FINAL Report:

Hurricane Michael Data Enhancement (Phase II), Performance of Modular Houses and FEMA Recovery Advisory Reviews

Project #: P0157245

Submitted to:

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1 RELEVANT SECTIONS OF THE FLORIDA BUILDING CODE

- 2017 Florida Building Code- Residential, Sixth Edition Chapter 6- Wall Construction (FBC, 2017)

- 2017 Florida Building Code- Residential, Sixth Edition Chapter 7- Wall Covering

- 2017 Florida Building Code- Residential, Sixth Edition Chapter 8- Roof Ceiling Construction all Covering (FBC, 2017)

- 2017 Florida Building Code- Residential, Sixth Edition Chapter 9- Roof Assemblies (FBC, 2017)

- 2017 Florida Building Code- Building, Sixth Edition, Chapter 14 “Exterior wall” (FBC, 2017)

- 2017 Florida Building Code- Building, Sixth Edition, Chapter 17 “Special installations and test”

1.1 Relevant Statutes, Standards, Definitions or Other Regulations:

- Florida Statute 553.36(13) defines a Modular Building as follows:

“Manufactured building”, “modular building,” or “factory-built building” means a closed structure, building assembly, or system of subassemblies, which may include structural, electrical, plumbing, heating, ventilating, or other service systems manufactured in manufacturing facilities for installation or erection as a finished building or as part of a finished building, which shall include, but not be limited to, residential, commercial, institutional, storage, and industrial structures. The term includes buildings not intended for human habitation such as lawn storage buildings and storage sheds manufactured and assembled offsite by a manufacturer certified in conformance with this part. This part does not apply to mobile homes.

- Florida Statute 553.80(d) states the following:

Building plans approved under s. 553.77(3) and state-approved manufactured buildings, including buildings manufactured and assembled offsite and not intended for habitation, such as lawn storage buildings and storage sheds, are exempt from local code enforcing agency plan reviews except for provisions of the code relating to erection, assembly, or construction at the site. Erection, assembly, and construction at the site are subject to local permitting and inspections.

- Florida Statute 553.37(3)-(5) states the following:
  (3) After the effective date of the Florida Building Code, no manufactured building, except as provided in subsection (12), may be installed in this state unless it is approved and bears the insignia of approval of the department and a manufacturer’s data plate. Approvals issued by the department under the provisions of the prior part shall be deemed to comply with the requirements of this part.

(4) All manufactured buildings issued and bearing insignia of approval pursuant to subsection (3) shall be deemed to comply with the Florida Building Code and are exempt from local amendments enacted by any local government.

(5) No manufactured building bearing department insignia of approval pursuant to subsection (3) shall be in any way modified prior to installation, except in conformance with the Florida Building Code.

2 BACKGROUND

Hurricane Michael (October 10, 2018) made landfall south of Panama City, FL with the National Hurricane Center reporting a minimum central pressure of 919 MB and maximum sustained winds of 150 mph. Peak wind gusts were measured near the eyewall at 130 mph (10 m height, open exposure, 3 second gust), but gusts may have been higher as several observation stations were damaged and stopped reporting. Post-storm analysis estimated that the design wind speeds for many structures were exceeded for a sizable region near Mexico Beach and further inland (Vickery et al. 2018). The hurricane particularly affected Mexico Beach and Panama City and nearby coastal towns as well as interior areas, such as Blountstown, FL, and Marianna, FL located north of the I-10 Interstate highway.

The research team, in collaboration with the NSF Structural Extreme Events Reconnaissance (StEER) network, conducted two damage surveys following the landfall of the hurricane and investigated the structural performance of buildings affected. Assessments were primarily conducted between October 13-15, 2018 and November 1-6, 2018. The research team collected data in Florida from Panama City Beach east and south to Indian Pass, FL and north to Marianna, FL. The communities assessed included: Panama City Beach, Panama City (and surrounding communities), Mexico Beach, Port St. Joe, Apalachicola, a few routes out to barrier islands in the region, and the inland communities of Blountstown and Marianna. Focus was primarily directed toward broadly assessing building performance over a large expanse of the impacted area and over a range of structural typologies, with particular emphasis on documenting both new and old construction, preferably in close proximity.

The research team was able to compare the performance of the houses in neighborhoods affected by Hurricane Michael using the year of construction to differentiate between those built before and after the Florida Building Code was first adopted in 2002. The research team also presented building performance based on wind and storm surge hazard in the Survey and Investigation of Buildings Damaged by Hurricane Michael Project Phase I (2019). The Second Phase of this project continued the data enhancement of the remaining areas and compared the performance of the Pre- and Post FBC buildings.

3 RESEARCH AIMS AND MOTIVATION

A result of the insurance crisis following the 2004 and 2005 hurricanes was that the legislature saw the impact Florida Building Codes can have on building damage and insurance losses. Subsequently, the state building code was revised further from the 2002 adoption to enhance the wind resistance measures of the code. The code now prioritizes property protection from hurricane winds and water intrusion and mitigation of existing buildings. The Florida Building Commission continues to focus on developing the fundamental science essential to good engineering standards and buildings codes, which serves as the motivation for this project.

Hurricane Michael provided a unique opportunity to understand the performance of nominally code-compliant buildings under near-design or even above-design hazard conditions. Since there are many different factors affecting the performance of an individual building, it is necessary to analyze large, high quality datasets containing as few errors as possible and with as little uncertainty as possible. The damage assessments conducted by the research team following Hurricane Michael consisted of a large collection of geolocated images and partially filled out survey forms for each structure assessed. Additional efforts following the field deployments were needed to enhance and perform quality control checks on the data to produce a robust, reliable final dataset. In Phase I of this project (Prevatt & Roueche, 2019), the research team was able to perform data enhancement of approximately 220 buildings. The goal of this Phase II project is to perform the DEQC process on the remaining buildings (about 500), and perform an exploratory analysis of the dataset to evaluate the relative performance of code-compliant construction.

A tangential motivation of this research is to assess the performance of modular homes, which are subject to the requirements of the Florida Building Code but are manufactured off-site. The null hypothesis is that the performance of these buildings is equivalent to a site-built home, all else being equal. This hypothesis will be tested using post-hurricane data collected by the PIs following Hurricanes Irma and Michael.

There are three primary tasks within the scope of this project. A summary of the methods and major findings from each task are provided in the following sections.

Modular (or manufactured homes) are defined in Section 1 of this report. This definition specifies that modular homes are manufactured off-site but conform to the provisions of the

Florida Building Code, unlike mobile homes (oftentimes also called manufactured homes if built after 1976) which conform to the federal Housing and Urban Development (HUD) standards. A review of a sample of modular home plans from the Florida Department of Business and Professional Regulation suggested most modular homes are constructed to conform specifically to the Florida Building Code Residential. The relative hurricane performance of modular homes vs traditional site-built homes is examined in this study using post-hurricane building performance data from Hurricanes Irma (2017) and Michael (2018).

3.1 Methods

A sample of 23 modular homes affected by Hurricane Irma was contained in the post-hurricane building performance dataset collected for a previous project (Prevatt and Roueche, 2018). Data for each home included the year built[1], first floor elevation, roof shape, structural system, building envelope materials, and component-level damage ratios (percentage of a building component that is damaged or removed by the hurricane). The Monroe County building department provided permit files for each of the modular homes to the research team which contained the manufacturer and building plans. From the permit files, the reconnaissance data was supplemented to obtain the design wind speed, exposure condition, and transverse lateral net wall pressure. Prior to 2002, modular home designs conformed to the Standard Building Code and had a design wind speed (50 year mean reoccurrence interval) of either 115 mph, 130 mph or 155 mph. Modular home designs after 2002 conformed to the Florida Building Code and had design wind speeds between 150 mph and 175 mph. Where noted, all but one home was designated as Exposure C. While the permit files contained the structural design details for each home, cladding details (product approval number, manufacturer, etc) were not documented. The maximum wind speed at each modular home location were interpolated from the ARA wind field (Vickery et al. 2017).

Modular homes were identified in Bay County using the public permit search platform (http://www.applications.co.bay.fl.us/Search/permit.aspx), which identified permits for modular homes as type DCA Modular. Thirty-eight homes were identified and located using this approach, but only twenty-eight were within the geographic boundaries of the supplemental data we used to assess damage and building attributes. For Gulf County, the

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[1] Year built for modular buildings can refer to either year of manufacture or year of installation, which may not be the same year. Where possible, we use the year of manufacture since that is best reflective of the code to which it was designed.

county interactive GIS platform was used to locate modular homes by searching for a specific parcel use code that was used for parcels containing modular homes. The GIS platform allowed parcels to be searched and extracted as a CSV file for further analysis. Twenty modular homes were selected using this platform for Gulf County. In addition, two modular homes had been assessed by the research team on-site during the previous, broader Hurricane Michael deployments. Altogether, this resulted in 50 modular homes for both Bay and Gulf Counties. Since only two of the homes were assessed in the on-site deployments, damage and building attributes for the remaining 48 homes were sourced entirely from supplemental data sources. Damage and building attributes were evaluated using licensed oblique and nadir pre- and post-hurricane imagery provided through the Eagleview ConnectExplorer platform (Figure 1). Where available, Google Streetview was also used to document damage and building attributes, utilizing the pre- and post-hurricane imagery. Public county records and permit files were used to obtain the year of installation and confirm other details such as roof cover type or wall cladding type. Permit documents were requested for the homes to identify the manufacturer and structural design parameters but were not available in Bay County due to Hurricane Michael damaging the Bay County Public Services building, destroying many of the paper records containing the permit files. A public records request was submitted to Gulf County that has not yet been completed at the time of this report. Building departments for both counties tried to be helpful as much as possible but were understandably overwhelmed with the rebuilding process.

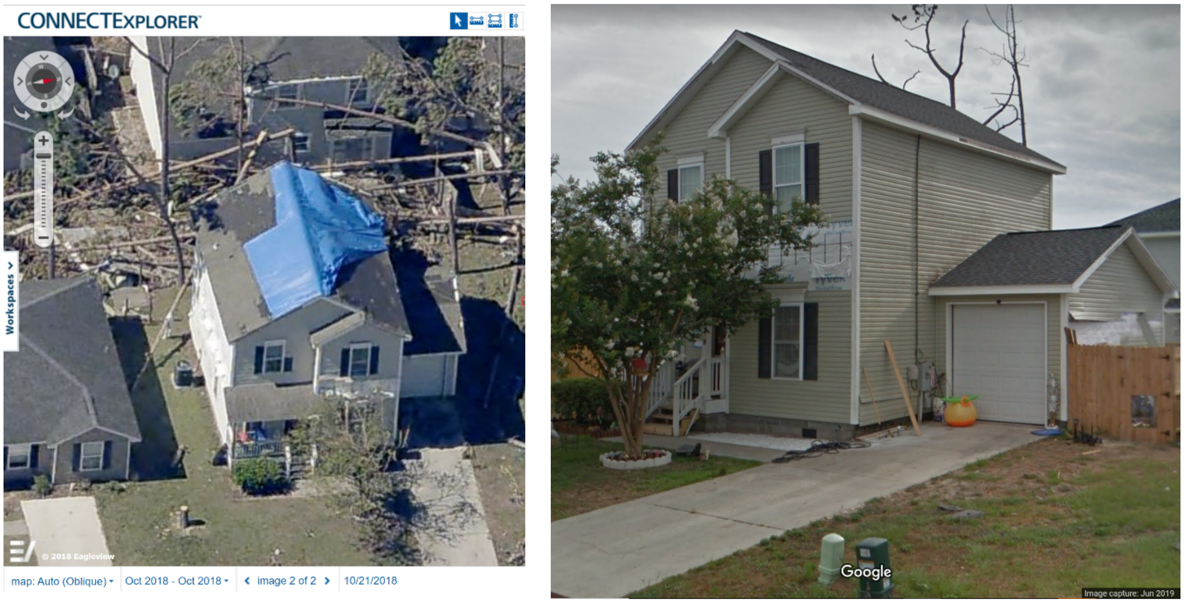

Figure 1. Supplemental data sources for identifying hurricane damage to modular homes. (Left) Eagleview ConnectExplorer platform (imagery collected 10/21/2018), and (right) Google Streetview (imagery collected June 2019).

Peak gust wind speeds were estimated at each home location in Gulf and Bay County using the ARA wind field (Vickery et al. 2018). The wind exposure surrounding most homes was noted to be suburban (Exposure B).

The performance of modular homes relative to site-built homes was assessed by selecting a sample of site-built single-family homes to match the key expected causal factors, specifically (1) a similar range of construction year, (2) a similar range of estimated wind speeds, (3) wood-frame construction, (4) one- or two-stories, and (5) similar first floor elevations. Regarding item (5), none of the modular homes in Bay and Gulf Counties had a first-floor elevation more than approximately 2 ft, so only site-built homes installed at grade level were used for comparison. In Monroe County, many of the modular homes were elevated, and so similarly elevated homes were used for comparison. In all, 50 homes were used from Gulf and Bay Counties for comparison, while 20 site-built homes in Monroe County were used. The lower sample size in Monroe County was simply due to a lack of buildings similar to modulars in the Hurricane Irma damage database. Modular homes tended to be newer (post 2002 FBC), and were wood-frame, while newer site-built homes tended to be constructed out of concrete masonry units or other forms of concrete construction and therefore were not an equivalent comparison. A summary of the modular and site-built homes is provided in Table 1, while a list of all homes used is provided in Appendix A. Locations of all homes are plotted in Figure 2.

Table 1. Characteristics of modular and site-built homes used to evaluate relative hurricane wind performance.

Parameter	**Gulf/Bay Modular**	**Gulf/Bay Site-Built**	**Monroe Modular**	**Monroe Site-Built**
Year Built (Mean / Std. Dev.)	2007 / 4.29	2007 / 7.32	2003 / 4.76	2006 / 7.20
Wind Speed, mph (Mean / Std. Dev.)	130 / 15.0	133 / 9.19	116 / 2.65	116 / 3.44
Stories (# 1 story / # 2 story)	42 / 8	39 / 11	20 / 3	16 / 4
First Floor Elevation, ft (Mean / Std. Dev.)	0.2 / 1.16	0 / 0	7.43 / 3.15	9.1 / 1.25

The relative performance of site-built and modular homes was assessed using the non-parametric Kruskal-Wallis method to test the null hypothesis that the wind damage rating (described in Section 5.1.2) for both site-built and modular homes was the same. Results of the Kruskal-Wallis test are presented as a p-value, which can be treated as the probability that the null hypothesis is true. The same approach was used for the component-level damage ratios as well, which included damage ratios for roof cover, roof sheathing, roof structure, wall cladding, and wall structure.

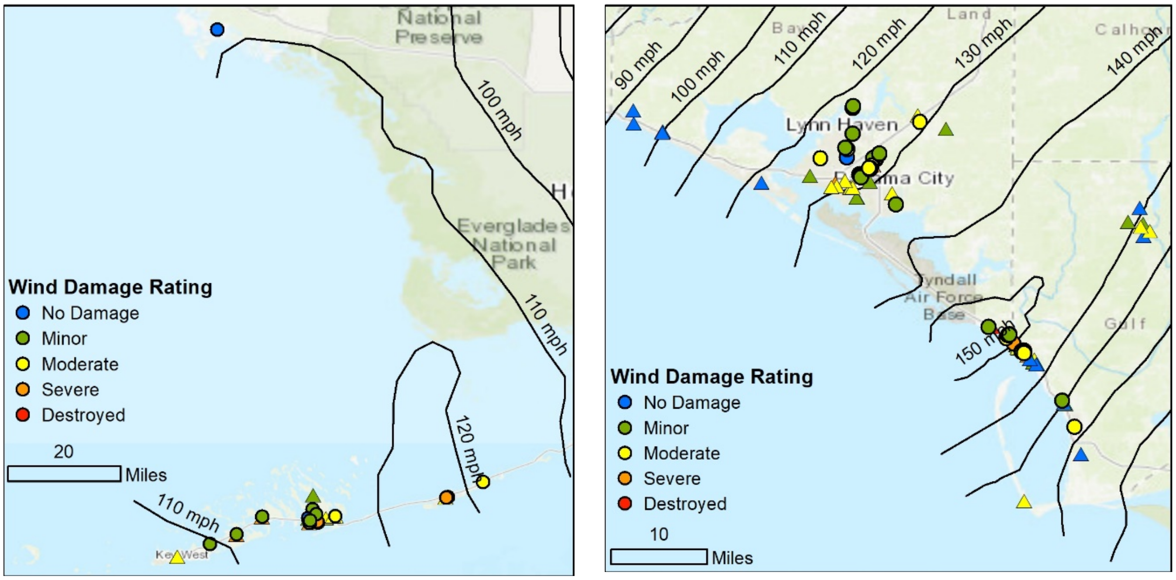

Figure 2. Locations of modular and site-built homes used to evaluate relative wind performance during (left) Hurricane Irma (2017); and (right) Hurricane Michael (2018). Circles indicate site-built homes and triangles indicate modular homes.

3.2 Results

The overall performance of modular homes and site-built homes in Hurricanes Irma (2017) and Michael (2018) were similar for our sample sets. In homes impacted by Hurricane Irma (2017), cladding (roof cover and wall cladding) was more vulnerable in modular homes, while roof sheathing and wall structure and sheathing was more vulnerable in site-built homes. Only the difference in wall cladding damage was significant at the 95% confidence level (calculated as (1 – p-value)*100%). None of the homes in this Irma sample set, either modular or site-built, experienced damage to the roof structure.

In Hurricane Michael, only minor differences were observed in the wind performance of modular and equivalent site-built homes. The mean wind damage rating was slightly lower in modular homes than site-built but was not statistically significant. Modular homes experienced significantly lower roof cover damage, although in both types of homes a disproportionate percentage of roof cover was still damaged relative to other building components. Wall substrate and wall structure damage was significantly higher in the modular homes this sample set, but this is only because the sample of site-built homes used in the comparison did not experience any wall structure damage. As shown in Section 5.2.1, some site-built homes in the overall dataset did experience wall substrate and wall structure collapse due to wind. Wall cladding performance in modular homes impacted by Hurricane Michael was equivalent to site-built homes unlike in Hurricane Irma.

Curiously, wall cladding damage in our samples of both site-built and modular homes impacted by Hurricane Irma were higher on average than that observed in our Hurricane Michael sample set, despite the absolute wind speed estimates being lower in Hurricane Irma, and the wind load ratio (squared ratio of estimated wind speed to design wind speed) being much lower in Irma than in Hurricane Michael. Overall wind damage ratings were similar in both sample sets despite the difference in hazard characteristics between the two storms.

Table 2. Relative performance of site-built (N = 20) and modular (N = 23) homes in Monroe County following Hurricane Irma (2017).

Damage Parameter	**Statistic**	**Site-Built Sample**	**Modular Sample**	**Kruskall-Wallis p-value**
Wind damage rating	Mean	1.55	1.96	0.098
	Std. Dev.	0.94	0.64	
Roof structure damage	Mean	0	0	-
	Std. Dev.	0	0	
Roof substrate damage	Mean	2.50	2.17	0.322
	Std. Dev.	5.50	8.50	
Roof cover damage	Mean	20.0	29.6	0.131
	Std. Dev.	20.0	21.8	
Wall structure damage	Mean	1.50	0.43	0.894
	Std. Dev.	6.71	2.09	
Wall substrate damage	Mean	2.50	0.87	0.246
	Std. Dev.	7.16	4.17	
Wall cladding damage	Mean	13.0	20.9	0.050
	Std. Dev.	21.3	18.3	

Table 3. Relative performance of site-built (N = 50) and modular (N = 50) homes in Bay and Gulf County following Hurricane Michael (2018).

Damage Parameter	**Statistic**	**Site-Built Sample**	**Modular Sample**	**Kruskall-Wallis p-value**
Wind damage rating	Mean	1.62	1.48	0.398
	Std. Dev.	0.73	1.25	
Roof structure damage	Mean	0.32	1.06	0.388
	Std. Dev.	2.12	4.95	
Roof substrate damage	Mean	1.46	1.34	0.685
	Std. Dev.	4.78	5.09	
Roof cover damage	Mean	20.5	14.9	0.033
	Std. Dev.	22.9	20.38	
Wall structure damage	Mean	0 / 0	0.94	0.042
	Std. Dev.	0	4.85	
Wall substrate damage	Mean	0 / 0	1.22	0.003
	Std. Dev.	0	4.91	
Wall cladding damage	Mean	5.64	5.36	0.117
	Std. Dev.	12.10	8.75	

4 TASK 2: HURRICANE MICHAEL DATA ENHANCEMENT

The original Hurricane Michael dataset described in Prevatt and Roueche (2019) contained 737 assessments, of which 704 were individual building assessments and the remaining 33 were general area assessments that broadly described the performance of multiple buildings within a specific area or region. Approximately 220 of the 704 building assessments were enriched in the Phase I study to quantify precise building attributes and component-level building damage extent. The objective of this Phase II effort was to extend the study to enrich the remaining 484 buildings affected by Hurricane Michael and perform an exploratory evaluation of the pre- and post-Florida Building Code building performance. The final dataset was also expanded to include 48 additional modular homes identified and assessed as described in Section 4, resulting in a total of 752 individual building assessments in the database.

4.1 Methods

The data enhancement and quality control process followed that developed by StEER (Roueche et al. 2019). Following this approach, the raw door-to-door (D2D) field data was supplemented with additional data sources including the processed densified point clouds and 3D meshes generated from the UAS data (using Structure-from-Motion techniques), the vehicle-mounted street-level panoramas, Bay and Gulf County property assessor databases, nadir imagery of affected areas (~ 25 cm ground sample distance) provided by the National Oceanic and Atmospheric Administration (NOAA), licensed oblique and nadir imagery from the Eagleview® Pictometry platform, and pre-event imagery from the Google Maps and Google Streetview platforms. Using these supplemental data sources, we enhanced the raw D2D dataset to define a full suite of building attributes, define as much of the structural load path as possible, and more precisely quantify damage by evaluating the percentage of damaged components for the roof structure, roof substrate, roof cover, wall structure, wall substrate, wall cladding, and fenestration. The damage ratios were estimated using all visible portions of the building, and any portion of the component no longer visible on the building was classified as damaged. The enhanced D2D dataset was quality controlled using both automated checks and reassessment of randomly sampled records to minimize errors and maximum consistency and reliability of the final dataset. Finally, the D2D dataset was enhanced with hazard and other contextual parameters, such as the design wind speed and the estimated maximum wind speed. This enhanced dataset is the basis of the current study, and includes both wind- and surge-induced damage. A detailed study of surge performance during Hurricane Michael was already performed by Kennedy et al (2020) using a portion of the data contained within this dataset. Major findings from Kennedy et al. (2020) are summarized in Section 4.3. The analysis in this report focuses on wind-induced damage and excludes buildings from the study that had observable structural surge damage. A spatial view of the dataset with wind damage ratings is provided in Figure 3.

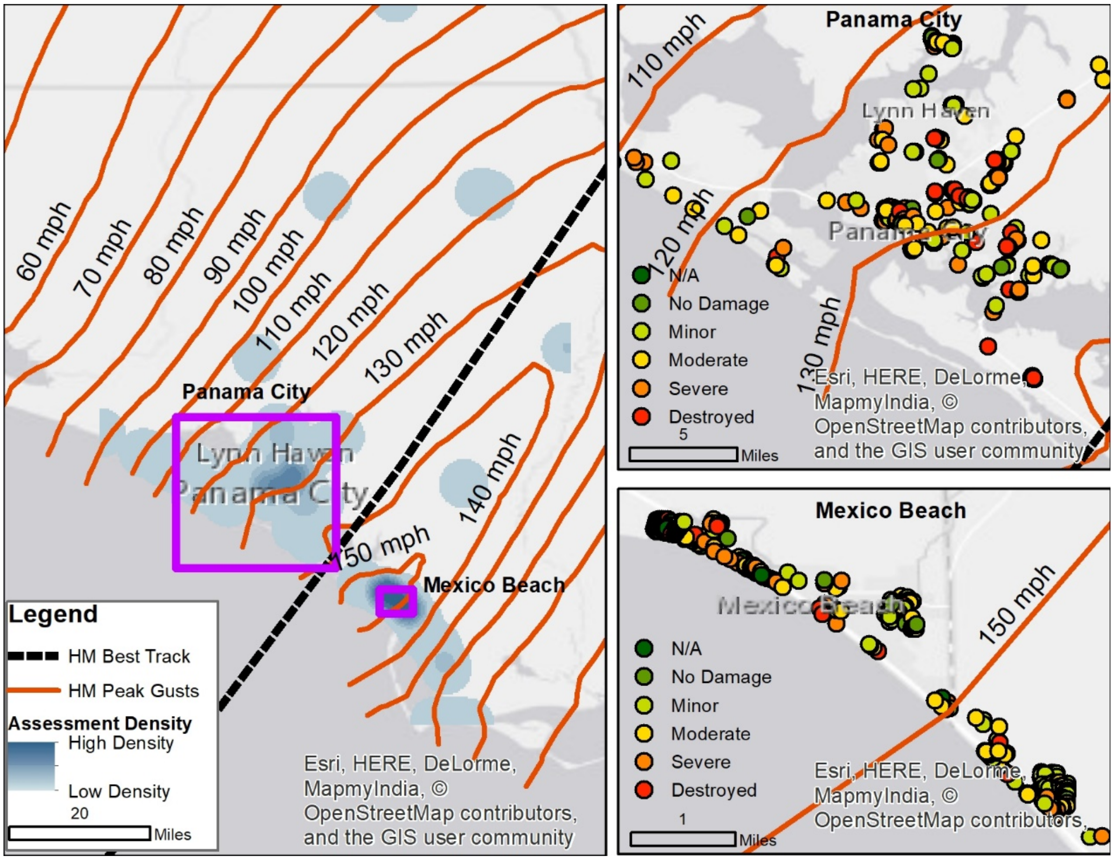

Figure 3. Assessment locations in Florida relative to estimated peak gust wind speeds (Vickery Peter et al. 2018) and best hurricane track (Beven et al. 2019). Wind damage rating are provided in the two inset figure for Panama City and Mexico Beach.

4.1.1 *Data Quality*

Each record in the Fulcrum database underwent an extensive Data Enrichment/Quality Control (DE/QC) process outlined in Roueche et al (2019). Records were updated to a specific stage, indicating the level of detail, and in some cases, uncertainty. As each record completed one of these stages, a code is updated within the record. A QC notes field is used to capture any relevant information related to the processing of the record, such as a source of unusually high uncertainty.

For all assessments, at least two data librarians participated in the DE/QC process of each record separately to help catch errors and reduce uncertainties. In addition, the entire dataset underwent a number of macro-level QC checks to identify potential errors, e.g., filtering the dataset for blank entries in the number of stories, searching for invalid field entries (e.g., 72 was entered for first floor elevation (ft) due to unit error), and more. Every effort was made to find and fix major errors or inconsistencies. However, there may still be small errors in a few records, and there is also uncertainty present due to incomplete data and/or use of engineering judgement.

To better quantify the potential for errors in the dataset, a random sample of 80 records from the preliminary final dataset was drawn and re-processed by members of the research team. Out of 6,240 fields contained within these records (78 per record), 100 fields were changed due to errors, yielding a change rate of 1.6%. Nearly 30% of the errors occurred in buildings with an overall damage rating classified as Destroyed. These buildings were more difficult to assess because less of the information could be inferred from the on-site investigations, requiring more extensive efforts to pull information from pre-event data sources that provided more opportunities for errors to be made. The most common error was a misclassification of wind damage rating (12 out of 80), but generally the wind damage rating was only adjusted by +/- 1 category (e.g., from Minor to Moderate). Other errors of note were the misclassification of the roof shape, misidentification of wall cladding, and misidentification of the foundation type.

4.1.2 *Damage Measures*

Damage was evaluated in two ways for most buildings:

1) Damage Ratings. Categorical damage ratings were assigned for wind, surge, and rainwater ingress hazards if possible. Each of these hazard-specific damage ratings have defined criteria as defined in Table 4, Table 5, and Table 6. An aggregate overall damage rating was also subjectively assigned to represent the worst-case damage state of the three hazard-specific damage ratings. The wind damage ratings are based on more quantitative criteria, while the surge and rainwater damage ratings follow more qualitative criteria. These criteria were developed primarily for single-family homes (Roueche et al. 2019), but were broadly applied to all building types in this study. The distribution of wind and surge damage ratings for the entire dataset is provided in Figure 4. Only 59 homes were accessible to allow for reasonable estimation of the rainwater ingress damage, 27 of which had some damage noted (Figure 5).

2) Damage Ratios: These are numerical quantities representing the percentage of a building component that is damaged or destroyed. Building components included roof structure, roof substrate (e.g., roof sheathing), roof cover, wall structure, wall substrate, wall cladding, fenestration, soffit, and fascia. Any component damaged or missing from the building was considered damaged. As a result, the damage ratios for cladding components can be overestimates of the damage, since cladding attached to roof or wall structure that was damaged is always classified as damaged, even though the cladding may have stayed attached to the failed substrate or structure. For example, if 20% of the roof structure (trusses or rafters) is removed, the roof sheathing and roof cover attached to it is also considered damaged, meaning that roof sheathing and roof cover damage must be at least 20%. In reality, the roof structure may have been the first component to fail, taking the roof sheathing and cover with it. Separating these failures and getting exact component damage ratios is generally not feasible, and so adjustments for this potential overestimation must be handled in the data analysis.

In the subsequent analysis presented in this study that focuses solely on wind performance, damage ratios were processed in the analysis to strip out any surge-induced damage. This was done by ignoring wall cladding and fenestration damage in homes with at least a moderate surge damage rating (N = 157), ignoring the wall structure damage if the surge damage rating was Very Severe or higher (N = 101), and finally ignoring the building altogether if the damage rating was Partial Collapse or higher (92).

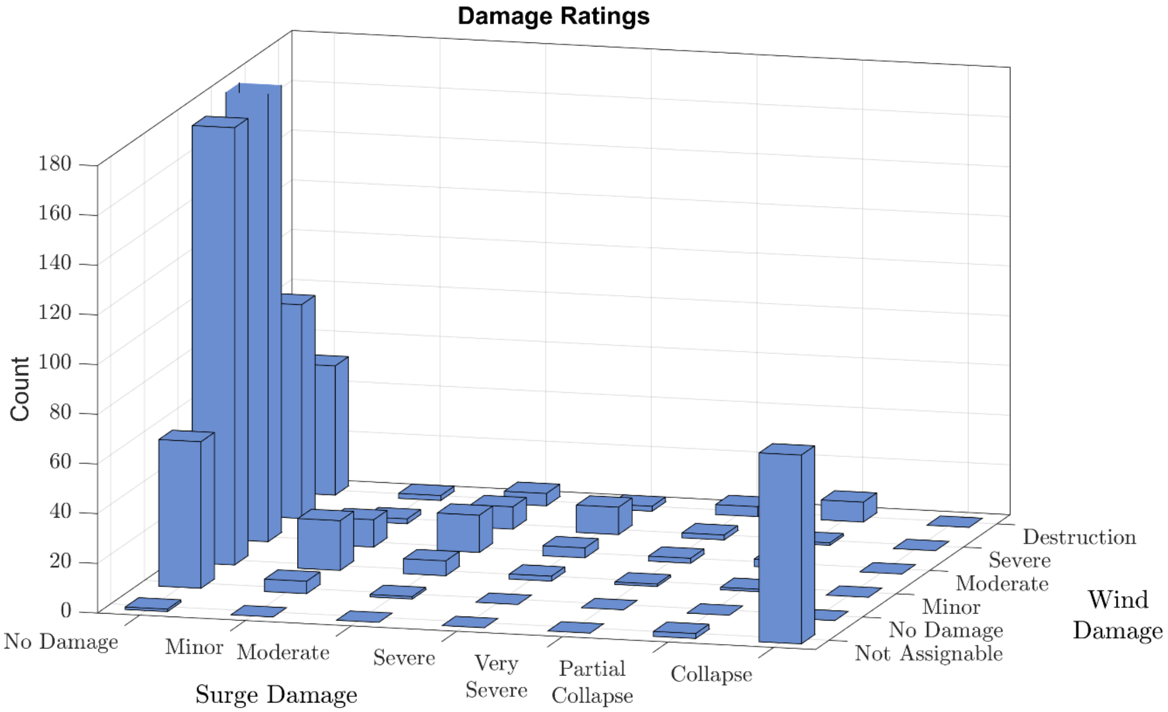

Figure 4. Distribution of wind and surge damage ratings.

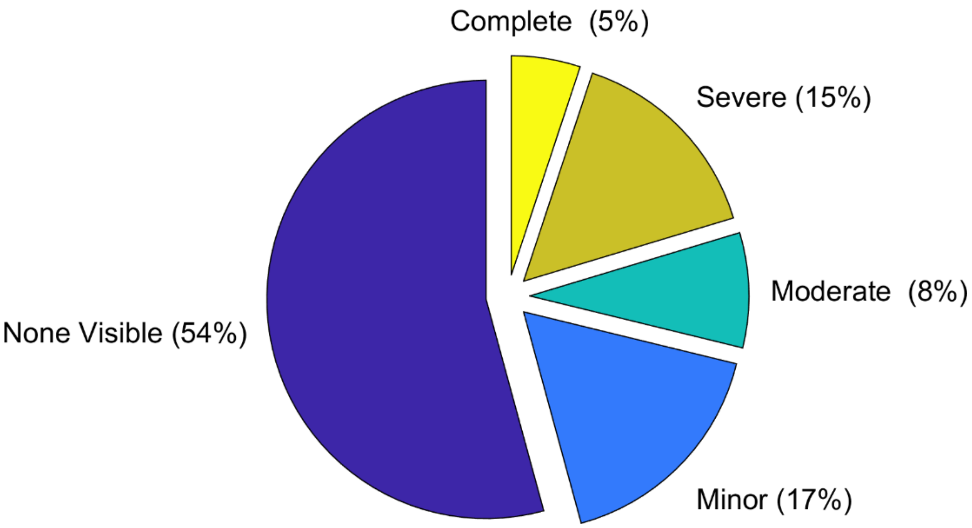

Figure 5. Distribution of rainwater ingress damage ratings (N = 59).

Table 4. Wind damage rating criteria.

		Presence or Extent of Failure in:				
Damage State [1]	**Short Description**	**Roof or Wall cover**	**Window or door**	**Roof or Wall substrate**	**Roof struct.**	**Wall struct. [2]**
0 No damage or very minor damage	*No visible exterior damage*	0%	No	No	No	No
1 Minor damage	*Damage confined to envelope*	> 0% and ≤ 15%	1	No	No	No
2 Moderate damage	*Load path preserved, but significant repairs required*	> 15% and ≤ 50%	> 1 and ≤ the larger of 3 and 20%	1 to 3 panels	No	No
3 Severe Damage	*Major impacts to structural load path*	> 50%	> the larger of 3 and 20% and ≤ 50%	> 3 and ≤ 25%	≤ 15%	No
4 Destroyed	*Total loss. Structural load path compromised beyond repair.*	> 50%	> 50%	> 25%	> 15%	Yes

Notes:
[1] A building is in the damage state if any of the shaded damage indicators in the corresponding row are observed.
[2] Wall structure refers to walls in living area only. The ground floor of elevated structures often have breakaway walls that can be easily damaged by storm surge. This damage is ignored in assigning the overall damage rating for wind.

Table 5. Surge damage rating criteria.

Damage State	Description
0 None	No floodwater impacts
1 Minor	Breakaway walls or appurtenant structures damaged or removed WITHOUT physical damage to remaining structure. No flood impacts the building.
2 Moderate	Some wall cladding damage from flood-borne debris. Breakaway walls or appurtenant structures damaged or removed WITH physical damaged to remaining structures.
3 Severe	Removal of cladding from "wash through" of surge without wall structural damage.
4 Very Severe	Failure of wall frame, repairable structural damage to any portion of building, or < 25% of building plan area unrepairable.
5 Partial Collapse	Building shifted off foundation, overall structure racking, > 25% of structure unrepairable.
6 Collapse	Total structural failure (no intact structure)

Table 6. Rainwater ingress damage rating criteria.

Damage State	Description
0 Unknown	No information concerning rainwater ingress is available; no access to interior.
1 None Visible	Interior was assessed but no evidence of rainwater ingress was observed.
2 Minor	Minor ingress through doors, windows, or isolated roof leaks.
3 Moderate	Visible puddles of water or damaged contents around multiple doors and windows and multiple roof leaks leading to puddling or damage to contents.
4 Severe	Severe inundation leading to partial collapse of roof ceiling, extensive puddling and interior contents loss.
5 Complete	Complete inundation throughout the structure with majority of contents affected.

4.1.3 *Wind Hazard Parameters*

The estimated maximum gust wind speed at the location of each building in the dataset was sourced from Vickery et al. (2018), which used a hurricane wind field model based on the full nonlinear solution of the equations of motion of a translating hurricane (Vickery et al. 2000). The hurricane wind field model was conditioned to Hurricane Michael using minimum central pressure, location of minimum central pressure, and the radius of maximum wind speed data provided by the National Hurricane Center at each advisory. Vickery et al. (2018) used ground-truth observations from the Florida Coastal Monitoring Program (Balderrama et al. 2011) and other surface observation stations to further refine the wind field model. Maximum wind speeds, standardized as 3 second gusts at 10 m height in open terrain ($z_0 = 0.03\ \mathrm{m}$), were provided over a regular grid with approximately 1 km spacing in the regions of interest. We then linearly interpolated these maximum wind speeds to estimate the maximum wind speed at each building location for the current study.

To provide further context to the estimated hazard conditions, the design wind speed and applicable design drag pressure, and the estimated building importance category, were also determined for each structure using the construction year of each building. The lateral design pressure (drag pressure) is the net lateral pressure on the building using applied stress design (ASD), and is defined as follows in Equation (1):

$$LDP = 0.00256 K_z K_d K_{zt} V_{design}^2 (Cp_{ww} - Cp_{lw})(ASD_{WindLoadFactor}) \quad (1)$$

where from ASCE 7 (ASCE 2017), K_z is the height and terrain coefficient, taken to be 0.85 (assuming open terrain and a mean roof height of 15 ft), K_d is the directionality coefficient taken to be 0.85, K_{zt} is the topographic coefficient taken to be 1, V_{design} is the 3-second gust wind speed at 33 ft above ground in open terrain for a specified mean reoccurrence interval, Cp_{ww} and Cp_{lw} are the windward and leeward wall pressure coefficients taken as 0.8 and -0.5 respectively, and finally $ASD_{WindLoadFactor}$ is the ASD wind load factor. An example of the calculations is provided in

Table 7 for a Risk Category II building in Mexico Beach, FL. Data is shown for buildings constructed prior to 2002 based on the Standard Building Code, which went into effect in 1974, when Florida required jurisdictions to adopt a model building code of some form. The majority of Florida adopted the Standard Building Code, which at the time required a lateral design pressure of 25 psf for buildings in coastal regions with heights below 30 ft.

The calculations in

Table 7 demonstrate a significant increase in lateral design pressure in the 2001, 2004 and 2007 editions of the Florida Building Code, followed by a reduction closer to the pre-FBC lateral design pressure in subsequent editions of the code. The major reason for the reduction was the change to ultimate design wind speeds in ASCE 7-10. Ultimate wind speeds in the Florida panhandle were very similar to the serviceability wind speeds in ASCE 7-05 and prior editions (50 year mean reoccurrence interval [MRI]), yet were now used with a 0.6 load factor rather than a 1.0 load factor. Figure 6 illustrates this effect by plotting the ASCE 7-10/16 wind contours for a Risk Category II building (700 year MRI) against the same from ASCE 7-98/02/05. The 700 year MRI for ASCE 7-98/02/05 is obtained by converting from the 50 year MRI wind speeds, which are provided in the ASCE 7-98/02/05 standards, using Equation (2):

$$V_{700yr} = V_{50yr} * \sqrt{0.6} \quad (2)$$

where 0.6 is the load factor used to convert between serviceability and ultimate wind loads (Line and Coulbourne 2012). The map shows that equivalent wind speeds in ASCE 7-98/02/05 were higher than those in ASCE 7-2010/2016 for the regions impacted by Hurricane Michael.

The lowered design wind speeds do not necessarily mean that buildings constructed to 2010 FBC and beyond should perform worse however. Changes to the wind-borne debris requirements, use of prescriptive provisions, changes to other aspects of the ASCE 7 wind design standards beyond wind speed (including increases in magnitudes of some aerodynamic coefficients), and multiple more minor code enhancements (e.g., ring shank nails required for roof decking in 2007 FBC, or limitations on the span of wood structural panels used as opening protection added in 2017 FBC) are also contributing factors. The net effect of these will be explored later in this report.

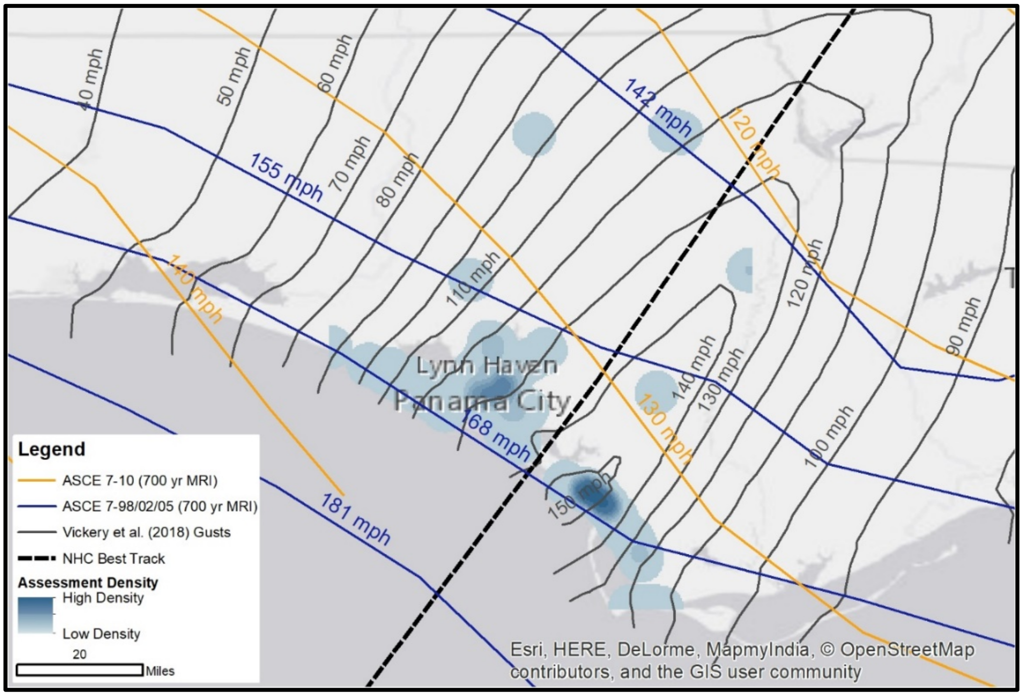

Figure 6. ASCE 7 design wind speeds (700 year MRI) relative to assessment locations and estimated peak 3 sec gusts (Vickery Peter et al. 2018)ic during Hurricane Michael.

Table 7. Lateral design pressures by building code edition for a typical building in Mexico Beach, FL.

Code Edition	Effective Date	ASCE Reference	Design Wind Speed (mph)	ASD Wind Load Factor	Lateral Design Pressure (psf)
Pre-FBC	Pre-2002	-	-	-	25
2001 FBC	March 2002	ASCE 7-98	130 mph	1	40.6
2004 FBC	October 2005	ASCE 7-02	130 mph	1	40.6
2007 FBC	March 2009	ASCE 7-05	130 mph	1	40.6
2010 FBC	March 2012	ASCE 7-10	133 mph	0.6	25.5
2014 FBC	June 2015	ASCE 7-10	133 mph	0.6	25.5
2017 FBC	Dec. 2017	ASCE 7-10	133 mph	0.6	25.5

The distribution of buildings in the dataset by building code edition is provided in Figure 7, and was used to capture some of the effects of building code changes in analysis described later in this report. It should be noted in Figure 7 that SBC w/ Inspections indicates a period of time (1994-2001) when the Standard Building Code was in use with licensed inspectors. Legislation was passed in 1994, in response to Hurricane Andrew's impacts on Florida in 1992, requiring building inspectors to be licensed.

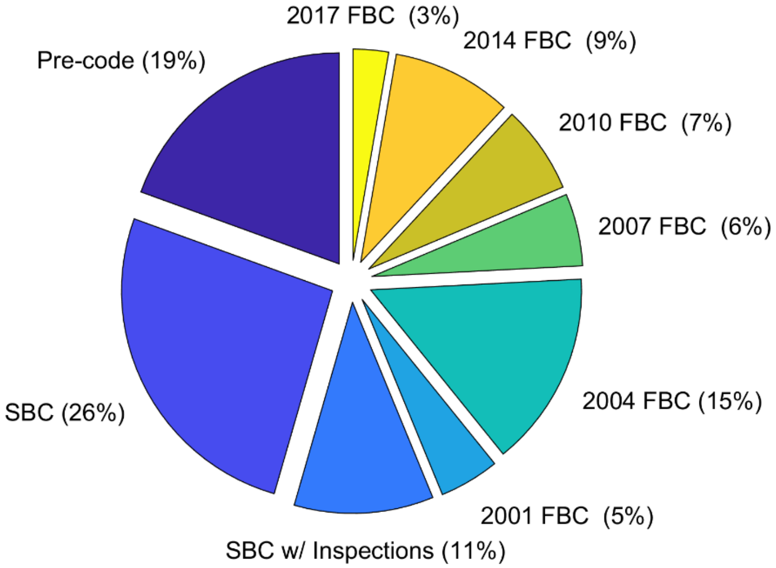

Figure 7. Distribution of buildings in the dataset by building code edition (N = 751).

To further assess wind hazard parameters, accounting for wind-borne debris (WBD) requirements in the analysis was also explored, but the application of the WBD requirements by local municipalities was not clear. Independent of the well-known changes to the wind-borne debris region ensuing from the “Panhandle Exemption”, the wind-borne debris region in the Florida panhandle has always included buildings within 1 mile of the mean high water line since 2002. The precise delineation of the wind-borne debris region is not apparent however, as the coastal mean high water line is constantly changing and is generally not precisely defined. One building official in Bay County indicated they “just measure the distance to the Gulf”. Others indicated it was left to the judgement of the individual inspector, which in much of Bay and Gulf County is handled by private companies. In an area like Panama City, with multiple bays and inlets, there may be confusion as to the practical delineation of the windborne debris region. For this study, we estimated the WBD region by evaluating the distance of each building from the coast, defined in two ways: 1) using the latest NOAA shoreline GIS data, and 2) drawing an approximation for the border of the main body of water forming the Gulf of Mexico. These two approximations for the coastal mean high water line are shown in Figure 8.

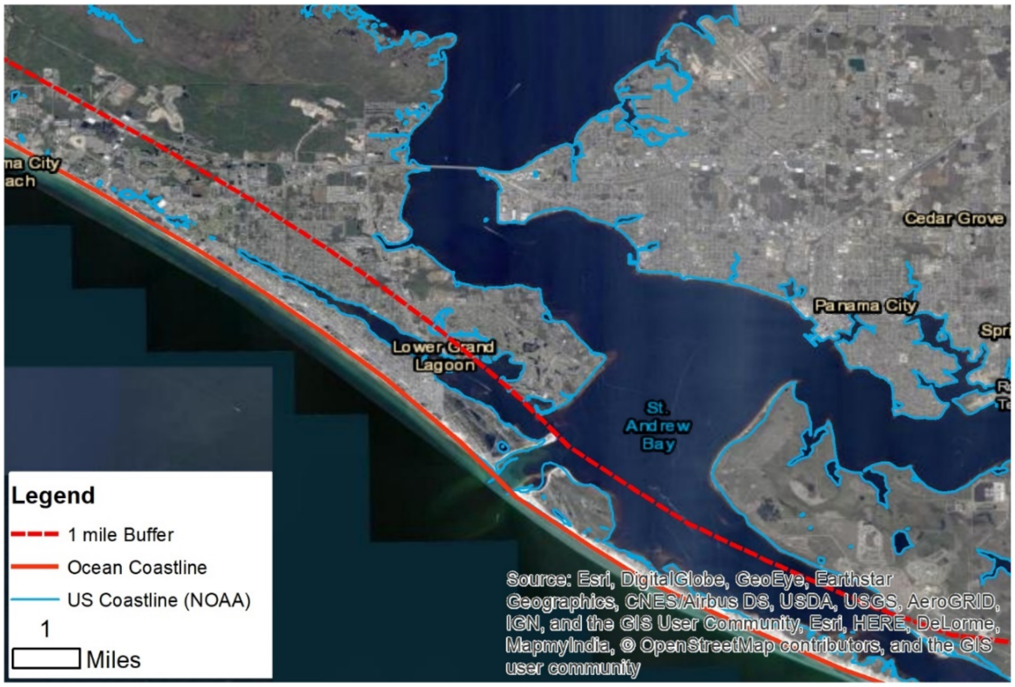

Figure 8. Approximate delineation of the wind-borne debris region based on 1 mile from mean high water line, subjectively shown here as the coastline bordering the Gulf of Mexico.

4.1.4 *Building Types*

The raw D2D dataset classified each building into one of 24 different building types as defined in Roueche et al. (2019), and broadly classified in Figure 9. For this study, we further classified each building as nominally falling under the jurisdiction of the Florida Building Code (FBC) versus the Florida Building Code Residential (FBCR). The Florida Building Code denotes this distinction in Section 101.2-Exceptions(1) as follows:

> *"Detached one- and two-family dwellings and multiple single-family dwellings (townhouses) not more than three stories above grade plane in height with a separate means of egress and their accessory structures shall comply with the Florida Building Code, Residential"*

In our dataset, this delineation was made by considering all single-family and multi-family homes (duplexes, townhomes, etc) three stories or less (two stories if an elevated structure) as FBCR, including modular homes but excluding mobile/manufactured homes. This criteria was used for all buildings independent of year built, resulting in 641 FBCR buildings and 143 FBC buildings, as shown in Figure 9.

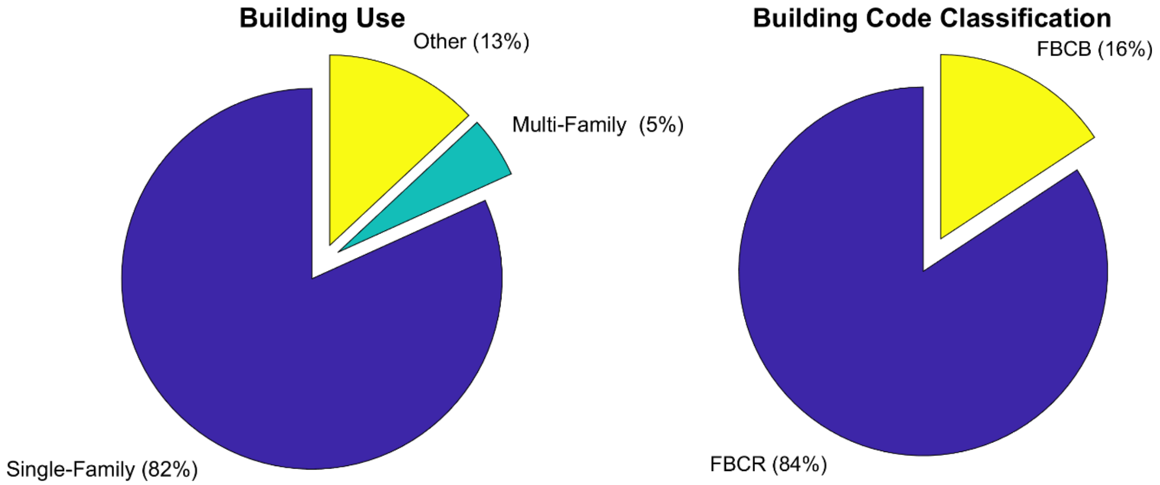

Figure 9. Distribution of buildings by (left) building use, and (right) building code classification.

4.2 Findings Related to Wind Hazards

Findings from analysis of the wind damage dataset are presented in two ways. First, we present a macro-level analysis of wind performance relative to the Florida Building Code. Second, we briefly summarize performance of roof cover, wall cladding and large openings. Collectively these analyses summarize some key findings in line with the scope of this project.

4.2.1 *Wind Performance Relative to the Florida Building Code*

A broad comparison is first conducted between buildings constructed before the 2001 Florida Building Code (pre-2001 FBC) and after (post-2001 FBC) construction using the ordinal wind damage ratings as described in Section 4.1.2. Comparisons are made for all buildings combined, and separately for buildings that would be expected to fall under the Florida Building Code (hereafter designated FBCB) and the Florida Building Code Residential (hereafter designated FBCR). The analysis (Table 8) shows that post-2001 FBC construction overall performed significantly better ($p < 0.01$ based on Kruskal-Wallis test) than pre-2001 FBC construction during Hurricane Michael with a mean wind damage rating of 2.08 for pre-2001 FBC buildings compared to 1.59 for post-2001 FBC buildings, despite both classes of buildings experiencing nominally the same mean estimated wind speeds per the ARA wind field. The improvements are also demonstrated in the distribution of wind damage ratings (Figure 10 and Figure 11), with post-FBC buildings experiencing no damage or minor damage more often than pre-FBC buildings. The improved performance correlates with strengthened wind code requirements, as demonstrated by a comparison of the mean wind load ratio for pre- and post-2001 FBC buildings. While estimated wind speeds were nominally the same for pre- and post-2001 FBC construction, the mean wind load ratio (ratio of demand to design) was 22% lower in post-2001 FBC buildings, corresponding well to the 24% reduction in mean wind damage rating for post-2001 FBC buildings. The same trend generally held true for both FBC and FBCR buildings. The difference in mean wind damage rating for pre-2001 FBCB and post-2001 FBCB was smaller (8.3%) and not statistically significant (p = 0.39), however the estimated wind speed for post-2001 FBCB buildings was 138 mph compared to 126 mph for pre-2001 FBCB buildings, resulting in mean wind load ratios that were nominally the same. The sample of post-2001 FBCB buildings constructed to the Florida Building Code in our dataset experienced higher wind speeds on average during Hurricane Michael then those built prior to the Florida Building Code yet still sustained slightly lower wind damage on average.

Extending the analysis to examine individual building components, the largest improvements from pre-FBC to post-FBC buildings is found in the MWFRS elements (roof structure and substrate/decking, and wall structure and substrate/sheathing), with smaller but still statistically significant improvements in cladding (roof cover) and fenestration (windows, doors) performance. Wall cladding was the one individual component that did not have a statistically significant improvement in performance between pre- and post-FBC for all buildings, with mean wall cladding damage ratios of 10.4% and 8.3% respectively for pre- and post-FBC buildings. Meanwhile, roof cover performance in post-FBC buildings was significantly improved over pre-FBC buildings, but roof cover was also by far the most vulnerable component, with mean damage ratios of 29% and 20% respectively. Performance improvements with time for roof and wall cladding are more difficult to assess however because year built is not a perfect proxy for the date of installation of the cladding material, particularly for older buildings. A deeper analysis of permit records would provide a more accurate assessment of temporal differences in roof and wall cladding performance.

Examining wind performance by specific code editions reveals that overall, pre-1994 buildings are the most vulnerable (Figure 12), with gradual improvements in each era until somewhat of a plateau is reached after the 2004 FBC (effective 2005) as shown in Figure 13 (note the square root y-axis used to better visualize differences in lower damage values) and Table 9. The data show the following trends:

- MWFRS failures (roof structure, roof sheathing/substrate, wall structure and wall sheathing/substrate), even during above design conditions, are rare in post-FBC buildings.
- Fenestration damage was also very low (less than 5% of fenestration damaged on average) in post-FBC construction.
- Roof cover performance shows a noticeable trend towards less damage on average with each subsequent code edition but this is likely due to improved requirements and the inverse relationship with material degradation and aging.

- Wall cladding damage on a given building is typically not as extensive as roof cover damage (roughly half on average), but actually shows an increasing trend with each code edition, the highest average wall cladding damage ratio (15%) occurring in buildings constructed between 2016-2018 and exceeding the average roof cover damage for that same era.
- The most marked improvements over time occur around 1994 and 2002 (Figure 13). The 1994 date is tied to the requirement for licensed inspectors in 1994, and perhaps an increased awareness of the importance of wind-resistant construction following Hurricane Andrew (1992). The 2002 date corresponds to the adoption of the first statewide Florida Building Code, resulting in another noticeable decrease in MWFRS and, to some extent, fenestration damage.

A few caveats are worth noting however regarding any trends demonstrated in Figure 13.

- The data shown here are not normalized by wind speed, although as shown in Table 9, samples each era had similar wind speed magnitudes, particularly in relation to the level of uncertainty inherent to the wind speed estimates.
- Year built is an imperfect proxy encompassing many different, and at times conflicting, factors, including changes to codes and standards, changes in construction practice and materials, availability of skilled labor, aging and degradation of materials (particularly relevant to cladding materials), and post-construction wind mitigation retrofit activity. For example, it is highly unlikely that a building constructed in the 1980s still has the original roof cover or even wall cladding, but any upgrades made to the building would not be captured by the year built.
- The damage ratios for fenestration and cladding are upper bounds because they assume that MWFRS failures also fail any cladding or fenestration supported by the MWFRS.

Considering FBC buildings only (i.e., not Florida Building Code Residential buildings), Figure 14 shows a more even distribution of wind performance across all eras, although pre-2002 buildings are still by far the most vulnerable. Table 10 shows that there is some evidence that the higher design wind speed in the 2002-2011 period improved MWFRS performance of buildings in that era compared to more recent buildings, although the sample size is relatively small (N = 12 for 2002-2011 buildings vs N = 12 for 2012-2018 buildings). Wall structure damage on average was higher in the 2012-2018 era (ASCE 7-10) than in the 2002-2011 era (ASCE 7-05), but the significance of this difference is limited by the small sample size, making it relatively easy to skew results based on a few non-representative samples (i.e., sampled because damage was present). Additional samples would need to be added from the supplemental data sources to explore performance differences between these eras more robustly.

Table 8. Statistical summary of pre- and post-2001 Florida Building Code performance for all buildings.

	Time Period	**Pre-2002**	**Post-2001**	Kruskall-Wallis p-value
	Number of Samples	326	323	
Wind Damage Rating	0, No Damage (%)	8.9	11.1	
	1, Minor (%)	24.2	38.7	
	2, Moderate (%)	31.3	34.4	
	3, Severe (%)	21.2	11.8	
	4, Destruction (%)	14.4	4.0	
Wind Damage Rating	Mean	2.08	1.59	< 0.01
	StD	1.18	0.97	
Roof Structure Damage (%)	Mean	9.9	1.5	< 0.01
	StD	22.1	8.2	
Roof Substrate Damage (%)	Mean	12.0	2.2	< 0.01
	StD	23.9	9.3	
Roof Cover Damage (%)	Mean	28.9	19.7	< 0.01
	StD	29.5	24.1	
Wall Structure Damage (%)	Mean	6.1	0.7	< 0.01
	StD	16.7	3.7	
Wall Substrate Damage (%)	Mean	6.0	1.0	< 0.01
	StD	15.7	4.6	
Wall Cladding Damage (%)	Mean	10.4	8.3	0.928
	StD	18.8	14.7	
MWFRS (%)	Mean	9.4	1.4	< 0.01
	StD	19.3	5.8	
Cladding (%)	Mean	19.3	10.4	< 0.01
	StD	22.5	12.6	
Fenestration (%)	Mean	8.7	3.3	< 0.01
	StD	18.7	8.4	
Contextual Parameters				
3s Gust Wind Speed (mph)	Mean	135.6	134.1	0.295
	StD	11.9	11.7	
Distance to the Coast (mi)	Mean	3.4	0.9	< 0.01
	StD	9.6	2.1	
Wind Load Ratio	Mean	1.78	1.39	< 0.01
	StD	0.30	0.41	

Table 9. Statistical summary of building wind performance for all buildings by major building code era. Colors indicate gradation across rows from lowest (dark green) to highest (red).

	Code	**Pre-SBC**	**SBC**	**SBC + Coastal**	**SBC w/ Inspect.**	**2001 FBC**	**2004 FBC**	**2007 FBC**	**2010 FBC**	**2014 FBC**
	Time Period	**1900-1973**	**1974-1985**	**1986-1993**	**1994-2001**	**2002-2004**	**2005-2008**	**2009-2011**	**2012-2015**	**2016-2019**
	Number of Samples	96	89	59	78	33	111	40	50	87
Wind Damage Rating	0, No Damage (%)	15	9	5	5	12	12	10	16	8
	1, Minor (%)	26	17	31	27	18	38	35	46	46
	2, Moderate (%)	29	29	17	45	45	38	43	24	29
	3, Severe (%)	16	27	29	17	18	8	10	12	14
	4, Destruction (%)	15	18	19	6	6	5	3	2	3
Wind Damage Rating	Mean	1.9	2.3	2.3	1.9	1.9	1.6	1.6	1.4	1.6
	StD	1.3	1.2	1.2	1.0	1.1	1.0	0.9	1.0	0.9
Roof Structure Damage (%)	Mean	6.2	16.3	14.0	4.4	5.5	1.0	1.0	1.0	0.6
	StD	15.9	29.6	25.4	12.5	20.3	5.3	5.7	4.5	3.0
Roof Substrate Damage (%)	Mean	8.5	19.2	17.4	5.0	7.6	1.5	1.3	1.5	1.0
	StD	18.8	31.1	27.7	12.6	21.1	6.1	5.8	5.6	3.8
Roof Cover Damage (%)	Mean	23.3	36.3	33.5	23.7	33.0	22.4	28.3	13.9	10.1
	StD	24.4	34.2	33.6	23.3	30.4	23.6	27.2	23.8	14.6
Wall Structure Damage (%)	Mean	3.3	9.7	9.6	3.2	0.8	0.3	0.3	1.0	0.7
	StD	10.0	22.2	18.9	13.1	4.4	1.4	1.1	5.1	3.6
Wall Substrate Damage (%)	Mean	3.6	8.1	12.0	2.0	1.1	0.3	0.4	2.3	0.8
	StD	10.7	19.8	21.2	7.6	5.3	1.5	1.8	6.8	3.7
Wall Cladding Damage (%)	Mean	4.8	13.6	16.5	6.6	4.4	5.4	6.9	5.9	14.9
	StD	11.1	21.9	22.7	13.4	9.1	9.2	10.8	12.8	21.1
MWFRS (%)	Mean	5.6	15.1	13.9	4.5	3.5	0.8	0.7	1.4	0.9
	StD	12.2	25.6	23.4	12.0	12.0	3.3	3.3	5.2	3.0
Cladding (%)	Mean	14.8	25.7	24.1	13.8	16.6	11.4	14.4	8.1	5.5
	StD	17.3	28.0	26.9	13.8	16.4	11.8	13.6	12.6	7.7
Fenestration (%)	Mean	3.9	13.0	13.9	4.8	4.7	2.7	3.3	3.4	3.1
	StD	9.5	24.2	24.4	10.4	9.0	6.1	7.3	7.5	10.3

Contextual Information

3s Gust Wind Speed (mph)	Mean	129.9	137.2	137.6	138.9	139.6	130.5	130.4	139.7	135.3
	StD	10.4	11.7	11.2	12.3	10.9	11.4	10.4	10.7	11.4
Distance to the Coast (mi)	Mean	4.4	6.2	0.4	1.1	0.8	1.4	0.9	0.6	0.6
	StD	11.9	12.8	0.5	2.4	0.8	3.2	1.7	1.3	0.6
Wind Load Ratio	Mean	1.6	1.8	1.8	1.9	1.2	1.1	1.1	1.9	1.7
	StD	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.3	0.3

Table 10. Statistical summary of building wind performance for buildings excluded from the Florida Building Code Residential, by major building code era. Colors indicate gradation across rows from lowest (dark green) to highest (red).

	Code	**Pre-SBC**	**SBC**	**SBC + Coastal**	**SBC w/ Inspect.**	**2001 FBC**	**2004 FBC**	**2007 FBC**	**2010 FBC**	**2014 FBC**
	Time Period	**1900-1973**	**1974-1985**	**1986-1993**	**1994-2001**	**2002-2004**	**2005-2008**	**2009-2011**	**2012-2015**	**2016-2019**
	Number of Samples	22	27	14	14	2	6	4	5	7
Wind Damage Rating	0, No Damage (%)	5	0	7	7	0	0	0	20	0
	1, Minor (%)	18	11	29	14	0	33	50	0	14
	2, Moderate (%)	23	22	14	36	50	33	25	40	43
	3, Severe (%)	23	33	36	14	50	0	0	20	29
	4, Destruction (%)	32	33	14	29	0	33	25	20	14
Wind Damage Rating	Mean	2.6	2.9	2.2	2.4	2.5	2.3	2.0	2.2	2.4
	StD	1.3	1.0	1.3	1.3	0.7	1.4	1.4	1.5	1.0
Roof Structure Damage (%)	Mean	11.8	24.0	11.8	15.4	7.5	10.0	9.0	9.0	2.5
	StD	22.6	33.4	18.8	22.5	10.6	16.7	18.0	12.4	4.2
Roof Substrate Damage (%)	Mean	15.0	27.1	12.8	15.0	12.5	12.0	9.5	12.0	1.0
	StD	22.3	33.9	20.6	22.1	17.7	17.9	17.7	14.4	2.2
Roof Cover Damage (%)	Mean	27.8	45.7	32.6	21.5	12.5	30.5	15.8	16.0	12.5
	StD	23.0	33.5	36.4	19.2	17.7	16.7	13.8	18.2	16.4
Wall Structure Damage (%)	Mean	10.0	23.1	7.9	17.0	0.0	2.5	1.3	10.0	4.5
	StD	15.9	33.7	13.1	31.2	0.0	4.2	2.5	14.1	7.0
Wall Substrate Damage (%)	Mean	9.8	19.9	10.4	5.7	0.0	1.7	1.8	18.4	3.0
	StD	16.2	32.6	16.3	15.1	0.0	4.1	2.4	12.3	4.5
Building Envelope Damage (%)	Mean	11.0	25.7	15.7	10.0	5.0	7.4	5.8	18.3	17.4
	StD	15.6	29.8	17.7	16.1	0.0	4.3	4.3	16.1	16.6
MWFRS (%)	Mean	12.3	24.6	11.7	17.1	5.0	6.0	5.4	12.4	3.6
	StD	18.1	30.7	16.4	22.9	7.1	9.6	10.1	12.5	5.1
Cladding (%)	Mean	21.8	36.8	24.0	16.6	6.3	16.1	8.8	17.2	8.3
	StD	23.0	30.0	23.7	14.1	8.8	8.6	7.9	14.0	8.0
Fenestration (%)	Mean	9.7	24.2	18.7	3.3	12.5	3.3	0.1	10.3	9.8
	StD	16.1	34.6	26.0	8.2	17.7	4.4	0.1	14.0	14.4

Contextual Information

3s Gust Wind Speed (mph)	Mean	124.7	126.2	127.7	123.4	149.2	138.9	133.5	137.7	137.3
	StD	12.1	10.7	8.6	14.0	1.1	12.0	11.0	10.7	16.1
Distance to the Coast (mi)	Mean	9.6	7.1	0.6	2.9	0.0	0.2	0.4	0.8	0.1
	StD	18.2	14.0	0.6	4.1	0.0	0.3	0.1	0.9	0.2
Wind Load Ratio	Mean	1.5	1.5	1.6	1.5	1.3	1.2	1.1	1.8	1.8
	StD	0.3	0.3	0.2	0.3	0.0	0.2	0.2	0.3	0.4

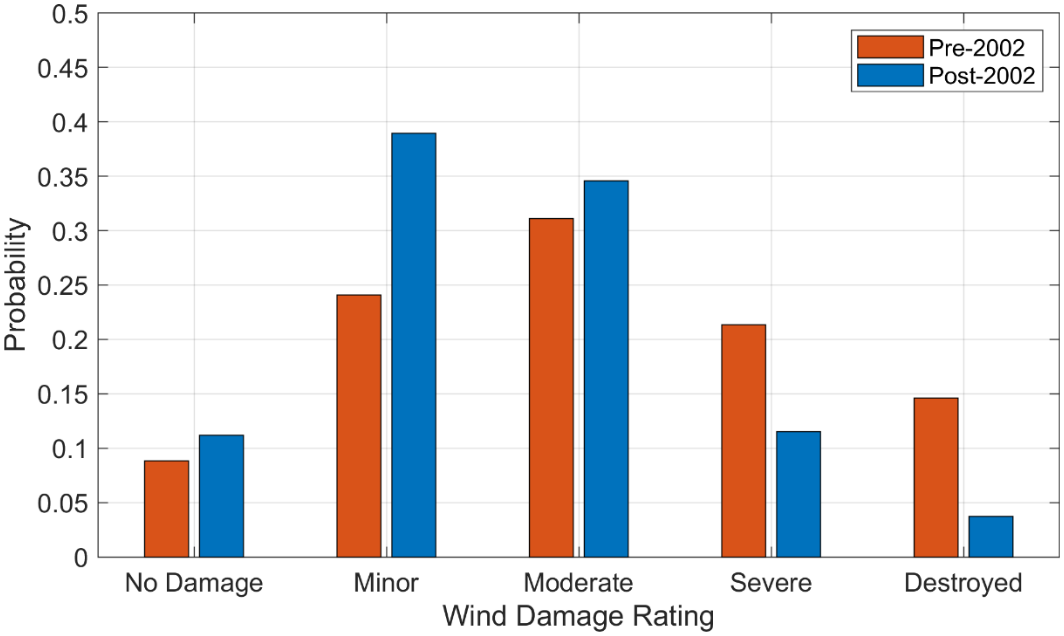

Figure 10. Relative distribution of wind damage ratings in pre-2002 (prior to 2001 FBC) and post-2002 (after 2001 FBC) buildings.

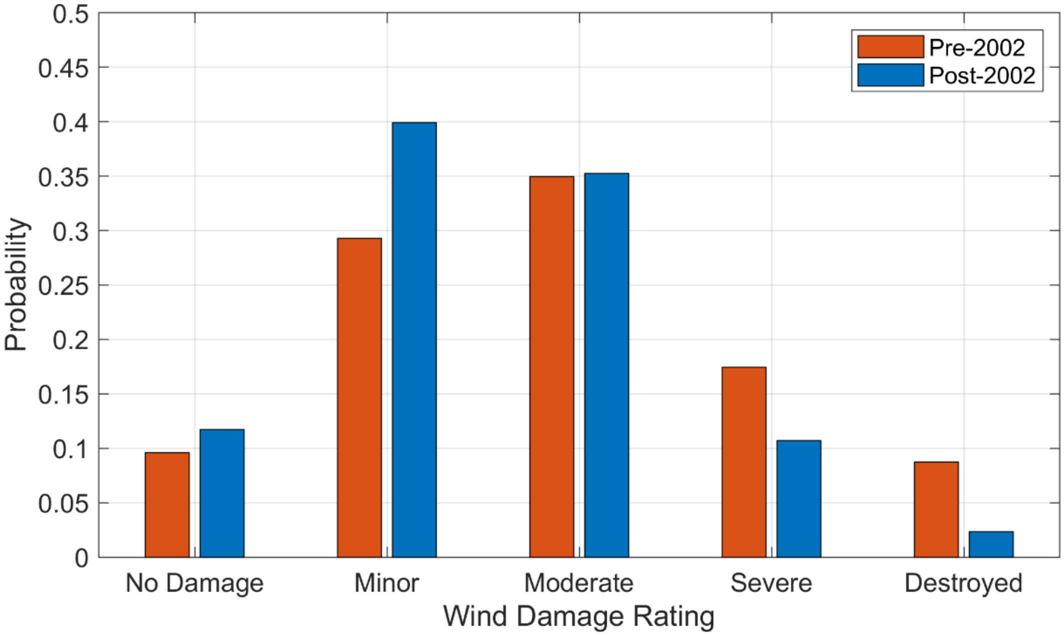

Figure 11. Relative distribution of wind damage ratings in pre-2002 (prior to 2001 FBC) and post-2002 (after 2001 FBC) Single-Family Residential buildings.

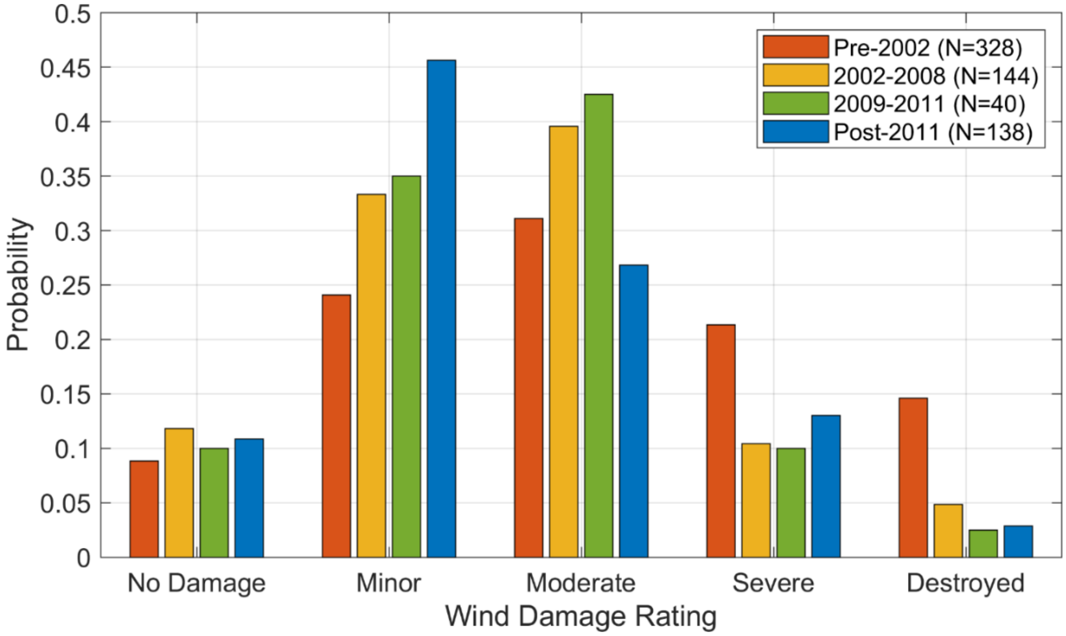

Figure 12. Distribution of wind damage ratings for all buildings by major era.

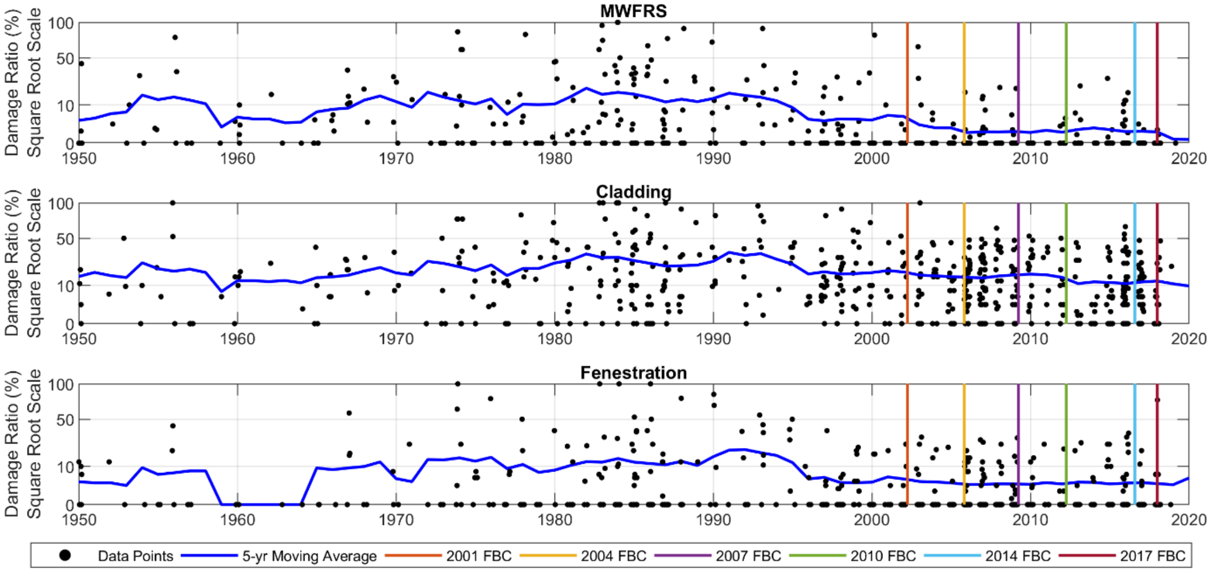

Figure 13. Changes in MWFRS, Cladding and Fenestration damage ratios with respect to year built and Florida Building Code editions. Damage ratios exclude any damage caused by storm surge.

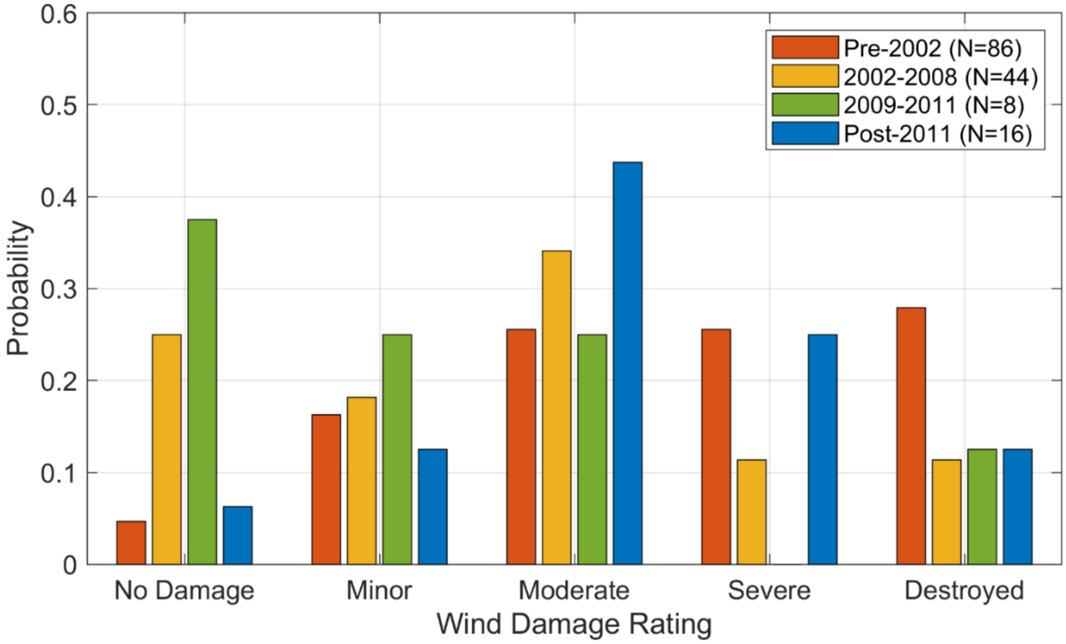

Figure 14. Distribution of wind damage ratings for all buildings excluded from using the Florida Building Code Residential, by major era.

4.2.2 ***Wind Performance of Roof Cover and Wall Cladding Materials***

The wind performance of different types of roof cover and wall cladding materials show some differences in performance (Figure 15 and Figure 16). However, a few clarifications are necessary before discussing the results.

1) The distinction between pre- and post-FBC relates to the construction year of the building itself, not the installation date of the cladding material.
2) Damage ratios are calculated assuming either 100% (upper bound of damage estimate) or 0% (lower bound of failure estimate) failure of the cladding material present on failed portions of the roof or wall MWFRS (roof and wall sheathing/substrate is included in the MWFRS). In other words, if 20% of the roof sheathing was removed, we assume the roof cover damage is equal to 20% to get the upper bound, and 0% to get the lower bound, then add any additional roof cover damage from the remaining portions of the roof.
3) Many buildings contain multiple wall cladding materials, and our assessments did not separate out damage ratios for each individual material present; only an overall wall cladding damage ratio was evaluated. As a result, the categories shown in Figure 16 are not mutually exclusive. Each category represents buildings that had the given wall cladding material, but other materials may also have been present and contributed to the damage ratios. A study using our approach but focusing solely on wall cladding

performance by material may result in a more precise estimate of performance differences.

4) Figure 15 and Figure 16 present the individual data points (filled circles, each representing a single building) as well as box plots with the top and bottom horizontal lines indicating the 75th and 25th percentiles respectively, and the middle horizontal line indicating the median of the data. Wall cladding damage is plotted on a square root scale to better visualize data closer to 0. Some materials have medians of 0%.

The data show that roof cover damage was highest in 3-tab shingles on homes constructed prior to the 2002 FBC and in a mixture of less common roof cover methods such as wood shingles. Post-FBC metal roofs and laminate shingle roofs performed better, albeit with 10%-20% of post-FBC metal roofs, and 36%-40% of post-FBC laminate shingle roofs, suffering more than 20% roof cover loss. For wall cladding, no clear differences were observed between pre- and post-FBC buildings. Buildings with vinyl siding were associated with the highest median and 75th percentile damage ratios, and buildings with brick the lowest. It was generally not possible to evaluate the exact wind resistance of the various cladding materials to separate into high wind-rated vs standard systems. Considering all wall cladding materials, 13% of post-FBC buildings experienced the loss of at least 20% of wall cladding.

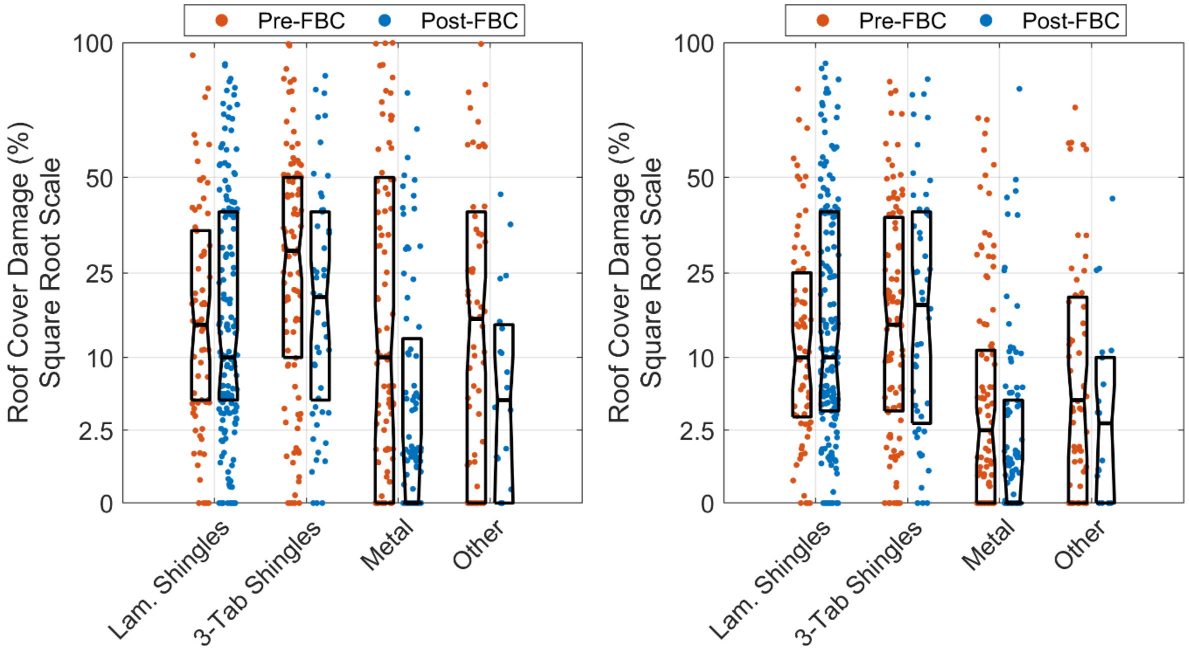

Figure 15. Roof cover damage ratios in pre- and post-FBC buildings by roof cover type (left) assuming 100% roof cover located on damaged roof substrate is also damaged; (right) assuming 0% of roof cover located on damaged roof substrate is also damaged.

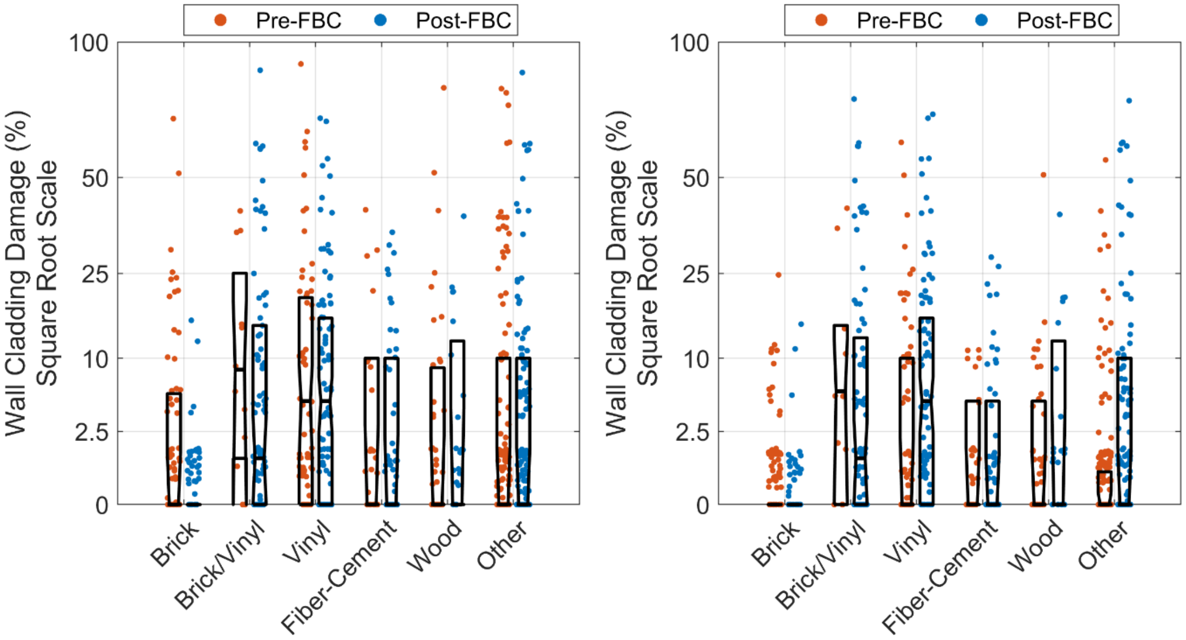

Figure 16. Wall cladding damage ratios in pre- and post-FBC buildings by cladding material; (left) assuming 1000% of wall cladding located on damaged wall substrate is also damaged; (right) assuming 0% of wall cladding located on damaged wall substrate is also damaged.

4.2.3 *Wind Performance of Large Doors*

Assessments documented any large doors that were present on the building and whether they failed or not, categorizing each as a garage door, roll-up door, sectional door, or other. Roll-up and sectional doors were broadly labeled as commercial doors, while single and double garage doors were labeled as residential. In most cases it was not possible to identify the exact model number or whether a large door was wind rated because of a lack of accessibility to the interior of the building. Overall, the damage rate for large doors was approximately 20%, with failure rates slightly higher in post-FBC doors than pre-FBC doors (Table 11). A few illustrative large opening failures are shown in Figure 17.

Table 11. Summary of large door performance in Hurricane Michael.

	All Doors		**Commercial Doors**		**Residential Doors**	
	Pre-FBC	Post-FBC	Pre-FBC	Post-FBC	Pre-FBC	Post-FBC
Count	109	177	15	5	94	172
Damaged	21	40	3	3	18	37
% Damaged	19%	23%	20%	60%[1]	19%	22%

[1] All three post-FBC commercial buildings with failed doors were sampled because of damage, and therefore the failure rates are likely not representative of the true failure rate.

Figure 17. Illustrative large door failures; (top left) pre-FBC residential building in Mexico Beach area, (top right) post-FBC building in Panama City, (bottom left) pre-FBC commercial building in Panama City, (bottom right) post-FBC commercial building in Panama City.

4.3 Findings Related to Surge Hazards

Kennedy et al. (2020) performed an analysis of surge-induced impacts from Hurricane Michael, using data that overlaps with that described in this study. The study area primarily focused on the Mexico Beach area, with some additional coverage southeast towards Port St. Joe. The majority of structures in the study area were residential and consisted of (1) older single family, at grade homes, (2) multi-family structures (i.e., townhomes), (3) pile-elevated wood-frame single family homes and small businesses; and (d) pile-elevated multifamily residential or commercial construction. The major findings and conclusions from the study related to building performance are summarized below:

- Damage for low-lying properties near the Mexico Beach cost was near-total, irrespective of construction type or age. This damage occurred even in areas designated by FEMA as having minimal flood risk.
- Structures elevated well above the 100 year base flood elevation had increased survival and reduced damage probabilities from waves and surge.
- Distance inland far enough to minimize wave heights reduced damage probabilities.
- No buildings built to minimum required standards for Bay County in FEMA X, AE or VE zones have a realistic probability of survival in a storm similar to Hurricane Michael.

The major conclusion from the study was that the 100 year base flood elevation produces a level of risk that is disproportionate to other hazards (wind, earthquake). Full context of the study and conclusions are discussed in Kennedy et al. (2020), which is provided in Appendix D.

5 TASK 3: RESEARCH OUTCOMES FROM FEMA'S MAT REPORTS

Following Hurricane Michael and the MAT Teams' investigation, FEMA released two important documents; Recovery Advisory 1 (FEMA, 2019a) and Recovery Advisory 2 (FEMA, 2019b) that outlined best practices for a) retrofitting buildings for wind resistance specifically for critical facilities and b) minimizing wind and water infiltration into residential buildings. Our scope includes determination of the extent that these recommendations are included into the FBC. The scope of work is:

- We will review the recently published documents and identify the differences between the current Building Code and the additional recommendations presented in the Recovery Advisory.
    - We were asked during our March 2020 presentation of our Interim Report to expand our review to the full FEMA P-2077: Mitigation Assessment Team Report - Hurricane Michael (FEMA, 2020) that was published in February 2020.
- Report the findings to the FBC, prioritizing the modifications for code changes for consideration in future codes.

The details here are also pertinent to both residential and some non-residential structures. The recommendations with FEMA P-2077 are directed to a broad cross-section of the construction industry;

"... to design professionals, contractors, building officials, facility managers, floodplain administrators, regulators, emergency managers, building owners and operators, academia, select industries and associations, local officials, planners, FEMA, and other interested stakeholders."

Some recommendations suggest places where building codes should be revised, while some encourages actions such as:

- developing/modifying training on the flood provisions in the FBC and local floodplain management ordinances
- encouraging pre-event evaluation of post-disaster needs
- further evaluation of the performance of concrete pile foundations
- prioritization of building inspections
- researching performance of commonly used ridge vent products
- researching and investigating the appropriate pressure-equalization factors (PEF) for vinyl siding wall cladding systems

- re-evaluating policies, procedures, and requirements for assessments of existing spaces for use as Hurricane Evacuation Centers (HEC)
- re-evaluating Enhanced Hurricane Protection Areas (EHPA) criteria and re-assess safety of existing EHPAs

The following recommendations of the FEM P-2077 directly address the Florida Building Code (FBC): 8a, 8d,15c,17c, 30, the ASCE 7 minimum wind load design standard: 8b, 8e, and the Florida Division of Emergency Management (FDEM): 10b, 11a, 14e, 15b, 17a. These recommendations suggest places where the respective codes, standards and policies should be revised. Further, FEMA P-2077 provides several recommendations for revised current test standards for building materials and products. These are related to ASTM International (ASTM): 6, 24a, 24c and 24d. The complete list of FEMA P-2077 recommendations, Table 6.2, are provided in Appendix C.

5.1 Recovery Advisory 1

This document (FEMA, 2019a) focuses on immediate lessons learned from Hurricane Michael regarding key wind retrofit guidelines for buildings located in hurricane-prone regions. It includes examples of observed ineffective wind retrofit projects found by the FEMA MAT Teams following Hurricane Michael.

Observations showed that

"…before repairing wind-damaged buildings or retrofitting a building to be more wind-resistant, all building elements should be assessed for vulnerability to high-wind events, even those that were not damaged. If undamaged elements are determined to have significant vulnerabilities, they should be mitigated as part of the repair work to help prevent future damage. Even when retrofitted elements perform well, if other non-retrofitted elements fail during a high-wind event, the whole retrofit project may be ineffective because the building did not achieve the target performance level intended by the retrofit."

To address this, five specific steps to develop a comprehensive plan for executing the needed retrofits and improve wind resistance of critical facilities and residential buildings has been derived. Figure 18 outlines the five-step process from Recovery Advisory 1 (RA 1) Report (FEMA, 2019a) as a recommended approach for consideration.

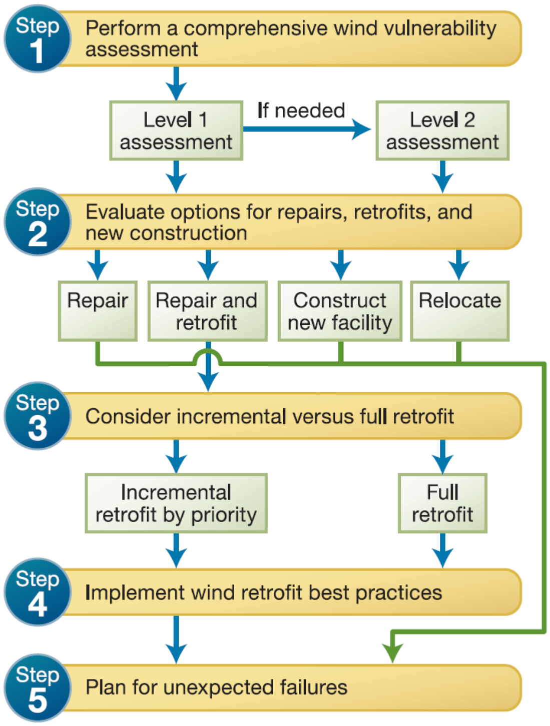

Figure 18. RA 1 flowchart showing five-step approach to improving wind resistance (FEMA, 2019a)

5.2 Recovery Advisory 2

This document (FEMA, 2019b) focuses on immediate lessons learned from Hurricane Michael regarding wind and water infiltration damage to existing residential buildings. Presented in this report are a series of best practices for roof coverings, underlayment, vents, exterior wall coverings, soffits, glazed openings and doors. The target audience includes building owners, operators, and managers; design professionals; building officials; contractors; and municipal building and planning officials. Table 12 summarizes the Recovery Advisory 2 (RA 2) Key Practices and compares those to the FBC-Building/Residential, 6th Edition (2017) requirements. Italic bold font in “Commentary” designates differences between RA 2 Key Practices and the FBC.

We note that all Key Practices of the RA 2 are addressed in the Report No 04-19 (Prevatt, 2019), titled “Investigation of Optional Enhanced Construction Techniques for the Wind, Flood, and Storm Surge Provisions of the Florida Building Code,” that was submitted to Florida Department of Business and Professional Regulation on December 27, 2019. This document provides enhanced construction techniques for strengthening the wind resistance, storm surge and flood resistance and water intrusion resistance provisions of the FBC based primarily on existing guidance and best practices including presented in RA 2 Report. Both FBC-Building/Residential, 6th and 7th Editions (2017 and 2020, respectively) were considered.

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Table 12. Comparison of Recovery Advisory 2 Key Practices vs. FBC Building/Residential, 6th Edition (20217) Requirement

Scope	Key Points	Recovery Advisory 2 (RA2) Key Practice	FBC B/R, 6th Edition (2017) Requirement	Commentary
Wind Performance of Asphalt Shingles	Testing and label	Testing and labeling are based on ASTM D7158.	B1507.2.7.1: Asphalt shingles shall be classified in accordance with ASTM D3161, ASTM D7158 or TAS 107. B 1507.2.3: Asphalt shingles shall be fastened to solidly sheathed decks. B 1507.2.4: Asphalt shingles shall only be used on certain roof slopes.	• FBC require same label and testing method as FEMA RA2 Report. • ***RA2 Report have addition requirement for shingles at rakes, eaves, hips.***
	Installation	• Shingles at rakes, eaves, hips, ridges and fastener location should be paid attention. • Enhanced flashing techniques could improve performance.		
Wind Performance of Concrete and Clay Roof Tiles	Design	Determine appropriate design wind loads using ASCE 7-16	B1507.3.2: Installation in accordance with FRSA/TRI (Florida High Wind Concrete and Clay Roof Tile Installation Manual). B1503.3.1: Concrete and clay tile shall be installed only over solid sheathing.	Both RA2 Report and FBC require that concrete and clay roof tiles installation should follow FRSA/TRI.
	Installation	• Installation should follow FRSA/TRI, (Florida High Wind Concrete and Clay Roof Tile Installation Manual). • For improved performance, use enhanced installation techniques mentioned in FEMA P-499, 2010, No 7.4		
Wind Performance of Metal Roof Systems	Testing and labeling	Metal panel roof systems are tested based on ASTM E1592(2017b)	B1507.4.3: Aluminum metal roof test should follow ASTM B209	***The FBC did not mention the ASTM E1592(2017b) test standard.*** ***The RA2 Report provides enhanced installation***
	Installation	For improved performance, use enhanced installation techniques for design and		

Scope	Key Points	Recovery Advisory 2 (RA2) Key Practice	FBC B/R, 6th Edition (2017) Requirement	Commentary
		installation mentioned in FEMA P-499, 2010, No 7.6	B1507.4.3: Cold-rolled copper roof test follow ASTM B370 B1507.4.1: Metal roof panel roof shall be applied to a solid or closely fitted deck B1507.4.2: Metal roof panels shall have Minimum slopes	***techniques to improve performance.***
Wind Performance of Ridge Vents and Off-Ridge Vents	Testing and labeling	Ridge vents were tested for resistance to wind and wind-driven rain based	TAS-100: Test procedure for the water infiltration resistance of a soffit ventilation.	The FBC provide specific test procedure for water penetration of ridge vents. ***The RA2 Report provides fastener requirement.***
	Installation	• Attach roof ventilation products properly • Ensure fasteners for ridge vents are of a sufficient length to penetrate the roof sheathing below.		
Wind Performance of Vinyl Siding	Testing and labeling	• Use Vinyl siding product comply with ASTM D3679(2017). • Ensure selected siding wind pressure rating that exceeds the local required design wind pressure. • Double or curled nail hem vinyl siding has the highest design wind pressure rating.	B1404.9. Vinyl siding shall be certified and labeled based on ASTM D3679. B1405.14.1. Siding and accessories shall be installed in accordance with approved manufacturer's instructions.	***The RA2 Report recommends using double or curled bail hem vinyl siding in high velocity region.***

Scope	Key Points	Recovery Advisory 2 (RA2) Key Practice	FBC B/R, 6th Edition (2017) Requirement	Commentary
	Installation	• Install vinyl siding over wood structural panel sheathing. • Use utility trim at top of walls and under windows where the nail hem has to be cut. • Use proper starter strips at the first course of the siding		
Wind Performance of Fiber-Cement Siding	Testing and labeling	Selected fiber cement siding is designed meet the design wind pressures in ASCE 7-16.	B1405.16: Fiber-Cement Siding should both satisfy water-resistive barrier requirements and manufacturer's instructions. B1405.16: Fastener shall be corrosion-resistant and be long enough to penetrate the studs at least 1 inch (25 mm).	***The RA2 Report recommends using face-nailing of fiber-cement siding in hurricane-prone regions.***
	Installation	Face-nailing of fiber-cement siding is recommended in hurricane-prone regions.		
Wind Performance of Soffits	Design	Use adjacent walls wind load to design soffits.	R703.11.1.4: Soffits should have same wind load resistant as wall. R703.11.1.4: Vinyl soffit panels shall be fastened to nailing strip, fascia.	• FBC have same requirement for soffit wind load design. • ***FBC did not have wind-driven testing requirement for soffit.*** • ***FBC did not limit the unsupported span of soffit and did not have***
	Testing	Soffit vents must be tested for resistance to wind and wind-driven rain.		
	Installation	• Secure fascia covers adequately. • Both end vinyl soffits panel are fastened to framing.		

Scope	Key Points	Recovery Advisory 2 (RA2) Key Practice	FBC B/R, 6th Edition (2017) Requirement	Commentary
		• Limit unsupported span of soffit panels to 12 in.		***requirement for fascia strength.***
Wind performance of Glazed Openings	Design	Glazed openings in wind-borne debris regions must be impact-resistant or be protected with shutter.	R301.2.1.2: Exterior glazed openings in buildings located in windborne debris regions shall be protected from windborne debris.	***The RA2 Report recommends some impact-resistant products.***
	Testing and labeling	Use recommended impact-resistant products mentioned in FEMA P-499, 2010, No. 6.2.		
Water Infiltration of Glazed Openings and Doors	Testing and labeling	Product labels and tests are based on AAMA/WDMA/CSA 101/I.S.2/A440.	B2410-2413: Windows and glazing requirement in high-velocity hurricane zone.	Both RA 2 Report and FBC require using AAMA/WDMA/CSA 101/I.S.2/A440 test standard to test fenestration water penetration.
	Installation	Use recommended installation and flashing methods for windows and doors mentioned in FEMA P-499, 2010, No.6.1.		

5.3 FEMA P-2077 Recommendations

Table 13 below includes the specific recommendations that are pertinent to FBC, FDEM and ASCE 7 wind load provisions respectively. These are extracted from the complete list of 69 recommendations of FEMA P-2077 Report (FEMA, 2020) that are provided for convenience in Appendix C.

Several recommendations have already been addressed in the FBC 6th and 7th editions.

The recently published Draft of the FBC-Building, 7th Edition (2020) incorporated recommendation FL-14e to Section 1507, introducing new subsections 1507.1.1.1-1507.1.1.3 to address recommendations of the use of underlayment systems that additionally function as a sealed roof deck (secondary roof sealing strategy proposed by IBHS).

Recommendation FL-17c, that suggests revising the FBC and FBCR to require labeling of vinyl siding, can be found in both FBC 6th (2017) and 7th (2020) Editions (FBC-Residential: Chapter 7, Section R703, R703.11; FBC-Building: Chapter 14, Section 1404, 1404.9).

Three of the 26 recommendations selected and presented in Table 13 recommendations marked with "*" (FL-14e, FL-16 and FL-17a) refer to Recovery Advisory 2 (FEMA, 2019b).

Table 13. 26 of 69 FEMA P-2077 recommendations addressed to FBC, FDEM, ASCE, ASTM and other related Action Offices that can be taken into consideration by FBC (extracted from Table 6-2, FEMA P-2077, see Appx. C)

Action Office / Recovery Support Function (RSF)	**FEMA P-2077 Recommendation**
Addressed to FBC:	
FBC, CPCB, Housing	**FL-8a.** The FBC should treat all areas within 1 mile inland from the entire Florida coastline as a WBDR.
IBC/IRC/FBC proponents, CPCB, Housing	**FL-8d.** The IBC/IRC/FBC should be updated where needed to ensure glazed window, skylight, door, and shutter assemblies have a permanent label that provides traceability to the manufacturer and product.
FBC, CPCB, Housing	**FL-15c.** The FBCR should be revised to require soffit panels to be labeled to provide traceability to the manufacturer and product.
FBC, CPCB, Housing	**FL-17c.** The FBC and FBCR should be revised to require vinyl siding be labeled to provide traceability to the manufacturer and product.
FBC, CPCB, Health and Social Services	**FL-30.** The FBC should provide more specific criteria with restrictions on how, when, and where roof aggregate can be used.

Action Office / Recovery Support Function (RSF)	FEMA P-2077 Recommendation
Addressed to FDEM:	
FDEM, CPCB	**FL-1a.** FDEM should consider developing/modifying training on the flood provisions in the FBC and local floodplain management ordinances.
FDEM, CPCB, Economic, Health and Social Services, Housing, Infrastructure, Natural and Cultural Resources	**FL-5b.** FDEM should continue to encourage pre-event evaluation of post-disaster needs and inform appropriate parties about assessing resources through SMAA and EMAC.
FEMA, FDEM, CPCB	**FL-10b.** FEMA and FDEM should consider providing a code change proposal to the International Codes requiring contractors and/or manufacturers to add length labels or incremental depth markers on vertical piles.
FEMA, FDEM, CPCB, Infrastructure	**FL-11a.** FEMA and FDEM should consider submitting a code change proposal to the FBC, applying ASCE 24 Flood Design Class 4 requirements outside the SFHA in moderate flood hazard areas (shaded Zone X) and to consider flood risk for minimal flood hazard areas (unshaded Zone X).
FEMA, FDEM, CPCB, Housing	**FL-14e*.** FEMA and FDEM should consider supporting current code change proposals to the 7th Edition FBC that provide for improved underlayment systems.
FEMA, FDEM, CPCB, Housing	**FL-15b.** FEMA and FDEM should consider submitting a code change proposal to the FBC requiring soffit inspections, and jurisdictions should prioritize performing soffit inspections.
FEMA, FDEM, CPCB, Housing	**FL-17a*.** FEMA and FDEM should consider submitting a code change proposal to the FBC requiring exterior wall covering inspections.
FDEM, CPCB	**FL-19c.** FDEM should consider delivering training on FEMA P-361 safe room design, construction, and operations and maintenance.
The State of Florida and FDEM, CPCB, Health and Social Services	**FL-21a.** The State of Florida and FDEM should consider re-evaluating their policies, procedures, and requirements for assessments of existing spaces for use as HES.
The State of Florida and FDEM, CPCB, Health and Social Services	**FL-21b.** The State of Florida and FDEM should consider re-evaluating EHPA criteria and re-assess safety of existing EHPAs, particularly those designed prior to the 6th Edition FBC (2017).
Addressed to ASCE:	
ASCE 7 Wind Load Task Committee, CPCB, Housing	**FL-8b.** The ASCE 7 Wind Load Task Committee should revise ASCE 7 to lower the basic wind speed trigger in ASCE 7 for requiring glazing to be protected on Risk Category IV buildings in the hurricane-prone region.

Action Office / Recovery Support Function (RSF)	FEMA P-2077 Recommendation
ASCE 7 Wind Load Subcommittee, CPCB	**FL-8e.** The ASCE 7 Wind Load Subcommittee should consider developing commentary on vestibule wind loads.
Addressed to ASTM:	
FEMA, AAMA/WDMA/CSA, IBHS, ASTM, ICC, CPCB, Housing	**FL-6.** FEMA should work with AAMA/WDMA/CSA, IBHS, ASTM, ICC®, and other select industry partners to incorporate more comprehensive water intrusion testing requirements that improve overall performance into testing standards.
ASTM E1886 Task Committee, CPCB	**FL-24a.** The task committee for ASTM E1886 should consider revising the standard to include the evaluation of the potential for the shutter assembly to unlatch during a storm.
ASTM E1886 Task Committee, CPCB	**FL-24c.** The task committee for ASTM E1886 should add corrosion criteria to the standard to help enable shutters to perform as intended over their useful life.
ASTM E1886 Task Committee, CPCB	**FL-24d.** The task committee for ASTM E1886 should evaluate the current perpendicular angle specifications for impacting a shutter during testing for its adequacy.
Other related recommendations that can be taken into consideration by FBC:	
Code enforcement authorities, CPCB, Housing	**FL-14a.** Code enforcement authorities having jurisdiction across Florida should make roof covering and underlayment inspections a priority.
Wind engineering research community, CPCB, Housing	**FL-7.** The wind engineering research community should perform a revised analysis of the ASCE 7 basic wind speed maps for the Florida Panhandle region to include data from Hurricane Michael.
Academia and pile industry groups, CPCB	**FL-10a.** Industry groups, interested stakeholders, and/or academia should further evaluate the performance of the concrete pile foundations that failed during Hurricane Michael to determine why they failed.
Ridge vent industry groups and academia, CPCB, Economic, Housing	**FL-16*.** Industry groups and academia should perform research on commonly used ridge vent products to better determine the causes of ridge vent failure and develop solutions.
Vinyl siding manufacturers, insurance organizations, CPCB, Housing	**FL-17b.** Vinyl siding manufacturers, insurance organizations, and other stakeholders should continue research and investigations of the appropriate PEF for vinyl siding.

Abbreviations used in Table 13:

AAMA = American Architectural Manufacturers Association
ASCE = American Society of Civil Engineers
ASTM = ASTM International
CPCB = Community Planning and Capacity Building
CSA = Canadian Standards Association
EHPA = Enhanced Hurricane Protection Area
EMAC = Emergency Management Assistance Compact
FBC = Florida Building Code
FBCR = Florida Building Code, Residential
FDEM = Florida Division of Emergency Management
FEMA = Federal Emergency Management Agency
HES = Hurricane Evacuation Shelter
IBHS = Insurance Institute for Business & Home Safety
IBC = International Building Code
ICC = International Code Council
IRC = International Residential Code
MAT = Mitigation Assessment Team
PEF = pressure equalization factor
SFHA = Special Flood Hazard Area
SMAA = Statewide Mutual Aid Agreement
WBDR = wind-borne debris region
WDMA = Window and Door Manufacturers Association

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APPENDIX A: MODULAR HOME DATABASE

The following table summarizes the modular and site-built home datasets from Hurricanes Irma (2017) and Michael (2018) used to perform an evaluation of the relative wind damage risk between these two building classes.

Table A1. Sample of modular homes impacted by Hurricane Irma (2017).

Record ID	Latitude	Longitude	Year Built	Number of Stories	Wind Damage Rating	Est. Wind Speed (mph)
a17b24a2-bf5b-433c-b001-7a4a94647b25	24.667503	-81.363726	2008	1	2	114
454bbca1-de2e-4dd0-8590-f3ed2887ca2f	24.656112	-81.405712	2006	1	3	117
7a62025e-e719-4a4c-9033-f8447a022689	24.654928	-81.406002	1995	1	3	117
fb11f220-b792-44fe-a5d2-d7dfce514d6e	24.670789	-81.346126	2003	1	1	117
bb2dae2a-e217-4c94-a819-634b377a9836	24.671695	-81.339281	2004	2	2	117
8a687902-0fa7-4b43-926e-9e190e329094	24.687328	-81.397769	2006	1	2	117
01bd7e22-b78d-49be-b3ff-d9bdfbb686ac	24.690018	-81.398649	2000	1	2	117
32c1b935-d086-4d5d-8f23-2bd154ee20ec	24.677912	-81.394068	2006	1	2	117
cacd978c-77f5-43b2-a5fd-9b2b863eb387	24.67794	-81.392963	2006	1	1	117
33e31a9b-935f-41f3-	24.689699	-81.398169	2000	1	2	117

Record ID	Latitude	Longitude	Year Built	Number of Stories	Wind Damage Rating	Est. Wind Speed (mph)
b6b4-c0fe9950cd63						
51628a86-03f0-41fc-b013-8705964c31e9	24.688449	-81.398368	2006	1	2	117
6235bee2-a740-4f47-b7dd-7a0ed23c001e	24.679144	-81.392485	2006	1	2	117
7a86ec00-fc86-4a85-998d-0be3b3d9fe40	24.672478	-81.345998	2005	1	2	117
9ad76948-5b0c-4fbb-ade5-3c0bec5aa8b2	24.689533	-81.397747	2006	1	2	117
c87859d1-3708-4b64-a3a1-ec27ec0d2654	24.688432	-81.397913	2007	1	2	117
d8c6d213-1b31-486c-bddf-1f4930df547d	24.678578	-81.393613	2004	1	1	117
83d51d77-2535-47de-a9a2-4af9872a6aa8	24.624706	-81.593166	2011	1	3	112
9e64a15f-58ab-4b72-b9d2-6453ce9a0e6f	24.567435	-81.744917	2007	2	2	109
4f4e7107-30ab-436b-8e15-b29505cf87b8	24.72593	-81.396403	1993	1	1	116
558619af-0dcf-4e86-a388-188559c60eaa	24.678866	-81.389673	1996	1	2	117
1c671342-fd75-4245-bb2e-45190d0d75b7	24.719417	-81.056247	2001	1	2	123

Record ID	Latitude	Longitude	Year Built	Number of Stories	Wind Damage Rating	Est. Wind Speed (mph)
4d5f3fed-bce5-4b62-bdb9-e345de291200	24.665816	-81.409096	1998	1	1	117
b886e99d-720d-434b-9404-7f877b20c6d0	24.670214	-81.528307	1996	2	3	111

Table A2. Sample of site-built homes impacted by Hurricane Irma (2017).

Record ID	Latitude	Longitude	Year Built	Number of Stories	Wind Damage Rating	Est. Wind Speed (mph)
d7a9dccc-c5a7-4e6a-94a0-37bc376c30d9	25.923327	-81.643774	2008	1	0	110
9cea39b8-23c9-489c-90c9-373dddfd5328	24.655576	-81.38537	1997	2	2	117
da865048-cdeb-4ee4-8dde-fdc5089f5f56	24.655569	-81.385183	1998	1	2	117
7acb1c1a-13ec-4308-a926-e5132ce6954b	24.658757	-81.386095	2008	2	3	117
4a69021f-6544-44c1-96a6-682b2e7ef296	24.656541	-81.406744	2015	1	3	117
d0212162-be42-4cc9-b82a-38e59e5de415	24.65532	-81.406439	2012	2	1	117
1fabc330-00b2-453e-8290-65270d6c1897	24.655725	-81.405125	2010	1	1	117
7ee2fc09-7277-450f-a044-fd8dec8fa8b7	24.654906	-81.40671	1995	1	2	117
8038b934-e08b-44fb-	24.672652	-81.340471	2006	2	2	117

Record ID	Latitude	Longitude	Year Built	Number of Stories	Wind Damage Rating	Est. Wind Speed (mph)
805d-a62115804f31						
2293a2cd-ee8d-4b72-a204-03a32230ed31	24.689619	-81.398899	2011	1	1	117
73d1c9aa-e581-4758-a353-e0d595640f04	24.721549	-81.05154	1997	1	1	123
53130e37-f266-4242-b6cb-b4394263277d	24.719515	-81.055558	1997	1	3	123
fe7ecf1f-f8fe-48d4-8dac-453dd82653be	24.667069	-81.409737	2017	1	0	117
a7181938-0896-4ddc-9d60-d77289f20520	24.625311	-81.593512	2002	1	1	112
5de49a9d-583b-49c6-b446-2fd9e1052531	24.600148	-81.662748	2002	1	1	110
a76fe876-c9f8-452d-8e9a-82d7fd83c129	24.677443	-81.389194	2016	1	1	117
99d6aba8-e822-4e0d-ab77-f530d8442c8a	24.670367	-81.528441	2007	1	1	111
c31d0d14-878b-4573-91b4-a585b72941c2	24.660893	-81.405357	2000	1	3	117
7124f855-bf5a-42b5-a463-fd17e084c853	24.661283	-81.405504	2016	1	1	117
38f3092d-04cd-4aa4-af71-9d553ad96ece	24.759729	-80.960521	2007	1	2	118

Table A3. Sample of modular homes impacted by Hurricane Michael (2018).

Record ID	Latitude	Longitude	Year Built	Number of Stories	Wind Damage Rating	Est. Wind Speed (mph)
545a4b4f-66ac-4a75-8dbf-ba8d97878a0f	29.952198	-85.420476	2004	2	1	150
6f03b824-85ef-467e-be47-252a77b169fa	29.924848	-85.384097	2016	1	1	149
9e65cb50-81fa-444b-869f-c3bcc39ac433	30.271264	-85.532722	2007	1	2	128
8f36c348-ffb5-4921-a58e-463d9fcbd88a	30.251066	-85.490213	2006	1	1	132
2f03d0ef-2fd8-418c-95d8-ef61527f000d	30.153952	-85.571730	2007	1	2	133
d1ed8ef5-8fca-4d71-9f0b-421af4070b93	30.206974	-85.602105	2006	1	4	128
ad0845ee-16e4-4498-9e6d-f36940848441	30.207215	-85.601984	2006	1	4	128
3aa70b6e-dc61-4ce4-ac41-fbca85760c3b	30.207945	-85.602198	2006	1	2	128
58aa147f-4f59-44a8-b049-31ef0e0794de	30.207516	-85.602988	2007	1	4	128
18276e14-a486-46f8-8268-2dd799076f40	30.196401	-85.600051	2008	2	3	128
1f2898a2-b686-47e6-9399-b9beda1807fa	30.196121	-85.600049	2008	2	3	128
f01cbd96-a6bc-4867-	30.195846	-85.600050	2008	2	3	128

Record ID	Latitude	Longitude	Year Built	Number of Stories	Wind Damage Rating	Est. Wind Speed (mph)
8b1e-38fe5a24de5b						
16d600e9-8098-4bd6-af9c-66121ebc2a7f	30.171467	-85.605306	2008	1	1	130
29462616-205e-4329-8d3a-b06fa5fe440b	30.146950	-85.624413	2007	1	2	131
dc48d264-ec2f-405f-8d33-53a38dd08490	30.146963	-85.624655	2006	1	1	131
cb98764e-8e8a-402a-b8f8-68948f70ccbe	30.180519	-85.695436	2007	1	1	126
2245181b-5fc6-4ce8-a484-2fe9b4efef86	30.169764	-85.768363	2007	1	0	122
e3d743da-3e7e-4fd8-b295-6b3d52f2a043	30.278555	-85.960801	2007	2	0	93
2cd71cd6-ecb4-43ad-99db-5f7b54723e92	30.259323	-85.960674	2006	1	0	94
e9c95bc1-9ca1-4f65-827c-4d05d15075c2	30.246850	-85.917383	2009	2	0	100
9a5763d9-aedc-4ea3-97be-cc2aff2fb4b5	30.246293	-85.917293	2008	1	0	100
3017664c-bd5a-48d1-90dc-ff71205a33eb	30.162016	-85.634521	2019	1	2	130
c4cd8201-fe35-4cb5-b75e-adc5163cfe50	30.162522	-85.630584	2006	1	2	130

Record ID	Latitude	Longitude	Year Built	Number of Stories	Wind Damage Rating	Est. Wind Speed (mph)
81060003-f115-4eda-9f89-eb221393b2f6	30.172954	-85.642454	2007	1	2	129
346dfc79-add1-40d4-aa05-a4f32cfc0331	30.169494	-85.657345	2007	1	3	129
e12f64dd-3d2a-4a6d-9132-e535b8ff499a	30.164839	-85.654789	2007	1	2	129
8c69f45e-aca2-4af1-a7c7-684216ae0ad5	30.163577	-85.662938	2007	1	2	129
21c4ba7b-8833-480c-b35e-f836b613a762	30.246495	-85.916930	2008	1	0	100
801214c5-ed44-47dc-82c0-95199d292339	30.246857	-85.916695	2008	1	0	100
c8482c96-c50b-49c2-ab3b-2bc6d69927e8	30.245200	-85.917324	2008	2	0	100
fdaa0e54-6b43-4687-bb65-e265012455a8	29.836253	-85.310785	2003	1	1	129
274a6fbf-a2d0-496b-ba4c-a18cb2111ae1	29.898903	-85.359132	2002	1	1	144
29d9bd3d-102b-4448-be6e-b3419e38be29	29.760940	-85.287360	2006	1	0	118
e35a61a0-b765-4936-8999-6f0b77bf8fb0	29.908823	-85.367606	2012	1	3	146
9d28457e-51b5-47ac-	30.089487	-85.192586	1999	1	0	137

Record ID	Latitude	Longitude	Year Built	Number of Stories	Wind Damage Rating	Est. Wind Speed (mph)
9722-bc9b08ee823a						
d8f15b9d-28cf-4748-afd5-3742b6aa5d08	30.131874	-85.198955	2009	1	0	140
54ec12d9-ca6c-4e0e-ac1d-957d59958ba6	30.107784	-85.193467	1999	1	1	138
596b753e-560d-4ffe-a3cf-83161d06fa80	29.923986	-85.381912	2007	1	2	149
ceec5d9b-dc9c-4dd6-94b0-a4fe8030f898	30.096748	-85.183274	2005	1	2	136
6caa48bd-6f81-4184-96ed-2d4ce7409900	30.110445	-85.216555	2012	1	1	140
019c7a63-c793-4a8f-add3-8f0438d0506b	29.903463	-85.357062	2013	1	2	144
3180aa8b-7018-47d0-817d-532e58b4ee1f	29.837162	-85.312542	2008	1	0	130
b6a344d9-e2d2-4dc4-b606-ccd8ea718739	29.920281	-85.380898	1999	1	2	148
df44b445-c1bd-4a43-912b-90b65853695a	29.920095	-85.381120	2010	1	2	148
4300456e-d242-434c-9fc6-e8c8b9797611	29.920607	-85.381989	1990	1	2	149
98a073e2-706d-4782-b00d-44caea66eab1	29.895730	-85.353250	2008	1	0	143

Record ID	Latitude	Longitude	Year Built	Number of Stories	Wind Damage Rating	Est. Wind Speed (mph)
7f17b891-799a-4265-b74c-0ed765ce3699	29.895717	-85.354068	2008	1	0	143
4dfe4cee-88f5-4353-9714-d12e285f81d8	29.904140	-85.363930	2011	1	0	145
1d5bd657-287e-4e3f-91eb-e6bfcdbf8535	30.103160	-85.197474	2005	1	2	139
f7f7320b-c823-437a-8abc-2ec7e55a5fc5	29.689947	-85.372675	2008	2	2	126

Table A4. Sample of site-built homes impacted by Hurricane Michael (2018).

Record ID	Latitude	Longitude	Year Built	Number of Stories	Wind Damage Rating	Est. Wind Speed (mph)
faf302ab-5633-416a-8ec7-6418cb471cf4	30.282409	-85.631676	2010	1	2	122
5c33b8e8-2cb2-468d-adda-fbc2717cdb52	30.285373	-85.630896	2014	1	1	122
253a5653-1a75-4276-98e5-180c9bd1f265	29.927386	-85.389041	1996	1	3	150
de36a0c9-5060-45c6-afd4-939111c3d150	30.181399	-85.618512	2006	1	2	129
f62d80e0-9d45-478c-a730-5262a1ffc667	30.181443	-85.620728	1998	1	1	129
2947e3aa-5d6e-4178-9617-2a4807f5a542	30.181911	-85.621214	1998	1	1	129
0bcada42-cc48-4889-	30.182333	-85.621599	2006	1	2	129

Record ID	Latitude	Longitude	Year Built	Number of Stories	Wind Damage Rating	Est. Wind Speed (mph)
a497-b3f757b308e0						
fbb468b0-9879-4975-93e9-d60ec90ddf78	29.934998	-85.399388	2017	2	2	150
6a36d8f3-5f28-4a22-b0e0-6086249f981e	30.180913	-85.618740	2008	1	2	129
cbf50cf1-a8c7-47b5-9ac8-936d65ec2132	29.915987	-85.375957	2017	1	1	147
c8cc248f-32fe-4192-97b6-b6ea95747b94	30.180628	-85.617033	2007	1	1	129
8a2845af-8ea0-4553-a5c7-9c67c19f827a	30.180963	-85.617731	2006	1	1	129
f1d7da45-68fc-4578-bb17-7d7faf62d574	30.181815	-85.621557	1998	1	2	129
21f9ff2c-f187-4766-9802-f2faa52228d7	30.207534	-85.599258	2012	1	3	128
f67c6bb6-d8ed-4b6a-9710-3d8a4f44c18d	30.207037	-85.600242	2012	1	1	128
5f6dd132-4ba2-4746-b0ee-8d0d4ae78d40	30.180506	-85.617804	2006	1	1	129
d42ff787-429c-4546-9234-4d82d057daa5	30.181358	-85.619811	2006	1	2	129
86686b3a-1faf-4d7b-8fef-34e9fe8a4f64	30.137349	-85.566346	2007	2	1	134
c2243783-9968-4069-8edb-337a4b2a1929	30.180817	-85.618371	2006	1	1	129

Record ID	Latitude	Longitude	Year Built	Number of Stories	Wind Damage Rating	Est. Wind Speed (mph)
c1a1e094-f72f-4643-bfd7-3ed81b135960	30.208323	-85.640254	2002	1	0	126
33b80641-f4f7-4946-9d82-3e07eb790d19	29.939494	-85.397271	2004	1	2	150
70d7f4fc-09f7-48a3-9da6-f235ae46a4dc	29.941526	-85.395056	2008	1	1	150
0d525f49-bf9a-4295-8103-784ac46f219b	29.940397	-85.395132	1998	1	1	150
023751a8-a3af-42c1-b6b1-3b71e5423637	29.914291	-85.375806	1998	2	1	147
12712ead-db5b-4db6-8eed-e0c0ce6a3bd2	29.914693	-85.376987	1997	1	1	147
5b4ad3b6-01cf-4145-b578-a43af2574007	29.916248	-85.373617	1996	2	2	147
5e73bb05-ddc3-4f4c-8172-7f9569d303ea	29.913199	-85.373052	1991	2	3	147
3cc70b11-9b6f-4cc0-abbb-c1c619f6d470	29.912834	-85.373315	1999	1	2	147
01613e70-d9ab-49c2-8b16-4bf422f98a2e	29.840754	-85.315528	2007	1	1	131
26886524-83d0-44e0-9df3-73e28e18a976	29.801561	-85.297073	1997	1	2	123
702c9e55-284d-4687-8dd1-b07caeb8b7d5	29.951929	-85.426601	2018	2	1	150

Record ID	Latitude	Longitude	Year Built	Number of Stories	Wind Damage Rating	Est. Wind Speed (mph)
f3597aba-f108-4b8c-acb3-9a4255d4609e	30.178304	-85.619280	2017	1	1	129
feb85ff7-f6a6-48b0-9fc4-2f72bb2a50f9	30.204914	-85.596374	2017	1	2	128
df468e28-fba7-4760-b2a3-01547984a88f	30.206975	-85.595758	2017	2	2	128
91664745-1949-4f3e-ad07-fdfb879ff4af	30.206226	-85.600525	2012	1	1	128
e8385b7b-8ca7-44fe-8cc6-3aac2f9d4edb	30.195423	-85.602431	2010	2	2	128
6a24b45e-af40-4130-bad9-f957b1be5e14	30.191913	-85.604232	2009	1	1	129
7a1609f5-ed25-46cd-8fab-322160056acd	30.191129	-85.603911	2010	1	3	129
fba628d5-8887-4d18-9c7a-3e6bd8360b5d	30.190955	-85.604312	2006	1	3	129
307ab433-218c-45cf-96a3-079bba737fe1	30.190742	-85.605497	2005	1	2	129
70e43a2d-a301-4969-9ff1-b892df698b1b	30.190702	-85.606066	2004	1	3	129
821a41cb-2139-4c56-b18a-5c6739927531	30.191622	-85.606413	2004	1	2	129
45a80b47-56f2-448a-b678-74a4b6fceb59	30.213466	-85.591171	2018	1	1	128

Record ID	Latitude	Longitude	Year Built	Number of Stories	Wind Damage Rating	Est. Wind Speed (mph)
d1889c8c-44e8-45fd-b4bc-c9c8f0d987bf	30.213437	-85.591613	2018	1	2	128
c87a0382-b6c1-47eb-80d7-77b28fc571f6	30.213617	-85.591575	2018	1	1	128
e537bbb6-311d-4a35-a510-aaca9392da25	30.261671	-85.529744	2017	2	2	129
86656f89-cc9e-4a71-8f9d-896684429f47	30.244164	-85.631752	2014	2	1	124
0fe48a2f-ed78-4c58-a207-7a06273e978c	30.220665	-85.639251	2008	1	2	126
87e0a3d6-f680-4af5-9617-1799b6349190	30.222330	-85.642212	2004	1	1	125
4f9e0ee2-fc15-441b-b68b-56193217f0ac	30.206458	-85.679557	2017	2	2	124

APPENDIX B: SUMMARY OF FIELDS IN THE ENHANCED HURRICANE MICHAEL DATASET

Table B1. List of fields present in the enhanced Hurricane Michael (2018) dataset.

Column		**Column Header**	**Field**	**Format**	**Response Choices / *Description***	**Percentage with Values (Excluding Unknowns)**
A	1	fulcrum_id	Record ID	Text	Auto-populated; unique ID associated with each record	100%
B	2	status	Damage State	Single Choice	0=No Damage 1=Minor 2=Moderate 3=Severe 4=Destroyed	100%
C	3	project	Project	Text	Hurricane Michael (2018)	100%
D	4	latitude	Latitude	Decimal	Auto-populated	100%
E	5	longitude	Longitude	Decimal	Auto-populated	100%
F	6	name_of_investigator	Name of Investigator	Text	Andrew Kennedy Brayan Wood Brett Davis David Prevatt David Roueche Daniel Smith Dean Ruark Doug Krafft Erin Koss Jean-Paul Pinelli John Cleary Justin Marshall Keith Cullum Kelly Turner Kurt Gurley Matt Janssen Oscar Lafontaine Tim Johnson	100%
G	7	date	Date	MM/DD/YYYY	Auto-populated	100%
H	8	general_notes	General Notes	Text	*Investigator/Librarian general notes*	0.51%
I	9	assessment_type	Assessment Type	Single Choice	Aerial Drive-by On-site Remote General Area Other	100%

Column		Column Header	Field	Format	Response Choices / *Description*	Percentage with Values (Excluding Unknowns)
J	10	all_photos	All Photos	Comma separated values	*Photos associated with record*	91.84%
K	11	all_photos_captions	All Photos Captions	Comma separated text	*All photo captions supplied by surveyor (if any*	0.51%
L	12	all_photos_urls	Direct Path to Photo Hosted on Fulcrum	URL	Auto-populated	91.84%
M	13	audio	Audio	Comma separated values	*Surveyor-supplied audio*	0.13%
N	14	audio_url	Direct Path to Fulcrum Entry	URL	Auto-populated	0.13%
O	15	overall_damage_notes	Overall Damage Notes	Text	*Overall damage notes supplied by surveyor/Librarian*	49.74%
P	16	hazards_present	Hazards Present	Multiple Choice (Comma separated text)	Flood Rain Surge Tree-fall Wind Wind-borne debris Unknown Other	99.87%
Q	17	wind_damage_rating	Wind Damage Rating	Single Choice	-1=Not Applicable 0=No Damage 1=Minor 2=Moderate 3=Severe 4=Destroyed	100%
R	18	surge_damage_rating	Surge Damage Rating	Single Choice	0=No Damage or Very Minor Damage 1=Minor 2=Moderate 3=Severe 4=Very Severe 5=Partial Collapse 6=Collapse	100%
S	19	rainwater_ingress_damage_rating	Rainwater Ingress Damage Rating	Single Choice	-1=Unknown 0=None Visible 1=Minor Ingress 2=Moderate	7.6%

Column		**Column Header**	**Field**	**Format**	**Response Choices / *Description***	**Percentage with Values (Excluding Unknowns)**
					3=Severe 4=Complete	
T	20	attribute_notes	Attribute Notes	Text	*Attribute notes supplied by surveyor/Librarian*	8.67%
U	21	address_sub_thoroughfare	House Number	Text	Auto-populated	99.23%
V	22	address_thoroughfare	Street Name	Text	Auto-populated	100%
W	23	address_suite	Suite Number	Text	Auto-populated	0.13%
X	24	address_locality	City/Town	Text	Auto-populated	100%
Y	25	address_sub_admin_area	County	Text	Auto-populated	100%
Z	26	address_admin_area	State	Text	Auto-populated	100%
AA	27	address_postal_code	Zip Code	Text	Auto-populated	100%
AB	28	address_country	Country	Text	Auto-populated	93.88%
AC	29	address_full	Full Address	Text	*Address supplied by surveyor/Librarian*	100%
AD	30	building_type	Building Type	Single Choice	Single Family Multi-Family Apartment Assisted Living Center Condominium Detached Garage Government Hotel/Motel Manufactured Home Manufacturing Plant Marina Office Park Shelter Professional Religious Restaurant Retail RV Service Station Shed Supermarket Warehouse Unknown Other	99.87%
AE	31	number_of_stories	Number of Stories	Integer	1-25	97.45%

Column		Column Header	Field	Format	Response Choices / *Description*	Percentage with Values (Excluding Unknowns)
AF	32	understory_pct_of_building_footprint	Understory Area(% of Building Footprint)	Single Choice	0% - 100%	80.87%
AG	33	first_floor_elevation_feet	First Floor Elevation in Feet	Decimal	0-13	85.46%
AH	34	year_built	Year Built	Integer	*Year of construction as indicated by public records or personal communication*	97.96%
AI	35	roof_shape	Roof Shape	Multiple Choice (Comma separated text)	Complex Flat Gable Gable/Hip Combo Gambrel Hip Mansard Monoslope Unknown Other	96.05%
AJ	36	roof_slope	Roof Slope	Integer	*Surveyor-supplied roof slope*	74.23%
AK	37	front_elevation_orientation	Front Elevation Orientation	Integer	*Surveyor-supplied front elevation orientation*	87.63%
AL	38	structural_notes	Structural Notes	Text	*Structural notes from surveyor*	8.42%
AM	39	mwfrs	Main Wind Force Resisting System	Multiple Choice (Comma separated text)	Roof Diaphragm, wood Roof Diaphragm, steel Roof Diaphragm, concrete Roof Diaphragm, composite Wall Diaphragm, wood Wall Diaphragm, steel Wall Diaphragm, concrete Wall Diaphragm, masonry	74.87%

Column		Column Header	Field	Format	Response Choices / *Description*	Percentage with Values (Excluding Unknowns)
					Wall, X-bracing Moment Frame Unknown Other	
AN	40	foundation_type	Foundation Type	Multiple Choice (Comma separated text)	Slab-on-grade Cast-in-place concrete piers Ground anchors and strapping Crawlspace Reinforced masonry piers Reinforced masonry stem wall Unreinforced masonry piers Unreinforced masonry stem wall Wood Piers <= 8 ft Wood Piers > 8 ft Unknown Other	58.42%
AO	41	wall_anchorage_type	Wall Anchorage Type	Multiple Choice (Comma separated text)	Anchor bolts with nuts and washers Anchor bolts with missing nuts and washers Metal straps Concrete nails Unknown Other	3.32%
AP	42	wall_structure	Wall Structure	Multiple Choice (Comma separated text)	Wood frame Masonry (reinforced) Masonry (unreinforced) Masonry (unknown) Concrete, tilt-up Concrete, moment resisting frame Steel, moment resisting frame Steel, braced frame Steel, cold form Insulated concrete form (ICF) walls	81.76%

Column		Column Header	Field	Format	Response Choices / *Description*	Percentage with Values (Excluding Unknowns)
					Solid Brick Wythe Unknown Other	
AQ	43	wall_substrate	Wall Substrate	Multiple Choice (Comma separated text)	Wood, sheathing (continuous) Wood, sheathing (corners only) Wood,dimensional planks Insulated sheathing Insulated foam board Non-engineered wood panel Metal panels Not Applicable Unknown Other	61.48%
AR	44	wall_cladding	Wall Cladding	Multiple Choice (Comma separated text)	Aluminum siding Brick Curtain wall EIFS Fiber-Cement Board Corrugated steel panels Plywood Siding Stucco Vinyl Siding (standard) Vinyl Siding (high wind rated) Vinyl Siding (unknown) Wood Boards Wood Shake/Shingle Unknown Other	92.86%
AS	45	soffit_type	Soffit Type	Multiple Choice (Comma separated text)	None Vinyl Metal Wood Unknown Other	66.58%
AT	46	front_wall_fenestration_ratio	Front Wall Fenestration Ratio	Single Choice	0%-100%	50.13%

Column		Column Header	Field	Format	Response Choices / *Description*	Percentage with Values (Excluding Unknowns)
AU	47	front_wall_fenestration_protection	Front Wall Fenestration Protection	Multiple Choice (Comma separated text)	None Unknown Impact Resistant Plywood/OSB Panel Hurricane Shutter Other	35.97%
AV	48	left_wall_fenestration_ratio	Left Wall Fenestration Ratio	Single Choice	0%-100%	47.07%
AW	49	left_wall_fenestration_protection	Left Wall Fenestration Protection	Multiple Choice (Comma separated text)	None Unknown Impact Resistant Plywood/OSB Panel Hurricane Shutter Other	33.42%
AX	50	back_wall_fenestration_ratio	Back Wall Fenestration Ratio	Single Choice	0%-100%	42.98%
AY	51	back_wall_fenestration_protection	Back Wall Fenestration Protection	Multiple Choice (Comma separated text)	None Unknown Impact Resistant Plywood/OSB Panel Hurricane Shutter Othe	33.04%
AZ	52	right_wall_fenestration_ratio	Right Wall Fenestration Ratio	Single Choice	0%-100%	46.30%
BA	53	right_wall_fenestration_protection	Right Wall Fenestration Protection	Multiple Choice (Comma separated text)	None Unknown Impact Resistant Plywood/OSB Panel Hurricane Shutter Other	34.06%
BB	54	large_door_present	Large Door Present	Multiple Choice (Comma separated text)	Yes No N/A	76.91%
BC	55	large_door_opening_type_front	Large Door Opening Type Front	Multiple Choice (Comma separated text)	None Single garage door (standard) Double garage door (standard) Single garage door (wind-rated)	76.02%

Column		**Column Header**	**Field**	**Format**	**Response Choices / *Description***	**Percentage with Values (Excluding Unknowns)**
					Double garage door (wind-rated) Single garage door (unknown) Double garage door (unknown) Sectional door Roll-up door Other	
BD	56	large_door_opening_type_left	Large Door Opening Type Left	Multiple Choice (Comma separated text)	None Single garage door (standard) Double garage door (standard) Single garage door (wind-rated) Double garage door (wind-rated) Single garage door (unknown) Double garage door (unknown) Sectional door Roll-up door Other	73.60%
BE	57	large_door_opening_type_back	Large Door Opening Type Back	Multiple Choice (Comma separated text)	None Single garage door (standard) Double garage door (standard) Single garage door (wind-rated) Double garage door (wind-rated) Single garage door (unknown) Double garage door (unknown) Sectional door Roll-up door Other	73.34%
BF	58	large_door_opening_type_right	Large Door Opening Type Right	Multiple Choice (Comma	None Single garage door (standard)	73.21%

Column		Column Header	Field	Format	Response Choices / *Description*	Percentage with Values (Excluding Unknowns)
				separated text)	Double garage door (standard) Single garage door (wind-rated) Double garage door (wind-rated) Single garage door (unknown) Double garage door (unknown) Sectional door Roll-up door Other	
BG	59	roof_system	Roof System	Multiple Choice (Comma separated text)	Steel, cold formed Steel, hot rolled Steel, joists Concrete slab Wood, rafter Wood, trusses Wood, unknown Unknown Other	81.12%
BH	60	r2wall_attachment	Roof to Wall Attachment	Multiple Choice (Comma separated text)	Toe-nails Metal ties Metal straps Bolted connection Welded connection Unknown Other	1.15%
BI	61	r2w_attachment_type	Roof to Wall Attachment Type	Text	*Surveyor-supplied roof to wall attachment type*	0.38%
BJ	62	roof_substrate_type	Roof Substrate Type	Multiple Choice (Comma separated text)	Plywood/OSB Dimensional lumber Metal deck Concrete None Unknown Other	53.44%
BK	63	roof_cover	Roof Cover	Multiple Choice (Comma separated text)	Asphalt shingles (3-tab) Asphalt shingles (laminated) Built-up with Gravel	93.11%

Column		Column Header	Field	Format	Response Choices / *Description*	Percentage with Values (Excluding Unknowns)
					Built-up without Gravel Clay tiles Concrete tiles Metal shingles Metal, corrugated Metal, standing seam Roll roofing Single ply Wood shake Wood shingle Unknown Other	
BL	64	secondary_water_barrier	Secondary Water Barrier	Multiple Choice (Comma separated text)	None Closed-cell urethane foam adhesive Fully adhered membrane High performance underlayment Self-adhering membrane over joints Unknown Other	1.79%
BM	65	overhang_length	Overhang Length	Integer	*Surveyor-supplied overhang length*	72.83%
BN	66	parapet_height_inches	Parapet Height in inches	Integer	*Surveyor-supplied parapet height*	66.07%
BO	67	wind_damage_details	Wind Damage Details	Text	*Wind damage notes from surveyor*	22.58%
BP	68	roof_structure_damage_	Roof Structure Damage	Single Choice	0%-100%	95.54%
BQ	69	roof_substrate_damage	Roof Substrate Damage	Single Choice	0%-100%	93.24%
BR	70	roof_cover_damage_	Roof Cover Damage	Single Choice	0%-100%	95.41%
BS	71	wall_structure_damage_	Wall Structure Damage	Single Choice	0%-100%	95.28%

Column		Column Header	Field	Format	Response Choices / *Description*	Percentage with Values (Excluding Unknowns)
BT	72	wall_substrate_damage_	Wall Substrate Damage	Single Choice	0%-100%	92.35%
BU	73	building_envelope_damage_	Building Envelope Damage	Single Choice	0%-100%	95.03%
BV	74	front_wall_fenestration_damage	Front Wall Fenestration Damage	Single Choice	0%-100%	91.96%
BW	75	left_wall_fenestration_damage	Left Wall Fenestration Damage	Single Choice	0%-100%	89.16%
BX	76	back_wall_fenestration_damage	Back Wall Fenestration Damage	Single Choice	0%-100%	86.99%
BY	77	right_wall_fenestration_damage	Right Wall Fenestration Damage	Single Choice	0%-100%	89.41%
BZ	78	large_door_failure	Large Door Failure	Multiple Choice (Comma separated text)	None Front Left Back Right All other	70.03%
CA	79	soffit_damage	Soffit Damage	Single Choice	0%-100%	50.77%
CB	80	fascia_damage_	Fascia Damage	Single Choice	0%-100%	81.63%
CC	81	stories_with_damage	Stories with Damage	Integer	*Surveyor-supplied stories with damage*	80.74%
CD	82	water_induced_damage_notes	Water Induced Damage Notes	Text	*Water induced damage notes from surveyor*	9.31%
CE	83	percent_of_building_footprint_eroded	Percent of Building Footprint Eroded	Single Choice	0%-100%	29.85%
CF	84	__damage_to_understory	Damage to Understory	Single Choice	0%-100%	33.80%
CG	85	maximum_scour_depth_inches	Maximum Scour Depth in inches	Integer	*Surveyor-supplied maximum scour depth*	28.19%

Column		**Column Header**	**Field**	**Format**	**Response Choices / *Description***	**Percentage with Values (Excluding Unknowns)**
CH	86	__piles_missing_or_collapsed	Piles Missing or Collapsed	Single Choice	0%-100%	37.24%
CI	87	__piles_leaning_or_broken	Piles Leaning or Broken	Single Choice	0%-100%	36.61%
CJ	88	cause_of_foundation_damage	Cause of Foundation Damage	Multiple Choice (Comma separated text)	Erosion Wave Flood Floating Debris Velocity Scour None Unknown Other	24.62%
CK	89	reroof_year	Reroof Year	Integer	*Surveyor-supplied reroof year*	0.38%
CL	90	retrofit_type_1	Retrofit Type 1	Text	*Surveyor-supplied retrofit description*	0.89%
CM	91	retrofit_1_year	Retrofit 1 Year	Integer	*Surveyor-supplied retrofit year*	0.26%
CN	92	retrofit_type_2	Retrofit Type 2	Text	*Surveyor-supplied retrofit description*	0.13%
CO	93	retrofit_2_year	Retrofit 2 year	Integer	*Surveyor-supplied retrofit year*	0%
CP	94	data_librarians	Data Librarian	Text	*Data Librarian Name*	99.36%
CQ	95	qc_progress_code	QC Progress Code	Single Choice	1 2 2e 3 3e	100%
CR	96	qc_notes	QC Notes	Text	*Notes from Data Librarians regarding the DE/QC process*	14.16%

APPENDIX C: COMPLETE LIST OF RECOVERY ADVISORY 2 RECOMMENDATIONS

Recommendation Scope	Number		FEMA P-2077 Recommendations
Floodplain management/requirement training/regulation/provision	1	FL-1a	The Florida Division of Emergency Management (FDEM) should consider developing/modifying training on the flood provisions in the Florida Building Code (FBC) and local floodplain management ordinances.
	2	FL-1b	Building Officials Association of Florida (BOAF) and other stakeholders should consider developing additional training on roles and responsibilities for communities contracting building department services to a private company.
	3	FL-3a	FEMA should update FEMA P-758, Substantial Improvement/Substantial Damage Desk Reference (2010h), and concurrently update FEMA 213, Answers to Questions about Substantially Damaged Buildings (2018a), to be consistent with the updated FEMA P-758.
	4	FL-3b	FEMA should consider expanding/clarifying existing training materials related to Substantial Improvement / Substantial Damage.
	5	FL-4	Communities should outline clear and consistent responsibilities when contracting with private-sector providers to administer all or part of the community's responsibilities under the FBC.
	6	FL-5a	FEMA should provide guidance to state and local governments on seeking assistance related to building code and floodplain management ordinance administration and enforcement authorized under Section 1206 of the Disaster Recovery Reform Act of 2018.
	7	FL-5b	FDEM should continue to encourage pre-event evaluation of post-disaster needs and inform appropriate parties about assessing resources through Statewide Mutual Aid Agreement and Emergency Management Assistance Compact.
Building envelope inspection	8	FL-2a	Local jurisdictions should make building envelope inspections a priority.
	9	FL-2b	BOAF, Florida Home Builders Association, and other stakeholders should consider developing training and creating a culture of emphasis on building envelope systems.
Fenestration test standard	10	FL-6	FEMA should work with the American Architectural Manufacturers Association / Window and Door Manufacturers Association / Canadian Standards Association, Insurance Institute for Business & Home Safety, International Code Council (ICC), and other select industry partners to incorporate more comprehensive water intrusion testing requirements that improve overall performance into testing standards.
Design wind speed in hurricane region	11	FL-7	The wind research engineering community should perform a revised analysis of the ASCE 7 basic wind speed maps for the Florida Panhandle region to include data from Hurricane Michael.
	12	FL-8a	The FBC should treat all areas within 1 mile inland from the entire Florida coastline as a wind-borne debris region (WBDR).
	13	FL-8b	The ASCE 7 Wind Load Subcommittee should revise ASCE 7 to lower the basic wind speed trigger in ASCE 7 for requiring glazing to be protected on Risk Category IV buildings in the hurricane-prone region.
	14	FL-8c	Building owners outside the WBDR but within the hurricane-prone region should consider protecting the glazed openings on their buildings.

Recommendation Scope	Number		FEMA P-2077 Recommendations
	15	FL-8d	The International Building Code / International Residential Code / FBC should be updated where needed to ensure glazed window, skylight, door, and shutter assemblies have a permanent label that provides traceability to the manufacturer and product.
	16	FL-8e	The ASCE 7 Wind Load Subcommittee should consider developing commentary on vestibule wind loads.
Flood hazard zone	17	FL-9	Communities should consider more stringent building requirements for development or reconstruction in the unshaded Zone X (area of minimal flood hazard) and shaded Zone X (area of moderate flood hazard).
	18	FL-11a	FEMA and FDEM should consider submitting a code change proposal to the FBC, applying ASCE 24, Flood Resistant Design and Construction, Flood Design Class 4 requirements outside the Special Flood Hazard Area (SFHA) in moderate flood hazard areas (shaded Zone X) and to consider flood risk for minimal flood hazard areas (unshaded Zone X).
	19	FL-11b	FEMA should consider developing a change proposal for ASCE 24 requiring consideration of flood risk for essential facilities outside the SFHA in minimal flood hazard areas (unshaded Zone X) and requiring Flood Design Class 4 to apply in moderate flood zones outside of the SFHA.
	20	FL-12	Local floodplain administrators, design professionals, and building owners should incorporate more freeboard than the minimum required in ASCE 24 based on Flood Design Class whenever possible.
House erosion	21	FL-13a	FEMA should review and update its Event-Based Erosion methodology.
	22	FL-13b	For parcels that are seaward of Florida's Coastal Construction Control Line, communities should require—and key stakeholders should encourage—the placement of houses with the maximum distance from the flood source possible within each parcel.
	23	FL-13c	The Florida Department of Environmental Protection should implement current best practices and consider revising its requirements for erosion vulnerability assessments for new construction in erosion control areas.
	24	FL-13d	Permitting agencies should evaluate permitting criteria and performance requirements for new or replacement bulkheads with respect to design conditions, including the effects of saturated backfill, wave forces, overtopping, and erosion on both the water and land sides.
	25	FL-13e	Communities and building owners should consider acquisition or relocation projects for existing buildings in areas highly vulnerable to erosion.
Concrete pile	26	FL-10a	Industry groups, interested stakeholders, and/or academia should further evaluate the performance of the concrete pile foundations that failed during Hurricane Michael to determine why they failed.
	27	FL-10b	FEMA and FDEM should consider providing a code change proposal to the International Codes requiring contractors and/or manufacturers to add length labels or incremental depth markers on vertical piles.
Roof Coverings	28	FL-14a	Code enforcement authorities having jurisdiction across Florida should make roof covering and underlayment inspections a priority.

Recommendation Scope	Number		FEMA P-2077 Recommendations
	29	FL-14b	Industry groups should assess the causes for the widespread asphalt shingle roof covering loss that was observed by the MAT
	30	FL-14c	Contractors and inspectors must ensure roof covering repairs and replacements conform with the FBC as required.
	31	FL-14d	On buildings built prior to the FBC, before installing a new roof covering, contractors should remove the existing roof covering to evaluate the roof sheathing attachment, and add supplemental fasteners in accordance with the wind mitigation provisions of FBC if the sheathing attachment is found to be deficient.
	32	FL-14e	FEMA and FDEM should consider supporting current code change proposals to the 7th Edition FBC that provide for improved underlayment systems.
	33	FL-14f	The Asphalt Roofing Manufacturers Association and National Roofing Contractors Association should consider updating their guidance materials based on observations from the 2017 and 2018 hurricanes.
Soffits	34	FL-15a	Designers, contractors, and inspectors should place more emphasis on proper soffit installation to limit wind-driven rain.
	35	FL-15b	FEMA and FDEM should consider submitting a code change proposal to the FBC requiring soffit inspections, and jurisdictions should prioritize performing soffit inspections.
	36	FL-15c	The Florida Building Code (FBCR), Residential should be revised to require soffit panels to be labeled to provide traceability to the manufacturer and product.
	37	FL-15d	Owners should determine whether the soffits attached to their house are “floated,” and, if so, take appropriate mitigating actions.
Rigid vent	38	FL-16	Industry groups and academia should perform research on commonly used ridge vent products to better determine the causes of ridge vent failure and develop solutions.
Wall coverings	39	FL-17a	FEMA and FDEM should consider submitting a code change proposal to the FBC requiring exterior wall covering inspections.
	40	FL-17b	Vinyl siding manufacturers, insurance organizations, and other stakeholders should continue research and investigations of the appropriate pressure equalization factor for vinyl siding.
	41	FL-17c	The FBC and FBCR should be revised to require vinyl siding be labeled to provide traceability to the manufacturer and product.
Vulnerabilities assessment	42	FL-18a	Designers and building owners should conduct a comprehensive vulnerability assessment as described in Hurricane Michael in Florida Recovery Advisory 1, Successfully Retrofitting Buildings for Wind Resistance (in FEMA P-2077, 2019d) before beginning a wind retrofit project.
	43	FL-18b	As appropriate, designers and building owners should consider damage to other buildings from high-wind events as vulnerabilities that should be addressed in their similar undamaged buildings.
	44	FL-18c	Designers, building owners, and operators of critical facilities should refer to FEMA 543, Design Guide for Improving Critical Facility Safety from Flooding and High Winds (2007a); FEMA 577, Design Guide for Improving Hospital Safety in Earthquakes, Floods, and High Winds (2007b); and FEMA P-424, Design Guide for Improving School Safety in Earthquakes, Floods, and High Winds (2010c) for additional guidance and

Recommendation Scope	Number		FEMA P-2077 Recommendations
			best practices for protecting critical facilities from flooding and high winds.
	45	FL-19a	Critical facilities that do not meet the FBC requirements for a Risk Category IV building should not be designated as essential facilities to support continuity of operations nor be occupied during a hurricane.
	46	FL-19b	Owners and authorities having jurisdiction with facilities that present a life-safety threat to occupants during a high-wind event or that need “near absolute protection” or life safety protection should consider designing and constructing a FEMA P-361–compliant safe room or ICC 500–compliant storm shelter for people to take shelter in during a storm.
	47	FL-19c	FDEM should consider delivering training on FEMA P-361, Safe Rooms for Tornadoes and Hurricanes: Guidance for Community and Residential Safe Rooms (2015c), safe room design, construction, and operations and maintenance.
	48	FL-20	The State of Florida should re-evaluate planning factors and considerations used to estimate hurricane evacuation shelter (HES) “demand in people,” so counties have adequate and more appropriate HES capacity during future hurricanes.
	49	FL-21a	The State of Florida and FDEM should consider re-evaluating their policies, procedures, and requirements for assessments of existing spaces for use as HES.
	50	FL-21b	The State of Florida and FDEM should consider re-evaluating EHPA criteria and re-assess safety of existing EHPAs, particularly those designed prior to the 6th Edition FBC (2017).
	51	FL-22	Critical facility owners and operators should perform a vulnerability assessment of their structures in comparison to the FBC Risk Category IV threshold to determine their risks and vulnerabilities, and a best path forward for mitigating them.
Wind driven rain	52	FL-23a	Designers should properly design rooftop equipment anchorage per the recommendations in Hurricanes Irma and Maria in the U.S. Virgin Islands Recovery Advisory 2, Attachment of Rooftop Equipment in High-Wind Regions (in FEMA P-2021, 2018c), and contractors should properly implement the anchorage design to prevent blow-off.
	53	FL-23b	Copings and edge flashings should comply with ANSI/SPRI/FM 4435/ES-1, Test Standard for Edge Systems Used with Low Slope Roofing Systems, to prevent blow-off.
	54	FL-23c	In high-wind regions, designers should provide an enhanced closure detail for hip and ridge closures on metal panel roofs, and contractors should take special care in properly installing them.
	55	FL-23d	Designers, contractors, and inspectors should place more emphasis on proper soffit installation to limit wind-driven rain.
	56	FL-23e	To help prevent entry of wind-driven rain into the building, designers should specify weather-stripping for, as well as consider designing vestibules at, exterior doors.
	57	FL-23f	FEMA Building Science should incorporate best practices for minimizing water infiltration into buildings from wind-driven rain into its relevant publications.
Screen Shutter	58	FL-24a	The task committee for ASTM E1886, Standard Test Method for Performance of Exterior Windows, Curtain Walls, Doors, and Impact Protective Systems Impacted by Missile(s) and Exposed to Cyclic Pressure Differentials, should consider revising the

Recommendation Scope	Number		FEMA P-2077 Recommendations
			standard to include the evaluation of the potential for the shutter assembly to unlatch during a storm.
	59	FL-24b	Existing glazing assemblies that have inadequate wind pressure or wind-driven rain resistance should be replaced with new assemblies rather than being retrofitted with shutters.
	60	FL-24c	The task committee for ASTM E1886 should add corrosion criteria to the standard to help enable shutters to perform as intended over their useful life.
	61	FL-24d	The task committee for ASTM E1886 should evaluate the current perpendicular angle specifications for impacting a shutter during testing for its adequacy.
Standing seam metal roof panel	62	FL-25a	Designers should specify, and contractors should properly install, standing seam metal panel systems that have been tested in accordance with ASTM E1592, Standard Test Method for Structural Performance of Sheet Metal Roof and Siding Systems by Uniform Static Air Pressure Difference.
	63	FL-25b	Designers should specify, and contractors should install, a roof deck with a secondary roof membrane for critical facilities designed with structural standing seam metal roof panels.
Membrane roof	64	FL-26	Designers should adequately design, and contractors should properly install, roof systems.
URM walls	65	FL-27	Owners and operators of buildings with unreinforced masonry walls should include the toppling risk of these walls during high-wind events in vulnerability assessments and should mitigate the risk.
Brick veneer	66	FL-28a	Building owners should have a vulnerability assessment performed for their existing building to ensure brick veneer is properly attached.
	67	FL-28b	Design professionals and contractors should improve installation of brick veneer in high-wind regions for new construction by ensuring it is properly attached.
Exterior Insulation and Finish System	68	FL-29	Designers should consider specifying a more robust wall assembly than Exterior Insulation and Finish System for new critical facilities.
Roof aggregate	69	FL-30	The FBC should provide more specific criteria with restrictions on how, when, and where roof aggregate can be used.

APPENDIX D: HURRICANE MICHAEL IN THE AREA OF MEXICO BEACH, FL (KENNEDY ET AL. 2020)

Hurricane Michael (2018) in the Area of Mexico Beach, Florida

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Abstract

Category 5 Hurricane Michael made landfall near Mexico Beach, Florida on October 9, 2018 with measured high water marks reaching 7.2m NAVD88. The town itself received great damage, with many areas destroyed down to foundations. Here, we document the storm and its effects on the greater Mexico Beach area: hazard, structural damage, and their relationships. Wave and surge damage was near-total for low-lying properties, but damage decreased greatly with increasing elevation. Major wave and surge damage was noted in FEMA X-Zones, which are out of the 100 year floodplain, and it is suggested that the 100 year storm is a deficient measure for categorizing flood risk.

Introduction

Hurricane Michael made landfall 13km (7 nautical miles, nm) west of Mexico Beach, Florida, USA at 18:00 UTC (13:00 local) on October 9, 2018 as a Category 5 storm with maximum one minute sustained winds of 140 knots (72m/s), and a minimum central pressure of 91.9 kPa (Beven II et al., 2019). Figure 1-a shows Michael's track and strength as it underwent rapid intensification before landfall, strengthening from Category 2 to 4 on the Saffir-Simpson scale within one six-hour period. Further intensification to Category 5 at landfall made Hurricane Michael the strongest storm ever recorded in the Florida Panhandle region. Prior to Michael, the strongest storm in the NOAA HURDAT2 database that made landfall within 65 nautical miles (nm) of Mexico Beach was Category 3 Hurricane Eloise (1975), which made landfall with 110 knot winds (57m/s) 51nm (93km) west of Mexico Beach near Miramar Beach, while unnamed 1851, 1877, and 1894 storms made landfall in the region with 100 knot, 100 knot, and 105 knot intensities respectively (51, 51, 54m/s). Most recently, Hurricane Kate (1985) was an 85 knot Category 2 (44m/s) storm that made landfall almost directly over Mexico Beach (Landsea and Franklin, 2013). Thus, Michael was stronger by far than any that local residents had experienced in their lifetimes, and was one of the strongest hurricanes by central pressure to make landfall in the continental United States (Beven II et al., 2019).

Michael generated catastrophic damage, with strong winds across the entire region and high storm surge and waves over the smaller area centered on Mexico Beach. Post-storm, a team of researchers travelled to the area to record perishable records of the waves, surge and damage from October 13-15, and November 1-8, 2018. This paper is a partial record of observations, interpretations, conclusions, and recommendations made by the team. For the purposes of this paper, we define the “Area of Mexico Beach” to include all coastline from 85.434°W to 85.356°W (Figure 1-b). This includes not only the town of Mexico Beach proper in Bay County, FL, but also contiguous areas in Gulf County as development is essentially continuous over the region.

Wind, Waves, Surge, and Runup

The only in situ instrument measurement of Michael’s waves and surge came from the United States Geological Survey (USGS) rapid gauge FLBAY03283, which was mounted to one of the pilings on the Mexico Beach Pier (Byrne Sr., 2019). The deck and almost all of the pilings seaward of the gauge were destroyed, but the gauge itself survived and provided good measurements. Figure 2 shows a time series of the instantaneous water levels (computed using the hydrostatic assumption, and with atmospheric pressure corrections using a nearby noninundated pressure gauge) measured every 30s on Oct 10, and a 15 minute average of these water levels which will be taken as the surge elevation. Figure 3 shows the overall gauge location in Mexico Beach, while Figure 4a shows a photograph of the gauge location post-storm.

Waves and surge began to rise consistently above the gauge elevation of 2.12m NAVD88 (North American Vertical Datum of 1988, which is within 2cm of the mean tide level in this area) just before 17:00 UTC (12:00 local), reaching a surge peak of 5.16m NAVD88, and a maximum instantaneous wave crest elevation of 6.28m (using the hydrostatic assumption) just before 17:30. These peaks were very short-lived, and by 19:00 only a few small wave crests were high enough to even reach the gauge. Realistically, most wave and surge damage likely occurred in the 1.5 hour period between 17:00 and 18:30 UTC (12:00-13:30 local). This maximum wave crest of 6.28m (20.6ft) NAVD88 occurred in a National Flood Insurance Program (NFIP) 4.27m (14ft) VE-Zone (highest risk in 100 year floodplain); no location in Mexico Beach (other than the pier in the ocean) had higher design elevations than this, while many inundated areas had much lower design elevations, and/or were in the lower risk AE zones (moderate wave action in 100 year floodplain) or in Zone X (500 year floodplain) as seen in Figure 3. Thus, the conditions during Michael at Mexico Beach greatly exceeded design conditions for the 100 year flood plain.

Because water levels were only measured at 30s intervals, no frequency information can be obtained about wave properties, but it is still possible to use the hydrostatic assumption to estimate time series of wave height at the pier. This is shown in Figure 2b, and was computed using $H_s = 4\sigma_W$ (Dean and Dalrymple, 1991; Kennedy et al, 2011) where σ_W is the standard deviation of water surface elevation over a 15 minute period, after subtracting the filtered surge time series. Heights reached a maximum of just over $H_s \approx 2$ m very near to the time of peak surge when mean water depths were likely greater than 3m above ground elevation (we do not know the ground elevation during the storm so it is not possible to say with certainty), so these were highly nonlinear waves capable of causing great damage to structures and infrastructure. At times when the wave troughs could be lower than the gauge elevation, wave height values are lower bounds, and Figure 2b demarcates these approximate times.

Although no other instrument records exist in the Mexico Beach area, both the present team and separately the United States Geological Survey took numerous high water marks (HWM). Table 1 lists present data, while Open-file Report 2019-1059 references the USGS data as a freely-available download (Byrne Sr., 2019); both show a picture generally consistent with the water level gauge. Figure 3 shows measured water levels from high water marks, and the location of the USGS water level gauge. Wave runup elevations were taken near the tops of the main runup debris piles, and not the height of scattered debris which might have slightly higher elevations. Similarly, interior water marks were taken at the highest clear indication, and ambiguous waterlines were ignored. The water levels shown here are fairly conservative, and therefore it remains quite possible that surge and/or runup exceeded the values presented in Table 1. Figure 4 shows examples of wave runup and high water marks, as well as the location of the USGS gauge at the Mexico Beach Pier.

High water mark elevations given in Figure 3 demonstrate both their changes in space, and overall consistency. In the northwestern area of Mexico Beach, flow depths were large from the beach to US98, with many measurements of 5-6m NAVD88. All of these high water marks were identified on surviving structures; no high water marks were found anywhere near the original shoreline, where waves were almost certainly larger. Moving southeast along the coastline, high water marks become significantly lower at around 85.4°W, at around 4-5m NAVD88. This is likely because measurements here were quite far inland. However, high water mark elevations increase strongly at around 85.393°W, where the beach is very narrow, and there are high ground elevations just across US 98. Runup here exceeded 7m in several locations as evidenced by undisturbed runup debris, with a maximum measured elevation of 7.2m NAVD88 (Figure 3b)). Moving farther southeast along the coast, HWM elevations decreased almost monotonically, with all HWM east of 85.36°W having elevations under 4m NAVD88. This is both farther from the storm center and the beginning of the area where sheltering from the St. Joseph Peninsula is important, so the decrease is not unexpected. Still, these maximum elevations of 4-7m NAVD88 in the vicinity of Mexico Beach remain extreme, and sufficient to deeply inundate much of the area.

Nearshore Erosion

Figure 5 shows a small but typical section of beach, and the erosion that occurred during Michael. Post-storm (October-November, 2018, US Army Corps of Engineers) and pre-storm lidar (April-May 2017, Northwest Florida Water Management District) are used to create a difference map, with positive numbers showing locations of erosion. Both datasets have standard errors listed as 10cm, which are much lower than the differences seen pre-to post storm. Aside from Michael, there were no major storms in the region in between survey periods.

The major difference in pre-storm and post-storm onshore data arises from the complete erosion of the coastal dune system, with up to several meters of elevation loss. Areas of deposition are seen landward in some locations, and represent debris piles generated from more seaward houses and other moveable objects. Figure 6 shows the two transects identified in Figure 5 before and after the storm, which clearly demonstrate the dune erosion. The dune crest elevations of around 4m in Transect 1 may also be compared to the peak surge value of 5.16m NAVD88 and peak wave crest of 6.28m NAVD88 measured at the nearby pier. These measured water levels greatly exceed the dune crest elevations, placing the system well into the inundation regime (Sallenger, 2000) where sediment transport increases greatly and heavy dune erosion is expected. Once dune erosion was complete, large waves would have been able to penetrate inland with relatively little to impede them before encountering the many structures located close to the shoreline. Transect 2 provides a second example with no large fronting dune, showing little overall erosion or accretion in the immediate beachfront area. However, both transects were chosen to intersect large debris piles, which were found in many inundated locations and will be assessed in more detail in a following section. These debris piles showed large increases in elevation to the tops of debris; however, actual ‘ground’ elevations underneath the debris had little to no erosion or accretion.

Infrastructure Damage

Infrastructure damage in the Mexico Beach region was severe and occurred from both wind and waves/surge. Critical facilities such as the Mexico Beach police and fire station were located well inland of US98 and did not experience significant damage from storm surge, but wind damage was observed. Fortunately, no hospitals or urgent care facilities were located in Mexico Beach, but the nearby larger regional center of Panama City contains many such facilities. Other critical infrastructure in Mexico Beach such as roads, telecommunication and power infrastructure experienced various levels of impacts from both surge and wind, and there was no power, water, gas, or sewage available during the team’s visits. Cellular service was restored rather quickly and was available throughout the town during reconnaissance.

Researchers noted partial washout of approximately 600 m of US98 in various locations between the western edge of Mexico Beach and HWY386 (a distance of approximately 5 km). A small vehicular bridge (span of ~15 m) across an inlet between 8th and 9th Streets collapsed, but a temporary bridge had already been installed by the time the damage assessments were conducted. Roueche et al (2018) provide additional information on infrastructure impacted by Hurricane Michael.

Structural Damage

With very few exceptions, damage from Hurricane Michael's wind, waves, and surge ranged from severe to catastrophic in the area of Mexico Beach. Many ground elevations near the shoreline, particularly in the western section of the study region, were 2.5-3m NAVD88, meaning that inundation depths were great enough that large damaging waves could reach structures once dunes had eroded. This resulted in areas where entire blocks of buildings were destroyed down to their foundation slabs. More inland areas with smaller waves were not damaged as completely, but still suffered significant inundation to walls, floors, and contents.

On the other hand, newer residential structures built according to the latest building code, and far enough inland or at high enough elevation to escape waves and surge, generally performed relatively well in spite of the extreme winds. Some newer and well-elevated neighborhoods suffered by-and-large little more than modest fenestration and roof cover damage. However, older structures were much more prone to severe wind damage, including significant roof cover and roof decking loss, which cascades into extreme water ingress and interior damage.

Near to the shoreline, the only structures that did not experience major damage were well-built elevated structures, and even these generally lost utility connections and often staircases (e.g Figure 8c), and were prone to interior water damage from loss of soffits and damaged fenestration. Figures 7-8 show examples of damage observed in the Mexico Beach area. Failure modes included destruction of the entire structural frame (7a), structures detaching from foundations either at grade (7b), or on top of piles (8a), loss of roof cover (7c), piled foundation loss of capacity or breakage (7d, 8a), wave damage to exposed structural components (8b), and erosional failures of foundations and associated components (8d). Observed structural failures are typical of large wave and surge events (Robertson et al., 2007; Tajima et al., 2014; Tomiczek et al., 2014; Hatzikyriakou et al., 2016) where inundation depths are large and waves can generate destructive loading on exposed structures.

To evaluate surge and wave induced damage patterns, it is helpful to examine aggregate damage results over the Mexico Beach area. Many different researchers in the field gave preliminary structural assessments. These included photographs, elevations, descriptions, and damage ratings by component and overall. Separate post-reconnaissance researchers used the field photographs to reassess the assessments for consistency, and to translate damage ratings to those of Tomiczek et al. (2017). For a given property, the individual performance of various structural components was evaluated to produce an overall rating between DS0 (no observed damage) and DS6 (structure removed from foundation) using the rubric in Table 2. Roof damage was neglected in this scheme, as roof damage to standing structures was almost certainly caused by extreme wind.

Elevations of lowest horizontal structural members (LHMs) in relation to wave crest elevations are extremely important to structural survival. These elevations were obtained using lidar-based bare earth DEMs taken post-Michael to give ground elevations in NAVD88 datum, which were added to LHM heights above grade, either measured in situ with rods or more approximately using Google Street View-based LHM height estimates (e.g. Tomiczek et al., 2017). Final LHMs reported here are in NAVD88 datum. Year of construction was taken from online county resources and offline property databases. Because the region had significant changes in inundation moving NW-SE, the overall coastline was divided into subareas as shown in Figure 9: either four (a-d) or two (N-S) depending on the properties considered.

Seaward of US98, there were four major types of construction: (a) Older single family, at-grade homes made of concrete masonry units (CMUs) or brick; (b) Connected townhouse-type structures, typically timber frame; (c) Pile-elevated wood-framed single family homes and small businesses; (d) Pile-elevated multifamily residential or commercial construction. As might be expected, at-grade construction performed very poorly near the shore, with frequency of survival increasing with increasing distance inland. A post-storm assessment was made for all structures and remains of structures that could be identified south of US98 between the western edge of Mexico Beach and the small bridge just west of 8th street (85.4028°W), and a less-complete assessment farther east to around 85.35°W. In many cases, multifamily units were treated as one structure when performance was similar, but individual units were also separated out when differences were noted.

Figure 10 shows overall surge and wave induced damage ratings for all structures surveyed by the team in the Mexico Beach area, divided into the four subregions in Figure 9. It is clear that in area (a) (farthest NW), large areas near the shoreline suffered complete damage, while the farthest SE section (d) showed areas near the shoreline with damage, but not anywhere near the extent of (a), with (b-c) demonstrating intermediate levels of damage.

Damage state was found to be a strong function of structural elevation as shown in Figure 11, particularly close to the shoreline. This is not at all surprising, as structures at higher elevations may encounter waves and surge for a shorter length of time, or not at all if they are sufficiently elevated. Structures built at grade were almost universally destroyed in the most severe conditions near the shoreline (DS 6), and were largely older single family houses. Structures at higher elevations demonstrated much higher survivability, although many of them still sustained significant damage. Farther inland, structures experienced an increased chance of survival both from the higher ground elevations and the dissipating wave heights, but damage still tended to be severe: very few structures surveyed had damage states less than DS2. Subregions c-d (SE Mexico Beach) showed lower damage states inland of US98, which will be explored in more detail later.

There were examples of good design and practice: the most impressive structural survival was the famous “Sand Palace” house built in 2018 and shown in Figure 8(c). Although it is in the first row of houses near the region of worst surge and damage, the Sand Palace only had damage to: (i) Utilities and local HVAC destroyed; (ii) Exterior staircase and lower storey breakaway walls and interior destroyed; (iii) A cracked window on the top floor; (iv) One electrical outlet on the top floor ceiling popped out of its socket due to the pressure difference between the house interior and attic; (v) Damage to parking slab and pavers; (vi) Minor water intrusion; (vii) One porch ceiling damaged. No roof damage was recorded. By the time of the team’s visit, the owners had installed solar panels and batteries to provide electricity and with the exception of town utilities were fully functional. The Sand Palace was in DFIRM Zone AE, elevation 12ft (3.66m) NAVD88, while the measured elevation of the lowest horizontal structural member (LHM) was 6.3m (20.7ft) NAVD88. This elevation almost exactly matched the largest measured wave elevation of 6.28m NAVD88 measured at the nearby pier. Because the pier was slightly seaward of the Sand Palace, wave crest elevations at the house would likely have been slightly lower. Thus, largest wave crests during the storm came close to, or barely touched, the LHM, and wave loads were certainly much lower than those experienced by houses at lower elevation. As reported, the Sand Palace cost approximately 15-20% additional per square foot when compared to standard construction practices (Dal Pino, 2019). After Michael, and compared to its neighbors, this additional cost seems very well spent. This case study also demonstrates that community resilience to natural hazards is only effective when the plurality of infrastructure are similarly mitigated. That is, the Sand Castle is a win for the owners, but the community they return to requires long term recovery efforts.

Damage by FEMA DFIRM Zone

Consideration of damage state compared to the structural elevation shows interesting patterns. General risk categories may be given by the Federal Emergency Management Agency (FEMA) definitions for their Digital Flood Insurance Rate Maps (DFIRMS). Zones VE and AE are designated Special Flood Hazard areas, and flood insurance is "mandatory with mortgages from federally regulated or insured lenders". VE Zones are areas "defined by the 1% annual chance (base) flood limits (also known as the 100-year flood) and wave effects 3 feet or greater". (https://www.fema.gov/media-library-data/20130726-1541-20490-5411/frm_p1zones.pdf). These areas have the greatest risk from 1 in 100 year surge and waves. One step down from this is the AE Zone. These are defined with Base Flood Elevations (BFEs) "that reflect the combined influence of [100 year] stillwater flood elevations and wave effects less than 3 feet". During Michael, it is clear that surge and waves greatly exceeded the 100 year inundation, and for this reason we will combine VE and AE zones since both almost certainly experienced large destructive waves.

The X-zone in the Mexico Beach area is, for the purposes of this paper, the region not in the 100 year flood plain. In practice, many homeowners take the X-zone as a region with no real hazard, and do not obtain flood insurance. During Michael, the hazard was severe, and Figure 10 shows that very many structures in the X zone were destroyed. Most of these structures were quite old and at low elevations, particularly in NW Mexico Beach. Here, as seen in Figure 10, entire sections of X zones were wiped clean to their foundations. Farther south in subareas c and d, there was much greater frequency of survival and lower damage in X zones.

The immediate survival or destruction of a structure is an important safety consideration. Here, destruction is defined by damage category DS6, where the structure is "slabbed"; that is to say it is completely removed from its foundations. Figure 12 shows the probability of slabbing during Michael for aggregated VE-AE zones, and for X Zones. Unsurprisingly, the probability of survival increases strongly with increasing building elevation. Somewhat surprisingly, the probabilities for VE-AE and X zones are almost identical, indicating that structural elevation was the overwhelming factor for survival. Because there was a range of inundation over the Mexico Beach region, this is reflected in the slabbing probabilities. Because Michael so greatly exceeded the 100 year event, the near-coast DFIRM zones behaved as one. We do note that our study looks almost exclusively at structures in the first few hundred meters from shore, and slabbing behavior would certainly be different farther inland.

Although all DFIRM zones showed similar slabbing probabilities when aggregated over the entire dataset, there were noticeable North-South differences. As seen in Figure 3, inundation decreased notably at the far southeastern end of the Mexico Beach. There was a corresponding decrease in the frequency of slabbing, as shown in Figure 13. Structures in the southern area had a survival probability roughly equivalent to a 1-2m higher structure in the northern portion of Mexico Beach. Once again, elevation relative to inundation appears to be the defining factor. The one exception is for elevations of 2-3m in South Mexico Beach, with only 1 structure measured in this bin and correspondingly low confidence in the 0 probability of slabbing. This structure was landward of US98 and suffered major damage but remained standing.

Debris Generation and Transport

The destruction of structures and infrastructure generated large amounts of debris, much of which was transported inland: Figure 14 shows typical examples of debris and debris piles. These could be quite large at times for both plan area and height above ground, as also seen in transects of Figure 6. At the large scale, this debris comprised entire structures detached from their foundations, cars, boats and other transportable large objects. Debris at the smaller scales included household goods and fractured components of structures and infrastructure. The sheer quantity of debris remaining within the town was large both because of the great destructive scale of the storm, and the rising elevations and intact structures inland which prevented the debris from being washed through as on an inundated barrier island.

Many debris piles or clusters were large enough to be clearly visible on aerial or satellite imagery. For the purposes of this paper, clusters are defined as a contiguous grouping of debris with characteristic length scale of at least 5m, and distinguishable on satellite images. Polygons enclosing clusters were generated manually using judgement, and are shown in Figure 15. In total, 1037 debris clusters were identified, with total plan areas of 28.0ha (69.3 acres). Large clusters were often seen to be bounded on the landward side by either topographic high elevations (particularly for runup), intact vegetation (trees and bushes), and structures blocking further transport. These clusters tended to be composed of floating debris, while heavier masonry and concrete tended to stay near to their original locations.

In some cases, such as in Figures 6(a) and 14(a) which show elevations and imagery from the same region, debris clusters had very high heights above ground, and may have been grounded during the storm: i.e., the cluster was higher than water levels and reached the ground, acting as a dam, collecting additional debris, and preventing further transport. Although no systematic study has yet been made, very large clusters not backed by a surviving structure often had large debris objects such as transported houses, roofs, or other large objects as nuclei. Figure 16 shows identified Large Debris Objects (LDOs), defined here as transported intact or semi-intact structural assemblies or whole structures, travel trailers, and recreational vehicles (RVs). Although structures are clear when out of place, trailers and RVs are fundamentally mobile and could have been brought in post-storm but prior to the satellite photograph. These were only counted when tipped over, part of a larger debris cluster, tight against another structure, or in a strange position.

All LDOs originated somewhere and in many cases, it was possible to conclusively determine pre-storm locations, particularly for structures and structural assemblies. Figure 17 shows distances moved by LDOs in the 301 cases where original locations could be identified. The large majority of LDOs moved relatively short distances, with 72% traveling less than 25m, 85% less than 50m, and 94% less than 100m. The longest identified distance travelled by a LDO was 325m for the roof of a house near the beach that was transported into an inland pine forest. Other studies have found that floating objects can travel large distances if unimpeded, with a largely intact house found to have floated 0.9km from its piled foundations during Hurricane Ike (Kennedy et al., 2011). Longer distances are very possible, but with increasing distance of travel also comes increased difficulty of identification. In the present case, pine forests were inland from almost all development, limiting the potential distance of LDO travel.

Discussion and Conclusions

Mexico Beach was an unfortunate testbed for the effects of waves and surge on a variety of construction types. Maximum water levels exceeded BFEs by several meters, and deep inundation was recorded well past the 100 year floodplain. Inundation elevations from wave runup were greatest on the side of a small hill by the beach, while surge inundation appeared to be largest in the northwestern Mexico Beach. Inundation decreased significantly in southeastern Mexico Beach, as this was both farther from the storm landfall and showed the beginnings of sheltering by the St. Joseph Peninsula. Inundation levels were much higher than dune crests, and no dunes survived the storm in the Mexico Beach area. However, severe inundation was local to Mexico Beach, and larger nearby cities like Panama City and Panama City Beach had much lower water levels and correspondingly lower coastal damage.

Damage for low-lying properties near the Mexico Beach coast was near-total, irrespective of construction type or age. Even in the X Zones that are out of the 100 year floodplain, inundation damage was severe, with entire blocks of houses destroyed to their foundations. Many structures in this region were old and at low elevation; many owners did not have flood insurance. Damage decreased greatly with increasing structural elevation, as was expected, and with increasing distance inland. Structures that were not completely destroyed by waves and surge generally had significant wind damage, with severe roof damage typical for older structures not built according to the most recent building code. Interior damage for flooded structures was significant. All utilities were lost during the storm and were slow to recover, with the notable exception of cellular service. The storm generated large amounts of debris transported by waves and surge, and created very large debris piles that generally accumulated against the side of a building, against vegetation, or on a hill slope. This was close to a worst-case scenario for the Mexico Beach area. However, good design and construction was rewarded. By far the most obvious example was the famous "Sand Palace", which survived Michael with relatively minor damage.

Some aspects of design and planning deserve more attention. Chief among them is the use of the 100 year floodplain to define areas of high risk and low risk. In wind engineering, Category II buildings (the most common type) use a 700 year return period for structural design (McAllister et al., 2018), which is much more severe. Earthquake design return periods for collapse vary depending on what is considered, but may specify a 2,475 year return period or the more severe 1% chance or less of collapse in 50 years, equating to a 5000 year collapse event (National Institute of Building Sciences, 2017). Tsunami standards in ASCE7-16 specify a 2% probability of being exceeded in 50 years, or a 2,475 year event (American Society of Civil Engineers, 2016). Thus, if a structure is to last 50 years, it has a 40% chance of experiencing at least one design flood event while only a 7% chance of the design wind event, a 2% probability of the design tsunami event, and the same probability or lower of a design earthquake event. For older construction not meeting the 100 year standard, as was found in much of Mexico Beach, the probabilities of failure are much greater. These are extremely bad odds for flood design, and are at the heart of why there is so much repeated damage and losses during storm surge and wave events. Design past the 100 year standard, or even recognition that areas past the 100 year flood plain have a real and non-negligible chance of inundation, damage, and collapse, would represent a fundamental change in outlook for coastal structure design, and one that is sorely needed.

Aspects that increased survival and reduced damage probabilities from waves and surge were:

1. Structural elevation above the highest observed high water marks, and much above the 100 year base flood elevation (BFE),

2. Distance inland far enough that wave heights decrease to less damaging levels,

3. Attention to details of construction and higher quality building components, including foundations, and building connections. Wind damage was also greatly decreased by high quality roof, window, and framing details, and by adherence to the newest Florida Building Codes.

To decrease the chance for a repeat of this scenario, standards far beyond the 100 year flood are necessary. Draft revisions for FEMA Digital Flood Elevation Rate Maps in Bay County, FL (http://portal.nwfwmdfloodmaps.com/esri-viewer/map.aspx?cty=MexicoBeach), show large areas levelled by Michael still remaining in the X-zone (no requirement for flood insurance and stated 0.2% annual chance of flood hazard), with many others in the 9-ft or 10-ft (2.7-3.0m) AE zone. The highest VE-zone elevation in developed areas is 14ft (4.3m), with 12ft (3.7m) VE-zones much more common. No buildings built to minimum required standards in these zones have a realistic probability of surviving Michael’s successor.

Data Availability Statement

Damage data that support the findings of this study may be available from the corresponding author upon reasonable request.

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Figure Captions

Figure 1. (a) Hurricane Michael's track before and after landfall. Symbol colors denote Saffir-Simpson storm category, and the 25m and 100m depth contours are as indicated. The small magenta inset immediately southwest of the "Mexico Beach" text indicates the study region. (b) The spatial extent of the study location outlined in red, with NOAA post-storm airborne imagery overlying a satellite-based background.

Figure 2. Time series of water surface elevation (m NAVD88) from USGS gauge FLBAY03283 at the Mexico Beach Pier. (a) (—) Unfiltered water level taken every 30 seconds; (—) Moving 15 minute average water level. (b) Significant wave height at pier. The shaded area represents the approximate time when the gauge did not go dry in wave troughs. Location is shown in Figure 3.

Figure 3. High water marks in the vicinity of Mexico Beach. (green) present measurements; (black) USGS; (red) peak elevation from USGS sensor at pier. FEMA flood zones are as shown in the legend. Highway US98 is the solid black line close to the coast, and the NOAA shoreline is shown as a dashed line. Elevations are given in NAVD88 datum.

Figure 4. Examples of water level measurements. (a) Location of USGS water level gauge at the Mexico Beach Pier, with bracket location circled; (b) Highest wave runup location; (c-d) Examples of interior watermarks.

Figure 5. Erosion example showing elevations in NAVD88 datum (a) Before; (b) After; and (c) Difference. Erosion is shown as positive and deposition as negative. Elevations for transects 1 and 2 are shown in Figure 6.

Figure 6. Before storm (-) and post-storm (- -) bare-earth elevation transects in NW Mexico Beach from the nominal shoreline to Hwy 98. Locations for Transects 1-2 are shown in Figure 5.

Figure 7. Examples of structural damage. (a) Complete destruction of at-grade house (DS6); (b) At-grade house detached from its foundations by waves and surge (DS6); (c) Damaged at grade house (note sheets of asphalt detached from road) (DS3); (d) Failure of prestressed concrete piling (DS6).

Figure 8. Examples of structural damage. (a) Complete failure of pile-elevated house (DS6); (b) Severe damage to beachfront pile-elevated row houses (DS5); (c) Minor damage to "Sand Palace" (DS3); (d) Scour and partial failure of concrete floor pad underneath pile-elevated house (DS5).

Figure 9. Locations of subregions a-d, and N-S used in Figures 10,13,15,16. The red asterisk shows the eastern end of the region where all structures seaward of US98 were evaluated for damage.

Figure 10. Surge and wave induced structural damage states as in Tomiczek et al. (2017). (black square) DS0; (green diamond) DS1; (cyan +) DS2; (magenta diamond) DS3; (blue x) DS4; (yellow triangle) DS5; (red *) DS6. (a) Subregion a; (b) Subregion b; (c) Subregion c; (d) Subregion d. FEMA DFIRM flood zones are as labelled.

Figure 11. Damage state vs elevation of lowest horizontal structural member in m NAVD88, and distance from shoreline in the subregions a-d as shown in Figure 9.

Figure 12. Slabbing probabilities as a function of elevation over the Mexico Beach region for (triangle) Combined VE and AE zones; (circle) X Zone. The shaded region shows the range of observed high water marks.

Figure 13. Slabbing probabilities for all flood zones combined as a function of location. (triangle) North Mexico Beach; (circle) South Mexico Beach. The shaded region shows the range of observed high water marks.

Figure 14. Examples of debris transport and deposition. (a) Western Mexico Beach (photograph by NOAA), showing large debris piles; (b) Boats and terrestrial debris; (c) Waverunner rental shack and other debris in forested area; (d) Large pile of woody debris and transported A-frame house grounded next to larger building; (e) 34m-long section of Mexico Beach pier deck grounded against houses.

Figure 15. Debris clusters in (a) North Mexico Beach area; (b) South Mexico Beach area.

Figure 16. Resting places for distinct Large Debris Objects (LDOs) identified in Mexico Beach post-Michael. (a) North Mexico Beach; (b) South Mexico Beach. Red lines indicate transport paths from original locations, where identified.

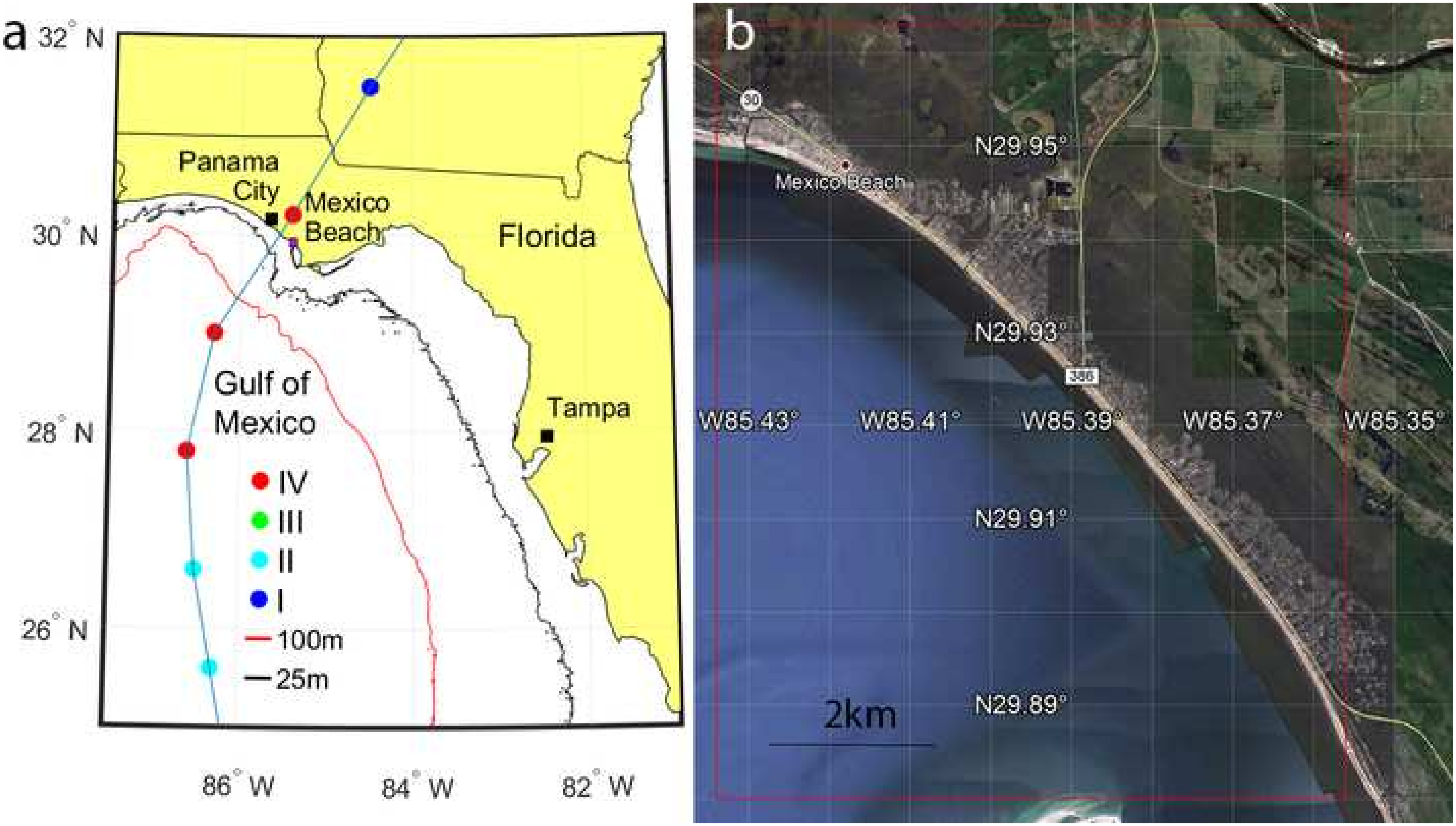
Figure 17. Distance moved for Large Debris Objects in cases where original locations could be determined.

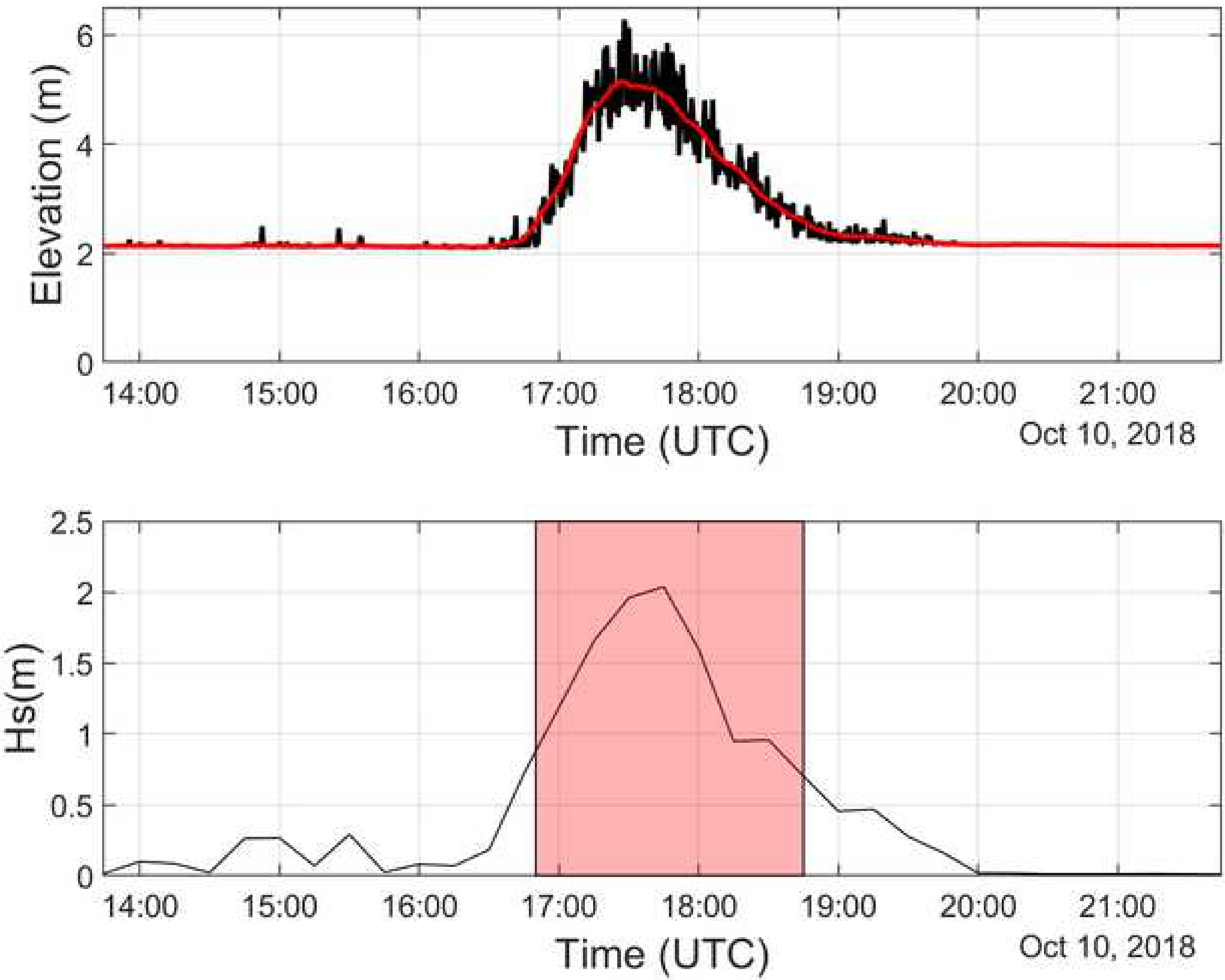
Table 1. High water marks measured during the present work. USGS measurements may be found in Byrne Sr. (2019).

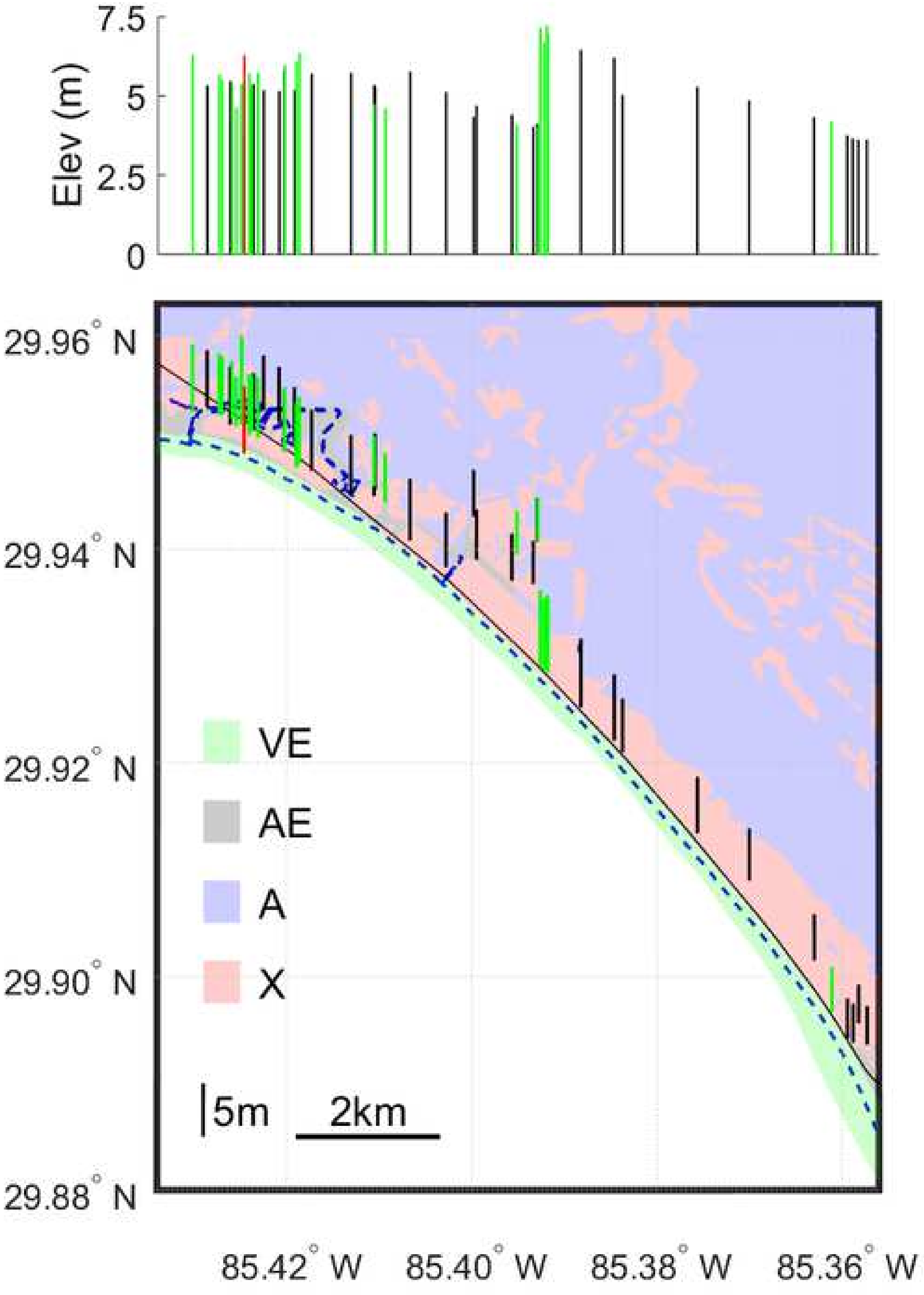
Latitude	Longitude	Elevation (NAVD88)	Description
29.952590	-85.426992	5.52	Mark inside building
29.952243	-85.425947	5.39	Mark inside building
29.951522	-85.425479	4.63	Mark in garage
29.952923	-85.430187	6.29	Eyewitness depth
29.956273	-85.424868	3.78	Wrack Line
29.945885	-85.410557	4.74	Mark inside building
29.939531	-85.395135	4.09	Mark in garage.
29.940754	-85.392837	4.04	Mark in building
29.952648	-85.427314	5.67	Mark inside garage
29.951655	-85.424893	5.38	Mark inside house
29.951396	-85.424061	4.80	Mark inside house
29.951023	-85.423786	5.31	Mark inside house
29.950682	-85.424071	5.71	Mark inside house
29.950422	-85.423121	5.73	Mark inside house
29.947654	-85.418985	6.09	Scratches on building exterior
29.947964	-85.418643	6.35	Scratches on building exterior
29.949224	-85.420235	5.96	Impact marks on building exterior
29.896666	-85.361097	4.21	Mark inside house
29.944418	-85.409357	4.60	Debris
29.929031	-85.392606	6.35	Runup debris
29.929045	-85.392600	7.13	Runup debris
29.928708	-85.392183	6.69	Runup Debris
29.928526	-85.391863	7.21	Runup Debris
29.928436	-85.391760	6.95	Runup Debris

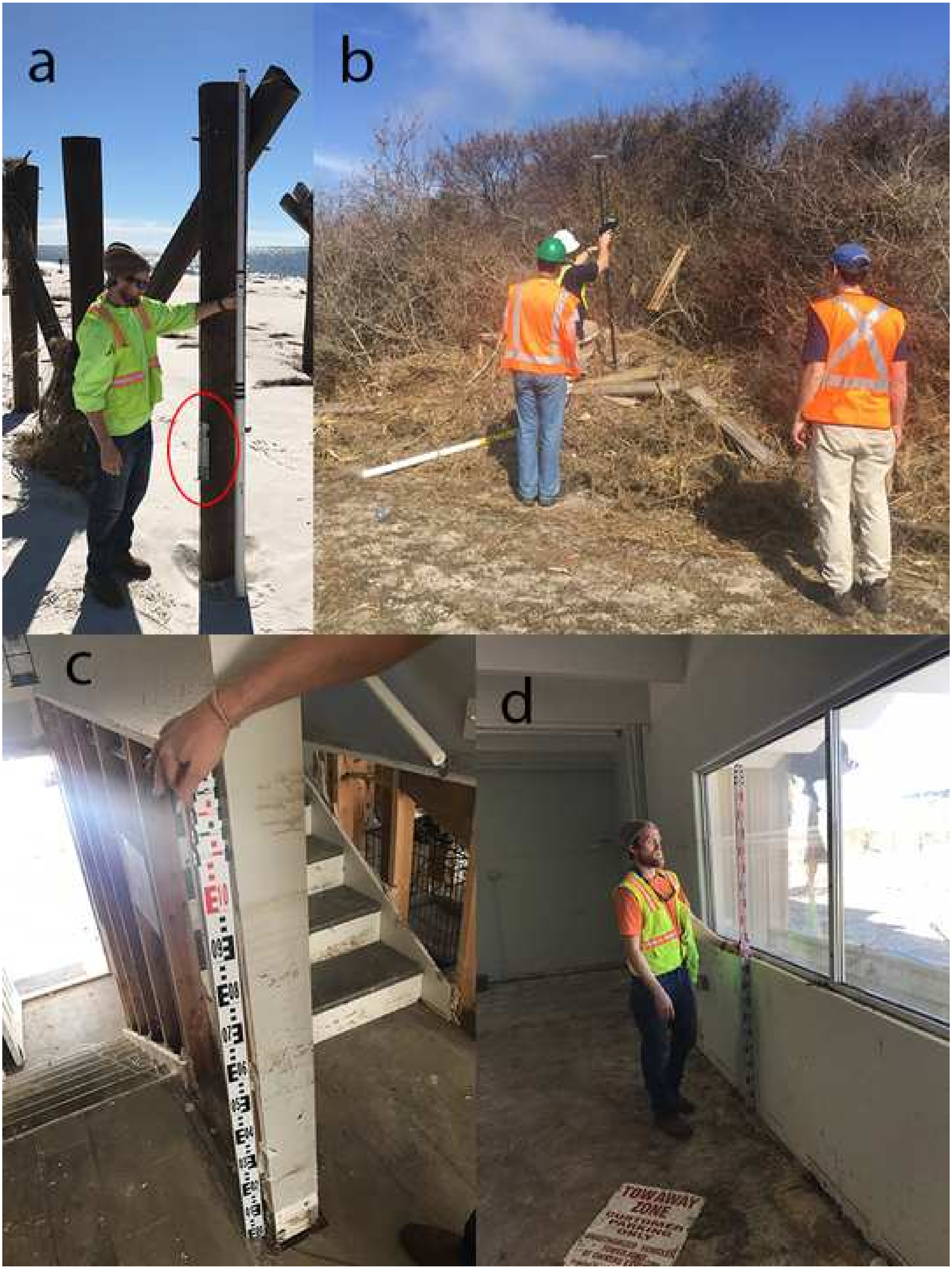
Component	0	1	2	3	4	5	6
Roof	• No visible damage	• Very few shingles missing (<15% of roof area) • Damage to gutters	• Significant amount of shingles missing 15-50% of roof area) • Interior of roof is NOT exposed	• Many shingles missing >50% of roof area) • Damage to roof frame	• Holes in roof due to debris or wind- sheathing is exposed but not house interior	• Large parts of roof are missing or collapsed; house is still intact	
Walls	• No visible damage	• Minor cladding removal (<10% of 1 wall) • Small scratches causing aesthetic damage	• Cladding has been removed from >10% of 1 wall or from multiple walls •Interior sheathing exposed on <10% of house	• Cladding has been removed from >25% of walls • >10% of sheathing is exposed but insulation and house interiors are not	• Minor structural wall damage, including debris caused holes or repairable damage	•Walls have collapsed, bent or are out of plumb, structural damage • Large holes in walls • major structural damage	
Foundation	• No visible damage	• Scour <0.5 feet deep around foundation • Water marks around foundation • Structurally sound	• Scour 0.5-1’’ deep • Structurally sound foundation • Evidence of weathering on piles	•Scour is between 1’-2’ • Structurally Sound Foundation • Minor damage to piles	• One pile out of plumb, or damaged • Scour >2’ deep • Minor damage to foundation	• Major but reparable foundation damage • House has differentially settled • >1 pile is damaged	• House is missing •Irreparable foundation damage
Attachments and Detached Structures: Stairways, Breakaway Walls, Air Conditioning, Sheds, etc.	• No visible damage	• <2 Exterior AC, pipes, etc., have been damaged or removed • Damage to stair, porches, detached garage, or walkways, most structures remain in tact	• 2 or more exterior amenities (stairways, electrical wiring, etc.) are gone or destroyed • Severe damage to decks, detached garages, etc.	• Detached structures destroyed/missing			
Openings: Windows, Doors, Attached Garages	• No visible damage	• 1 window or door is broken (glass only) • Screens may be damaged or missing	• >1 window is broken but damage is all on lower story of 2+ story houses • <4 total openings are damaged • Damage to frames of doors and windows	• 4 or more windows and doors are broken •1 or more doors was removed • Damage to windows /doors on upper levels • Attached garage door damaged or gone (bent or otherwise broken)			
Interior	• No visible damage	• Minor flood damage • Minimal/no evidence of rain intrusion- minor water damage in corners or around windows only • Minor water damage to interior furnishings	• Evidence of flooding • Water marks (0-1’) above floor • Evidence of rain intrusion- dampness/water damage on <10% of wall area (one wall) • Wet spots observed on <10% of ceiling, no sagging • Water damage to interior furnishings	• Significant flooding • Water marks (1’-2’) • Ceiling damage from rain- wet spots, evidence of dripping 10-50% of ceiling area • Dampness on 10-50% of wall areas • Mold	• Water marks (2’-4’) • Ceiling water damage affecting stability- wet spots over 50%,evidence of dripping and sagging • Dampness on >50% of wall areas •Evidence of dripping or cracks on walls	• Water marks 4’ or higher • Ceiling damage from rain- wet spots and sagging • Structural Damage to interior walls (not fixable)	

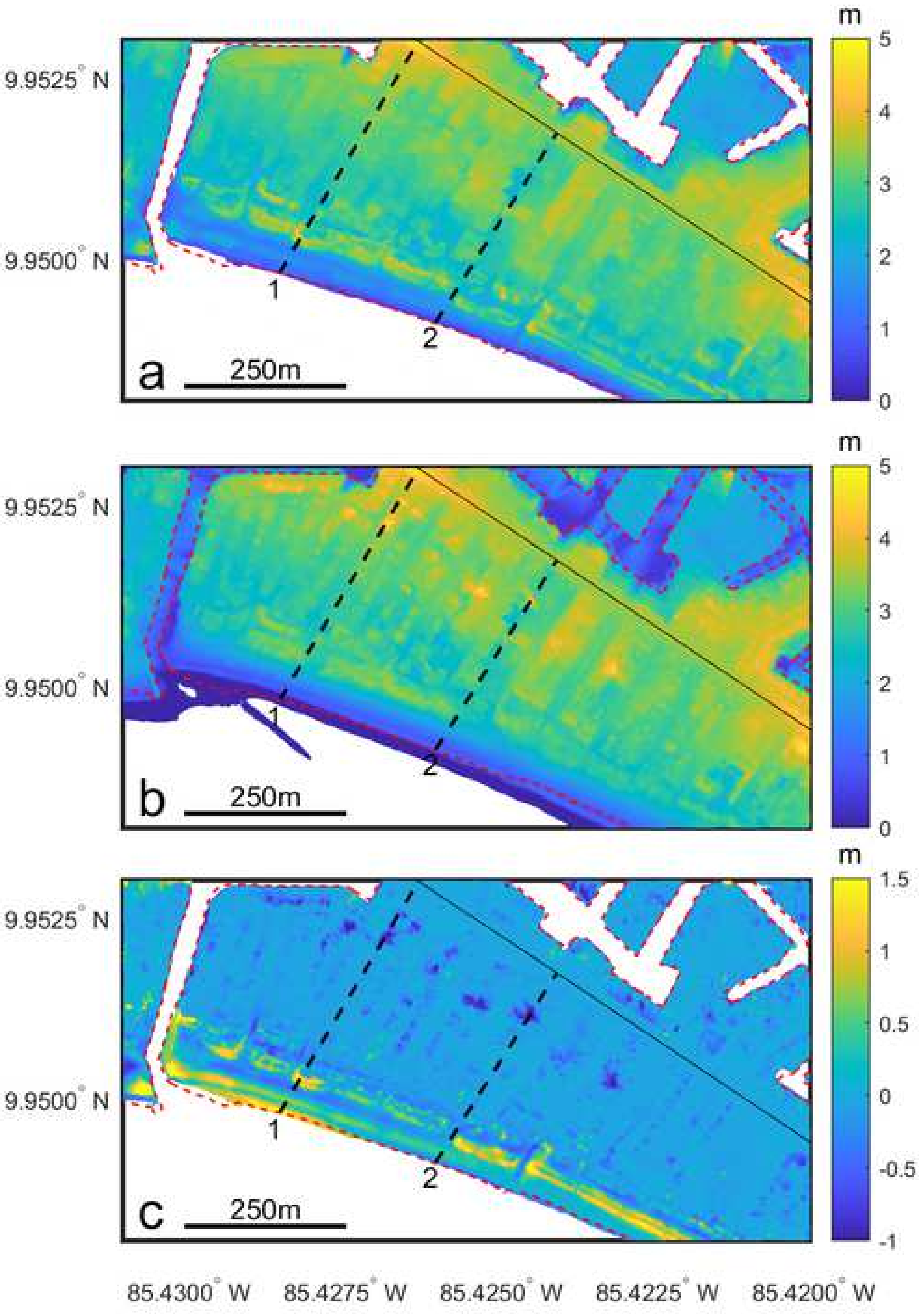
Table 2: Damage State Component Classification Methodology from Tomiczek et al. (2017).

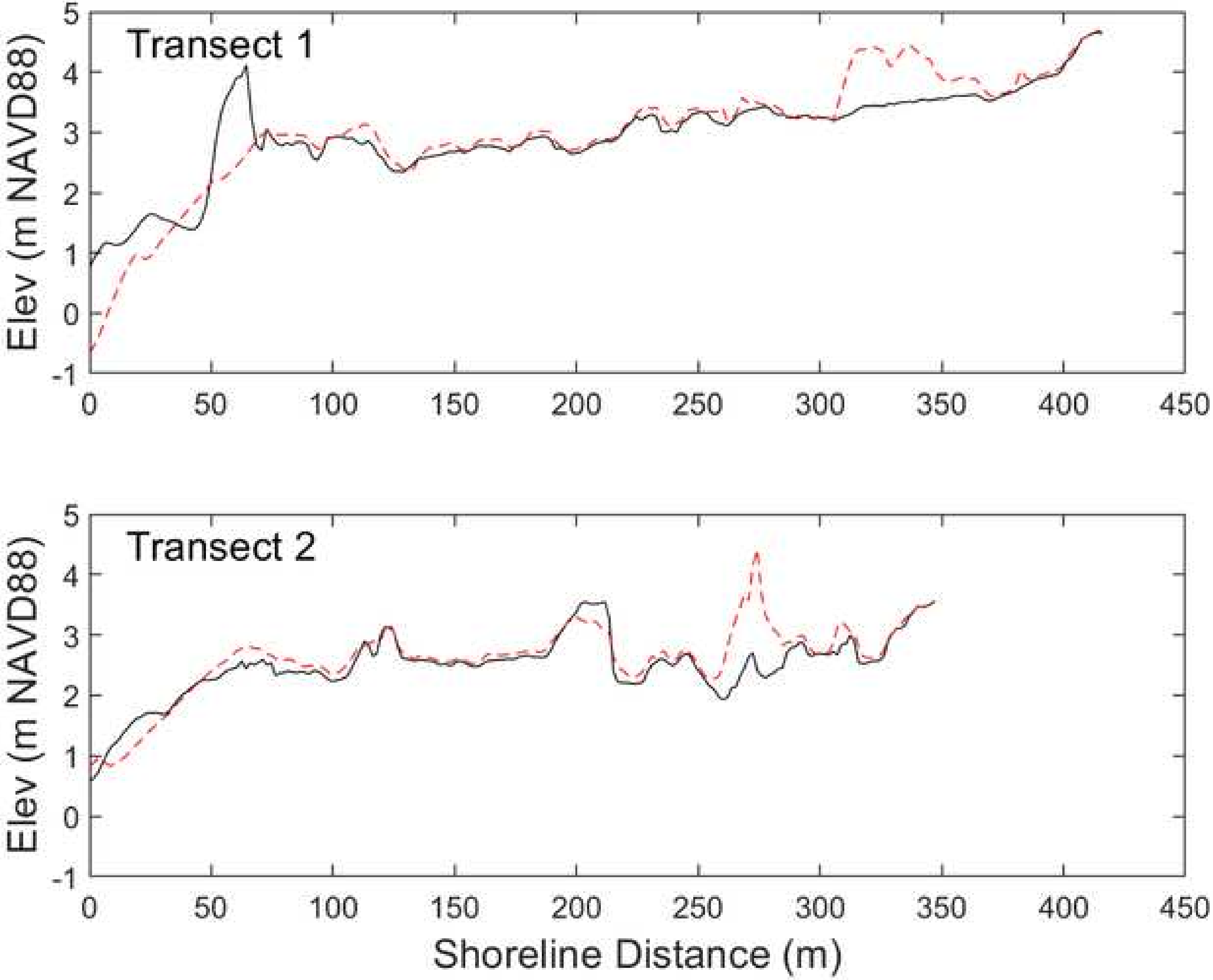

a
32° N
30° N
28° N
26° N
86° W
84° W
82° W
Panama City
Mexico Beach
Florida
Tampa
Gulf of Mexico
● IV
● III
● II
● I
100m
25m
b
30
Mexico Beach
N29.95°
N29.93°
386
W85.43°
W85.41°
W85.39°
W85.37°
W85.35°
N29.91°
N29.89°
2km


6
4
2
0
Elevation (m)
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00
Time (UTC)
Oct 10, 2018
2.5
2
1.5
1
0.5
0
Hs(m)
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00
Time (UTC)
Oct 10, 2018


7.5
5
2.5
0
Elev (m)
29.96° N
29.94° N
29.92° N
29.90° N
29.88° N
85.42° W
85.40° W
85.38° W
85.36° W
VE
AE
A
X
5m
2km

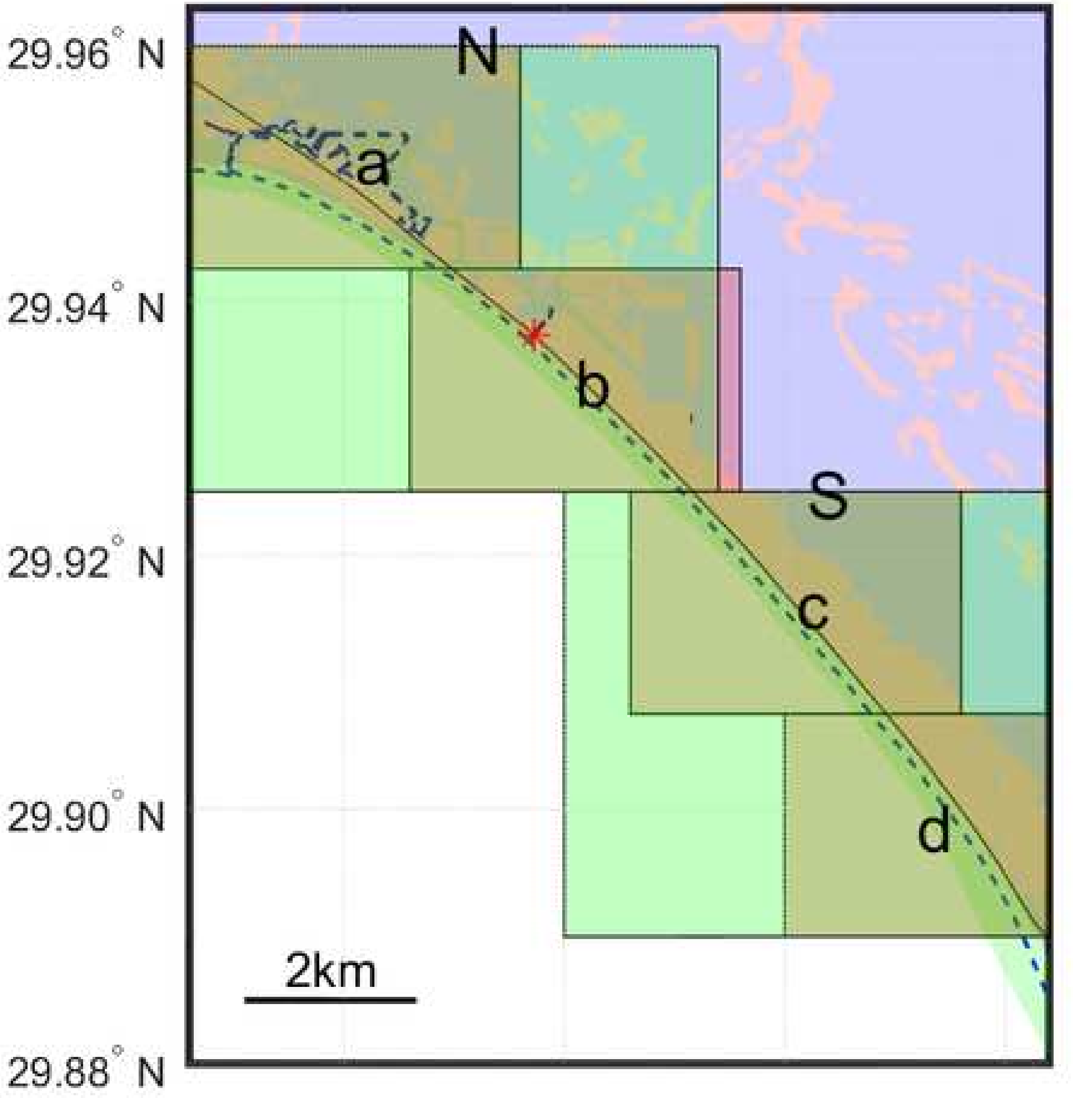

a
b
c
d
TOWAWAY ZONE
CUSTOMER PARKING ONLY

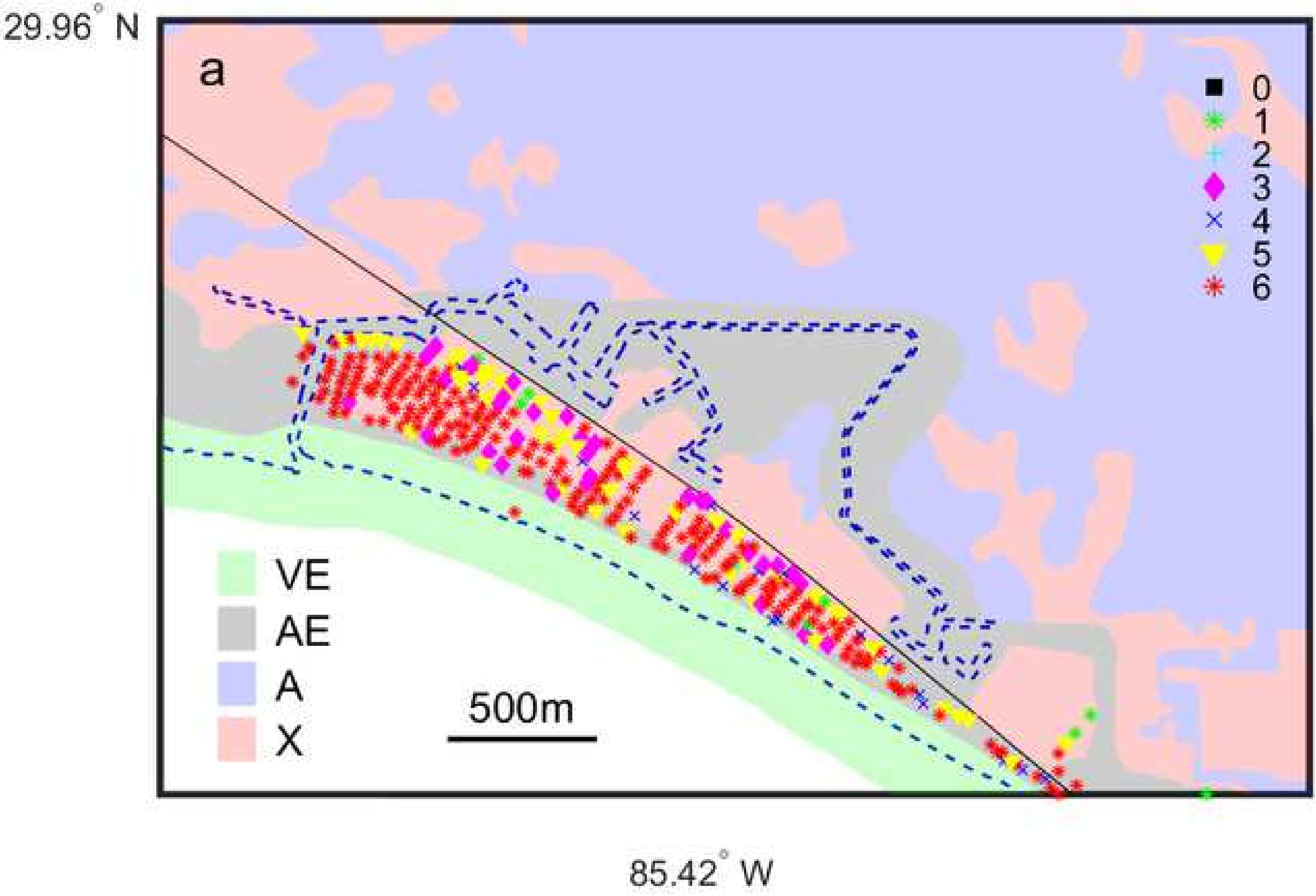

m
5
4
3
2
1
0
9.9525° N
9.9500° N
1
2
a
250m
m
5
4
3
2
1
0
9.9525° N
9.9500° N
1
2
b
250m
m
1.5
1
0.5
0
-0.5
-1
9.9525° N
9.9500° N
1
2
c
250m
85.4300° W
85.4275° W
85.4250° W
85.4225° W
85.4200° W

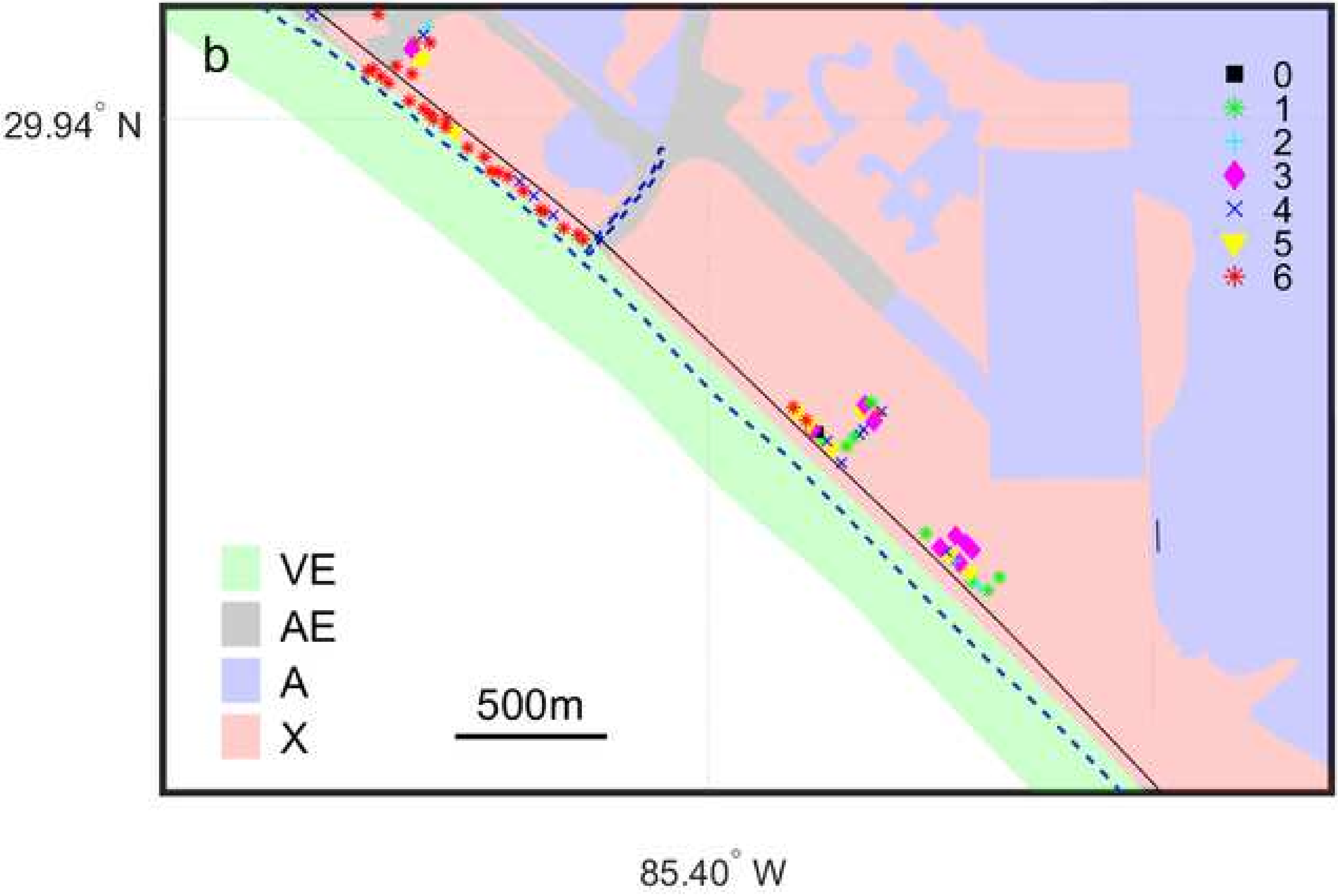

Transect 1
Elev (m NAVD88)
5
4
3
2
1
0
-1
0
50
100
150
200
250
300
350
400
450
Transect 2
Elev (m NAVD88)
5
4
3
2
1
0
-1
0
50
100
150
200
250
300
350
400
450
Shoreline Distance (m)

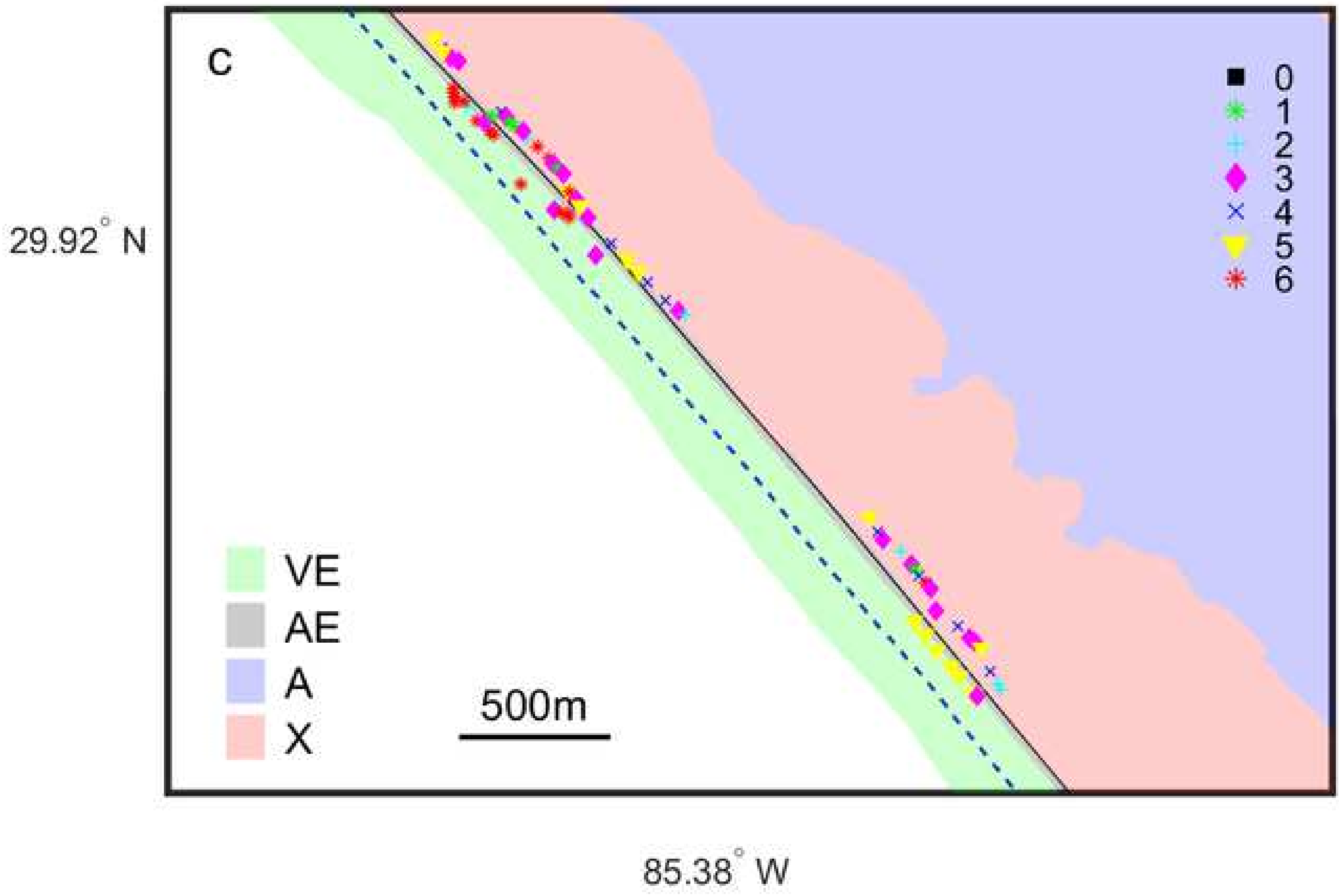

a
b
c
d

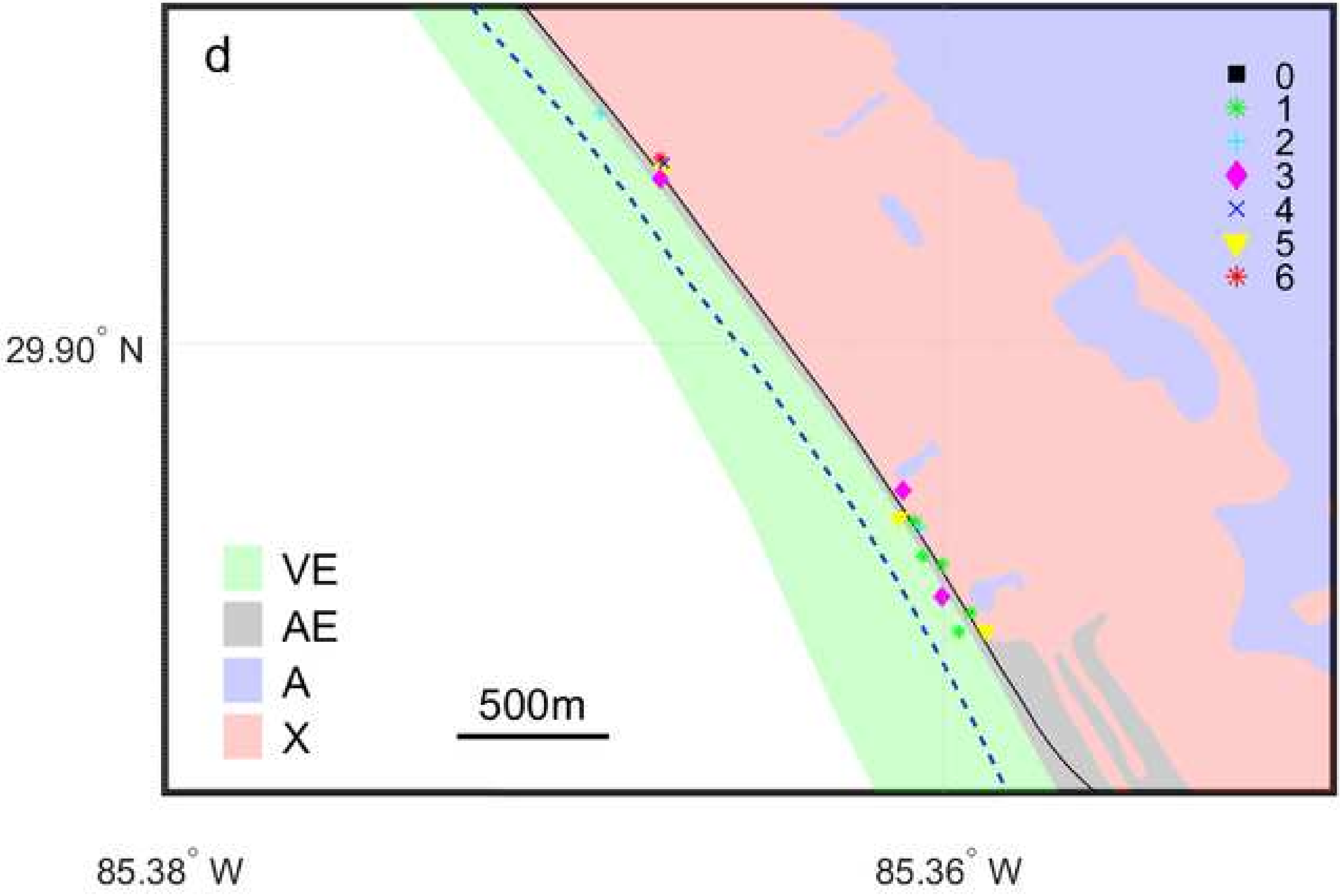

a
b
c
d

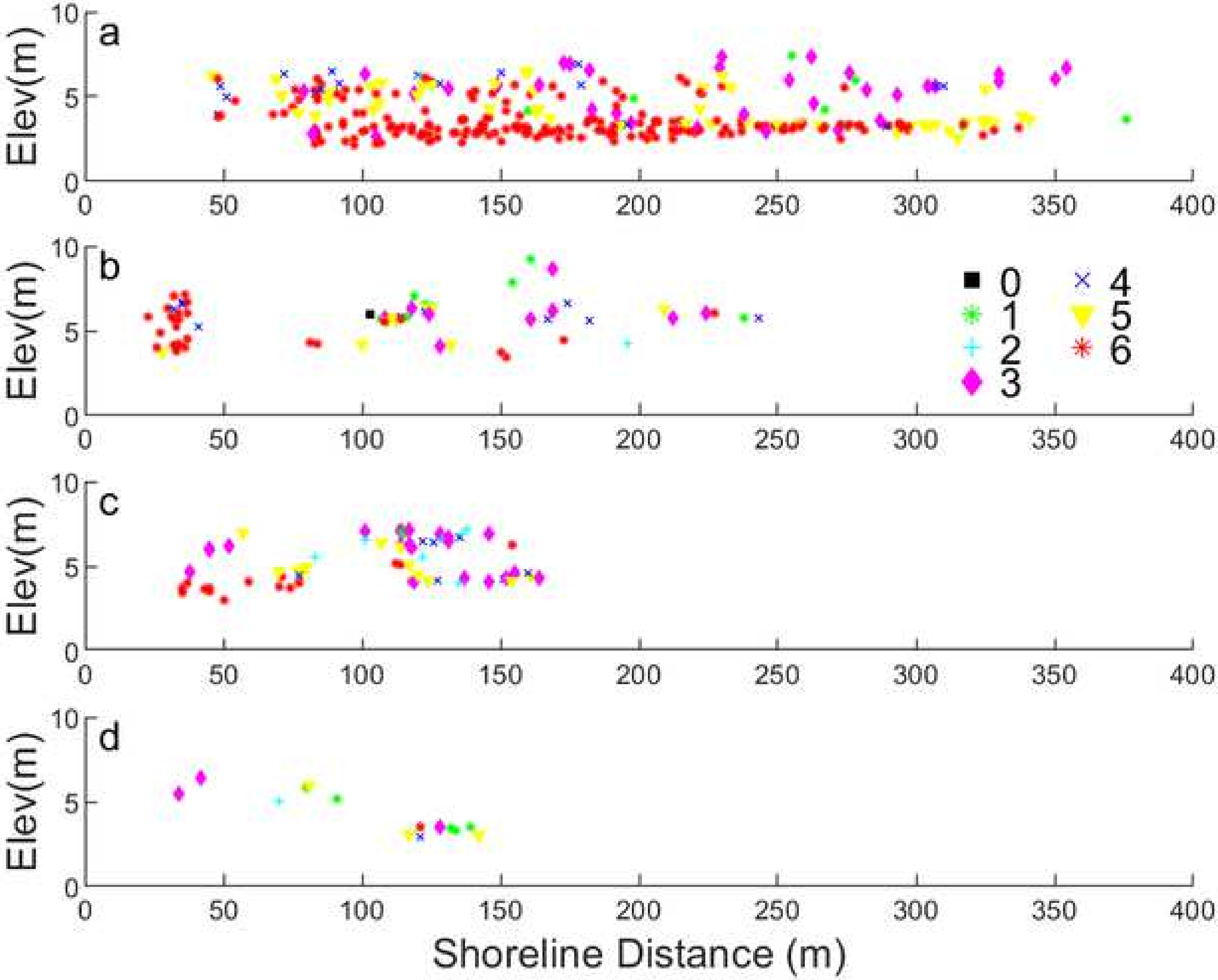

29.96° N
29.94° N
29.92° N
29.90° N
29.88° N
85.42° W
85.40° W
85.38° W
85.36° W
N
S
a
b
c
d
2km

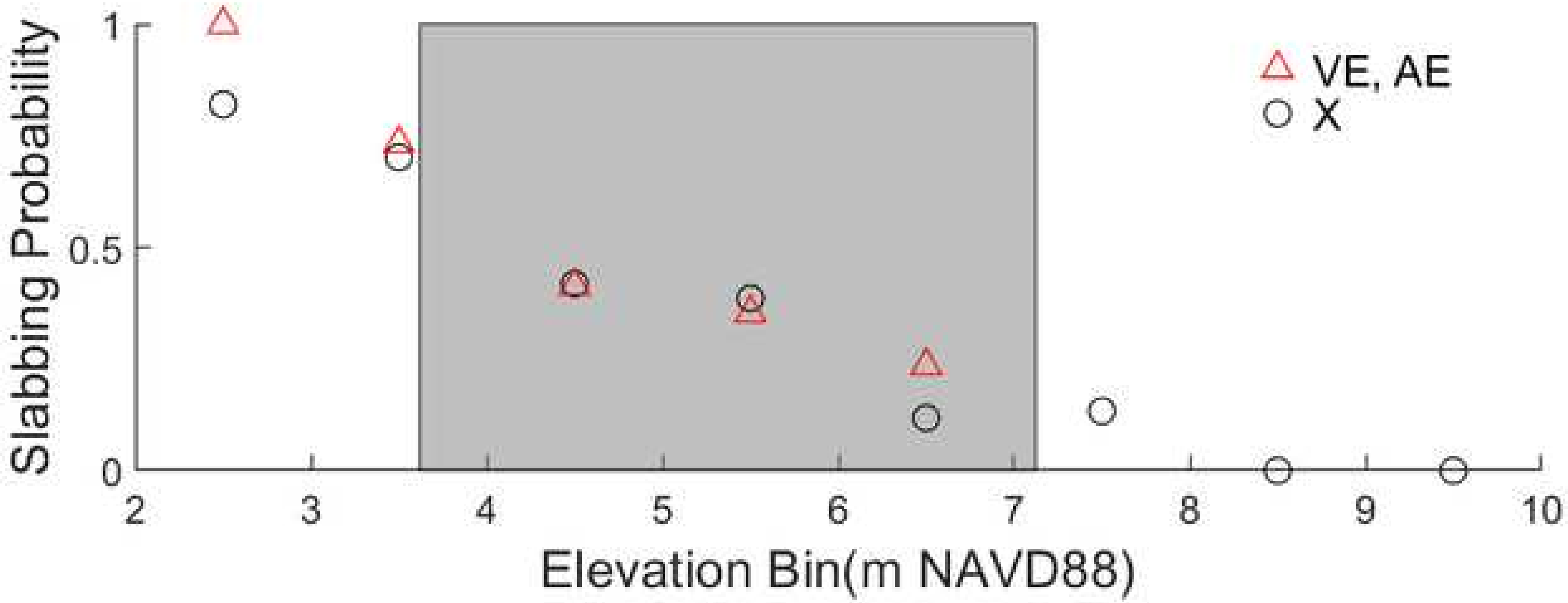

29.96° N
a
0
1
2
3
4
5
6
VE
AE
A
X
500m
85.42° W

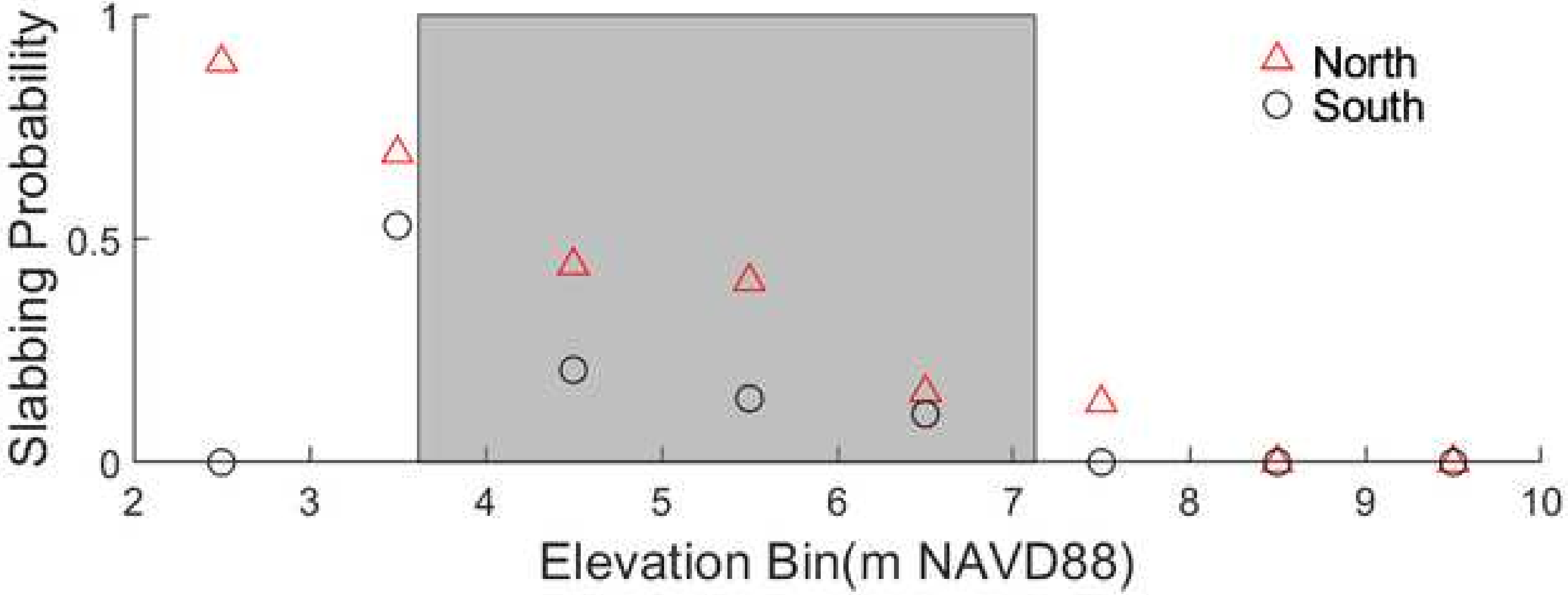

b
29.94° N
85.40° W
500m
VE
AE
A
X
0
1
2
3
4
5
6

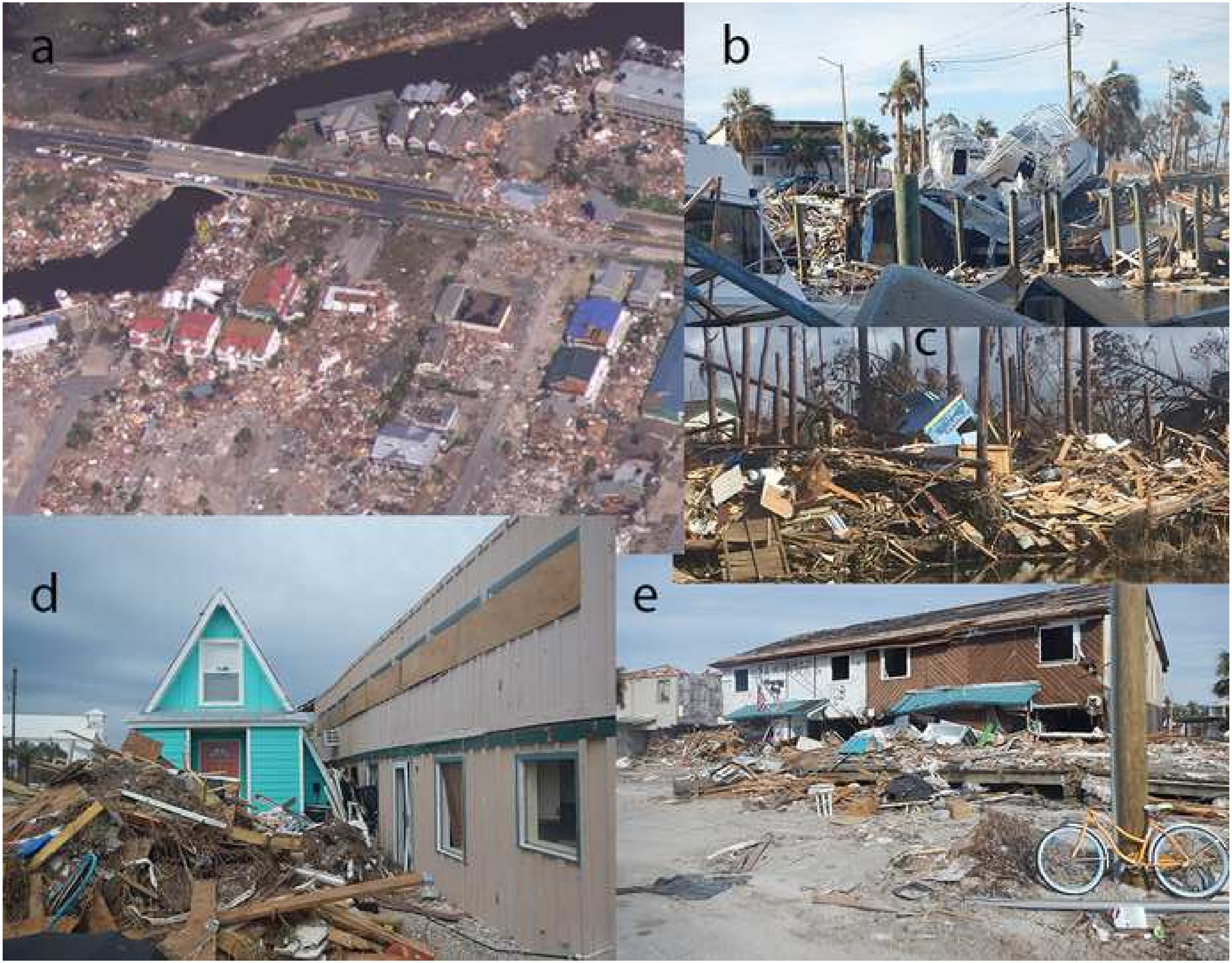

c
0
1
2
3
4
5
6
29.92° N
85.38° W
VE
AE
A
X
500m

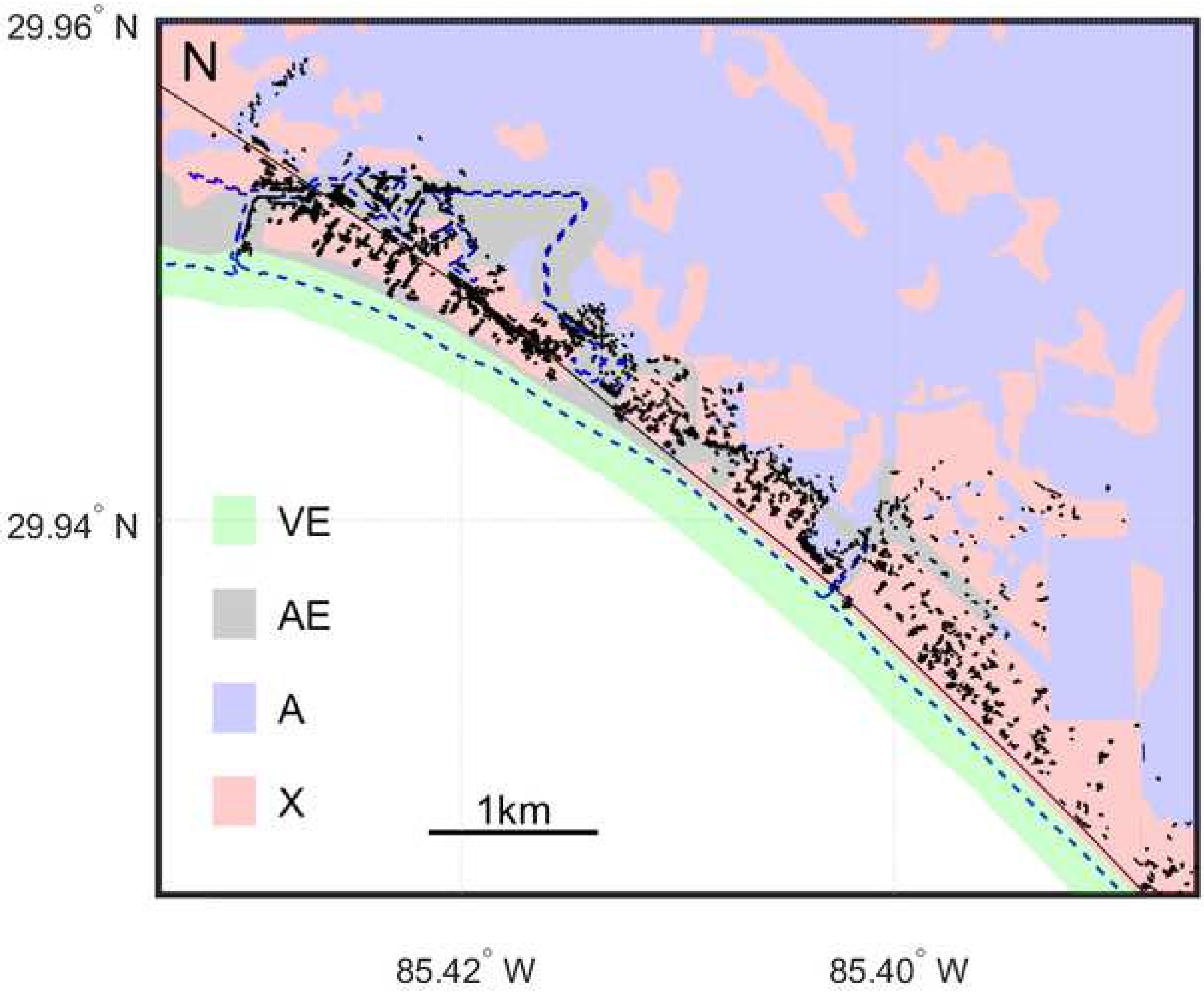

d
0
1
2
3
4
5
6
29.90° N
VE
AE
A
X
500m
85.38° W
85.36° W

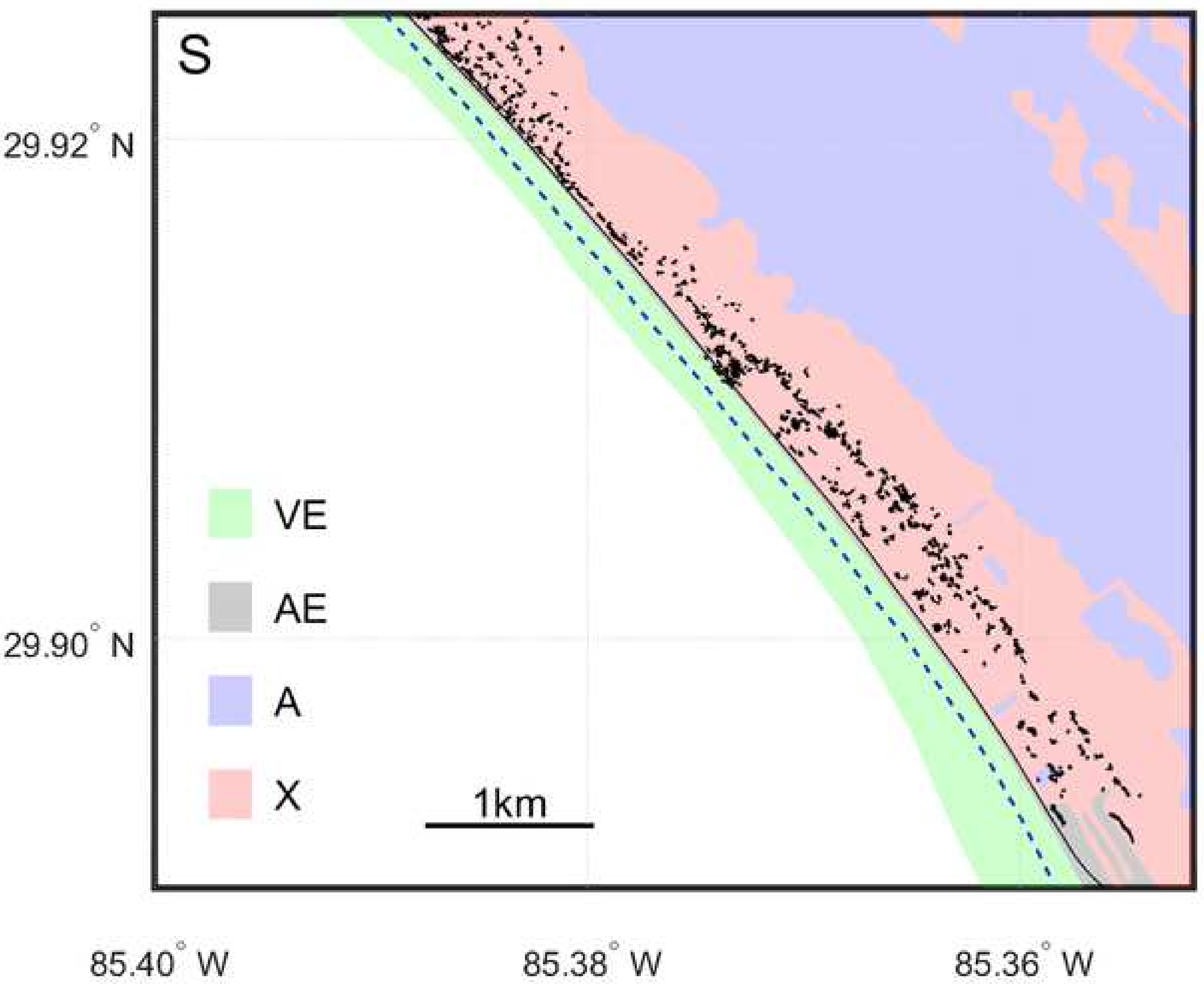

a
b
c
d
Elev(m)
10
5
0
0
50
100
150
200
250
300
350
400
Shoreline Distance (m)
■ 0
✳ 1
+ 2
◆ 3
× 4
▼ 5
✳ 6

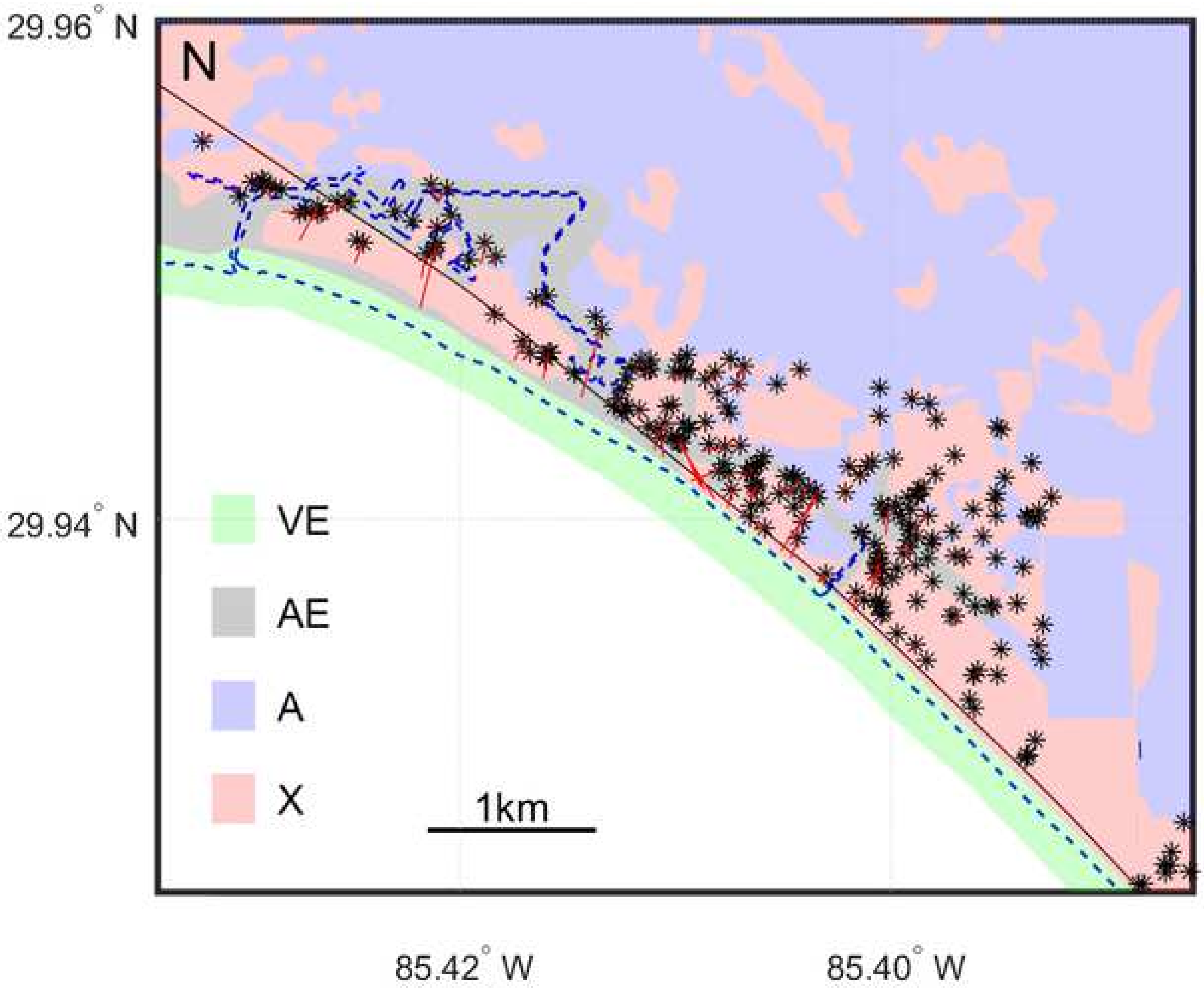

Slabbing Probability
1
0.5
0
2
3
4
5
6
7
8
9
10
Elevation Bin(m NAVD88)
△ VE, AE
○ X

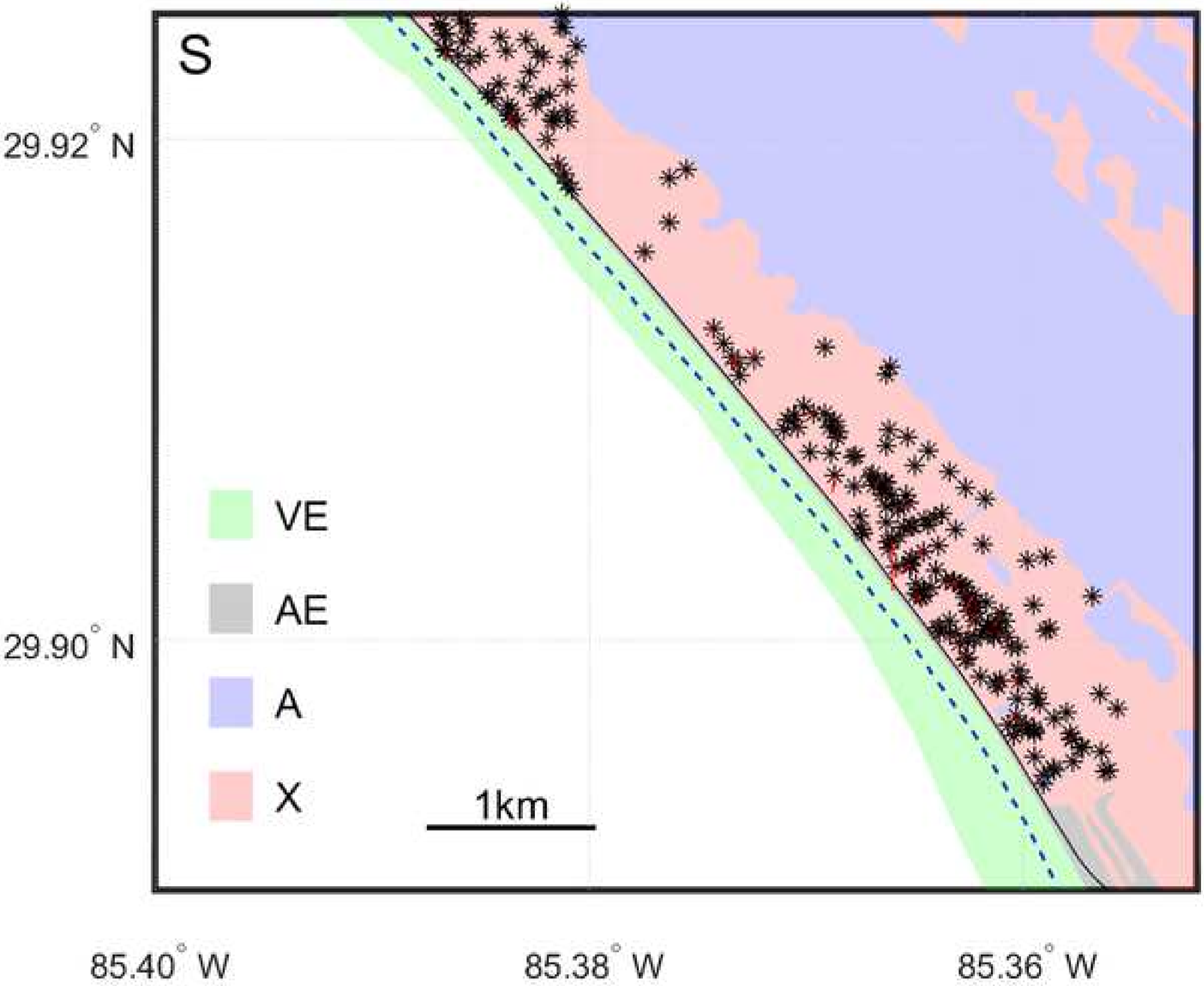

Slabbing Probability
1
0.5
0
2
3
4
5
6
7
8
9
10
Elevation Bin(m NAVD88)
△ North
○ South

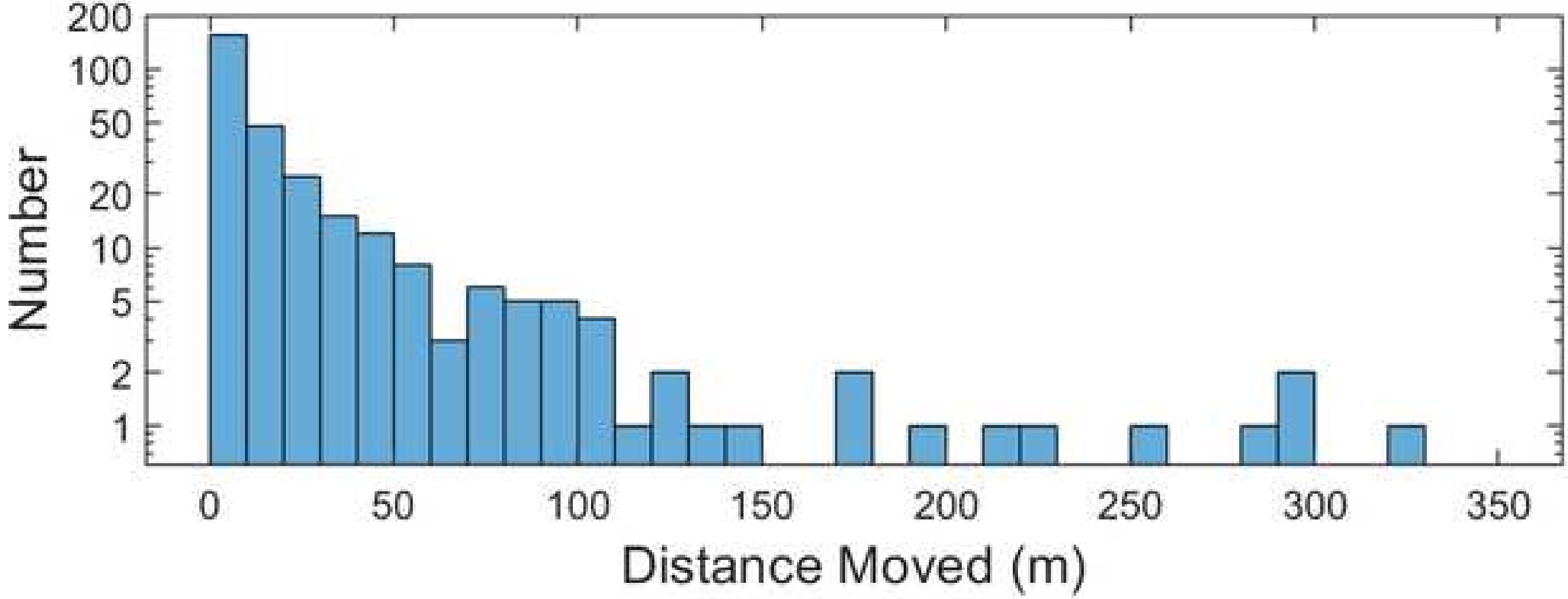

a
b
c
d
e


29.96° N
N
29.94° N
VE
AE
A
X
1km
85.42° W
85.40° W


S
29.92° N
29.90° N
VE
AE
A
X
1km
85.40° W
85.38° W
85.36° W


29.96° N
29.94° N
85.42° W
85.40° W
N
VE
AE
A
X
1km


S
29.92° N
29.90° N
VE
AE
A
X
1km
85.40° W
85.38° W
85.36° W


Number
200
100
50
20
10
5
2
1
0
50
100
150
200
250
300
350
Distance Moved (m)