165-175 mph. Goodland, Everglade City: 160-170 mph. Ponte Vedra Beach, St. Augustine: 150-160 mph. Miami: 175-185 mph. Marathon, Cudjoe Key, Key West: 170-180 mph. Collier and Lee Counties: 160 - 170 mph. Miami Dade: 175-185 mph. Monroe County: 170-185 mph.	Although there is plenty of evidence of wind-borne debris damage caused by hurricane Irma in multiple damage assessment reports (FBC, FEMA, RICOWI, etc.) all the surveys took place in the wind-borne debris region where the design wind speeds were not exceeded. Unfortunately, there are no inland areas that could provide evidence of wind-borne debris.
Michael	2018	Inland Bay	Florida Panhandle: Bay, Calhoun, Franklin, Gulf, Jackson, and Wakulla Counties. Panama City.	161 mph. Panama City: 135-140 mph	Bay, Franklin, Gulf, Wakulla: 150-160 mph. Calhoun and Jackson: 140-150 mph. Panama City: 150-160 mph	Many communities along Michael's track experienced wind speeds exceeding the design wind speeds specified in ASCE 7-10 for Risk Category II buildings. Wind gusts surpassed design levels by over 10% in several counties. Data from the Florida Coastal Monitoring Program (FCMP) confirmed wind gusts exceeding 120 mph for extended periods near the affected areas. Notable wind-borne debris damage was observed and reported in areas like Mexico Beach and Panama City, where estimated wind speeds exceeded design levels, though these areas were not classified as wind-borne debris regions under ASCE-7 standards due to their distance from the coast.
Ian	2022	Charlotte Harbor	Ft. Mayers, FL. Cape Coral, FL. Punta Gorda, FL. Port Charlotte, FL.	Ft. Mayers and Cape Coral, 90-130 mph. Cayo Costa, 150 mph. Iona, 140.3 mph (peak wind gust). Punta Gorda, 135 mph.	Ft. Mayers 160-170 mph. Cape Coral, 170-180 mph. Punta Gorda,160-170 mph.	Estimated peak winds approached but remained slightly below the design levels specified under the building code. However, the event likely represented a design-level wind event for buildings constructed under pre-Hurricane Andrew code. Failures of auxiliary structures, roof coverings, and cladding elements created substantial wind-borne debris impacts, exacerbating the failure of openings like windows and doors. Limited imagery from multiple sources (IBHS, RICOWI and StEER reports).

4.4 Detailed damage assessments by storm

4.4.1 Hurricane Charley (2004)

Hurricane Charley struck Punta Gorda, Florida, in 2004. The storm crossed barrier islands, including Cayo Costa and Gasparilla, with recorded wind speeds reaching 150-145 mph. Despite this, the design wind speed for the area where damage assessments were carried out by the Mitigation Assessment Team (MAT) from the Federal Emergency Management Agency (FEMA) was noted to be 110-130 mph, indicating that the observed wind speeds exceeded the design wind speeds for the sites of interest (FEMA, 2005).

The Port Charlotte and Punta Gorda areas, located within the wind-borne debris region, suffered extensive damage, while inland areas like Arcadia, outside this region, experienced less severe effects. Key findings from damage assessments (from the University of Florida and the Insurance Institute for Business & Home Safety: IBHS) highlight the vulnerability of unprotected glazing. In Punta Gorda and Port Charlotte, where wind speeds ranged from 125–130 mph, one-third of homes without shutters had broken windows, compared to minimal damage in areas with winds below 100 mph. Homes with shutters or laminated glass experienced significantly less damage, demonstrating the importance of these protective measures. Despite this, debris from poorly constructed structures and roof coverings caused significant damage even in lower-wind-speed areas.

Significant damage was frequently observed in areas where clay and concrete tiles were used as roof coverings and in neighborhoods where the building began to fail and wood structural members were released as missiles. Although a number of buildings with mortar-set tiles lost significant number of tiles (Figure 5), many landed a relatively short distance from the building. Figure 6 shows the impact of a roof tile that punctured a Miami-Dade County-approved shutter and broke the window.

Figure 5. Extensive damage of pre-2001 FBC home. Broken windows caused by wind-borne debris during Hurricane Charley (2004).

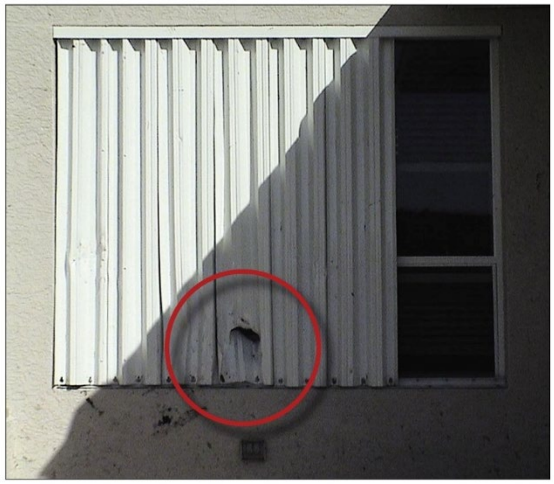

Figure 6. A roof tile punctured a Miami-Dade County approved shutter in Punta Gorda Florida during Hurricane Charley (2004).

The importance of the height at which debris was released was also evident as far inland as the Orlando area. When a piece of debris is released into the wind field at a significant height, there is greater potential for that debris to remain aloft and be accelerated to wind speeds approaching the wind speeds of the event than for debris released or generated lower to the ground. An example of this was observed in the atrium of the hotel shown in Figure 7.

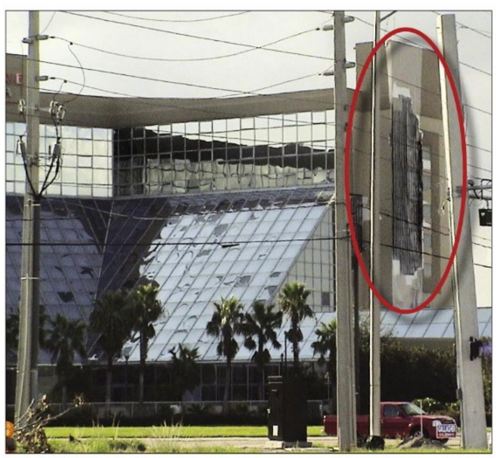

Figure 7. Damage to glass atrium in Orlando caused by wind-borne debris during Hurricane Charley (2004).

Wind-borne debris observed by the mitigation assessment team included roof coverings, structural and non-structural building elements, tree limbs, refuse containers, lawn furniture, and vehicles. Figure 8 through 10 show examples of wind-borne debris. Small debris, such as the roof shingle stuck in the side of the column in Figure 5, must have traveled at least a mile because this community only allowed tile roofs. As expected, larger items did not travel as far, although the section of roofing from a wood-frame building on Captiva Island traveled approximately 200 yards after being separated from the original structure.

Figure 8. Asphalt shingle on a column in Punta Gorda during Hurricane Charley (2004)

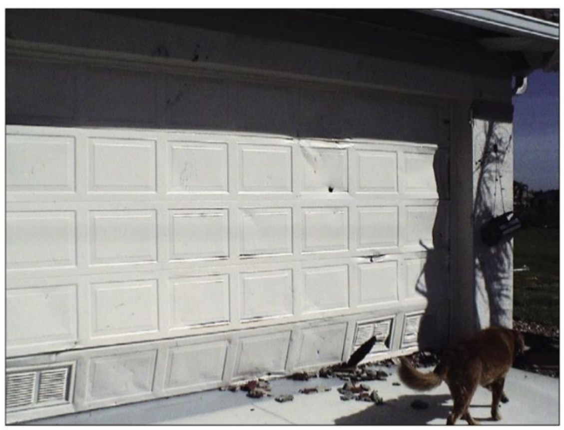

Figure 9. Damage to a garage door in Punta Gorda during Hurricane Charley (2004)

Figure 10. Impact of structural wood in the gable end in Pine Island during Hurricane Charley (2004)

While the Florida Building Code does not apply directly to manufactured homes, a significant amount of aluminum and sheet metal debris from attached structures that failed and glazing damage was observed even in inland mobile home parks. A manufactured home park observed with homes spaced considerable distances apart appeared to have greater wind-borne debris damage (Figure 11).

Figure 11. Wind-borne debris damage on windows caused metal roof panel and siding in Port Charlotte during Hurricane Charley (2004).

It was clear, through investigations at a number of hospitals and other buildings with aggregate roof surfacing, that the aggregate could cause damage to windows on the building itself. The damage to windows in the intensive care unit of the hospital in Arcadia (Figure 12) was a prime example of this effect.

Figure 12. Damage in the windows in a hospital in Arcadia during Hurricane Charley (2004). EWS = 110-120 mph.

In addition to wind-borne debris, wind forces caused larger objects to fail and create falling debris. Buildings were damaged by several types of falling objects, including trees, communications towers, rooftop equipment, and chimneys. The uprooting or fracture of large pine and hardwood trees was observed throughout the areas surveyed. On the barrier islands, the extent of tree damage resulted in severe access problems by blocking roads and driveways and creating a severe fire danger. Inland, the tree damage was more isolated, but was frequently spectacular as trees came to rest on buildings or sliced through buildings. Manufactured homes typically suffered the greatest damage from tree fall. Figure 13 shows a fallen communications tower at a fire station. Figure 14 to Figure 21 shows additional wind-borne debris damage caused by hurricane Charley in several locations (both site built and manufactured).

Figure 13. Fire station with a missile (in the red circle) caused by Hurricane Charley (2004), in Punta Gorda.

Figure 14. Broken window from debris (in the red circle) caused by Hurricane Charley (2004), in Punta Gorda.

Figure 15. Broken windows in an office caused by Hurricane Charley (2004) in Punta Gorda.

Figure 16. Windows broken in a manufactured home by wind-borne debris during Hurricane Charley (2004) at the east of Port Charlotte.

Figure 17. Broken window by wind-borne debris during Hurricane Charley (2004), in Deep Creek.

Figure 18. Metal awning shutter penetrated by a missile in Zolfo Springs during hurricane Charley (2004).

Figure 19. Broken glass windows caused by wind-borne debris during hurricane Charley (2004) in Wauchula.

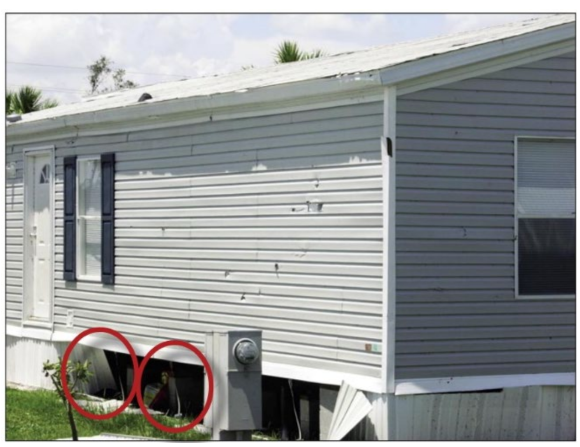

Figure 20. Vinyl siding affected in several location by wind-borne debris in Zolfo Springs during Hurricane Charley (2004).

Figure 21. Broken window caused by wind-borne debris in a high school in Punta Gorda during Hurricane Charley (2004).

4.4.2 Hurricane Ivan (2004)

The analysis of wind speeds during Hurricane Ivan, performed by FEMA, indicates that the maximum recorded 3-second peak gusts at 10 meters ranged from 109 mph in Gulf Shores and Pensacola Beach to 117 mph in Perdido Key. These values are significantly below the design wind speeds stipulated by current building codes, which prescribe 140–150 mph for the affected coastal areas. Compared to the estimated wind speeds, the actual wind speeds were approximately 20% lower than those required by the Florida Building Code (FBC) for this region. However, they were close to or exceeded the design levels used in the Standard Building Code over the past two decades.

4.4.3 Hurricane Katrina (2005)

Roofing Industry Committee on Weather Issues, Inc. (RICOWI), investigated damage caused by Hurricane Katrina in the landfall regions in Louisiana and Mississippi. Estimated wind speeds at damage locations came from simulated hurricane models prepared by Applied Research Associates of Raleigh, North Carolina. A dynamic hurricane wind field model was calibrated to actual wind speeds measured at 12 inland and offshore stations. The maximum estimated peak gust wind speeds in Katrina were in the 120–130 mph range. Among all the pictures in the report, there was no evidence of wind-borne debris damage. This event specifically was characterized by the flooding caused by the storm rather than the damage cause by the wind speeds.

4.4.4 Hurricane Ike (2008)

In 2008, RICOWI released a wind investigation report detailing the impacts of Hurricane Ike across Galveston Bay, Texas. The recorded wind speeds ranged from 90 to 110 mph, while design wind speeds were estimated to be between 130 and 150 mph. The findings emphasized the importance of reinforcing building standards to withstand such extreme weather events, particularly in coastal regions susceptible to hurricanes.

4.4.5 Hurricane Harvey (2017)

Hurricane Harvey is the second-most costly hurricane in U.S. history (after adjusting for inflation), behind Hurricane Katrina (2005). The topography of the area resulted in the strongest winds flowing over the relatively smooth Copano Bay into two neighborhoods (Rockport Northwest and Holiday Beach). According to IBHS, this allowed the mean flow to speed up relative to overland exposures upstream and these two neighborhoods had the most severe total damage of the areas investigated. The locations of both these neighborhoods are shown in Figure 22. Holiday Beach and Rockport Northwest had the most severe structural damage of all areas visited.

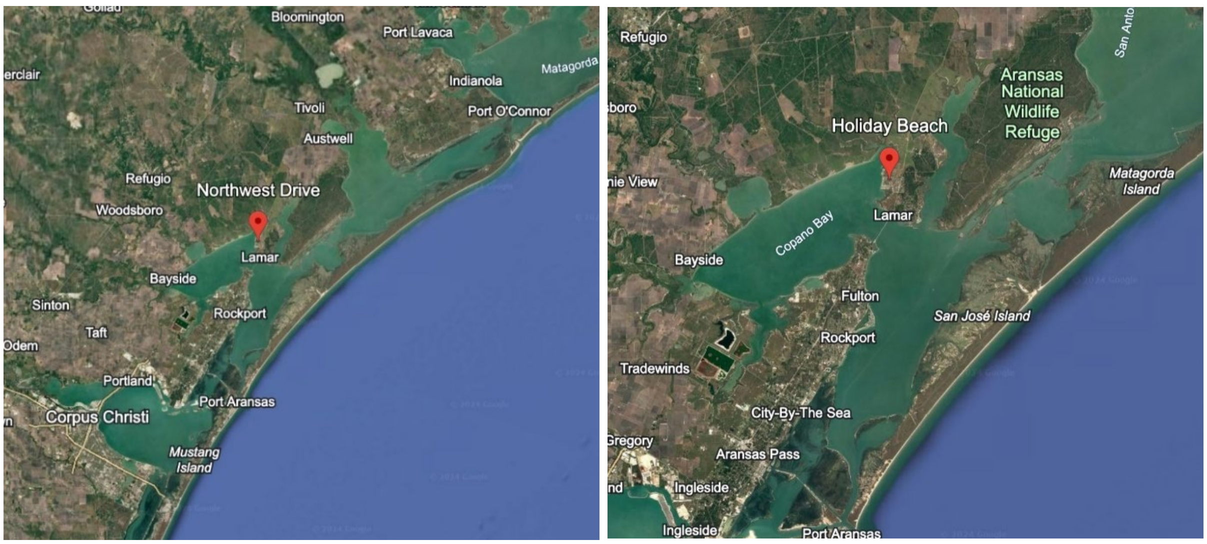

Figure 22. Location of Rockport Northwest (left) and Holiday Beach neighborhoods (right).

Although the assessment areas in Portland, Aransas Pass, Mustang Island and Port Aransas were within one half mile of the shore, the overland fetch reduced the mean wind speeds, thus causing less damage.

In addition to observing general damage trends, damage was investigated by neighborhood, which allowed for an examination of the effects of wind speed and construction era. All the neighborhoods investigated by the IBHS team were located within the ASCE 7-10 design wind speed zone of 140–150 mph. Newer homes in these areas should have been able to resist wind pressures and loads associated with 140–150 mph winds. However, none of the areas investigated experienced peak 3-second gust wind speeds higher than 140 mph, meaning the design pressures and loads should not have been exceeded, yet damage still occurred to both newer and older homes (Figure 23).

Location	Construction Era	Estimated Wind Speed	General Damage State
Portland	1960s–1970s	80–90 mph	Minor: finishes, attached structures, roof cover
Ingleside	1960s–1990s	80–90 mph	Minor: finishes, garage, rooftop items, roof cover
Mustang Island	1990s–2010s	90–100 mph	Minor: finishes, garage, door, attached structures
Aransas Pass	1990s–2000s	110–120 mph	Minor: finishes, garage, rooftop items, roof cover
Port Aransas North	1960s–2010s	110–120 mph	Minor (newer homes), Major (older homes): finishes, wall structure, garage, windows, doors, attached structures, roof cover, roof structure
Rockport Southeast	2000s	120–130 mph	Minor: finishes, roof cover
Holiday Beach	1960s–1990s	120–130 mph	Major: finishes, wall structure, garage, windows, doors, attached structures, roof cover, roof structure
Port Aransas South	2000s–2010s	120–130 mph	Minor: finishes, wall structure, garage, windows, doors, attached structures, roof cover, roof structure
Rockport Northwest	1960s–2010s	130–140 mph	Major: finishes, wall structure, garage, windows, doors, attached structures, roof cover, roof structure

Figure 23 Damage survey locations and characteristics. Source IBHS, Hurricane Harvey Wind Damage Investigation.

The IBHS team noted generally better performance of both residential and commercial buildings in areas of newer construction compared to older construction. Examples are shown in Figure 24 and Figure 25.

Figure 24. Comparison of two homes located 250 ft apart that experienced similar wind speeds during hurricane Harvey (2017) but performed very differently in Port Aransas North. The older construction was built in 1987(left), and newer construction was built in 2006 (right).

Figure 25. Comparison of two commercial buildings located 1 mile apart that experienced similar wind speeds during hurricane Harvey (2017) but performed very differently in Port Aransas North. The older construction was built in 1984(left) and newer construction was built in 2017 (right).

4.4.6 Hurricane Michael (2018)

FEMA compared Hurricane Michael’s estimated 3-second gust wind speeds to the basic design wind speed from the ASCE 7-10 for Risk Category II buildings. Many communities along the track of Hurricane Michael experienced wind speeds that exceeded design level wind speeds. Wind speeds in excess of ASCE 7-10 design levels occurred in Bay, Calhoun, Gadsden, Gulf, Jackson, and Liberty Counties (see Figure 26). In some locations, the wind speeds produced by Hurricane Michael exceeded ASCE 7 Risk Category II wind speeds by more than 10 percent. The highest wind gust recorded on land was 129 mph at a mobile weather station at Tyndall Air Force Base. This mobile weather station was installed by the University of Florida/Weatherflow in the hours preceding landfall. Shortly after recording the gust of 129 mph, the mobile weather station failed. A wind gust of 102 mph was recorded at the airport in Marianna, FL, near the state line with Georgia; the weather station at the airport remained in operation throughout the event. The mitigation assessment team report from FEMA found some wind-borne debris in residential buildings in Mexico Beach and Panama City (Figure 27). In those cases, the estimated wind speed exceeded the design wind speed. However, the observations correspond to areas not considered as wind-borne debris areas according to ASCE-7 because the observations were beyond 1-mile of the coast (Figure 28 to Figure 33).

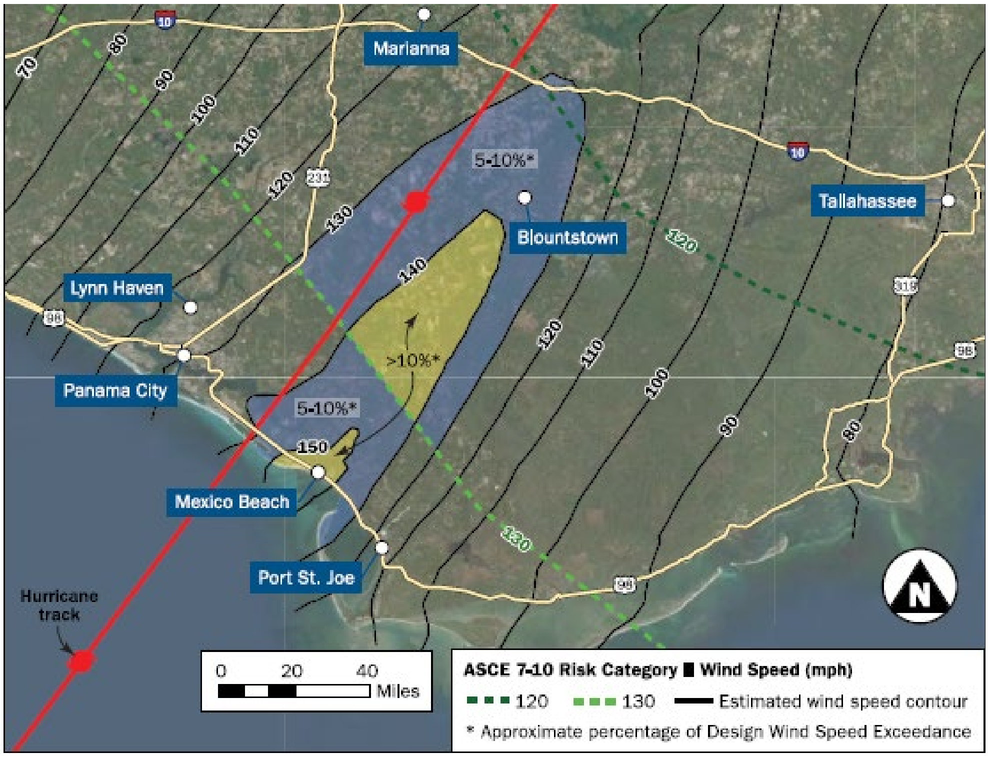

Figure 26. Wind swath plot showing the approximate exceedance of the design wind speed.

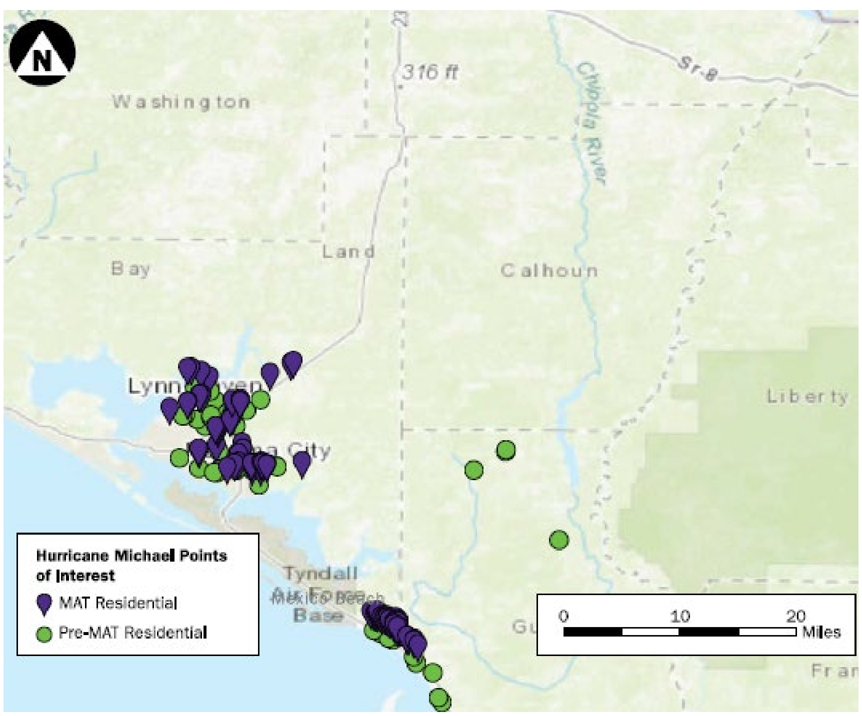

Figure 27. Residential and non-residential sites visited by FEMA hurricane Michael mitigation assessment team.

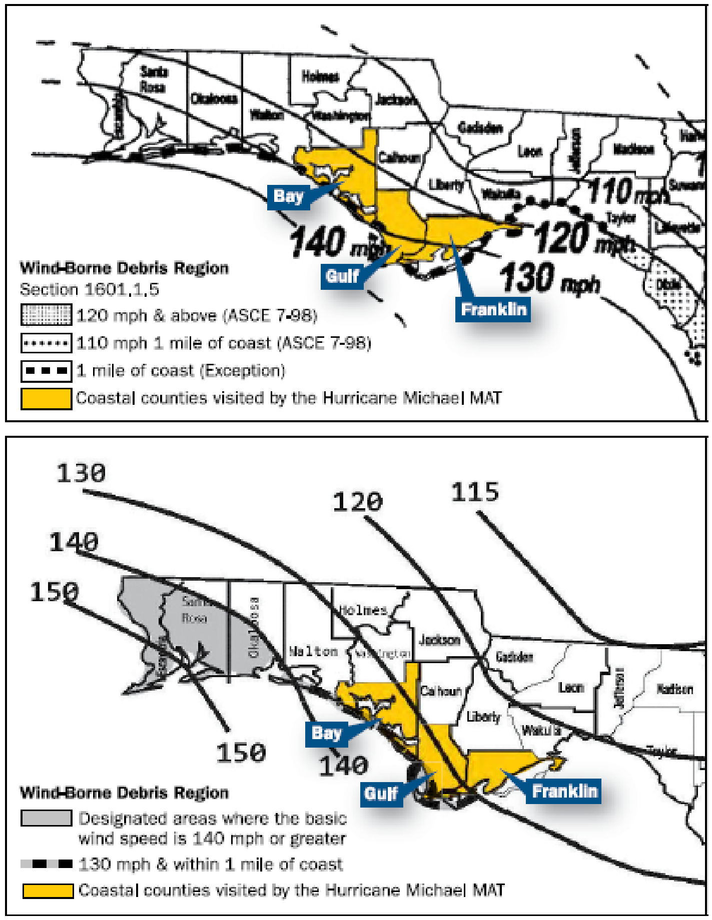

Figure 28. Design wind speeds according to ASCE 7-98 (top) and ASCE 7-10 (bottom) and the location of the counties visited by the Hurricane Michael Mitigation assessment team.

Figure 29. Impact resistant window after Hurricane Michael (2018) in a house built in 2010, located in Mexico Beach. Estimated wind speeds (150 mph) exceeded the design wind speeds (130 mph).

Figure 30. Glazed opening damage after Hurricane Michael (2018) in a house built in 2005, located in Panama City. Estimated wind speeds (128 mph) did not exceed the design wind speeds (133 mph).

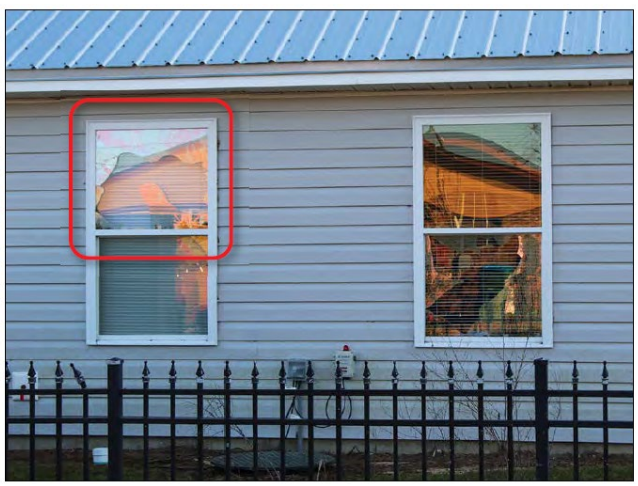

Figure 31. Glazed opening damage after Hurricane Michael (2018) in a house built after 2017, located in Panama City. Estimated wind speeds (134 mph) did not exceed the design wind speeds (135 mph).

Figure 32. Glazed opening damage caused by an asphalt shingle after Hurricane Michael (2018) in a house built in 2012, located in Panama City. Estimated wind speeds (150 mph) exceeded the design wind speeds (126 mph).

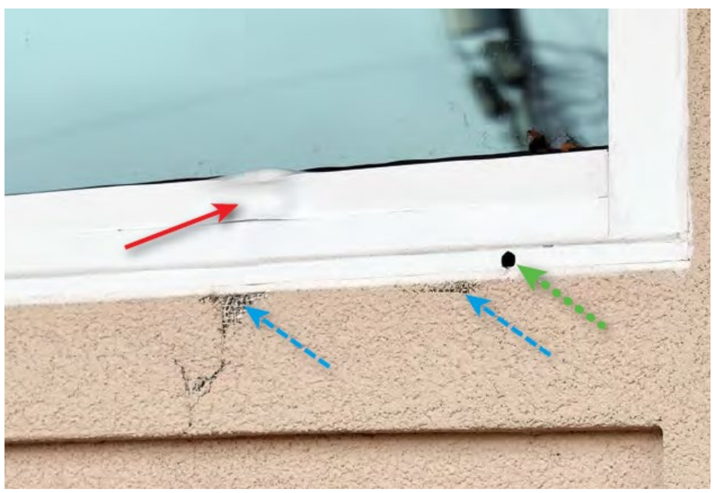

Figure 33. Window struck by wind-borne debris in Panama City during hurricane Michael (2018).

According to Structural Extreme Event Reconnaissance Network (StEER), the National Weather Service reported that at the time of landfall of Hurricane Michael (2018), hurricane-force winds extended outward up to 45 miles (75 km) from the center and tropical-storm-force winds extended outward up to 175 miles (280 km). In addition to the wind gust of 129 mph reported at the Panama City Airport, other notable maximum wind gusts in the region were 89 mph in Apalachicola (FL), 71 mph in Tallahassee (FL), and 115 mph in Donalsonville (GA). It should be noted that these are isolated observations and winds in other locales were likely higher. Additionally, many instruments failed during the storm, so the maximum wind gusts were not captured in some locations. For example, the Florida Coastal Monitoring Program (FCMP) deployed three towers for this event. One of these towers recorded a wind gust of 130 mph near

Tyndall Air Force Base before the tower was overturned, destroying the instrument. A different FCMP Tower reported a one-hour period where wind gusts remained over 120 mph.

The StEER Hurricane Michael Preliminary Virtual Assessment Team Report analyzed the structural impacts of Hurricane Michael. The report highlighted extensive wind and storm surge damage, with wind speeds exceeding design levels and storm surge causing catastrophic destruction, particularly in Mexico Beach (Figure 34). Older structures, especially those built before the 2002 Florida Building Code, experienced significant failures, including roof and wall collapses, while newer buildings fared better but still suffered damage to cladding, windows, and roof systems.

Figure 34. Widespread devastation to wood-framed single and multi-family residences in Mexico Beach with few survivors in areas with highest inundations (Source: New York Times)

Wind-borne debris posed a major threat, leading to secondary damage in areas not classified as wind-borne debris regions under ASCE-7 standards. Figure 35 to Figure 39 show some examples of the observed wind-borne debris damage caused by Michael in Panama City and Mexico Beach, often at distances exceeding three miles from St. Andrew Bay. The report emphasized the effectiveness of updated building codes while identifying gaps in addressing extreme wind and surge events. It recommended revising codes to include higher wind speeds and storm surge considerations, improving resilient designs with elevated construction and better anchoring, and enhancing risk assessments for inland exposure and wind-borne debris impacts. Strengthening critical infrastructure and promoting public awareness of resilient practices were also highlighted as priorities to enhance disaster preparedness and recovery.

Figure 35. Damage to a garage door in Panama City during Hurricane Michael (2018). House was built between 2000-2009 and located 3.39 miles from St. Andrew Bay. Estimated wind speeds (129-150 mph) might have exceeded the design wind speeds (135 mph).

Figure 36. Damage to a window cause by wind-borne debris in Panama City during Hurricane Michael (2018). House was built between 2000-2009 and located 3.27 miles from St. Andrew Bay. Estimated wind speeds (129-150 mph) might have exceeded the design wind speeds (135 mph).

Figure 37. Damage to windows in a hose located in Panama City during Hurricane Michael (2018). House was built between 1990-1999 and located 3.25 miles from St. Andrew Bay. Estimated wind speeds (129-150 mph) might have exceeded the design wind speeds (135 mph).

Figure 38. Damage to a window in Panama City during Hurricane Michael (2018). House was built between 2010-2019 and located 3.39 miles from St. Andrew Bay. Estimated wind speeds (129-150 mph) might have exceeded the design wind speeds (135 mph).

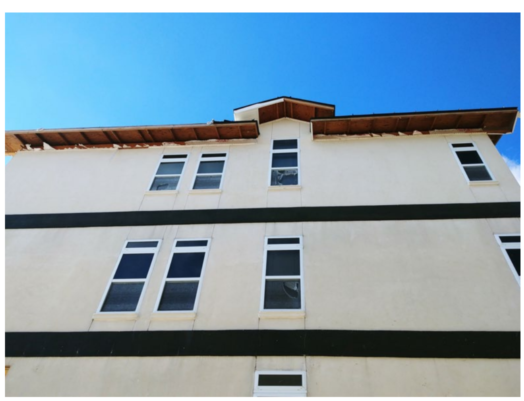

Figure 39. Damage to few windows in the shoreline of Mexico Beach during Hurricane Michael (2018). House was built between 2000-2009. Estimated wind speeds (150 mph) exceeded the design wind speeds (136 mph).

4.4.7 Hurricane Ian (2022)

In the case of Hurricane Ian (2022), IBHS reported that estimated peak winds approached but fell just below design levels for the area impacted under the modern building code; however, the event likely was a design level event for older code regimes, pre-Hurricane Andrew. The areas of Punta Gorda and Port Charlotte that were impacted by Hurricane Ian were the same areas hit by Hurricane Charley in 2004. The research report from IBHS states that the design wind speeds for the damage assessment areas where between 160 – 170 mph, and the observed wind speeds during the event where 150 mph, 140.3 mph and 135 mph in Cayo Costa, Iona and Punta Gorda, respectively. The same results were observed by RICOWI, Inc in their wind investigation report. According to RICOWI, in Cape Coral and Ft. Mayers, wind speeds between 90 – 130 mph were observed, while the design wind speeds for both places were 170 – 180 mph and 160 – 170 mph.

Structural wind damage was rare in site-built structures, even north of the track where peak wind estimates were highest, but there were isolated examples of structural roof failures and partial wall collapses in older residential buildings built prior to the adoption of the Florida Building Code in 2002 (StEER report). Given the limitations of the imagery used in this study, it is difficult to determine if wind-borne debris impacts on tiles had an influence on damage location (IBHS report, Part I). The failure of auxiliary structures, all roof cover types, and other cladding elements led to substantial wind-borne debris impacts on structures, exacerbating failures of openings such as windows and doors (IBHS report, Part II).

5 Florida Lake region housing analysis

This section analyzes the characterization of housing located within regions with designated design wind speeds of 130–140 mph and situated within one mile of bodies of water that contribute to an upwind Exposure D condition. This characterization provides critical insights into the distribution, geometry, and other attributes of typical neighborhoods in Florida, serving as essential input for the simulation-based approach to be conducted in this study by ARA (Task 3). Figures 1-3 (in Section 2) illustrate the locations of the primary bodies of water within the defined region of interest in Florida.

5.1 Methodology

The methodology begins with an investigation of major lakes, inland bays, and any body of water with a fetch greater than 5,000 feet in regions within the 130–140 mph design wind speeds. For this characterization, the identified water bodies were categorized into two regions: Central Florida and the Florida Panhandle.

Dr. David Roueche from Auburn University developed a GIS-based software application that provides detailed information on individual parcels across Florida, including geometry, year of construction, and other relevant attributes[2]. Using this app, a representative neighborhood was selected for each identified body of water. Within these neighborhoods, a typical residential building was chosen as an example for analysis. Tables 4 and 5 present the characteristics of these selected residential buildings for Central Florida and the Florida Panhandle, respectively. These tables include information such as the county, associated lake or inland bay and its fetch, the construction year of the selected house, the house plan dimensions, spacing between houses (both on the same street and across the street), the number of stories, and the potential for future housing developments. Additionally, in Table 4 and Table 5 several of the lakes that are within are adjacent to state parks are appropriately highlighted, which indicates that there is no potential for new housing developments.

Appendix A presents figures that represent the neighborhoods selected in Central Florida and the Florida Panhandle as part of the characterization methodology.

5.2 Analysis results

For Central Florida, the majority of housing developments around lakes were constructed between 1980 and 1990, coinciding with a period of rapid population growth and urban expansion. The region, particularly around Orlando, saw significant development driven by economic opportunities, the tourism industry, and the area's natural appeal, including its many lakes. Future development in these regions remains a possibility. A typical house in Central Florida is a single-story structure with a 45 x 60 ft plan. The typical spacing between houses is approximately 80 feet along the same street and 165 feet across the street.

In the Florida Panhandle, fewer lakes and inland bays meet the criteria for inclusion in the region of interest. While the majority of housing developments were built between 1980 and 1990, as in Central Florida, a significant portion of developments in this area predate this decade, resulting in a noticeable presence of older neighborhoods. The potential for future developments in this region is minimal, except for rebuilding in the place of tear-downs. Typical houses in the Florida Panhandle also feature a single-story structure with a 45 x 60 ft plan. The typical spacing in these neighborhoods is approximately 90 feet along the same street and 165 feet across the street.

[2] Rouche, D. (2024). https://auburnuniversity.maps.arcgis.com/apps/mapviewer/index.html?webmap=6658c8891ba949bd9034d3a412640b88

Table 4. Characteristics of the distribution of a typical neighborhood and single-family houses in Central Florida in the 130-140 mph design wind speed region adjacent to large inland bodies of water.

County	Lake/ inland bay	Fetch (ft)	Neighborhood	Building Year	House Plan	Distance between houses		No. of stories	Potentially new dev.
						Same street	Across street		
Lake County	Lake Apopka	39311	Winter Garden	**2000-2009**	50x60 ft	90 ft	150 ft	2	Yes
	John's Lake	8530	Killarney	**2000-2009**	50x70 ft	75 ft	180 ft	1	Yes
	Clermont Chain of Lakes								
	Lake Louisa	14488	Clermont	1990-1999, **2000-2009**	50x60 ft	80 ft	170 ft	1	Yes
	Lake Minnehaha	17057	Clermont	**1980-1989**, 1990-1999, 2000-2009	50x65 ft	90 ft	180 ft	1	Yes
	Lake Minneola	11482	Minneola	**2000-2009**	45x60 ft	85 ft	170 ft	1	Yes
	Lake Harris Chain of Lakes								
	Big Lake Harris	27814	Leesburg	**1950-1959**, 1960-1969, 1970-1979, 1980-1989,	30x55 ft	80 ft	190 ft	1	Yes
	Little Lake Harris	28491	Howey-in-the-Hills	1950-1959, **1960-1969**, 1970-1979, 1980-1989,	45x75 ft	95 ft	170 ft	1	Yes
	Lake Eustis	25387	Leesburg	1950-1959, 1960-1969, 1970-1979, **1980-1989**, 2000-2009	54x55 ft	80 ft	210 ft	1	Yes
	Lake Dora	28592	Tavares	1950-1959, 1960-1969, 1970-1979, **1980-1989**, 2000-2009, 2010-2019, 2020-2029	40x50 ft	75 ft	150 ft	1	Yes
	Lake Griffin	Lake Griffin State Park							
	St. Johns River	River Preserve State Park							
Sumter County	Lake Panasoffkee	42637	Lake Panasoffkee	1950-1959, 1960-1969, **1970-1979**, 1980-1989, 1990-1999, 2000-2009, 2010-2019, 2020-2029	55x45 ft	75 ft	160 ft	1	Yes
Marion County	Lake Weir	18648	Ocklawaha	**1950-1959,** 1960-1969, 1970-1979, 1980-1989, 2010-2019, 2020-2029	50x40 ft	70 ft	150 ft	1	Yes
Volusia	Lake George	62247	Georgetown	1950-1959, 1960-1969, **1970-1979**, 1980-1989, 1990-1999, 2000-2009,	45x40 ft	90 ft	140 ft	1	Yes

				2010-2019, 2020-2029					
Polk County	Arbuckle	Blue Jordan Swamp							
	Lake Alfred	7309	Lake Alfred	1950-1959, 1960-1969, **1970-1979**, 1980-1989, 1990-1999, 2000-2009, 2010-2019,	60x40 ft	85 ft	155 ft	1	Yes
	Lake Ariana	56492	Auburndale	**1950-1959**, 1960-1969, 1970-1979, 1980-1989, 1990-1999, 2000-2009, 2010-2019, 2020-2029	55x45 ft	80 ft	140 ft	1	No
Seminole County	Lake Monroe		Sanford	**1950-1959**, 1960-1969, 1970-1979, 1980-1989, 1990-1999, 2000-2009, 2010-2019, 2020-2029	50x40 ft	60 ft	160 ft	2	Yes
	Lake Jessup/Lake Harney	14658	Winter Springs	1960-1969, **1970-1979**, 1980-1989, **1990-1999**, 2000-2009, 2010-2019	55x45 ft	70 ft	160 ft	2	Yes
Orange County	Lake Conway	5944	Belle Isle	**1950-1959**, 1960-1969, 1970-1979, 1980-1989, 1990-1999, 2000-2009, 2010-2019, 2020-2029	75x50ft	80 ft	175 ft	1	No - seems unlikely
	Butler Chain of Lakes								
	Lake Butler	7769	Windermere	1950-1959, 1960-1969, 1970-1979, **1980-1989**, 1990-1999, 2000-2009, 2010-2019, 2020-2029	80x60 ft	100 ft	200 ft	2	Yes
	Lake Down	7893	Windermere	1970-1979, **1980-1989,** 1990-1999, 2000-2009, 2010-2019, 2020-2029	95x85 ft	150 ft	250 ft	1	Yes
	Lake Tibet	10790	Bay Hill	1970-1979, 1980-1989,	85x70 ft	100 ft	200 ft	2	No

				2010-2019, 2020-2029					
	Lake Louisa	14488	Clermont	1950-1959, 1970-1979, 1980-1989, 1990-1999, **2000-2009**, 2010-2019, 2020-2029	55x45 ft	90 ft	200 ft	1	Yes
Osceola County	Lake Kissimmee	61062	Uninhabited- Wildlife Reserve						
	Lake Tohopekaliga	43270	Kissimmee	1950-1959, 1970-1979, **1980-1989**, 2010-2019	70x60 ft	115 ft	200 ft	1	Yes

Table 5. Characteristics of the distribution of a typical neighborhood and single-family houses in the Florida Panhandle in the 130-140 mph design wind speed region adjacent to large inland bodies of water.

County	**Lake/ inland bay**	**Fetch (ft)**	**Building Year**	**House Plan**	**Distance between houses**		**Land Size**	**No. of stories**	**Potentially new dev**
					Same street	**Across street**			
Bay County	Deer Point Lake	12000-15000	**1980-1989**, 1990-1999, 2000-2009	50x65 ft	85-100 ft	170-190 ft	95x120 ft	1	Yes
	St. Andrews Bay	30000-35000	**1950-1959**, 1960-1969, 1970-1979	35x50 ft	75 ft	150 ft	65x120 ft	1	No
	East Bay	25000-30000	**1980-1989**	50x60 ft	90-100 ft	160-180 ft	75x120 ft	1	Yes
Gulf County	Lake Wimico	12000-14000	Surroundings not populated						No
	St Joseph Bay	25000-30000	1960-1969, 1970-1979, **1980-1989**	45x50 ft, 25x60 ft	100 ft	160 ft	110x120 ft	1	Yes
Walton County	Lake Powell	7500-8000	WBDR						
Washington County	Gap Lake	5000-5500	Lake not large enough						

6 Conclusions

The review of historical information, literature, and hurricane damage assessment reports at this stage of the study confirm the need for a more rigorous scientific investigation to quantify the relative risk of wind-borne debris damage in hurricane-prone regions that are adjacent to Exposure D conditions, whether the conditions are due to proximity to the coast or a large inland body of water.

ASCE 7 introduced provisions for design against wind-borne debris in 1995 with a single trigger wind speed. Subsequent cycles of ASCE 7 increased the blanket trigger wind speed but still included the lower wind speed trigger for buildings within one mile of the coast. The one-mile distance was based on anecdotal observations from post-hurricane damage assessments; however, this distance has not been validated through scientific methods. In ASCE 7-22, the definition of a WBDR was simplified to remove reference to the coast and to replace it with an Exposure D condition (at least 5,000 ft of upwind fetch of water). This change was viewed by ASCE 7-22 Wind Loads Subcommittee members as a correction to a previous error and a path to simplifying the challenge of consistently defining the meaning of the coast. The result of this change in the standard, and subsequent adoption by the 8th Ed. of the Florida Building Code, Residential (2023) resulted in many new WBDRs in Central Florida adjacent to large lakes and in the Florida Panhandle adjacent to bays.

Damage assessment reports from two storms (Hurricane Charley and Hurricane Michael) demonstrated the potential for wind-borne debris damage at wind speeds between 125 and 140 mph at distances over three miles from coastal Exposure D conditions. We have not identified reports of wind-borne debris damage during design wind speed events in inland areas with Exposure D conditions from lakes with design wind speeds between 130 and 140 mph. The lack of data is likely due to the limited number of design level wind events in these inland regions. Post-storm damage assessments are intended to provide a representative sampling rather comprehensive documentation and are typically prioritized to coastal regions due to relatively higher damage levels, so a dearth of observations does not preclude that such damage occurs.

Research studies have demonstrated how building envelope breaches from wind-borne debris can increase wind loads resulting in further damage to the structure. Studies have shown how protective measures, such as impact resistant glazing, can reduce the risk for this damage, and these results underpin the design code requirements for opening protection for buildings in designated WBDRs. Researchers have developed and experimentally validated debris transport models; however, there has been no specific study of how wind-borne debris regions should be designated relative to upwind terrain conditions and how the risk for wind-borne debris damage varies with distance from terrain condition transitions. While some limited research has demonstrated how transition regions between terrain conditions impact wind loads, this research has not yet been extended to the impact on debris generation, transport, and damage.

In support of upcoming modeling activities to quantify the risk of wind-borne debris damage in coastal and inland WBDRs, a comprehensive summary of housing developments near Central Florida lakes and Panhandle bays has been generated. This data will be ingested into a model that will provide a preliminary quantification of wind-borne debris risk and how that risk varies with distance to the shore of the lake, bay, or coast.

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8 Appendix A. Inland WBDR Neighborhood Analysis Images

The following figures represent the neighborhoods selected for Central Florida (Figures 40-60 and the Florida Panhandle (Figures 61-64) analysis. The neighborhoods are highlighted in magenta rectangles.

8.1 Central Florida neighborhoods around lakes/inland bays

Figure 40. Lake County – Lake Apopka neighborhood selection.

Figure 41. Lake County – John's Lake neighborhood selection

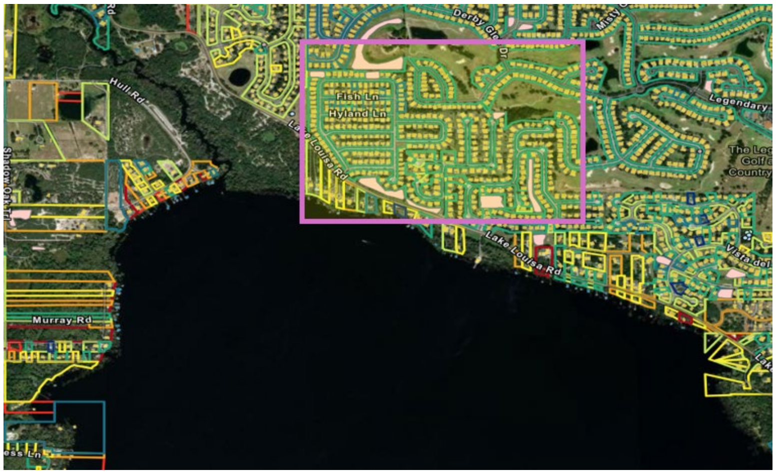

Figure 42. Lake County – Lake Louisa neighborhood selection

Figure 43. Lake County – Lake Minnehaha neighborhood selection

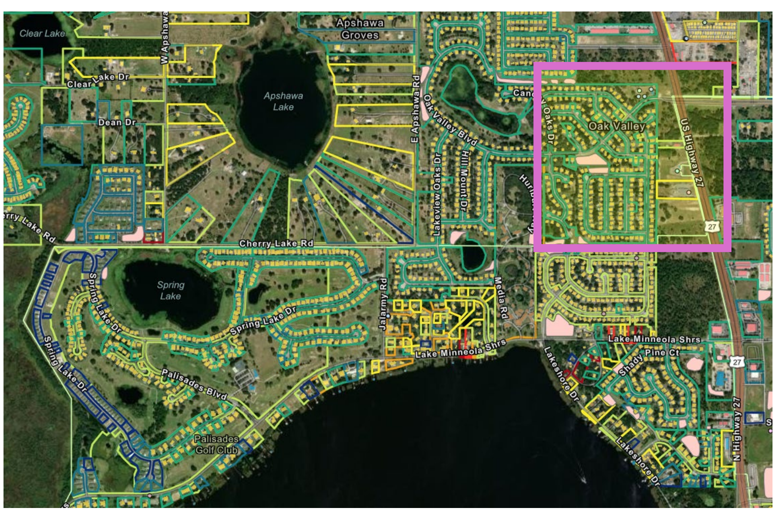

Figure 44. Lake County – Minneola neighborhood selection

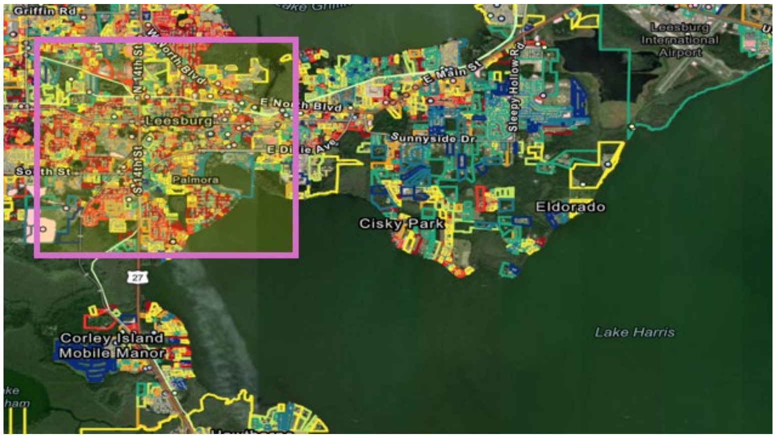

Figure 45. Lake County – Big Lake Harris neighborhood selection

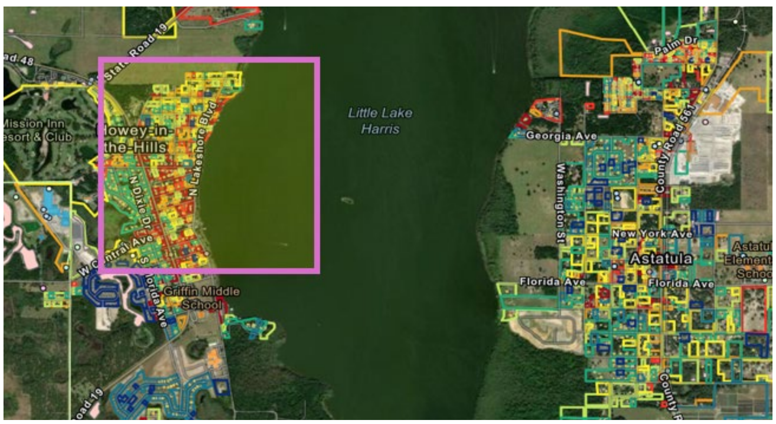

Figure 46. Lake County – Little Lake Harris neighborhood selection

Figure 44. Lake County – Lake Eustis neighborhood selection

Figure 47. Lake County – Lake Dora neighborhood selection

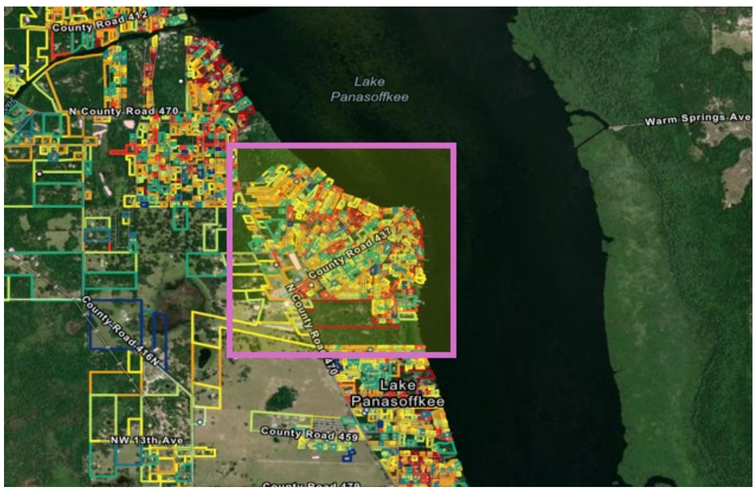

Figure 48. Sumter County – Lake Panasoffkee neighborhood selection

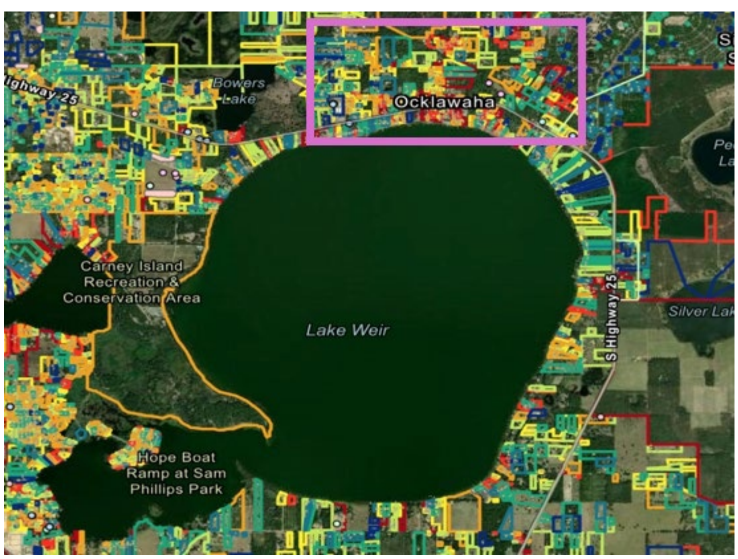

Figure 49. Marion County – Lake Weir neighborhood selection

Figure 50. Volusia County – Lake George neighborhood selection.

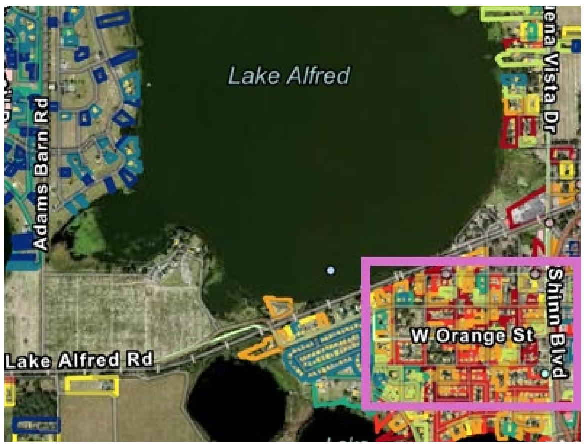

Figure 51. Polk County – Lake Alfred neighborhood selection.

Figure 52. Polk County – Lake Ariana neighborhood selection.

Figure 53. Seminole County – Lake Monroe neighborhood selection.

Figure 54. Seminole County – Lake Jessup/Lake Harney neighborhood selection.

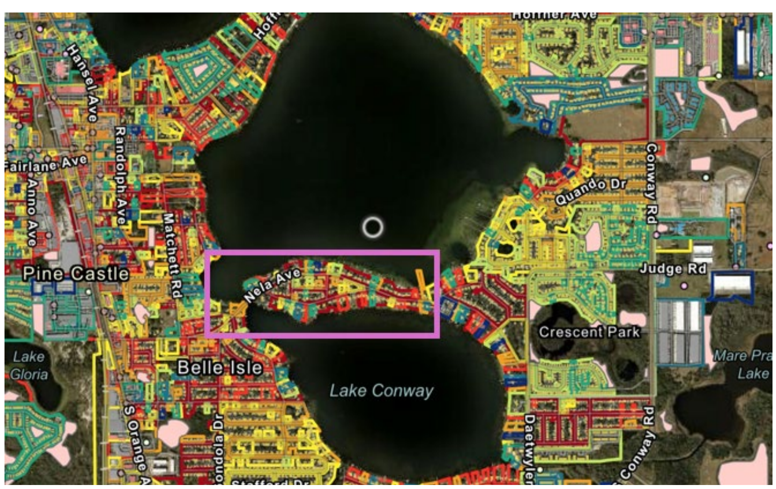

Figure 55. Orange County – Lake Conway neighborhood selection.

Figure 56. Orange County – Lake Butler neighborhood selection.

Figure 57. Orange County – Lake Down neighborhood selection.

Figure 58. Orange County – Lake Tibet neighborhood selection.

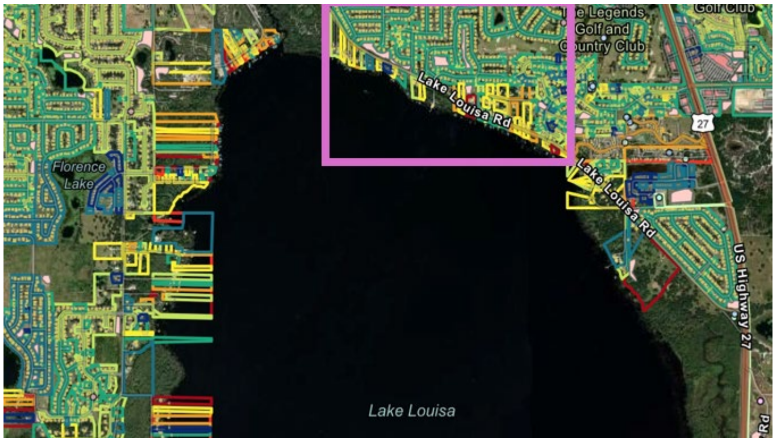

Figure 59. Orange County – Lake Louisa.

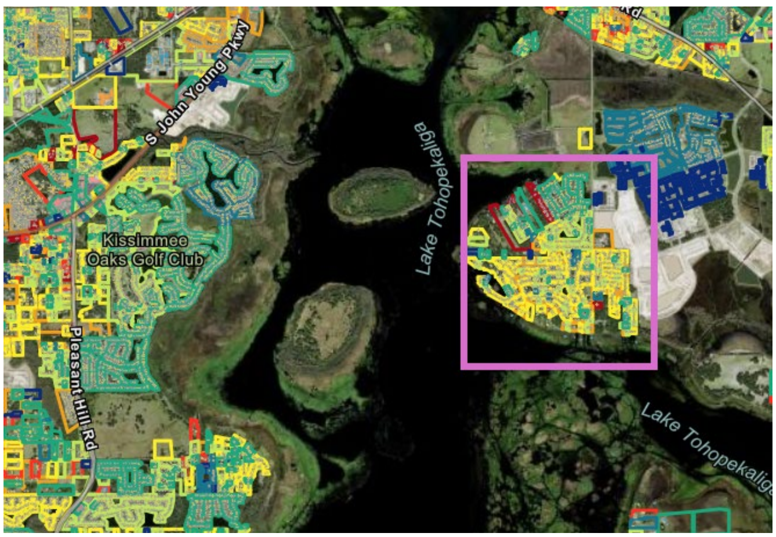

Figure 60. Orange County - Lake Tohopekaliga neighborhood selection.

8.2 Florida Panhandle neighborhoods around lakes/inland bays

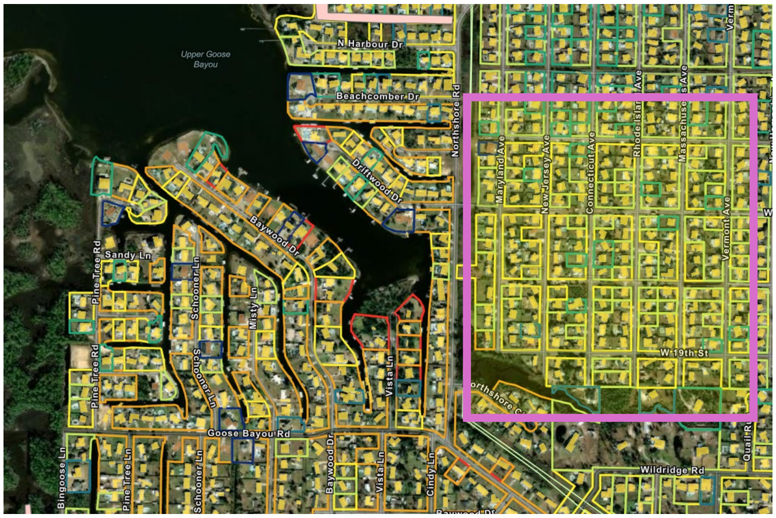

Figure 61. Bay County - Deer Point Lake neighborhood selection.

Figure 62. Bay County – St. Andrews Bay neighborhood selection.

Figure 63. Bay County – East Bay neighborhood selection.

Figure 64. Gulf County – St. Joseph Bay neighborhood selection.