FLORIDA HURRICANE LOSS MITIGATION PROGRAM

2018 ANNUAL REPORT

January 1, 2019

Prepared by

Florida Division of Emergency Management

Rick Scott	Wes Maul
Governor	Director

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EXECUTIVE SUMMARY

This document satisfies subsection 215.559 (6) Florida Statutes (F.S.), by providing a full report and accounting of activities and evaluation of such activities. The time period covered by this report is July 1, 2017- June 30, 2018 or State Fiscal Year (SFY) 2018. Based on section 215.559 (1), F.S., the Hurricane Loss Mitigation Program is established in the Division of Emergency Management. The Division receives an annual appropriation of $10 million from the investment income of the Florida Hurricane Catastrophe Fund authorized under the Florida General Appropriation Act and Section 215.555 (7) (c), F.S. The Public Shelter Retrofit Program, Tallahassee Community College's (TCC) Mobile Home Tie-Down Program, Florida International University's (FIU) Hurricane Research Program and Mitigation Program, account for a combined $6,500,000 or sixty-five (65%) percent of the SFY 2018 $10 million appropriation. The remaining thirty-five (35%) percent is used to implement a residential wind retrofit program that includes both physical wind retrofits of Florida residences and public outreach for education about retrofits to citizens and local government officials and their staff. In compliance with the appropriation language for SFY 2018, these funds were distributed as required.

The Shelter Retrofit Program and TCC's Mobile Home Tie-Down Program have separate reporting requirements as stated in Section 252.385, F.S., and Section 215.559 (2) (a), F.S., respectively. A separate report from FIU is also required. The Shelter Retrofit Program Report is prepared annually and separately submitted to the Governor and the Legislature pursuant to Section 252.385, F.S. The TCC and FIU reports are attached.

BACKGROUND

In the aftermath of Hurricane Andrew, the Florida Legislature created a series of programs to stabilize the economy and insurance industry. These programs consist of the following:

- Citizens Property Insurance Corporation (formed from a merger of the Florida Windstorm Underwriting Association and the Florida Residential Property and Casualty Joint Underwriting Association), the state insurance plan for residents unable to obtain a conventional homeowners insurance policy;

- The Florida Hurricane Catastrophe Fund, section 215.555 F.S., a re-insurance fund established to limit insurance exposure after a storm;

- The Bill Williams Residential Safety and Preparedness Act, which in 1999 created the Hurricane Loss Mitigation Program, section 215.559 F. S., with an annual appropriation of $10 million.

Based on Section 215.559 (1) F. S., the Hurricane Loss Mitigation Program is established in the Division of Emergency Management. The Division receives an annual appropriation of $10 million from the investment income of the Florida Hurricane Catastrophe Fund authorized under the Florida General Appropriation Act and Section 215.555 (7) (c) F. S. The purpose of the $10 million annual appropriation is to provide funding to local governments, State agencies, public and private educational institutions, and nonprofit organizations to support programs that improve hurricane preparedness, reduce potential losses in the event of a hurricane, and to provide research and education on how to reduce hurricane losses.

The funds are also to be used for programs that will assist the public in determining the appropriateness of particular upgrades to structures and in the financing of such upgrades, or to protect local infrastructure from potential damage from a hurricane. Section 215.559 F.S., establishes minimum funding levels for specific program areas and creates an Advisory Council to make recommendations on developing programs.

Specific Program Areas and Funding Levels

Shelter Retrofits - According to Section 215.559 (2) (a) F. S., $3 million of the annual $10 million appropriation for the Hurricane Loss Mitigation Program is directed to retrofit existing public facilities to enable them to be used as public shelters. An annual report of the state's shelter retrofit program, entitled the Shelter Retrofit Report, is prepared annually and separately submitted to the Governor and the Legislature pursuant to section 252.385 F.S. The remaining $7 million of the $10 million appropriation is allocated according to different subsections in Section 215.559, F. S., as described below.

Tallahassee Community College (TCC) - As required by section 215.559 (2) (a) F. S., TCC is given an annual allocation of $2.8 million or 40 percent of the remaining $7 million. The funds are administered by TCC and are to be used to mitigate future losses for mobile homes, and to provide tie-downs to mobile home in communities throughout the State of Florida. Please see Appendix A for TCC's 2017-2018 Annual Report.

Florida International University (FIU) - As required by Chapter 215.559 (3), F. S., FIU is allocated $700,000, or 10 percent of the remaining $7 million. The funds are administered by FIU and dedicated to hurricane research at the Type I Center of the State University System to support hurricane loss reduction devices and techniques. Please see Appendix B for FIU's 2017-2018 Annual report.

Hurricane Loss Mitigation Program (HLMP) – The remaining $3.5 million provided grant funding to governmental entities, nonprofit organizations, and qualified for-profit organizations as a means to improve the resiliency of residential, community, and government structures within their communities. The HLMP utilized a benefit-cost analysis (BCA) for each of the submitted projects in order to ensure that the recommended mitigation retrofits were cost-effective. Materials and labor costs were also closely monitored through each construction project.

PROGRAM ACTIVITIES

July 1, 2017- June 30, 2018

HLMP Funding Distribution-

In January 2017, the Division issued a Request for Proposal (RFP) for projects funded during the SFY 2018 for the annual appropriative amount of $3.5 million as appropriated by 215.559, Florida Statute. A review panel appointed by the Division selected eligible applicants based on priority, need, benefit, and alignment with local mitigation strategy projects. Based on this evaluation process, the Division initially contracted with 15 grant recipients to conduct wind mitigation retrofits to homes in the cities of St. Lucie County, City of Flagler Beach, City of North Lauderdale, Rebuild Northwest Florida, City of Bunnell, Centro Campesino, City of Miami Gardens, West Florida Regional Planning Council, Taylor County, Miami Dade County, City of Hallandale Beach, Broward County, City of Sarasota, City of Deerfield Beach, and Franklin County.

In 2017, the Florida Legislature approved the HLMP's request to revert and re-appropriate unspent funds from previous grant cycles, granting the program an opportunity to award additional applicants. The City of Apalachicola, Grace and Truth Community Development Corporation, Calhoun County, Lake and Sumter Emergency Recovery, City of Bradenton, City of Coral Springs, City of Tamarac, City of Lauderdale Lakes, Alachua County, Pasco County, and the City of Pompano Beach were additionally awarded. The Division received a total of thirty-nine proposals for this grant cycle and each of the twenty-six accepted proposals were awarded the mitigation construction grant in the amount of $194,000. The project agreements were funded with an initial period of performance closeout date of June 30, 2018. Agreements were distributed to the recipients in July of 2017.

In 2018, the Florida Legislature approved the HLMP's request to revert and re-appropriate unspent funds from previous year's grant cycle, which had not been included in the previous appropriation. At the directive of the Division's leadership, and in order to provide pertinent funding to the citizens of Florida before hurricane season, recipients who had been effective and efficient in their current projects were permitted to submit additional cost effective projects for funding. This decision allowed for the increased funding of 11 ongoing HLMP18 projects. Due to the increased funding, some recipients requested additional time to spend the new funds. All projects POP's were extended to December 31st 2018, where needed. This decision led to an inclusion of hundreds of homes that otherwise would not have been retrofitted.

HLMP Outreach- Due to recent outreach success, the Division decided to keep outreach in house. The HLMP focused mainly on the floridadisaster.org website for public outreach. This site provides citizens and potential recipients all the information and forms needed to apply to the HLMP program. It also includes an additional hurricane retrofit guide to help citizens make informed decisions on how to prepare their homes from potentially hazardous weather.

PROGRAM ANALYSIS

Project Number	Recipient	Mitigation completed	Properties Mitigated	Award amount	Actual Amount Spent*	Percent of Award Spent*
HLMP18-002	St. Lucie County	Residential	8	$219,000.00	$219,000.00	100.00%
HLMP18-003	City of Flagler Beach	Residential	10	$220,000.00	$219,706.82	99.87%
HLMP18-004	City of North Lauderdale	Residential	11	$244,000.00	$244,000.00	100.00%
HLMP18-005	RNWFL	Residential	244	$1,294,000.00	$1,294,000.00	100.00%
HLMP18-006	City of Bunnell	Residential	6	$194,000.00	$140,723.11	72.54%
HLMP18-007	Centro Campesino	Residential	20	$388,000.00	$388,000.00	100.00%
HLMP18-008	City of Miami Gardens	Residential	8	$194,000.00	$194,000.00	100.00%
HLMP18-009	West Florida Regional	Residential	12	$194,000.00	$168,939.31	87.08%
HLMP18-010	Taylor County	Residential	3	$194,000.00	$135,641.95	69.92%
HLMP18-011	Miami-Dade County	Residential	12	$229,000.00	$229,000.00	100.00%
HLMP18-012	Hallandale Beach	Residential	6	$194,000.00	$157,833.28	81.36%
HLMP18-013	Broward County	Residential	7	$194,000.00	$120,483.00	62.10%
HLMP18-014	City of Sarasota	Residential	5	$194,000.00	$194,000.00	100.00%
HLMP18-015	City of Deerfield Beach	Residential	6	$194,000.00	$116,650.00	60.13%
HLMP18-016	Franklin County	Residential	16	$374,000.00	$374,000.00	100.00%
HLMP18-017	City of Apalachicola	Residential	7	$194,000.00	$194,000.00	100.00%
HLMP18-018	Calhoun County	Residential	14	$300,000.00	$280,765.87	93.59%
HLMP18-019	LASER	Residential	6	$194,000.00	$188,321.19	97.07%
HLMP18-020	City of Lauderdale Lakes	Residential	7	$194,000.00	$194,000.00	100.00%
HLMP18-021	Alachua County	CSS Building	1	$194,000.00	$194,000.00	100.00%
HLMP18-023	City of Pompano Beach	Residential	14	$294,000.00	$294,000.00	100.00%
HLMP18-024	Bradenton	Residential	11	$194,000.00	$184,428.42	95.07%
HLMP18-026	Tamarac	Residential	7	$194,000.00	$194,000.00	100.00%
TOTAL			**441**	**$6,278,000.00**	**$5,919,492.95**	**94.29%**

Figure 1

Totals-

Greatest Possible Expenditures	**$6,278,000.00**
Total Homes	**441**
Amount per Home	**$14,235.83**
Actual Expenditures	**$5,919,492.95**
Total Homes	**441**
Amount per Home	**$13,422.89**

Figure 2

Benefit Cost Analysis by SFY

Project Designation	Applicant Name	BCA Generated Benefits	Cost	Return on Investment (ROI)	Notes
HLMP18-000	TCC	-	-	-	NO BCA Generated
HLMP18-001	FIU	-	-	-	Research Grant
HLMP18-002	St. Lucie County	$266,428.00	$219,000.00	21.66%	
HLMP18-003	City of Flagler Beach	$252,125.00	$219,706.82	14.76%	
HLMP18-004	City of North Lauderdale	$410,862.00	$244,000.00	68.39%	
HLMP18-005	RNWFL	$3,568,468.03	$1,294,000.00	175.77%	
HLMP18-006	City of Bunnell	$68,297.00	$140,723.11	-51.47%	
HLMP18-007	Centro Campesino	$564,246.00	$388,000.00	45.42%	
HLMP18-008	City of Miami Gardens	$149,225.00	$194,000.00	-23.08%	
HLMP18-009	West Florida Regional	$158,474.00	$168,939.31	-6.19%	
HLMP18-010	Taylor County	$94,172.00	$135,641.95	-30.57%	
HLMP18-011	Miami-Dade County	$283,100.00	$229,000.00	23.62%	
HLMP18-012	Hallandale Beach	$148,172.00	$157,833.28	-6.12%	
HLMP18-013	Broward County	$109,530.00	$120,483.00	-9.09%	
HLMP18-014	City of Sarasota	$88,523.00	$194,000.00	-54.37%	
HLMP18-015	City of Deerfield Beach	$152,167.00	$116,650.00	30.45%	
HLMP18-016	Franklin County	$267,612.00	$374,000.00	-28.45%	
HLMP18-017	City of Apalachicola	$211,037.00	$194,000.00	8.78%	
HLMP18-018	Calhoun County	$288,724.00	$280,765.87	2.83%	
HLMP18-019	LASER	$55,148.00	$188,321.19	-70.72%	
HLMP18-020	City of Lauderdale Lakes	$184,455.00	$194,000.00	-4.92%	
HLMP18-021	Alachua County	$757,186.00	$194,000.00	290.30%	
HLMP18-023	City of Pompano Beach	$389,610.00	$294,000.00	32.52%	
HLMP18-024	Bradenton	$269,019.00	$184,428.42	45.87%	
HLMP18-026	Tamarac	$205,484.80	$194,000.00	5.92%	
TOTALS		**$8,942,064.83**	**$5,919,492.95**	**51.06%**	

Figure 3

Three Year Annual Growth

Average Annual Growth

Award					
	HLMP16	**HLMP17**	**Percent Change From Previous Year**	**HLMP18**	**Percent Change From Previous Year**
Number of Homes	198	204	3.03%	441	116.18%
Amount per Home	$16,404.04	$19,119.17	16.55%	$14,235.83	-25.54%
Amount per Home Acounting for Inflation*	$16,404.04	$18,794.41	14.57%	$13,376.56	-28.83%

** Inflation calculated with CPI-U method From U.S Burenu of Labor and Statistics*

Actual					
	HLMP16	**HLMP17**	**Percent Change From Previous Year**	**HLMP18**	**Percent Change From Previous Year**
Number of Homes	198	204	3.03%	441	116.18%
Amount per Home	$13,646.30	$16,122.85	18.15%	$13,422.89	-16.75%
Amount per Home Acounting for Inflation*	$13,646.30	$15,848.98	16.14%	$12,838.49	-18.99%

Return on Investment					
	HLMP16	**HLMP17**	**Percent Change From Previous Year**	**HLMP18**	**Percent Change From Previous Year**
Cost	$2,581,016.22	$3,097,060.35	19.99%	$5,919,492.95	91.13%
Benefit	$2,783,460.20	$3,585,554.18	28.82%	$8,942,064.83	149.39%
Return on Investment	7.84%	15.77%	101.09%	51.06%	223.73%

Figure 4

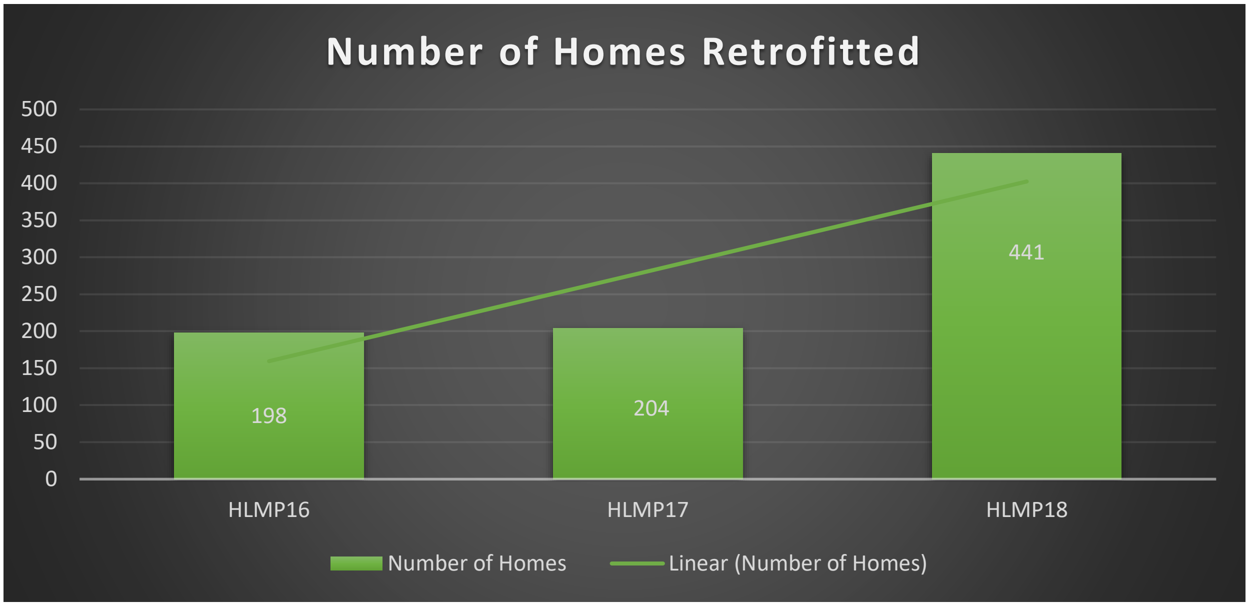
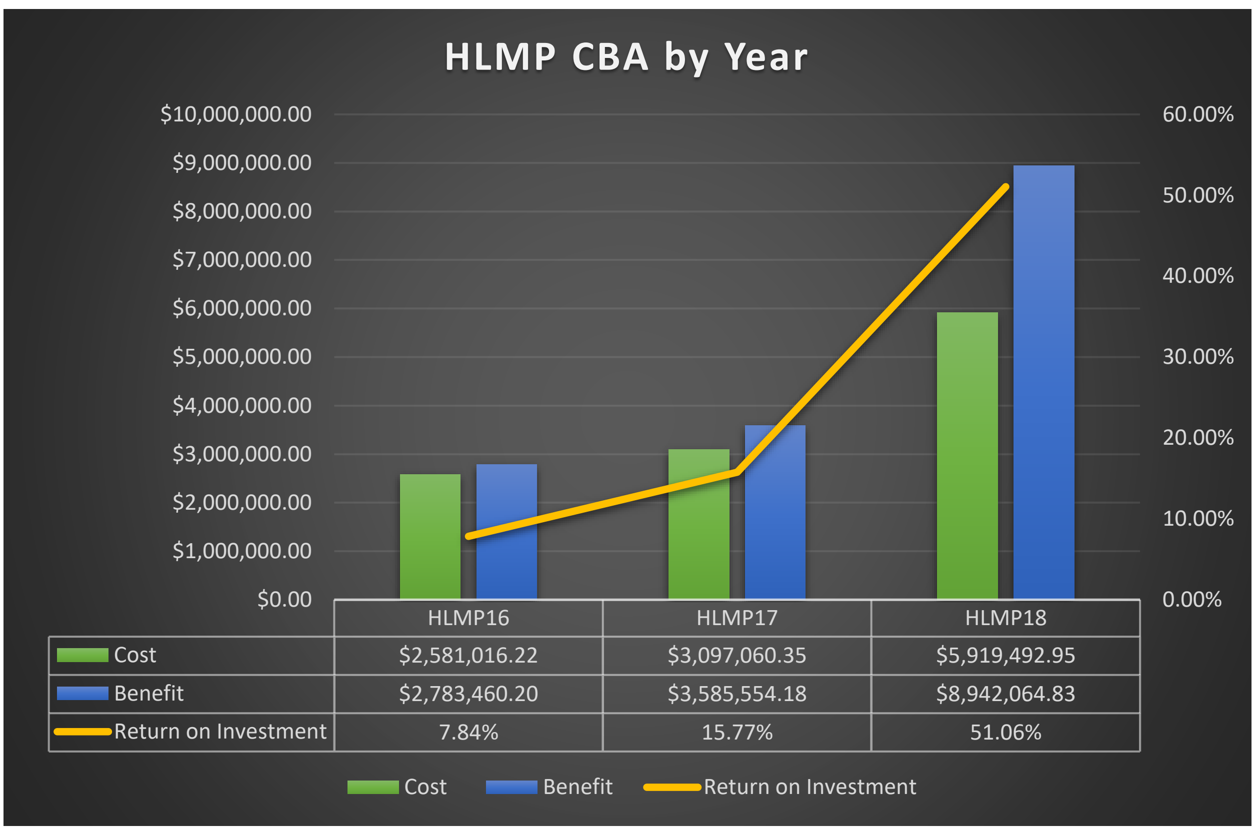


Figure 5



	HLMP16	HLMP17	HLMP18
Cost	$2,581,016.22	$3,097,060.35	$5,919,492.95
Benefit	$2,783,460.20	$3,585,554.18	$8,942,064.83
Return on Investment	7.84%	15.77%	51.06%

Figure 6

Analysis Discussion- The total expenditures to contract reward ratio for the SFY 2018 is 94.29%. This number was generated by adding the total expenditures from Figure 1 and dividing by the sum of total contract rewards of Figure 1. When compared to the ratio of awards spent from the SFY 2017 (81.75% HLMP Annual Report SFY 2017), this shows an increase of percentage of funds spent of 15.3%. This means that 15.3% more of the allocated funds are being used to provide retrofitting for citizens. 441 total homes have been retrofitted in the 2018 SFY (Figure 2), this is 166% higher than last year's total homes (Figure 4&5). Figure 5 also includes the Linear trend for the amount of homes that the HLMP retrofitted each year. This figure shows that in 2018, the HLMP program had substantially increased the number of homes retrofitted. Despite increasing construction costs across the state, HLMP project costs per home have decreased by 25.5% (Figure 4) in the 2018 SFY. Moving to Figures 3 and 6, the Return on Investment (ROI) for SFY 2018 was 51% (Figure 3). This is a 224 % increase from last year's ROI of 15.77% (Figure 6). This number indicates that the HLMP yielded 224% more returns per dollar spent than it did in the previous year.

PROGRAM GOALS AND RECOMMENDATIONS

The Division of Emergency Management is committed to developing programs to educate the public on ways to reduce the impact of a disaster. The Hurricane Loss Mitigation Program educates the public and local communities on wind-mitigation programs that will increase structural survivability for residences and to aid Florida homeowners in obtaining a financial discount for insurance. Through a comprehensive outreach campaign, additional communities will have an opportunity to participate in the grant program.

The Division has the following goals to increase participation in the program:

- Moving forward, the Division would like to focus on more community based mitigation. The program has enhanced its scope of work to include storm related mitigation efforts that can be undertaken within the confines of State Statute 215.555.

- Induction of more pamphlets and physical material to better educate citizens and localities about the HLMP.

- Provide fresh strategies on the Florida Division of Emergency Management's new website in support of local government's mitigation efforts.

- Conduct a minimum of four, Community Education Visits (CEV) across the state to promote a partnership strategy that includes the whole community. This whole community strategy seeks to bring together representatives from county government, municipal government, local non-profit entities, and qualified for for-profit entities.

- Re-engage the Division's relationship with other Mitigation units including Hazard Mitigation Grant Program (HMGP), Floodplain and External Affairs in outreach events, seminars, and conferences with the aim and purpose of cross-promoting mitigation resources across the State of Florida.

Discussion

In mid-2017, the Hurricane Loss Mitigation Program began managing the Shelter Survey and Retrofit Program grants and contracting needs. HLMP applied current grant management processes to existing and new projects being managed by the Shelter Program. With the resources available within the Mitigation Bureau's Finance Unit, Shelter payments, contracting, and reporting has become a streamlined process within HLMP's daily operations.

The Hurricane Loss Mitigation Program has worked with the Mitigation Bureau's Technical Unit to design streamline processes for the project management of the Shelter Retrofit Program. Modernized Scopes of Work have been finalized with the collaboration of the Shelter Retrofit Program, Technical Unit, and Hurricane Loss Mitigation Program. New review processes and detailed requirements within the Scope of Work will strengthen regulation and monitoring while providing the recipient with a clearer understanding of their goals and objectives.

The Hurricane Loss Mitigation Program is working towards adopting processes that have proven success in the Mitigation Bureau's federal grant programs. HLMP project and grant management training programs are continuously evolving to include the best practices experienced by the state funded grant program and federal grant management programs. Additionally, custom scope templates have been designed for the various newly permissible mitigation project types that are being managed by HLMP. These new scopes are Florida specific, project specific, and provide clear instruction on the compliance requirements set forth by the state of Florida, the Division of Emergency Management, and the Bureau of Mitigation.

2017-2018 ANNUAL REPORT

TALLAHASSEE COMMUNITY COLLEGE

MOBILE HOME TIE DOWN PROGRAM

The Mobile Home Tie-Down Program continued to be a popular and a successful program during the 2017-2018 fiscal year. There were a number of necessary changes to the program this year again to continuously provide improvement to the structure of the Program and how Tallahassee Community College manages it. The program instituted new changes in this year's execution of the grant: 1. Multiple Vendors will be chosen for this and future years of the program, 2. The Individual Component of the program was implemented with a separate proposal, 3. The use of Quality Assurance Inspectors was also implemented as part of the College's Quality Control procedure. All changes were made to allow for more homeowners to participate and to increase the visibility of the grant among Floridians and Vendors looking to beinvolved with the Hurricane Residential Mitigation Program. As a result of such changes the College experienced protest to the implementation of a more efficient price structure on the Parks proposal, which delayed our program start date for the Parks by four months. As a result, the program finally resumed November 1, 2017. Even with the shortened timeframe again this year TCC was able to complete, Two thousand three-hundred and ninety (2390) homes this past year almost double the amount the year prior. The program was successfully completed in ten (10) mobile home communities across seven (7) different Florida counties. In all Three-million three-hundred thousand dollars ($3,300,000) were expensed on the grant spending 100% of the allocated funds of 2.8 Million and utilizing an additional five hundred thousand in ($500,000) in increased funding.

	PARK NAME	ADDRESS	CITY	COUNTY	# OF HOMES
1	CRYSTAL LAKE MHP	850 Memorial Dr.	Avon Park	Highlands	274
2	COLONY COVE II MHP	101 Amsterdam Ave	Ellenton	Manatee	128
3	BONNY SHORES	164 Bonny Shores Dr,	Lakeland	Polk	106
4	CYPRESS LAKES ASSOC	10000 US HWY 98 N	Lakeland	Polk	400
5	COUNTRY SIDE @ VERO	8775 20th St	Vero Beach	Indian River	302
6	COLONIAL COLONY S	1275 Beville Rd	Daytona Beach	Volusia	148
7	RIDGE MANOR CO-OP	1301 Old Polk City Rd	Haines City	Polk	117
8	OAK HILL VILLAGE	101 Oakhill Ridge Rd	Valrico	Hillsborough	128
9	FEATHEROCK	2200 Highway 60 East	Valrico	Hillsborough	273
10	FAIRWAYS	14205 E. Colonial Dr.	Orlando	Orange	278

Upon completion of a community The Florida Department of Highway Safety and Motor Vehicles (D.H.S.M.V), Division of Motor Vehicles, Manufactured Housing Section completes a random inspection of a minimum of 10% of the homes. This is to verify the items were actually installed by the vendor and installed according to the manufacturer's specifications.

As is the case every year, critical assistance and advisement was provided by the Federation of Mobile Home Owners (FMO) and Florida Manufactured Housing Association, Inc. in sending out our Community Interest Verification form. This begins the process of intake and eligibility for the program.

The intake and eligibility process began as site visits were scheduled and completed at nine (10) communities throughout the year. These communities were evaluated and the following deliverables were completed during this process:

- Interviews with management and/or homeowner association representatives.
- Visual inspections of all homes within the community.
- Intake training for the homeowners' association representatives.

Since Communities are no longer required to have 60% participation of the eligible units. Tallahassee Community College began accruing a listing of all interested Communities and Individuals for the completion of the scope of work and participation into the program. Site visits are no longer the responsibility of the vendor for eligibility evaluation but the sole responsibility of the College.

During the 2017-2018 program year nine (9) resident meetings were conducted by the Program Contractors. These meetings were conducted with homeowner's association board members, volunteers and, on many occasions, all residents of a particular community. Additionally, Tallahassee Community College, Windstorm Mitigation Inc. (contractor), and Storm Ready Services Inc. (contractor) responded to over four hundred (400) resident inquiries during this program year.

Individual Component. The process for implementing the Individual Component is complete and completed a total of two-hundred thirty-six (236). As part of this effort TCC has developed a website for participant intake and the link to the website is:
http://www.tcc.fl.edu/about/college/administrative-services/contracts-and-grants/mobile-home-tie-down-program/

Quality Control Inspector. To ensure every resident receives quality services from the grant. TCC is looking to contract services with a Quality Control Inspector. This person's responsibilities will be to inspect 30% of the Individual Homeowner's serviced by the program as a way to ensure a quality product is being provided to the homeowner and provided by the vendor. FLHSMV is providing the services to assist TCC in vetting the vendors interested in participating in the program as part of our quality control. These services were provided by AWC Pool and Construction and Beryl Engineering.

We looked for the following experience and qualifications for all parties:

Mobile Home Installer's License (AWC)

Licensed Home Inspector (Beryl)

Engineering License or Engineer employed/contracted by firm (particularly experience with the Insurance Industry) (Beryl and AWC)

Both AWC and Beryl will act in conjunction with the QA review established here at the College.

Program Webinar. There was a Pre-Bid Conference held on July 13th to ensure the vision, expectation of the program is communicated clearly too all participants. This was a recorded session and provided to all interested parties for future use and reference.

Moving Forward.

TCC has a waiting list now for the program participants as a result of the new guidelines which will be between 3-5 years before we can address any additional parks due to the large response from Florida residents. Albert Wynn has been promoted within the College and is no longer the Program Coordinator.

Please refer any questions relating to this report or the Program in general to:

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FLORIDA INTERNATIONAL UNIVERSITY
International Hurricane Research Center

A Resource for the State of Florida

HURRICANE LOSS REDUCTION FOR HOUSING IN FLORIDA

FINAL REPORT
For the Period August 7, 2017 to June 30, 2018

A Research Project Funded by:
The State of Florida Division of Emergency Management
Through Contract #18HL-AG-11-23-05-019

Prepared by
The International Hurricane Research Center (IHRC)
Florida International University (FIU)

August 13, 2018

Final Report

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Section 1
Executive Summary

Seven major efforts were identified by the International Hurricane Research Center (IHRC) for the Residential Construction Mitigation Program (RCMP) Fiscal Year 2017-2018 funding in the areas of structural mitigation analysis, socioeconomic research, data dissemination to stakeholders and education and outreach. In keeping with the comprehensive agenda of the research topics for this project, the IHRC organized a multidisciplinary team of researchers, students and support staff to complete the stated objectives. The following is a summary of research findings:

Holistic Testing to Determine Wind Driven Rain (WRD) Intrusion Reduction for Shuttered Windows (PI: Dr. Arindam Gan Chowdhury)

Shutter systems on windows or impact rated window systems are commonly implemented in hurricane-prone regions to mitigate the building envelope against high wind pressures and wind-borne debris impacts. However, the presence of shutter systems (or impact rated window systems) may also have a beneficial effect in mitigating against water intrusion caused by wind-driven rain (WDR). Currently, there is little information available on how shutters (or impact rated windows) can minimize water intrusion through window systems under hurricane-level wind and WDR conditions. To overcome this knowledge deficit, the objectives of the current research were to quantify water intrusion volumes through full-scale window assemblies under simulated wind and WDR conditions.

This study investigated water intrusion through two full-scale window assemblies: a nonimpact-rated window and an impact-rated window. Both window systems were compliant with existing standards. Additionally, a third test case was investigated by installing an accordion shutter system over the nonimpact window to determine the shutter's ability to reduce water intrusion through the window. Major findings of this study included: 1) both the impact window and the accordion shutter test cases allowed substantially less water intrusion than the nonimpact window test case, 2) the presence of an accordion shutter system reduced the pressure differential across the nonimpact-rated window in the range of 6-14%. The accordion shutter significantly reduced the volume of water intrusion through the nonimpact window by 77-87%, 3) for the double-hung windows tested in this study, the primary locations for water intrusion were between the lower sash bottom rail and the window sill, and at the meeting rails between the upper and lower sashes.

Existing test protocols do not appear to adequately address water intrusion caused by WDR under the simulated service conditions generated in these experiments, which represented tropical storm, hurricane, and major hurricane wind velocities. Improvements to existing fenestration test protocols should be explored to better simulate WDR effects on window assemblies, thereby improving the overall resistance of the building envelope to undesirable water intrusion effects.

The results of this study demonstrate that water intrusion through a window assembly may occur well below the window's design pressure. This indicates that window assemblies which pass existing performance standards for water intrusion may not prevent water intrusion under dynamic hurricane wind conditions. It is recommended that improvements to the existing test protocols continue to be explored.

The preliminary dataset provided in this study may be used by risk modelers to enhance the general understanding of water intrusion vulnerability. For hurricane-prone regions, the presence of shutters clearly reduced the amount of water intrusion through the window. Although the impact-resistant window performed well comparatively, it is suggested that there may be merit in installing storm shutters over impact windows to further minimize water intrusion. Further experiments may be conducted with the accordion shutter installed over the impact window to determine if the water intrusion through the window can be reduced or eliminated. Future studies may explore the vulnerability of different window types beyond the double-hung styles tested in the current study. The water intrusion mitigation capabilities of other common shutter systems (e.g. vinyl screens, aluminum storm panels, and plywood sheets) should be explored.

Investigation and Incorporation of WOW Testing Outputs in the Florida Public Hurricane Loss Model (PI: Dr. Jean Paul-Pinelli and Kurt Gurley)

One of the key components of a better mitigated and therefore more disaster-resilient Florida involves recovery and reconstruction funding for homeowners, and a key element of that funding derives from insurance coverage, which is increasingly driven by cost considerations. The Florida Public Hurricane Loss Model (FPHLM), which has been supported by, provides a means of evaluating hazard insurance rate requests independently of the proprietary models used by private insurers. The model is continually refined to both satisfy the standards issued by the Florida Commission on Hurricane Loss Projection Methodology, and incorporate the current state-of-knowledge in the methodologies employed by the meteorological, engineering, actuarial, statistical, and computer science teams.

The Wall of Wind (WOW) research is largely focused on filling critical gaps in the engineering state-of-knowledge on building performance in hurricane winds via experimental methods. WOW DEM projects for FY 2016-2017 addressed the efficacy of a retrofit technique for roof-to-wall connections of residential buildings and assesses the aerodynamics of elevated homes. The incorporation of these experimental results within the FPHLM were investigated.

The summary results of this investigation are as follows:

- The fiber-reinforced polymer (FRP) roof-to-wall (r2w) connection capacity was implemented in the personal residential (PR) and commercial residential (CR) FPHLM models. The PR model simulations showed a reduction in vulnerability for the FRP retrofitted model, while the CR model showed a difference in physical damage to the r2w connections but not the resultant vulnerability. This was attributed to a difference in how the PR and CR models handle the relationship between r2w failure and wall failure, and indicates a need to update the CR model in this regard.

- The distribution of loading among adjacent r2w connections in the FPHLM was determined to be adequately similar to the FIU test results.
- The FPHLM engineering team developed an elevated single story structure model. The observations from the FIU WOW testing of an elevated single story structure guided this development. The preliminary results of the simulations demonstrate the increased vulnerability of the elevated model when compared to its on-grade companion model. This behavior is as-expected due to differences in wind speed at the roof height of an elevated and on-grade structure. Additional testing and validation of this first-generation model is required before adoption within the FPHLM model library.

The benefits of these mitigation measures (stronger FRP connections, and elevating the building) and whether or not there shall be cost effective, shall depend on the combinations of mitigation implemented, and the local wind climate.

Evaluation of Scaled Model Reliability for Study of Wind Load Path in Low-Rise Light-Framed Wood Structures (PI: Dr. Ioannis Zisis)

Wind engineering research is directly associated to the aforementioned extreme wind events. Wind-structure interaction is a special field of engineering, which has a scope to study the wind effects on buildings. Several studies were conducted specifically to evaluate the effect of wind action on structures, such as residential buildings and other shared public spaces. The contribution of both wind tunnel experiments and full-scale field monitoring on the development of modern wind standards and building codes of practice is of great significance. Concepts related to structural integrity during extreme wind events have been studied extensively using boundary layers wind tunnels and verified by monitoring wind-induced pressures on constructed buildings.

In this study, two 1:5 scaled models were constructed following the same geometry (length, width, and height of the model) of a wind tunnel test model from the Tokyo Polytechnic University database (TPU - http://wind.arch.t-kougei.ac.jp/system/eng/contents/code/tpu). Two finite element models, identical in to the physical models in overall geometry, were developed in order to compare results between the experiment and numerical simulations, and study the concept of wind load paths and structural attenuation. The objective was to generate data that can be used to evaluate the feasibility of using reduced size structural members in smaller than full scale structural models and still predict accurately their response.

When comparing the uplift forces acquired from the physical models to that estimated by the ASCE 7-16 critical value, the physical small-size members (SSM) model at 80 mph wind speed agrees well with the theoretical value, while the full-size members (FSM) model shows significant discrepancies (but most likely due to the previously noted sensor malfunctions). The load distribution between FSM and SSM models correlate well, but it also shows certain differences that can be attributed to the modified wind load paths created by the two different structural systems. This is an important finding that needs to be investigated further, which would provide more insight in the use of reduced scale members and their effect on the overall response of the structural system.

The physical testing of two models with same overall dimensions and geometry but different structural members provided significant information about the wind load transfer mechanisms to the foundation of the structure. Such information helped the research team calibrate the numerical models and study the effects of different structural properties on the overall performance of scaled structural systems. Further research is indicated to be able to provide more detailed comparisons and advanced analysis, which will be important to achieving the goal of reduced scale structural testing in a controlled laboratory setting. The accomplishment of this testing technique will allow for cost and time effective testing of different structural systems that will help us improve our knowledge of wind resilient construction methods.

Development of a Combined Storm Surge Rainfall Runoff Model Phase 1 – Proof of Concept via Initial Model Development and Testing (Dave Kelly, Yuepeng Li, Keqi Zhang)

The purpose of this project was to develop a directly coupled model combining storm surge with overland flooding caused by rainfall. The primary tasks completed include the parametrization of tidal forcing, hurricane wind driven (using two parametric model) storm surges with wetting and drying (inundation), and the parametrization of surface run-off (overland flooding) due to rainfall induced by hurricanes. These parametrizations and modules have taken place in a newly developed model that is based on the open source TELEMAC 2D hydrodynamic model.

A pilot study to develop an integrated storm surge and freshwater flood model for coastal urban areas was developed by leveraging an existing and well established hydrodynamic model. The primary tasks completed during this Phase included (1) the parameterization of tidal forcing in a robust and stable manner, (2) the incorporation of hurricane wind driven forcing, (3) the incorporation of hurricane induced storm surge inundation, (4) the parametrization of freshwater overland flooding (due to hurricane induced rainfall), and (5) the preliminary validation of South Florida Basins with historical and hypothetical hurricanes. The coding to create a stable model for this effort was much more time intensive and complex than was originally envisaged.

In addition, before the contributions of freshwater and storm surge flooding can be fully explored, the surface water runoff module needs to be completely validated. As a result, the comparison maps could not be provided at this time. The team continues to collect the freshwater flooding data of historical hurricanes to work on this issue, and will provide the detail comparison flooding maps during the 2018-19 Fiscal Year.

Development of the Method to Extract the Ground Elevations of Buildings (PI: Dr. Keqi Zhang)

The Principal Investigator was not able to complete Research Area 5 during this contract period due to a long-term illness. This activity will not be included within the scope of work during Fiscal Year 2018-19. Funds will be returned and reappropriated.

Assessing the Economic Effectiveness of Individual Property and Community Flood Mitigation Activities in Escambia County Florida (PI: Jeffrey Czajkowski, Marilyn Montogomery)

The communities of Escambia County Florida analyzed in this study - the City of Pensacola, unincorporated Escambia County, and Pensacola Beach - have several different flood problems, including notably flooding from storm surge. Specifically, this report first examines the economic effectiveness of mitigating single-family homes located in Escambia County, Florida, against storm surge risks. In this study researchers address comprehensive community-based approaches to flood risk mitigation that have a connection from mitigation benefits of individual structures to that of communities, with the goal of enhancing communities' resilience to flood risks.

The study analyzed the economic effectiveness of mitigating single-family homes against coastal surge risks by (1) elevating homes, (2) demolishing and acquiring homes, and (3) building floodwalls around homes. Three mitigation measures were examined by computing the benefit-cost ratios (BCRs) for mitigation projects. The first economic effectiveness assessment methodology is via the Federal Emergency Management Agency (FEMA) benefit-cost analysis (BCA) toolkit. In addition to the FEMA BCA toolkit, a second economic effectiveness assessment methodology was used that allows for analyzing a larger dataset of homes and incorporates a variety of sea level rise scenarios out to the year 2100 to compute future annualized avoided losses into the benefit-cost analyses.

For the FEMA BCA toolkit mitigation analysis the team analyzed a total of 39 representative sample homes across unincorporated Escambia County, the City of Pensacola, and Pensacola Beach. Any one of the three mitigation techniques can be economically effective for homes at risk to the 10% and 4% annual chance surge risk zones, or NFIP VE flood zones, with low first-floor elevations (FFEs). Demolition and acquisition is the least economically effective method, largely due to the high costs of these projects. Building floodwalls is economically effective for more homes than the other two mitigation techniques, as the costs of floodwalls are generally lower than elevation or acquisition. The sensitivity analyses of the total 39 sample homes analyzed with the Toolkit indicate that choice of discount rate (7% or 4%) has a greater impact on our results than varying the project lifetimes (ranging from 30 years to 100 years for projects).

The results of the bulk analyses on 6,820 homes across unincorporated Escambia County, the City of Pensacola, and Pensacola Beach reveal similar trends as those obtained from the Toolkit. It is generally only economically effective to mitigate homes in the 10% or 4% annual chance surge zones with low FFEs; 11 percent of the homes analyzed in the bulk analysis are in the 10% or 4% annual chance surge zones and are also economically effective to mitigate. Floodwalls are economically effective for substantially more homes than elevation, and demolition and acquisition with a 7% discount rate is not economically effective for any home in our dataset.

It is shown that mitigating individual homes against surge risks can be economically effective in particular circumstances; for example, single-family homes with low first-floor elevations and open foundations in the 10% or 4% annual chance surge zones are economically effective to elevate. However, examining the economic effectiveness of individual home mitigation cannot capture community-level benefits, as mitigating individual properties eventually translates into better neighborhood- and community-level resilience to flooding. Therefore, it is suggested that broader benefits of flood risk mitigation beyond an individual property owner must be analyzed and ultimately incorporated into a mitigation economic effectiveness analysis.

In Escambia County there are three separate communities that participate in the Community Rating System (CRS) – the City of Pensacola, Pensacola Beach, and unincorporated Escambia County. Previous research has generated the benefits from avoided losses due the CRS activities of Escambia County. However, from an economic effectiveness standpoint, the costs of implementing the CRS program in Escambia County have not been ascertained. The team initiated a pilot study in Escambia to collect this information. An overview of the approach and lessons learned are provided, with CRS cost information pending as of the date of this report. Key findings from the pilot study include: costs of managing the CRS are not regularly tracked by the CRS coordinators; basing the costs on the percentage of total points earned is a good starting point but not wholly reflective of total costs; given the external connections of the CRS to other departments and program, costs external to the CRS need to be collected; and while the existing costs of managing the program are certainly helpful, understanding the cost to improve CRS rankings would be very useful.

Education and Outreach Programs to Convey the Benefits of Various Hurricane Loss Mitigation Devises and Techniques (PI: Erik Salna)

IHRC staff developed and coordinated educational partnerships, community events, and outreach programs that promoted hurricane-loss mitigation and the objectives of the RCMP. The four efforts included:

Wall of Wind Mitigation Challenge (WOW! Challenge): Wednesday, May 23rd, 2018
The IHRC developed the Wall of Wind Mitigation Challenge (WOW! Challenge), a judged competition for South Florida high school students. As the next generation of engineers to address natural hazards and extreme weather, this STEM education event features a competition between high school teams to develop innovative wind mitigation concepts and real-life human safety and property protection solutions. The mitigation concepts are tested live at the Wall of Wind (WOW) Experimental Facility (EF), located on FIU's Engineering Campus. The objective for the 2018 Wall of Wind Mitigation Challenge was for students to improve a building's aerodynamic performance. Over 125 attendees participated in the event, including teams from six South Florida high schools, involving 100 students and 12 teachers.

Eye of the Storm (Science, Mitigation & Preparedness) Event: May 19th, 2018
The Museum of Discovery & Science (MODS), located in Fort Lauderdale, FL, assisted the IHRC in planning, coordinating and facilitating this public education event that showcased special hands-on, interactive activities and demonstrations teaching hurricane science, mitigation and preparedness. Over 2,800 people attended *Eye of the Storm* and 34 South Florida agencies and organizations participated.

Get Ready, Florida! The National Hurricane Survival Initiative:
The IHRC's Erik Salna collaborated with the National Hurricane Survival Initiative (NHSI) and their annual hurricane preparedness campaign to make hurricane safety a year-round culture in Florida. The IHRC contributed hurricane mitigation and preparedness information for protecting your family, home and business. For 2018, the NHSI focused on Florida, with a 30 minute TV program, Get Ready, Florida! Over 367,000 Florida residents have viewed the TV program with a Total Publicity Value over $1.4M.

NOAA Hurricane Awareness Tour – May 11th, 2018
In conjunction with NOAA's National Hurricane Preparedness Week, IHRC joined the NOAA Hurricane Awareness Tour at the Lakeland Linder Regional Airport in Lakeland, Florida. "Hurricane Hunter" aircraft and IHRC mitigation exhibit were on display and toured by close to 389 South Florida area students and approximately 800 public residents.

A Resource for the State of Florida

SECTION 2

Holistic Testing to Determine Wind Driven Rain (WRD) Intrusion Reduction for Shuttered Windows

A Report Submitted to:

The State of Florida Division of Emergency Management

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Holistic Testing to Determine Wind-Driven Rain (WDR) Intrusion Reduction for Shuttered Windows

Introduction

Shutter systems on windows or impact rated window systems are commonly implemented in hurricane-prone regions to mitigate the building envelope against high wind pressures and wind-borne debris impacts. However, the presence of shutter systems (or impact rated window systems) may also have a beneficial effect in mitigating against water intrusion caused by wind-driven rain (WDR). Currently, there is little information available on how shutters (or impact rated windows) can minimize water intrusion through window systems under hurricane-level wind and WDR conditions. To overcome this knowledge deficit, the objectives of the current research were to quantify water intrusion volumes through full-scale window assemblies under simulated wind and WDR conditions. Water intrusion volumes were measured with and without the presence of an accordion shutter system installed over a standard window. An impact-resistant window was also tested for comparison. The effects of wind direction and storm duration were considered during the study.

Background

The vulnerability of the building facade to WDR effects, including deterioration, interior content damage and serviceability disruptions due to mold and mildew growth, has been well-recognized in the literature (e.g. Choi 1999, Straube and Burnett 2000, Blocken and Carmeliet 2004, Salzano et al. 2010, and Kubilay et. al 2014). Specific to hurricane-prone regions in the U.S., damage assessment studies published by the Federal Emergency Management Agency (FEMA) following the active 2004 and 2005 Atlantic hurricane seasons identified several instances where significant losses to building interiors and contents directly resulted from water intrusion through various openings and breaches of the building envelope (FEMA 2005a, 2005b). More than a decade later, water intrusion continues to be a problem during hurricanes. Following Hurricane Irma in 2017, damage observations in Florida determined that soffit failures were a primary source of WDR-related water intrusion into attic spaces, which led to interior damage; these observations prompted FEMA to publish a Recovery Advisory (RA) recommending more stringent soffit design and installation details (FEMA 2018).

Since all building envelope systems are exposed to weather, there is a continuing need for WDR research to validate and enhance damage estimates generated by existing risk assessment models such as FEMA-HAZUS (discussed in Subramanian et al., 2014) and the Florida Public Hurricane Loss Model (FPHLM) (discussed in Baheru, Chowdhury, and Pinelli 2014). Currently, interior damage estimates in these models are calculated as a function of the total volume of water intrusion into a building, which is itself determined through semi-empirical models, assumed WDR parameters, and engineering judgement (Baheru, Chowdhury, and Pinelli 2014). In the absence of quantitative field or test-based data, there is a substantial level of uncertainty in the estimated volume of water intrusion and subsequent damage estimates created by the risk models. The current research project is aimed at reducing this level of uncertainty by providing a database of water intrusion volumes through full-scale window assemblies exposed to simulated hurricane wind and WDR conditions.

To date, several researchers have contributed to the development of important WDR parameters and prediction models. Choi (1993, 1994, 1999), proposed a method to determine the WDR deposition on building facades through CFD modeling of the wind flow pattern and raindrop trajectories around a building. Straube and Burnett (1998) studied the WDR-induced wetting, water penetration, and drying patterns for common brick veneer wall cladding systems, and compared their results against existing test procedures developed by the American Society for Testing and Materials (ASTM) and the American Architectural Manufacturers Association (AAMA). Straube and Burnett (2000) developed a model for predicting rainwater deposition on a building based on an analysis of more than 1,000 15-min natural rain events on a test house at the University of Waterloo in Ontario, Canada. Hangan (1999) developed a CFD model to predict raindrop trajectories and wetting patterns for two building shapes, and he compared the modeling results against experimental datasets obtained from boundary layer wind tunnel (BLWT) testing.

Blocken and Carmeliet (2004) compiled a comprehensive summary of WDR literature, examining available information across various disciplines; their paper discussed experimental measurements, semi-empirical modeling methods which combined theoretical calculations with field measurements, and numerical simulations for WDR measurements and predictions with an emphasis on building science applications. Blocken and Carmeliet (2005) described a novel setup for full-scale WDR measurements conducted on a model building instrumented at the Laboratory of Building Physics, Katholieke Universiteit Leuven, located in Flanders, Belgium. These results became a preliminary database of WDR deposition values for buildings. Abuku et al. (2009), Blocken and Carmeliet (2010), Blocken et al. (2010), and Blocken et al. (2011) compared the development and application of three different WDR models: a semi-empirical model developed by the International Standards Organization (ISO, 2009), the semi-empirical model developed by Straube and Burnett (1998, 2000), and the numerical CFD model first developed by Choi (1993, 1994) and then enhanced by Blocken and Carmeliet (2002, 2007). These papers demonstrated the ability of CFD modeling to produce reliable WDR deposition results but acknowledged the cost and complexity of the CFD modeling as major limitations to its widespread practicality; the authors recognized the importance of the semi-empirical methods, despite their limitations, and argued that CFD modeling may enhance the overall accuracy and adoption of the semi-empirical models. Foroushani et al. (2014) conducted CFD modeling to investigate the effect of roof overhangs on WDR deposition. The study found that the overhang's ability to protect the building façade was dependent on its size and on the oncoming wind parameters. Further, the presence of an overhang was able to protect the upper half of the building by reducing WDR deposition by as much as 80%, although the lower half of the building façade was generally unaffected by the presence of the overhang. Kubilay et al. (2014)

presented full-scale WDR measurements collected on the façades of two different cubic structures situated within a 3×3 array of 2 m cubes. This experimental setup was located in Dübendorf, Switzerland. Measured results were compared against predictions derived from two semi-empirical models, one of which underestimated the WDR and the other overestimated the average WDR.

Due to the specific geographical locations of most experimental datasets, the available WDR depositions were not measured under extreme wind and rain conditions associated with hurricanes. However, recent efforts have been made to characterize WDR parameters, such as raindrop size distribution (RSD) and rain rate, specifically during hurricanes to better understand these extreme weather conditions. Tokay et al. (2008) reported fundamental rain parameters acquired by disdrometer field measurements during seven tropical cyclones during the 2004-2006 Atlantic hurricane seasons. These findings indicated relatively high concentrations of small and medium-sized raindrops during tropical cyclones, producing high values for the raindrop number concentration, the liquid water content, and the rain rate. Friedrich et al. (2013) reported RSD measurements gathered during Hurricane Ike in 2008 and also during convective thunderstorm events in the Great Plains region of the United States during 2010; this research discussed inherent limitations in disdrometer measurements during high wind events and recommended the use of articulating instruments during high wind measurements to reduce certain measurement errors. Numerical modeling of WDR effects under extreme wind conditions has also been attempted. Research by van de Lindt and Dao (2009), Dao and van de Lindt (2010) and Dao and van de Lindt (2012) combined CFD and finite element (FE) modeling to develop fragility curves for rainwater intrusion through a wood frame roof system applicable to residential construction. These results led to the development of a loss model for both structural and nonstructural losses in wood frame construction due to hurricanes, where the nonstructural losses were primarily attributed to rainwater intrusion (van de Lindt and Dao 2012).

Although full-scale field measurements are necessary for validation of semi-empirical and numerical modeling of WDR effects, one major limitation to full-scale field measurements is the temporal dependence on natural wind and rain events to occur before useful data may be acquired. One method for overcoming this limitation is the development of large-scale testing facilities capable of simulating accurate and repeatable wind and WDR conditions. At the University of Florida (UF), Salzano et al. (2010) conducted an extensive study of water penetration at the window-wall interface using common installation methods for residential wood framing and concrete masonry walls. In this study, the window systems were tested in an air chamber under static air pressure conditions and cyclic air pressure conditions, as well as under dynamic WDR conditions generated by the UF Hurricane Simulator; the pressure and time of leakage were reported by Salzano et al. (2010), but water intrusion volumes were not measured. Van Straaten et al. (2010) explored the possibility of testing window assemblies under more accurate wind loading patterns when compared to a conventional test protocol, ASTM E331 (American Society for Testing and Materials 2000). To accomplish this, researchers installed a pressure load actuator (PLA) system over a full-scale window assembly.

Pressure time histories obtained from BLWT testing were reproduced by the PLA system to simulate realistic time-varying wind loads on the window. At Florida International University (FIU), Bitsuamlak et al. (2009) assessed water intrusion through secondary water barriers on a roof system under simulated hurricane conditions with the six-fan Wall of Wind (WOW) facility. Chowdhury et al. (2011) conducted similar experiments with the 6-fan WOW system to investigate water intrusion volumes through commonly installed roof vent devices. Baheru, Chowdhury, Bitsuamlak, Masters, and Tokay (2014) and Baheru, Chowdhury, Pinelli, and Bitsuamlak (2014) reported their efforts to simulate hurricane-level wind and WDR conditions with the 12-fan WOW facility at FIU. Under these simulated conditions, Baheru, Chowdhury, and Pinelli (2014) conducted a detailed study of water deposition on the façade of a 1:4 scale residential building model to improve the risk assessment methodology in the FPHLM.

In general, the primary attributes that govern building water intrusion may be categorized as the following: pathways, sources, and driving forces (Beall 2000). Baheru, Chowdhury, and Pinelli (2014) summarized three distinct pathways for water intrusion into buildings: 1) envelope defects, such as poorly sealed joints or penetrations in the building envelope; 2) existing openings, such as roof, attic, and soffit vents; and 3) envelope breaches, such as openings that result from component failure or debris impact. Sources of WDR water intrusion are typically divided into two subcategories: water that enters an opening or breach due to directly impinging raindrops versus water that enters due to surface runoff rainwater that has accumulated around the opening or breach. Finally, driving forces for WDR have been identified as the wind-induced inertial force, the gravitational force, and the viscous force of the liquid; of these three, the wind-induced inertial force is the predominant driving force of WDR through a building's wall (Baheru, Chowdhury, and Pinelli 2014). The scope of the current research project is focused primarily on determining water intrusion through an envelope defect – specifically, the water intrusion volume through window systems due to wind-induced inertial forces.

From a design perspective, windows and shutters must be able to withstand the Components and Cladding (C&C) design loads for the region of installation, as determined by ASCE 7. Additionally, local jurisdictions may require specific product approvals for window and shutter systems since they are essential for maintaining the integrity of the building envelope. External building components installed in coastal regions of South Florida must satisfy the minimum test requirements described in *Florida Building Code, Test Protocols for High-Velocity Hurricane Zones* (International Code Council, Inc., 2017). Within this volume of the *Florida Building Code* (FBC), window systems installed in the High Velocity Hurricane Zone (HVHZ) may fall under the requirements of Testing and Application Standard (TAS) 201, 202, and 203. TAS 201 details windborne debris impact testing requirements, TAS 202 describes requirements for uniform static air pressure testing and water intrusion resistance, and TAS 203 designates the requirements for cyclic pressure loadings. Nonimpact-rated windows are required to satisfy TAS 202 requirements only, whereas impact-rated windows would be required to satisfy all three of these standards. One outcome of these testing standards is the experimental validation of window design pressure (DP), defined as the uniform static positive or negative air pressure that a window system is designed to withstand under service load conditions.

Considering the above testing standards, water intrusion is only addressed in the TAS 202 standard. The TAS 202 test procedure requires an application of 75% DP in the positive and negative directions for 30 s each, and then this process is repeated at 150% DP for the same 30 s durations. After the window assembly passes the uniform static pressure testing, water is then applied to the window at a minimum rate of 5 gallons per hour (gph) per square foot, which correlates to a rain rate of approximately 8.0 in/hr on the test specimen. The TAS protocol requires the rain simulation to occur with a minimum static air pressure of 15% DP applied across the window for a duration of at least 15 min. It is hypothesized that this procedure does not adequately determine a window assembly's ability to resist water intrusion for two reasons: First, the water intrusion requirements are conducted at only 15% DP, a much lower DP than what the window may experience during hurricane-level WDR events under service conditions. Second, while the application of static air pressure is sufficient to determine the strength of the window assembly, it does not replicate the dynamic time-dependent pummeling effect of the wind and rain on the window assembly that would occur during an actual hurricane. Since the wind-induced inertial force is a primary driving force of water intrusion, the necessary dynamic interaction that may force water to flow through a potential envelope defect is lacking in the standard test protocols.

Methodology

To achieve the project objectives, water intrusion volumes were investigated for three test configurations, hereafter described as follows:

1. Nonimpact window
2. Impact-resistant window
3. Accordion shutter (installed over the nonimpact window)

Full-scale window assemblies were installed on a large-scale building model, which was then tested under simulated wind and WDR conditions generated by the 12-fan WOW. The current water intrusion research was conducted on a large-scale residential building model constructed from structural insulated panels (SIPs). The test model had dimensions of approximately 108 × 96 × 118 in (L × W × H), and a gable roof (5:12 slope) with 12 in overhangs on all sides. One full-scale window was installed on each of the four walls of the SIP model, and a 28 × 80 in door was installed on one of the eave walls for interior access. All windows fit into rough openings of 26.5 × 38.375 in. The SIP material consisted of an insulating foam core sandwiched between two fiberglass sheathing surfaces, and this material comprised all four walls and the roof of the structure. The SIP material was not vulnerable to water absorption or saturation from the WDR, which was advantageous for the current water intrusion study because the focus was water intrusion through the window assembly itself. A sealant was carefully applied around the window-wall interfaces during window installation to minimize the potential for water intrusion through these joints. The SIP model was built on top of a custom steel base, which secured the building model to the WOW turntable. Additionally, two large ratchet straps were installed over the roof of the SIP building model as an additional precaution to avoid any damage to the building at the highest wind speeds tested. An image of the SIP building model is shown in Figure 1, and the three window test configurations are shown in Figures 2a-2c.

Figure 1 Large-scale SIP building model installed on WOW turntable.

Figure 2 Window and shutter test configurations: a) Nonimpact window, b) Impact-resistant window, and c) Accordion shutter (installed over nonimpact window).

Due to the symmetry of the gable end walls on the SIP building model, the gable windows were chosen for the current water intrusion study. The nonimpact window was installed on one gable wall, and the impact-resistant window was installed on the opposite gable wall. The accordion shutter system was installed over the nonimpact window during the shutter tests, and it was completely removed from the wall during the nonimpact window tests, as shown in Figure 2. To investigate the effect of wind direction, the windows were tested with winds applied normal to the gable end wall (defined as the 0° wind direction), and at oblique angles of +/- 15° from the perpendicular position (defined as 15° and 345° wind directions, respectively). A diagram of the test setup illustrating the experimental wind directions is shown in Figure 3.

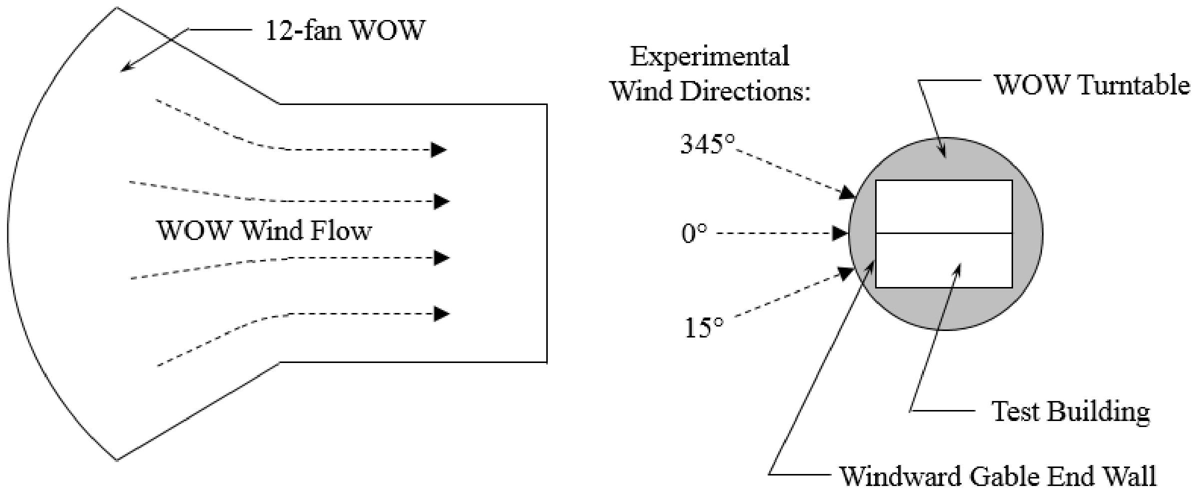

Figure 3 Plan view diagram of experimental test setup.

The specific windows chosen for this study were off-the-shelf double-hung window assemblies purchased from a local home improvement store. Manufacturers' documentation indicated that the standard window conformed with the TAS 202 requirements, and the impact-rated window conformed with the TAS 201, TAS 202, and TAS 203 requirements. The documentation stated the standard window DP was +/- 50 psf, and the impact window DP was +/- 60 psf. The extruded aluminum accordion shutter system was custom fabricated for the test windows by a licensed South Florida shutter vendor. Documentation was provided with the shutter system to verify that the design conformed with HVHZ requirements of the 2017 FBC, 6th ed.

Limitations of typical static pressure testing were overcome in this project by subjecting the test window assemblies to dynamic wind and WDR conditions generated by the 12-fan WOW facility at FIU. Researchers decided to study the water intrusion effects at three target window pressures: approximately 15-20% DP, 30-35% DP, and the maximum window pressure achievable by the 12-fan WOW. The lowest %DP values were chosen to compare WOW test results with the TAS 202 requirements, and the two other %DP values were chosen to understand the potential water intrusion impacts under hurricane and major hurricane conditions. The target window pressures were generated by adjusting the 12-fan WOW throttle rate to yield different wind speeds applied to the test specimen. To determine wind speeds that would generate the target window pressures for WDR testing, the pressure differential across the window needed to be measured at various wind speeds. This was accomplished by temporarily lifting the lower sash of the nonimpact window and installing a mock plexiglass windowpane within the window frame (Fig. 4a). The mock windowpane allowed researchers to collect pressure measurements without compromising the integrity of the actual window glass during the subsequent WDR testing. The mock windowpane contained six internal and six external pressure taps (Fig. 4b). The difference between the internal and external pressure measurements at a given location yielded the window pressure differential (or the net pressure) at that point. A Scanivalve DSM 4000 acquired pressure time histories from a ZOC33 pressure scanner attached to the pressure taps (Fig 4c). Initial pressure data was sampled at a rate of 520 Hz and a WOW throttle rate of 73% (approximately 100 mph wind speed on the window assembly). The window pressure differential was analyzed on a 3-sec gust basis. Initial pressure test results indicated WOW throttle percentages of 45%, 57%, and 100% would yield the approximate window %DPs of interest. These corresponded to respective test wind speeds of 62 mph, 78 mph, and 137 mph measured at the center of the window assembly. Window pressure measurements were recorded at WOW throttle rates of 45%, 57% and 80% to ensure consistency of the peak pressure coefficient across the window at different wind speeds. Note that pressure data were not collected at 100% WOW throttle due to measurement range limitations of the ZOC33 module. Instead, the window %DP was estimated for WOW 100% throttle based on the 3-sec peak pressure coefficients determined from the other wind speeds tested.

Figure 4 Window Pressure Measurement Setup: a) Mock plexiglass windowpane, b) Internal and external pressure tap detail, and c) Scanivalve pressure measurement system located inside the test building.

Following the pressure testing, WDR tests were conducted to quantify the volume of water intrusion through the windows. WDR tests were conducted for the three test wind speeds at different time intervals: the lowest, middle, and highest wind speed tests were conducted for 15 min, 10 min, and 3 min durations, respectively. To collect water intrusion, custom-made catch basins were designed and constructed from nominal 1/4" inch clear plexiglass sheeting. The catch basins were mounted with bolts onto the internal walls of the building model surrounding each window opening. A generous bead of marine-grade adhesive/sealant was placed between the catch basin and the interior wall to form a water-tight seal between the two surfaces. An air vent was located at the top of the catch basin to maintain the correct internal pressure on the window; the design and location of the air vent minimized the possibility of any water intrusion through the window from escaping the catch basin. A drain, located at the bottom of the catch basin, was built from a PVC ball valve and 3/8-in ID tubing; this allowed researchers to drain out the collected water at the end of each test. Figure 5 shows the typical catch basin installation details. The data collection procedure adopted during the WDR tests was to visually document the collected water with a photograph, and then drain the water from the catch basin into collection bags. The mass of water collected during each test was determined by weighing the difference of the water collection bags before and after the test. The volume of water intrusion was calculated from the measured mass of collected water and the known density of water. Since the catch basins were constructed from transparent plexiglass panels, GoPro cameras were placed around the exterior of the catch basin to record video of the water intrusion during each test (Fig. 5). The goal of video recording was to aid in identifying the specific location(s) of water entry through the window systems since the building model could not be occupied during the wind testing for safety reasons. It is noted that the windows were tested in the fully closed positions with all latches engaged prior to the installation of the water catch basins. It is also noted that the exterior window insect screens were removed during the WDR tests conducted in this study. A summary of the test protocol considered during this study is shown in Table 1.

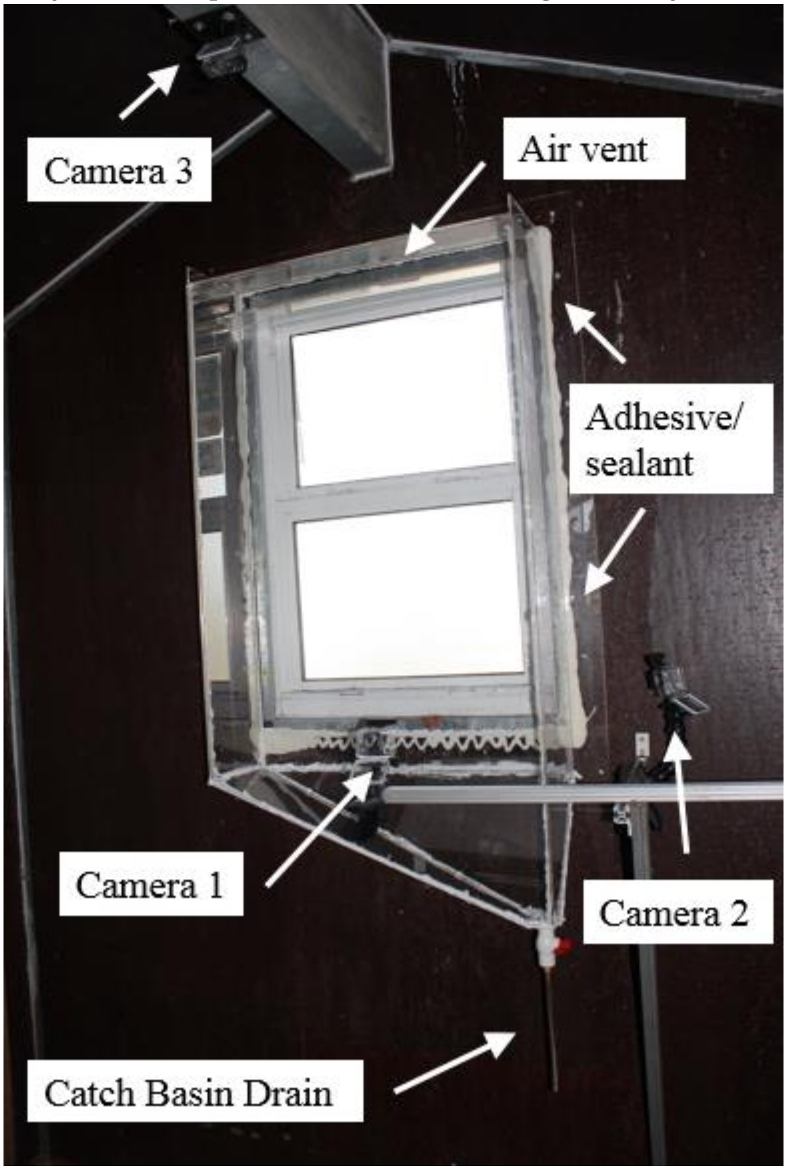

Figure 5 Catch basin installation for WDR testing.

Test Case	Pressure Measurement Configuration	Wind Driven Rain	Wind Direction(s)	WOW Throttle %	Target wind speed[a] (mph)	Test Duration
Pressure	Preliminary	None	0°	73	100	2 min
Pressure	Nonimpact	None	345°, 0°, 15°	45	62	2 min
Pressure	Nonimpact	None	345°, 0°, 15°	57	78	2 min
Pressure	Nonimpact	None	345°, 0°, 15°	80	110	2 min
Pressure	Accordion	None	345°, 0°, 15°	45	62	2 min
Pressure	Accordion	None	345°, 0°, 15°	57	78	2 min
Pressure	Accordion	None	345°, 0°, 15°	80	110	2 min
Nonimpact	None	Yes	345°, 0°, 15°	45	62	15 min
Nonimpact	None	Yes	345°, 0°, 15°	57	78	10 min
Nonimpact	None	Yes	345°, 0°, 15°	100	137	3 min
Impact	None	Yes	345°, 0°, 15°	45	62	15 min
Impact	None	Yes	345°, 0°, 15°	57	78	10 min
Impact	None	Yes	345°, 0°, 15°	100	137	3 min
Accordion	None	Yes	345°, 0°, 15°	45	62	15 min
Accordion	None	Yes	345°, 0°, 15°	57	78	10 min
Accordion	None	Yes	345°, 0°, 15°	100	137	3 min

[a]3-sec gust at mid-window height (z = 72 in)

Table 1 Window pressure and WDR test matrix

Atmospheric boundary layer (ABL) and turbulence characteristics are simulated at the 12-fan WOW facility by a system of triangular spires and floor roughness elements (Fig 6). The arrangement of spires and roughness elements during this study produced open terrain characteristics. Wind velocity and turbulence characteristics were recorded through a series of pitot-static and high frequency cobra probe measurements. The 12-fan WOW open terrain ABL profile is shown in Figure 7. Wind speeds reported in this study were recorded at a height of $z = 72$ in, the approximate mid-height of the windows above ground level. This reference height was chosen to correlate wind speed characteristics with available WDR information. Prior to conducting the water intrusion experiments, researchers verified the total water flow rate through the 12-fan WOW WDR system to be approximately 24 gpm, corresponding to a rainfall intensity of approximately 8.5 in/hr across the wind field cross sectional area, which is comparable to the TAS 202 required rain rate.

Figure 6 12-fan WOW spires and floor roughness elements.

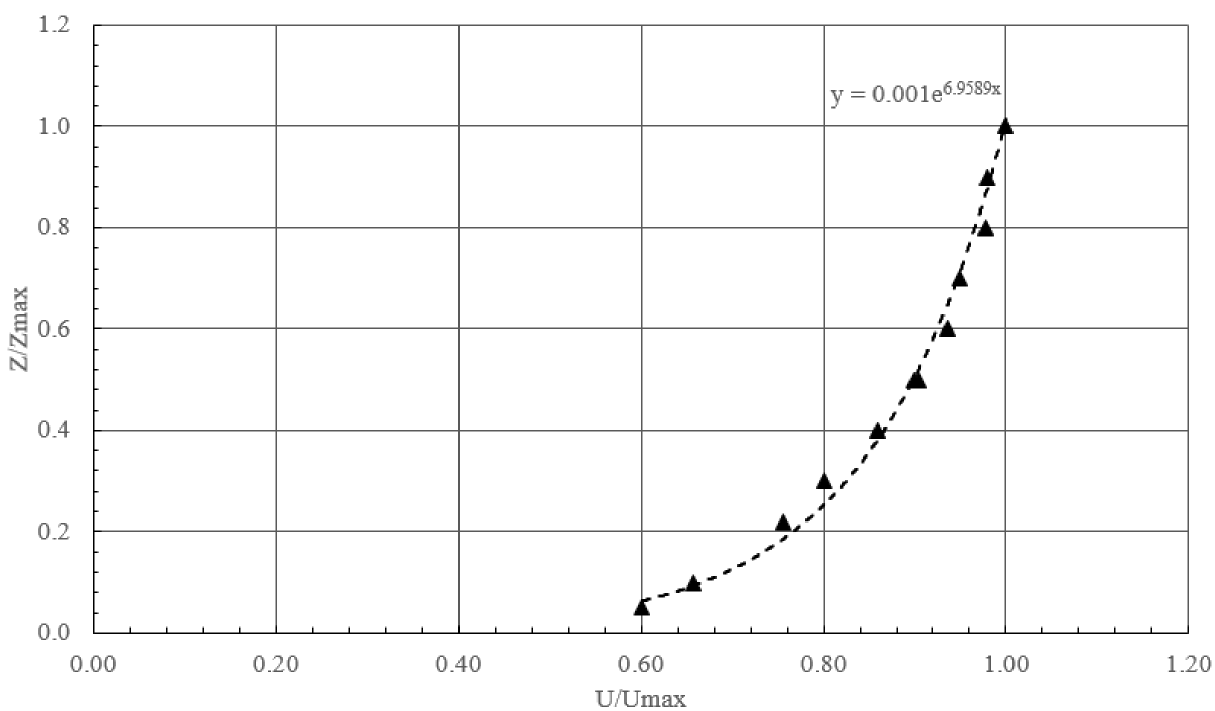

Figure 7 12-fan WOW mean velocity profile for open terrain.

Calculations

Baheru, Chowdhury, and Pinelli (2014) expressed water intrusion information for a given location on the building façade in terms of two nondimensional parameters: the rain admittance factor (RAF) to quantify water intrusion due to direct impinging raindrops, and the surface runoff coefficient (SRC) to quantify water intrusion due to surface runoff rainwater. RAF and SRC are calculated by Equations 1 and 2, respectively:

$$RAF = \frac{RR_{b,\mathrm{DI}}}{RR_v} \tag{1}$$

$$SRC = \frac{RR_{b,\mathrm{SR}}}{RR_v} \tag{2}$$

The term $RR_{b,\mathrm{DI}}$ in Equation 1 is defined as the rain rate at a given point on the building facade due to direct impinging raindrops, and the term $RR_{b,\mathrm{SR}}$ in Equation 2 is defined as the rain rate at a given point on the building facade due to the surface runoff rainwater. In both equations, the and the term RR_v is the free stream wind driven rain rate measured at a given reference height. Values of $RR_{b,\mathrm{DI}}$ and $RR_{b,\mathrm{SR}}$ are found by Equations 3 and 4, respectively:

$$RR_{b,DI} = \frac{V_{o,\mathrm{DI}}}{A_o t} \tag{3}$$

$$RR_{b,SR} = \frac{V_{o,\mathrm{SR}}}{A_{\mathrm{SR}} t} \tag{4}$$

In Equation 3, $V_{o,\mathrm{DI}}$ is the volume of water that enters an opening due to direct impinging raindrops, and A_o is the area of the opening. Similarly, for Equation 4, the term $V_{o,\mathrm{SR}}$ is the volume of water that enters an opening due to surface runoff rainwater, and A_{SR} is defined as the area of the building façade over which surface runoff rainwater may reach a given opening. For both equations, t is the duration of the WDR event. In general, the total volume of WDR intrusion through a given opening on a building envelope, V_{tot}, may be calculated as the sum of the water intrusion volume due to direct impinging raindrops, V_{DI}, and the water intrusion volume due to surface runoff rainwater, V_{SR}:

$$V_{tot} = V_{DI} + V_{SR} \tag{5}$$

Rather than attempting to distinguish the volume of water intrusion due to direct impinging raindrops versus the volume due to surface runoff, the current study focused on finding the total volume of water intrusion, V_{tot}, accumulated from both water intrusion mechanisms impacting the window simultaneously. Consequently, RAF and SRC values are not reported. Instead, the observed water intrusion is reported as the total rain rate into the building through the window as a function of the total volume of water intrusion, symbolized here as $RR_{b,tot}$. Values of $RR_{b,tot}$ were calculated according to Equation 6, below.

$$RR_{b,tot} = \frac{V_{tot}}{A_e t} \tag{6}$$

In Equation 6, the total volume, V_{tot}, has the same meaning as defined in Equation 5, and t again represents the duration of the WDR event. The term A_e was adopted here to represent the effective area of the window for the combined effects of direct impinging raindrops and surface runoff rainwater. The effective area was calculated as the area of the window itself (direct impinging raindrop region) plus the area of the wall directly above the window extending to the gable roof overhang (surface runoff region). Because the standard window and the impact-resistant window were of the same dimensions, the effective area applied to these two test cases was the same; however, a larger effective area was applied to the accordion shutter test case because the accordion shutter framing extended wider, above, and below the window opening. Measurements used to calculate the effective areas are illustrated in Figure 8.

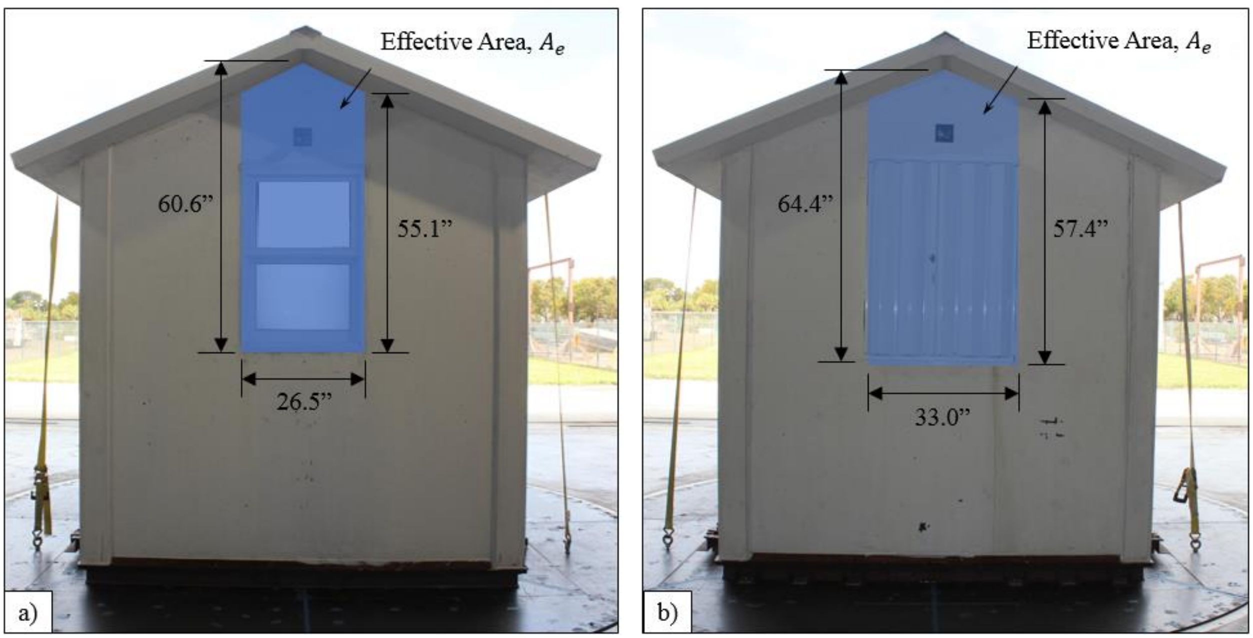

Figure 8 Dimensions for calculating window effective area, A_e. a) Nonimpact and impact-resistant windows, and b) Accordion shutter.

Results

Analysis of the pressure measurements revealed that the 3-sec gust peak pressure coefficients were similar for all pressure taps, confirming that pressures on windows are spatially uniform for small windows away from the corners of the building (Van Straaten et al., 2010). A summary of results for the pressure measurement test cases are shown in Table 2. These findings indicate that the 3-sec peak pressure differential across the mock windowpane was consistent among all wind speeds tested. The measured pressure coefficients were used to predict the differential pressure across the window during the full speed test cases (WOW 100% throttle/137 mph wind speed at mean window height). A small sheltering effect on the window pressure differential due to the accordion shutter can be seen in the data by the slight decrease in pressure coefficients when comparing the window only test case to the equivalent accordion shutter test case. In terms of the measured pressure differential across the interior and exterior surfaces of the window, the sheltering effect caused by the presence of the accordion shutter ranged between 6-14% for the wind angles measured in this study. There is also a small discrepancy between the observed pressure coefficients for the 345° and 15° test cases, with the 15° test case yielding slightly higher pressure coefficients.

Pressure Measurement Case	Wind Direction (deg)	Window Pressure Differential, $C_{p,3\ sec}$			
		62 mph	78 mph	110 mph	137 mph (estimated)
Nonimpact	345°	1.1	1.1	1.1	1.1
Nonimpact	0°	1.3	1.3	1.3	1.3
Nonimpact	15°	1.2	1.2	1.2	1.2
Accordion	345°	0.9	0.9	0.9	0.9
Accordion	0°	1.2	1.2	1.2	1.2
Accordion	15°	1.1	1.1	1.0	1.1

Table 2 Window pressure measurement results

WDR test results are summarized in Table 3, and Plots of $RR_{b,tot}$ vs. %DP are shown in Figure 10 for each wind angle tested. The WDR test results show that significant amounts of water intrusion were observed for all test cases considered in this study. Overall, the standard nonimpact window allowed the largest amount of water intrusion. Both the impact window and the accordion shutter test cases allowed substantially less water intrusion than the nonimpact window test case. Although the impact-resistant window allowed slightly less water intrusion in terms of volume compared to the accordion shutter case, the impact window and the accordion shutter allowed similar rates of water intrusion in terms of $RR_{b,tot}$ due to the accordion shutter's larger effective area.

Test Case	Wind Speed[a] (mph)	345° Wind Direction				0° Wind Direction				15° Wind Direction			
		Window ΔP (psf)	%DP	V_{tot} (in^3)	$RR_{b,tot}$ (in/hr)	Window ΔP (psf)	%DP	V_{tot} (in^3)	$RR_{b,tot}$ (in/hr)	Window ΔP (psf)	%DP	V_{tot} (in^3)	$RR_{b,tot}$ (in/hr)
Nonimpact	62	10.7	21.4%	70.9	0.185	12.7	25.4%	536.1	1.399	11.9	23.8%	325.1	0.848
Nonimpact	78	17.0	34.1%	273.9	1.072	20.4	40.9%	321.0	1.256	18.9	37.9%	250.4	0.980
Nonimpact	137	51.8	103.6%	70.2	0.916	62.1	124.3%	72.9	0.951	57.8	115.6%	60.8	0.794
Impact	62	10.7	17.8%	29.2	0.076	12.7	21.2%	40.1	0.105	11.9	19.8%	52.7	0.137
Impact	78	17.0	28.4%	25.8	0.101	20.4	34.1%	45.8	0.179	18.9	31.6%	41.2	0.161
Impact	137	51.8	86.3%	8.9	0.116	62.1	103.6%	11.8	0.154	57.8	96.4%	8.7	0.113
Accordion	62	9.3	18.6%	50.5	0.100	11.9	23.7%	76.0	0.151	10.7	21.4%	48.8	0.097
Accordion	78	14.7	29.4%	44.5	0.133	18.8	37.6%	71.4	0.213	16.8	33.5%	32.7	0.097
Accordion	137	45.2	90.4%	14.2	0.141	57.1	114.1%	15.1	0.150	51.3	102.7%	10.6	0.106

[a]3-sec gust at mid-window height (z = 72 in)

Table 3 Experimental results for WDR-induced water intrusion through windows.

For all three test configurations, the greatest amount of water intrusion occurred at the 0° wind direction when the wind and WDR were applied perpendicular to the gable end wall; less water intrusion occurred at both 15° and 345°, indicating that *normal* winds (i.e., winds perpendicular to the window systems) are likely the worst-case scenario for water intrusion. The largest overall volume of water intrusion observed was 536.1 in^3 through the nonimpact window at the 0° wind direction, 62 mph test case. This volume correlates to an equivalent water intrusion rate, $RR_{b,tot}$, of 1.399 in/hr through the standard window at approximately 25% DP. Conversely, the least amount of water intrusion observed was 8.7 in^3, which correlated to a water intrusion rate of $RR_{b,tot} = 0.113$ in/hr through the impact window at 96% DP.

The plots in Figure 9 show a generally flat trend for the water intrusion rate through the impact window and accordion shutter test cases, indicating that the water intrusion rate was minimally affected by wind speed and test duration for these two test cases. For the nonimpact window, the observed water intrusion rate generally decreased as the wind-induced %DP increased on the window, with a major exception occurring during the 62 mph test case at 345°. It is hypothesized that the simulated RSD may play a role in this decreasing trend. As the wind speeds around the building model increased, the smaller-sized raindrops in the WOW experimental simulation may have been carried around the building model by the strong flow pattern, rather than hitting the windward wall.

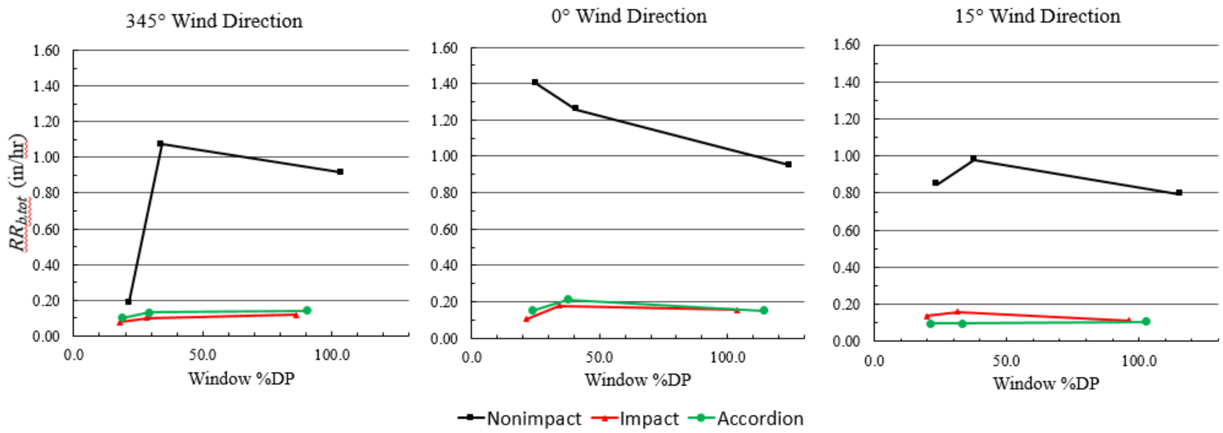

Figure 9 Plots of $RR_{b,tot}$ vs. %DP for WDR testing.

Notably, the WDR results indicate that the presence of the accordion shutter system significantly reduced the amount of water intrusion through the nonimpact window. Neglecting the anomalous 62 mph test case at 345°, the presence of the accordion shutter reduced the amount of water intrusion through the nonimpact window by 77-87%, even though the window pressure differentials were only reduced by 6-14%. Figure 10 shows a side-by-side comparison of the water collected in the catch basin for the 0° wind direction 62 mph test cases, with and without the accordion shutter installed. This provides compelling evidence that the installation of hurricane shutters may have benefits beyond impact resistance by also mitigating risks associated with water intrusion through windows and doors.

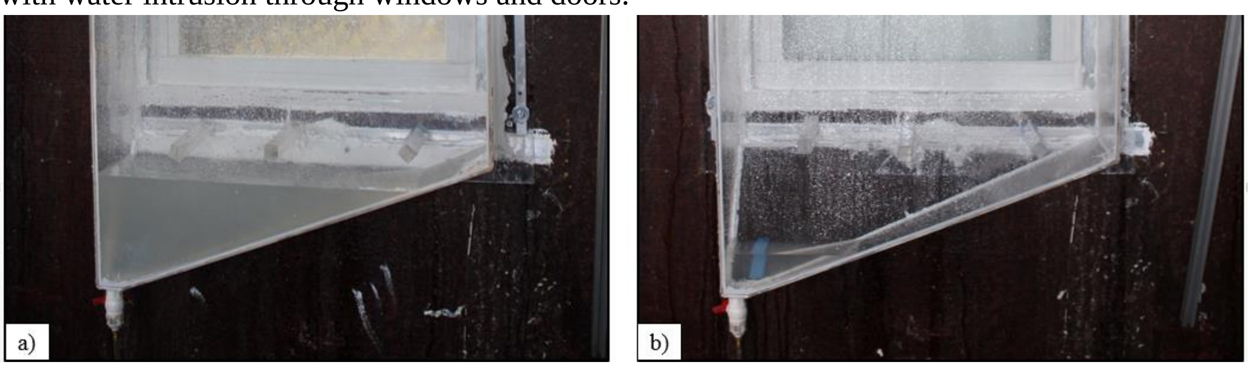

Figure 10 Comparison of water intrusion collected in catch basin for 0° wind direction, 62 mph test case. a) Nonimpact window, and b) Accordion shutter.

Analysis of video footage revealed the predominant water intrusion locations for each test case. First, video footage of the nonimpact window revealed that water entered between the bottom rail of the lower sash and the window sill, and also through the meeting rails (check rails) between the upper and lower sashes of the double-hung window. Visually, it appeared that the greatest amount of water intrusion was through the lower left corner of the window when viewing the window from the interior of the building outward. An example of the observed water intrusion is shown in a still shot from the video recorded during the 62 mph, 0° wind direction test case (Fig. 11). Second, video footage revealed that the impact window allowed water intrusion primarily at the corners between the lower sash bottom rail and the window sill. Water did not immediately enter the window when the WDR experiments began but occurred after several minutes elapsed and enough water accumulated at the bottom of the window to spill over the top of the sill back plate. Once the accumulated water was high enough to spill over the sill, it continued steadily flowing for the remainder of the tests (Fig. 12). Third, video footage of the accordion shutter tests revealed water intrusion predominantly occurred along the seam between the bottom rail of the lower sash and the window sill. It appeared that surface runoff rainwater entering from above the window/shutter setup and raindrops being blown upward from the bottom openings of the shutter were the sources of this water intrusion. Compared to the nonimpact tests, video footage of the accordion shutter tests did not reveal any noticeable water entering through the meeting rails between the upper and lower window sashes, indicating a beneficial sheltering effect due to the presence of the window (Fig. 13).

Figure 11 Observed water intrusion through the nonimpact window (62 mph, 0° wind direction).

Figure 12 Observed water intrusion through the impact-rated window (62 mph, 0° wind direction): a) prior to water intrusion, b) water intrusion commencement, and c) steady flow of water intrusion for remainder of test.

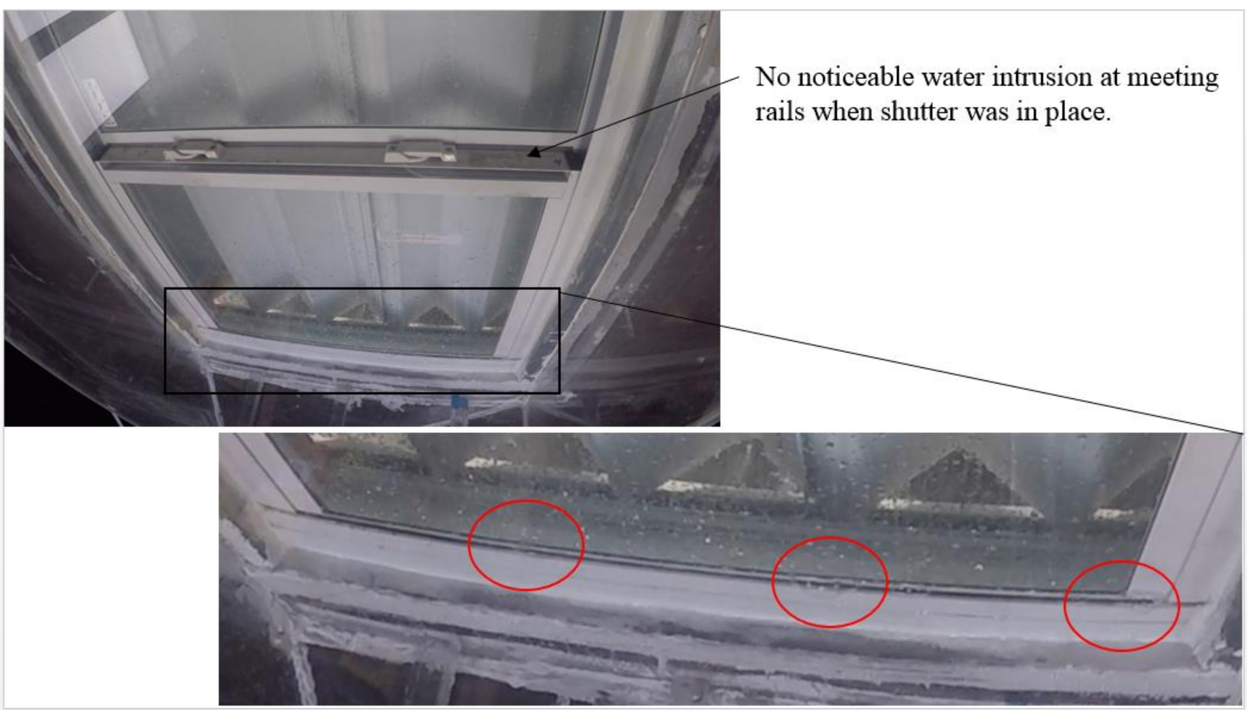

Figure 13 Observed water intrusion through the nonimpact window with the accordion shutter installed (62 mph).

Conclusions

This study investigated water intrusion through two full-scale window assemblies: a nonimpact-rated window and an impact-rated window. Both window systems were compliant with existing TAS standards for the HVHZ. Additionally, a third test case was investigated by installing an accordion shutter system over the nonimpact window to determine the shutter's ability to reduce water intrusion through the window. The following points summarize the findings of this study:

- Water intrusion was observed for all wind speeds and wind directions tested in this study.
- Both the impact window and the accordion shutter test cases allowed substantially less water intrusion than the nonimpact window test case.
- The presence of an accordion shutter system reduced the pressure differential across the nonimpact-rated window in the range of 6-14%. The accordion shutter significantly reduced the volume of water intrusion through the nonimpact window by 77-87% (excluding the 345° wind direction, 62 mph test case).
- For the double-hung windows tested in this study, the primary locations for water intrusion were between the lower sash bottom rail and the window sill, and at the meeting rails between the upper and lower sashes.
- Existing test protocols do not appear to adequately address water intrusion caused by WDR under the simulated service conditions generated in these experiments, which represented tropical storm, hurricane, and major hurricane wind velocities.
- Improvements to existing fenestration test protocols should be explored to better simulate WDR effects on window assemblies, thereby improving the overall resistance of the building envelope to undesirable water intrusion effects.

The research findings can be incorporated in the Florida Public Hurricane Loss Model to assess cost-benefit of the WDR mitigation technology and hurricane loss modeling for buildings with shuttered and impact windows.

The results of this study demonstrate that water intrusion through a window assembly may occur well below the window's DP. This indicates that window assemblies which pass existing performance standards for water intrusion may not prevent water intrusion under dynamic hurricane wind conditions. It is recommended that improvements to the existing test protocols continue to be explored. Since large-scale wind testing is not economically viable for widespread adoption, improved pressure testing methods, such as the PLA system coupled with BLWT data as suggested by Van Straaten et al. (2010), may be a promising enhancement to existing product approval methodologies.

The preliminary dataset provided in this study may be used by risk modelers to enhance the general understanding of water intrusion vulnerability. For hurricane-prone regions, the presence of shutters clearly reduced the amount of water intrusion through the window. Although the impact-resistant window performed well comparatively, it is suggested that there may be merit in installing storm shutters over impact windows to further minimize water intrusion. Further experiments may be conducted with the accordion shutter installed over the impact window to determine if the water intrusion through the window can be reduced or eliminated. Future studies may explore the vulnerability of different window types beyond the double-hung styles tested in the current study. The water intrusion mitigation capabilities of other common shutter systems (e.g. vinyl screens, aluminum storm panels, and plywood sheets) should be explored.

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FIU International Hurricane Research Center

FLORIDA INTERNATIONAL UNIVERSITY

A Resource for the State of Florida

SECTION 3

Investigation and Incorporation of Wall of Wind testing outputs in the Florida Public Hurricane Loss Model

A Report Submitted to:
The State of Florida Division of Emergency Management

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INVESTIGATION AND INCORPORATION OF WOW TESTING OUTPUTS IN THE FLORIDA PUBLIC HURRICANE LOSS MODEL

Introduction.

One of the key components of a better mitigated and therefore more disaster-resilient Florida involves recovery and reconstruction funding for homeowners, and a key element of that funding derives from insurance coverage, which is increasingly driven by cost considerations. The Florida Public Hurricane Loss Model (FPHLM), which has been supported by, provides a means of evaluating hazard insurance rate requests independently of the proprietary models used by private insurers. The model is continually refined to both satisfy the standards issued by the Florida Commission on Hurricane Loss Projection Methodology, and incorporate the current state-of-knowledge in the methodologies employed by the meteorological, engineering, actuarial, statistical, and computer science teams.

The Wall of Wind (WOW) research is largely focused on filling critical gaps in the engineering state-of-knowledge on building performance in hurricane winds via experimental methods. WOW DEM projects for FY 2016-2017 address the efficacy of a retrofit technique for roof-to-wall connections of residential buildings and assesses the aerodynamics of elevated homes. The incorporation of these experimental results within the FPHLM is investigated in this report.

1 Evaluation and processing of the WOW test results under investigation (FIU 2017-2018).

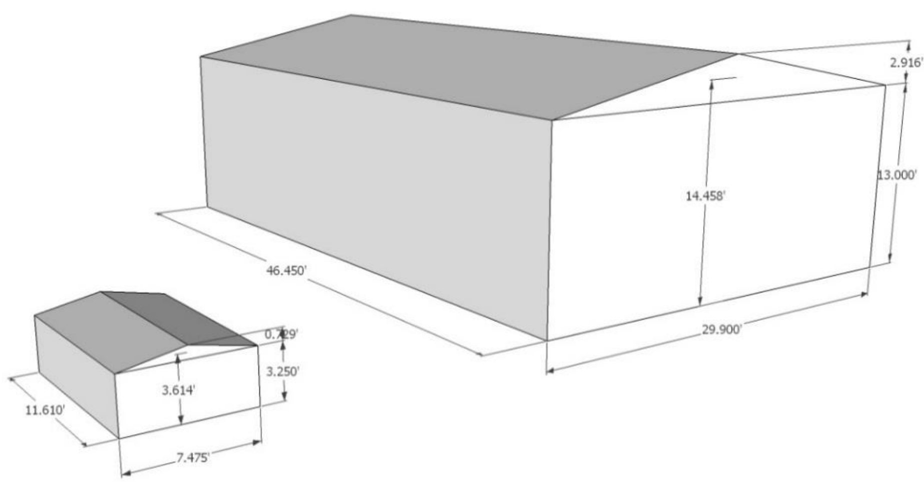
Research included the evaluation of FRP (fiber-reinforced polymer) roof-to-wall connection retrofits (r2w), wind uplift load distributions for roof to wall connections, and wind loads on elevated structures.

- FRP roof-to-wall connection retrofits

FIU performed a series of laboratory experiments to determine the applicability and strength of fiber-reinforced polymer composite materials to replace or enhance the connections between the roof and wall systems in residential construction. The published results (Canbek et al. 2011) were the basis for the investigation to incorporate FRP into the FPHLM. FIU investigated multiple configurations (applications). Among the configurations tested, Configuration ‘A’ using GFRP (glass fiber-reinforced polymer) was chosen for modeling in the FPHLM. This is consistent with the authors' recommendation based on field application feasibility.

- Roof to wall wind uplift load distribution

FIU constructed a 1:4 scale model of a rectangular gable end building, typical of residential construction (Figure 1). Load cells were placed at the interface of the walls and roof in four locations to measure the resultant wind uplift when the model is subjected to strong winds in the WOW facility (Figure 2). The four locations were in the corner, midway along the roofline, and two additional locations in between (Figure 3). The purpose is to quantify both the nominal uplift and the distribution of this uplift along the length of the roofline. The FPHLM represents uplift load at each individual connection using load sharing tributary area concepts as the load on the roof is transferred through the r2w connections and into the walls. This investigation compares the resultant r2w load distribution currently employed in the FPHLM with that measured in the WOW facility to assess either sufficient similarity or a motivation to modify the FPHLM.



1:4 Scale model Full scale

Figure 1: Scale model (tested) and full scale subject (source: FIU)

Figure 2: 1:4 scale model on WOW turntable (left). Installed load cell at r2w connection (right) (source: FIU)

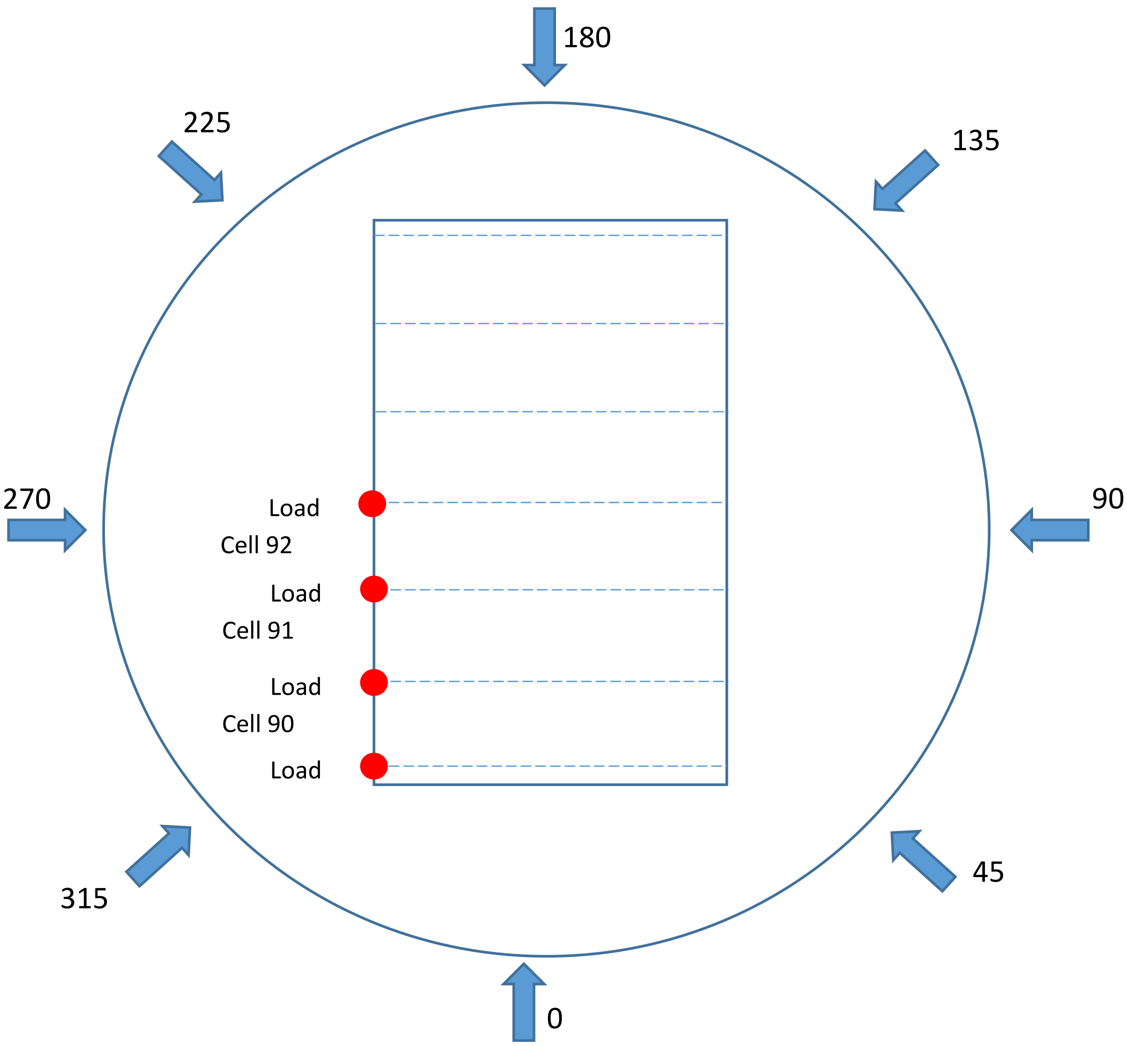


Figure 3: Load cell locations along the length of the 1:4 scale model and approach wind directions (source: FIU)

- Wind loads on elevated structures

Portions of the coastal Florida residential building stock are built in locations that necessitate elevating the first occupied floor of the residence to mitigate flood and storm surge damage. FIU performed WOW testing on a 1:5 scale model of a single story elevated residential building with full scale dimensions of 28.75 × 21 × 12.5-ft (L × W × H) with a 7 ft elevation to the first floor elevation (FFE) and 4 on 12 roof slope (Figure 4). 363 pressure taps were installed over the roof, walls and floor surfaces to monitor wind pressure loads during testing. The scale model was also tested with no elevation (on-grade) to provide a point of comparison to determine the influence of elevation on the wall and roof loading.

The FPHLM has recently developed an elevated structure model to estimate vulnerability to damage from storm surge. However, a companion wind vulnerability model of an elevated structure has not yet been developed. The WOW pressure results were analyzed to aid in the development of such an elevated structure wind vulnerability model.

Figure 4: Rendering of the subject elevated structure (left) and 1:5 scale model on WOW turntable (right) (from Chowdhury et al. 2017)

2 Incorporation of the WOW test results in the FPHLM

- Roof to wall wind uplift load distribution: implementation in the FPHLM

Comparison of the R2WC loads calculated using the current FPHLM methodology and the R2WC loads estimated based on the WOW test data

Section 1.2 describes the FIU WOW testing on the 1:4 scale rectangular plan model to measure the wind uplift at four r2w connection locations (Figures 1 – 3). Due to physical limitations (dimensions and constructability) of the load cell placement in the scale model, the spacing of the load cells on an equivalent full scale structure was approximately 6 ft between load cells. A typical timber frame residential roof system has a roof truss spacing of 2 ft between adjacent trusses, and each truss connected to the wall top plate with a r2w connection. The FPHLM models each of these r2w connections individually (2 ft spacing). Due to this r2w connection spacing mismatch, we do not have a one-to-one mapping of WOW measured uplift with the individual r2w connections in the FPHLM. Further, the FIU uplift load test results are presented as dimensionless load coefficients, while the FPHLM uses pounds of uplift force. For these reasons, the uplift measurements on the FIU scale model are used to evaluate the FPHLM r2w connection load distributions in a qualitative manner.

Figure 5 presents the uplift at the corner (cell 89 in Figure 3) as a function of approach wind direction as defined in Figure 3. The right plot is the FIU test measurement, and the left plot is the uplift that occurs in the FPHLM as an average of the two corner-most r2w connections. Overall it can be observed that the trend in corner uplift is very similar as a function of approach wind direction.

Figure 6 presents directionally enveloped uplift results for the FIU testing and the FPHLM uplift. Directionally enveloped refers to the process of selecting the maximum uplift value among the eight directions tested for each connection individually (the largest magnitude mean value from Figure 5). For example, the maximum uplift value for cell 89 is from 0 degrees, while the maximum uplift value for cell 92 is from 270 degrees. Figure 6-a is the FIU WOW measured uplift at the four locations indicated in Figure 3 (in this plot a negative value indicates uplift). It is observed that the maximum uplift is at the corner (89), the minimum is at the center of the roof length (92) and the cells 90 and 91 are in between these values. Figure 6-b presents the FPHLM results when adjacent r2w connections are averaged to emulate the same locations on the roof represented by the more sparsely spaced FIU load cells, and normalized by the highest magnitude. Figure 6-c averages every pair of FPHLM r2w connections over the same length of roof, while Figure 6-d presents the individual r2w connections between cells 89 – 92 in the FPHLM without averaging. Thus each plot in Figure 6 spans from the corner to midway through the length of the roof.

The relevant comparison is not related to magnitudes shown, but rather the trend of the distribution of uplift load from the corner to mid-roof length. Observe that both the FIU testing and the FPHLM show the same trend of higher uplift at the corner, and decreasing in magnitude as we progress to mid-roof length. Figure 6-d shows an exception to this at the first corner r2w connection. This is expected, as the far corner r2w connection has tributary area (connected sheathing assigned to that connection) to only one side, while the first r2w connection has considerably more tributary area (sheathing on both sides). The spatial resolution of the FIU load cells does not allow the capture of this effect, as cell 89 represents an average over the multiple individual connections spaced 2 feet apart.

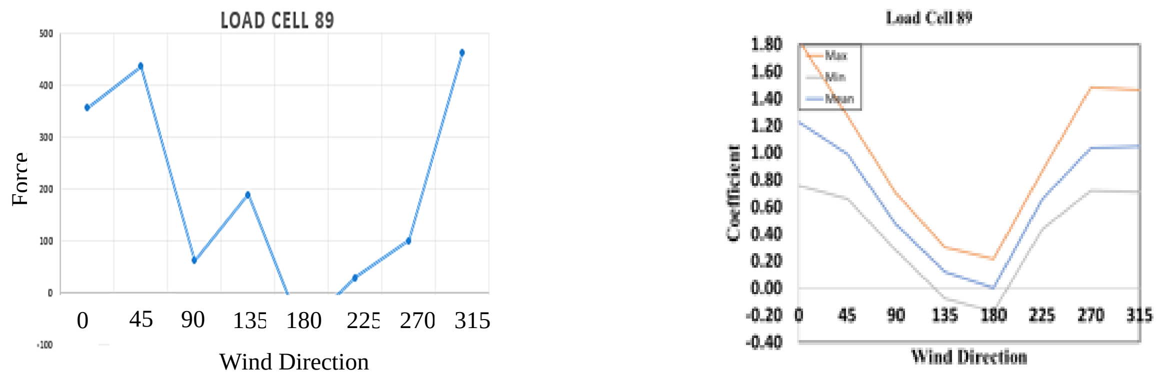
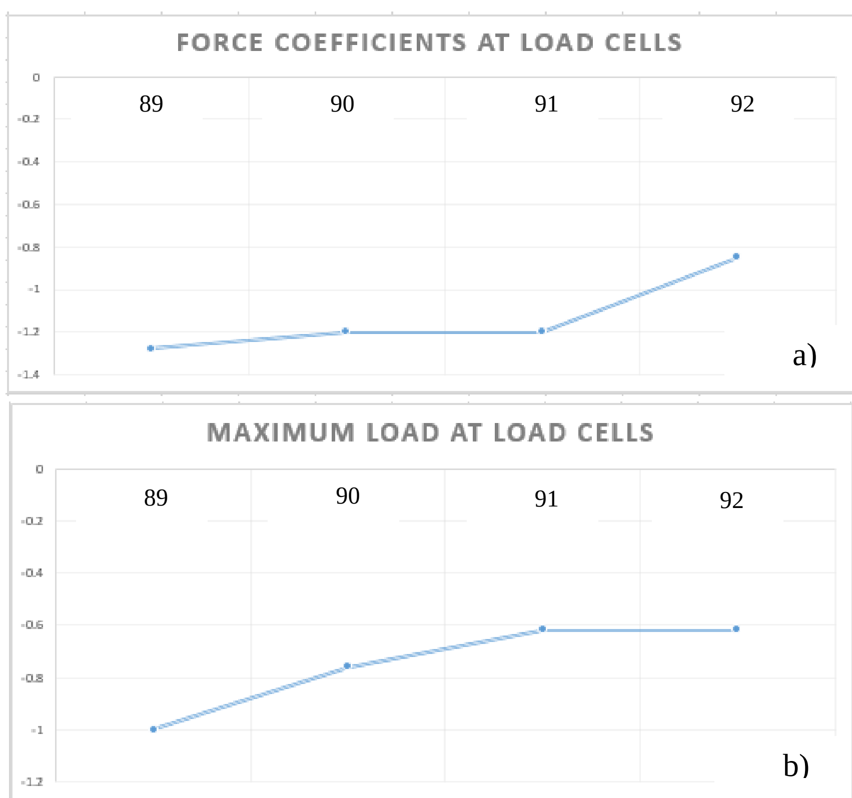


Figure 5: Uplift at corner r2w connection as a function of wind direction. FPHLM uplift (left), FIU WOW measured uplift (right)



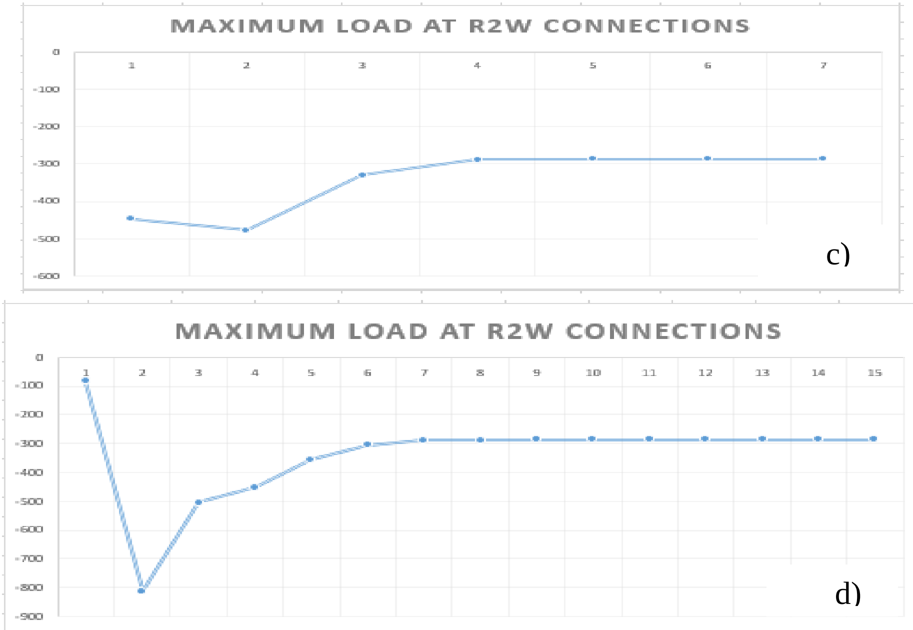


Figure 6: Directionally enveloped maximum uplift loads: a) FIU WOW measured uplift (negative indicates uplift), b) FPHLM model with multiple adjacent r2w connection values averaged to emulate FIU four load cell locations, magnitude normalized c) FPHLM model with every pair of r2w connection values averaged over the same roof length, d) FPHLM individual r2w connection values (no averaging) over the same roof length

Investigation of possible modification of the wind load distribution on roof-to-wall connections in the FPHLM

Efforts to better match the r2w connection load distribution would largely be addressed by a re-assignment of the directionalized pressure zones on the roof in the FPHLM to more precisely match the pressures on the roof of the FIU model. However, the FPHLM is meant to represent a variety of similar shaped structures, and not a single individual structure. Fine tuning the pressure zones to this specific scale model may have unintended negative consequences for other structures the FPHLM represents (different building heights, roof slopes, roof shapes and approach terrain). The conclusion of this investigation is that the FPHLM is sufficiently capturing the behavior observed in the FIU WOW tests.

- FRP roof-to-wall connection retrofits: implementation in the FPHLM

Upgrade of the roof-to-wall connection models to include an additional capacity option equivalent to the FRP connections tested in the WOW

The most recent FRP r2w connection testing work at FIU focused on an application that produced uplift capacities suitable for up to Category 3 hurricane (Chowdhury et al. 2017). In the existing FPHLM, currently available metal connectors exceed that FRP capacity. The FIU laboratory results reported in Canbek et al. (2011) were higher than those reported in the Chowdhury et al. (2017) study, and were implemented in this investigation to determine the influence of high-end FRP capacities. In Chowdhury et al. (2017), the most feasible FRP connection, as reported by the authors, demonstrated a mean failure capacity that slightly exceeds the clip-type metal r2w connection option in the current FPHLM for models of medium strength. This new r2w capacity option was implemented in both the commercial residential (CR) and personal residential (PR) models.

Determination of the cost of FRP R2WC for new connections and replacement of damaged connections

Canbek et al. (2011) studied the use of Fiber Reinforced Polymer (FRP) in roof-to-wall connections and Figure 7 and Table 1 show their cost analysis. The prices shown are only for the connection, not accounting for the labor. The authors affirm that Glass Fiber Reinforced Polymer (GFRP) is more effective than Carbon Fiber Reinforced Polymer (CFRP) in this study since the resistance is similar but the price of the first one is lower. In the Personal Residential and Commercial Residential models of the FPHLM, the cost of roof-to-wall connections are not explicitly taken into account (PR) or are very small compared to the prices of other components (CR). A cost analysis provided an estimate of the difference in price between a typical connection and an FRP connection, using manufacturer's catalogs. A typical connection that would be replaced by an FRP roof-to-wall connection cost $0.68 (Simpson, 2017), which is approximately the same as the FRP connection presented in Canbek et al. (2011). Figure 8 shows the conventional or typical connection used to determine the cost. Since the price of a conventional connection is similar to the price of the FRP connection, there were not changes in the cost for the roof-to-wall analysis in the FPHLM models.

Table 1 – Cost comparison between glass fiber reinforced polymer and carbon fiber reinforced polymer

Type of FRP Used	Price of FRP without epoxy ($/in^2)	Resin Consumption (gal/in^2)	Price of Epoxy for 4 Gallons Kit ($)	Cost of a Single FRP Tie with Epoxy ($)
GFRP	0.013	0.0001102	272.41	0.73
CFRP	0.0123	0.0001102	272.41	4.71

Figure 7 – Roof-to-wall connection using FRP (Canbek et al., 2011).

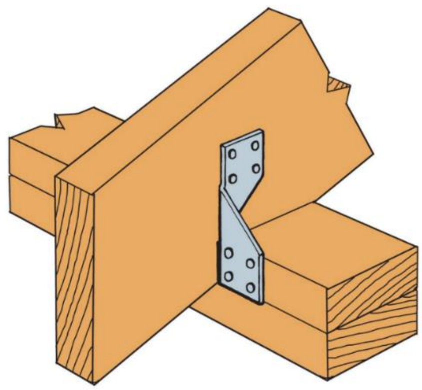


Figure 8 - Simpson H3 connection (https://www.homedepot.com/p/Simpson-Strong-Tie-18-Gauge-Hurricane-Tie-H3/100375009)

Monte Carlo simulations to generate damage matrices and vulnerability curves of selected FPHLM buildings retrofitted with FRP connections

Construction practice and building codes have changed over time. The FPHLM includes models that represent a range of eras of construction. Baseline weak, medium and strong models have been developed and expanded into numerous subclasses, for example a weak model with strong roof cover. For the FRP investigation, the baseline weak, medium and strong models were run with their default r2w connection capacities. Simulations were then run for the weak model with the retrofitted FRP r2w connection for both PR and CR. Thus FRP was investigated within the context of applying it as a damage mitigation method for the existing older residential building inventory.

Results are presented with and without FRP r2w connections from two perspectives: 1) The physical damage that occurs to primary exterior components of the building (roof cover, roof sheathing, r2w connections, windows and doors) as a function of peak 3-second wind speed. 2)

The vulnerability of the structure in a damage ratio (cost of repair to cost of building) as a function of wind speed.

Figure 9 presents the physical damage for the baseline weak and the weak with the retrofitted FRP r2w connections as a function of peak 3-second gust wind speed. The top row is the personal residential (PR) model results, and the bottom row is the commercial residential (CR) results. The left column is the baseline weak model, and the right column is the weak model with retrofitted FRP r2w connections.

It can be observed from the PR results (top row) that both the percent damage to the r2w connections and the walls were reduced as a result of the FRP retrofit. For the CR results (bottom row), the r2w damage was the only component with a reduction due to the FRP retrofit. The reason for and implication of this differing behavior from PR to CR is discussed in the next section.

These physical damage curves are input to the costing model to determine the loss ratio (vulnerability) of the models.

Figure 10 presents the vulnerability comparisons for PR (top) and CR (bottom). The top plot of PR vulnerabilities compares the baseline weak (blue), weak with retrofitted FRP r2w connections (magenta), the medium baseline model (green), and the baseline strong model (red). The bottom plot is the commercial residential (CR) baseline weak (blue) and weak with retrofitted FRP r2w connections (red). It can be observed that the PR model indicates a significant reduction in vulnerability from weak to weak with FRP r2w connections past 120 mph gusts. The standard medium model is less vulnerable than weak with FRP up to 155 mph when the curves converge, and the standard strong model is less vulnerable than all other models shown. This relative behavior is expected given that the FRP capacity is higher than the default r2w capacity of the weak model, slightly higher than the default of the medium model, and lower than that of the strong model. This indicates the potential for FRP r2w connections to be a feasible mitigation strategy for weak homes with toe nail r2w connections.

Figure 10 also shows that in the case of the CR model (bottom), the vulnerability of the baseline weak model and the weak model with RFP r2w connections are almost identical. This is in contrast with the companion PR comparison in the top plot (blue vs magenta). The reason for this is related to the wall damage discussed in the previous section. Reducing wall damage has a very large impact on reducing vulnerability. The CR model (Figure 9 bottom) does not couple the wall damage to the loss of r2w connections, while the PR model does (Figure 9 top). Thus the PR model shows a significant reduction in vulnerability due to the influence of the FRP on the wall damage.

These results highlight the necessity of modifying the CR model to incorporate the influence of r2w connection failures to wall failures, and is currently being pursued.

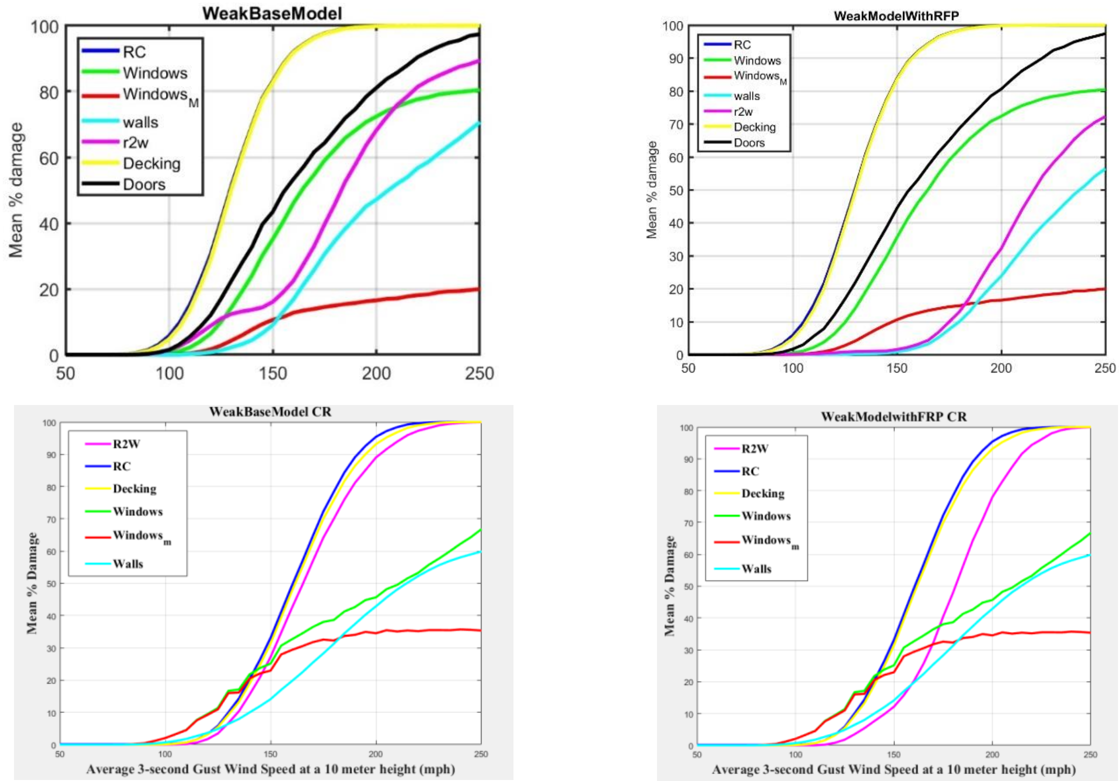


Figure 9: physical damage to weak baseline models (left column) and weak models with FRP retrofit r2w connections (right column). Top row is PR model, bottom row is CR model

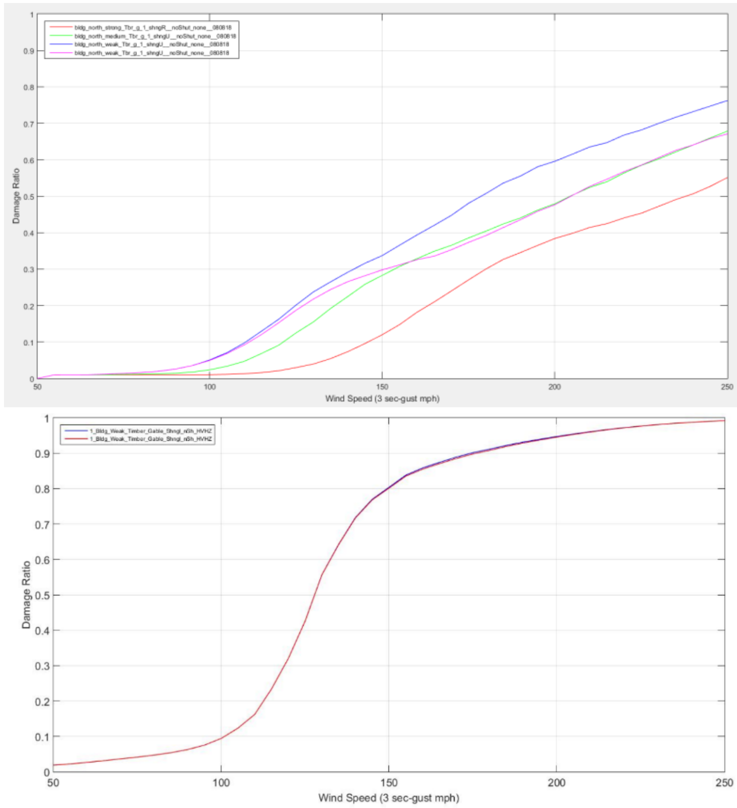


Figure 10: Vulnerability (loss ratio) of PR (top) and CR (bottom) models. Top: PR baseline weak (blue), weak with retrofitted FRP r2w connections (magenta), the medium baseline model (green), and the baseline strong model (red). Bottom: CR weak baseline models (blue) and weak models with retrofitted FRP retrofit r2w connections (red).

Preliminary comparisons, for benefit/cost evaluation, of the aggregated losses for specific building examples with the new mitigated model against the losses produced by the current version of the model.

The comparisons of the vulnerability curves for timber structures in Figures 8 to 10 show the following. The PR model emphasizes interior damage due to loss of sheathing, roof cover, or gable end, which are all independent of the roof-to-wall connection strength. If the strength of the plywood deck and roof cover is not increased, increasing the roof-to-wall connections alone will do little good at low to moderate wind speeds. At higher wind speeds, the stronger roof-to-wall connections improve the integrity of the box system in the frame structure, which leads to lower vulnerability, and hence lower damage and lower insured losses.

The CR model does not currently capture this benefit as explained above.

However, it must be emphasized that the stronger FRP connections will never be used as a single mitigation measure, but will be a critical part of a combination of mitigation measures, which, as a minimum, shall also include stronger decking attachment and opening protection, per the Florida Building Code.

Previous studies (Torkian et al, 2014) have shown that in this case, the benefit can exceed the cost of the mitigations, depending on the particular combination of mitigation measures, and the wind climate of different regions of Florida.

- Development of a simple model for one elevated structure based on the elevated structure tested in the WOW

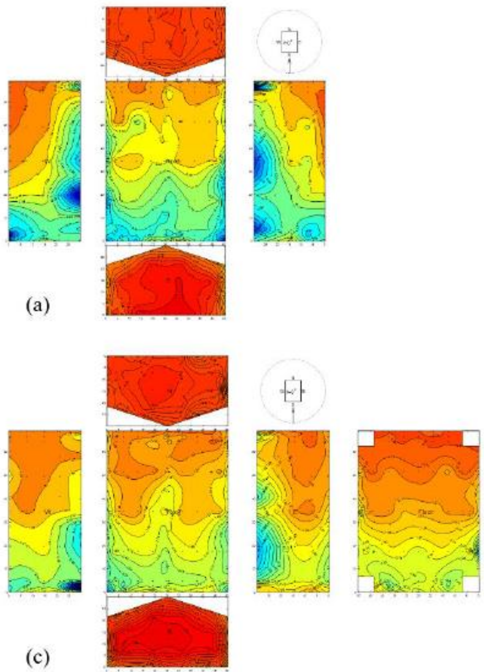
Implementation in the FPHLM

Currently the FHPLM includes single story structures on-grade (not elevated). It is desired to develop a model to represent elevated structures built in flood/surge prone regions. The FIU WOW testing results on the 1:5 scale model elevated single-occupied-story structure (see section 1.3 and Figure 4) were analyzed to determine whether the development of the FPHLM model would require consideration of uplift loads and failure modes resulting from wind under the structure producing upward pressure on the floor system. Such loads and failure modes would be added onto the existing single story on-grade model to develop the elevated model. The wall and roof pressures were also evaluated to determine if wind load coefficients differ appreciably between the on-grade and elevated structures. Additionally, the cost of construction (for loss ratio calculation) requires modification to reflect the cost of an elevated structure.

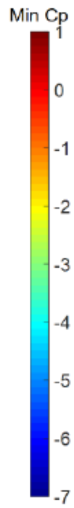
Figure 11 presents the contours of peak pressure coefficients over the surface of the scale model on-grade (labeled (a)) and elevated (labeled (c)) for four wind directions between 0 and 90 degrees (refer to Figure 3). A review of these floor surface pressure contours (provided in Chowdhury et al. 2017) revealed that the wind on the underside of the scale model elevated structure provided a negative (suction - downward) pressure over most of the floor surface from each of the four wind directions tested between 0 and 90 degrees. The net effect is a downward pressure, not an uplift load from winds on the underside of the structure. The right-most bottom contour in each of the (c) plots in Figure 11 exhibit almost exclusively negative values over the floor surface. This indicates that the elevated model for FPHLM does not need to consider floor system uplift failure modes.

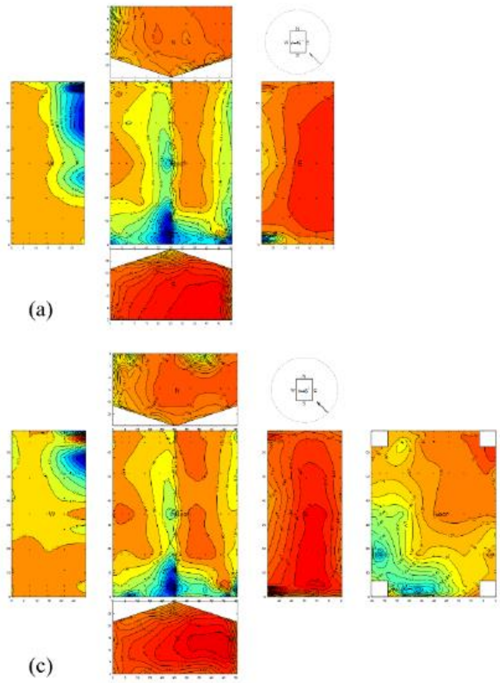
Figure 11 also provides a comparison of wall and roof pressures for the elevated and on-grade structures. For a given wind direction, the magnitude and contour shape of a given surface is similar (not identical) between the on-grade and elevated structures.

Given the above observations, the first iteration of the FPHLM single story CR elevated structure model was produced along with trial results. The approach was to use the existing 2-story on-grade FPHLM model as a basis, and eliminate the damage accumulated on the first story, as this would be open volume in an elevated structure. The resulting physical damage matrices (the medium for quantifying the damaged exterior building components) are then processed through the vulnerability model as a single story on-grade structure using a modified cost scheme to reflect the difference in cost between the on-grade and elevated structures. Section 2.3.2 will present and discuss comparative results for an on-grade and an elevated structure.

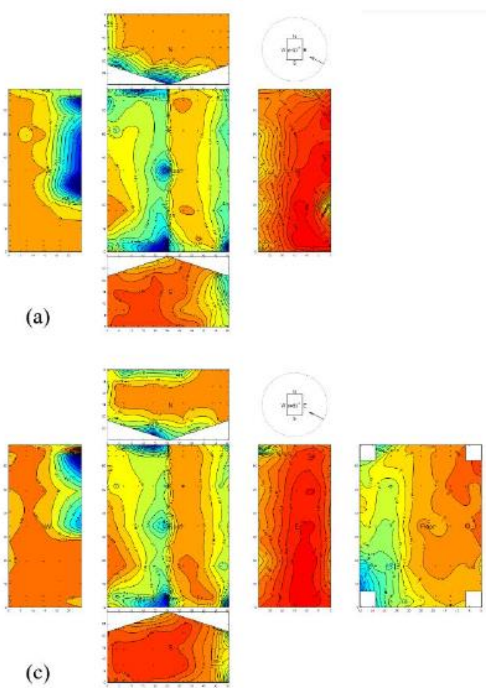


Wind approach angle 0 degrees

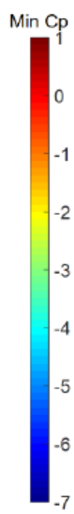


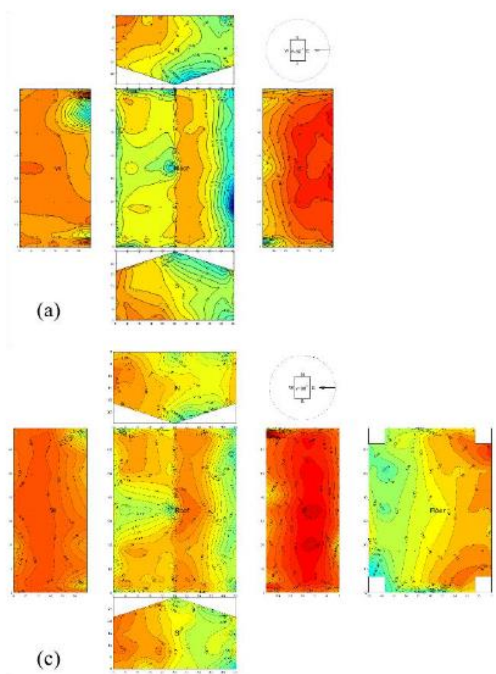


Wind approach angle 45 degrees



Wind approach angle 63 degrees





Wind approach angle 90 degrees

Figure 11: Peak minimum pressure coefficient distributions over the surface of a structure on-grade ((a) in each figure window) and the same structure when elevated ((c) in each figure window). The indicated wind directions coincide with Figure 3. Contour plots are from Chowdhury et al. 2017.

Determination of the cost of elevated buildings for new construction and repair of existing damaged construction

The elevated structure model is as follows. A 2 story weak model, with timber exterior walls and gable roof, has all the components removed from the first story. This leaves only the columns to support the second story, which becomes the first story of the elevated structure. The cost analysis reflects that strategy, where the cost for the components that were removed was set to be 0 and the cost for the foundation was increased according to Pinelli et al (2015). This process affects other parameters because some of them are associated with the respective area of the floors and the CR model has different configurations for each story living area.

Table 2 and Table 3 show the cost modifications to estimate the cost of the one story elevated structure. First the value for a 2 story building foundation is assumed to be $5.25/ft^2 of living area in the current on grade two story CR model. For the elevated one story building with wood wall, piles replace the footing of the 2-story building model. The cost of the new foundation according to Pinelli et al (2015) is $39.14/ft^2 of living area. Notice that the costs for first story exterior wall and wall cover were set to be 0 in Table 3 once they were removed from the model to create an elevated structure.

Since the living area of a 1-story elevated structure is half the living area of the 2-story on grade structure, the unit costs in $/ft^2 of living area of the elevated structure for the story walls, roof structure and cover, and soffit are twice the unit costs of the on-grade structure.

Table 2 – Cost summary of a two story weak wood on-grade building

	Cat 1	Cat 2	New	Repair	%	Units
Site work	All		0.63	0.63	1%	$/ft2 living area
Foundation	All		5.25	5.25	7%	"
Exterior Wall	Wall	1st Story	2.56	2.41	3%	"
		2nd Story	4.23	3.98	5%	
	Wall Cover	1st Story	-	1.20	1%	"
		2nd Story	-	1.99	2%	
Roof Structure	Truss + Crane		0.96	1.37	2%	"
	Sheathing		1.45	2.03	3%	"
	R2W		-	0.48	1%	"
Windows/ Doors and sliding doors	Window		0.60	1.44	2%	"
	Doors		0.63	0.87	1%	"
	Sliders		1.23	1.47	2%	"
Roof Cover	Shingles		2.90	3.48	4%	"
Interior	All		31.67	40.00	50%	"
Mechanical	All		5.31	6.56	8%	"
Plumbing	All		15.00	10.00	12%	"
Electrical	All		8.00	8.00	10%	"
Soffits	All		0.11	0.16	0%	"
Permitting	All		0.24	0.12	0%	"

Table 3 – Summary cost for a one story elevated weak wood building

	Cat 1	Cat 2	New	Repair	%	Units
Site work	All		0.63	0.63	1%	$/ft2 living area
Foundation	All		39.14	39.14	32%	"
Exterior Wall	Wall	1st Story	0.00	0.00	0%	"
		2nd Story	8.45	7.95	7%	
		3rd Story	-	-		
	Wall Cover	1st Story	-	0.00	0%	"
		2nd Story	-	3.98	3%	
		3rd Story	-	-		
Roof Structure	Truss + Crane		1.91	2.74	2%	"
	Sheathing		2.90	4.06	3%	"
	RtW		-	0.96	1%	"
Windows/ Doors and sliding doors	Window		0.60	1.44	1%	"
	Doors		0.63	0.87	1%	"
	Sliders		1.23	1.47	1%	"
Roof Cover	Shingles		5.80	6.96	6%	"
Interior	All		31.67	40.00	33%	"
Mechanical	All		5.31	6.56	5%	"
Plumbing	All		15.00	10.00	8%	"
Electrical	All		8.00	8.00	7%	"
Soffits	All		0.22	0.32	0%	"
Permitting	All		0.48	0.24	0%	"

Monte Carlo simulations to generate damage matrices and vulnerability curves of the elevated building.

The first generation FPHLM single occupied story elevated structure model described at the end of section 2.3 was run along with its on-grade single story companion model. This was done for weak, medium and strong models. Figure 12 presents the physical damage to the weak on-grade model (top left), the physical damage to the weak elevated model (top right), and their comparative vulnerabilities (bottom: blue = elevated, red = on-grade). As expected, the relationship between higher elevation and higher wind speed produces more physical damage and a more vulnerable elevated structure compared to the on-grade companion structure. Figures 13 and 14 present these same comparisons for the medium and strong models, and show similar expected trends.

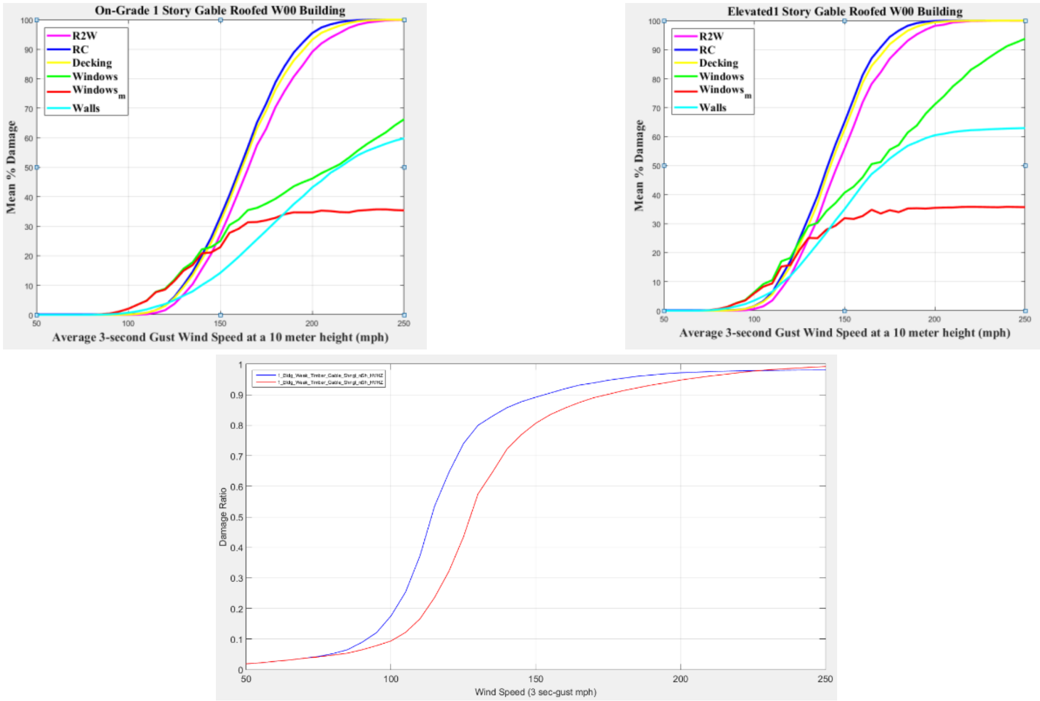


Figure 12: Weak strength model results. Top left: single story on-grade physical damage. Top right: single story elevated physical damage. Bottom: single story on grade vulnerability (red), single story elevated vulnerability (blue).

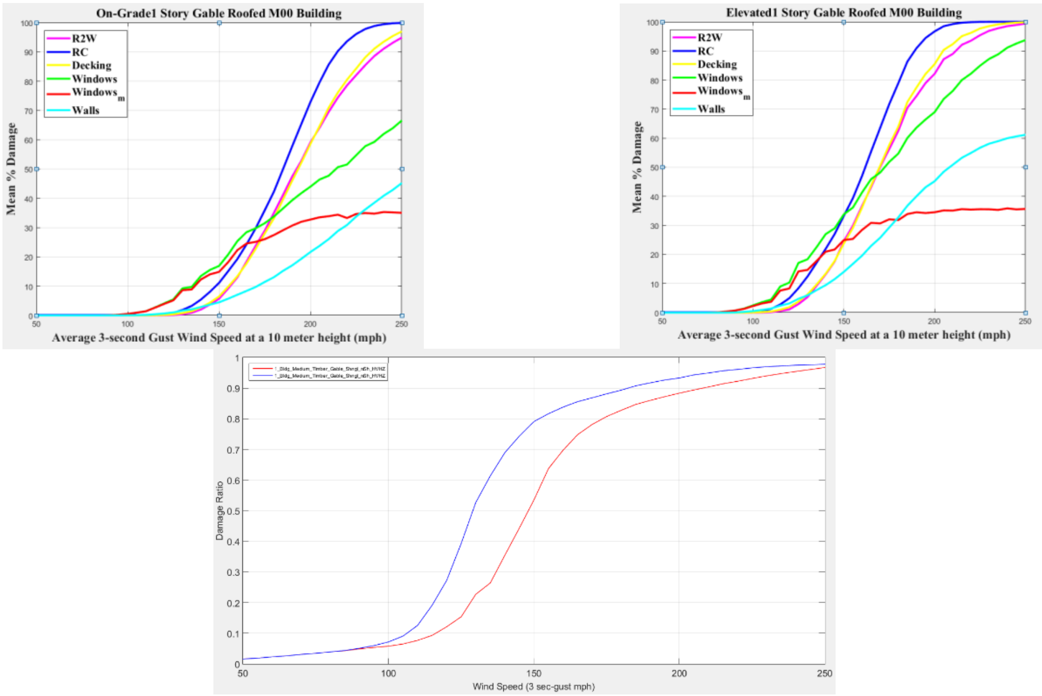


Figure 13: Medium strength model results. Top left: single story on-grade physical damage. Top right: single story elevated physical damage. Bottom: single story on grade vulnerability (red), single story elevated vulnerability (blue).

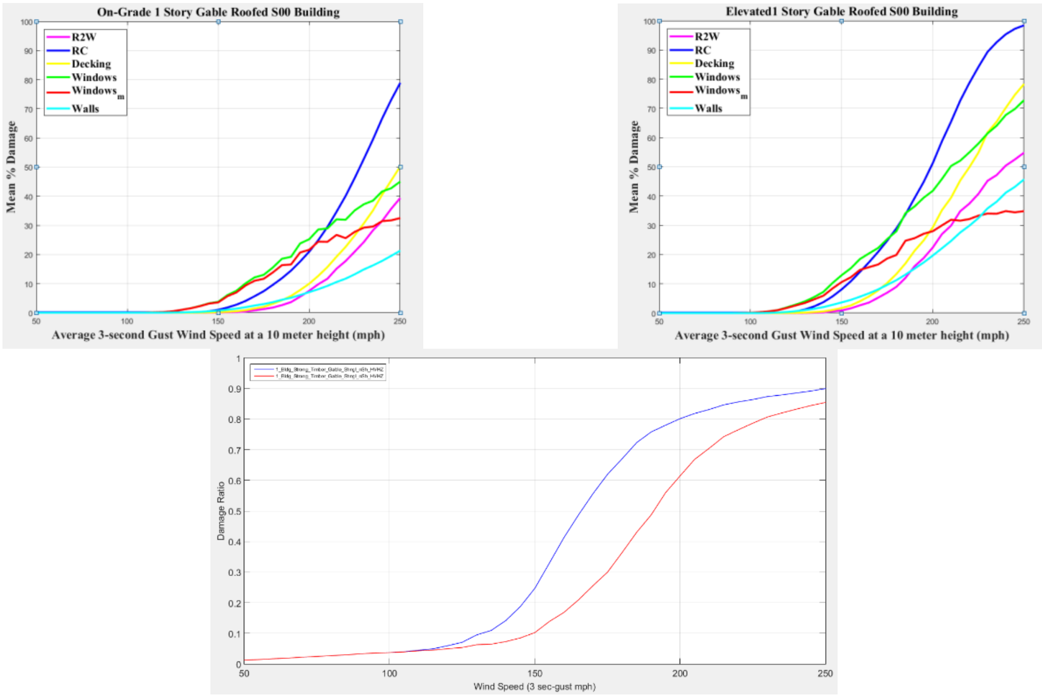


Figure 14: Strong model results. Top left: single story on-grade physical damage. Top right: single story elevated physical damage. Bottom: single story on grade vulnerability (red), single story elevated vulnerability (blue).

Preliminary validation of modeled losses against actual claim data, if these data become available.

Lamentably, no claim data is currently available for elevated structures. In general, insurance companies do not provide information on whether or not a structure is elevated. This situation might change in the future once the claim data for hurricane Irma in the Keys becomes available, since a majority of the buildings in the Keys are elevated.

- Conclusions and future refinements for formal implementation

The summary results of this investigation are as follows:

- The FRP r2w connection capacity was implemented in the PR and CR FPHLM models. The PR model simulations showed a reduction in vulnerability for the FRP retrofitted model, while the CR model showed a difference in physical damage to the r2w connections but not the resultant vulnerability. This was attributed to a difference in how the PR and CR models handle the relationship between r2w failure and wall failure, and indicates a need to update the CR model in this regard

- The distribution of loading among adjacent r2w connections in the FPHLM was determined to be adequately similar to the FIU test results
- The FPHLM engineering team developed an elevated single story structure model. The observations from the FIU WOW testing of an elevated single story structure guided this development. The preliminary results of the simulations demonstrate the increased vulnerability of the elevated model when compared to its on-grade companion model. This behavior is as-expected due to differences in wind speed at the roof height of an elevated and on-grade structure. Additional testing and validation of this first-generation model is required before adoption within the FPHLM model library.
- The benefits of these mitigation measures (stronger FRP connections, and elevating the building) and whether or not there shall be cost effective, shall depend on the combinations of mitigation implemented, and the local wind climate.

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A Resource for the State of Florida

SECTION 4

Evaluation of Scaled Model Reliability for Study of Wind Load Path in Low-Rise Light-Framed Wood Structures

A Report Submitted to:

The State of Florida Division of Emergency Management

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Acknowledgements
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Introduction

Numerous disasters have occurred across the globe over the past few decades. The impact of these events in several cases was catastrophic, causing thousands of fatalities and billions of dollars in overall and insured losses. Some of the most fatal and costly events were the result of extreme wind events such as hurricanes, typhoons and tornadoes which were reported and tracked in the United States and around the globe. The social and economic impact associated with these disasters has initiated a drastic response from several political and academic institutions.

Wind engineering research is directly associated to the aforementioned extreme wind events. Wind-structure interaction is a special field of engineering, which has a scope to study the wind effects on buildings. Several studies were conducted specifically to evaluate the effect of wind action on structures, such as residential buildings and other shared public spaces. The contribution of both wind tunnel experiments and full-scale field monitoring on the development of modern wind standards and building codes of practice is of great significance. Concepts related to structural integrity during extreme wind events have been studied extensively using boundary layers wind tunnels and verified by monitoring wind-induced pressures on constructed buildings.

A significant portion of wind engineering research focuses on the wind-induced loading on structures and on the codification of the research findings. A key component that has not yet been investigated adequately is the flow of wind-induced forces through the structural system of low-rise residential scale systems (i.e. light-frame wood structures (LFWS)) and their attenuation due to dynamic and other structural aspects. In a prior field study that was carried out by Zisis & Stathopoulos [(1)], wind monitoring of a full-scale wood building subjected to natural wind action revealed invaluable information related to the wind-induced response as well as the attenuation effect on wind loads. Despite the long duration of this field study, the collected data were limited by location-specific meteorological characteristics. The stationary records acquired corresponded to only two dominant wind direction ranges, and the maximum wind gusts rarely exceeded the 45-mph mark. Investigations using full-scale wood structures, such as the work done by Zisis & Stathopoulos [(1)] and Wolf & McCarthy [(2)], are costly and time consuming, and thus attention has shifted towards small-scale modeling as seen in studies by Kittel [(3)] and Datin [(4)].

One of the problems with small-scale modeling of wood structure lies in the fact that wood is a nonhomogeneous, orthotropic material. When a wood timber board is sawn to provide small scale truss element, its cross-section will contain only a few annual growth rings, and depending on whether late or early wood is included, the stiffness and strength of the element can be variable. Also, it is impractical to scale down the frequency and size of knots in a model wood element sawn out of a lumber. So, uncertainty in material property is an inevitable feature of any small-scale model of a wood structure.

Another difficulty in scaling down the wooden building is related to proper modeling of connections. The small connections with the exact dimensions required by similitude are not available and even if they were, they would be quite fragile and therefore too weak when being pressed into the wood [(3)]. So, the best way to scale down connections is modeling techniques that acquire compositing galvanized metal sheets with staples, which leads to relaxation of some similitude requirements.

All of these inaccuracies in constructing small-scale models lead to uncertainty in prediction of the behavior in the small-scale structural system. While some of the studies like Datin [(4)] have simply neglected the effect of these uncertainties on the results, some others have come up with compensating approaches. For example, in the study performed by Kittel [(3)], special attention was dedicated to selection of wooden boards, so that the same board was used for fabrication of both prototype and 1:3 scaled models. Also, to correctly simulate the standard grade of wood, the maximum size of knot (2-inch knot in a 2x4 board) was scaled to 5/8 of an inch for scaled model boards. In this study for modeling the connections several models for each type of connections (e.g. metal plate connectors (MPCs)) were developed in small scale, then the scaled models that had the most similarity in force-deformation curves to the prototype connection were selected to be implemented in small-scale truss assembly. Although this method is a great step toward more accurate simulations, it is still imperfect due to some limitations. First, it requires special attention for selecting the wood boards where even the size of knots needs to be scaled down, making it costly and time consuming. Second, modeling the MPCs is a trial and error procedure that requires application of galvanized metal sheets and staples, instead of actual metal plate connectors.

Lastly, the modification of scaled elements is limited to only a few types of components including truss framing boards and truss connections (tension splice joint, a MPC and a heel joint), so the rest of the elements including studs, sheathing, anchor bolts, and nails are left uninvestigated. On the other hand, if all of these neglected elements were to be modified using the same approach the task would then be as cumbersome as full-scale testing, and there would be no advantage in scaled modeling.

In this study, two 1:5 scaled models were constructed following the same geometry (length, width, and height of the model) of a wind tunnel test model from the Tokyo Polytechnic University database (TPU - http://wind.arch.t-kougei.ac.jp/system/eng/contents/code/tpu). Two finite element models, identical in to the physical models in overall geometry, were developed in order to compare results between the experiment and numerical simulations, and study the concept of wind load paths and structural attenuation.

Experimental Setup and Testing

In the past, wind-induced structural system force related studies required field monitoring of the instrumented full-scaled facilities, but recent advantages on large-scale laboratory facilities allowed for large- and full-scale testing in a controlled environment. A facility with such unique capabilities is the Wall of Wind (WOW) at Florida International University (FIU). The WOW (Figure 1) is an open jet wind tunnel which can generate Category 5 hurricane wind speeds (Saffir-Simpson hurricane wind scale). The facility includes 12 electric fans that produce a wind field of 20-ft wide and 14.-ft high, allowing for large-scale aerodynamic testing.

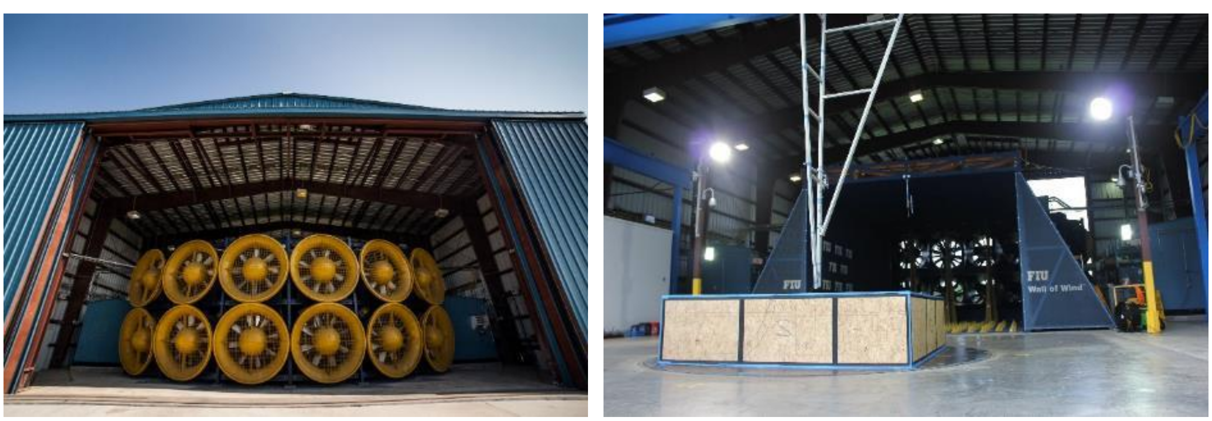

Figure 1: FIU's Wall of Wind

Two experiments on 1:5 scaled models of a flat roof prototype from the TPU database were conducted at the WOW. The models were instrumented with 16 unidirectional load cells (4 at each wall) to measure the overall uplift and gravity forces acting on the models (Figure 2). These load cells acted as anchor bolts.

Each model had a footprint of 10.5-ft by 10.5-ft with a height of 2.625-ft. A *full-size members* (FSM) model consisted of a 2x6 (1.5-in x 5.5-in) bottom plate, 2x6 studs, 2x6 double top plate, and 2x8 (1.5-in x 7.25-in) roof joists. The other prototype, a *small-size members* (SSM) model, consisted of a 2x3 (1.5-in x 2.5-in) bottom plate, 2x3 studs, 2x3 double top plate, and 2x4 (1.5-in x 3.5-in) roof joists. The studs and roof joists were spaced at 9.5-in center-to-center. Although originally the selection of the reduced size members was planned to be made using the finite element model, it was decided that only the commonly available (at hardware stores) framing lumber can be used reliably without compromising the strength and quality properties of the specimens. The wood type used for all framing members, except for the 2x8's, was spruce-pine-fir (SPF) #2. The 2x8 roof joist members were of southern yellow pine (SYP) #2. Oriented strand board (OSB) of 7/16-in thickness was used as roof and wall sheathing for both models. Figure 3 - Figure 13 show model construction of both the SSM and FSM models.

The roof to wall connectors (RTWCs) used were the Simpson Strong-Tie ST-H2A connectors, which help provide a continuous load path from the joists to the top plate and down to the studs. The frame to frame connectors (FTFCs) used at the stud-to-bottom plate interface were Simpson Strong-Tie ST-RSP4 connectors. In addition to these connectors, the studs were also attached to the plates by toe-nailing. Typical connections are shown in Figure 14 - Figure 16.

Originally, one of the models would be equipped with pressure taps to capture the wind-induced pressures on the building envelope (i.e. walls and roof). It was decided to omit the pressure tap measurements and use the available data from the TPU database. The addition of the pressure measurement task would add to the cost of the model construction and require additional testing time. The TPU database provided all the necessary pressure time histories for the selected building geometries, which served as the input load in the numerical simulation.

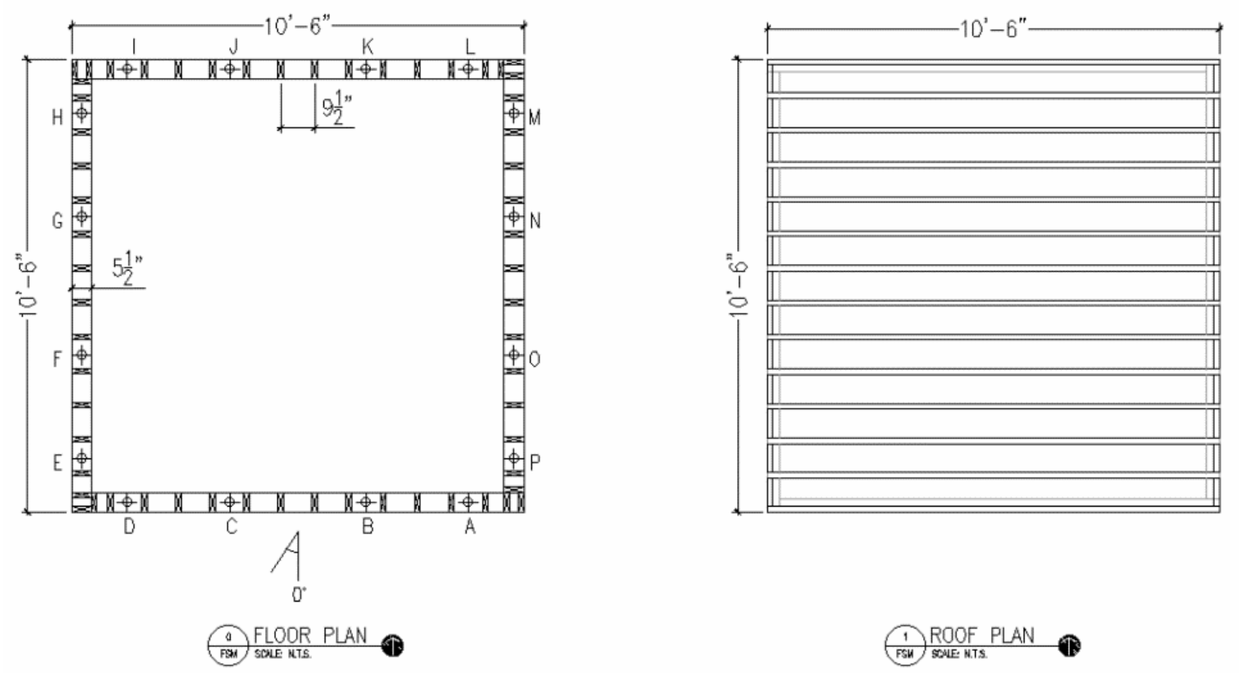

Figure 2: Typical layout of load cell supports (FSM shown)

Figure 3: SSM model walls constructed

Figure 4: SSM wall close-up

Figure 5: Top plate lapping at corners, typical

Figure 6: SSM model with wall sheathing attached, SW corner

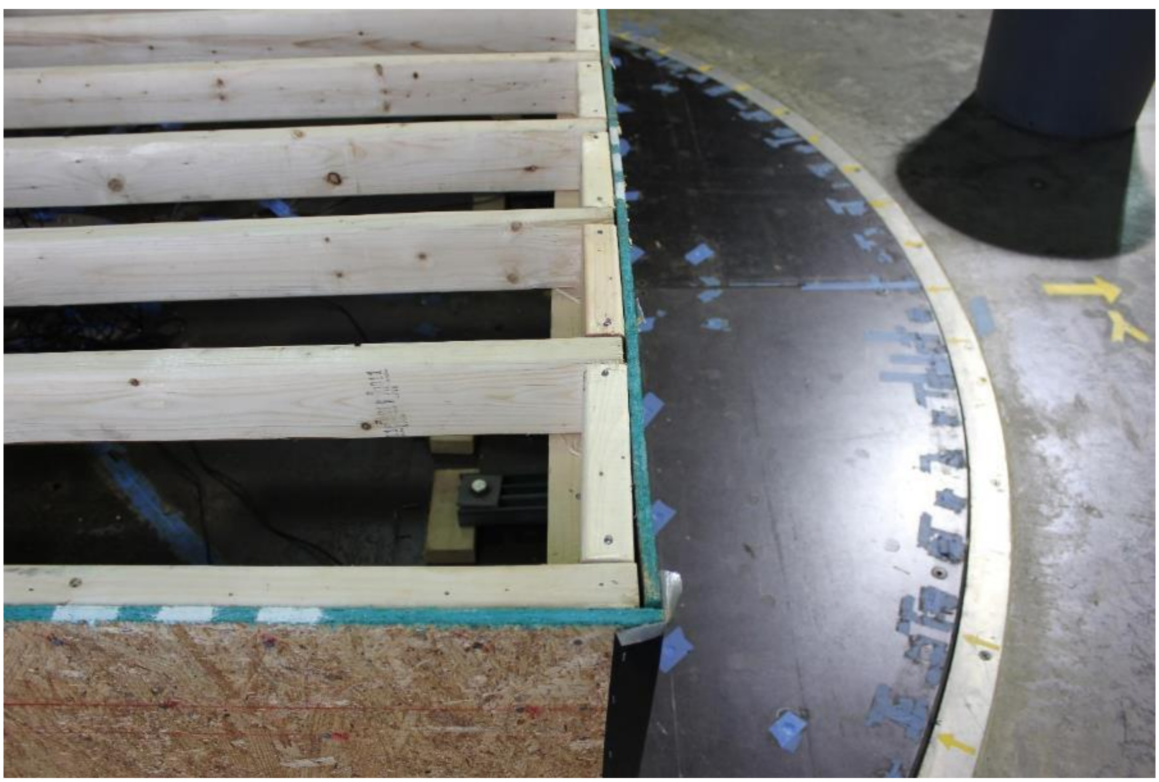

Figure 7: SSM model with attached blocking between roof joists

Figure 8: FSM wall framing, typical

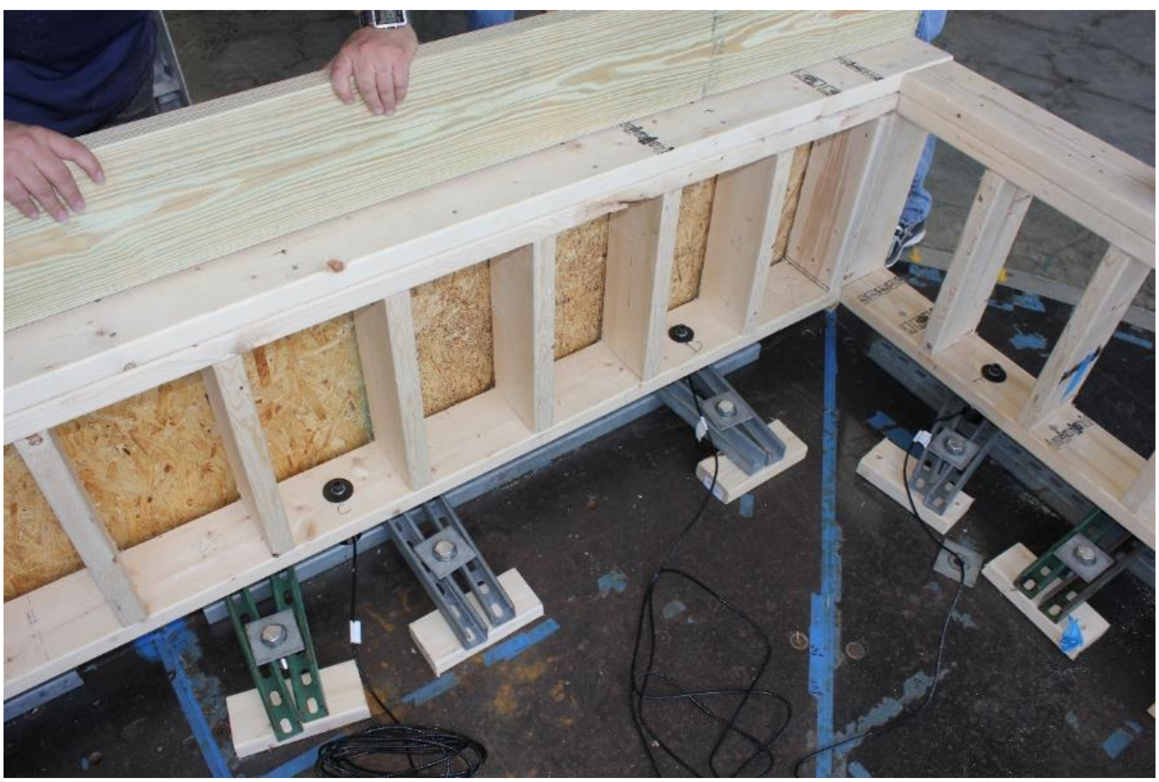

Figure 9: FSM model wall framing attached to load cells (with load cells anchored to base)

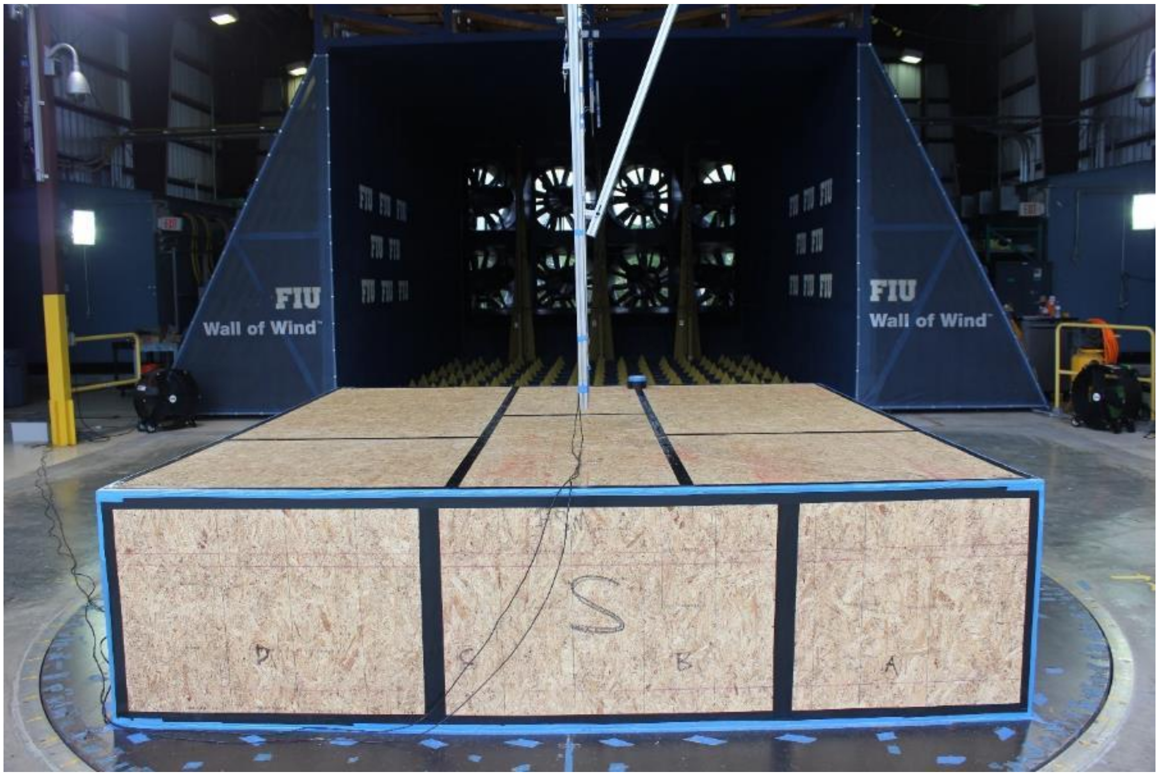

Figure 10: FSM model ready for testing, S wall

Figure 11: FSM model SW walls

Figure 12: FSM model S wall, pre-test

Figure 13: SSM model SW walls. pre-test

Figure 14: Connectors at roof-to-wall and wall-to-foundation interface

Figure 15: ST-RSP4 connector at stud-to-bottom plate, typical

Figure 16: ST-H2A connector at joist-to-top plate / top plate-to-stud, typical

The sheathing to frame connectors (STFCs) were 6d nails at the walls and #6 screws at the roof. The screws allowed for fairly easy removal of roof panels without destroying any of the attached instrumentation. A conventional spacing for the nails and screws was used: 6-in center-to-center edge spacing and 12-in center-to-center field spacing.

In addition to load cells, the models were instrumented with strain gages attached to roof joists and wall studs. Figure 17 - Figure 20 show typical load cells and strain gages as installed.

Figure 17: Load cell anchored to ground using uni-strut braces

Figure 18: Uni-struts anchored to ground w/ anchor bolt

Figure 19: Load cells and strain gages installed on FSM model

Figure 20: Strain gage attached to roof joist

The structures were subjected to flows with wind speeds of 40-mph and 80-mph from a range of 0-180° at intervals of 15°. Each test was conducted for a duration of 60-sec. Time-histories of forces were collected at the foundation level in the Z-direction (out-of-plane) as well as strain gage time histories at joists and studs. Figure 21 - Figure 22 show sample time histories for some load cells and strain gages.

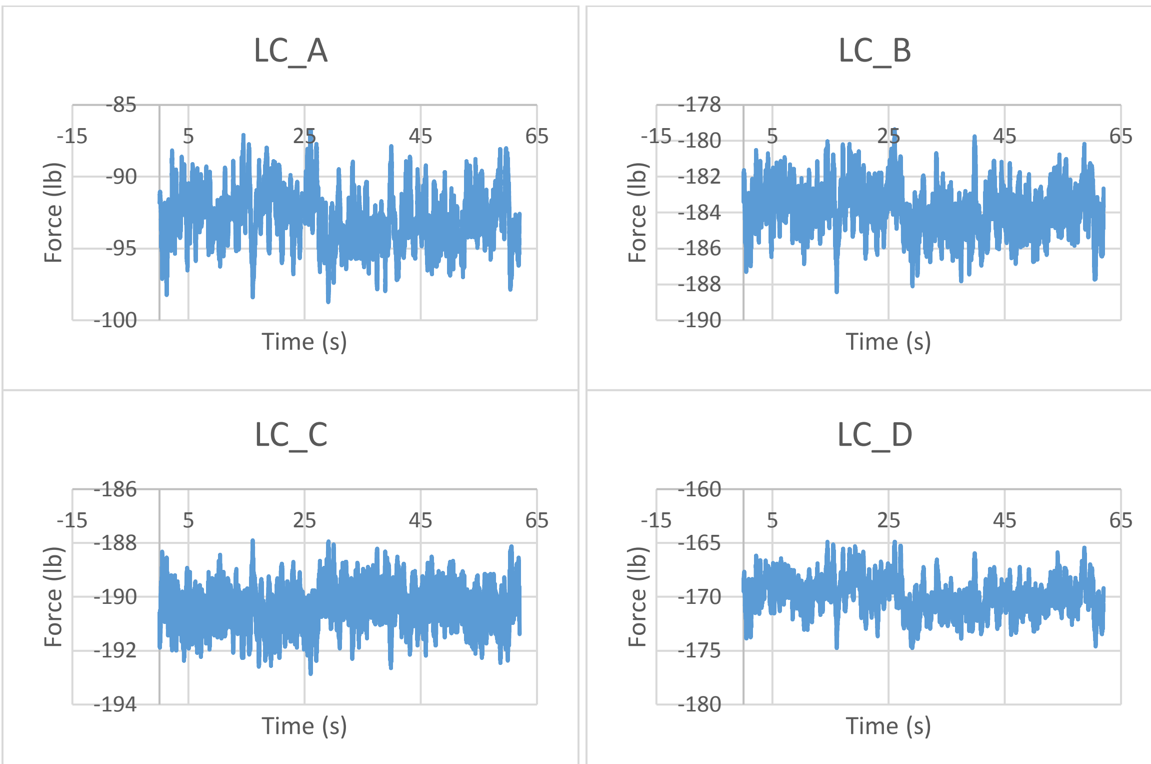

Figure 21: Force time histories of FSM at 0 degree wind AoA and 40 mph wind speed

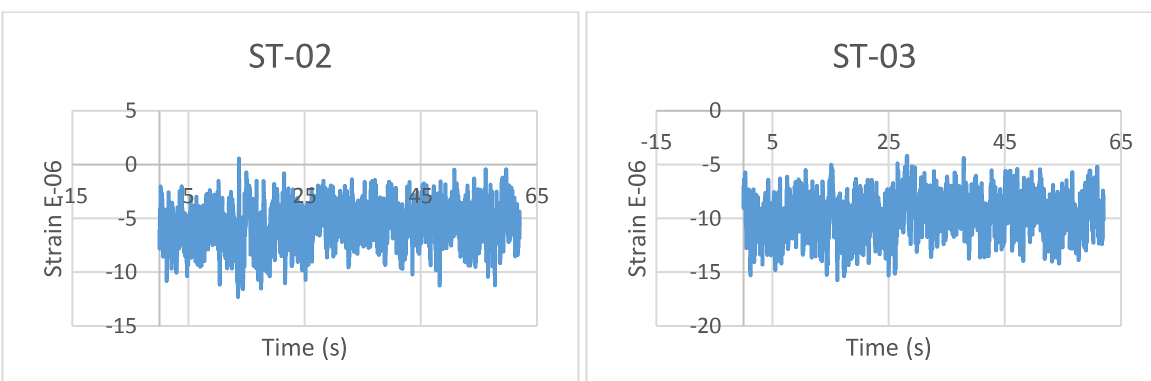

Figure 22: Strain time histories of FSM at 0 degree wind AoA and 40 mph wind speed

Finite Element Analysis

The experimental buildings were numerically modelled using the structural analysis and design software SAP2000 (Computers and Structures, Inc.). The framing elements were modelled using SAP2000's Draw Frame command with the lumber's actual dimensions from the built prototypes. The roof and walls OSB sheathing was modelled using the Thin Shell command, which was then meshed to 6-in x 6-in sections to simulate the fastening schedule. Connections were modelled as rigid links with linear behavior in all six directions. Wind load time histories were input as forces in their corresponding global coordinates according to the TPU model's instrument locations. Table 1 and Table 2 show material properties used for modelling. Figure 23 and Figure 24 show the undeformed and deformed shape resulting from a sample time history analyses.

Table 1: SPF No.2 materials properties for SAP2000 models

E	1,200,000	psi
U	0.4	
A	4.00E-06	
G	428,600	psi

Table 2: OSB material properties for SAP2000 models

E1	1377858.389	psi
E2	1377858.389	psi
E3	1377858.389	psi
U12	0.35	
U13	0.35	
U23	0.4	
A1	4.00E-06	
A2	40.00E-06	
A3	2.70E-05	
G12	137785.8389	psi
G13	137785.8389	psi
G23	20667.9	psi

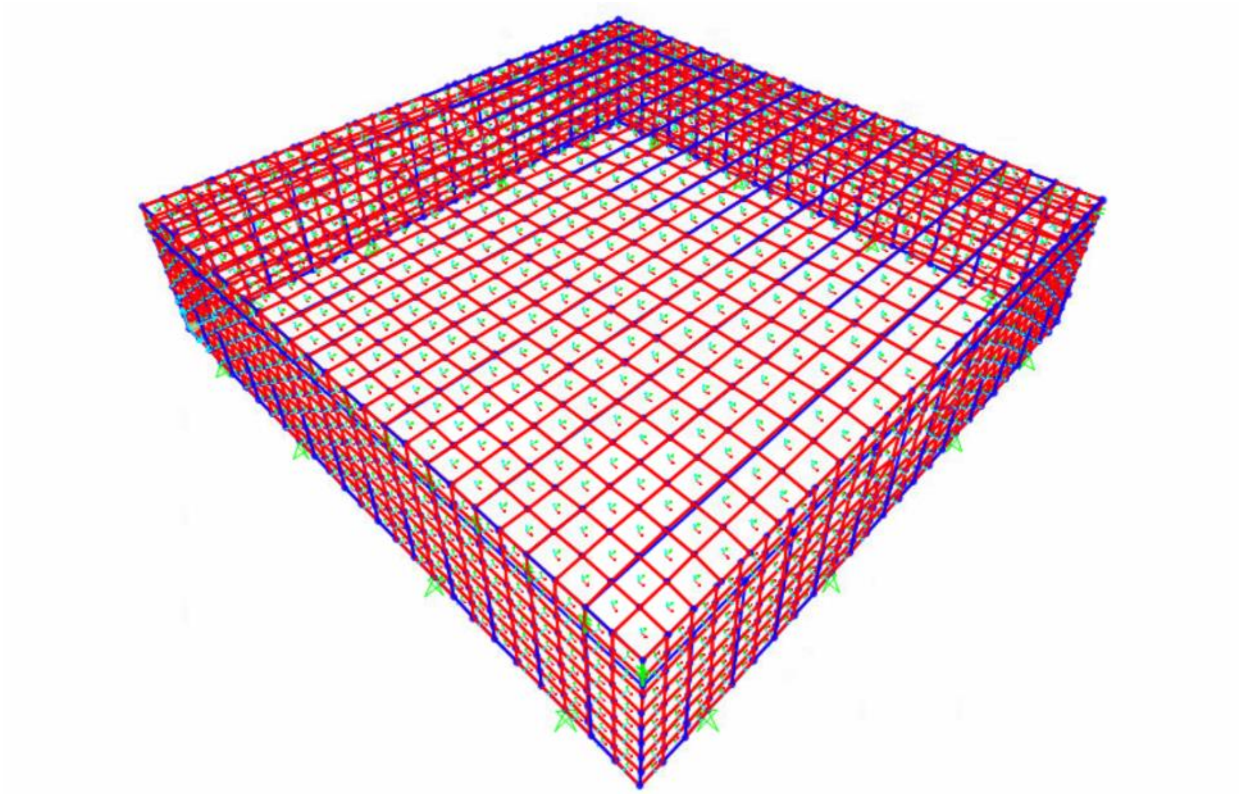

Figure 23: Isometric view of FE model - Undeformed shape

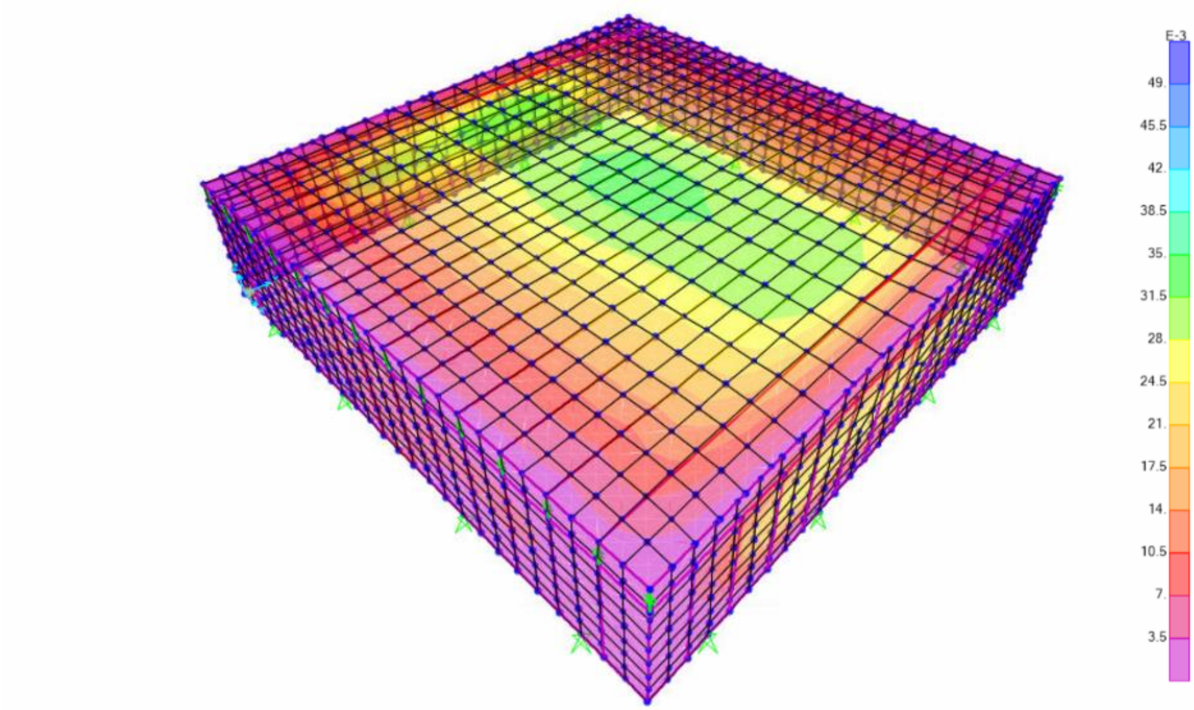

Figure 24: Isometric view of FE model - Deformed shape (SF: 1)

Data Analysis Methods

For this investigation, two different data analysis methods were utilized. The finite element method was utilized to numerically estimate uplift forces expected in the building. The finite element model was designed with SAP2000, and pressure data time histories taken from the TPU model were added to the model to estimate realistic forces experienced at the location of the loadcells. For this finite element model, two different structures were analyzed, one using the FSM and one using the SSM member sizes. The mean values of the structures were calculated to find the expected forces at the specific locations.

The second part of the investigation consisted of analyzing data acquired from the two physical models tested (FSM and SSM) at the WOW. The mean values were calculated and a "zero-drift" removal process was performed. These two models possessed the same physical properties as the finite element models.

The results in this chapter are presented for numerical models and scaled models tested at the WOW. The mean forces obtained at 66 percent throttle (80 mph) wind speed and different wind angles of attack are discussed in this section.

The FSM and SSM were installed on top of 16 foundation loadcells with no other point of contact between the bottom members of the structures and floor (turn table of the WOW). It should be noted that due to instrumentation failure, there were four loadcells (F, G, J and K) that did not record data during the tests while loadcell O was found to report erroneous data. The time histories of each wall were plotted to see the behavior of the force as wind induced forces were applied to the different models. Figure 25 shows the time histories of loadcells located at the South wall that faces the wind at 0 degrees wind angle of attack. As can be seen, the load that the loadcells underwent are between ~ 150 and ~250 lbs. Figure 26 shows the time histories of loadcells installed under the West side of the building at 0 degrees wind angle of attack, with the forces found to be between ~250 and ~340 lbs. The loadcells installed under the North wall have a significant difference in measured load as one of the loadcells measures ~50 lbs while the other measures ~245 lbs, as shown in Figure 27. Figure 28 shows the time histories of all loadcells installed under the East wall, and the forces experienced by the loadcells are between ~130 and

375 lbs (as noted previously, loadcell "O" is a straight line, showing a data recording failure during the test). It needs to be noted that at 0 degrees, it is expected that loadcells M and H measure similar values as they are installed in the same location in opposite sides (refer to Figure 2); however, the difference in their readings deviate from each other from ~250 lbs and ~150 lbs. On the other hand, loadcells P and E compare well and their readings are similar, ~375 lbs and ~340 lbs.

It should also be noted that the uplift generated by the 12 loadcells was expected to be less than the theoretical uplift, due to the missing readings of the 4 non-reading loadcells, as previously mentioned. A conservative theoretical estimation of uplift (theoretical uplift) was calculated by assuming a roof pressure coefficient (C_p) of -0.9 (Based on figure 27.3-1 – ASCE 7-16) and compared to the experimental uplift. At 0 degrees, the theoretical uplift at 80 mph is expected to be about 1500 lbs (Table 3). At 0 degrees wind angle of attack, the mean resultant uplift force was found to be ~2450 lbs for the FSM and ~1450 lbs for the SSM models (Table 4 and Table 5). Although the SSM models are very close to the expected value, the difference to the FSM model is significant. It is expected to see similar uplift forces between FSM and SSM models, but further investigation is indicated to understand the discrepancies between the results obtained from the different models due to scaling effects of structural members and due to sensor malfunctions that occurred during the experimental tests, e.g. the Loadcell "O" malfunction (Figure 28).

The load distribution between the two models was also investigated. Figure 29 shows the load distribution of the FSM model. From the graph it can be seen that the distribution among all loadcells is within a range of 2% and 16%. When compared to the results obtained from the SSM model (Figure 30), a load distribution between 0% and 24% is seen. From both graphs, it is seen that load distribution from the FSM model is more symmetrical than the SSM model, partially due to the different stiffness of the structural systems in the two models (the FSM model being much stiffer than the SSM model). Deflections experienced by the SSM model may allow for a more varied distribution of loads as deflection must be counteracted by the loadcells. Regardless of the discrepancies, the trends of load distribution between the two models compare well and the collected data and can be utilized along with the numerical model to better understand the effect of the reduced size members.

When analyzing the load distribution at 0 degrees between the FSM and SSM models, there are discrepancies in the value of total force that is obtained at each loadcell. Normally, the SSM model loads are lower than those experienced by the FSM except two locations, that is loadcells A, D and L, located at the corners of the building (Figure 31). The loads experienced by both SSM and FSM models are expected to undergo, to a certain degree, similar trends and similar force values; however, from the results it can be seen that the trends are somewhat similar, but the forces experienced by the loadcells in the SSM and FSM models are in some cases considerably different. The same is seen when a comparison at 45 degrees and 90 degrees is performed, as shown in Figure 32 and Figure 33. These differences between the FSM and SSM models might be partially justified by the altered wind load path that was created by the use of different structural members.

Table 3: Theoretical uplift forces at 80 mph

Cp:	-0.9	-	at 2.63 ft height
V:	112.009	ft/s	
A:	110.25	ft^2	
ρ:	0.002377	slug/ft^3	
F:	**-1479.54**	**lbs**	

Table 4: Loadcell mean uplift forces for FSM model at 80 mph

Deg	TOTAL (lbs)
0	2443.617

Table 5: Loadcell mean uplift forces for SSM model at 80 mph

Deg	TOTAL (lbs)
0	1416.767

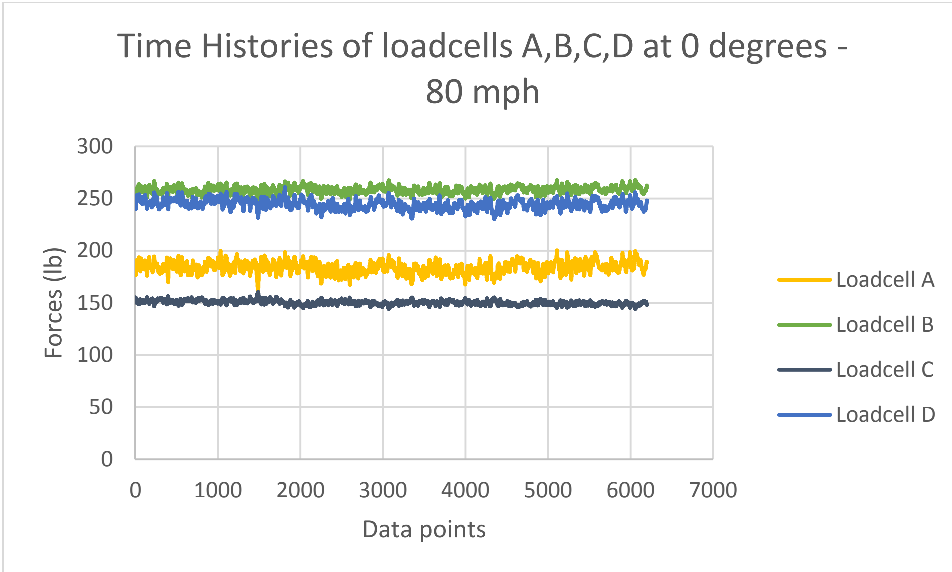

Figure 25: Force time history for loadcells A, B, C and D at 0 degrees and 80 mph wind speed

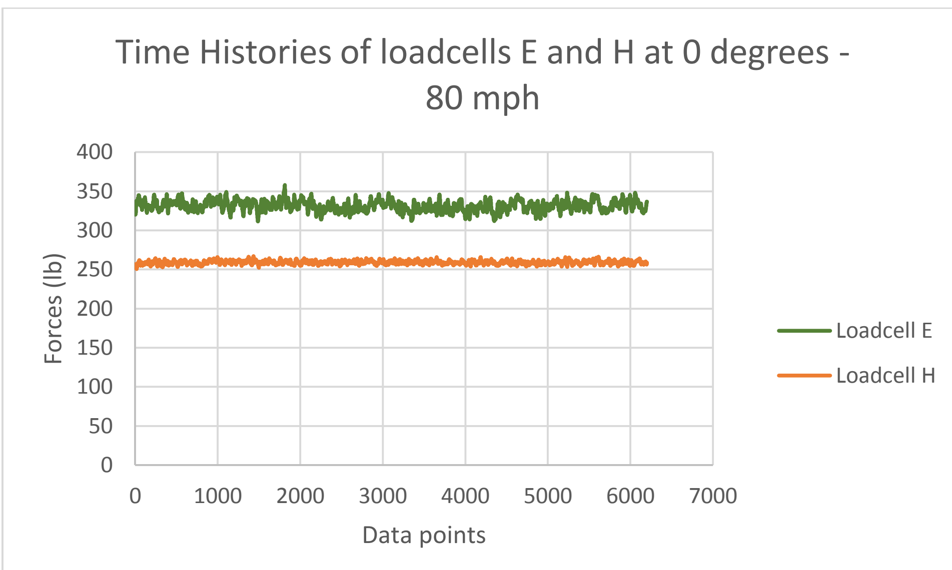

Figure 26: Force time history for loadcells E and H at 0 degrees and 80 mph wind speed

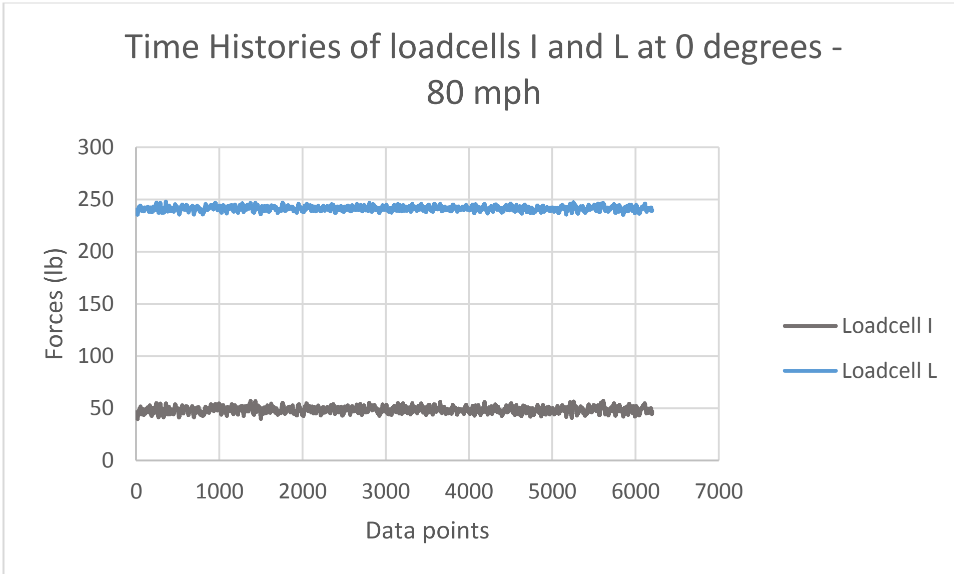

Figure 27: Force time history for loadcells I and L at 0 degrees and 80 mph wind speed

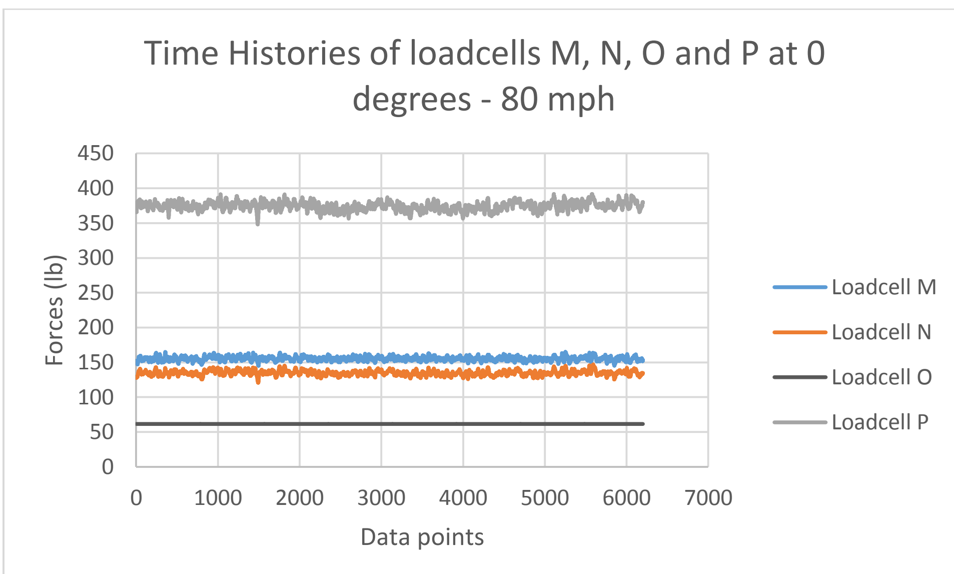

Figure 28: Force time history for loadcells M, N, O and P at 0 degrees and 80 mph wind speed

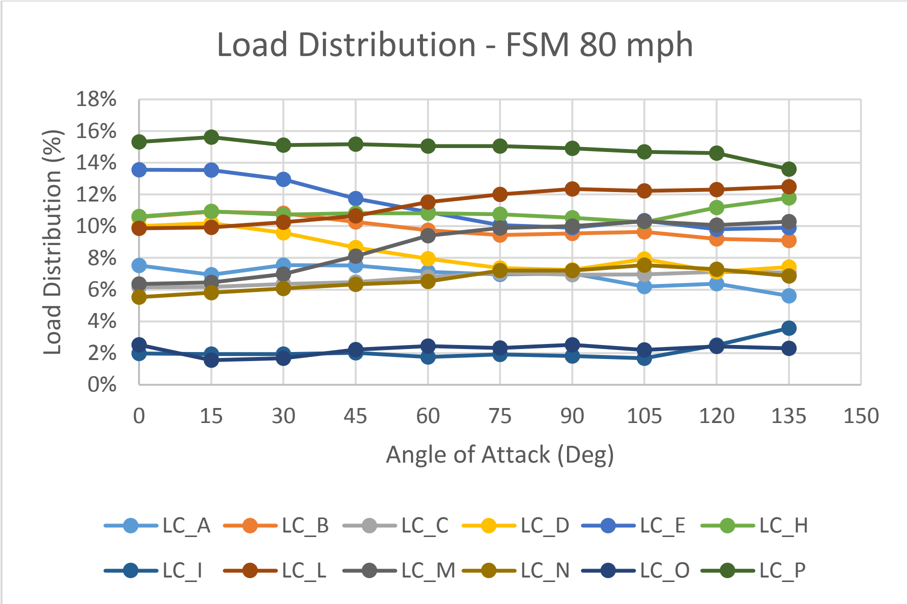

Figure 29: Load distribution of FSM model at 80 mph

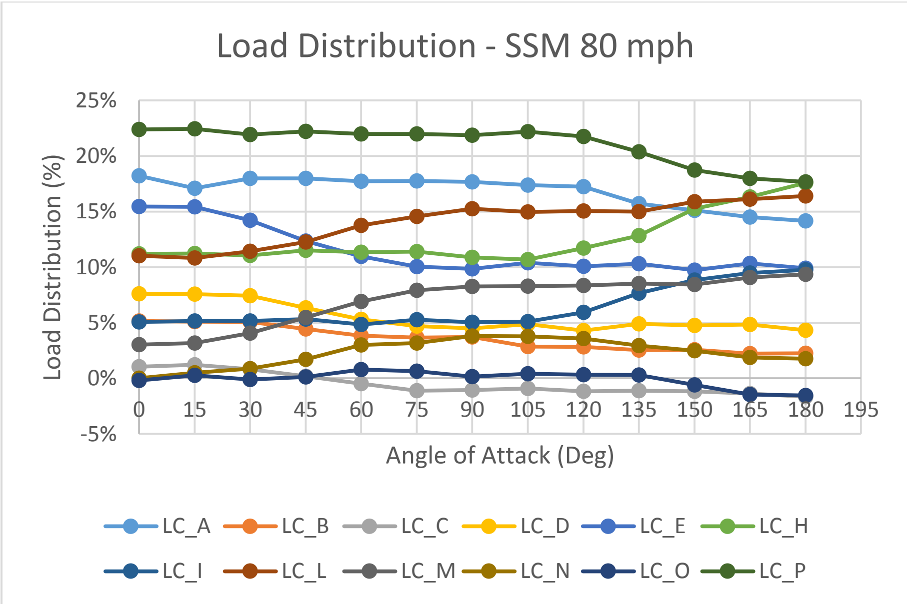

Figure 30: Load distribution of SSM model at 80 mph

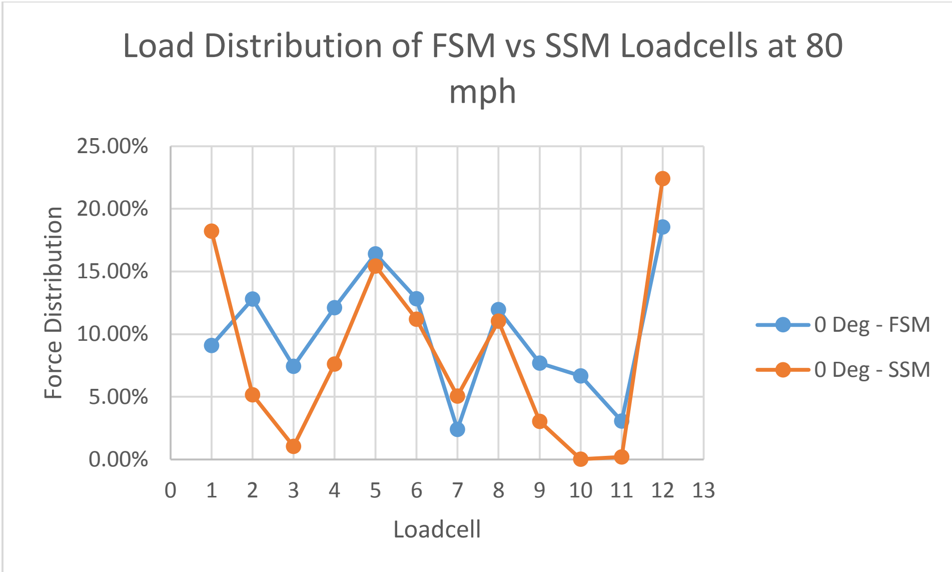

Figure 31: Load distribution of FSM vs SSM at 0 deg - 80 mph

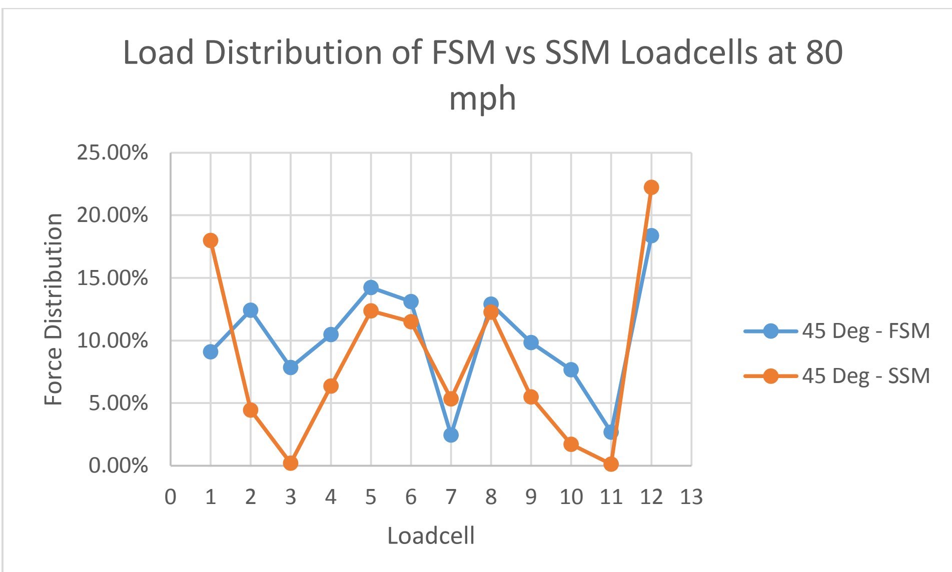

Figure 32: Load distribution of FSM vs SSM at 45 deg - 80 mph

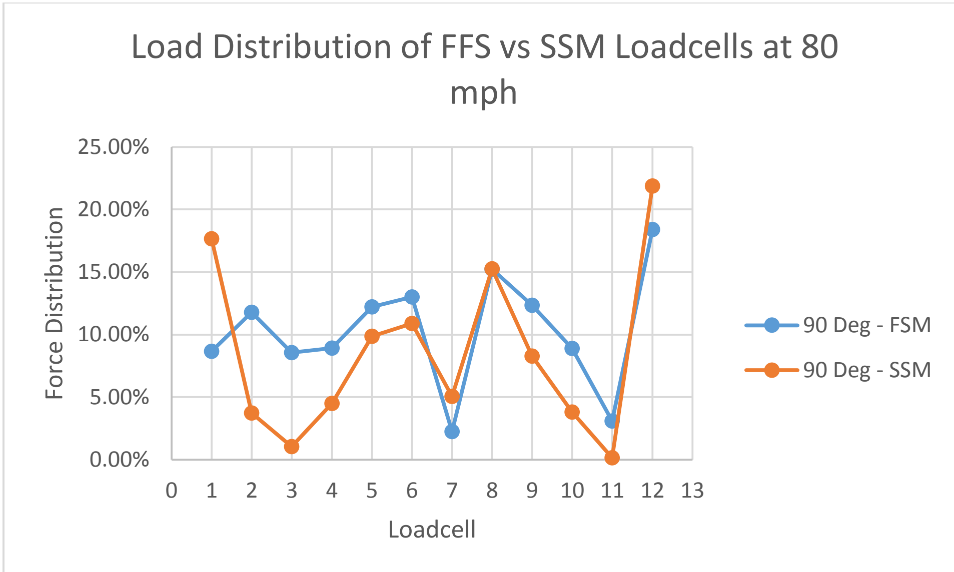

Figure 33: Load distribution of FSM vs SSM at 90 deg - 80 mph

Conclusion

Physical testing and finite element modeling were incorporated in this study to examine the wind-induced load paths on low-rise buildings. The objective was to generate data that can be used to evaluate the feasibility of using reduced size structural members in smaller than full scale structural models and still predict accurately their response.

When comparing the uplift forces acquired from the physical models to that estimated by the ASCE 7-16 critical value, the physical SSM model at 80 mph wind speed agrees well with the theoretical value, while the FSM model shows significant discrepancies (but most likely due to the previously noted sensor malfunctions). The load distribution between FSM and SSM models correlate well, but it also shows certain differences that can be attributed to the modified wind load paths created by the two different structural systems. This is an important finding that needs to be investigated further, which would provide more insight in the use of reduced scale members and their effect on the overall response of the structural system.

The physical testing of two models with same overall dimensions and geometry but different structural members provided significant information about the wind load transfer mechanisms to the foundation of the structure. Such information helped the research team calibrate the numerical models and study the effects of different structural properties on the overall performance of scaled structural systems. Further research is indicated to be able to provide more detailed comparisons and advanced analysis, which will be important to achieving the goal of reduced scale structural testing in a controlled laboratory setting. The accomplishment of this testing technique will allow for cost and time effective testing of different structural systems that will help us improve our knowledge of wind resilient construction methods.

Benefits to the State of Florida

The aim of this project is to provide an increased understanding of the wind load path concept in residential structures and identification of critical components in the integrity of residential structural systems which in turn will allow for the enhancement of current building codes and wind standards. With extended knowledge on wind-structure interaction, wind researchers can assist state policy makers to better understand coastal vulnerability and mitigation benefits and consequently to improve community planning, zoning, code development, and disaster response. Lastly, this, and other projects alike at the WOW, support the development of trained workforce with expertise in hurricane-structure interaction and risk assessment is also through the involvement of graduate and undergraduate students.

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A Resource for the State of Florida

SECTION 5

Development of a Combined Storm Surge Rainfall Runoff Model Phase 1 – Proof of Concept via Initial Model Development and Testing

A Report Submitted to:
The State of Florida Division of Emergency Management

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Development of a Combined Storm Surge Rainfall Runoff Model Phase 1 – Proof of Concept via Initial Model Development and Testing.

1. Introduction

The purpose of this project was to develop a directly coupled model combining storm surge with overland flooding caused by rainfall. Phase 1 is focused on a proof-of-concept, so the work described in this report should be regarded as the first stage in the overall goal of developing a fully validated model of the entire Florida coastal region. The primary tasks completed include the parametrization of tidal forcing, hurricane wind driven (using two parametric models) storm surges with wetting and drying (inundation), and the parametrization of surface run-off (overland flooding) due to rainfall induced by hurricanes. These parametrizations and modules have taken place in a newly developed model that is based on the open source TELEMAC hydrodynamic model.

The first stage of this work was to develop required modules and functions with the capability to solve the above features. According to the scope of work, the TELEMAC model was chosen as the base to build on. This model utilizes an unstructured grid comprising Delaunay Triangles (Galland, et al., 1991). The TELEMAC model (also, more recently, referred to as the open TELEMAC-MASCARET system), was developed over the last 30 years by part of the R&D group of Électricité de France (EDF) energy. Having had such a long period of well-funded development, and being open source, the model is extremely comprehensive and flexible. Moreover, the model has the capacity to include discharges due to rivers and hydraulic control structures such as reservoir gates (Goutal and Maurel, 2002; Goutal et al., 2012). The TELEMAC model was made open source a decade ago and has been extremely well validated over many years, and it includes distributed memory parallelisation via the Message Passing Interface (MPI) library to reduce computational time.

The rainfall module developed at the IHRC (International Hurricane Research Center) is built to read the Integrated Multi-satellite Retrievals for GPM (IMERG) precipitation product. The IMERG is created by inter-calibrating, merging and interpolating all available satellite microwave precipitation estimates, together with microwave-calibrated infrared (IR) satellite estimates, precipitation gauge analyses, and potentially other precipitation estimators at fine time and space scales for the TRMM and GPM eras over the entire globe (Huffman et al. 2015). The IMERG product provides the continuous observations of global precipitation with a temporal resolution of half-hour and spatial resolution of 0.1 degree. Liu (2016) demonstrated that IMERG data tends to have a more accurate estimation over land because of the gauge adjustment used in the product.

The CN (Curve Number) approach (Ponce & Hawkins, 1996) implemented within the TELEMAC model is used to estimate the runoff on the watershed of South Florida. A CN is a quantitative representation of the relationship between land use, soil type, water movement, and the resultant potential runoff driven from rainfall. The bottom friction on the grid is parametrized using spatially varied Manning's Coefficients derived from the USGS NLCD (national land cover data) and the classification system (Mattocks & Forbes, 2008; Liu, et al., 2013; Zhang, et al., 2013).

A high resolution grid has been generated for the South Florida area for verification purposes. This first iteration grid is focused on the City of Miami Beach with a street level resolution of about 10 meters being achieved there; this level of resolution is two orders of magnitude finer than the less important deep water areas. The edge length of the elements in the unstructured triangular grid varies from Order of 7.5km down to Order of 10 m.

In this project, this grid was initially employed to simulate 4 historical hurricanes, Frances 2004, Wilma 2005, Matthew 2016, and Irma 2017. After running the validation cases for the four historical hurricanes, 10 hypothetical hurricanes were simulated using the same grid to demonstrate the capability, robustness and stability of the newly developed model. The 10 hypothetical hurricanes are all Category 5 hurricanes with different forward directions, moving speeds, landfall locations, and Radius of Maximum Wind across the South Florida area. Meanwhile, simple rain fields for the hypothetical hurricanes are prescribed using a parametric model based on the R-CLIPPER approach (Marks & DeMaria, 2003).

Overall, the new developed model has proven to be stable, robust, and efficient. The computational time (CPU time) of the new TELEMAC-based model is reasonable. On a suitable grid (typically comprising between 0.7 M and 1 M nodes and approximately 1.5 M to 2 M elements), a modern desktop workstation with 16 processes and 64 GB random access memory (RAM) is sufficient to run the developed model. With such a machine, a typical combined rainfall runoff and storm surge simulation (including tide) can be undertaken in less than 30 minutes of machine time for a 4-day long (real time) storm simulation.

2. TELEMAC 2D Base Model Description

2.1 Governing Equations

The TELEMAC2D model solves the non-linear shallow water (NLSW) equations. The NLSW equations are derived from the Navier-Stokes equations under the assumption that the flow is irrotational and that the vertical acceleration is of negligible importance (Peregrine, 1972). This equation set is valid for shallow water, or long waves. The type of waves observed in rivers and due to rainfall flooding and storm surge fall into the long wave category. A relatively detailed description of the equations and overview of the solution technique (including a justification) is given below.

In vector form, with the water depth denoted by h and the, depth-averaged, water velocity denoted by $u = [u, v]^T$, we can write the NLSW equations, in primitive variable form, as

$$\frac{\partial h}{\partial t} + u \cdot \nabla h + h\nabla \cdot u = S_h \quad (1)$$

$$\frac{\partial u}{\partial t} + u \cdot \nabla u + h\nabla \cdot u = S_m \quad (2)$$

where $\boldsymbol{S_h}$ and $\boldsymbol{S_m}$ denote the vectors of source terms in the continuity and momentum equations respectively. These source terms include the effects of bottom geometry, Coriolis force, bottom friction, rainfall and infiltration. A description of the components that make up these source terms, excluding those terms due to rainfall and runoff, can be found in Kelly *et al*. (2016) and is not included here. Integration of the NLSW with respect to time yields up the instantaneous values of water depth (and thus free surface) and depth-averaged velocity components. Integration of the equations at discrete time intervals therefore provides full detail of the time-evolution of the flow within the constraints of the shallow water framework (Peregrine, 1972).

2.2 Numerical Solution Technique

The open TELEMAC2D software includes both finite element (FE) and finite volume (FVM) solution techniques for the NLSW equations. For this work we choose to use a FE-type solution technique, as opposed to a FVM-type solution technique. The primary reason for this is that, in TELEMAC2D, the FE solver has been implemented in a fully implicit form. The FVM solvers in TELEMAC2D and many well-known codes, such as the USACE HEC-RAS models, are currently fully explicit. Even with distributed memory parallelization, run times for explicit schemes can still be prohibitive for large domains (>0.5M computational nodes and >1M elements) because the time step restrictions for explicit schemes are governed by the CFL criterion (Courant et al., 1967) and are relatively stringent. The advantage of using a fully implicit solver is that we can employ a Courant number (Courant et al., 1967) greater than unity, and thus use a larger time-step, making our simulations computationally more efficient. Initial testing at the IHRC has demonstrated a *three-fold* decrease in computation time when using the TELEMAC FE model compared with the TELEMAC FVM model.

2.2.1 Time Integration

Writing down the basic time differencing scheme used by TELEMAC we can first write down a first-order Euler discretization in time for the continuity and momentum equations as:

$$\frac{h^{n+1}-h^n}{\Delta t} u \cdot \nabla h + h\nabla \cdot u = SRC_h \qquad (3)$$

$$\frac{u^{n+1}-u^n}{\Delta t} + u \cdot \nabla u + h\nabla \cdot u = S_{mx} \qquad (4)$$

In order to achieve second-order accuracy in time, in TELEMAC the spatial gradient and divergence terms are evaluated in a semi-implicit manner such that the water depth is written as:

$$\theta h^{n+1} + (1-\theta)h^n \qquad (5)$$

where $\theta > 0.5$, to ensure stability; the velocity components are dealt with in a similar fashion. The semi-implicit form described above necessitates a special treatment of the non-linear term $h\nabla \cdot u$which in TELEMAC is handled using sub-iteration to give

$$h\nabla \cdot u = \tilde{h}\nabla \cdot \{\theta_u u^{n+1} + (1-\theta_u)u^n\} \qquad (6)$$

where:

$$\tilde{h} = \theta_h h^{n+1} + (1-\theta_h)h^n \qquad (7)$$

Note that separate implicit coefficients, $\theta_h$and θ_u, are used for depth and velocities. The use of this sub-iterative procedure works to further stabilize the TELEMAC model. The non-linear velocity advection is handled in a similar manner

$$u \cdot \nabla u = \tilde{u} \cdot \nabla\{\theta_u u^{n+1} + (1-\theta_u)u^n\} \quad (8)$$

Where

$$\tilde{u} = \theta_u u'^{n+1} + (1-\theta_u)u^n \quad (9)$$

Note that the value of $u'^{n+1}$is itself the latest *approximation* of u^{n+1}at the current sub-iteration level. It should be noted that TELEMAC utilises distinct relaxation coefficients for velocity advection and diffusion.

2.2.2 Spatial Discretization in TELEMAC (FE)

Letting ***w***=*[u,v,h]*^{T} be the vector of (primitive) dependent variables, then the NLSW equations for mass and momentum (including all relevant source terms) can be written in the form

$$L(w) = f \quad (10)$$

where *L* is the linear operator comprising the requisite combination of difference operators and ***f*** is the vector of source terms.

At a discrete approximation level we cannot guarantee that $L(w) = f$; however, in the variational method employed by TELEMAC the purpose is to at least minimise the value of *L(**w**)-**f***. At node points it is assumed that the value of ***w*** is exact, the value between the node points is approximated by some form of interpolation. In TELEMAC the computational domain is decomposed into a finite number of triangular elements and each triangular element has co-ordinate nodes and interpolation nodes. In the FE approach values of the independent variables ***w*** are approximated at the interpolation points (mesh nodes) by a suitable interpolation function

$$w = \sum_{i=1}^{np} w_i \varphi_i \quad (11)$$

where *np* is the total number of discretization points (mesh nodes), $w_i$is the approximate value of the dependent variable *w* at a mesh node,$\varphi_i = \varphi_i(x,y)$is a basis, or shape, function whose value is unity at the mesh point *i* and whose value decreases, linearly, to zero outside the mesh segment. For TELEMAC's unstructured triangular mesh each basis function is defined as$\varphi_i = ax + by + c$ where *a,b* and *c* depend on the triangle such that $\varphi_i = 1$at point *i* and is 0 outside of the basis function extent (i.e. outside the domain of influence of cell *i*).

As was noted in FE guise, TELEMAC uses a variational formulation for the variables *u,v* and *h* in order to minimise the value of *L(**w**)-**f***. The variational formulation requires test functions denoted by $\Psi_i$the test functions are defined so that the dot product $\int_\Omega (L(w) - f)\Psi_i d\Omega = 0$. The choice of test functions defines the type of FE method used. The well-known Galerkin method (Hervouet, 2007), for example, uses test functions that are the same as the basis functions $\Psi_i = \varphi_i$. For the NLSW equations TELEMAC employs test functions that are distinct from the basis functions (Hervouet, 2007). Different basis functions for water depth and velocity can also be employed in TELEMAC so that the discretization for water depth can be distinct from that of the velocity components. The variational formulation for the NLSW equations uses the basis functions$\varphi_i^h$and $\varphi_i^u$for the water depth and velocity

components respectively and the test functions Ψ_i^h and Ψ_i^u for the continuity and momentum equations respectively. The number of bases for depth and velocity can be different. For example, if a linear function is used for velocity and a higher-order quadratic function for the water depth.
The form of the continuity and momentum equations used by the FE version of TELEMAC2D is

$$\int_\Omega \left(\frac{h^{n+1}-h^n}{\Delta t}\right)\Psi_i^h d\Omega + \int_\Omega (u\cdot\nabla h)\Psi_i^h d\Omega + \int_\Omega (h\nabla\cdot u)\Psi_i^h d\Omega = \int_\Omega S_h \Psi_i^h d\Omega \tag{12}$$

for every point 1<*i*<*nph* on the mesh with *nph* being the number of depth computation points. Similarly, the momentum equations are integrated-up as:

$$\begin{aligned}\int_\Omega \left(\frac{u^{n+1}-u^n}{\Delta t}\right)\Psi_i^u d\Omega + \int_\Omega (u\cdot\nabla u)\Psi_i^h d\Omega = -\int_\Omega \quad \theta_h g \frac{\partial(h^{n+1}-h^n)}{\partial x}\Psi_i^u d\Omega \\ -\int_\Omega \quad g\frac{\partial B}{\partial x}\Psi_i^u d\Omega + \int_\Omega F_x \Psi_i^u d\Omega + \int_\Omega \frac{1}{h}\nabla\cdot(h\upsilon_e\nabla(u))\Psi_i^u d\Omega\end{aligned} \tag{13}$$

for the *x*-component and:

$$\begin{aligned}\int_\Omega \left(\frac{v^{n+1}-v^n}{\Delta t}\right)\Psi_i^u d\Omega + \int_\Omega (u\cdot\nabla v)\Psi_i^h d\Omega = -\int_\Omega \quad \theta_h g \frac{\partial(h^{n+1}-h^n)}{\partial y}\Psi_i^u d\Omega \\ -\int_\Omega \quad g\frac{\partial B}{\partial y}\Psi_i^u d\Omega + \int_\Omega F_y \Psi_i^u d\Omega + \int_\Omega \frac{1}{h}\nabla\cdot(h\upsilon_e\nabla(v))\Psi_i^u d\Omega\end{aligned} \tag{14}$$

for the *y*-component, for every point 1<*i*<*npu* on the mesh with *npu* being the number of velocity computation points. Here g is the acceleration due to gravity, υ_e is the diffusion coefficient and *Fx* and *Fy* are the Coriolis coefficients in the *x* and *y* directions respectively. Functions like the diffusion terms contain second-order derivatives (in space) therefore, one approach is to integrate them by parts so that we have

$$\int_\Omega \nabla\cdot(\upsilon_e\nabla(u))\Psi_i^u d\Omega = \int_\Gamma \Psi_i^u \upsilon_e \nabla(u)\cdot n d\Gamma - \int_\Omega \upsilon_e \nabla(u)\cdot\nabla(\Psi_i^u) d\Omega \tag{15}$$

which also contains the boundary terms. Note that in-order to handle dry beds, before integration by parts, TELEMAC employs a simplification to the diffusion terms in order to avoid division by zero in dry areas:

$$\int_\Omega \frac{1}{h}\nabla\cdot(h\upsilon_e\nabla(v))\Psi_i^u d\Omega \approx \int_\Omega \nabla\cdot(\upsilon_e\nabla(v))\Psi_i^u d\Omega \tag{16}$$

2.2.3 Velocity advection:

For advection, we use an N-type distributive-type scheme (Roe & Sidilkover, 1992), the narrow (N) scheme (Hervouet, 2007) is employed for this study. We note in passing that the use of semi-Lagrangian advection (the method of characteristics) is unsuitable as only the first-order MOC is monotonicity preserving without the explicit use of a limiter or nonlinear filter. Here we provide a brief overview of the N-scheme used for advection in TELEMAC.

Denoting the advection quantity by *f* then the transport equation governing advection if the quantity *f* is

$$\frac{\partial f}{\partial t} + u \cdot \nabla f = 0 \qquad (17)$$

The quantity *f=f(x,y)* and it can be approximated linearly thus for each vertex of a triangular element $f(x_i, y_i) = a + bx_i + cy_i$. The values of b and c are the x and y components of the gradient of f respectively, the gradients are constant on a triangular element. The surface ST of the element can be written in the form of a matrix determinant

$$S_T = 0.5 \begin{vmatrix} 1 & x_1 & y_1 \\ 1 & x_2 & y_2 \\ 1 & x_3 & y_3 \end{vmatrix} \qquad (18)$$

As the gradients *b* and *c* form the solution of a Cramer system. Using these definitions in TELEMAC the second term on the LHS of the transport equation can be written as,

$$u \cdot \nabla f = \frac{1}{S_T} \sum_{i=1}^{3} \quad f_i k_i \qquad (19)$$

For each of the triangular elements that make up the TELEMAC mesh a constant velocity for each element is assumed and the normal vectors at each of the 3 vertices are defined as $\boldsymbol{n_1} = [y_2\text{-}y_3, x_3\text{-}x_2]^T$, $\boldsymbol{n_2} = [y_3\text{-}y_1, x_1\text{-}x_3]^T$ and $\boldsymbol{n_3} = [y_1\text{-}y_2, x_2\text{-}x_1]^T$. By definition it follows that:

$$\sum_{i=1}^{3} \quad n_i = 0 \qquad (20)$$

For each triangle and *i=1..3* TELEMAC introduces the quantity $k_i = \frac{1}{2} u \cdot n_i$and it clearly it follows tha$\sum_{i=1}^{3} \quad k_i = 0$. Another key quantity is the $\Phi_T = \sum_{i=1}^{3} \quad f_i k_i$. The N-scheme re-writes this equation in a form in which only differences in *f* appear

It should be noted that, when using the N-scheme, there is no advantage of assuming the velocity to vary linearly within an element, as the N-scheme utilizes the element average velocity (this is similar to the approach employed in a FVM discretization).

2.2.4 Telemac FVM Implementation

In Finite Volume (FVM) form TELEMAC2D uses an unusual vertex-centered FVM scheme applied to the same unstructured Delaunay triangulated mesh as the FE scheme. The TELEMAC finite volume model is based on the use the divergence form of the NLSW equations solved via approximate Riemann solvers (Toro, 1997). The FVM schemes in TELEMAC2D have one distinct advantage over the FE schemes in that they enable solution of the divergence form of the NLSW equations in a shock capturing manner. This means that any shock waves (i.e. bores or hydraulic jumps) that are present or develop will be of the correct strength and propagate at the correct speeds. TELEMAC offers a number of options for the type of approximate Riemann solver; however, the only modern, i.e. Riemann solver based, high-order FVM scheme available in TELEMAC is the Weighted Average Flux (WAF) scheme (Ata, et al., 2013). This is the most suitable of the FVM schemes in TELEMAC for use in simulation storm surges due to the fact that it is both high-order and shock capturing.

2.3 A note on shocked flows

The FE version of TELEMAC utilizes the primitive variable form of the NLSW equations under a shock capturing approach, without the explicit treatment of shocks as moving internal boundaries. Solving the primitive variable form of the NLSW equations without explicit shock fitting with a FD or FVM scheme can potentially lead to the incorrect behaviour of shock waves, i.e. shocks of the wrong strength that move at an incorrect speed. It should be noted that all FE solutions without explicit treatment of shocks are continuous. It is shown by Hervouet (2007) that practically, in many instances, the use of the distributive FE method to solve the primitive variable form has little detrimental effect on the simulation of stationary hydraulic jumps and moving hydraulic jumps (shocks). In all instances the FE solution to the NLSW equations can be considered to be far superior to solutions of the diffusion wave equations which are typically used to model flooding and runoff and are themselves simplified NLSW equations. All the FVM schemes in TELEMAC are shock capturing it is therefore safe to use any of these schemes for flows that may develop shocks as the simulation progresses. It is important to be aware of this information when performing simulations that are likely to develop shock waves, i.e. wave due to the opening of control structures in canals.

2.4 A note on transmissive BCs

In FVM schemes, zero gradient boundary conditions are easily implemented using ghost cells and zeroth-order extrapolation. In FE schemes, this type of boundary is much more difficult to achieve. For the continuity equation, denoting the domain boundary by Γ, then the boundary integral is

$$\int_{\Gamma} hu\vec{n}\Phi_i^h d\Gamma = \theta \int_{\Gamma} hu^{n+1} \cdot \vec{n} \tag{21}$$

In this model, where necessary, as a first approximation we employ a Sommerfeld-type approach where we approximate the velocity at boundary nodes by the wave celerity at those nodes. This enables us to allow for a free outflow when using the FE approach. There is certainly room for improvement here.

2.5 Tidal BCs

As part of this work the original TELEMAC tidal boundary conditions have been modified in order to enhance stability. A Flather type boundary condition is implemented and tides are internally generated in the model using linear superposition of constituent data obtained from the OSU TPXO global data base.

3. Rainfall runoff model: Curve Number (CN) approach

The Curve Number (CN) approach developed by Soil Conservation Services (SCS), is an empirical method to estimate runoff generated by rainfall (NRCS, 1986). The CN method uses soil, land use, and antecedent moisture parameters to estimate a curve number that ranges in value from 0 to 100. Higher CN values indicate areas with a higher potential for runoff generation during a rainfall event. The approach of the rainfall runoff modelling is to parameterise the hydrological abstractions (losses) which comprise:

(i) interception storage (due to vegetation etc.),
(ii) surface storage,
(iii) infiltration,
(iv) evaporation,
(v) evapotranspiration.

For storm-type modelling as the first approximation, the CN runoff model can be considered to be appropriate even for large watersheds. In storm situations infiltration tends to be the dominant form of hydrological abstraction, interception will also cause losses but, typically, to a much lesser extent. With P being the rainfall depth, P_e being the runoff depth, and F being the loss due to hydrological abstraction, it follows from conservation of mass as,

$$P = P_e + F \tag{22}$$

Runoff begins after a minimum amount of rain has fallen, this amount of lost rain is typically referred to as the initial abstraction (denoted as I_a), which is lost due to the combination of interception, infiltration and surface storage (USDA SCS, 1972). The conservation equation can also be written as:

$$P = P_e + I_a + F_a \tag{23}$$

The CN runoff model is based on the assumption that retention of water is proportional to runoff. A relationship between the two is specified as:

$$\frac{F_a}{S} = \frac{(P_e)^2}{(P - I_a)} \tag{24}$$

The maximum potential retention, or soil moisture, is denoted by S in unit of mm.

In the present model, spatially varying CN values have to be calculated by the user for the entire computational domain. The CN is first used to calculate the potential maximum retention (S) after runoff begins using equation (25).

$$S = (\frac{1000}{CN} - 10) \tag{25}$$

The potential maximum soil moisture is then used to determine the initial abstraction (I_a), which is the amount of precipitation (P) that is intercepted before runoff occurs (Equation 26).

$$I_a = 0.2 \times S \tag{26}$$

If precipitation depth is less than the initial abstraction, no runoff occurs. The initial abstraction is then used in the runoff equation to determine total runoff (Q in eq. 27). Both initial abstraction and runoff are estimated in unit of mm of runoff.

$$Q = \frac{(P - I_a)^2}{P - I_a + S} \tag{27}$$

As the spatially-varying CN values are a model input, CN can be calculated for the model domain using datasets downloaded from the USDA-NRCS National Geospatial Data Gateway (https://datagateway.nrcs.usda.gov). The datasets used to determine the CN values were the eight-digit hydrologic unit code (HUC-8) watersheds from USDA–NRCS, land use data from the 2011 National Land Cover Database (NLCD 2011), and the SSURGO hydrologic soil group from USDA–NRCS.

Land cover data overlapping the model domain were summarized into several distinct classifications, each representing a unique land use category. The soils in the HUC-8 watersheds were categorized into four hydrologic soil groups. The HSGs are classified from A to D, with group A representing soils with high permeability, and group D representing soils with low permeability. The land use categories and hydrologic soils groups were consolidated across the model domain to calculate the curve number for each unique combination of values (Table 1). In addition to land use type and soil type, curve number also depends on antecedent moisture condition (AMC) of the soils. The antecedent moisture condition represents the amount of saturation in the soil. The AMC is categorized into three conditions: AMC I, AMC II, and AMC III. AMC I represents soils that are dry and are able to infiltrate water at a higher rate, AMC II represents soils that have an average moisture condition and are able to infiltrate water at an average rate, and AMC III represents soils that are wet and are able to infiltrate water at a lower rate.

Table 1. Curve Number and soil type of Group A, B, C, and D

Soil Type	CN (A)	CN (B)	CN (C)	CN (D)
Water	100	100	100	100
Open Space (Good)	39	61	74	80
Residential - 1/2 acre	54	70	80	85
Residential - 1/8 acre	77	85	90	92
Commercial & Business	89	92	94	95
Fallow -Bare Soil	77	86	91	94
Oak-Aspen (Good)	30	30	41	48
Woods (Good)	30	55	70	77
Woods (Fair)	36	60	73	79
Brush (Fair)	35	56	70	77
Pasture, Grassland (Fair)	49	69	79	84
Meadow	30	58	71	78
Row Crops - SR (Good)	67	78	85	89
Woody Wetlands	100	100	100	100
Emergent Herbaceous Wetlands	100	100	100	100
Water	100	100	100	100
Open Space (Good)	39	61	74	80
Residential - 1/2 acre	54	70	80	85
Residential - 1/8 acre	77	85	90	92
Commercial & Business	89	92	94	95
Fallow -Bare Soil	77	86	91	94
Oak-Aspen (Good)	30	30	41	48
Woods (Good)	30	55	70	77
Woods (Fair)	36	60	73	79
Brush (Fair)	35	56	70	77
Pasture, Grassland (Fair)	49	69	79	84
Meadow	30	58	71	78
Row Crops - SR (Good)	67	78	85	89

Woody Wetlands	100	100	100	100

For urban areas around Miami Beach, as a first approximation, a CN value of 87.5 was chosen based on Table 1.

4. Bottom friction model

Manning's coefficients for grid cells over the land were estimated using the 2011 national land cover datasets (NLCD) created by the U.S. Geological Survey (USGS). A table of Manning's coefficients (Table 2) corresponding to different land cover categories (Zhang et al., 2013) was employed in this study. If the spatial resolution of NLCD is smaller than the element size, an average Manning's coefficient (n_a) for a grid cell was calculated using

$$n_a = \frac{\sum_{i=1}^{N}(n_i\alpha) + n_w\beta}{N\alpha + \beta} \quad (28)$$

where n_i is the Manning's coefficient value of a NLCD pixel within a model grid cell, α is the area of a NLCD pixel, N is the total number of NLCD pixels within a model cell, n_w is the Manning's coefficient for the oceanic area β that are not covered by NLCD pixels.

Table 2. Manning's coefficients for various categories of land cover.

NLCD Class Number	NLCD Class Name	Manning Coefficient
11	Open Water	0.020
12	Perennial Ice/Snow	0.010
21	Developed Open Space	0.020
22	Developed Low Intensity	0.050
23	Developed Medium Intensity	0.100
24	Developed High Intensity	0.130
31	Barren Land (Rock/Sand/Clay)	0.090
32	Unconsolidated Shore	0.040
41	Deciduous Forest	0.100
42	Evergreen Forest	0.110
43	Mixed Forest	0.100
51	Dwarf Scrub	0.040
52	Shrub/Scrub	0.050
71	Grassland/Herbaceous	0.034
72	Sedge/Herbaceous	0.030
73	Lichens	0.027
74	Moss	0.025
81	Pasture/Hay	0.033
82	Cultivated Crops	0.037
90	Woody Wetlands	0.140
91	Palustrine Forested Wetland	0.100
92	Palustrine Scrub/Shrub Wetland	0.048
93	Estuarine Forested Wetland	0.100
94	Estuarine Scrub/Shrub Wetland	0.048
95	Emergent Herbaceous Wetlands	0.045

96	Palustrine Emergent Wetland (Persistent)	0.045
97	Estuarine Emergent Wetland	0.045
98	Palustrine Aquatic Bed	0.015
99	Estuarine Aquatic Bed	0.015

5. Parametric Wind Models

As part of this work two distinct parametric wind and atmospheric pressure models, the Holland (1980) model and the Myers and Malkin (1961) model which was adapted for SLOSH by Jelesnianski et al. (1992), have been added to the TELEMAC model. The Holland (1980) model is extremely well known and well documented. Thus, it will not be described here, for a detailed description the interested reader is referred to the paper by Holland (1980). The Myers & Malkin (1961) wind model is less well known and it is therefore briefly described in this report.

The wind and atmospheric pressure fields are generated based on the parameters of atmospheric pressure drop and radius of maximum wind speed. The pressure, wind speed, and wind direction are computed from a stationary, circularly symmetric storm using the balance of forces along a surface wind trajectory and normal to a surface wind trajectory. The governing equations for the adapted Myers & Malkin (1961) wind model are:

$$\frac{1}{\rho}\frac{dp}{dr} = \frac{k_s V^2}{\sin\phi} - V\frac{dV}{dr} \qquad (29)$$

and

$$\frac{1}{\rho_a}\frac{dp}{dr} = f_c V\frac{V^2}{r}\cos\phi - V^2\frac{d\phi}{dr}\sin\phi + k_n V^2 \qquad (30)$$

where r is the distance from the storm center, p is the pressure, φ is the inflow angle across circular isobars toward the storm center, and V is the wind speed. The values of k_s and k_n are empirically determined coefficients and f_c is the Coriolis force. Two equations can be solved for p and φ if the form of wind speed profile V is supplied. The new TELEMAC2D-based model follows the approach employed in the SLOSH model and uses the following wind speed profile for a stationary storm:

$$V(r) = V_R\frac{2RMW\cdot r}{RMW^2 + r^2} \qquad (31)$$

where *RMW* is the radius of maximum wind. A number of the base TELEMAC2D subroutines were modified in order to allow for the inclusion of these two parametric hurricane wind and pressure models. New subroutines were also introduced; a list of modified subroutines and newly introduced subroutines is provided below:

6. Associated Subroutines in the Modified TELEMAC2D model

6.1 New Subroutines

Telemac2dmof.f90 – A new module named hurriwind.mod was introduced to store variables specific to the hurricane wind field.

SLOSHDAT.f90 – A new subroutine was introduced. The purpose of this routine is to read in the hurricane track file data into arrays, and to perform any necessary unit conversions.

GETWIND.f90 – This subroutine calculates and outputs the wind speed at a specified radius, the inflow angle and the hurricane induced pressure drop.

HOLLANDWINDFIELD.f90 – This new subroutine implements the Holland (1980) wind field at nodes on the unstructured TELEMAC grid. The subroutine provides time and space varying wind components and a parametric pressure field.

SLOSHWINDFIELD.f90 - This new subroutine implements the Myers & Malkin (1961) wind field, described briefly above, at nodes on the unstructured TELEMAC grid.

6.2 Modified Subroutines

Modifications were also made to a number of existing TELEMAC subroutine. The list is too exhaustive to include here; however, all the modified subroutines are present in the princi.f TELEMAC fortran file that is compiled at run-time. The *telemac.dico* code, which acts as an interface between the control file and the underlying Fortran code was also modified. These modifications included the addition of new *KeyWords* and their meanings (see Appendix).

7. Verifications of 4 Historical Hurricanes

For the purpose of the validation of the storm tide and overland flooding model, four historical hurricanes were simulated: Hurricane Frances (2004), Hurricane Wilma (2005), Hurricane Matthew (2016), and Hurricane Irma (2017). The results of a forecast type validation hurricane simulation are presented in the following sections. It is important to note that the simulation results presented here are not the final and detailed hindcasting products with re-analysis wind fields, and finely tuned bathymetry, Curve Numbers, and friction coefficients.

7.1 Simulation Grid

The South Florida grid is a circular domain covering the all of South Florida and the adjacent coastal and oceanic area with a varied grid cell resolution from 10 meters to 7.5 km. The mesh comprises of approximately 878,723 nodes, and 1,755,240 elements (Fig. 1). The domain's shape and location are very similar to the South Florida Basin of SLOSH used by National Hurricane Center (NHC) of National Oceanic and Atmospheric Administration (NOAA), in order to facilitate comparison of the two model results in the next phase.

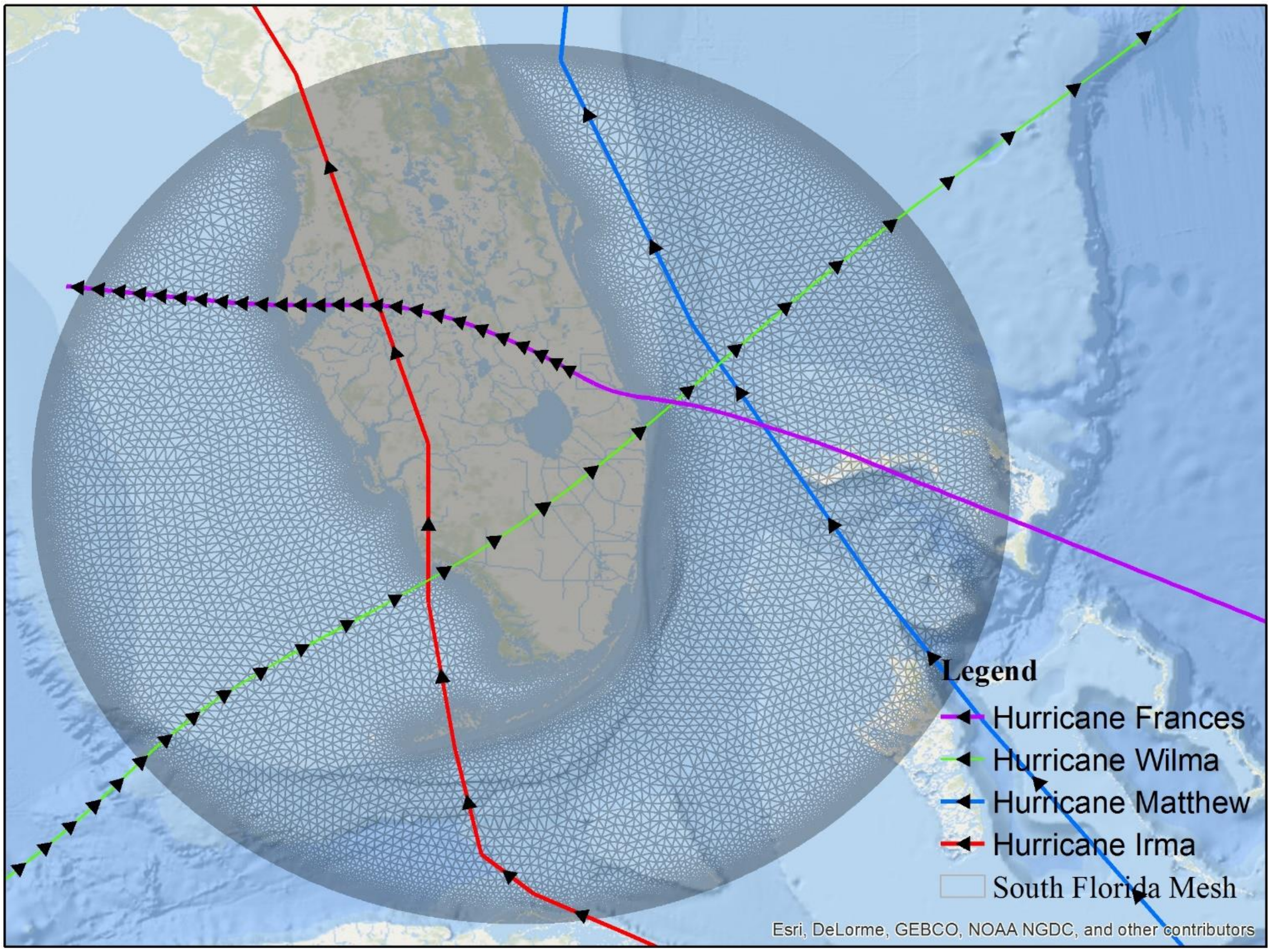

Fig. 1. South Florida Mesh and 4 Historical Hurricanes around Florida, Hurricane Frances (2004), Hurricane Wilma (2005), Hurricane Matthew (2016), and Hurricane Irma (2017).

The finest resolution of the grid is around 10 meters, covering the whole City of Miami Beach (Fig. 2). The streets, channels, and rivers are resolved at least by one grid cell (element).

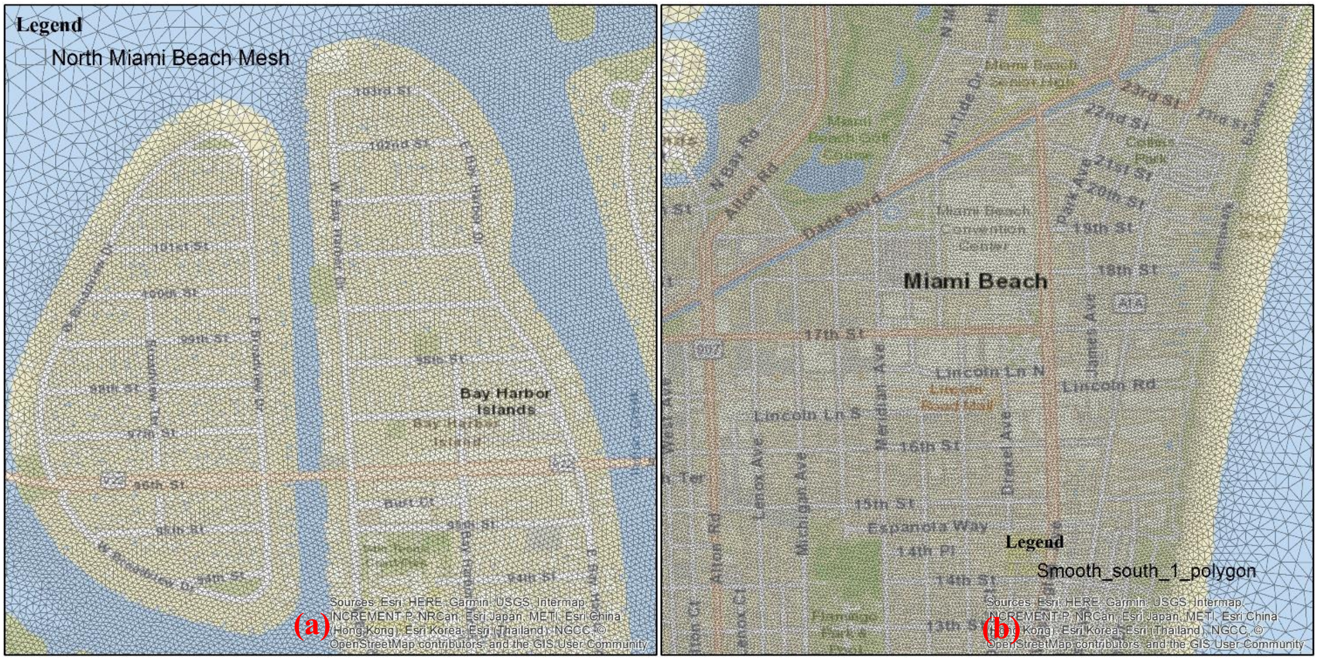

Fig. 2. South Florida Mesh at North Miami Beach (a) and South Miami Beach near Miami Beach Convention Center (b), the finest grid resolution is 10 meters.

7.2 Bathymetry

The South Florida Water Management District (SFWMD) 5-m digital elevation model (DEM) data was used to derive the elevation over the fine-resolution model grid if the data were available for the study area (http://apps.sfwmd.gov/gisapps/sfwmdxwebdc/). The Florida Geographic Data Library (FGDL) 5-m DEM data were used for areas without SFWMD DEMs (https://www.fgdl.org/metadataexplorer/explorer.jsp). NOAA 2-minute Global Relief Model (ETOPO2) and 3-arc-second Coastal Relief Model were combined to obtain bathymetric data for the model grid. Fig. 3 represents the grid bathymetry at North and South Miami Beach with very high resolution (around 10 meters). It would appear that the complicated streets, rivers and channel geometry can be resolved reasonably well with triangular cells with a 10m edge length.

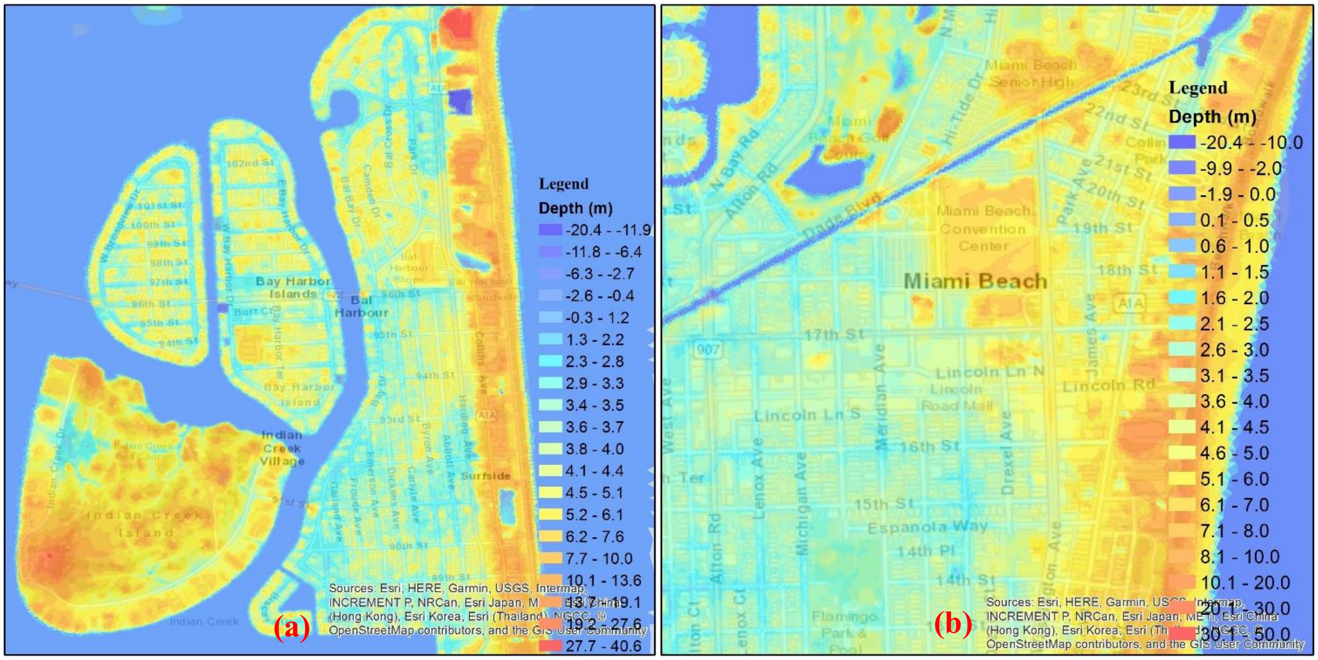

Fig. 3. Bathymetry above NAVD 1988 at North Miami Beach (a) and South Miami Beach near Miami Beach Convention Center, the finest grid resolution is 10 meters.

7.3 Curve Number

Fig. 4 shows the spatially varying CN distribution calculated using the method outlined in Section 3. The CN of the water cells was set to be a constant value of 100. On land the CN varied from 30 to 100, with the lowest values on the west coast.

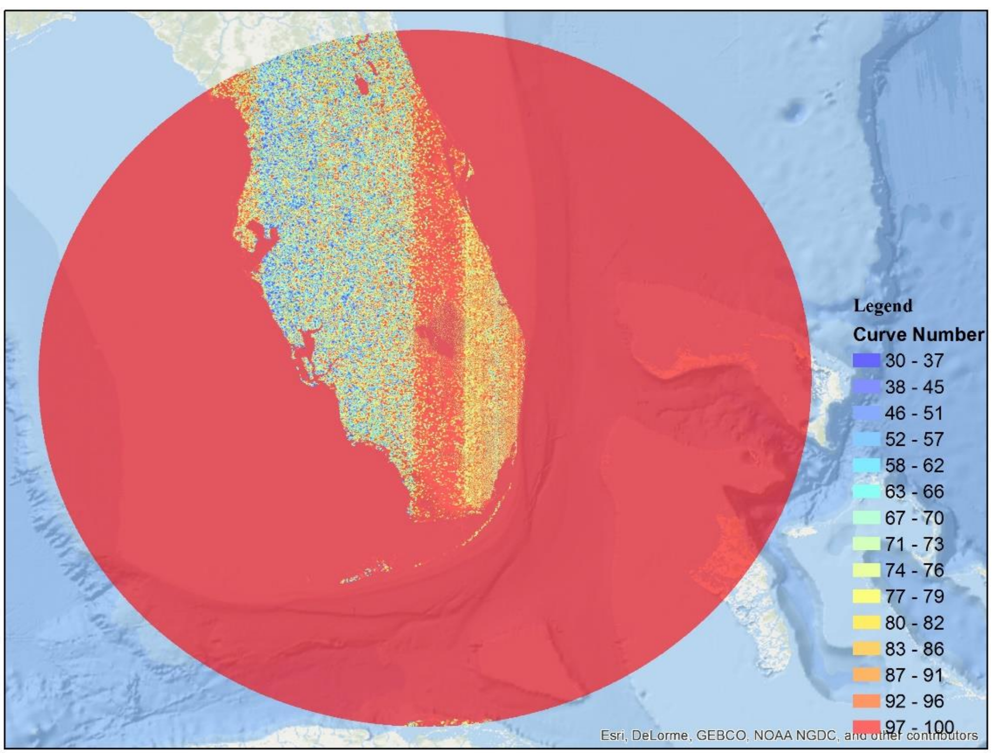

Fig. 4. Curve Number calculated based on the 2011 national land cover dataset and soil type.

7.4 Manning's Coefficient Values

Fig. 5 shows the spatially varying Manning's Coefficient distribution that was employed in this report. The high Manning's coefficient values occur along the coastal area, especially at the Everglade area with mangrove, while the east coastal area has smaller Manning's coefficients. The Manning's coefficient of the ocean bottom was set to be a constant value of 0.02.

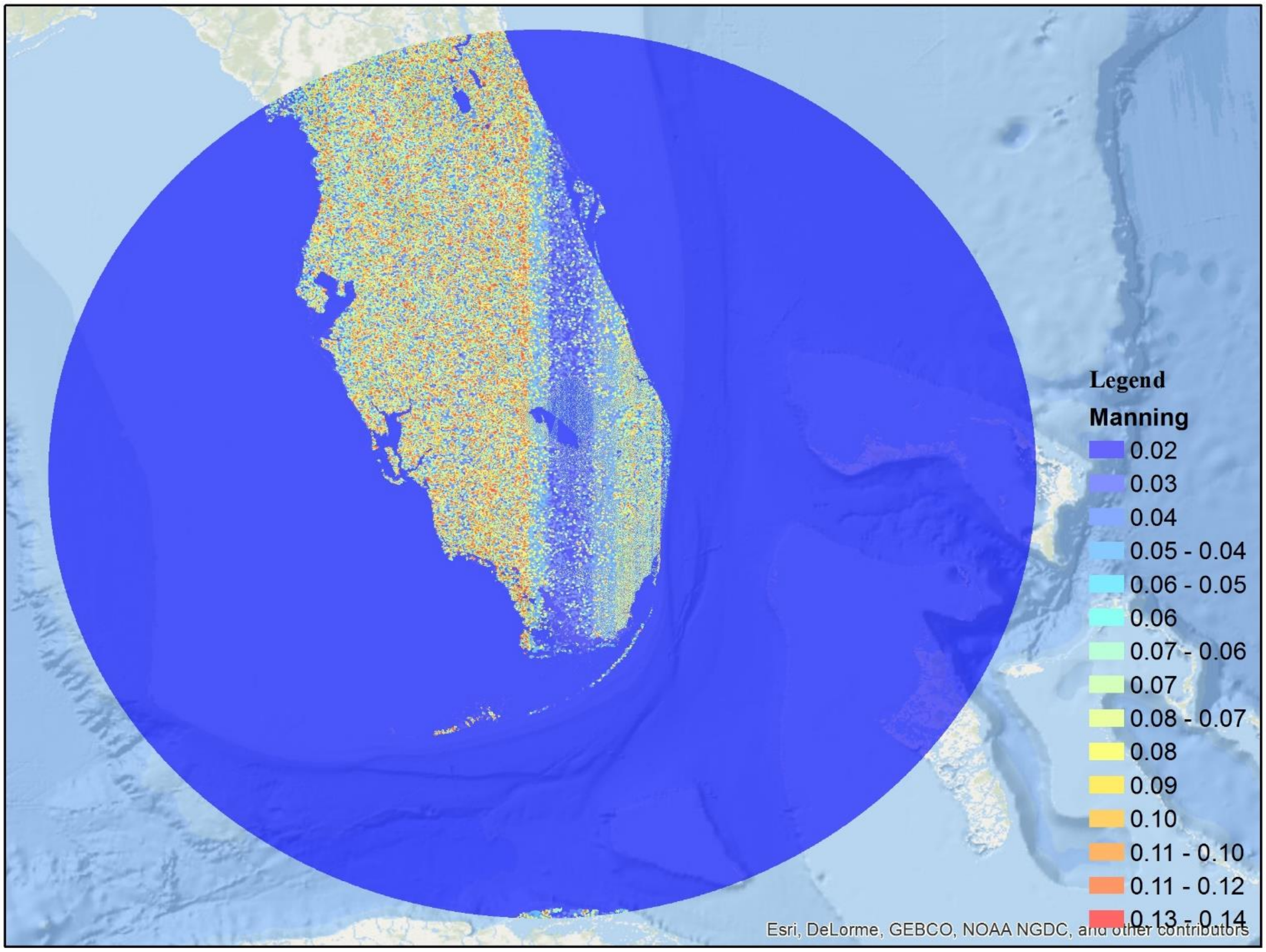

Fig. 5. Manning's Coefficients calculated based on the 2011 national land cover dataset.

7.5 Wind Data

Simulations were performed for each of the four historical hurricanes with the wind field being provided by the internal parametric model. The tracks used are from NHC hurricane best track data with location, central pressure drop, and radius of maximum winds (RMW). The wind fields are calculated inside of the model driven by either the Holland (1980) or Myers & Malkin (1963) wind field used by SLOSH (see Section 5).

7.6 Rainfall Data

Rainfall data for the more recent historical hurricanes (Matthew and Irma) was obtained from the Integrated Multi-satellite Retrievals for Global precipitation measurement data (IMERG) and stored in a netCDF format. A Fortran program was written to convert the netCDF data into the requisite SELAFIN file format to the newly developed TELEMAC based storm surge model. This program is called *convertRain.f90*.

7.7 Time series comparison

Frances passed over the central sections of the state of Florida only three weeks after Hurricane Charley on September of 2004, causing significant damage to the state's citrus crop. Frances moved slowly, between 5 to 10 mph, remained stable at Category 2 intensity with 105 mph maximum sustained winds attacked the east coast of Florida between Fort Pierce and West Palm Beach at 11 pm of September 4. The storm then moved briefly offshore Florida into the northeast Gulf of Mexico. Very heavy rains fell in association with this slow moving and relatively large hurricane, which led to floods in Florida.

The numerical simulation of Frances was conducted from 1200 UTC 1 September to 0900 UTC 8 September 2004. As shown in Fig. 6, modeled time-series of water levels were compared well to the observed water levels. The modeled peak surges were slightly under-predicted with a small phase shift at the Fort Myers and Naples stations, likely a misrepresentation of bathymetry/topography associated with coarse grids of local resolution. A clear advantage of the new model is its ability to run stable with very little ‘spin-up’ time.

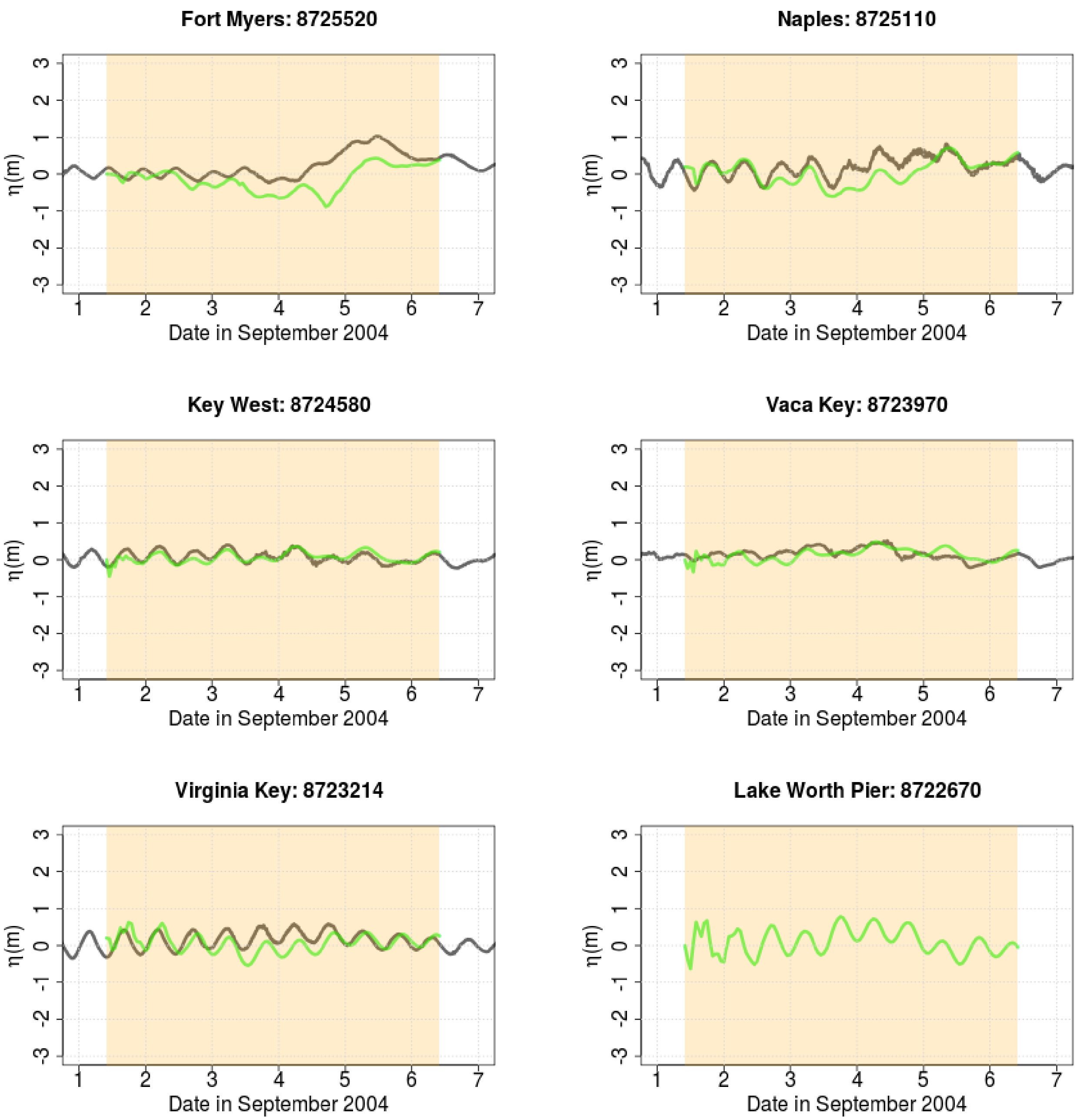

Fig. 6. Computed storm surges (green line) vs. measured water levels (grey line) at 6 NOAA tidal stations during Hurricane Frances 2004.

Wilma made landfall in Cape Romano of Florida with winds of 120 mph as a Category 3 hurricane on October 24 2005. At least 62 deaths were reported, and damage is estimated at $20.6 billion occurred in the United States alone. As a result, Wilma is ranked among the top five most costly hurricanes ever recorded in the Atlantic and the fifth costliest storm in United States history.

Storm tide simulation for Hurricane Wilma was conducted starting at 0000 UTC on 22 October and ending at 0430 UTC on 25 October 2005. Comparison of observed and computed storm tides indicates that the model produces reasonable comparison with the measurement (Fig. 7). One unique feature of

Wilma is that there was a double peak tide at Naples. When Wilma approached the Key, the south wind push water from outside and built up at Naples, which is the first peak surge. After Wilma made landfall, the north wind push the built up water to south, and set up another surge peak after Hurricane. Both model and measurements indicate the same phenomenon.

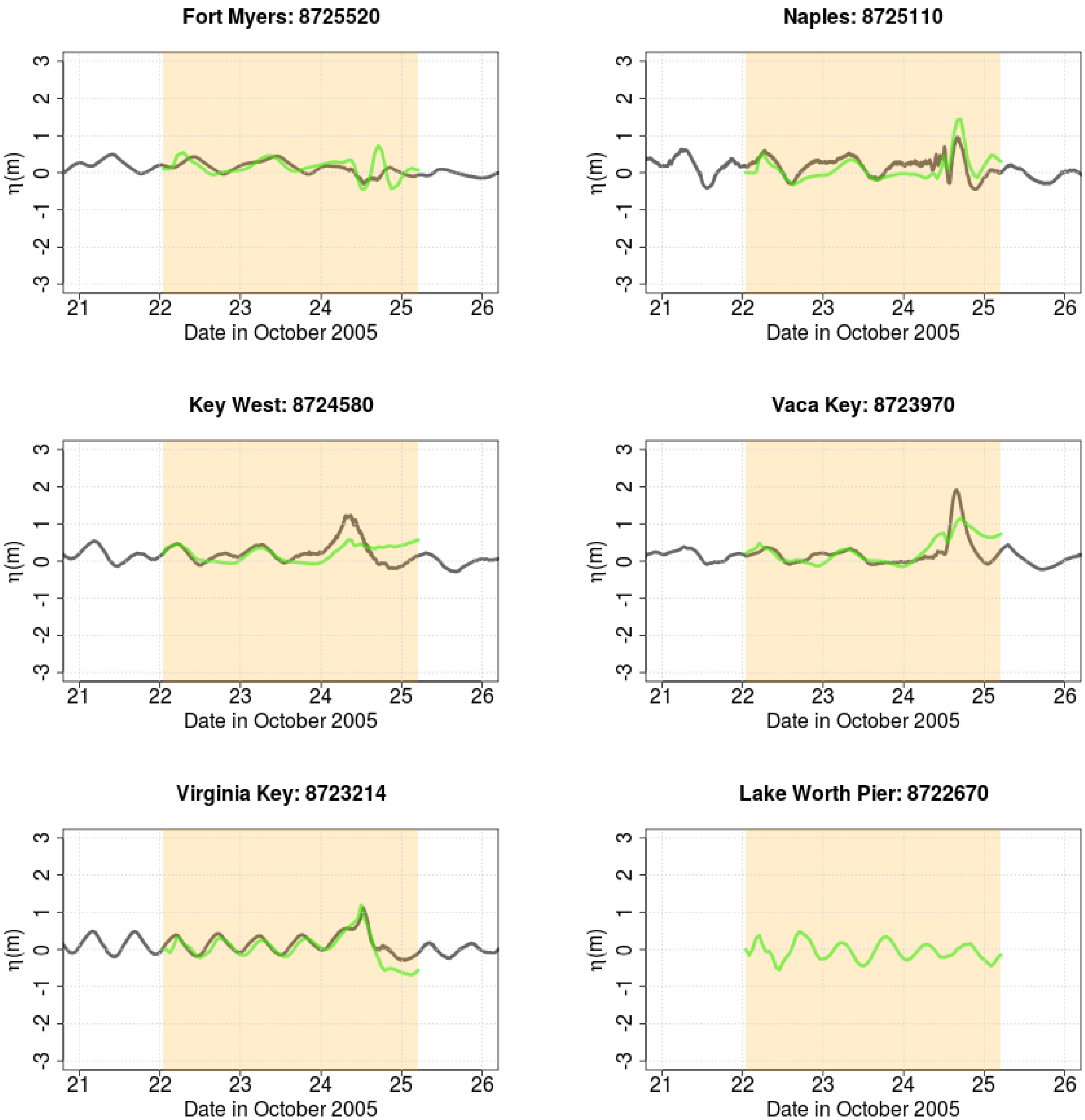

Fig. 7. Computed storm surges (green line) vs. measured water levels (grey line) at 6 NOAA tidal stations during Hurricane Wilma 2005.

Hurricane Matthew caused catastrophic damage and widespread devastation in the southeastern United States. Matthew threatened to be the first storm of Category 3 or higher intensity to strike the United States since Wilma, but Matthew stayed just offshore paralleling the Floridian coastline.

The storm tide simulation for Hurricane Matthew was conducted starting at 0000 UTC on 6 October and ending at 0000 UTC on 10 October 2016. Comparison of observed and computed storm tides indicates that there was only a very small storm surge caused by Matthew at all 6 NOAA gauges (Fig. 8).

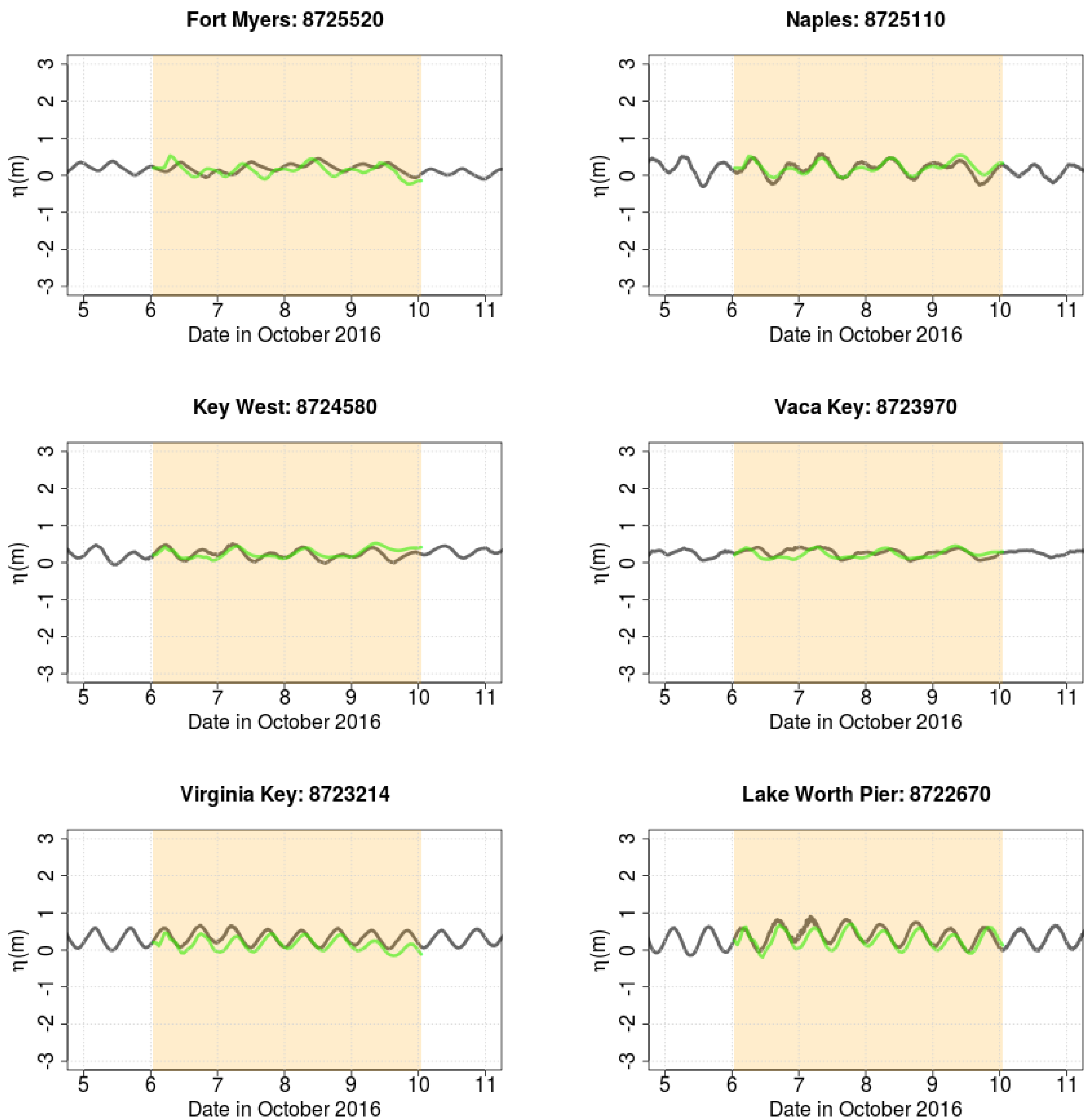

Fig. 8. Computed storm surges (green line) vs. measured water levels (grey line) at 6 NOAA tidal stations during Hurricane Matthew 2016.

Hurricane Irma was an extremely powerful and catastrophic Cape Verde hurricane,
the strongest observed in the Atlantic in terms of maximum sustained winds since Wilma, and the

strongest storm on record to exist in the open Atlantic region. Irma made first landfall at Florida on Cudjoe Key with winds at 130 mph (215 km/h) on September 10, and made another landfall in Florida on Marco Island later that day.

The simulation of Irma was conducted from 0000 UTC 8 September to 0000 UTC 12 September 2017. As shown in Fig. 9, the modeled time-series of water levels compare reasonably well to the observed water levels. The modeled peak surges were slightly over-predicted with a small phase shift at the Fort Myers and Naples stations. It should be noted that this is the same as Frances, a misrepresentation of bathymetry/topography associated with coarse local grid resolution in that area is the most likely cause of these discrepancies. Another possible reason is that the simple parametric wind field model cannot resolve the complicated storm structure of Irma.

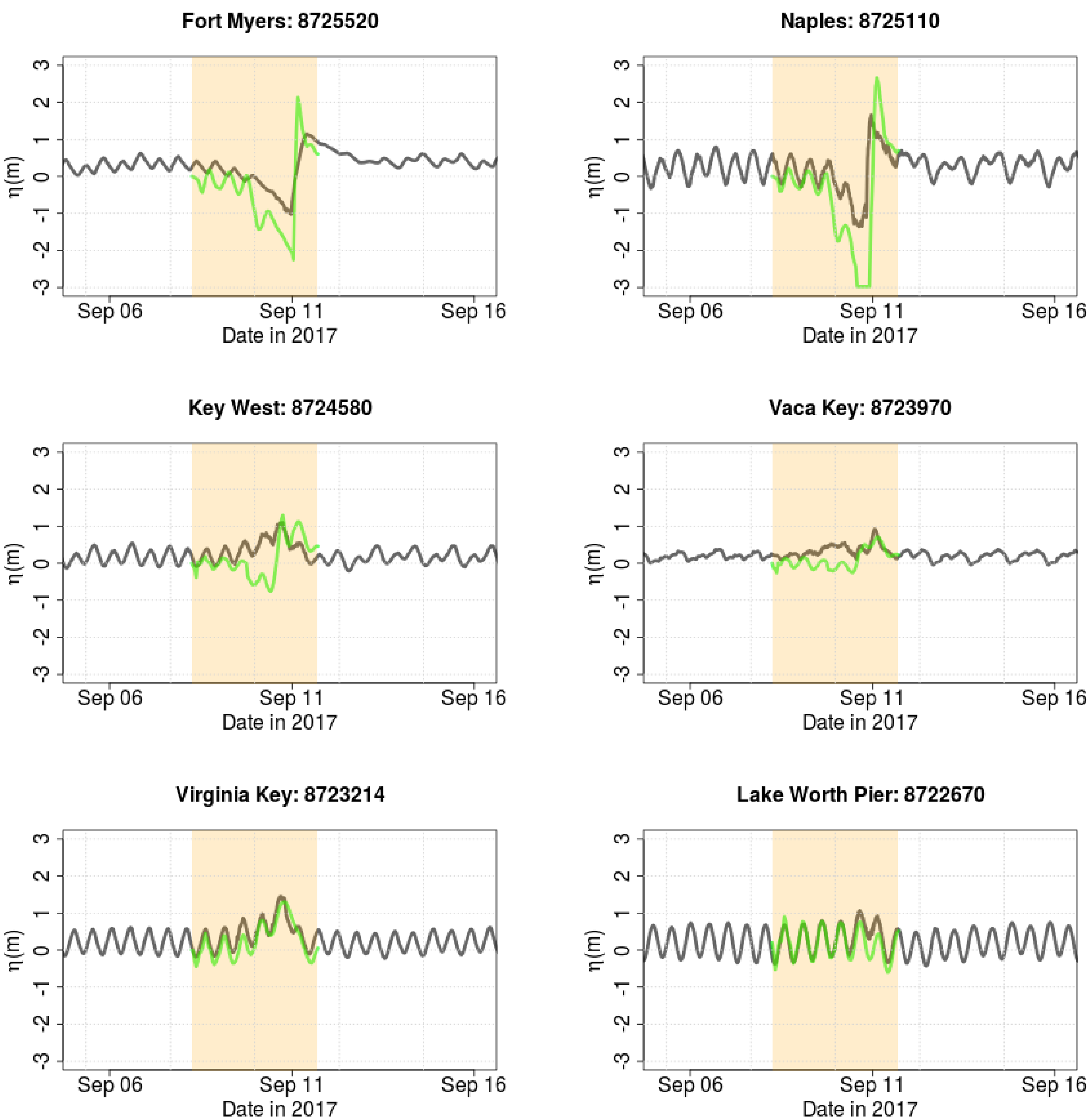

Fig. 9. Computed storm surges (green line) vs. measured water levels (grey line) at 6 NOAA tidal stations during Hurricane Irma 2017.

7.8 Spatial distribution of computed peak storm surges with overlanding flooding caused by rainfall

Fig. 10 shows the computed peak storm tide heights combined with the overland flooding caused by rainfall above the NAVD 88 for the four historical Hurricanes. The maximum peak storm tide heights computed Frances, Wilma, Matthew, and Irma are 3.7, 4.9, 2.5, and 4.0 m respectively.

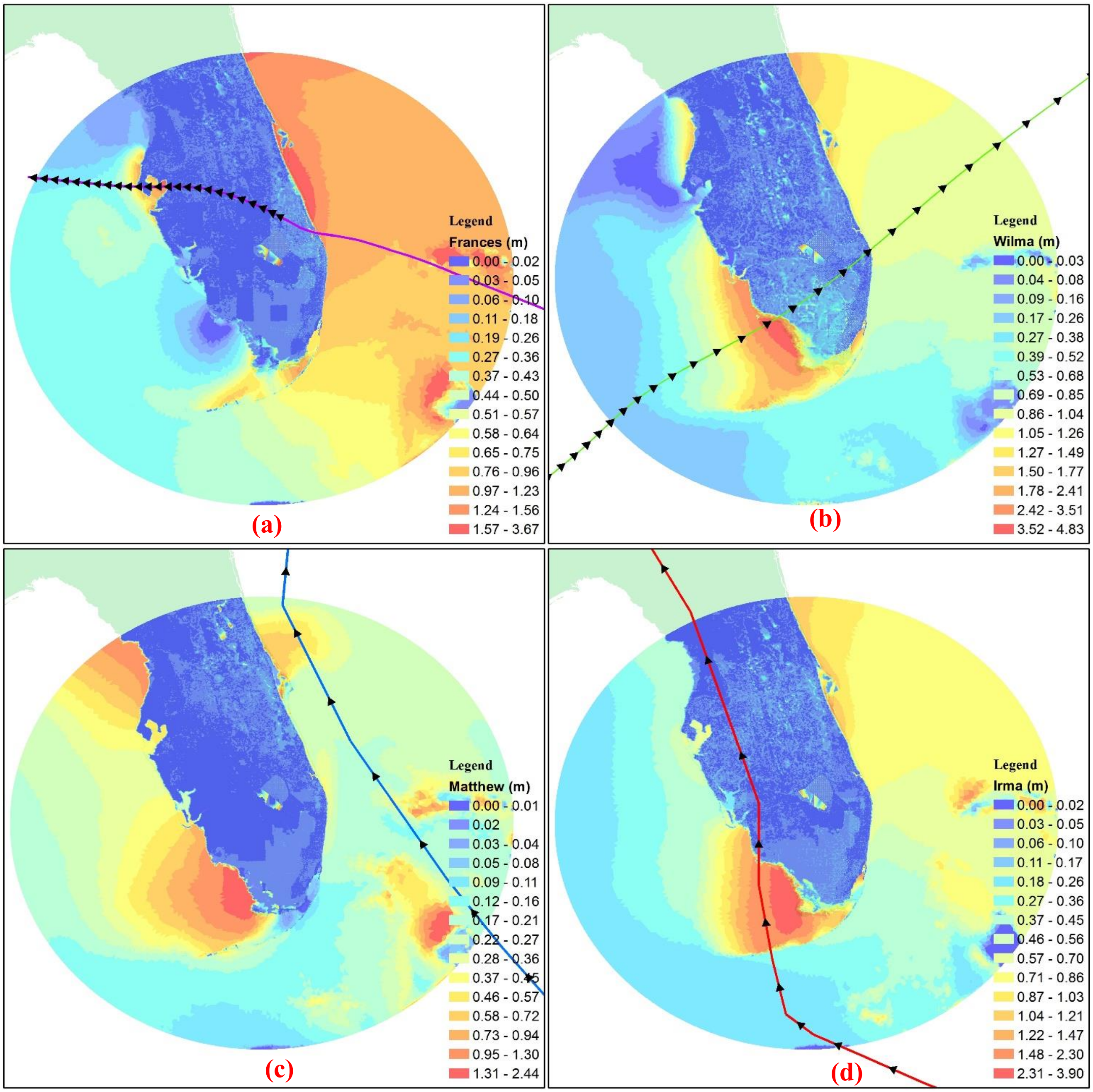

Fig. 10. Computed peak storm tide heights combined with overland flooding for Hurricanes Frances 2004 (a), Wilma 2005 (b), Matthew 2016 (c), and Irma 2017 (d).

Fig. 11 shows the computed peak storm tide heights around North Miami Beach for the four historical Hurricanes. Hurricanes Frances and Matthew did not produce much surge near North Miami Beach, while Wilma and Irma produced 2.2 and 1.7 m surge respectively. Since Matthew and Irma passed a fairly large distance away from North Miami Beach, the overland flooding caused by rainfall is quite small, less than 0.5 meter. Frances and Wilma are close to North Miami Beach, and produces relatively higher flooding on the street. For example, it is predicted that Wilma produced about 0.8 meters of overland flooding on several streets.

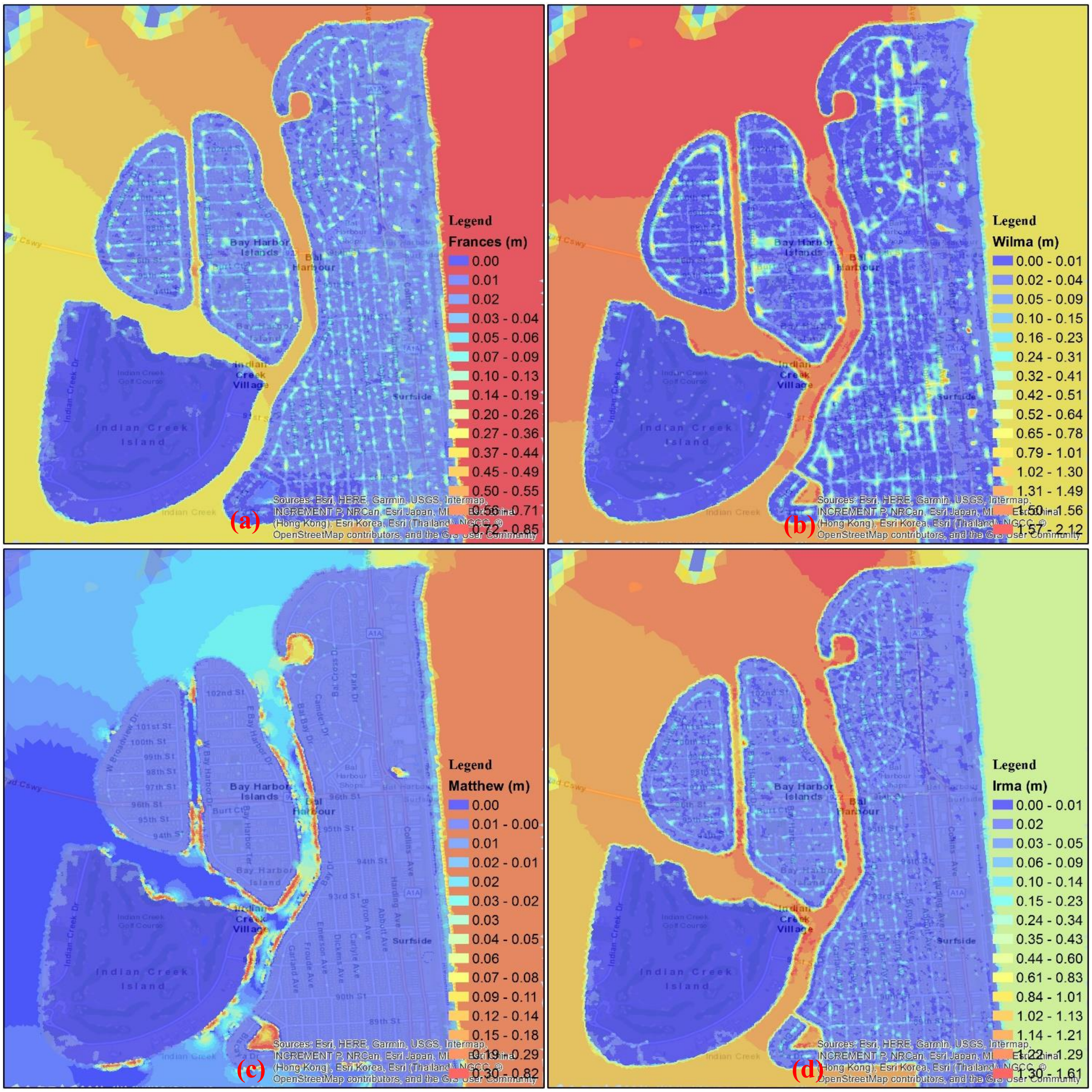

Fig. 11. Computed peak storm tide heights combined with overland flooding for Hurricanes Frances 2004 (a), Wilma 2005 (b), Matthew 2016 (c), and Irma 2017 (d) near North Miami Beach.

Fig. 12 shows the computed peak storm tide heights around South Miami Beach for the four historical Hurricanes. As was the case for North Miami Beach, Hurricanes Frances and Matthew did not produce much surge, whilst Wilma and Irma produced much higher surge. Meanwhile, it is predicted that Wilma produced about 0.7 meters of overland flooding on several streets.

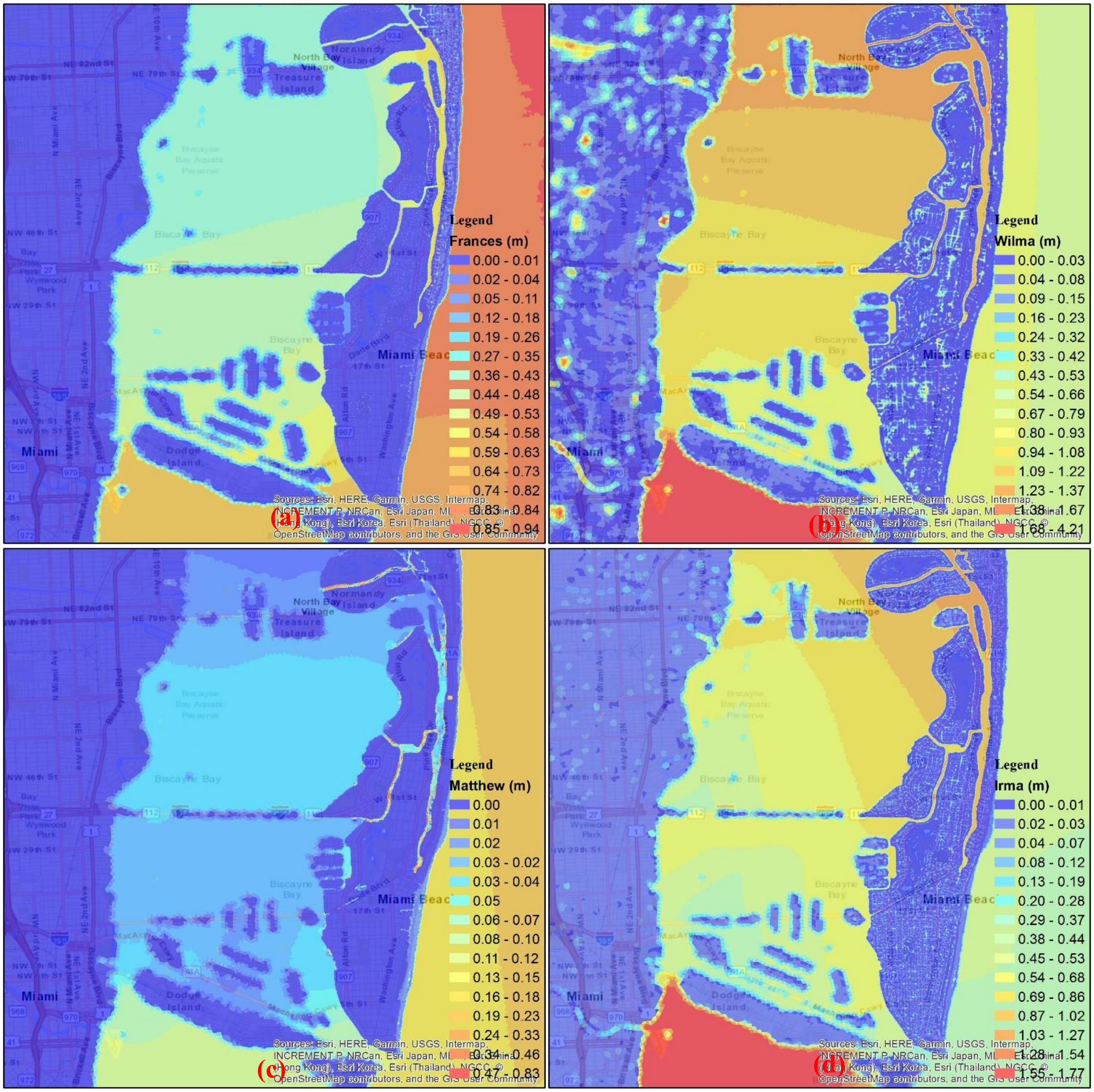

Fig. 12. Computed peak storm tide heights combined with overland flooding for Hurricanes Frances 2004 (a), Wilma 2005 (b), Matthew 2016 (c), and Irma 2017 (d) near South Miami Beach.

8. Hypothetical Hurricanes

One of the important criteria of any Storm Surge and Overlanding Flooding model is the numerical stability of the model. In other words, the model has to be stable and robust under extreme events, like Category 5 hurricanes from all possible directions. In order to prove the capability and stability of the newly developed model, 10 synthetic hurricanes were performed with different hurricane track directions.

8.1 Hurricane tracks

According to the historical hurricane data, 10 synthetic hurricanes were generated with different forwarding direction, landfall location, moving speed, and radius of maximum winds (Fig. 13). All synthetic hurricanes are Category 5 hurricanes for the purpose to demonstrate the capability of the model.

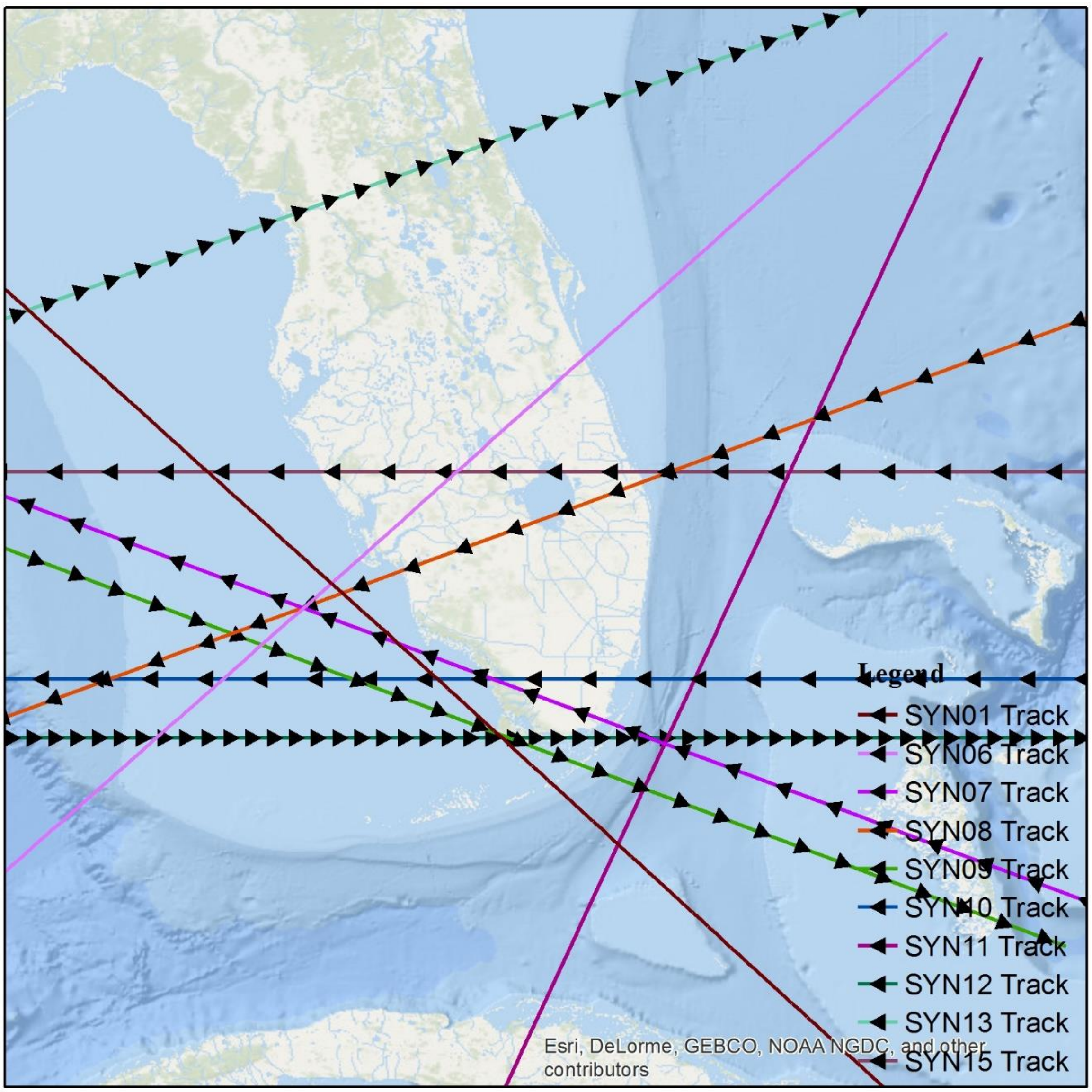

Fig. 13. Category 5 Synthetic Hurricanes generated with different forwarding direction, landfall location, moving speed, and radius of maximum winds around South Florida

8.2 Rainfall Model based on R-CLIPPER

A program was written in the R language in-order to generate a simple rain field. The output of this R program is in the same netCDF format as the IMERG and other rainfall data provided for the historical hurricanes (see Section 3). Therefore, the same Fortran code can be used to convert this netCDF rain file into the requisite SELAFIN format.

The model currently includes a very simplistic rainfall forecast model that is based on the R-CLIPER model developed at NOAA (Marks & DeMaria, 2003). R-CLIPER includes a basic decay approach in-order to handle storms after they make landfall. In the R-CLIPER approach, the rainfall climatology was reduced to a linear fit of the mean rainfall rates by hurricane radius (r) and time (t) after the hurricane makes landfall (Marks & DeMaria, 2003). In the R-CLIPER model the Rainfall rate (R_{rn}) is given as,

$$R_{rn}(r,t) = (ae^{-\alpha t} + b)e^{\frac{-(r-r_m)}{r_e}} \tag{32}$$

The parameters a and α are defined by fitting the gauge data variation in time, and b is fitted to the measured data by radius. r_m is the radius of maximum rainfall, and r_e is 500 km. This simple methodology produces a circularly symmetric rainfall distribution that can be combined with the hypothetical hurricane tracks to produce a band of rain along the forecast track.

In theory, the method is valid both before and after the hurricane makes landfall, with the rainfall rate decaying once landfall has been made. The R-CLIPPER parametric rainfall model has been implemented in the new TELEMAC-based model, in order to provide rainfall data to test the model with extreme hypothetical storm scenarios. Therefore, this rainfall model of this phase should be considered strictly as a proof-of-concept only. In the next phase the rainfall model requires improvement in-line with the rest of the modules.

8.3 Spatial distribution of computed peak storm surges with Hypothetical Hurricanes

8 hypothetical hurricanes are selected to plot the spatial distribution of the computed peak surges with overland flooding. Figs. 14 and 15 shows the computed peak storm tide of the Synthetic Hurricanes 01, 06, 07, 08, and 09, 10, 12, 15 respectively. The maximum peak surges are 7.0, 6.4, 4.8, 5.0, 5.3, 5.0, 5.7, and 4.0 meters for the above 8 hurricanes. The highest surge usually happens near Naples and Fort Myers, and also the region between the Keys and the South-West Costal area of Florida. The overland flooding could be significant under extreme hurricane conditions, like synthetic hurricanes 06, 08, and 15. The magnitude of the maximum flooding caused by rainfall could reach up to 1 meter around some of the tributary rivers.

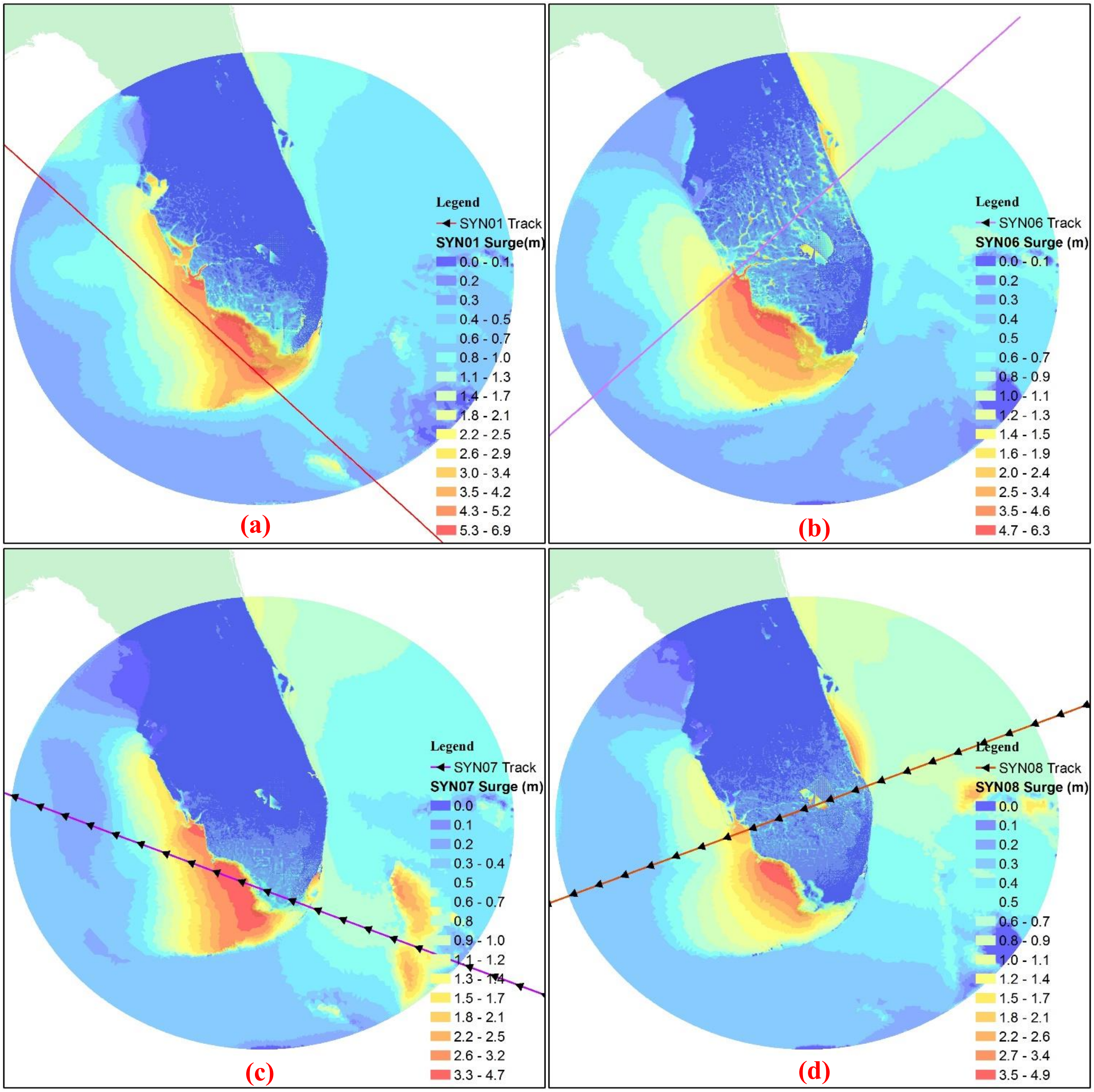

Fig. 14. Computed peak storm tide heights combined with overland flooding for Synthetic Hurricanes 01 (a), 06 (b), 07 (c), and 08 (d).

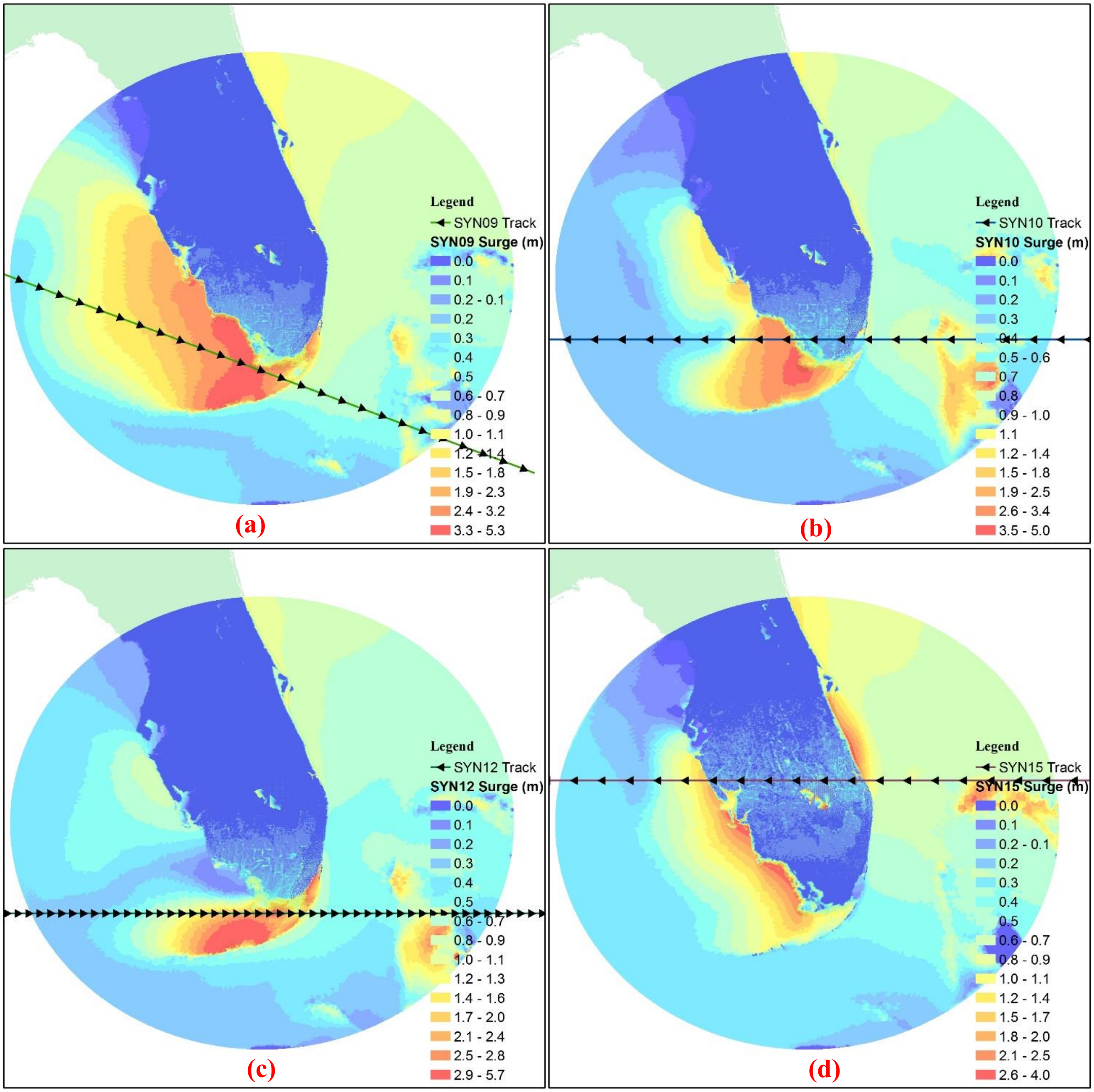

Fig. 15. Computed peak storm tide heights combined with overland flooding for Synthetic Hurricanes 09 (a), 10 (b), 12 (c), and 15 (d).

9. Summary of the newly developed model

The newly developed TELEMAC-based combined storm tides with overland flooding model represents the state-of-the-art in storm surge modelling. There are a number of unique features of the model which are described here:

a) The model is based on the openTELEMAC library developed by Électricité de France (EDF) over the last 30+ years. The base code is well established and used by the French Nuclear power industry as well as multiple agencies throughout Europe (i.e. the Centre for Environment, Fisheries and Aquaculture Science (CEFAS), which is an executive agency of the United Kingdom Government Department for the Environment).

b) The model solves the NLSW equations based on the unstructured and boundary conforming mesh, which will represent the complex domain geometry and features such as rivers particularly well.

c) The model has the capability to run as a Massively Parallel model using domain decomposition based on the Metis library, and can be used on varying from multicore desktops up to 1000+ process supercomputers.

d) Two distinct parametric wind models: Myers and Malkin (1961), also known as the SLOSH model, and the Holland (1980) model, are employed into the model.

e) The model is able to run on multiple scales ranging from very fine street level resolution O(10 m) to the largest grid size in the open ocean O(10 km).

f) The new module of overland flooding caused by rainfall has been parametrised using the Method of Abstractions, developed by the US Soil Conservation Service (Ponce & Hawkins, 1996). Under this approach infiltration potential is characterized by an empirically derived Curve Number (CN).

g) The TELEMAC source code has been extensively modified in order to improve generation of tides, transmissive boundary conditions, include parametric wind models and accept time and space varying rainfall and wind (from re-analysis data such as NOAA H*WIND) as model inputs.

10. Additional Code Developed as Part of This Project

The following codes compile to stand-alone executable and are used to provide input data for the new TELEMAC-based model.

a) ConvertRain.f90 – This Fortran code (as a stand-alone executable) reads in time and space varying rainfall data in a netCDF format on a structured rectangular grid. The code performs interpolation of the spatial varied data, and outputs the requisite SELAFIN format binary file.

b) ConvertTrack.f90 – This code (as a stand alone executable) converts hurricane track files from either UNISYS format (i.e. track files downloaded from http://weather.unisys.com/hurricanes/search), or CEST XML format into the requisite ASCII format for the new TELEMAC-based model.

c) *CLIPER.R* – This R code reads in a hurricane track file that must contain the hurricane center position as well as the radius of maximum winds (RMW). The code outputs a spatial and temporal varying rain fall rate, according to the simple NOAA R-CLIPER model of Marks & DeMaria (2003). The output file is in netCDF format, which can be converted to the requisite SELAFIN format.

11. Proposed Future Work

The newly developed TELEMAC-based model represents a cutting-edge storm surge model, which can simulate the storm tides and overland flooding on the same mesh in a fully coupled fashion. However, there are a number of areas for improvement. The following areas are identified for improvement.

11.1 Re-analysis Wind Data (Year 2)

At present, the TELEMAC-based model is capable of generating its own wind field. While the model is not yet capable of reading in temporal and spatial varying wind data provided by meteorology model. This capability is straightforward to add and will certainly improve the hindcasting simulations.

11.2 Rainfall Runoff Model (Year 2)

The CN based approach currently implemented in the TELEMAC-based model provides a reliable first approximation. The approach had been internally validated for the run-off due to hurricane Harvey. An improvement would certainly be made by considering a more complete infiltration model based on the modified Green & Ampt approach (Triadis and Broadbridge, 2010; 2012).

11.3 Riverine Systems (Year 3)

In the work presented here the dynamic interaction between river discharge and storm surge is not included in the modelling. Inclusion of this effect (which is possible using the newly developed TELEMAC-based model) could increase the storm surge and serve as an obstacle for the river discharge. The storm surge propagation upriver that is currently predicted by the model is not reliable due to the current mesh quality (i.e. the non-inclusion of the river center lines as fixed nodes) and non-inclusion of high resolution bathymetric data for rivers.

11.4 Dynamic Set-Up (Year 3)

Although short waves are can be computed in the new model (via TELEMACS built in spectral wave model TOMAWAC), they can only be used to evaluate the static wave setup. The additional *dynamic* run-up and overtopping is not included in the model. Thus, it is highly likely that the model will underestimating the extent, and depth, of the coastal flooding (just due to the salt water) at least locally.

12. Conclusions

A pilot study to develop an integrated storm surge and freshwater flood model for coastal urban areas was developed by leveraging an existing and well established hydrodynamic model. The primary tasks completed during this Phase included (1) the parameterization of tidal forcing in a robust and stable manner, (2) the incorporation of hurricane wind driven forcing, (3) the incorporation of hurricane induced storm surge inundation, (4) the parametrization of freshwater overland flooding (due to hurricane induced rainfall), and (5) the preliminary validation of South Florida Basins with historical and hypothetical hurricanes. The coding to create a stable model for this effort was much more time intensive and complex than was originally envisaged.

In addition, before the contributions of freshwater and storm surge flooding can be fully explored, the surface water runoff module needs to be completely validated. As a result, the comparison maps could not be provided at this time. The team continues to collect the freshwater flooding data of historical hurricanes to work on this issue, and will provide the detail comparison flooding maps during the 2018-19 Fiscal Year.

As is well known, Florida has the longest coastline in the United States, and barrier islands can be found along more than 1,000 km of coast and on which more than 1,000,000 people live. The development of a robust state-of-the-art integrated storm surge and freshwater flooding model for barrier islands will provide the Florida Department of Emergency Management with quantitative information to help predict, respond to, and reduce the impacts of coastal flood disasters. Importantly, the developed model is efficient; sensible runtimes (~30 minutes for a 4-day tide-surge-overland flood simulation) are possible on current high-performance desktop computers with multiple cores.

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A Resource for the State of Florida

SECTION 6

Development of the Method to Extract the Ground Elevations of Buildings

A Report Submitted to:
The State of Florida Division of Emergency Management

Prepared By:
Keqi Zhang

The International Hurricane Research Center (IHRC)
Florida International University

August 13, 2018

The Principal Investigator was not able to complete Research Area 5 during this performance period per the executed contract due to a long-term illness. This activity will not be included within the scope of work during Fiscal Year 2018-19. Funds will be returned and reappropriated.

A Resource for the State of Florida

SECTION 7

Assessing the Economic Effectiveness of Individual Property and Community Flood Mitigation Activities in Escambia County Florida

A Report Submitted to:
The State of Florida Division of Emergency Management

Prepared By:
Jeffrey Czajkowski and
Marilyn Montogomery

The International Hurricane Research Center (IHRC)
Florida International University

August 13, 2018

Assessing the Economic Effectiveness of Storm-Surge Oriented Flood Mitigation Activities in Escambia County Florida

A Report Submitted to:
Florida Division of Emergency Management

July 31, 2018

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Executive Summary

The communities of Escambia County Florida analyzed in this study - the City of Pensacola, unincorporated Escambia County, and Pensacola Beach - have several different flood problems, including notably flooding from storm surge. Given the historical recurring frequency and extensive damage from these flood events in these communities, as well as the likely enhanced future storm surge flood risk, in this report we further undertake research on the economic effectiveness of associated flood mitigation activities that serve to reduce the inherent flood risk. Specifically, this report first examines the economic effectiveness of mitigating single-family homes located in Escambia County, Florida, against storm surge risks. While this individual home mitigation analysis represents the bulk of the report, we recognize that the benefits of flood mitigation should be examined beyond the scale of individual homes. Therefore, we also introduce and discuss comprehensive community-based approaches to flood risk mitigation that have a connection from mitigation benefits of individual structures to that of communities, with the goal of enhancing communities' resilience to flood risks.

We analyze the economic effectiveness of mitigating single-family homes against coastal surge risks by (1) elevating homes, (2) demolishing and acquiring homes, and (3) building floodwalls around homes. We examine these three mitigation measures by computing the benefit-cost ratios (BCRs) for mitigation projects. Note that a BCR of 1 or greater indicates that a project is economically effective. Our first economic effectiveness assessment methodology is via the Federal Emergency Management Agency (FEMA) benefit-cost analysis (BCA) toolkit. We use the FEMA BCA Toolkit because it is the standard tool and methodology utilized by those applying for FEMA mitigation grants for flood mitigation activities including property owners, communities, and the state. We perform a number of sensitivity analyses on the key parameters from the toolkit such as the discount rate. In addition to the FEMA BCA toolkit, we use a second economic effectiveness assessment methodology that allows for analyzing a larger dataset of homes and incorporates a variety of sea level rise scenarios out to the year 2100 to compute future annualized avoided losses into the benefit-cost analyses.

For the FEMA BCA toolkit mitigation analysis we analyzed a total of 39 representative sample homes across unincorporated Escambia County, the City of Pensacola, and Pensacola Beach. We found that generally, any one of the three mitigation techniques can be economically effective for homes at risk to the 10% and 4% annual chance surge risk zones, or NFIP VE flood zones, with low first-floor elevations (FFEs). For example, we found 7 of the 24 homes in these 10% and 4% annual chance surge risk zones were economically effective to elevate. We also find that it is commonly more economically effective to elevate homes as high as possible, since the majority of elevation costs are associated with the first foot of elevation. Demolition and acquisition is the least economically effective method, largely due to the high costs of these projects. Building floodwalls is economically effective for more homes than the other two mitigation techniques, as the costs of floodwalls are generally lower than elevation or acquisition. Our sensitivity analyses of the total 39 sample homes analyzed with the Toolkit indicate that choice of discount rate (7% or 4%) has a greater impact on our results than varying the project lifetimes (ranging from 30 years to 100 years for projects). We also examine changes to the costs of mitigation and when we reduce costs of elevation to 25% of the total costs, all homes in the 10% annual chance surge zone except one are economically effective to elevate. When costs of demolition and acquisition and building floodwalls are reduced to 25%, 5 homes in the 10% annual chance surge zone are economically effective to mitigate with either of these two mitigation approaches. While we reduced the costs of mitigation projects by 25%

increments for the sake of our sensitivity analyses, we acknowledge that it would be difficult to reduce mitigation costs to 25% of the totals for actual mitigation projects.

The results of our bulk analyses on 6,820 homes across unincorporated Escambia County, the City of Pensacola, and Pensacola Beach reveal similar trends as those obtained from the Toolkit: it is generally only economically effective to mitigate homes in the 10% or 4% annual chance surge zones with low FFEs; 11 percent of the homes analyzed in the bulk analysis are in the 10% or 4% annual chance surge zones and are also economically effective to mitigate. Floodwalls are economically effective for substantially more homes than elevation, and demolition and acquisition with a 7% discount rate is not economically effective for any home in our dataset.

We also compare our mitigation BCR results to those from previous studies in Texas and New York. The Texas study similarly finds that if elevation to existing homes is to be undertaken as a flood mitigation effort, it must be done very selectively from an economic perspective due to the relatively significant costs of elevation of existing structures. In New York, none of the storm surge barrier nor hybrid (i.e., building codes with protection of critical infrastructure) approaches analyzed are economically beneficial under current levels of flood risk or a modeled "low" climate change scenario (30 cm of sea-level rise). However, when a low 4% discount rate is considered, all strategies make economic sense if sea level rise occurs and climate change increases the frequency of storms. In Pensacola, similar relaxations of discount rates and higher sea-level risk scenarios lead to more favorable BCRs.

As we have shown, mitigating individual homes against surge risks can be economically effective in particular circumstances; for example, single-family homes with low first-floor elevations and open foundations in the 10% or 4% annual chance surge zones are economically effective to elevate. However, examining the economic effectiveness of individual home mitigation cannot capture community-level benefits, as mitigating individual properties eventually translates into better neighborhood- and community-level resilience to flooding. Therefore, we advocate that broader benefits of flood risk mitigation beyond an individual property owner must be analyzed and ultimately incorporated into a mitigation economic effectiveness analysis. These additional broader benefits include but are not limited to emergency response/rescue services, frequent damage to exterior property improvements, damage to vehicles, and recurring damage from foundation and crawlspace flooding. To better understand the linkages between individual and community level flood mitigation, in this chapter we discuss the Flood Risk Reduction and Risk Assessment (RA/RR) Plan from the Charlotte Mecklenburg Storm Water Services (CMSWS) Department, and the Community Rating System (CRS) of the national Flood Insurance Program (NFIP). Both the Flood RA/RR Plan and the CRS are comprehensive community-based approaches to flood risk mitigation that have a connection from mitigation benefits of individual structures to that of communities, with the goal of enhancing communities' resilience to flood risks.

The Flood RA/RR plan provides an alternative to the implementation of property flood mitigation not solely limited to an individual property mitigation BCR > 1, but used in conjunction with this criteria and including broader benefits to the property. Importantly, this methodology is also built upon economic principles relating to the capturing of indirect and intangible benefits of the flood risk mitigation effort relevant to include in a BCA. And given that these indirect and intangible disaster losses are difficult to identify and quantify, and hence are seldom considered in BCAs, we advocate that the Flood RA/RR Plan should be investigated for other communities to implement its principles, such as those we examined in Escambia County, Florida.

In Escambia County there are three separate communities that participate in the CRS – the City of Pensacola, Pensacola Beach, and unincorporated Escambia County. Previous research has generated the benefits from avoided losses due the CRS activities of Escambia County. However, from an economic effectiveness standpoint, the costs of implementing the CRS program in Escambia County have not been ascertained. We initiated a pilot study in Escambia to collect this information. As an existing CRS cost study in Virginia has also found, this important cost information is difficult to collect. We provide an overview of our approach and lessons learned, with CRS cost information pending as of the date of this report. Key findings from the pilot study include: costs of managing the CRS are not regularly tracked by the CRS coordinators; basing the costs on the percentage of total points earned is a good starting point but not wholly reflective of total costs; given the external connections of the CRS to other departments and program, costs external to the CRS need to be collected; and while the existing costs of managing the program are certainly helpful, understanding the cost to improve CRS rankings would be very useful.

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1.0 Introduction

Floods have historically had more impact in the U.S. than any other natural hazard, with future flood risk expected to rise due to growing concentration of exposure in high risk areas combined with increased climate-induced hazard patterns due to sea level rise and more intense hurricanes. Additionally, researchers have identified links between human induced climate change and intensification of heavy precipitation events (Min et al. 2011[1]). Consequently, there is a mounting interest in enhancing *ex-ante* preparedness and resilience for such events at both the individual homeowner and the community level. However, mitigation can be expensive (often having high upfront costs), and unless these actions are shown to be economically effective to undertake, there may be little individual homeowner and/or broader community political support. Thus, in this study we further existing research on flood risk assessment and the economic outcomes of homeowner mitigation activities in the City of Pensacola, Pensacola Beach, and southern portions of unincorporated Escambia County Florida. Specifically, we assess the economic effectiveness of elevating homes, demolishing and acquiring homes, and building floodwalls around homes to mitigate flood hazards using two analytical approaches: the Federal Emergency Management Agency's (FEMA's) Benefit-Cost Analysis (BCA) Toolkit, and a method explicated in Montgomery and Kunreuther (2018). Then given our results, we discuss the importance of how mitigating individual properties should be linked to broader community-level resilience to flooding. From this broader community level perspective we use Charlotte Mecklenburg Storm Water Services Department Flood Risk Assessment and Risk Reduction Plan as well as the Community Rating System (CRS) of the National Flood Insurance Program (NFIP) as templates to guide future research endeavors.

Florida itself is a particularly flood-prone state because of its low-lying topography, tropical and subtropical climate, and miles of coastline exposed to hurricane and storm surge hazards. According to data published online by the National Flood Insurance Program (NFIP) in May 2017[2], Florida is ranked fifth among all U.S. states for dollar amounts of flood insurance claims since the inception of the National Flood Insurance Program (NFIP) in 1968. And importantly for our study, one-sixth of Florida's NFIP claims are from Escambia County, although this county has only 1.5% of Florida's population (according to the U.S. Census Bureau population estimates for July 2016[3]). Located in the northwestern-most extent of the Florida panhandle, the study areas for this research are areas of southern unincorporated Escambia County, the City of Pensacola, and Pensacola Beach. Figure 1 is a map showing our study areas.

The communities of Escambia County have several different flood problems, storm surge and non-storm surge oriented in nature. These flood issues are highlighted in the below table from page 28 of the flood insurance study (FIS) that accompanies the preliminary digital flood insurance rate map (DFIRM)[4] that has a date of January 27, 2017. Beyond the flood hazards themselves, Escambia County has a number of

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[1] https://www.nature.com/articles/nature09763: Min, Seung-Ki, Zhang, Xuebin, Zwiers, Francis W., Hegerl, Gabriele C. Human contribution to more-intense precipitation extremes. *Nature* - 470, pages 378–381 (17 February 2011) http://dx.doi.org/10.1038/nature09763.

[2] National Flood Insurance Program (NFIP) loss statistics can be found at https://bsa.nfipstat.fema.gov/reports/1040.htm.

[3] County-level population and ranks can be searched in U.S. Census Bureau quick facts at https://www.census.gov/quickfacts/.

[4] The Preliminary FIS Report for Escambia County can be queried and downloaded at FEMA Flood Map Service Center, located online at https://msc.fema.gov/portal/advanceSearch. Flood insurance studies, DFIRMs and preliminary DFIRMs for all NFIP communities in the U.S. can be queried and downloaded at the FEMA Flood Map Service Center.

other factors that contribute to its flood risk. Pensacola Beach is a low-lying barrier island fronting the Gulf of Mexico, with few small sand dune systems to protect development that have been eroded due to hurricanes and tropical storms. The terrain of Escambia County is also conducive to flooding. In the southwest portion of the County, west of Pensacola, there are somewhat impermeable, poorly drained soil formations with a seasonably high water table within 1 to 2 feet of the ground surface[5]. The southwest portion of Escambia County is mostly poorly drained wetlands.

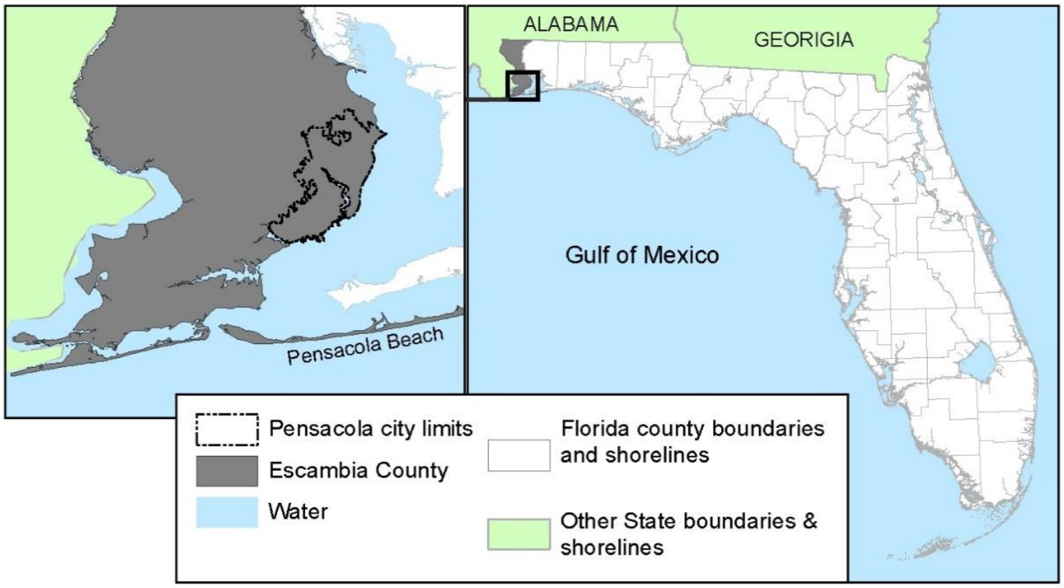

Figure 1. Study areas of Escambia County, the City of Pensacola, and Pensacola Beach.

Flooding Source	Description of Flood Problems
Gulf of Mexico	Flooding in Escambia County results primarily from tidal surge and overflow of streams and swamps associated with rainfall runoff. Major rainfall events occur as a result of hurricanes, tropical storms, and thundershowers associated with frontal systems. Some of the worst floods to occur in northwestern Florida were the result of high intensity rainfall during hurricanes.
Escambia River	The Escambia River is the largest river in the county and accounts for much of the flooding in the area. The river is characterized by wide, flat floodplains varying from several thousand feet to several miles wide. The flat slopes and wide, heavily vegetated floodplains enhance the flood problem by preventing the rapid drainage of floodwaters. At flood stage, the river's waters cover large areas, flooding farmland, fishing resorts, and other businesses built on the floodplain.

[5] From page 5 of the 2006 Flood Insurance Study for Escambia County. Citation: Federal Emergency Management Agency (FEMA). (2006). Flood Insurance Study Escambia County, Florida and incorporated areas. Available at: https://msc.fema.gov/portal/advanceSearch, accessed July 25, 2017.

Table 1. Table 6 from page 28 of the preliminary flood insurance study for Escambia County summarizing the two principal flood problems by flooding source in Escambia County.
Subsequently there have been a number of significant flood events in Escambia County. For example, the particularly heavy rainfall events in June 2012[6] and April 2014[7]. The April 2014 event had observations recorded at Pensacola Airport of a one-hour rainfall amount of 5.68 inches, and total estimated rainfall of 20.47 inches and was declared a Major Disaster Declaration[8]. The National Weather Service estimates the April 2014 flash flood event somewhere between a 1 in 200 year and 1 in 500 year precipitation event. Escambia County has a history of pluvial flash flooding, that often occurs at a very localized scale, involving storm water system failures. To date, DFIRM data do not include pluvial hazards in maps and insurance rating simply because modeling such localized flood risks is very costly. From a storm-surge perspective a total of 6,340 NFIP claims have been incurred in the three communities of our study from 1978 to 2014, representing 44 percent of the total claims incurred here during this timeframe.[9] Four relatively recent tropical cyclone events - Hurricane Ivan in 2004 (2,331 claims), Hurricane Opal in 1995 (1,504 claims), Hurricane Georges in 1999 (611 claims) and Hurricane Dennis in 2005 (281 claims) – represent 75 percent of the total storm-surge claims in our study area. The total 6,340 storm-surge claims equated to $291 million dollars in building and content damage, or roughly $45,000 in flood damage per claim.

Given the recurring frequency and extensive damage from these flood events in our study area, our goal herein is to further research on the economic effectiveness of associated flood mitigation activities that serve to reduce the inherent flood risk. To assess economic effectiveness of mitigation activities we utilize a benefit-costs analysis (BCA). BCA is a framework that supports transparent, coherent, and systematic decision-making based upon a common monetized yardstick that can be used to evaluate various risk reduction strategies (Czajkowski, Kunreuther and Michel-Kerjan 2012; Mechler and Islam 2013). In a BCA, all benefits and costs accruing over time are monetized and aggregated so that they can be compared using the common economic efficiency criterion. In general, if the stream of discounted benefits exceeds the stream of discounted costs (i.e., positive net present value economic benefits) a proposal is considered 'economically efficient'. In particular we focus on the resulting benefit-cost ratio (BCR). With a BCR the total discounted benefits are divided by the total discounted costs. By definition, a BCR of 1 means that the expected discounted benefit of implementing the mitigation equals its cost. Any measure where a BCR is greater (less) than 1 is considered to be economically-effective (not economically effective) and should (should not) be implemented as the benefits exceed (do not exceed) costs and a project thus adds (does not add) value to society.

We start by providing a detailed examination of the economic effectiveness of mitigating individual single-family detached homes against flood risk. In order to accomplish this we employ FEMA's BCA Toolkit software to assess economic effectiveness of mitigating flood risks. The BCA Toolkit[10] is traditionally used to implement BCA and produce reports to accompany grant applications submitted under FEMA's Hazard Mitigation Assistance Grant Programs, such as the Hazard Mitigation Assistance (HMA) program. Therefore, the BCA methodology involved in the BCA Toolkit is approved by FEMA for mitigation grants and it is the most appropriate software to use in this research on mitigating homes in the U.S. against flood hazards.

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[6] https://www.weather.gov/mob/2012_JuneFlood
[7] https://www.weather.gov/mob/2014_April29_FlashFlood
[8] https://www.fema.gov/disaster/4177
[9] 2014 National Flood Insurance Program data
[10] The BCA Toolkit can be downloaded at https://www.fema.gov/media-library/assets/documents/128334.

We lack riverine flood risk data that are more granular than what are included in the DFIRM data for Escambia County, but we have granular storm surge risk data comprised of five return periods and surge heights that we analyze in our BCAs. While the surge data do not include riverine and pluvial flood risks, surge risk is again of particular concern in our study area, especially Pensacola Beach.

Our research is designed to answer the following research questions:

1. What are the characteristics of single-family detached homes in unincorporated Escambia County, City of Pensacola, and Pensacola Beach that contribute to economic effectiveness of mitigating surge hazards?
    - The mitigation activities we examine are elevating homes, demolishing and acquiring homes, and building floodwalls around homes.
2. How do the following variables affect the economic effectiveness of flood mitigation activities using BCA: choice of depth-damage function in flood risk assessment, project useful lifetimes (i.e., the time span over which benefits are calculated), discount rates for future benefits, and costs of mitigation projects?
3. What are the strengths and limitations of assessing economic effectiveness of flood mitigation techniques using (a) the FEMA BCA Toolkit, and (b) a method developed using IBM SPSS Statistics and Microsoft Excel software programs (as in Montgomery and Kunreuther 2018)?
4. How can the Charlotte Mecklenburg Storm Water Services Department Flood Risk Assessment and Risk Reduction Plan and the NFIP Community Rating System (CRS) inform research on the linkages between individual property mitigation and community-level flood resilience?

To answer these questions the remainder of the report is organized as follows: Section 2 details our individual property hazard and mitigation data as well as the economic effectiveness methodology we employ including all sensitivity analyses; Section 3 presents and discusses the individual property mitigation benefit-cost results for the Escambia County study area as well as comparisons to some other geographic areas of the U.S.; Section 4 moves the analytical focus beyond the economic effectiveness of individual property mitigation to broader community level resilience efforts; finally Section 5 provides the concluding discussion.

2.0 Individual Property, Surge Hazard and Mitigation Economic Effectiveness Assessment Data and Methodology

Chapter 2 Summary

Our goal is to analyze the economic effectiveness of mitigating single-family homes against coastal surge risks by (1) elevating homes, (2) demolishing and acquiring homes, and (3) building floodwalls around homes. We will examine these three mitigation techniques for homes in unincorporated Escambia County, the City of Pensacola, and Pensacola Beach because these communities are at significant risk of surge hazards. Economic effectiveness is assessed by computing the benefit-cost ratios (BCRs) for mitigation projects; and a BCR of 1 indicates that a project is economically effective. In order to accomplish this, in this chapter we detail the properties to be used in our analysis, their associated relevant exposure characteristics and storm-surge hazard risk, and how their economic effectiveness will be assessed in two main ways.

Our first economic effectiveness assessment methodology is via the FEMA BCA toolkit. We use the FEMA BCA Toolkit because it is the standard tool and methodology utilized to apply for FEMA mitigation grants for our three mitigation activities, such as through the Hazard Mitigation Grant Program (HMGP). Additionally given these results, we detail how we will conduct sensitivity analyses of the economic effectiveness of elevating homes, demolishing and acquiring homes, and building floodwalls around homes by varying the following parameters:

- Using 7% and 4% discount rates for discounting future benefits
- Varying the useful lifetimes of projects; i.e., the time horizon over which benefits are discounted
- Reducing the total costs of the mitigation projects by increments of 25% to assess a break-even point; i.e., percentages of costs of mitigation projects at which benefit-cost ratios approach 1.

In addition to the FEMA BCA toolkit, we describe our second economic effectiveness assessment methodology utilizing a more automated process implemented using statistical and spreadsheet software. Our automated process addresses several limitations of the Toolkit, such as:

- analyzing a large dataset with a fairly automated, transparent process, and
- incorporating a variety of sea level rise scenarios into benefit-cost analyses.

2.1 Geospatial analysis to prepare the home dataset

The first step in our analyses involved selecting a sample of single-family homes at risk from surge hazards to be analyzed with the FEMA BCA Toolkit to assess the economic effectiveness of elevating the homes, demolishing and acquiring the homes, and building floodwalls around homes to mitigate surge hazards. The BCA Toolkit is limited in conducting a batch analysis of large samples of homes and projects, so we selected three separate samples of homes from the City of Pensacola, unincorporated Escambia County, and Pensacola Beach respectively. We chose 14 homes in Pensacola, 14 in Escambia County, and 11 from Pensacola Beach that are at risk to surge hazards according to our storm surge risk data, called U-Surge[11] (detailed below). Our total sample of 39 homes originates from 2015 Escambia County parcel data (from the Escambia County Property Appraiser (ECPA) office), and building footprints obtained from the City of Pensacola and Escambia County GIS departments.

The geospatial procedures to prepare the homes' dataset were implemented with ArcGIS Desktop[12] software (version 10.2.2). First, we prepared our residential dataset by joining parcel attributes required to estimate flood risk and exposure from the ECPA's 2015 parcel dataset to the parcel outlines. The parcel attributes relevant to determining flood risk included land use type, improvements values, year of construction, foundation and frame types, number of floors, and heated area in square feet. Next, we spatially joined building footprints within the Pensacola city limits to the single-family parcels that contained them to assign the parcel attributes to the building footprints. Then, we intersected the buildings within parcels feature class with the effective flood zones from the 2006 FEMA Digital Flood Insurance Rate Map (DFIRM) for Escambia County to attribute buildings with a DFIRM flood zone. The DFIRM for Escambia County is published as an ArcGIS geodatabase that can be downloaded at FEMA Flood Map Service Center.

Then we attributed building footprints with first floor elevation (FFE) information, most of which were based on elevation statistics from the 2006 LiDAR-derived digital elevation model (DEM) from the Northwest Florida Water Management District. The average elevation of the DEM within each building footprint was chosen as a basis to estimate FFEs of single-family homes, except for homes that had a geocoded elevation certificate (EC)[13]. For the homes that lacked a geocoded EC, we applied the following assumptions[14] to estimate FFE based on average elevation within building footprints and foundation type according to the ECPA parcel data:

1. If foundation type is slab above grade, then add 2 feet to the average elevation of the DEM within the building footprint to estimate FFE. According to the ECPA, slab above grade foundations are elevated at least 3 blocks, and a standard block is 8 inches high.
2. If foundation type is slab on grade, then simply use the average elevation of the DEM within building footprint as FFE.

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[11] https://www.u-surge.net/about.html
[12] More information on ArcGIS Desktop can be found at http://desktop.arcgis.com/en/.
[13] We obtained ECs from the City of Pensacola, Escambia County, and Santa Rosa Island Authority in late summer of 2016. We were able to geocode 19 ECs for the City of Pensacola, 27 ECs in unincorporated Escambia County, and 67 on Pensacola Beach. Some ECs that we obtained from the City and County were for homes that were still under construction so we could not geocode them with our 2015 parcel dataset. Therefore, the majority of our homes at risk to surge in the City, County, and Beach have FFEs that are estimated using 2006 LiDAR-derived digital elevation model (DEM) and the assumptions listed above.
[14] Email communication with an Appraisal Supervisor at ECPA provided the following information on foundation types listed in the ECPA data: a slab above grade foundation is built up by 3 blocks or more, typically for sloped lots; and a wood foundation with a subfloor is an elevated home on pilings or crawlspace. Assumptions 1 and 2 listed on this page are minimum heights based on our understanding of these foundations types from our communications with personnel at the ECPA. Assumptions 3 and 4 are somewhat arbitrary, but piling homes usually have higher foundations than crawlspace homes.
Assumptions of FFEs based on foundation type were also ground-truthed for a sample of homes in Pensacola and Sanders Beach with visual inspections and conversations with homeowners. We conducted sensitivity analyses of FFE assumptions with two alternative sets of assumptions based on foundation types. The results are not presented herein but are available from the authors on request.

3. If foundation type is pilings, then add 6 feet to average elevation of the DEM within building footprint to estimate FFE.
4. If foundation type is wood with a subfloor, then add 3 feet to average elevation of the DEM within building footprint to estimate FFE. Wood with subfloors, according to the ECPA data, are elevated homes not on a slab.

The ECs that we geocoded for the Pensacola Beach homes include FFE and lowest adjacent grade (LAG) information obtained from site-specific professional surveys. Therefore, we did not need to make any assumptions to estimate FFEs for these homes.

In the BCA Toolkit, there are three types of foundations: slab, pile, and pier. Slab foundations include both on-grade and off-grade slabs from the ECPA data; pile foundations are pilings; and we treated wood with subfloor foundations from the ECPA data as pier foundations.

2.2 Flood risk data: U-Surge

Once ECs had been geocoded and FFEs had been estimated for all single-family homes in our dataset, we then intersected the building footprints with surge risk data called U-Surge, from Marine Weather & Climate[15]. Based on observations from the National Oceanic and Atmospheric Administration (NOAA), tide gauges and other data sources, storm surge data from 1900 to 2016 for Escambia County were analyzed and used to develop the U-Surge dataset for our study area. The U-Surge dataset was produced from a regression analysis of water level (storm tide height) as the dependent variable and frequency (return period) as the independent variable, and involved conversion of all high water marks to the one common vertical datum, the North Atlantic Vertical Datum of 1988 (NAVD88), to enable statistical analysis.[16]

U-Surge data for surge risks (water elevations and probabilities) in Pensacola for the year 2017 were utilized for analysis. The U-surge data are more granular than DFIRM data because surge hazards are disaggregated into annual probabilities of 10%, 4%, 2%, 1%, and 0.2%. DFIRM data include flood elevations only for the 1% annual chance flood zones, and this elevation is called the base flood elevation (BFE) in DFIRMs. Each annual surge probability event has a corresponding surge height, as shown in Table 2 (in feet). The U-Surge data are based on a log-linear regression model that fits surge heights as the dependent variable against return period for events that occurred in Pensacola from 1900 to 2016. The equation for Pensacola is

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[15] https://www.u-surge.net/about.html

[16] Bilskie, M.V., Hagen, S.C., Alizad, K., Medeiros, S.C., Passeri, D.L., Needham, H.F., and Cox, A. Dynamic simulation and numerical analysis of hurricane storm surge under sea level rise with geomorphologic changes along the northern Gulf of Mexico. Earth's Future, 2016; 4(5): 177-193.
Needham, H.F., and B.D. Keim. A Storm Surge Database for the U.S. Gulf Coast. International Journal of Climatology, 2012; 32(14):2108-2123.
Needham, H.F., B.D. Keim, and D. Sathiaraj. A Review of Tropical Cyclone-Generated Storm Surges: Global Data Sources, Observations and Impacts. Reviews of Geophysics, 2015; 53(2): 545-591.
Needham, H.F., B.D. Keim, D. Sathiaraj, and M. Shafer. A Global Database of Tropical Storm Surges. EOS, Transactions American Geophysical Union, 2013; 94(24): 213-214.
Needham, H.F. A Data-Driven Storm Surge Analysis for the U.S. Gulf Coast. 2014. Louisiana State University (LSU) Digital Commons, LSU Doctoral Dissertation. Located online at https://digitalcommons.lsu.edu/cgi/viewcontent.cgi?article=4249&context=gradschool_dissertations.

$$y = 3.9105 \ln(x) - 4.0896$$

with x = return period and y = storm tide height above NAVD88.

There are no control variables in this equation for Pensacola, and the $R^2 = 0.95385$. This equation and the surge risk data utilized in this report are valid for the Pensacola area, which is spatially defined as a 10-mile radius from the City of Pensacola[17] and includes the homes in our analyses in unincorporated Escambia County, City of Pensacola, and Pensacola Beach.

Table 2. Stillwater surge elevations in feet for each probability event for Pensacola relative to NAVD88 (North Atlantic Vertical Datum of 1988) for year 2017. Storm tide return levels based on observed data from 1900-2016 (117 years) for the Pensacola area. (Source: U-Surge. 2017 Marine Weather & Climate https://www.u-surge.net/pensacola.html).

Annual probabilities of surge events	Stillwater surge elevation (feet)
10%	4.91
4%	8.50
2%	11.21
1%	13.92
0.2%	20.21

Homes that coincide with surge hazards were attributed with the minimum surge elevation based on the five annual probability events shown in Table 2, and then surge elevations that were higher were also attributed to the homes to calculate the total surge risk for homes. For example, if a home is coincident with the surge elevation corresponding to the 2% annual surge event, then we can assume it is also vulnerable to the 1% and 0.2% annual chance events.

2.3 Selecting the sample of homes for analysis with the BCA Toolkit

The sample of homes was derived from a stratified random sampling approach, with homes in Pensacola, unincorporated Escambia County, and Pensacola Beach within the five annual chance surge risk zones. Homes were selected by surge zones with different foundations (either slab or open foundations), with one floor/story. We over-sampled in the two most risky surge zones (the 10% and 4% annual chance zones).

The sample homes within each of the three study areas are shown in Figures 2 through 4. In Figure 2, the City of Pensacola sample homes are mapped. Figure 3 shows the map of the unincorporated Escambia County sample of homes, and Figure 4 shows the Pensacola Beach sample of homes. The system for attributing the sample homes shown in Figures 2 through 4 with unique identifiers is as follows: the first capitalized letter(s) indicates the study area (P for Pensacola, E for Escambia County, and PB for Pensacola Beach). After the study area letter is a hyphen and a lower-case letter indicating

[17] https://digitalcommons.lsu.edu/cgi/viewcontent.cgi?article=4249&context=gradschool_dissertations

the foundation type (s for slab, c for crawlspace or pier, and p for pilings); then another hyphen followed by a number representing the annual chance surge zone the home coincides with (i.e., 10 = 10% annual chance surge zone, 4 = 4% annual chance surge zone, 2=2% annual chance surge zone, 1=1% annual chance surge zone, and 02=0.2% annual chance surge zone). After the number denoting the annual chance surge risk zone is another hyphen and a number unique to each of the three study areas. For example, sample home P-s-1-11 is a slab foundation home in Pensacola, at risk to the 1% annual chance surge event, and is the 11th home in the set of Pensacola sample homes.

We selected fourteen homes each in Pensacola and unincorporated Escambia County, and eleven homes in Pensacola Beach for a total of 39 homes in our sample. Table 3 shows pertinent attributes of our sample of homes needed for analysis of economic effectiveness of flood mitigation with the BCA Toolkit.

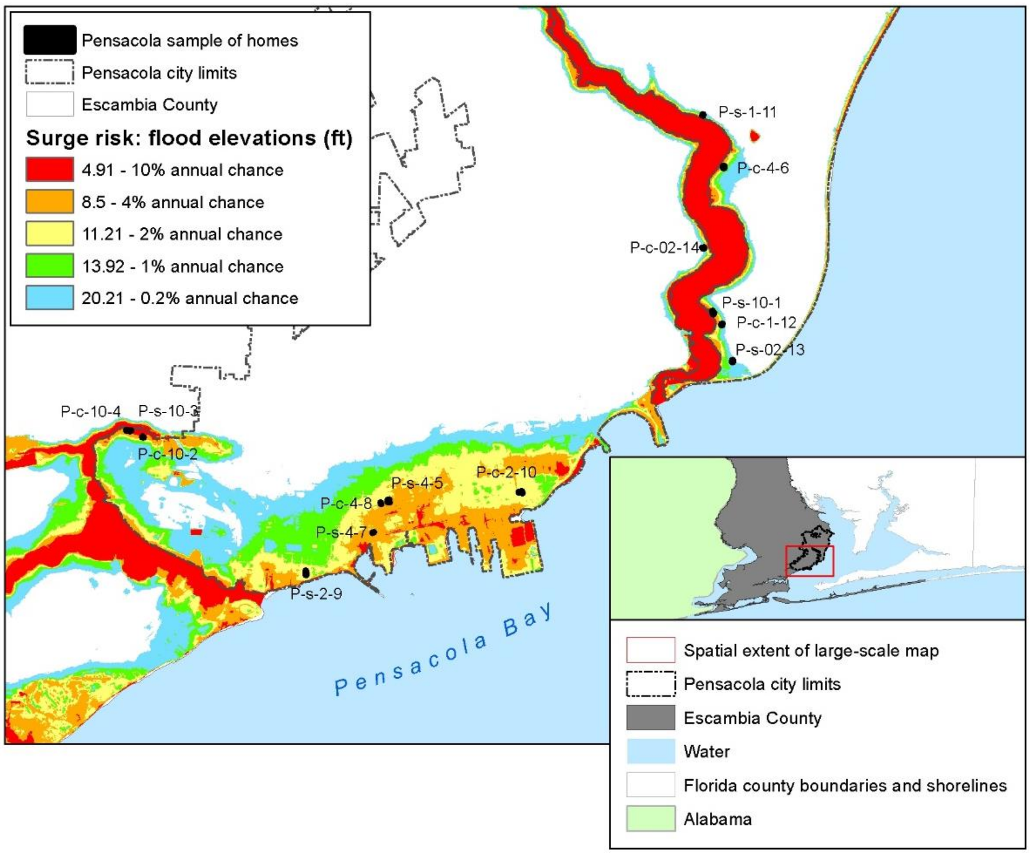


Figure 2. City of Pensacola sample of homes for which the economic effectiveness of flood mitigation techniques is analyzed with FEMA's BCA Toolkit.

It is impossible to select as many homes with different foundation types in each surge zone in Pensacola Beach as it is for Pensacola and Escambia County homes for two reasons. One reason is that Pensacola Beach is exposed to much more surge risk: for example, there is only one single-family home within the 0.2% annual chance surge zone on Pensacola Beach and all other homes are within greater annual chance surge zones. The second reason is that there are many attached dwelling units on Pensacola Beach, for which it would be complicated or impossible to elevate or demolish and acquire. We analyzed only single-family homes in this report.

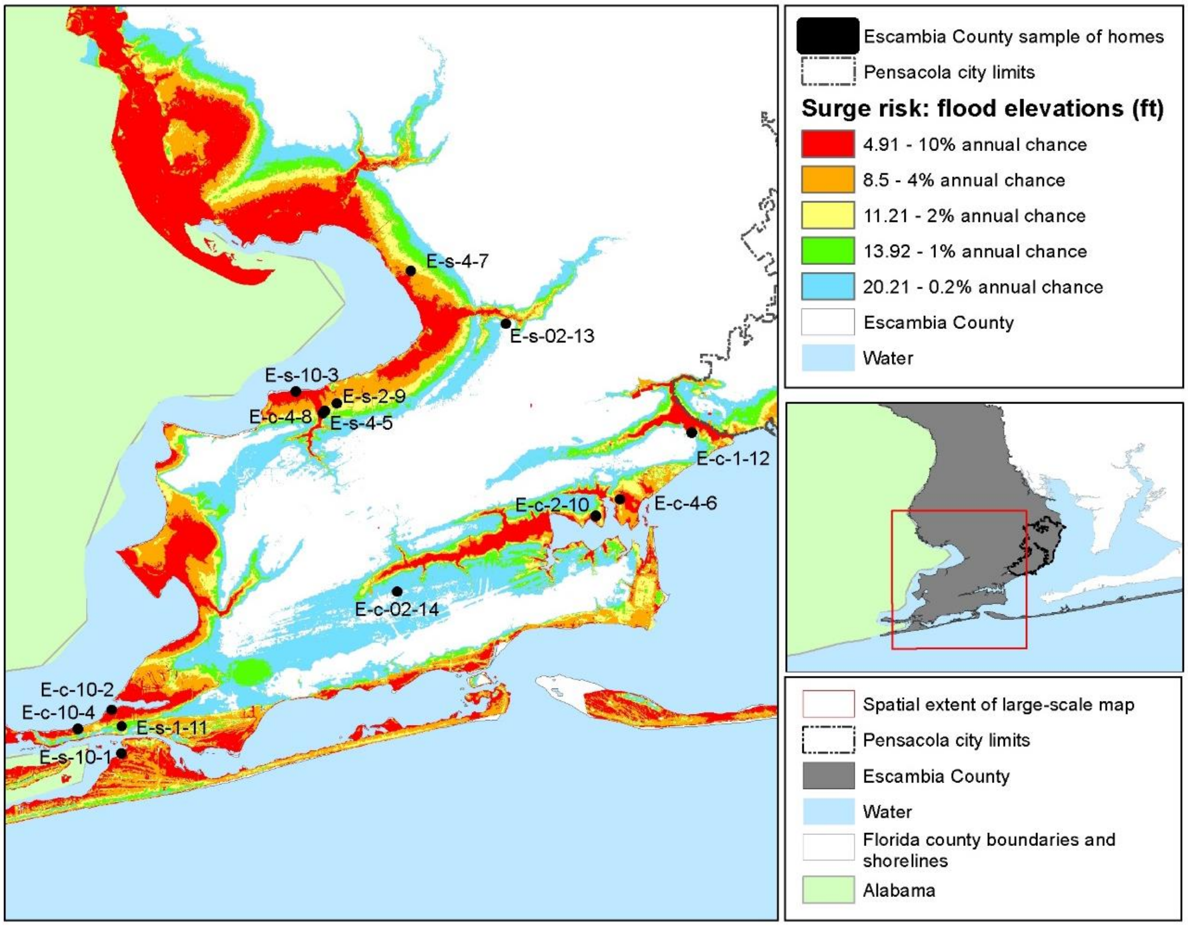


Figure 3. Unincorporated Escambia County sample of homes analyzed for economic effectiveness of flood mitigation techniques using FEMA BCA Toolkit software.

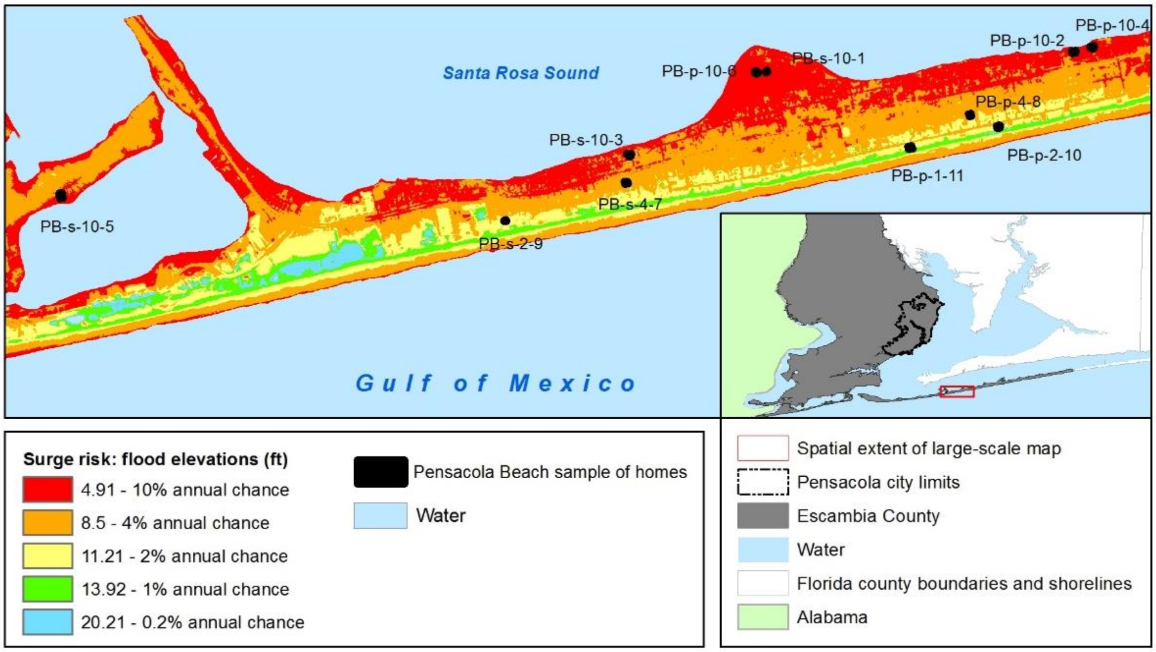


Figure 4. Pensacola Beach sample of homes analyzed for economic effectiveness of flood mitigation techniques using FEMA's BCA Toolkit.

The economic effectiveness of three different flood mitigation activities are assessed for sample of homes using the FEMA BCA Toolkit: **elevation, demolition and acquisition, and constructing floodwalls**. For the representative homes on Pensacola Beach, the economic effectiveness of **elevation and acquisition** are assessed to mitigate surge hazards. All of Pensacola Beach has VE zone construction standards[18], which prohibit construction of floodwalls on the island. In Appendix A, we provide detailed step-by-step methodology for how we used the BCA Toolkit to assess economic effectiveness of mitigating sample homes against surge risks. In the subsequent section, we provide a broad overview of how we used the BCA Toolkit to analyze the sample homes.

2.4. Analyzing the sample homes with the BCA Toolkit

We used the FEMA Toolkit to calculate the BCRs for mitigating the sample homes against surge hazards by elevating them, demolishing and acquiring them, and building floodwalls around them. The attributes of the sample homes shown in Table 3 comprise much of the input for the BCA Toolkit. We employed the U-Surge surge risk data as the flood hazard data since the Flood Module of the Toolkit requires flood hazard data with multiple return periods. A limitation of the Toolkit is that the maximum number of return periods users we can input is four, despite that the U-Surge surge risk data includes five return intervals and flood heights.

[18] From the most recent version of the Escambia County Land Development Code, located online at https://myescambia.com/docs/default-source/sharepoint-developmental-services/land-development-code.pdf; on page LDC 4: 46 it states: "(b) Standards for buildings and structures within the jurisdiction of the SRIA. (1) Buildings and structures shall be designed and constructed to comply with the more restrictive applicable requirements of the Florida Building Code, Building Section 3109 and Section 1612 or Florida Building Code, Residential Section R322, applicable to coastal high hazard areas."

Each sample home is denoted at risk to coastal flood hazards in the Toolkit since we are using surge risk data, but we choose "V" zone coastal flooding in the Toolkit if the sample home coincides with a VE zone according to the 2006 effective DFIRM for Escambia County. All other sample homes are attributed as "A" zone coastal flooding. We selected either the USACE generic depth-damage function or the FIA function for homes coincident with A zones of the 2006 effective DFIRM, and the Expert Panel or FIA depth-damage functions for homes in VE zones according to the 2006 effective DFIRM. The USACE generic function is not an option for mitigating VE zone homes, and the Expert Panel functions are available only for V zone homes. See Table 3 for the DFIRM effective flood zone and surge risk zone for all of our sample homes.

For elevating homes, we calculated BCRs using the Toolkit for elevating homes by 2, 4, 6, and 8 feet. Guidance on estimating the costs of elevating homes comes from FEMA P-312 (2009) and is referenced and documented in Appendix B.

For demolishing and acquiring homes, we used an HMA grant development spreadsheet provided to us by Charlotte Mecklenburg Storm Water Services Department to approximate the total costs of demolition and acquisition. This spreadsheet is attached to this report as a Microsoft Excel file (named "HMA Development Spreadsheet_Acquisitions PNS sample homes.xlsx").

For building floodwalls around homes, we estimated the costs to build 2' and 4' high floodwalls around the perimeters of homes according to FEMA P-312 (2009) and this is documented and further explained in Appendix C. We calculated the perimeters of the building footprints in GIS, and used the perimeters as the length of the floodwalls to be built.

Standard values for the useful lifetimes of the three types of projects we examined were input into the Toolkit as they appear in Appendix C of the BCA Toolkit Reference Guide[19]. The standard discount rate of the BCA Toolkit is 7%.

[19] https://www.fema.gov/media-library-data/20130726-1736-25045-7076/bca_reference_guide.pdf

Table 3. Sample homes with attributes needed for analysis of the economic effectiveness of flood mitigation techniques using the BCA Toolkit.

Home number (unique identifier)	Address	Year built	Heated area (square feet)	Perimeter of home/ bldg. footprint (feet)	Bldg. replace-ment value	Value ($) per square foot	Foundation type	Frame	FFE (ft)	Average Lidar-derived ground elevation (ft) within bldg. footprint	LAG for homes with EC	Flood Zone (2006 effective DFIRM for Escambia County)	Annual chance surge risk zone (U-Surge)
P-s-10-1	621 BAYOU BLVD	1972	640	315	$49,967	$78.07	slab	wood	5.90	5.90		AE	10%
P-c-10-2	3175 BAYOU DR	1953	1334	149	$63,047	$47.26	crawlspace/ pier	wood	8.37	5.37		AE	10%
P-s-10-3	3330 BAYOU DR	1979	1479	183	$59,721	$40.38	slab	wood	4.30	4.30		AE	10%
P-c-10-4	3370 BAYOU DR	1953	1178	201	$55,595	$47.19	crawlspace/ pier	wood	7.05	4.05		AE	10%
P-s-4-5	151 DONELSON ST	2004	1120	162	$207,446	$185.22	slab	wood	7.97	7.97		AE	4%
P-c-4-6	2251 BANQUOS CT	1960	2786	268	$177,518	$63.72	crawlspace/ pier	wood	12.41	9.41		AE	4%
P-s-4-7	414 S A ST	2005	1025	178	$49,931	$48.71	slab	wood	8.66	8.66		AE	4%
P-c-4-8	620 W INTENDENCIA ST	2006	1188	202	$55,020	$46.31	crawlspace/ pier	wood	11.02	8.02		AE	4%
P-s-2-9	1408 SONIA ST	1943	408	368	$122,373	$299.93	slab	masonry	10.73	10.73		AE	2%
P-c-2-10	308 S ALCANIZ ST	1946	528	433	$106,296	$201.32	crawlspace/ pier	wood	12.67	9.67		X	2%
P-s-1-11	2581 BAYOU BLVD	1970	504	193	$140,430	$278.63	slab	wood	15.80	15.80		X	1%
P-c-1-12	500 BAYOU BLVD	1928	912	214	$140,811	$154.40	crawlspace/ pier	wood	16.23	13.23		X	1%
P-s-02-13	2805 E JACKSON ST	2003	2001	250	$129,135	$64.54	slab	wood	20.30	18.30		X	0.2%
P-c-02-14	1716 OSCEOLA BLVD	1960	2525	251	$124,585	$49.34	crawlspace/ pier	wood	22.92	19.92		X	0.2%
E-s-10-1	14150 RIVER RD	1971	1215	211	$62,990	$51.84	slab	wood	4.13	4.13		AE	10%
E-c-10-2	5490 CRUZAT WAY	1968	1218	194	$48,971	$40.21	crawlspace/ pier	wood	6.68	3.68		AE	10%
E-s-10-3	210 RIOLA PL	1995	1118	200	$89,782	$80.31	slab	wood	3.18	3.18		AE	10%

E-c-10-4	5720 ONO AVE	1992	1539	196	$70,524	$45.82	crawlspace/ pier	wood	8.28	5.28		AE	10%
E-s-4-5	486 HERRON VILLA LN	1994	1120	197	$67,963	$60.68	slab	wood	9.12	9.12		A	4%
E-c-4-6	420 S 1ST ST	1940	1089	159	$37,415	$34.36	crawlspace/ pier	wood	10.51	7.51		AE	4%
E-s-4-7	9291 PLUMIERA PL	2000	1590	211	$83,643	$52.61	slab	wood	7.47	7.47		AE	4%
E-c-4-8	491 HERRON VILLA LN	1989	1827	246	$92,819	$50.80	crawlspace/ pier	wood	9.39	6.39		AE	4%
E-s-2-9	10747 JOLYNE DR	1980	1038	179	$50,865	$49.00	slab	wood	9.32	9.32		A	2%
E-c-2-10	427 BAUBLITS CT	1944	1041	105	$46,719	$44.88	crawlspace/ pier	wood	13.09	10.09		AE	2%
E-s-1-11	14178 INNERARITY PT RD	1996	1092	159	$50,419	$46.17	slab	wood	12.74	12.74		X	1%
E-c-1-12	13 AUDUSSON AVE	1949	1025	246	$48,327	$47.15	crawlspace/ pier	wood	16.52	13.52		X	1%
E-s-02-13	7705 PONTIAC DR	1973	1000	188	$48,950	$48.95	slab	wood	20.55	20.55		X	0.2%
E-c-02-14	9775 NORTH LOOP RD	1959	1000	176	$55,749	$55.75	crawlspace/ pier	masonry	23.27	20.27		X	0.2%
PB-s-10-1	803 CORTO DR	1954	1350	174	$51,732	$38.32	slab	masonry	3.50	2.92	2.80	AE	10%
PB-p-10-2	100 ENTRADA 1	2005	2416	289	$252,260	$104.41	pilings	wood	4.98	3.99	3.68	VE	10%
PB-s-10-3	339 PANFERIO DR	1955	2354	245	$92,484	$39.29	slab	masonry	4.48	4.48		AE	10%
PB-p-10-4	100 ENTRADA 2	1962	1178	283	$73,277	$62.20	pilings	masonry	4.40	3.38	3.40	AE	10%
PB-s-10-5	218 SABINE DR	1969	3816	455	$210,338	$55.12	slab	wood	5.89	5.05	5.27	AE	10%
PB-p-10-6	808 RIO VISTA DR	2011	1176	213	$111,000	$94.39	pilings	wood	16.79	5.07	4.10	AE	10%
PB-s-4-7	309 MALDONADO DR	1962	1225	213	$56,889	$46.44	slab	masonry	7.42	7.42		AE	4%
PB-p-4-8	1200 MALDONADO DR	1984	2094	212	$121,406	$57.98	pilings	wood	18.95	6.53	8.50	AE	4%
PB-s-2-9	105 ARIOLA DR	1953	1899	168	$77,756	$40.95	slab	masonry	9.81	9.81		AE	2%
PB-p-2-10	1208 ARIOLA DR	1997	2170	253	$157,098	$72.40	pilings	wood	19.10	9.57	7.80	VE	2%
PB-p-1-11*	1014 ARIOLA DR	1997	4677	278	$440,037	$94.09	pilings	wood	17.89	11.89		VE	1%

***Note**: home PB-p-1-11 has 2 stories but its building footprint area is very similar to the heated area in square feet according to the ECPA data, so we treat it as a 1-story home in the BCA Toolkit.

2.5 Sensitivity Analysis: adjusting useful lifetimes and discount rates, and break-even costs

Once we had examined the economic effectiveness of the three flood mitigation activities for every sample home using the BCA Toolkit, we implemented sensitivity analyses in Microsoft Excel. We varied the project useful lifetimes, and examined how a 4% discount rate affects BCRs in addition to FEMA's standard 7% discount rate. Regarding the choice of annual discount rates, FEMA uses 7% for evaluating mitigation grant proposals (FEMA 2009) while the National Institute of Building Sciences used a discount rate of 2.2% in evaluating the cost effectiveness of hazard mitigation projects in the U.S. (Multihazard Mitigation Council, 2017). We follow Aerts et al. (2014) who analyzed flood mitigation options in New York City by using 4% and 7% annual discount rates as low and high rates: 4% as it is the rate used by the Netherlands for long-term projects reducing societal risk and funded by governmental entities, and 7% because it is the rate used by FEMA for evaluating mitigation projects (DHS FEMA, 2009; Aerts et al., 2014).

We also examined different percentages of costs of mitigation projects to see what the "break-even" costs are. "Break-even" costs in our context are defined as the percentages of mitigation project costs at which the benefit-cost ratios are 1. We obtained the annual benefits for mitigating each sample home from the BCA Toolkit, and then used the present value function in Microsoft Excel to implement sensitivity analyses varying project useful lifetimes and discount rates.

In our sensitivity analysis of home elevation as a flood mitigation strategy, we examined useful lifetimes of 30, 50, 80, and 100 years; and discount rates of 4% and 7%. The BCA Toolkit has a standard useful life for home elevation of 30 years, with acceptable range of 30 to 50 years[20]. We only examined home elevation by eight feet in our sensitivity analyses since eight feet was most commonly the most economically effective height for our representative homes.

In our analyses of the economic effectiveness of acquiring homes, we do not vary the project useful lifetimes because we used the FEMA standard useful lifetime of 100 years. This is because 100 years is the maximum timespan over which benefits are computed in any BCA using the Toolkit, and 100 years is also the only FEMA acceptable value for an acquired home lifetime. Demolishing and acquiring a home as part of a FEMA flood mitigation project requires that the land parcel the home is on be converted to open space for perpetuity, thus 100 years is probably intended to represent perpetuity in the BCA Toolkit.

When we analyze floodwalls, we examine project useful life times of 50, 80, and 100 years, recognizing that the FEMA standard lifetime for a floodwall project is 50 years with an acceptable range of 35 to 50 years.

When assessing break-even costs, we incrementally subtracted 25% of total project costs for each mitigation activity, and we used the standard values dictated by the BCA Toolkit. For example, when we examined break-even costs for all projects, we used the standard 7% discount rate; and we used project lifetimes of 30 years for elevation, 100 years for demolition and acquisition, and 50 years for floodwalls.

2.6 Computing BC ratios for mitigating homes at risk to surge without the Toolkit

Once we had calculated the BC ratios for each of the 39 sample homes in the FEMA BCA Toolkit, we computed the BC ratios without the Toolkit using SPSS Statistics software and Microsoft Excel. This was done not only on the 39 sample homes, but also for a much larger set of properties, n = 6,820 including the 39 toolkit homes. The

[20] Appendix D of the FEMA BCA Toolkit Reference Guide (located online at https://www.fema.gov/media-library-data/20130726-1736-25045-7076/bca_reference_guide.pdf) lists standard values and acceptable limits for all project useful lifetimes.

methodology we used to compute BC ratios for home elevation without the Toolkit is explained in Montgomery and Kunreuther (2018). This approach to estimating expected losses to floods for homes exposed to surge risk involves the USACE Institute of Water Resources (IWR) depth-damage function exported from Hazus with the R statistical software. GIS was used as explained above to intersect sample homes with U-Surge surge data to obtain flood depths inside homes based on the difference between flood elevations and FFEs for each annual probability surge event.

To estimate homes' vulnerability to storm surge hazards, we subtract the homes' FFEs from the surge water elevations to obtain the water depths inside the homes for each flood frequency/probability surge event for every year from 2017 to 2100. We computed AALs for all homes vulnerable to surge risks using the equation in the Hazus Technical Manual (version 2.1, page 14-38):

$$AAL = [(f_{10} - f_{25}) * ((L_{10} + L_{25})/2)] + [(f_{25} - f_{50}) * ((L_{25} + L_{50})/2)] + [(f_{50} - f_{100}) * ((L_{50} + L_{100})/2)] +$$

$$[(f_{100} - f_{500}) * ((L_{100} + L_{500})/2)] + (f_{500} * L_{500})$$

where $f_x = 1/x$ (frequency/probability of an x-year flood event) and L_x are the losses attributable to the x-year event (expressed as percentages of building and contents) where x=10, 25, 50, 100 and 500.

The AAL equation is based on the annual probability of each flood with the corresponding flood depths inside the home, and the damage to buildings and contents attributed to each depth of water inside homes according to the USACE IWR depth-damage function.

We examined the economic effectiveness of elevating homes by 8' in our bulk analyses because elevating as high as possible is commonly more economically effective than elevating to lower heights, and 8' is the maximum home elevation given in FEMA (2009). For computing the benefits of elevating homes by 8', we compute the AALs before and after elevation and take the difference between the two AALs for each year, both with and without sea level rise.

We computed BCRs with the benefits in the form of annual savings in surge risk-based AAL premiums for every year from 2017 to 2100 after elevating homes by eight feet according to the NOAA Low, Intermediate-High, and High sea level rise (SLR) scenarios and the USACE IWR depth-damage function. As stated above, we examine reductions in surge risks from elevating homes out to 2100 because the CRS manual (FEMA, 2017)[21] recommends that community flood mitigation projects should consider SLR projection to 2100. Benefits of elevating homes by 8' are discounted by 4% and 7% assuming no SLR, and with the NOAA Low, Intermediate-High, and High SLR scenarios. Costs of elevating homes by 8' are estimated in the same manner as above according to FEMA P-312 (2009), as shown in Appendix B. Figure 5 shows the relative SLR in feet for Pensacola according to the NOAA Low, Intermediate-High, and High SLR scenarios.

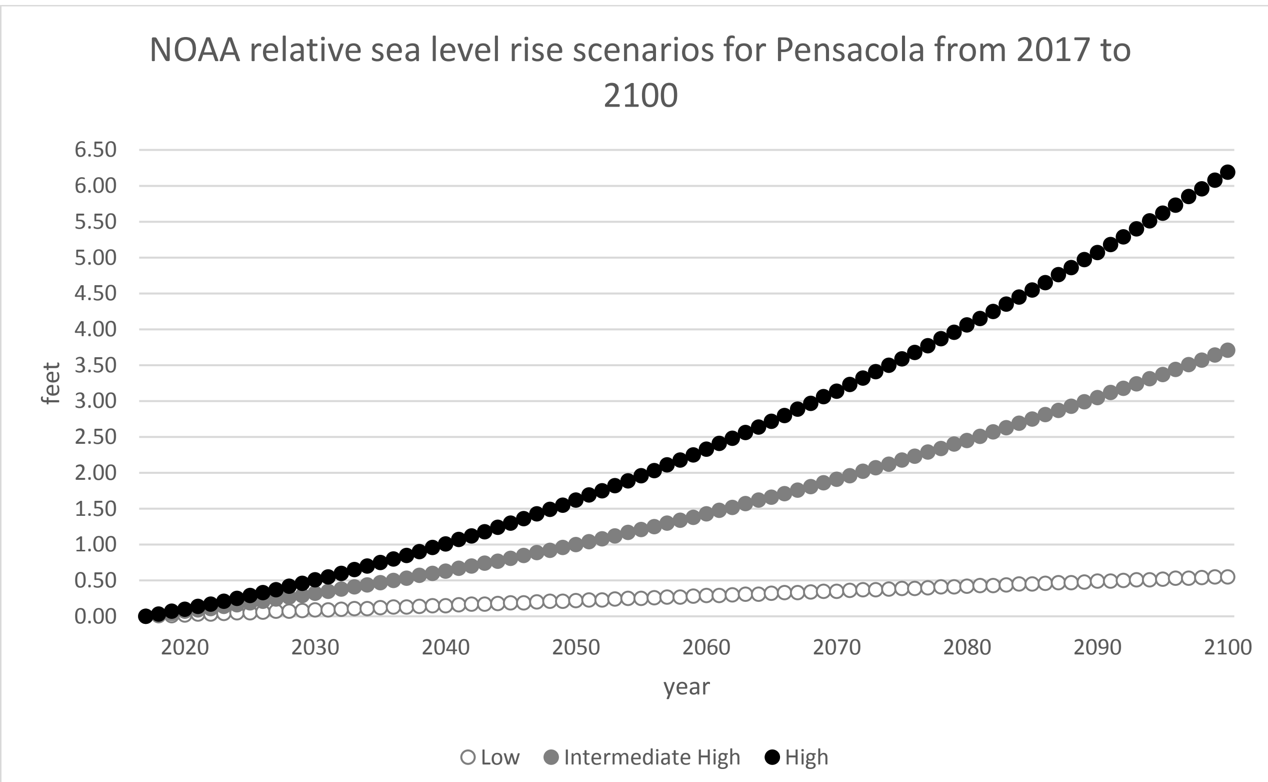
To calculate BC ratios for demolition and acquisition of homes at risk to surge, we computed the costs in the same manner as above with guidance from Charlotte Mecklenburg Storm Water Services Department (discussed in Appendix A). Benefits of acquiring homes were the AALs computed for homes using the AAL equation from

[21] Federal Emergency Management Agency (FEMA). (2017). *National Flood Insurance Program (NFIP) Community Rating System (CRS) Coordinator's Manual*. Available at: https://www.fema.gov/media-library/assets/documents/8768, accessed June 16, 2017.

the Hazus Technical Manual for every year from 2017 to 2100, without SLR and with SLR according to the NOAA Low, Intermediate-High, and High SLR scenarios. Benefits were discounted with 4% and 7% discount rates.

To calculate BC ratios for building floodwalls around homes, we computed the costs to build 4’ high floodwalls around homes (as detailed in Appendix A). We exclude homes with piling foundations from floodwalls because we assume that piling foundations are 6’ above the ground surface elevation thus it does not make sense to build a 4’ foot floodwall around a home that is already 6’ above the ground. Pensacola Beach homes are excluded from analyses of floodwalls because all structures on Pensacola Beach are subject to coastal high hazard building regulations, thus floodwalls are prohibited structures on Pensacola Beach, as stated above.

Figure 5. Estimated relative sea level rise scenarios (in feet) for Pensacola for every year from 2017 to 2100 according to National Oceanic and Atmospheric Administration (NOAA) (see http://corpsclimate.us/ccaceslcurves.cfm). Years are labeled on the horizontal axis in yen-year increments starting at 2020.



To estimate the savings in flood AALs due to floodwalls, we assume no flood losses until surge heights are over 4’ for homes. Therefore, losses due to surge for homes with floodwalls are the differences between surge elevations and 4’, and then we add the FFEs for homes. Therefore, the benefits in avoided losses from surge risks due to 4’ high floodwalls are most for slab on-grade foundation homes, followed by homes with slab above grade foundations, and then crawlspace and pier foundations. This is because we assumed that FFEs of slab on-grade homes are the same as the average ground elevation within the building footprint, FFEs of slab above grade foundation homes are 2’ above the average ground elevation within the building footprint, and FFEs for crawlspace and pier foundation homes are 3’ above the average ground elevation within the building footprint. As with home elevation and acquisition, benefits are estimated for every year from 2017 to 2100, without SLR and with SLR according to the NOAA Low, Intermediate-High, and High SLR scenarios; and discounted by 4% and 7%.

The USACE IWR function relates percentages of building and contents replacement values lost with each whole foot of flood water in each home. It does not vary according to the DFIRM flood zone that homes are in, but it is based on single-family detached homes without basements, and the number of floors in a home. We assumed that all homes in our analyses lack basements, which is most commonly the case for homes in Escambia County. We also assumed that contents replacement values are half of building replacement values (as in Dorman et al. 2018, and Montgomery and Kunreuther 2018), and building replacement values are the improvements values based on the ECPA data: the same as the building replacement values that are input for the Toolkit.

3.0 Individual Property Mitigation Benefit-Cost Results

Chapter 3 Summary

In this chapter we present the results of our analyses of the economic effectiveness of mitigating homes against surge risks for elevating homes, demolishing and acquiring homes, and building floodwalls around homes. A benefit-cost ratio of 1 indicates economic effectiveness, so in all charts showing BC ratios we have highlighted the axis indicating BC ratios equal to 1.

First we analyzed a total of 39 sample of homes across unincorporated Escambia County, the City of Pensacola, and Pensacola Beach using the FEMA BCA Toolkit. We found that generally, any one of the three mitigation techniques can be economically effective for homes at risk to the 10% and 4% annual chance surge risk zones, or NFIP VE flood zones, with low first-floor elevations (FFEs). For example, we found 7 of the 24 homes in these in these 10% and 4% annual chance surge risk zones were economically effective to elevate. We also found that it is commonly more economically effective to elevate homes as high as possible, since the majority of elevation costs are associated with the first foot of elevation. Demolition and acquisition is the least economically effective method, largely due to the high costs of these projects. Building floodwalls is economically effective for more homes than the other two mitigation techniques, as the costs of floodwalls are generally lower than elevation or acquisition.

Our sensitivity analyses of the total 39 sample homes analyzed with the Toolkit indicate that choice of discount rate (7% or 4%) has a greater impact on our results than varying the project lifetimes (ranging from 30 years to 100 years for projects). When we reduce costs of elevation to 25% of the total costs, all homes in the 10% annual chance surge zone except one are economically effective to elevate. When costs of demolition and acquisition and building floodwalls are reduced to 25%, 5 homes in the 10% annual chance surge zone are economically effective to mitigate with either of these two techniques. While we reduced the costs of mitigation projects by 25% increments for the sake of our sensitivity analyses, we acknowledge that it would be difficult to reduce mitigation costs to 25% of the totals for actual mitigation projects.

The advantages and limitations of the FEMA BCA Toolkit are also discussed. Some limitations of the Toolkit are addressed with our bulk analysis method, such as incorporating benefits into the future with a choice of sea level rise scenarios and the ability to conduct economic analyses on a large dataset of homes.

The results of our bulk analyses on 6,820 homes across unincorporated Escambia County, the City of Pensacola, and Pensacola Beach reveal similar trends as those obtained from the Toolkit: it is generally only economically effective to mitigate homes in the 10% or 4% annual chance surge zones with low FFEs; 11 percent of the homes analyzed in the bulk analysis are in the 10% or 4% annual chance surge zones and are also economically effective to mitigate. Floodwalls are economically effective for substantially more homes than elevation, and demolition and acquisition with a 7% discount rate is not economically effective for any home in our dataset.

Finally, we compare our mitigation BCR results to those from previous studies in Texas and New York. The Texas study similarly finds that if elevation to existing homes is to be undertaken as a flood mitigation effort, it must be done very selectively from an economic perspective due to the relatively significant costs of elevation to existing structures. In New York, none of the storm surge barrier nor hybrid (i.e., building codes with protection of critical infrastructure) approaches analyzed are economically beneficial under current levels of flood risk or a modeled "low" climate change scenario (30 cm of sea-level rise). However, when a low 4% discount rate is considered, all

strategies make economic sense if sea level rise occurs and climate change increases the frequency of storms. In Pensacola, similar relaxations of discount rates and higher sea-level risk scenarios lead to more favorable BCRs.

3.1 Elevating homes

For all of our sample homes (listed in Table 3 above), we examined the costs and benefits of elevating homes by 2', 4', 6', and 8' using the FEMA BCA Toolkit. We examined results using both the USACE generic depth-damage function and the FEMA FIA function for homes coinciding with A zones in the 2006 Escambia County effective DFIRM homes, and the Expert Panel and FEMA FIA functions for homes coincident with V zones in the DFIRM. However, as stated above, the FEMA FIA function consistently underweights damages from floods relative to both the USACE generic and Expert Panel functions; therefore BC ratios derived from the FEMA FIA functions are lower than BC ratios using the other two functions. Consequently, we omit presentation of results based on the FEMA FIA function.

The economic effectiveness of elevating homes most often increases with greater elevations. Therefore, we show results for elevating homes by 8' in our presentation of results for home elevation. Sample homes are grouped by the annual chance surge risk zone they coincide with, and BC ratios were calculated based on the FEMA standard values of 7% discount rate and 30 year useful lifetimes for a residential elevation project.

In Figures 6 through 9, we show BCRs for elevating homes by 8' using both 7% and 4% discount rates. But, in each of these figures we vary the project useful lifetimes over which benefits are discounted: Figure 6 shows BCRs based on 30-year lifetimes, Figure 7 shows BCRs based on 50-year lifetimes, Figure 8 shows BCRS based on 80-year lifetimes, and Figure 9 shows BCRs based on 100-year lifetimes. From our analyses of economic effectiveness testing 7% and 4% discount rates and various project lifetimes, we observe that the choice of discount rate has a larger impact on economic effectiveness (i.e., BCRs) than project lifetimes over which we calculated benefits, no matter the mitigation activity we are examining.

In Figures 6 through 9, we have limited the vertical axis showing the BCRs for each home at 1.8, so that the variation in BCRs for the sample homes are better displayed. Some homes have BCRs that are much higher than 1.8, but it is important to note that any BCR equal or greater than one indicated economic effectiveness. We have also highlighted the gridline for BCR =1 with a black line in all of the bar charts to emphasize the threshold value for economic effectiveness. For bar representing homes with BCRs much greater than 1.8, we have labeled the bar with the BCR value.

The BCRs indicate that it is almost always more economically attractive to elevate by the highest possible elevation, because the majority of the costs of elevation are associated with the first few inches of elevation. However, when we examined the benefits of elevating sample homes by various heights, as shown in Table 4, we observed that one sample home has greater benefits at a 6' elevation than an 8' elevation: E-c-2-10. Sample home E-c-2-10 is in the 2% annual chance surge zone, which has a surge height of 11.21', but it has an estimated FFE of 13.09'. Therefore, although it is in an area at risk to surge it has a high enough FFE that the benefits of elevating by 6' are greater than those associated with an 8' elevation. Further, the benefits of elevating sample home E-s-02-13 by 6' and 8' are identical in value, which is expected given that this home is only at risk to the 0.2% annual chance surge event (with an elevation of 20.21') and has an FFE of 20.55'. This is because annualized losses for sample home E-s-02-13 are estimated to be zero after elevating this home by 6'.

Figure 6 evidences that with the 7% and 4% discount rates and 30-year lifespan, it is only economically effective to elevate homes that are at risk to the 10% annual chance surge risk zone. Although slab foundation homes (indicated with “s” as the second alphanumeric character of the unique identifiers labeled on the horizontal axis) are more costly to elevate, home E-s-10-3 is economically attractive to elevate even with the 7% discount rate. Using a 7% discount rate makes it economically feasible to elevate only 2 homes: E-s-10-3 and PB-p-10-2. The primary reason why these two homes are economically attractive to elevate is because they have very low FFEs (3.18’ and 4.98’ respectively) and are in the 10% annual chance surge zone. The 10% annual chance surge heights is 4.91’. Further, home PB-p-10-2 is in a VE zone so the Expert Panel depth-damage function we used to produce the BCR for elevating by 8’ is very high.

When using a 4% discount rate, three homes are economically attractive to elevate. The third home that is economically effective to elevate is PB-p-10-4, which also has a very low FFE of 4.40’ and is in the 10% annual chance surge zone.

In all the bar charts presented herein, the V zone homes have an asterisk immediately after their unique identifier labeled under the horizontal axes. As V zone homes are subject to wave action hazards, we observe that they are relatively economically attractive to elevate for the annual chance surge zone they coincide with. For example, home PB-p-2-10 is the most economically attractive home to elevate in the 2% annual chance surge zone; and home PB-p-1-11 is the most economically attractive home to elevate in the 1% annual chance surge zone. The Expert Panel depth-damage functions used in the Toolkit for V zone homes attribute much more expected losses due to floods relative to the USACE generic functions for A zone homes. The Expert Panel depth-damage functions are unavailable in the Toolkit for A zone homes, and the USACE generic function is unavailable for V zone homes.

Table 4. Costs to elevate homes by 2', 4', 6', and 8'; and benefits over 30 years discounted by 7% for elevating by 2', 4', 6', and 8'. Homes are listed and grouped by descending annual chance surge risk. Home numbers with an asterisk behind them are in VE zones.

	Home number	costs to elevate 2'	costs to elevate 4'	costs to elevate 6'	costs to elevate 8'	benefits 2'	benefits 4'	benefits 6'	benefits 8'
10% annual chance surge risk	P-s-10-1	$51,200	$53,120	$55,040	$56,320	$14,848	$22,842	$26,419	$29,286
	P-c-10-2	$38,686	$42,688	$46,690	$49,358	$8,511	$12,380	$15,875	$17,769
	P-s-10-3	$118,320	$122,757	$126,455	$130,152	$31,717	$48,155	$56,432	$60,237
	P-c-10-4	$34,162	$37,696	$40,641	$43,586	$384,199	$480,579	$676,051	$744,060
	E-s-10-1	$97,200	$100,845	$103,883	$106,920	$35,964	$54,456	$63,369	$67,360
	E-c-10-2	$35,322	$38,976	$42,021	$45,066	$12,009	$17,929	$21,431	$22,984
	E-s-10-3	$89,440	$92,794	$95,589	$98,384	$88,608	$125,158	$140,159	$149,338
	E-c-10-4	$44,631	$49,248	$53,096	$56,943	$36,972	$56,178	$65,905	$70,344
	PB-s-10-1	$118,800	$122,850	$126,225	$129,600	$33,264	$51,597	$58,064	$62,208
	PB-p-10-2*	$70,064	$77,312	$83,352	$89,392	$336,307	$500,209	$573,462	$606,972
	PB-s-10-3	$207,152	$214,214	$220,099	$225,984	$29,016	$44,255	$51,051	$56,046
	PB-p-10-4	$70,680	$74,214	$77,159	$80,104	$37,322	$56,774	$66,773	$71,253
	PB-s-10-5	$305,280	$316,728	$326,268	$335,808	$63,405	$97,428	$112,563	$123,891
	PB-p-10-6	$34,104	$37,632	$40,572	$43,512	$1,022	$1,582	$3,192	$4,593
4% annual chance surge risk	P-s-4-5	$89,600	$92,960	$96,320	$98,560	$33,152	$47,410	$58,755	$65,050
	P-c-4-6	$80,794	$89,152	$97,510	$103,082	$8,887	$14,264	$15,602	$17,524
	P-s-4-7	$82,000	$85,075	$87,638	$90,200	$6,076	$9,484	$11,152	$12,585
	P-c-4-8	$34,452	$38,016	$40,986	$43,956	$3,524	$5,479	$6,728	$7,216
	E-s-4-5	$89,600	$92,960	$95,760	$98,560	$7,168	$11,155	$13,406	$15,770
	E-c-4-6	$31,581	$34,848	$37,571	$40,293	$2,211	$3,833	$5,260	$5,641
	E-s-4-7	$127,200	$131,970	$135,945	$139,920	$14,431	$20,921	$25,801	$28,414
	E-c-4-8	$52,983	$58,464	$63,032	$67,599	$9,193	$14,708	$17,671	$19,566
	PB-s-4-7	$107,800	$111,475	$114,538	$117,600	$9,702	$14,492	$18,326	$19,992
	PB-p-4-8	$60,726	$67,008	$72,243	$77,478	$1,822	$2,680	$3,612	$4,649
2% annual chance surge risk	P-s-2-9	$35,904	$37,128	$38,352	$39,168	$8,258	$12,252	$15,724	$16,842
	P-c-2-10	$15,312	$16,896	$18,480	$19,536	$3,522	$6,589	$7,762	$8,205
	E-s-2-9	$83,040	$86,154	$88,749	$91,344	$4,982	$7,754	$9,762	$10,961
	E-c-2-10	$30,189	$33,312	$35,915	$38,517	$1,509	$2,665	$3,232	$3,081
	PB-s-2-9	$167,112	$172,809	$177,557	$182,304	$5,013	$10,369	$12,429	$12,761
	PB-p-2-10*	$62,930	$69,440	$74,865	$80,290	$18,879	$26,387	$34,438	$37,736
1% annual chance surge risk	P-s-1-11	$40,320	$41,832	$43,344	$44,352	$2,016	$3,347	$4,334	$6,653
	P-c-1-12	$26,448	$29,184	$31,920	$33,744	$1,587	$2,627	$4,150	$6,074
	E-s-1-11	$81,280	$84,328	$86,868	$89,408	$2,438	$4,216	$4,343	$5,364
	E-c-1-12	$29,725	$32,800	$35,363	$37,925	$595	$656	$1,415	$1,896
	PB-p-1-11*	$135,633	$149,664	$161,357	$173,049	$25,770	$44,899	$53,248	$60,567
0.2% annual	P-s-02-13	$160,080	$166,083	$172,086	$176,088	$1,601	$3,322	$5,163	$5,283
	P-c-02-14	$73,225	$80,800	$88,375	$93,425	$1,465	$2,424	$3,535	$3,737

	Home number	costs to elevate 2'	costs to elevate 4'	costs to elevate 6'	costs to elevate 8'	benefits 2'	benefits 4'	benefits 6'	benefits 8'
chance surge	E-s-02-13	$80,000	$83,000	$85,500	$88,000	$800	$1,660	$1,710	$1,760
	E-c-02-14	$60,000	$63,000	$65,500	$68,000	$600	$1,260	$1,965	$2,040

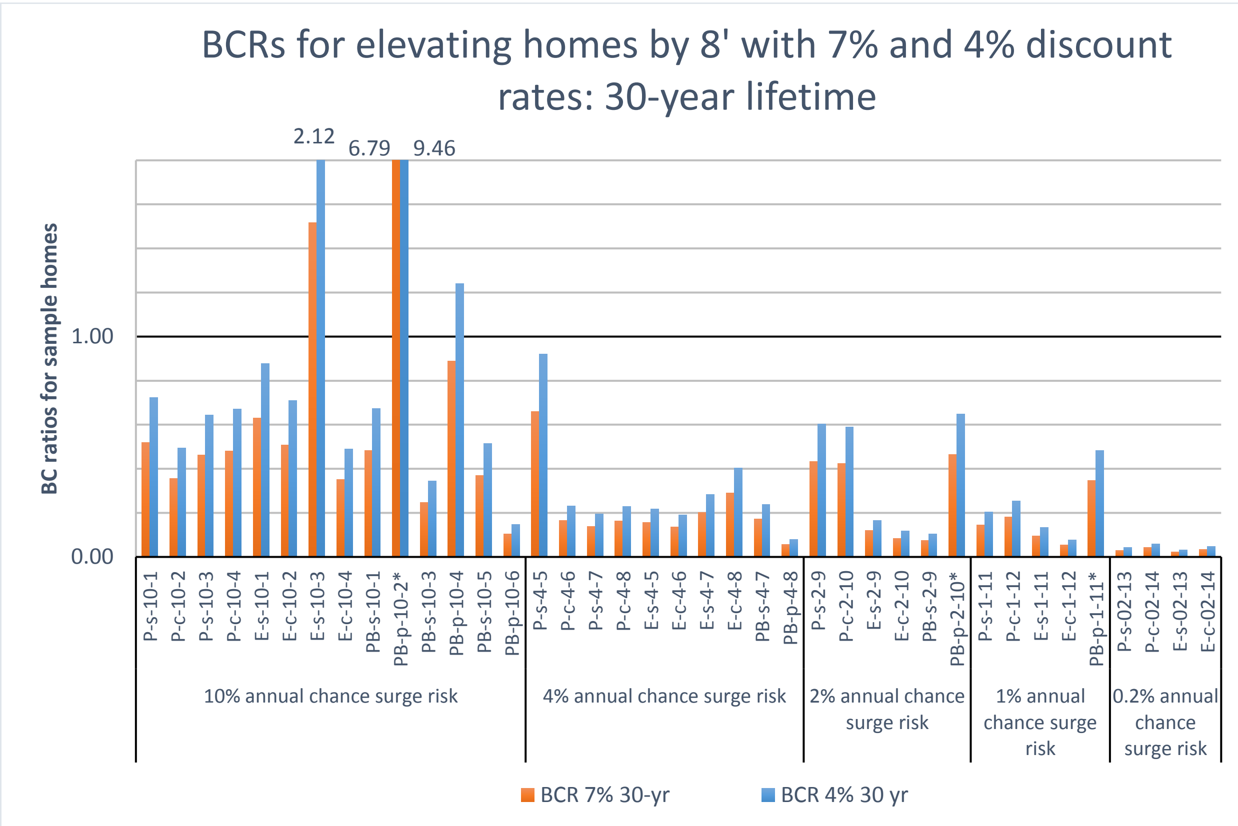


Figure 6. Benefit-cost (BC) ratios for elevating sample homes by 8' according to the USACE generic depth-damage function for A zone homes or the Expert Panel depth-damage functions for V zone homes. The V zone homes have an asterisk immediately after their unique identifier, and all homes are labeled underneath the horizontal axis. Bars symbolizing BC ratios that are over 1.8 are labeled with their value at the top of the bar.

Figure 7 shows that three of our sample homes are economically attractive to elevate by 8' using a 50 year lifetime and 7% discount rate, but five are economically attractive to elevate with a 4% discount rate. Consequently, increasing the useful lifetime, i.e., the time horizon over which benefits are assessed, from 30 to 50 years leads to two more homes being economically attractive to elevate when the discount rate is 4%. With the 7% discount rate, E-s-10-3 and PB-p-10-2 are economically attractive to elevate by 8', and home PB-p-10-4 has a BCR of 0.99 when the useful life is either 30 or 50 years. With 50 year lifetime and 4% discount rate, home P-s-4-5 is economically attractive to elevate although it is in the 4% annual chance surge zone.

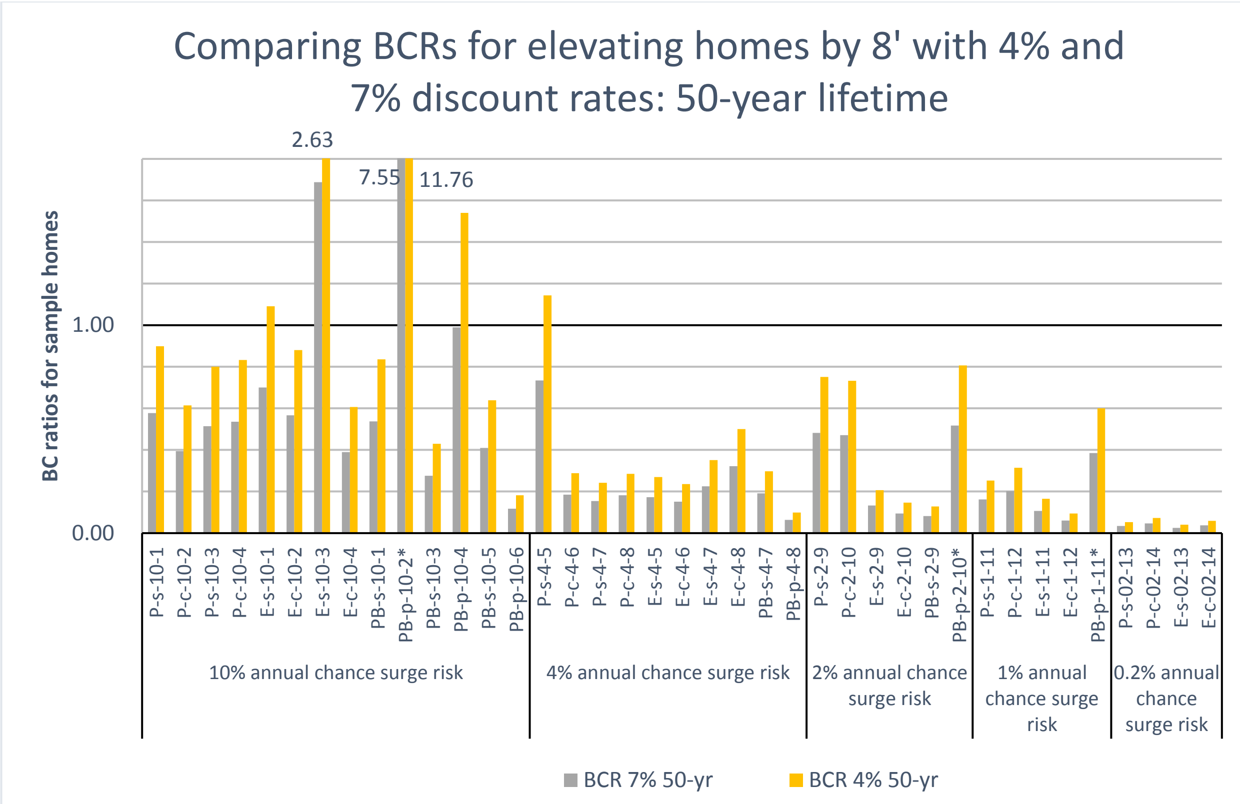


Figure 7. Benefit-cost (BC) ratios for elevating sample homes by 8' according to the USACE generic depth-damage function for A zone homes or the Expert Panel depth-damage functions for V zone homes. The V zone homes have an asterisk immediately after their unique identifier, and all homes are labeled underneath the horizontal axis. Bars symbolizing BC ratios that are over 1.8 are labeled with their value at the top of the bar.

Figure 8 shows that when the useful lifetime is 80 years and discount rate is 4%, six homes are economically attractive to elevate by 8'. With a 7% discount rate and 80-year lifetime, three homes are economically attractive to elevate by 8' (homes E-s-10-3, PB-p-10-2, and PB-p-10-4).

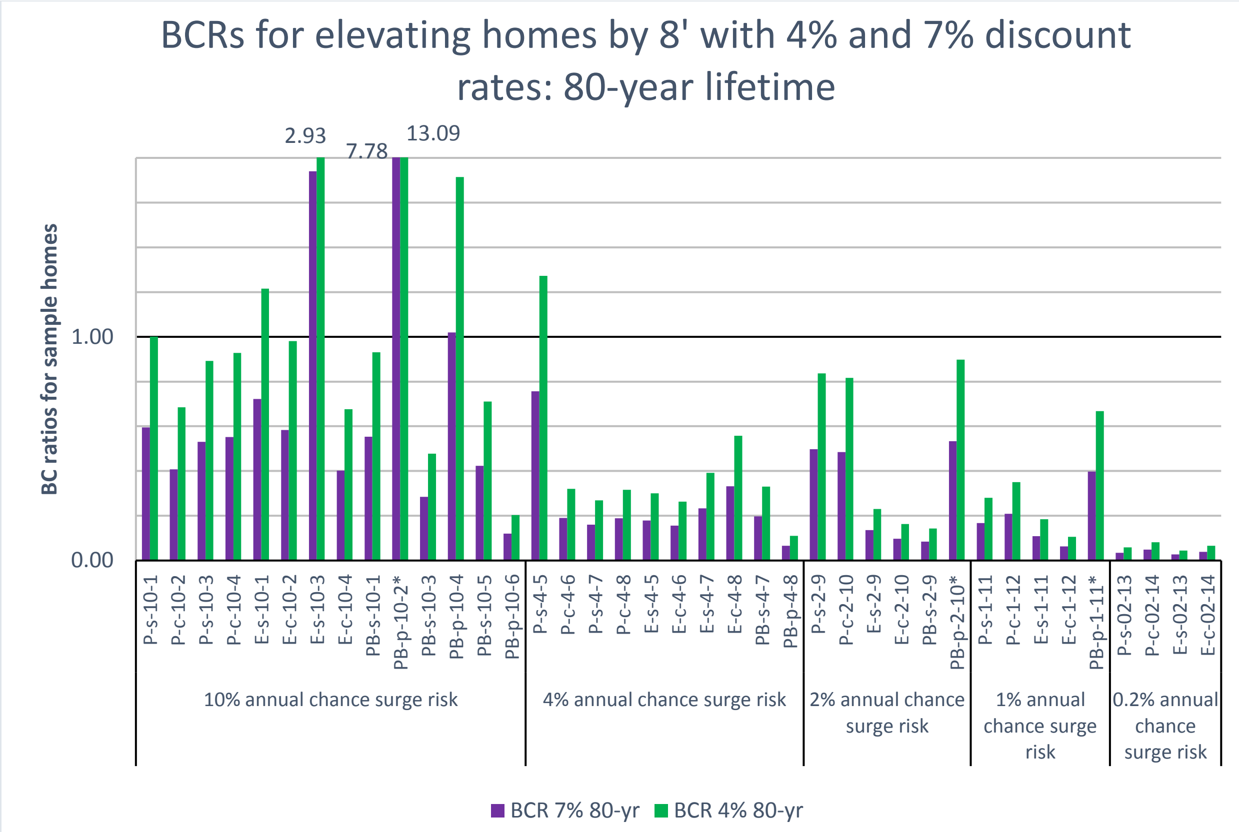


Figure 8. Benefit-cost (BC) ratios for elevating sample homes by 8' according to the USACE generic depth-damage function for A zone homes or the Expert Panel depth-damage functions for V zone homes. The V zone homes have an asterisk immediately after their unique identifier, and all homes are labeled underneath the horizontal axis. Bars symbolizing BC ratios that are over 1.8 are labeled with their value at the top of the bar.

In Figure 9, we show BCRs for sample homes based on 100-year lifetimes and 4% and 7% discount rate. One hundred years is the longest allowable lifetime according to FEMA guidance for the BCA Toolkit (specifically, Appendix C of the June 2009 BCA Reference Guide). It is economically effective to elevate seven homes by 8' with 4% discount rate and 100-year lifetime. It is economically effective to elevate three homes by 8' with 100-year lifetime and 7% discount rate, thus changing the lifetime from 80 to 100 years does not increase the number of homes that it is economically attractive to elevate.

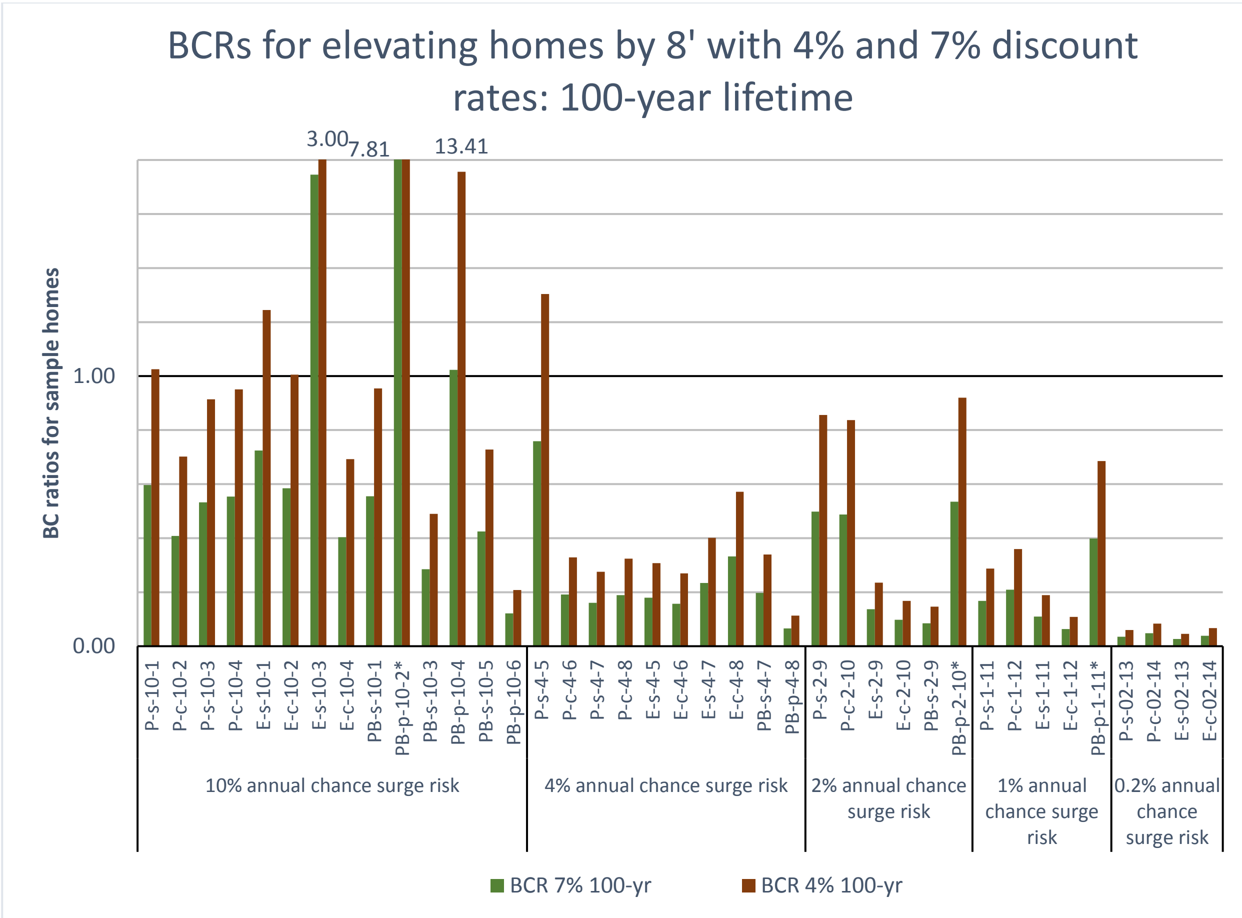


Figure 9. Benefit-cost (BC) ratios for elevating sample homes by 8' according to the USACE generic depth-damage function for A zone homes or the Expert Panel depth-damage functions for V zone homes. The V zone homes have an asterisk immediately after their unique identifier, and all homes are labeled underneath the horizontal axis. Bars symbolizing BC ratios that are over 1.8 are labeled with their value at the top of the bar.

In Figure 10, we present BCRs for elevating sample homes by 8' if we use 100%, 75%, 50%, and 25% of the costs of elevation. We used incremental percentages of the costs in a sensitivity analysis to assess the "break-even" point: i.e., the point at which BCRs are at least 1 and mitigation is economically effective. We use the standard FEMA values of 30 years for elevation lifetime and 7% discount rate when we varied the costs in Figure 9. We omitted home PB-p-10-2 since it has a BCR well above one with 100% of costs to elevate by 8' and 30-year lifetime and 7% discount rate.

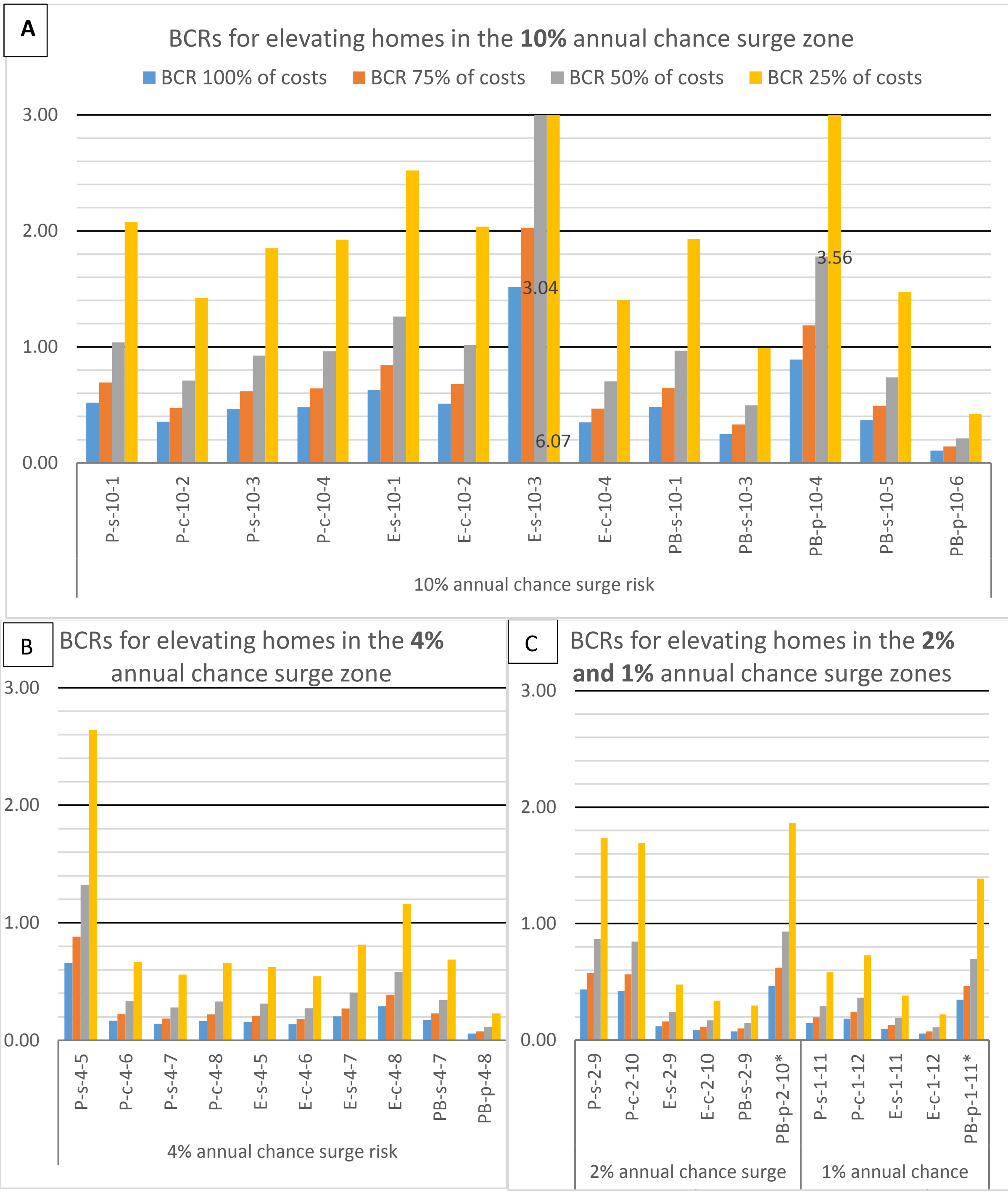


Figure 10. Benefit-cost (BC) ratios for elevating sample homes in the (A) 10% annual chance surge zones, (B) 4% annual chance surge zones, and (C) 2%, and 1% annual chance surge zones by 8’, with 100%, 75%, 50%, and 25% of total elevation project costs. Project useful life is 30 years and discount rate is 7%. We omit results for homes in the 0.2% annual chance surge zone because the highest BCR for these four homes is 0.17 when costs are only 25% of total costs to elevate by 8’. Results are based on the USACE generic depth-damage function for A zone homes or the Expert Panel depth-damage functions for V zone homes (V zone homes are indicated with an

asterisk after their unique identifier as labeled underneath the horizontal axis). Bars that represent BCRs exceeding 3 are labeled with their value in the center or bottom of the bar.

In the sensitivity analyses results shown in Figure 10, using only 25% of elevation costs causes almost all sample homes in the 10% annual chance surge zone to be economically attractive to elevate by 8'. The BCR for home PB-s-10-3 for 25% of costs is 0.99, which is practically economically effective to elevate. The only home that is not economically effective to elevate by 9' in the 10% annual chance surge zone is home PB-p-10-6: 25% of elevation costs makes the BCR for this home only 0.42. This is because the FFE for home PB-p-10-6 is very high at 16.79', and this FFE is from an elevation certificate so it is accurate and not based on assumptions. Home PB-p-10-6 was built on pilings in 2011, and according to the 2006 effective DFIRM this home is in an AE zone with a static BFE of 9 feet. The Escambia County Land Development Code dictates that new homes must have a freeboard of 3 feet[22] thus this home would have had a minimum required FFE of 12 feet.

3.2 Demolishing and acquiring homes

Of the three mitigation activities we examined, demolition and acquisition is generally least economically attractive. Our cost estimate methodology for the demolition and acquisition projects are informed by guidance from Charlotte-Mecklenburg Storm Water Services Department, but our home and land values are based on 2015 parcel data for Escambia County. It is very difficult to know how FEMA, and local and State governments actually negotiate amounts and cost-sharing proportions to offer homeowners for buyouts. We downloaded open data from FEMA[23] from a webpage entitled "OpenFEMA Dataset: Hazard Mitigation Assistance Mitigated Properties - V1" but it did not provide any data on actual amounts paid to homeowners in Escambia County for acquired homes. Perhaps the actual amounts paid are sensitive data and thus not provided to the public.

In Table 5 we show sample homes by surge risk zone, with the annualized losses before acquisition, and the total estimated costs of demolition and acquisition. In Figure 11 we present BCRs for all of our sample homes with the FEMA standard values of 100 year lifetimes and 7% and 4% discount rates. Only one home has a BCR over 1: PB-p-10-2, a home on pilings with a very low FFE of 4.98' in a VE zone. This FFE of 4.98' is based on elevation certificate data and is thus accurate. Since this home was built in 2005 prior to the 2006 DFIRM, it was built to the standards of the previous effective DFIRM which is why it has such a low FFE. However, the estimated cost to demolish and acquire this home is $575,559, which is a relatively high cost for our sample homes. Furthermore, it is economically attractive to acquire home PB-p-10-2 because it is at risk to VE zone flood hazards, thus the Expert Panel depth-damage function was used in the Toolkit.

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[22] The most recent version of the Escambia County Land Development Code is located online at https://myescambia.com/docs/default-source/sharepoint-developmental-services/land-development-code.pdf. On page LDC 4: 8, the Code includes this text: "Other duties of the Floodplain Administrator. The Floodplain Administrator shall have other duties, including but not limited to: (1) In coordination with the Building Official review all permits for construction within the Special Flood Hazard Areas to ensure that the proposed project meets the freeboard requirements. In Escambia County the freeboard requirement is 3 feet above the designated FEMA Base Flood Elevation."

[23] https://www.fema.gov/openfema-dataset-hazard-mitigation-assistance-mitigated-properties-v1

Table 5 Annual benefits of demolishing and acquiring homes, and total estimated costs of demolition/ acquisition project. Homes are listed and grouped by descending annual chance surge risk zone.

	Home number	Annual benefits	Total cost of acquisition projects
10% annual chance surge risk	P-s-10-1	$2,829	$578,846
	P-c-10-2	$1,829	$159,217
	P-s-10-3	$5,638	$196,805
	P-c-10-4	$2,131	$180,651
	E-s-10-1	$6,277	$433,719
	E-c-10-2	$2,274	$266,539
	E-s-10-3	$13,424	$225,811
	E-c-10-4	$2,083	$211,340
	PB-s-10-1	$6,557	$184,480
	PB-p-10-2*	$61,795	$575,559
	PB-s-10-3	$5,408	$318,121
	PB-p-10-4	$6,692	$456,119
	PB-s-10-5	$11,980	$630,346
	PB-p-10-6	$694	$285,161
4% annual chance surge risk	P-s-4-5	$7,506	$492,894
	P-c-4-6	$2,608	$756,932
	P-s-4-7	$1,334	$100,618
	P-c-4-8	$879	$107,207
	E-s-4-5	$1,650	$163,836
	E-c-4-6	$653	$111,926
	E-s-4-7	$2,924	$227,109
	E-c-4-8	$2,134	$319,029
	PB-s-4-7	$2,062	$241,541
	PB-p-4-8	$661	$315,215
2% annual chance surge risk	P-s-2-9	$2,046	$357,250
	P-c-2-10	$1,211	$480,496
	E-s-2-9	$1,184	$137,714
	E-c-2-10	$500	$111,047
	PB-s-2-9	$1,546	$320,552
	PB-p-2-10*	$3,759	$689,210
1% annual chance surge risk	P-s-1-11	$994	$818,084
	P-c-1-12	$941	$393,086
	E-s-1-11	$569	$150,887
	E-c-1-12	$314	$127,952
	PB-p-1-11*	$6,317	$1,047,822
0.2% annual chance surge	P-s-02-13	$666	$338,412
	P-c-02-14	$481	$423,148
	E-s-02-13	$251	$131,926
	E-c-02-14	$288	$142,440

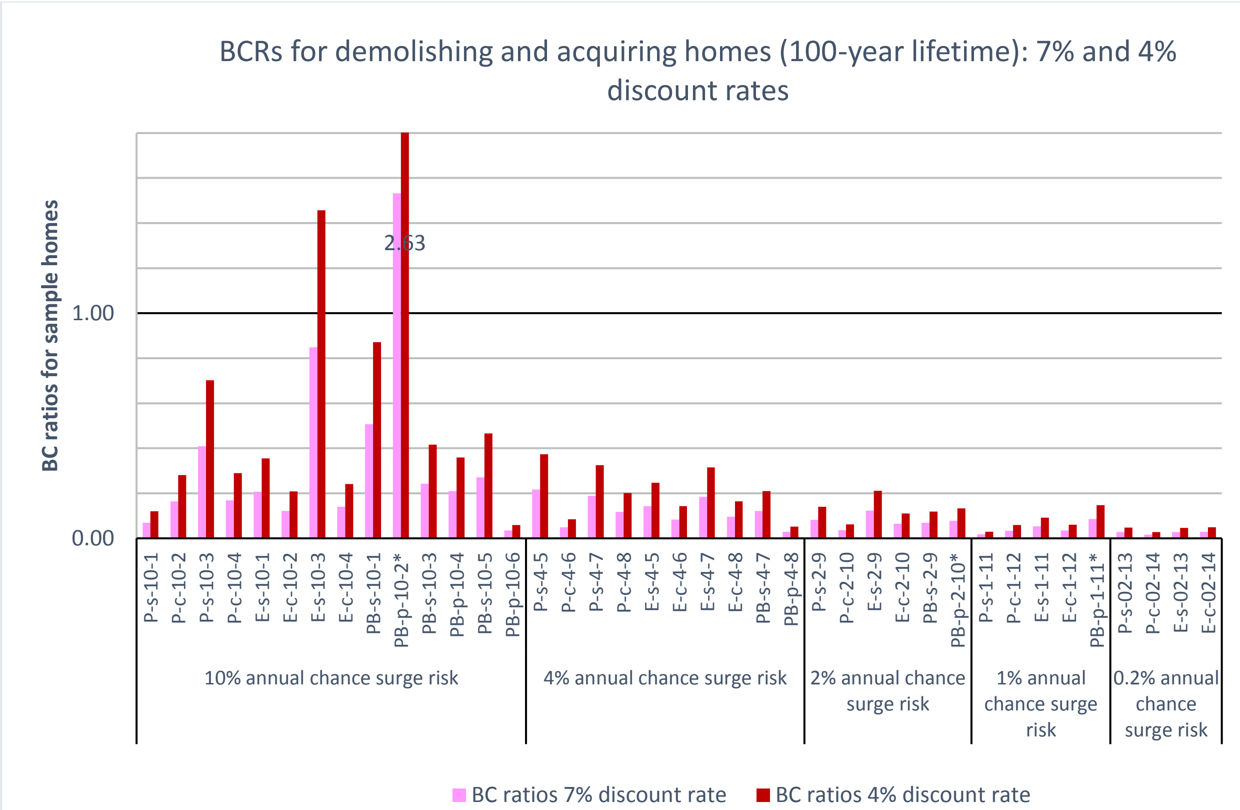

Figure 11. BC ratios for demolishing and acquiring sample homes, with lifetime of 100 years and 4% and 7% discount rates. Sample homes are grouped by the annual chance surge risk zones they coincide with, and labeled with their unique identifiers under the horizontal axis. V zone homes have an asterisk after their unique identifier. The bar that represent a BCR exceeding 1.8 is labeled with its value in the center of the bar.

When the 4% discount rate is used, home E-S-10-3 is economically effective to demolish and acquire. Home E-s-10-3 has very high benefits for mitigating it against flood hazards and it has the lowest FFE (at 3.18') of all of our sample homes. The annual benefits of demolishing and acquiring home E-s-10-3 are $13,424 (before any discounting into the future) and the total costs of acquiring this home are relatively moderate at $225,811. It is also economically effective to elevate home E-s-10-3 despite that it has a slab foundation. The costs for elevating home E-s-10-3 by 8' are $98,384, and its annual benefits of elevating 8' are $12,034 (before discounting into the future). However, judging the BCRs for elevating and acquiring home E-s-10-3 using the standard FEMA values for lifetimes and 7% discount rate, it is more economically effective to elevate this home than to demolish and acquire it. Because acquisition is so costly, it is rarely the most economically attractive mitigation option.

The third highest BCR for acquisition shown in Figure 10 is that for home PB-s-10-1, which is a slab foundation home in the 10% annual chance surge zone on Pensacola Beach. Although there are few slab foundation homes anywhere on Pensacola Beach, efforts and resources could be directed at demolishing and acquiring slab foundation homes in the 10% annual chance surge zones. Given the history of catastrophic hurricanes affecting the Pensacola area, and the vulnerability of Pensacola Beach to surge hazards, it may be prudent to mitigate slab homes on Pensacola Beach with demolition and acquisition.

In Figure 12, we present BCRs of demolition and acquisition projects for sample homes in the 10% and 4% annual chance surge zones based on 100%, 75%, 50, and 25% of costs. When costs are reduced to 25%, five sample homes have BCRs over or near 1. Four of these five homes have slab foundations, and the piling foundation home PB-p-10-2 is economically attractive to demolish and acquire because it is within a VE flood zone. These five homes have a maximum FFE of 5.89'; not 1 foot over the surge height for the 10% annual chance event of 4.91'. The maximum building value of these four Pensacola Beach homes is $252,260 (home PB-p-10-2 which is in a VE zone). A home value of $252,260 for a Pensacola Beach home is fairly low given the high amenity value of any dwelling on this barrier island, although it is slightly higher than our average building value of $213,419 for our Pensacola Beach sample homes.

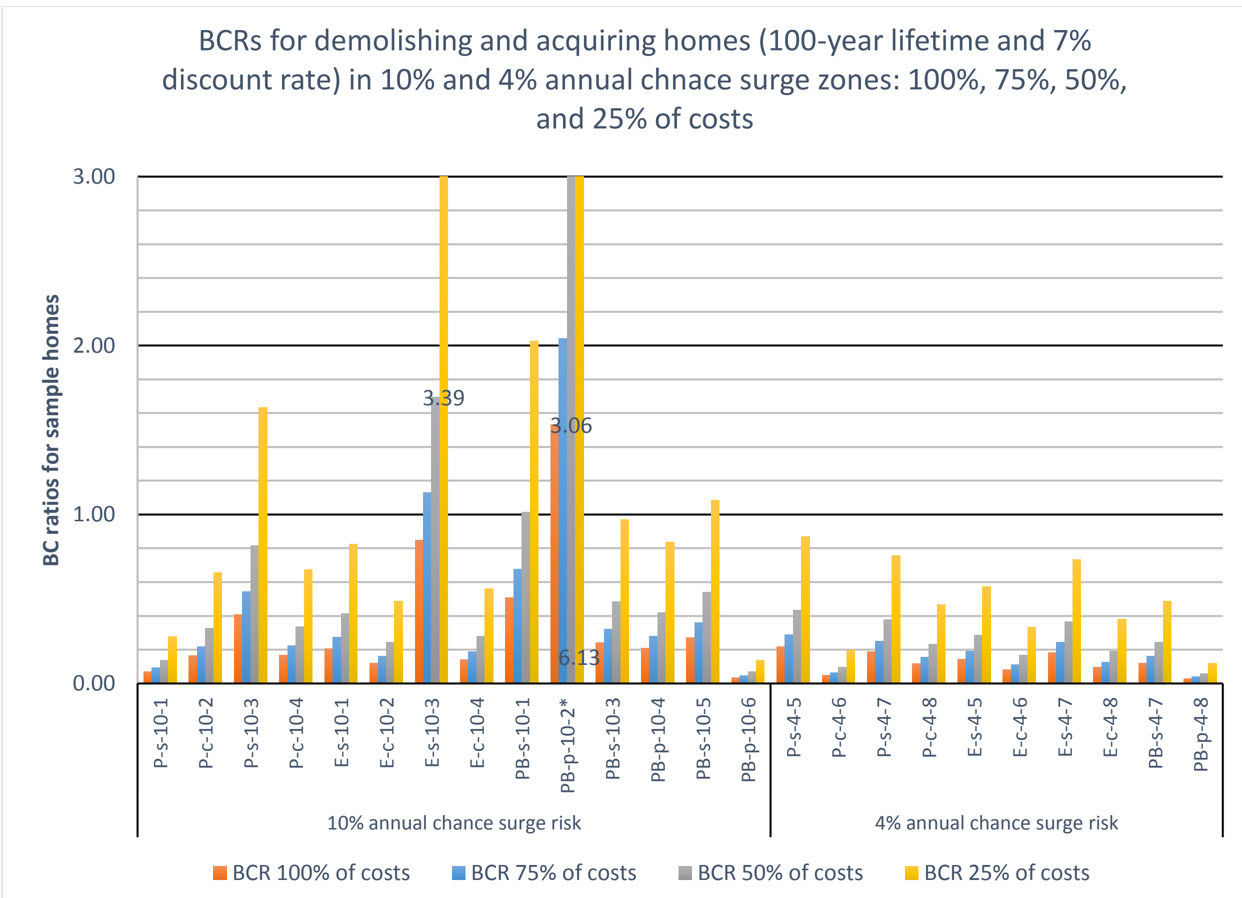

Figure 12. Benefit-cost (BC) ratios for demolishing and acquiring sample homes in the 10% and 4% annual chance surge zones, with 100%, 75%, 50%, and 25% of total project costs. Project useful lifetime is 100 years and discount rate is 7%. We omit results for homes in the 2%, 1%, and 0.2% annual chance surge zones because the BCRs for these homes are very low (even with only 25% of project costs). Results are based on the USACE generic depth-damage function for A zone homes or the Expert Panel depth-damage functions for V zone homes (V zone homes are indicated with an asterisk after their unique identifier as labeled underneath the horizontal axis). Bars that represent BCRs exceeding 3 are labeled with their value in the center or bottom of the bar.

3.3 Building floodwalls

We examined the economic effectiveness of building 2’ and 4’ high floodwalls around our Pensacola and Escambia County sample of homes to mitigate flood hazards. We did not consider floodwalls around Pensacola Beach homes because the Escambia County Land Development Code prohibits the construction of hard barriers on this barrier island community due to regulations that treat all of Pensacola Beach as a high hazard coastal area[24].

We assumed the FFEs of crawlspace/pier homes in Pensacola and Escambia County are three feet above ground level since we do not have an EC for any of those homes. Building a 2’ high floodwall around a home with FFE 3’ above the ground would be illogical. Further, building a 4’ high floodwall around our sample of crawlspace foundation homes in Pensacola and Escambia County was consistently very economically ineffective; therefore in Figure 12 we present results of BCAs for building floodwalls only around our slab foundation homes.

Figure 13 shows BCRs for building 2’ and 4’ high floodwalls around sample homes with slab foundations in Pensacola and Escambia County to mitigate flood hazards. The FEMA standard useful lifetime of 50 years for floodwalls was used in BCAs, as well as the standard 7% discount rate.

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[24] From the most recent version of the Escambia County Land Development Code, located online at https://myescambia.com/docs/default-source/sharepoint-developmental-services/land-development-code.pdf; on page LDC 4: 46 it states: “(b) Standards for buildings and structures within the jurisdiction of the SRIA. (1) Buildings and structures shall be designed and constructed to comply with the more restrictive applicable requirements of the Florida Building Code, Building Section 3109 and Section 1612 or Florida Building Code, Residential Section R322, applicable to coastal high hazard areas.”

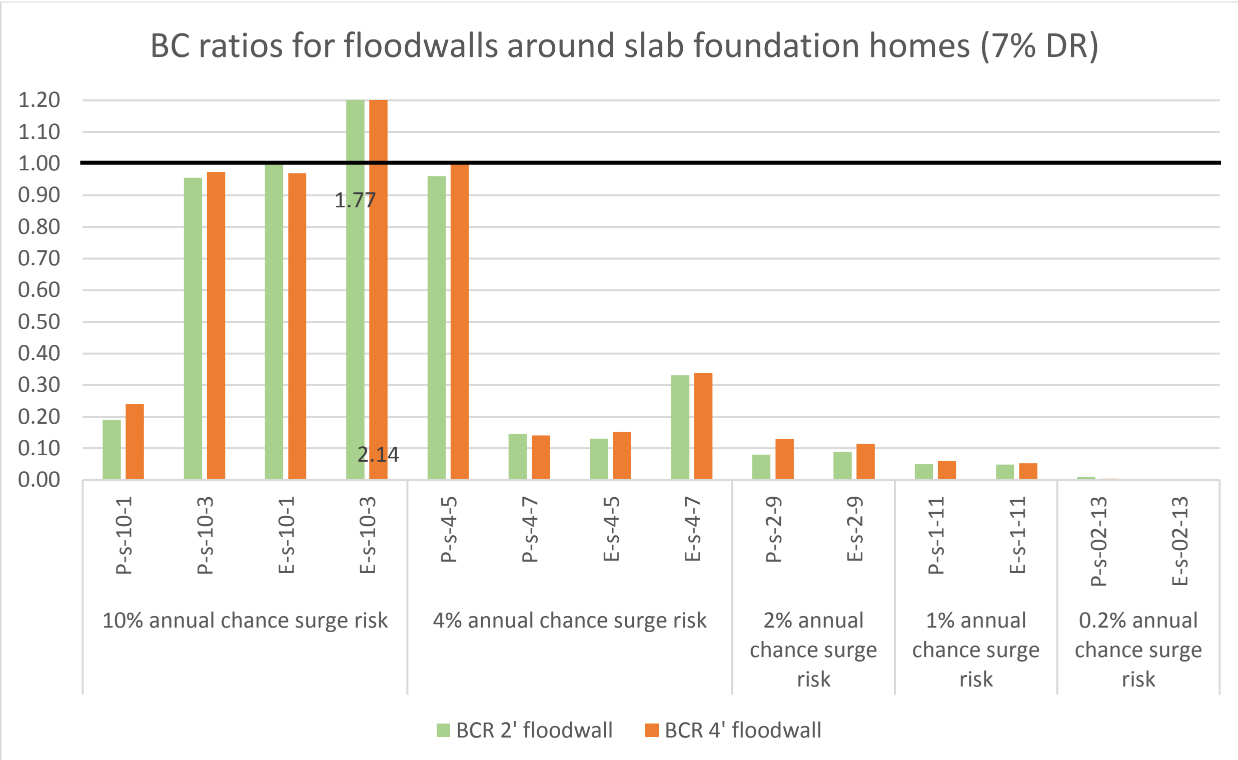

Figure 13. BC ratios for building 2’ and 4’ high floodwalls for slab foundation sample homes in Pensacola and Escambia County. Discount rate for BCA is 7% and project lifetime is 50 years. Bars that represent BCRs exceeding 1.20 are labeled with their value on the bar, in the center or bottom of the bar.

Figure 13 indicates that it is economically effective, or nearly economically effective, to build floodwalls around four slab foundation homes. While elevation is often economically effective the higher that homes are elevated, in one case for home E-s-10-1, the lower floodwall of 2’ high is slightly more economically effective than a 4’ floodwall. The costs and annual benefits of a 2’ floodwall for home E-s-10-1 are $38,193 and $2,775 respectively; while the costs and annual benefits of a 4’ floodwall are $52,341 and $3,676. Nevertheless, the economic effectiveness of 2’ and 4’ high floodwalls are generally similar.

In Figure 14, we examine BCRs for building 4’ floodwalls around all Pensacola and Escambia County sample homes, with both slab and crawlspace/pier foundations, but we show BCRs with both 4% and 7% discount rates and the standard useful life of 50 years. With the lower discount rate of 4%, it is economically attractive to build 4’ high floodwalls around four slab foundations homes, one of which is in the 4% annual chance surge zone. The home P-c-10-4 has the smallest perimeter of our sample homes that are in the 4% annual chance surge zone and have slab foundations. The costs of building floodwalls are primarily dependent on the perimeter of the home around which the wall will be built. We used the perimeters of the homes’ building footprints to estimate costs of floodwalls, recognizing that floodwalls are not built immediately adjacent to homes but have space between the floodwall and the home. Therefore, the costs of our floodwalls herein are probably underestimated. Nevertheless, the relative economic effectiveness of building floodwalls around our sample homes can be assessed with our methodology.

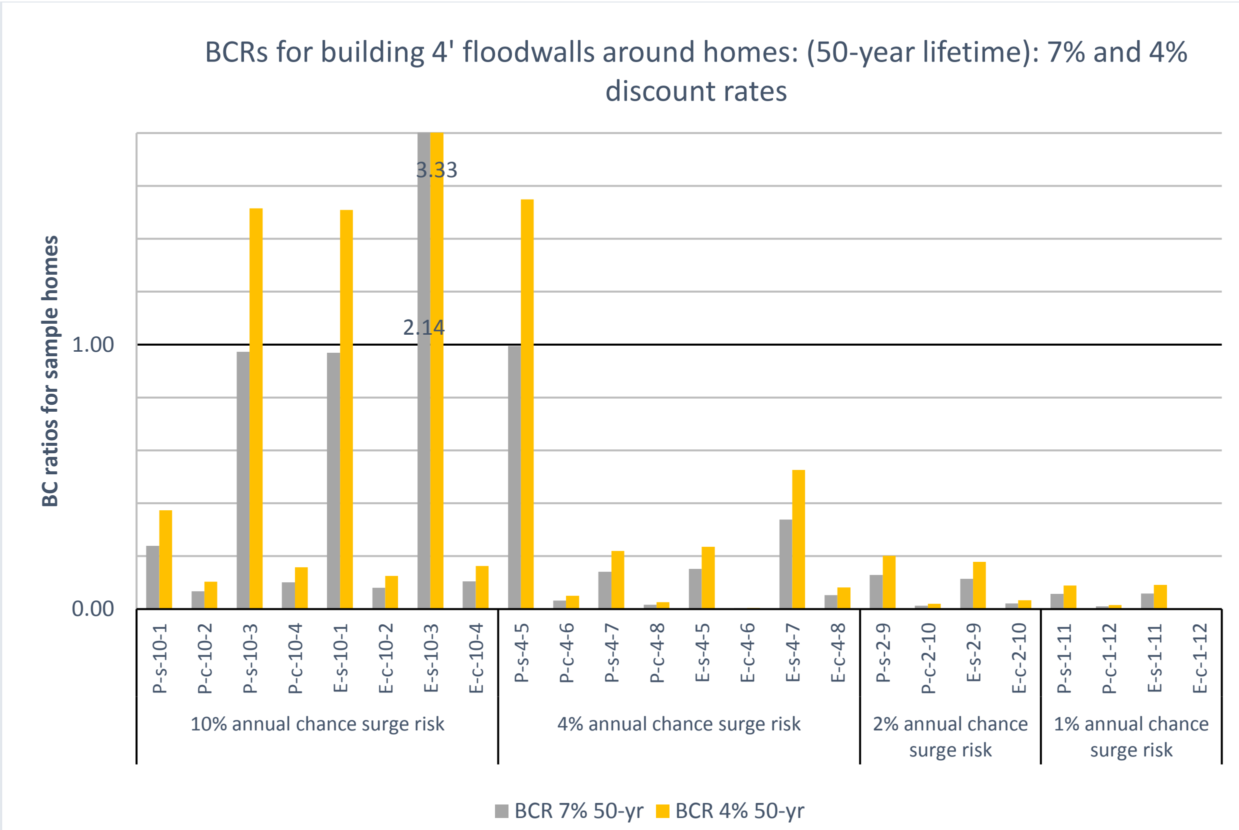

Figure 14. Benefit-cost (BC) ratios for building 4’ floodwalls around sample homes in Pensacola and unincorporated Escambia County using a 50-year project lifetime and 4% and 7% discount rates for BCA. BCRs are based on the USACE generic depth-damage function. Sample homes are grouped by the annual chance surge zone they coincide with, and are labeled with their unique identifiers under the horizontal axis. We omit results for homes in the 0.2% annual chance surge zone because the BCRs for these four homes are zero. The gray bars are the BC ratios based on a discount rate of 7%, and the yellow bars are BCRs based 4% discount rates. Bars that represent BCRs exceeding 1.8 are labeled with their value in the center or top of the bar.

Similar to how we increased useful lifetimes of elevation projects to 50, 80, and 100 years, we also increase project useful lifetime for floodwalls from 50 to 80 years, and 100 years. We do not look at 30-year useful lifetimes for floodwalls because the FEMA standard useful lifetime for a floodwall is 50 years. In Figures 15 and 16, we show BCRs for building 4’ floodwalls around slab homes in Pensacola and Escambia County with 4% and 7% discount rates, but Figure 15 shows BCRs with 80-year lifetimes and Figure 16 shows BCRs with 100-year lifetimes. Varying discount rates and useful lifetimes for floodwalls around crawlspace foundation homes does not cause any of these crawlspace home to be economically attractive candidates for 4’ high floodwalls. The maximum number of homes for which it is economically effective to build 4’ floodwalls to mitigate surge hazards is five homes, which is applicable when the 4% discount rate is used and any lifetime we examined.

Comparing the economic effectiveness of elevating and building floodwalls around slab foundation homes shows that in some cases, one mitigation activity is more economically effective than the other. For example, it is more economically effective to build a 4’ high floodwall around homes P-s-10-3, E-s-10-1, and P-s-4-5 than it is to elevate them by 8’, when examining BCRs with the same useful lifetimes of 50-years for elevation and floodwalls and same discount rates (of either 4% or 7% for both elevation and floodwalls).

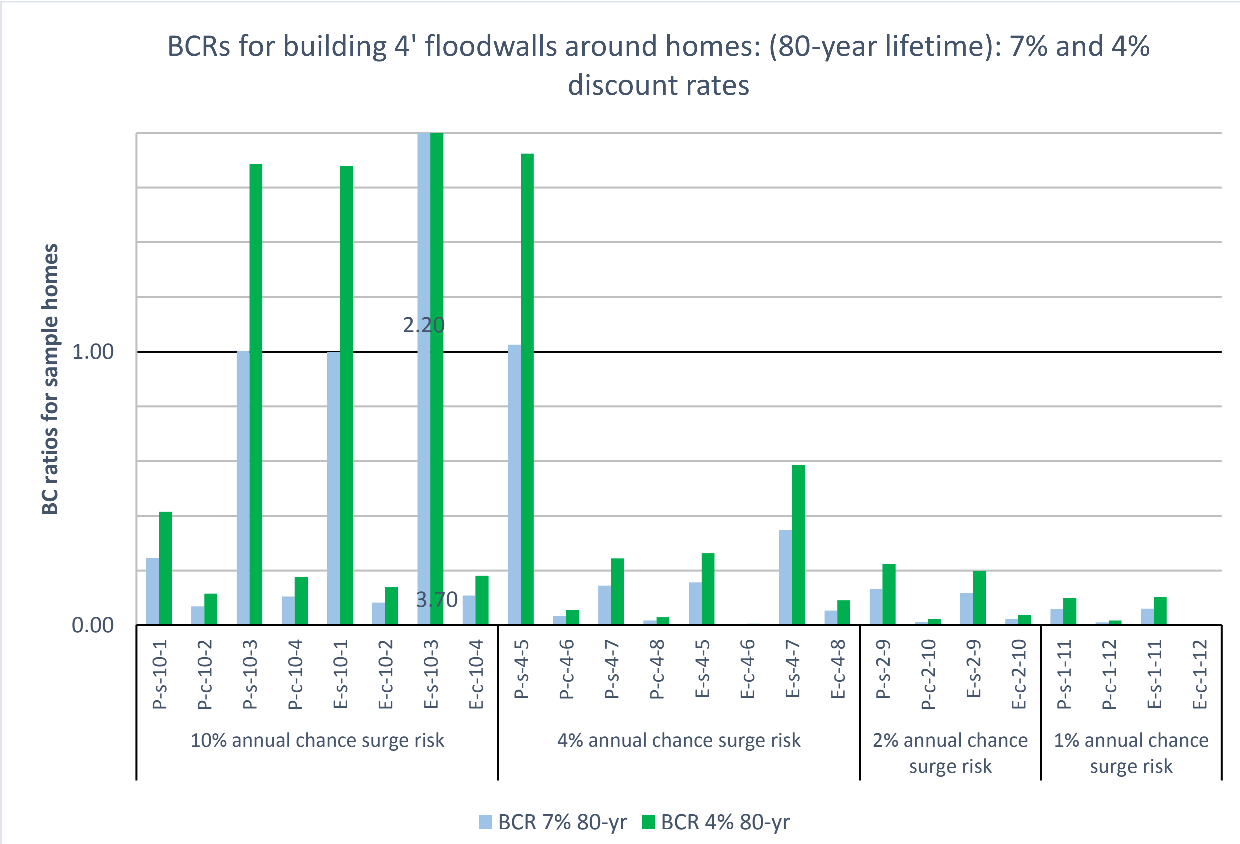

Figure 15. Benefit-cost (BC) ratios for building 4’ floodwalls around sample homes in Pensacola and unincorporated Escambia County using an 80-year project lifetime and 4% and 7% discount rates for BCA. BCRs are based on the USACE generic depth-damage function. Sample homes are grouped by the annual chance surge zone they coincide with, and are labeled with their unique identifiers under the horizontal axis. We omit results for homes in the 0.2% annual chance surge zone because the BCRs for these four homes are zero or 0.01. The blue bars are the BC ratios based on a discount rate of 7%, and the green bars are the BCRs based on 4% discount rates. Bars that represent BCRs exceeding 1.8 are labeled with their value in the center or bottom of the bar.

In Figure 17, we examine BCRs for building 4’ high floodwalls when the costs are 100%, 75%, 50%, and 25% of total costs. The results do not change substantially because BCRs indicating economic effectiveness for building floodwalls are either near 1 with 100% of costs, or are so low that even 25% of costs do not make BCRs near 1. Only home E-s-4-7 that has a BCR of 0.34 for 100% of costs for a 4’ floodwall with 50-year lifetime and 4% discount rate becomes economically effective to build a floodwall around it when costs are between 50% and 25% of total floodwall costs. Home P-s-4-5 is an economically effective candidate for floodwalls despite that it is in the 4% annual chance surge zone because it has a very high building value per unit area, at $185.22 per square foot; and a low FFE of 7.97'.

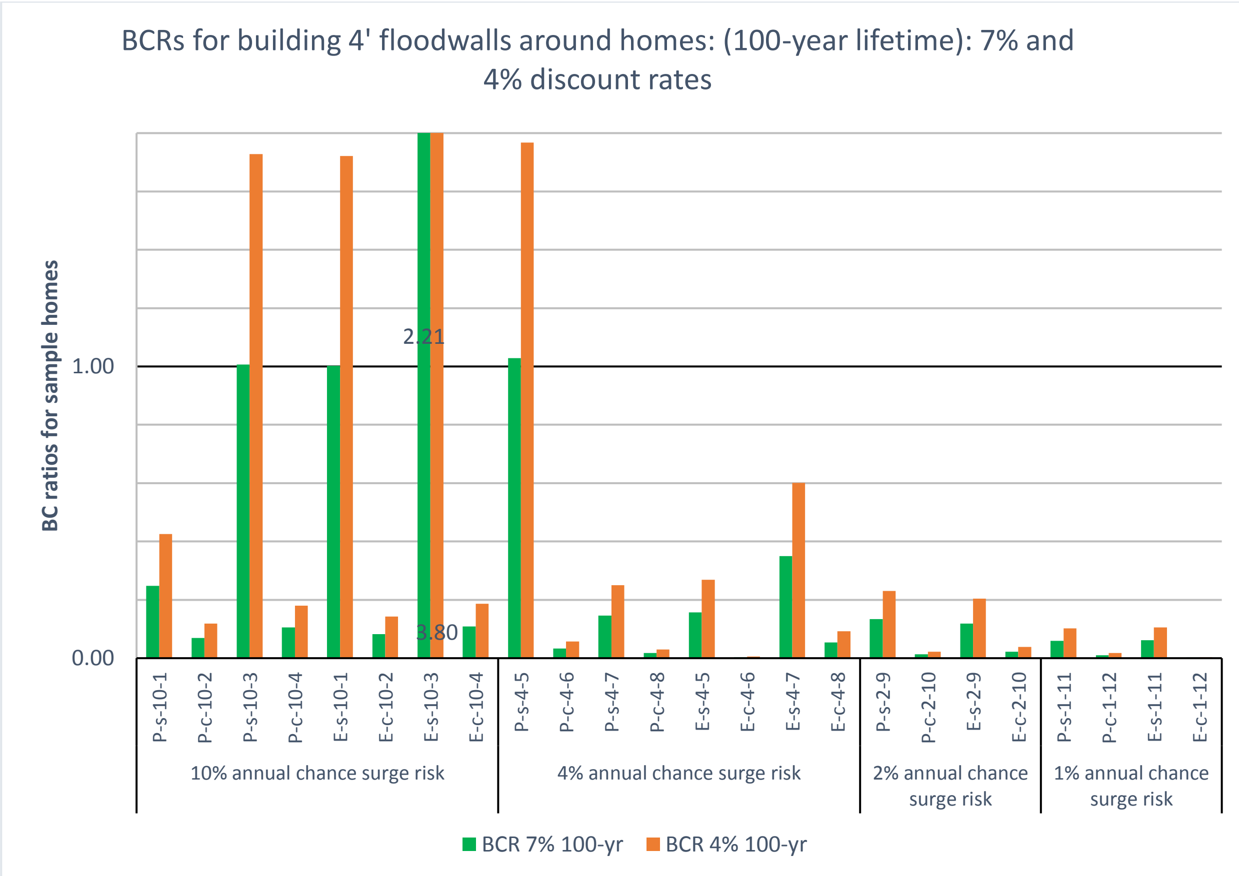

Figure 16. Benefit-cost (BC) ratios for building 4' floodwalls around sample homes in Pensacola and unincorporated Escambia County using a 100-year project lifetime and 4% and 7% discount rates for BCA. BCRs are based on the USACE generic depth-damage function. Sample homes are grouped by the annual chance surge zone they coincide with, and are labeled with their unique identifiers under the horizontal axis. We omit results for homes in the 0.2% annual chance surge zone because the BCRs for these four homes are zero or 0.01. Bars that represent BCRs exceeding 1.8 are labeled with their value in the center or bottom of the bar.

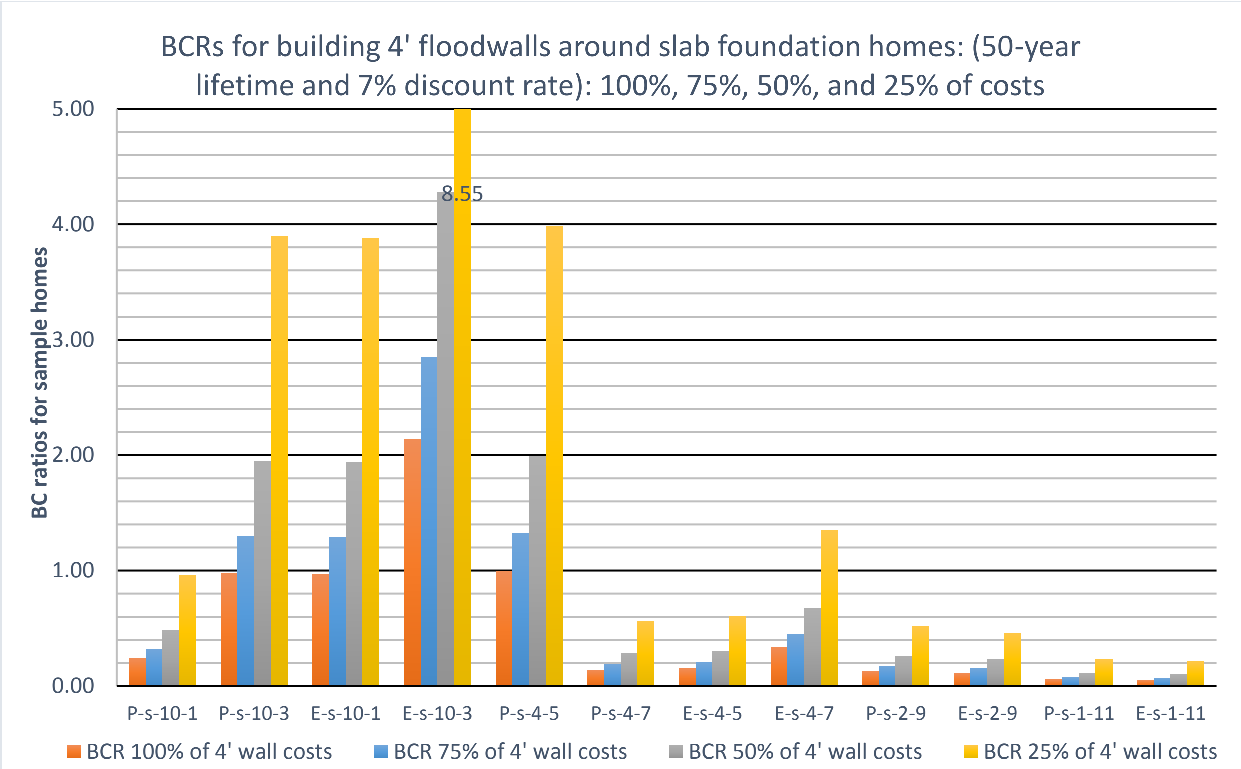

Figure 17. Benefit-cost (BC) ratios for building 4' floodwalls around sample homes with slab foundations in the 10%, 4%, 2%, and 1% annual chance surge zones, with 100%, 75%, 50%, and 25% of total project costs. We omit results for homes in the 0.2% annual chance surge zone because the highest BCR for these four homes is 0.02, even with only 25% of project costs. The bar that represents a BCR exceeding 5.0 is labeled with its value toward the top of the bar.

3.4 Summary of results of benefit-cost analyses using the FEMA BCA Toolkit

We have implemented several benefit-cost analyses (BCAs) with the FEMA BCA Toolkit to assess the economic effectiveness of elevating homes, demolishing and acquiring homes, and building floodwalls around homes to mitigate surge risks. Once we obtained the annual benefits from each mitigation project for each sample home from the Toolkit, we tested how different discount rates, project lifetimes, and percentages of projects costs impact results of BCAs using Microsoft Excel.

We observe that it is only economically effective to mitigate homes with any of the three methods we assessed in the 10% and 4% annual chance surge zones. Using the lower discount rate of 4% instead of 7% in BCAs has a greater impact on the results than varying the project useful lifetimes. Of the three mitigation actions we examined, elevating homes by 8' is the most effective method for the greatest number of our sample homes; and elevation is especially economically effective when using the 4% discount rate. Building flood walls around slab foundation homes can be economically attractive if homes are in the 10% and 4% annual chance surge zones. Demolition and acquisition is the least economically attractive mitigation option that we examined because it is much more costly than elevation or flood walls.

We used the USACE generic depth-damage function rather than the FEMA FIA function for A and X zone homes, and the Expert Panel functions instead of the FEMA FIA functions for V zone homes. This is because the FEMA FIA function dramatically underweights damages from floods when compared to the USACE generic and Expert Panel functions. If we had used the FEMA FIA function, our results would show much less economic effectiveness for all our sample homes and mitigation projects.

3.5 Advantages and Limitations of the BCA Toolkit Approach

There are several advantages associated with using the BCA Toolkit. Probably the most important strength is that the methodology is created by FEMA with the purpose to analyze mitigation options for grant applications. Therefore, with adequate documentation of project costs, the Toolkit should generate results of BCAs that meet FEMA's requirements for grant applications.

Annualized losses are automatically calculated for structures based on user inputs of flood hazard data, structure information, and depth-damage functions. Users can also aggregate several structures, with different mitigation actions, into one project and obtain an aggregate (project-level) BCR to submit as part of a FEMA grant application. Additionally, analyses of community- or neighborhood-level projects can be conducted, such as building a storm water improvement project that would benefit several properties.

The FEMA BCA Toolkit also has several limitations. Importing tables of structures with Excel or text files is sometimes problematic as the software will produce several warning messages and become inoperable. However, the reasons why Excel or text files of imported data sometimes cause the software problems are unknown. Because data for every mitigation project must be hand entered for almost every individual field of the form, working with the Toolkit can be prone to data-entry errors.

It is also impossible to export depth-damage functions from the Toolkit, therefore we are not able to see whether damages attributable from flood depths in homes from the USACE generic and FEMA FIA functions in the Toolkit are the same as the USACE IWR and FEMA FIA functions from Hazus. The depth-damage functions that come with the Hazus software can be exported as text files using R packages. We also cannot know exactly how the Toolkit estimates expected annual losses (AALs) based on annual chance events and corresponding flood depths inside homes. For example, Hazus estimates AALs with the following equation from the Hazus Technical Manual (version 2.1, page 14-38):

$$AAL = [(f_{10} - f_{25}) * ((L_{10} + L_{25}) /2)] + [(f_{25} - f_{50}) * ((L_{25} + L_{50}) /2)] + [(f_{50} - f_{100}) * ((L_{50} + L_{100}) /2)] + [(f_{100} - f_{500}) * ((L_{100} + L_{500}) /2)] + (f_{500} * L_{500})$$

where $f_x = 1/x$ (frequency/probability of an x-year flood event) and L_x are the losses attributable to the x-year event (expressed as percentages of building and contents); and x=10, 25, 50, 100 and 500.

The limit of four flood return intervals (annual chance events) with associated flood elevation is also an important limitation of the Toolkit. It reduces the granularity of the surge risk data we employed, as the surge data has five annual chance events with surge heights. This is particularly salient for homes exposed to the greatest risk of surge: the 10% annual chance event. Homes exposed to the 10% annual chance surge event are also exposed to the 4%, 2%, 1%, and 0.2% annual chance events; but in the Toolkit we are only able to input annual chances of 10%, 2%, 1%, and 0.2% surge events. Therefore, the Toolkit probably underestimates annualized losses for homes in the 10% and 4% annual chance surge zones.

We used the short form of the flood module in the Toolkit, as opposed to the long form of the flood module. The long form has more capabilities than the short form, but these capabilities are dependent on more detailed flood risk data from either a Flood Insurance Study (FIS) or a Hydrology & Hydraulic (H&H) study. Since we used the U-Surge data as flood risk data for every home, these data are not from an FIS or an H&H study, therefore we could not use the long form of the BCA Toolkit.

Users can only incorporate future conditions with sea level rise using the long form of the flood module in the BCA Toolkit. Therefore we could not assess economic effectiveness of flood mitigation going into the future with sea level rise, which is an important shortcoming for our Escambia County study area that is vulnerable to sea level rise.

Additionally, automated batch analysis of many mitigation projects simultaneously is very problematic with the Toolkit. However, this is a limitation for our research herein as the Toolkit is intended for developing mitigation grant applications for FEMA and not explicitly for research.

An important limitation of the Toolkit is that there are limited resources to learn the software: there are few training sessions and the accompanying manuals are outdated with respect to the most recent version of the software. The most recent version of the Supplement to the Benefit-Cost Analysis Reference Guide has a June 2011 publication date and the Benefit Cost Analysis Reference Guide was published in June 2009. Our analyses were implemented in the Toolkit version 5.3.0 which was published in September 2015.

3.6 Results of bulk analysis without the Toolkit

Now we present and discuss the results of the bulk analyses we implemented with IBM SPSS Statistics software (i.e., without the Toolkit). Summary statistics for attributes of our homes at risk to surge datasets are shown in Table 6, grouped by study area. The summary statistics shown in Table 6 are for the entire datasets of single-family homes at risk to surge (i.e., not limited to our sample of homes analyzed with the Toolkit), consequently in the bulk analysis we analyze now 6,820 homes compared to 39 with the FEMA BCA toolkit. (For a summary statistic comparison, please refer to Table 3 above in Section 2 for the attributes of our total sample of 39 homes analyzed with the BCA Toolkit). Building replacement values are the improvements value from the ECPA parcel data, contents replacement values are estimated at half of the building replacement values (following Kunreuther et al. 2018), and year built and heated square feet are from the ECPA parcel data. First floor elevations (FFEs) are based on the lidar elevation data and our assumptions explained above; or FFEs are from elevation certificates for certificates that were geocoded. In Table 7 we show the counts of each type of foundation for the homes we analyzed in the bulk analysis.

It is somewhat surprising that the maximum building replacement value of the three study areas does not occur on Pensacola Beach, but it is important to keep in mind that our datasets of homes in each study area include only single-family detached homes. We do not include land values in our BCAs except for the demolitions and acquisitions, and land values are from the ECPA parcel data. The minimum and maximum values for building and contents replacement values were taken from the improvement values from the Escambia County Property Appraiser's 2015 parcel layer, but we removed any buildings with values less than $1,000. Although $1,000 is a very low building value, these are the data by which property taxes are assessed for the 2015 tax year in all of Escambia County therefore it is the best available data.

In Table 8, we show the total counts and percentages of homes in each annual chance surge zone; and in Table 9 we show the total counts and percentages of homes in each FEMA flood zone.

Table 6. Summary statistics for homes at risk to surge according to the U-Surge data for Pensacola, unincorporated Escambia County, and Pensacola Beach. Homes are identified within of the three study areas as being at risk to surge if they coincide with the horizontal extent of the U-Surge data.

		N	Min	Max	Average	St. Dev.
Pensacola homes at risk to surge	building replacement value	1,337	$1,386	$2,935,885	$137,485	$216,090
	contents replacement value	1,337	$693	$1,467,943	$68,743	$108,045
	year built	1,337	1810	2014	1958	31
	heated square feet	1,337	252	12,725	2,044	1,388
	FFE	1,337	3.81	28.38	15.44	4.55
Escambia County homes at risk to surge	building replacement value	4,600	$1,008	$1,657,426	$95,672	$80,504
	contents replacement value	4,600	$504	$828,713	$47,836	$40,252
	year built	4,600	1900	2014	1975	20
	heated square feet	4,600	306	9,008	1,780	758
	FFE	4,600	3.09	27.10	14.98	4.85
Pensacola Beach homes at risk to surge	building replacement value	883	$25,741	$1,700,988	$214,010	$179,540
	contents replacement value	883	$12,871	$850,494	$107,005	$89,770
	year built	883	1951	2014	1986	18
	heated square feet	883	576	8,810	2,440	1,040
	FFE	883	2.86	20.7	10.43	3.47

Table 7. Counts of homes by foundation types in each of the three study areas.

Escambia County	Crawlspace/ pier	1,391
	Pilings	259
	Slab above grade	42
	Slab on grade	2,908
Pensacola	Crawlspace/ pier	846
	Pilings	4
	Slab above grade	41
	Slab on grade	446
Pensacola Beach	Crawlspace/ pier	48
	Pilings	624
	Slab above grade	1
	Slab on grade	210

Table 8. Counts of homes in City of Pensacola, unincorporated Escambia County, and Pensacola Beach in each annual chance surge zone.

		Count of homes	Percent
annual chance surge zone	10%	664	9.7
	4%	1526	22.4
	2%	967	14.2
	1%	887	13.0
	0.2%	2776	40.7

Table 9. Counts of homes in City of Pensacola, unincorporated Escambia County, and Pensacola Beach in each FEMA flood zone (according to the 2006 effective DFIRM).

		Count of homes	Percent
FEMA flood zone (2006 DFIRM or EC where applicable)	A	205	3.0
	AE	1875	27.5
	AO	14	0.2
	VE	241	3.5
	X	4485	65.8

3.6.1 Elevating homes at risk to surge by study area and surge/flood zones

An important benefit of our bulk analysis is that we incorporated sea level rise (SLR) according to three different NOAA scenarios for Pensacola, in addition to being able to easily analyze many homes at once. We analyzed economic effectiveness of mitigating homes in our bulk analyses from 2017 to 2100, or 83 years, thus benefits of mitigation increase with time as sea level rises but future benefits are also discounted by 7% and 4%. For elevating homes to mitigate them against surge hazards, we assessed only elevating by 8' since it is commonly the most economically attractive option for elevation over 2', 4', or 6' of elevation.

Pensacola Beach homes are most economically attractive to elevate by 8', followed by Escambia County homes (generally), and then Pensacola homes. This is primarily because the greatest risk of storm surge is on the beach, and the unincorporated County areas are more exposed to surge risks than the City of Pensacola.

As expected, using the NOAA High SLR scenario generates the highest BCRs for elevating homes by 8', but decision-makers considering elevation as a home flood mitigation strategy should consider the homes that are outliers: i.e., homes that are represented with circles or asterisks in every box plot that have a BCR over 1.[25]

In Figures 18 and 19, we show average BCRs for all 6,820 homes in our entire dataset (all three study areas) by annual chance surge risk zone (Figure 18) and 2006 effective DFIRM flood zone (Figure 19). For the averages in both Figures 18 and 19 by surge or flood zone, there is a bar representing (a) no SLR and 7% discount rate; (b) no SLR and 4% discount rate; (c) NOAA Low SLR scenario and 7% discount rate; (d) NOAA Low SLR scenario and 4%

[25] Associated boxplots are in appendices E, F, and G as detailed below

discount rate; (e) NOAA Intermediate- (Int) High SLR scenario and 7% discount rate; (f) NOAA Intermediate- (Int) High SLR scenario and 4% discount rate; (g) NOAA High SLR scenario and 7% discount rate; and (h) NOAA High SLR scenario and 4% discount rate. We present boxplots showing the statistics of our results for elevating homes in Appendix E-1.

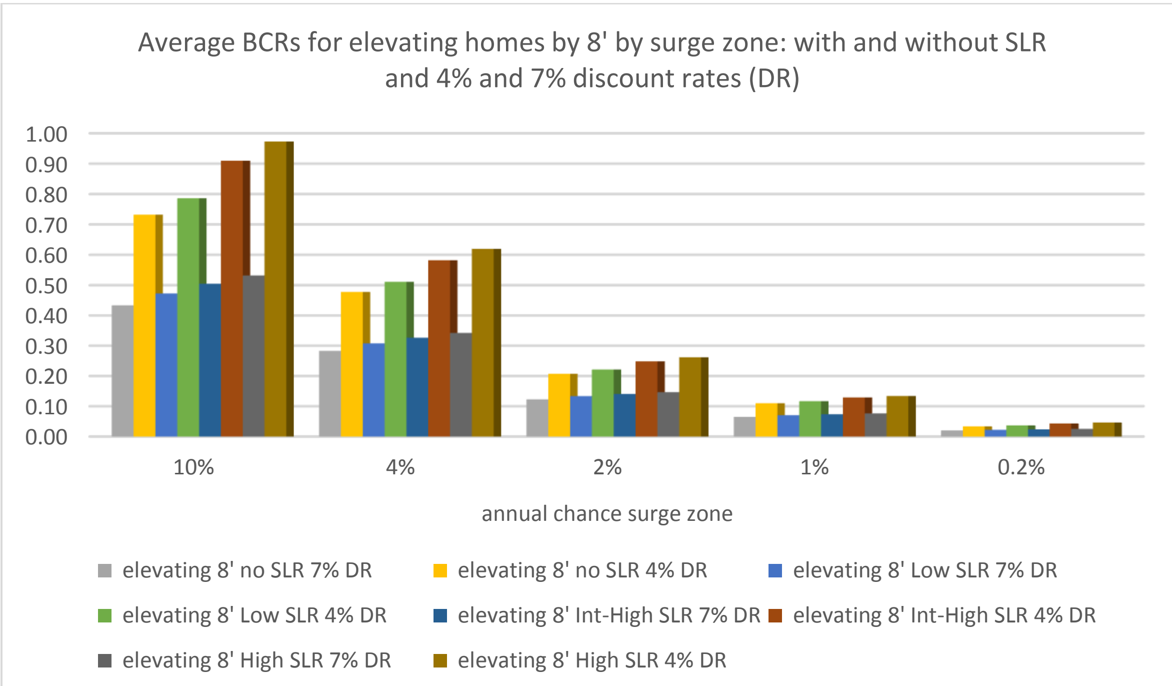

Figure 18. Average BC ratios for elevating homes in each annual chance surge zone by 8’ with no sea level rise (SLR) from 2017 to 2100; and NOAA Low, Intermediate-High, and High SLR scenarios from 2017 to 2100. Discount rates (DR) used in BCA are either 7% or 4%.

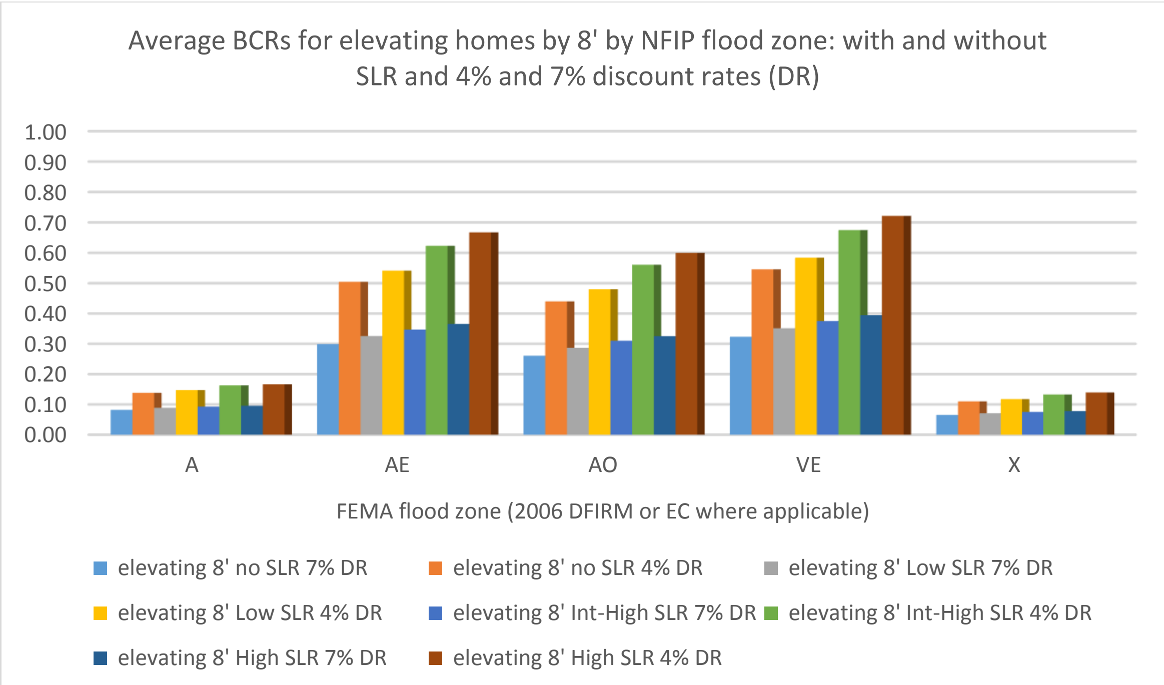

Figure 19. Average BC ratios for elevating homes by 8' in each FEMA flood zone (according to the 2006 effective DFIRM for Escambia County that each home coincides with, or elevation certificate) with no sea level rise (SLR) from 2017 to 2100; and NOAA Low, Intermediate-High, and High SLR scenarios from 2017 to 2100. Discount rates (DR) used in BCA are either 7% or 4%.

It is expected that average BCRs by annual chance surge zone would exhibit the pattern observed in Figure 18: descending values by lower annual chance surge risk zone. Furthermore, the pattern of average BCRs by NFIP flood zone observed in Figure 19 is somewhat expected as well. This is largely because we used the USACE IWR depth-damage function for all bulk analyses which does not differentiate by flood zone. Since our surge data represent stillwater surge heights, the USACE IWR depth-damage function we used is most appropriate for stillwater hazards in contrast to flood hazards with velocity. The homes in A zones have practically the same average BCRs for elevation as those in X zones. A zones in DFIRMs are Special Flood Hazard Areas (SFHAs) that lack detailed hydraulic and hydrodynamic (H&H) analysis implemented within them: they are approximated SFHAs without delineated BFEs. They tend to occur in less hazardous areas because areas with more risk are prioritized for detailed H&H analyses. This partly explains why the average BCRs for A zones, despite that A zones are SFHAs, are as low as those in X zones.

In Figures 20 and 21, we present BCRs that are aggregated by annual chance surge zone and FEMA flood zone, respectively. Aggregate BCRs are computed by dividing the sum of benefits of elevating all homes in the same surge (Figure 20) or flood zone (Figure 21) by the sum of all costs of mitigating the homes. Although average and aggregate BCRs are fairly similar in value for homes by surge and flood zones, employing aggregate BCRs is an approach used by floodplain managers in applying for FEMA mitigation grants. For example, suppose there is a group of homes that are identified as candidates for federal funding for flood mitigation, but not all individual homes have a BCR of 1 according to analyses of mitigation. If the entire group of candidate homes are analyzed together with the Toolkit, an aggregate BCR might be at least 1 and therefore the entire group of homes is deemed economically effective to mitigate in a project and thus submitted to FEMA in one application for funding. This is a way to fund mitigation for structures that have BCRs under 1 but are still considered worthwhile to mitigate. Reporting aggregate, project-level BCRs for FEMA mitigation applications is reasonable given that BC analyses involves many assumptions such as the discount rate and useful lifetime of projects.

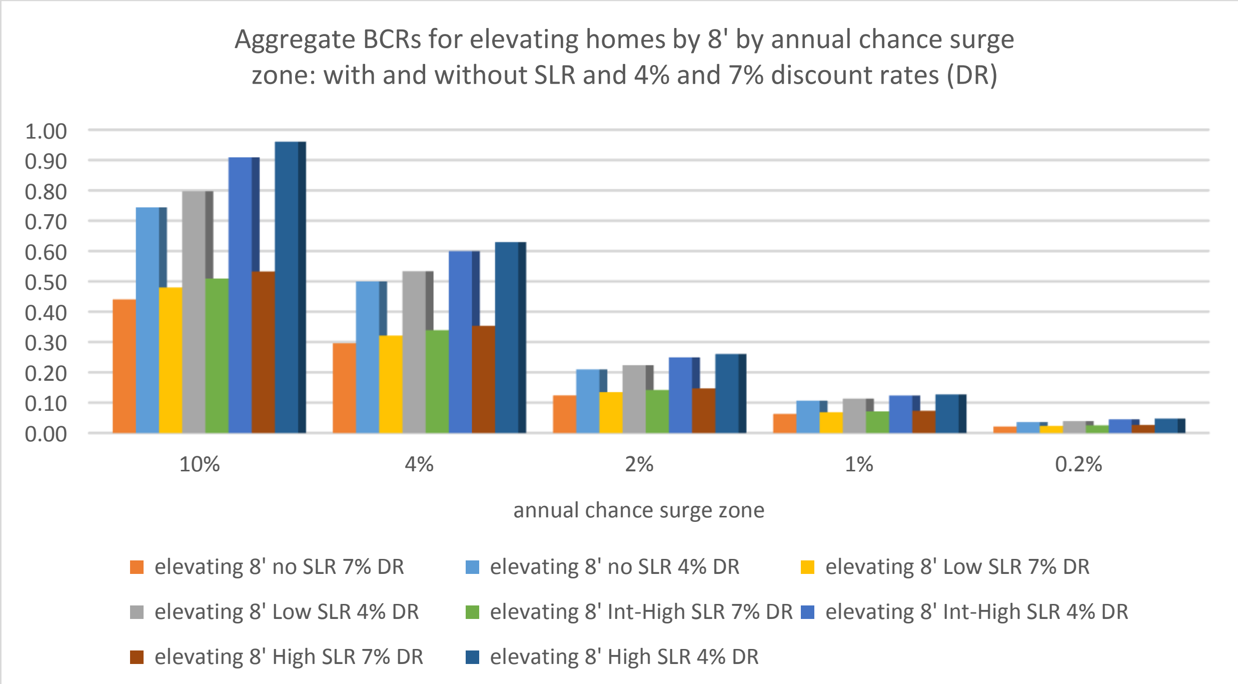

Figure 20. Aggregate BCRs for elevating homes by annual chance surge zone with and without SLR and using 7% and 4% discount rates for discounting benefits from 2017 to 2100.

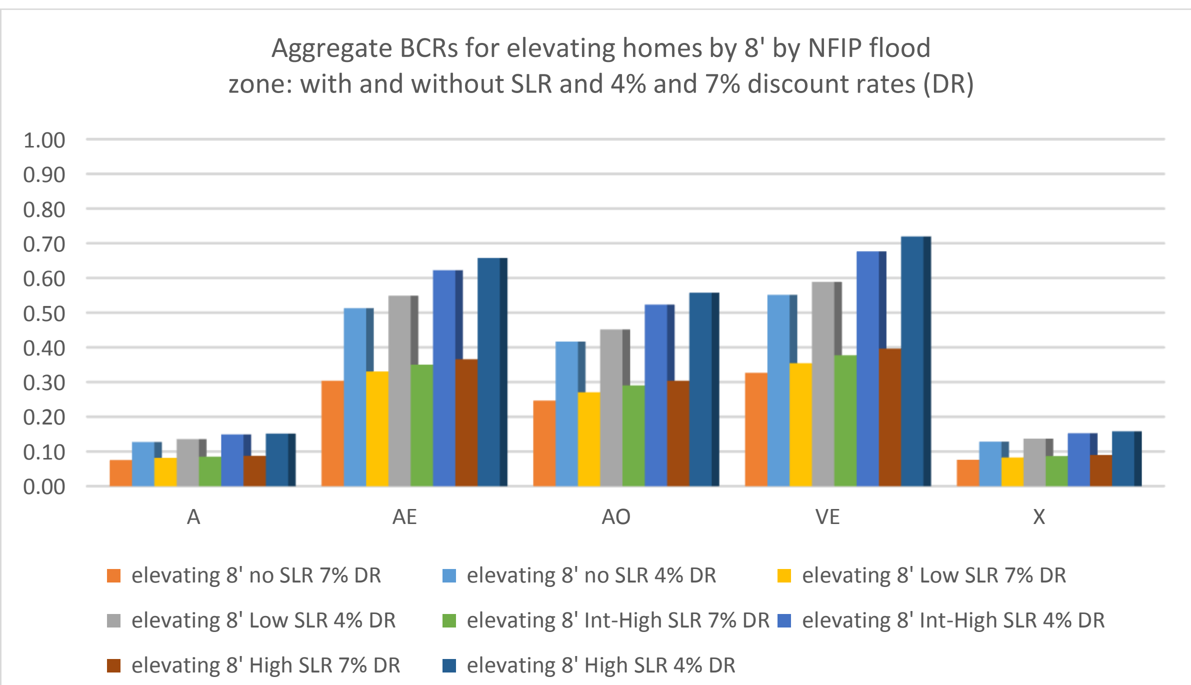

Figure 21. Aggregate BCRs for elevating homes by FEMA flood zones with and without SLR and using 7% and 4% discount rates for discounting benefits from 2017 to 2100.

To better understand the homes for which it is economically effective to elevate by 8’ to mitigate surge hazards, we selected homes with a BCR of 0.9 or greater for analyses with no SLR and 7% discount rate and we show pertinent variables for these homes in Table 10. We chose homes with a BCR of 0.9 because 0.9 is near 1 (indicating economic effectiveness), but primarily to obtain a larger sample of homes with which to assess the attributes that contribute to economic effectiveness of elevation as a mitigation strategy. All of the homes for which it is economically effective to elevate, shown in Table 10, are in the 10% and 4% annual chance surge zones, but more of them are in the 4% annual chance surge zone. This is probably because homes on the waterfront usually have high values despite that they are more exposed to surge risks. Most of the homes have piling foundations and are on Pensacola Beach. Homes with piling foundations are less costly to elevate than slab foundations, and the majority of homes in Pensacola Beach are on pilings. Pensacola Beach has the most risk from surge than unincorporated Escambia County and the City of Pensacola.

Table 10. Attributes of homes with a BCR of 0.9 or greater for elevation by 8’, based on BCA with no SLR and 7% discount rate.

Homes with BCR >=0.9 to elevate by 8' with no SLR and 7% discount rate (n=47)			
		Count	**Percent (of 47)**
annual chance surge zone	10%	20	42.6
	4%	27	57.4
FEMA flood zone (2006 DFIRM or EC where applicable)	AE	32	68.1
	VE	15	31.9
Foundation type	Crawlspace/ pier	10	21.3
	Pilings	29	61.7
	Slab on grade	8	17
Study area	Escambia County	8	17
	Pensacola	7	14.9
	Pensacola Beach	32	68.1

3.6.2 Demolishing and acquiring homes at risk to surge by study area and surge/flood zone

We show boxplot figures summarizing our results for demolishing and acquiring homes in Appendix E-2, and we show average BCRs of acquiring homes by annual chance surge zone and FEMA flood zone in Figures 22 and 23 respectively. The results indicate that it is not economically effective to demolish and acquire any home in Escambia County, the City of Pensacola, or Pensacola Beach, when analysis involved no SLR and 7% discount rate. When considering the most likely scenario of economic effectiveness of our mitigation techniques tested herein, which is analyses involving the 4% discount rate and the NOAA High SLR scenario for years 2017 to 2100, only one home was economically effective to demolish and acquire: a slab on-grade home with an assumed first floor elevation of 3.21 in the 10% annual chance surge zone, located in unincorporated Escambia County. The address of this home is 350 Riola Place, which is the same street as one of our sample homes (E-s-10-3). The total estimated cost of demolishing and acquiring this home is $554,445, and the mean cost for demolishing and acquiring unincorporated Escambia County homes in the 10% annual chance surge zone is $445,716. The annualized losses to floods for this home are $18,748; and with NOAA High SLR scenario and 4% discount rate the losses are $510,875 (when discounted over 83 years). The BCR is not 1, it is 0.92; but it is the only home with BCR of 0.9 or greater.

Demolishing and acquiring homes is very rarely economically effective because of the high costs associated with buying out the homeowners of these homes. We present aggregate BCRs of demolishing and acquiring homes by annual chance surge zone in Figure 24, and aggregate BCRs by FEMA flood zone in Figure 25. As with our results for elevating homes, the average and aggregate BCRs for acquiring homes are similar, and the average and aggregate BCRs are all well below 1. It is unfortunate that acquiring homes is generally economically ineffective, as acquiring a home and removing it from the floodplain is the most certain and effective method of flood risk mitigation. Additionally, if FEMA funds are used to acquire homes, the property must be preserved as open space for perpetuity, ensuring that there will not be a structure rebuilt there in a location that is flood-prone. On the other hand, when property is bought out with FEMA mitigation funds, municipalities lose the tax revenue generated from privately-owned property and this might be a particularly significant drawback for communities in Florida. Loss of property tax revenue is particularly problematic in Florida because there is no state income tax, therefore the State and its communities are reliant on property taxes for revenue.

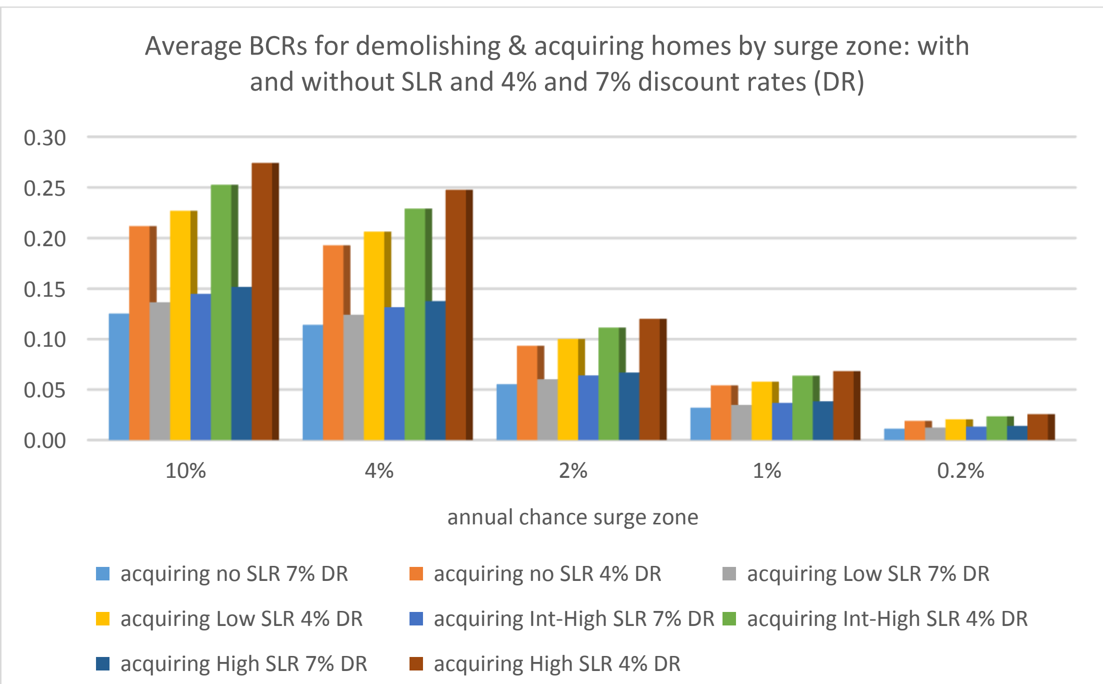

Figure 22. Average BC ratios for demolishing and acquiring homes in each annual chance surge zone with no sea level rise (SLR) from 2017 to 2100; and NOAA Low, Intermediate-High, and High SLR scenarios from 2017 to 2100. Discount rates (DR) used in BCA are either 7% or 4%.

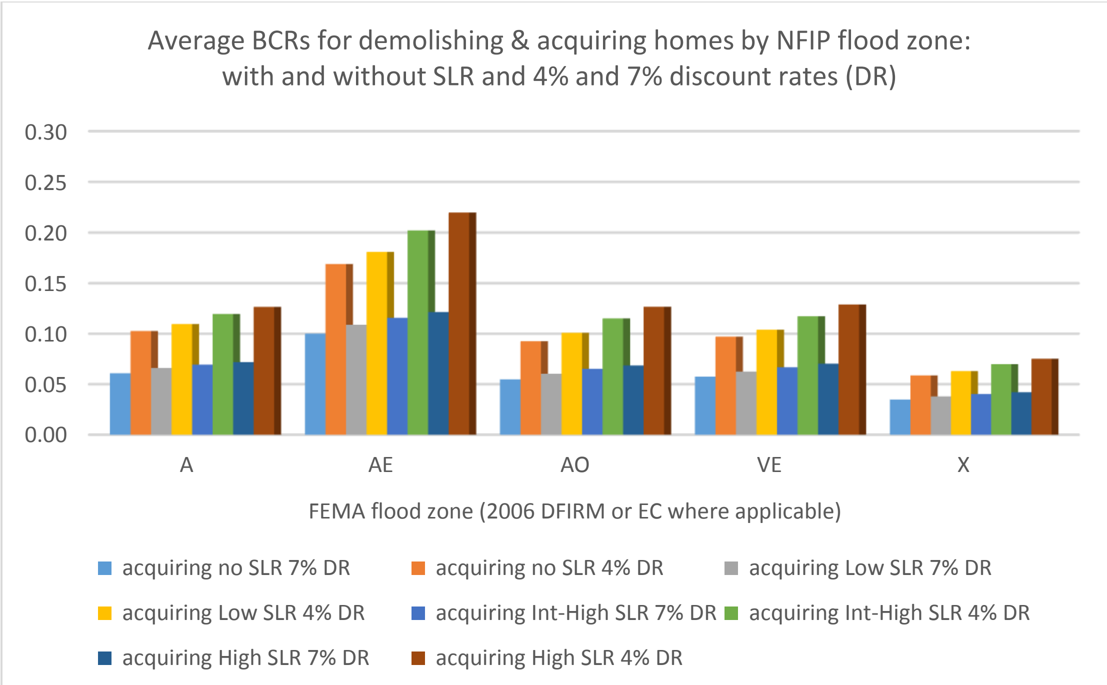

Figure 23. Average BC ratios for demolishing and acquiring homes in each FEMA flood zone (according to the 2006 effective DFIRM for Escambia County that each home coincides with, or elevation certificate) with no sea level rise (SLR) from 2017 to 2100; and NOAA Low, Intermediate-High, and High SLR scenarios from 2017 to 2100. Discount rates (DR) used in BCA are either 7% or 4%.

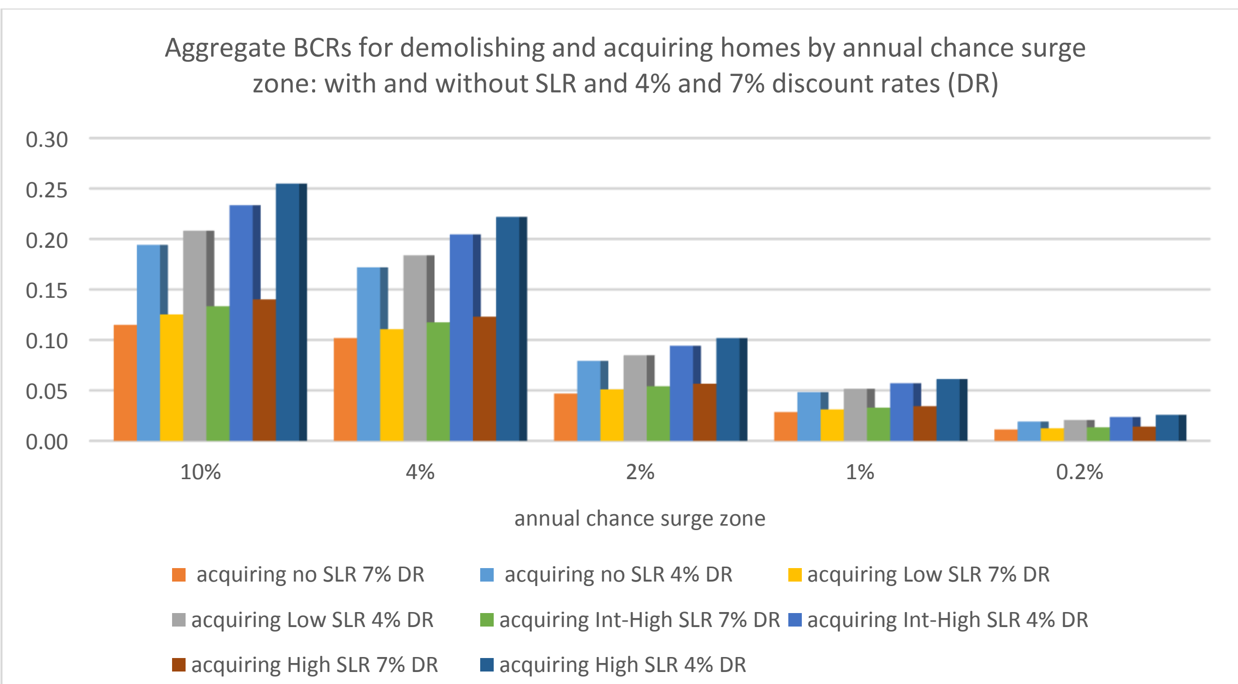

Figure 24. Aggregate BCRs for demolishing and acquiring homes by annual chance surge zone with and without SLR and using 7% and 4% discount rates for discounting benefits from 2017 to 2100.

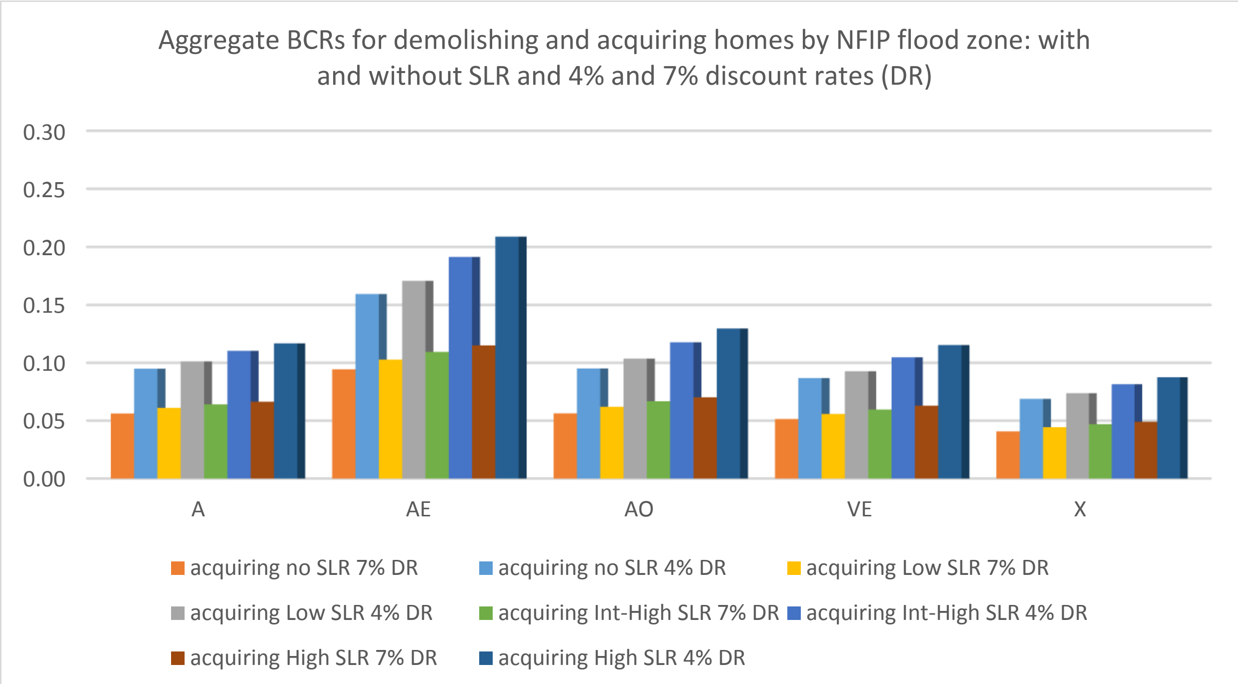

Figure 25. Aggregate BCRs for demolishing and acquiring homes by FEMA NFIP flood zone with and without SLR and using 7% and 4% discount rates for discounting benefits from 2017 to 2100.

3.6.3 Building 4' high flood walls around homes: results presented by study area and surge/flood zones (omitting Pensacola Beach)

Building 4' high floodwalls around homes appears to be the most economically effective flood mitigation technique that we examined. In Figure 26 below, we present average BCRs for building 4' high floodwalls around homes by annual chance surge zone, and in Figure 27 we show average BCRs for floodwalls by FEMA flood zones. Boxplots showing the statistics of our results for building 4' floodwalls appear in Appendix E-3. When comparing the average BCRs for floodwalls shown in Figures 26 and 27 to the average BCRs for elevating homes by 8' by surge zone in Figure 18 and by FEMA flood zone in Figure 19, it appears that building floodwalls is a more economically attractive mitigation technique. However, it must be noted that FEMA grant programs do not fund floodwalls for residential structures. FEMA flood mitigation programs fund elevation, demolition and acquisition, and demolition and reconstruction to mitigate residential structures against flood risks.

In Figure 26, the average BCRs for homes in the 10% annual chance surge zone evidence lower economic effectiveness of floodwalls with SLR relative to BCRs for floodwalls without SLR. A similar trend is observed in Figure 27 for homes in VE FEMA flood zones. This is because in areas at greatest risk to surge, a 4' high floodwall is not high enough to prevent flooding for all homes. This is an important consideration for floodwalls as a flood mitigation technique: according to FEMA P-312 (2009 version), the maximum height of a floodwall should only be 4'; therefore they should not be constructed in very high risk flood areas. Further, we examined the cost-effectiveness of floodwalls for homes in in VE zones that are not in Pensacola Beach, but floodwalls should probably not be constructed in VE zones that have wave action hazards. Nevertheless, our approach to assessing economic effectiveness of surge mitigation techniques only accounts for stillwater flood elevations explicitly, and hard structures such as floodwalls should be employed prudently in areas at risk to floods with velocity hazards.

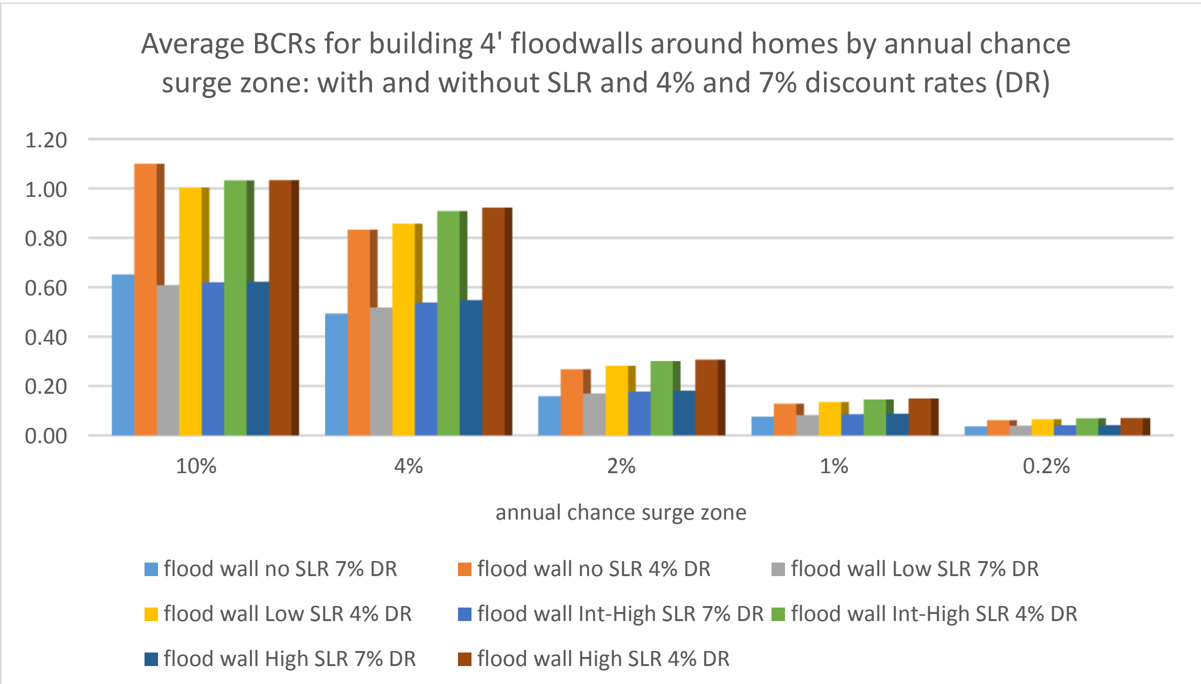

Figure 26. Average BC ratios for building 4' floodwalls around homes in each annual chance surge zone with no sea level rise (SLR) from 2017 to 2100; and NOAA Low, Intermediate-High, and High SLR scenarios from 2017 to 2100. Discount rates (DR) used in BCA are either 7% or 4%.

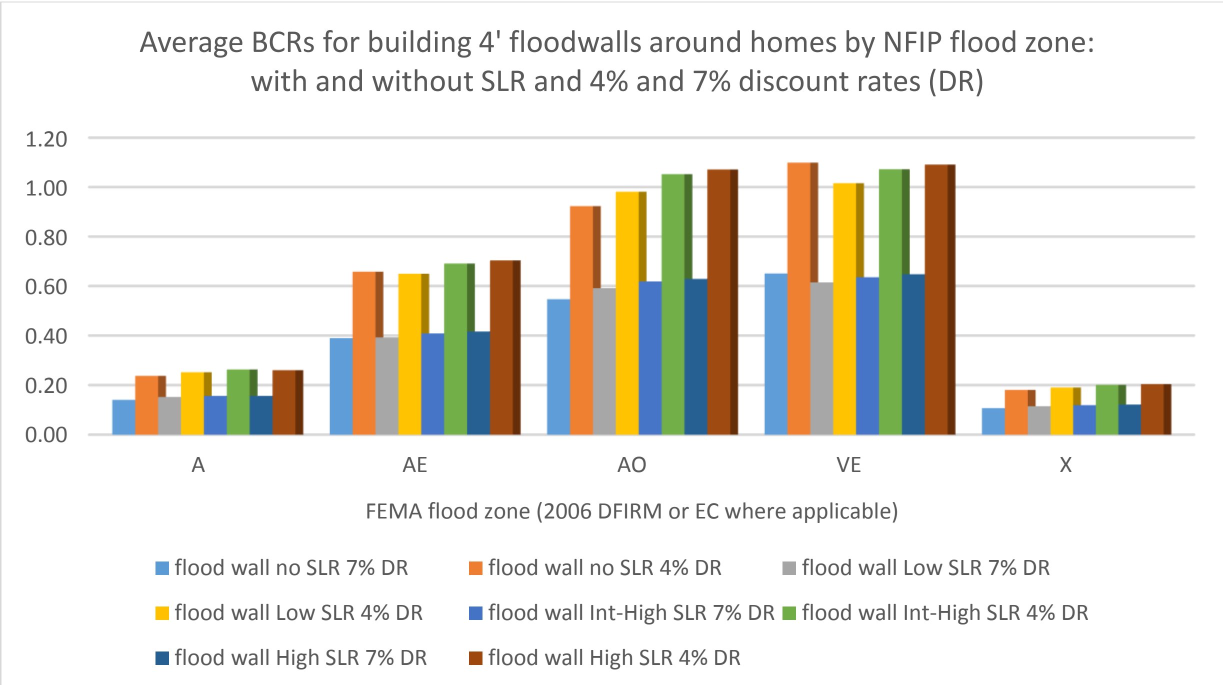

Figure 27. Average BC ratios for building 4' floodwalls around homes in each FEMA flood zone (according to the 2006 effective DFIRM for Escambia County that each home coincides with, or elevation certificate) with no sea level rise (SLR) from 2017 to 2100; and NOAA Low, Intermediate-High, and High SLR scenarios from 2017 to 2100. Discount rates (DR) used in BCA are either 7% or 4%.

In Figures 28 and 29 we show BCRs for 4' high floodwalls to mitigate surge risks that are aggregated by annual chance surge zone and FEMA flood zones, respectively. The aggregate BCRs of homes in the 10% annual chance surge zone are significantly greater than those for any other surge or flood zone. The aggregate BCR values for homes in the 4% annual chance surge zone are close in value to those for homes in the AE, AO, and VE FEMA flood zones. Aggregate BCRs for homes in FEMA VE flood zones are slightly higher than those for homes in the other FEMA flood zones, and this is because the VE zone is including some homes with high surge risks.

When considering our three surge/flood mitigation techniques, floodwalls might be a more complicated method than elevation or acquisition to mitigate flood risks. This is because once floodwater elevation surpasses the elevation of the floodwall (for example, herein 4'), floodwater might be held within the floodwall and cause more damage to the home than if there were no mitigation technique. Hydrostatic pressure of floodwater surpassing the floodwall height could significantly damage a home. Furthermore, floodwalls have potentially dire implications for residents who choose to stay in their home during a flood event because they feel that the floodwall will protect them from flooding.

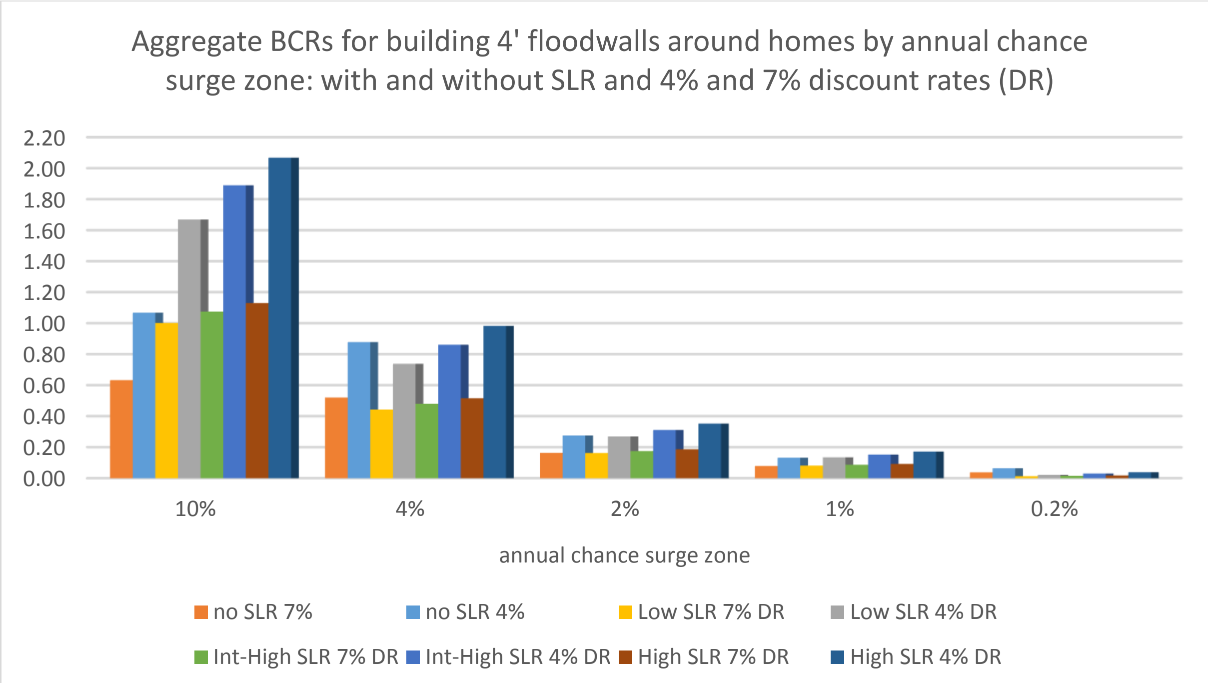

Figure 28. Aggregate BCRs for building 4' floodwalls around homes by annual chance surge risk zone with and without SLR and using 7% and 4% discount rates for discounting benefits from 2017 to 2100.

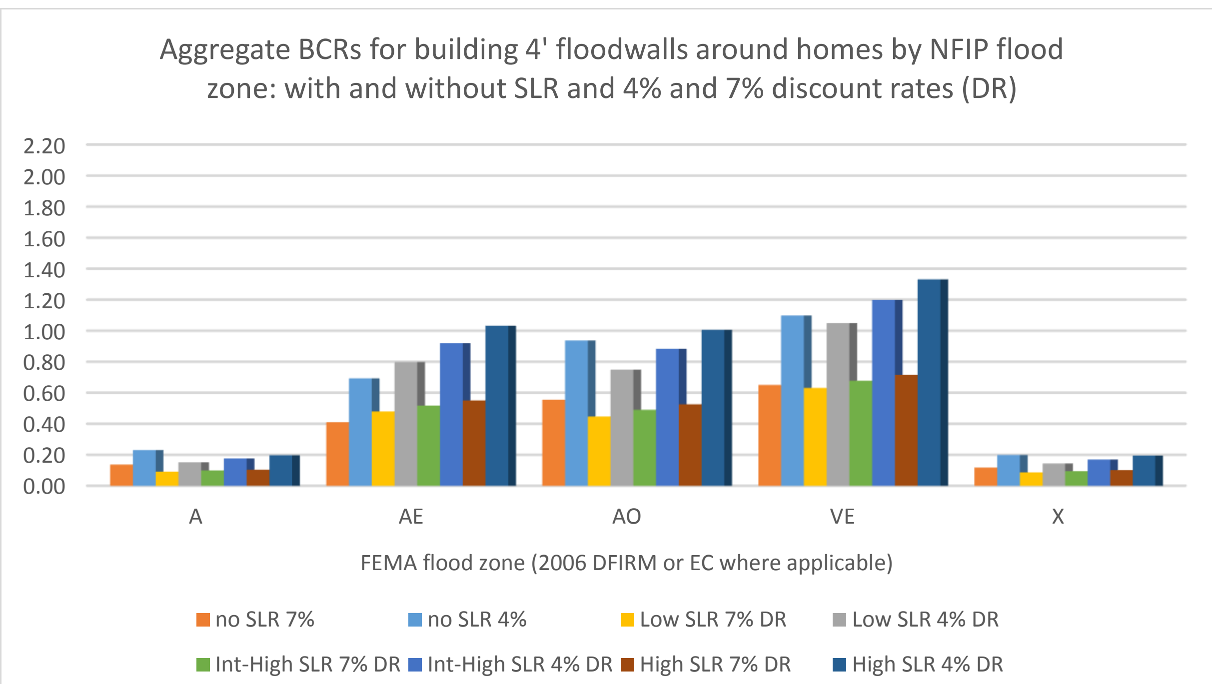

Figure 29. Aggregate BCRs for building 4' floodwalls around homes by FEMA NFIP flood zone with and without SLR and using 7% and 4% discount rates for discounting benefits from 2017 to 2100.

As we did with homes that are economically effective elevate by 8’, we examined homes that are economically effective to build 4’ floodwalls around them by selecting homes with a BCR or 0.9 or greater, in analyses involving no SLR and a 7% discount rate. Similar to our examination of elevating homes by 8’, we chose homes with a BCR of 0.9 to build 4’ floodwalls around them because 0.9 is near 1, and mainly so that we could obtain a larger sample of homes with which to assess the attributes that contribute to economic effectiveness of floodwalls as a mitigation strategy. These homes for which it is economically effective to mitigate with 4’ high floodwalls are shown in Table 11. As with homes that are economically effective to elevate, most homes that are economically effective to mitigate with floodwalls are located at risk to 4% annual chance surge events. Homes in AE FEMA flood zones are most commonly economically effective to either elevate or build floodwalls around them, as compared to other FEMA flood zones. Homes with slab on-grade foundations comprise 95% of all the 208 homes for which it is economically effective to mitigate with floodwalls, and most of these homes are in unincorporated Escambia County. Our findings suggest that based on BCAs, homes with slab foundations should be mitigated against surge risks with floodwalls, while homes with open foundations are better mitigated against surge risks with elevation.

Table 11. Attributes of homes with a BCR of 0.9 or greater for building a 4' floodwall, based on BCA with no SLR and 7% discount rate.

Homes with BCR >=0.9 to build 4' floodwall (n=208)			
		Count	**Percent (of 208)**
annual chance surge zone	10%	46	22.1
	4%	155	74.5
	2%	7	3.4
FEMA flood zone (2006 DFIRM or EC where applicable)	AE	119	57.2
	AO	2	1
	VE	4	1.9
	X	83	39.9
Foundation type	Crawlspace/ pier	2	1
	Slab above grade	8	3.8
	Slab on grade	198	95.2
Study area	Escambia County	168	80.8
	Pensacola	40	19.2

3.7 Summary of results of benefit-cost analyses using the bulk analysis approach

The results of our bulk analyses on 6,820 homes across unincorporated Escambia County, the City of Pensacola, and Pensacola Beach reveal similar trends as those obtained from the Toolkit: it is generally only economically effective to mitigate homes in the 10% or 4% annual chance surge zones with low FFEs. Floodwalls are economically effective for substantially more homes than elevation, and demolition and acquisition with a 7% discount rate is not economically effective for any home in our dataset. Floodwalls are a particularly economically attractive mitigation option for homes with slab on-grade foundations at risk to 4% annual chance surge risks, while elevation is an economically attractive mitigation strategy for open foundation homes at risk to 10% and 4% annual chance surge events.

We observe that in both our bulk analysis and our sample home analysis with the Toolkit, that the choice of discount rate (4% or 7%) has a significant impact on the economic effectiveness of mitigation projects. An interim report on the economic effectiveness of flood mitigation for the U.S. by the National Institute of Building Sciences used a very low discount rate of 2.2%, and revealed that for homes at risk to coastal surge[26], $7 is saved for every $1 spent on building new construction 1 foot above BFE (Multihazard Mitigation Council, 2017). However, that 2017 report (Multihazard Mitigation Council, 2017) focuses on elevating new construction, not elevation of existing buildings as we have done here.

[26] Homes at risk to coastal surge in the 2017 report are defined as homes in V and VE NFIP flood zones (Multihazard Mitigation Council, 2017).

3.8 Comparing Escambia County BCR Results to Other Parts of the U.S.

Our toolkit and bulk analysis results presented above both suggest that generally, any one of the three mitigation techniques can be economically effective for homes at risk to the 10% and 4% annual chance surge risk zones, or NFIP VE flood zones, with low first-floor elevations (FFEs). We are interested in how these results compare to similar flood mitigation analyses in other geographic areas. We present here the results from two studies – one conducted in Texas as well as one in New York City.

3.8.1 Texas Flood Mitigation BCA

Czajkowski et al. (2012) conducted a flood mitigation BCA that illustrates the capacity of a catastrophe risk model to be applied on a large number of structures. Their BCA was conducted in Texas which is exposed to both storm surge related flooding and to typical riverine flooding and the second most populous state in the United States with over 24 million residents (one-third residing in a coastal county). Here we provide an overview of the BCA results in regard to elevation of existing single-family residences.

<u>Approach</u>

Without floor mitigation exceedance probability curves for riverine and storm-surge flood risk were generated for Travis and Galveston counties for over 300,000 equally valued $175,000 representative homes (see Figure 30).

Figure 30. Focus of the Texas Case Study (Galveston and Travis Counties, Texas, USA) *Source: Czajkowski et al. (2012)*

Vulnerability for flood hazards in this risk analysis represents the relationship of water depth and mean damage ratio on the single-family residential properties. However, for flood mitigation assessment purposes, flood risk for elevated properties were then assessed by reducing inundation levels due to assumed higher elevation of structures based on 2, 4, and 8 feet elevations heights. Figure 31 presents a conceptual rendering of reducing the 1000 year inundation level due to increased home elevation. These specific levels of elevation were chosen based upon cost of elevation data obtained from FEMA associated with elevating homes 2, 4, and 8 feet.

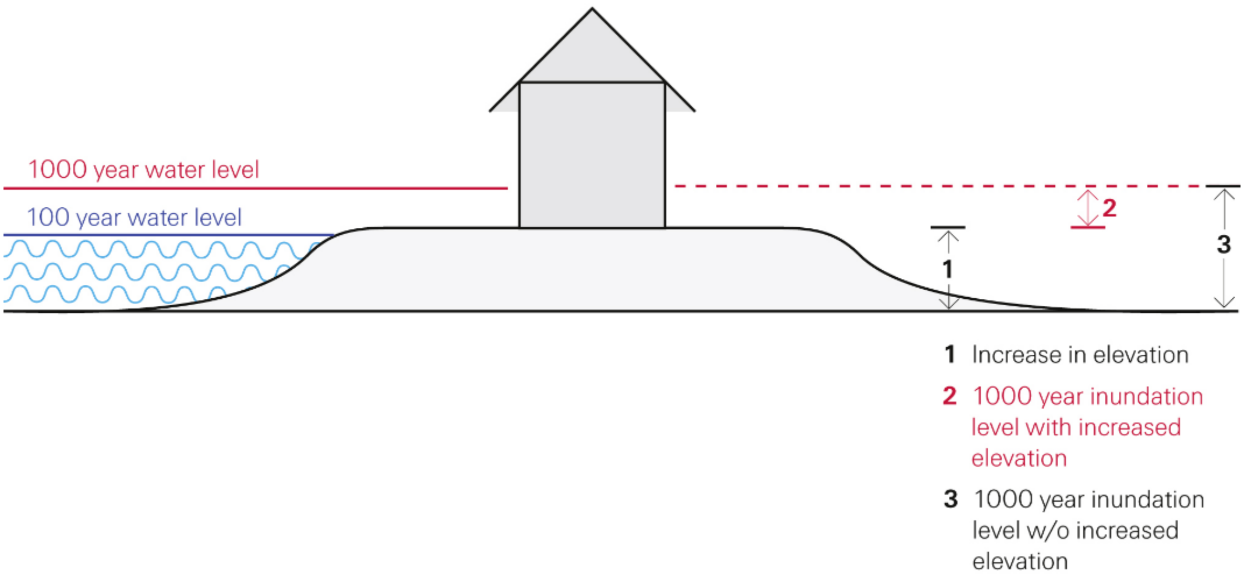

Figure 31. Illustrative flood model elevation mitigation option. *Source: Czajkowski et al. (2012)*

In their probabilistically based analysis, benefits due to elevation are ultimately shown through shifts (reductions) in the determined EP curves. Table 12 presents the key return period loss values for Travis County assuming no elevation mitigation as well as elevation of 2, 4, and 8 feet. The associated county baseline EP curve and the shifted downward curves due to 2, 4 and 8 feet of elevation are illustrated in Figure 32. Of the 226,407 residences in Travis County, 60,869 had some level of loss reduction associated with the elevation implementation. Based on the data in Table 12 the total losses associated with the 10,000 year event without mitigation are reduced by 13%, 24% and 57% for levels of 2, 4, and 8 feet of elevation. Loss reductions for the other key return periods due to elevation range from 30-90% of the unmitigated losses.

Table 12. Travis County Key Return Period Losses with and without Elevation. *Source: Czajkowski et al. (2012)*

ReturnPeriod	No Mitigation	2 Feet	4 Feet	8 Feet
10000	$ 1,012,836,772	$ 880,428,366	$ 768,023,069	$ 437,453,474
1000	$ 585,633,951	$ 409,284,929	$ 249,609,742	$ 95,733,654
500	$ 424,267,558	$ 276,504,642	$ 187,933,290	$ 65,444,889
250	$ 296,221,335	$ 185,902,081	$ 119,265,425	$ 33,576,788
100	$ 191,655,065	$ 115,194,851	$ 66,488,639	$ 21,380,664
50	$ 124,496,724	$ 76,482,603	$ 41,642,040	$ 10,329,674

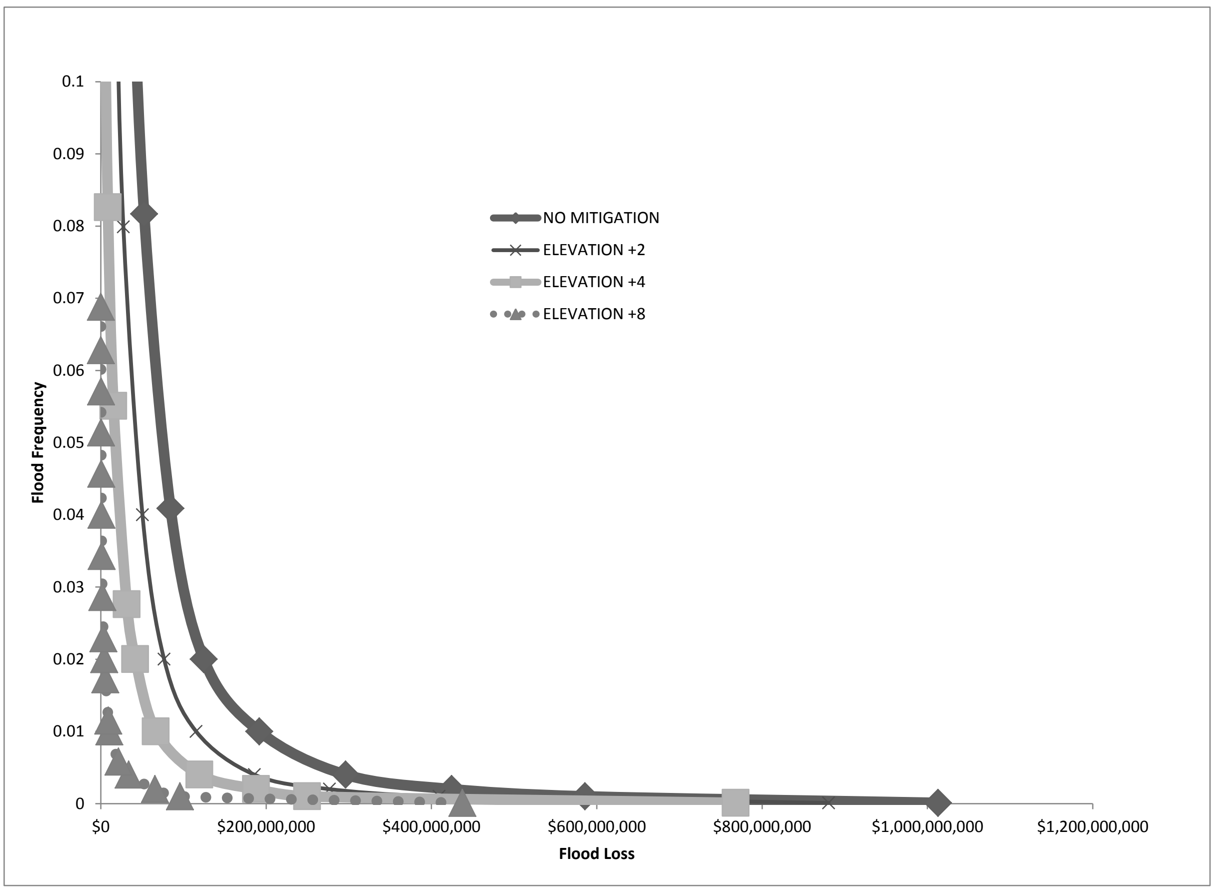

Figure 32. Travis County EP Curves with and without Elevation. *Source: Czajkowski et al. (2012)*

<u>Results</u>

While the above percentage reduction results generated indicated significant reductions to AAL in percentage terms, it was necessary to understand the magnitude of these benefits in economic terms via a benefit-cost analysis. Table 13 provides the average benefits to elevation (i.e., AAL reduction) due to 2, 4, and 8 feet of elevation for each county as well as across the applicable FEMA flood zones in each county, taken over a 25 year time period with no discounting. From this table we see that from an economic perspective, while the percentage reductions in AAL are significant, this does not necessarily translate into relatively significant dollar values. For example, the average 95% AAL reduction due to 8 feet of elevation in the Travis County X500 zone is worth $10,025 over 25 years, or roughly a $401 annual benefit. Average benefits to elevation over 25 years range from $973 to $14,227 for 2 feet of elevation, $1,472 to $25,455 for 4 feet of elevation, and from $1,799 to $32,603 for 8 feet of elevation. These values are greater in Galveston than in Travis, and more significant in the 100-year flood plains in each county as compared to outside of them. (i.e., in the X zone).

Table 13. Average Annual Reduction to Elevation over 25 Years, No Discounting. *Source: Czajkowski et al. (2012)*

	Total County		V Zone		A Zone		X500 Zone		X Zone	
	Galveston	Travis	Galveston	Travis	Galveston	Travis	Galveston	Travis	Galveston	Travis
Elevation										
2 ft	$ 6,800	$ 2,793	$ 11,754	N/A	$ 12,885	$ 14,227	$ 6,496	$ 5,127	$ 4,007	$ 973
4 ft	$ 10,519	$ 4,703	$ 18,496	N/A	$ 19,123	$ 25,455	$ 10,636	$ 8,219	$ 6,234	$ 1,472
8 ft	$ 15,462	$ 5,912	$ 28,494	N/A	$ 27,260	$ 32,603	$ 16,833	$ 10,025	$ 8,852	$ 1,799

Of course, these are just average numbers meaning there are values that are higher and lower accordingly. When maximum values for each zone were investigated instances of significant benefits to elevation were determined with maximum values being $55,938 for 2 feet, $78,597 for 4 feet, and $106,460 for 8 feet, or a $2,237, $3,143, and $4,258 annual benefit per level of elevation respectively.

In order to undertake a benefit-cost analysis of elevation, the costs of elevating existing structures were assessed. For existing single-family residences, FEMA provides the cost of elevation per square foot by construction and foundation types in their guide to retrofitting existing structures for providing flood protection (FEMA, 2009b). For their benefit-cost analysis they used the values from the two cost extremes: 1) frame construction having a basement or crawlspace foundation with cost per square foot of $29, $32, and $37 for 2, 4, and 8 feet of elevation; and 2) masonry construction with a slab-on-grade foundation with cost per square foot of $88, $91, and $96 for 2, 4, and 8 feet of elevation. For the representative $175,000 homes used in the analysis they assumed 2,000 square foot of house footprint for the analysis. The total elevation costs used in this analysis based on this assumption are presented in Table 14. We see that elevating any existing structure, even wood frame homes with a crawlspace, is relatively expensive. For example, to elevate 4 feet a 2,000 square foot wood frame home with a crawlspace costs $64,000. Elevating slab-on-grade masonry homes is approaching nearly $200,000 in expenses whether for 2, 4, or 8 feet of elevation.

Table 14. Total Cost of Elevation by Housing Type. *Source: Czajkowski et al. (2012)*

Construction	Foundation	Cost per Square Foot of Elevation	Total Elevation Cost for 2,000 Sq Ft Home
Wood Frame	Crawlspace	2 ft = $29	$ 58,000
		4 ft = $32	$ 64,000
		8 ft = $37	$ 74,000
Masonry	Slab-on-grade	2 ft = $88	$ 176,000
		4 ft = $91	$ 182,000
		8 ft = $96	$ 192,000

From an economic perspective, undertaking an action such as elevation flood mitigation is considered worthwhile when the benefits are greater than the costs, or similarly when the ratio of benefits over costs is greater than one. Further, these benefits and costs can be accrued over different future time periods, where benefits and costs occurring in future periods need to be discounted to compute the present value. Using their derived benefits from elevation (which occur on an annual basis over the length of the house such as 25 years), combined with our upfront costs of elevation summarized above, they undertook a benefit-cost analysis of elevation mitigation across different time horizons and discount rates. The average benefit-cost ratios by flood zone for Travis County for their two construction/foundation housing types are provided in Table 15. These particular average ratios are determined assuming 25 years of benefits at a 0% discount rate.

Table 15. Travis County Average Benefit-Cost Ratios per Level of Elevation by Flood Zone and Housing Type over 25 Years and a 0% Discount Rate. *Source: Czajkowski et al. (2012)*

House Type	FEMA Flood Zone	Average B/C Ratio 2 Feet Elevation	Average B/C Ratio 4 Feet Elevation	Average B/C Ratio 8 Feet Elevation
WOOD FRAME / CRAWLSPACE	A	0.25	0.40	0.44
	X500	0.09	0.13	0.14
	X	0.02	0.02	0.02
MASONRY / SLAB-ON-GRADE	A	0.08	0.14	0.17
	X500	0.03	0.05	0.05
	X	0.01	0.01	0.01

Given the discrepancy between the benefit values due to elevation and the relative large costs of elevation for existing structures, it is not surprising to find these values on average are all less than one. However, we do see certain housing types within specific flood zones doing better than others such as A zone homes that are wood frame with a crawlspace. We further illustrate in Figure 33 a Travis County best-case scenario for an X500 wood frame/crawlspace home elevated 8 feet using various time horizons of 25, 10, 5, and 1 year as well as various interest rates of 0%, 5%, 10%, and 15%. While the 25 year time horizon at 0% discount rate is greater than one so that it is deemed economically worthwhile, as soon as these benefits are discounted by an interest rate of 5% the ratio drops below one to 0.61. Similar drop-offs in benefit-cost ratios occur for the 10 and 5 year time horizon scenarios that are at 0.43 and 0.21 even with 0% discounting.

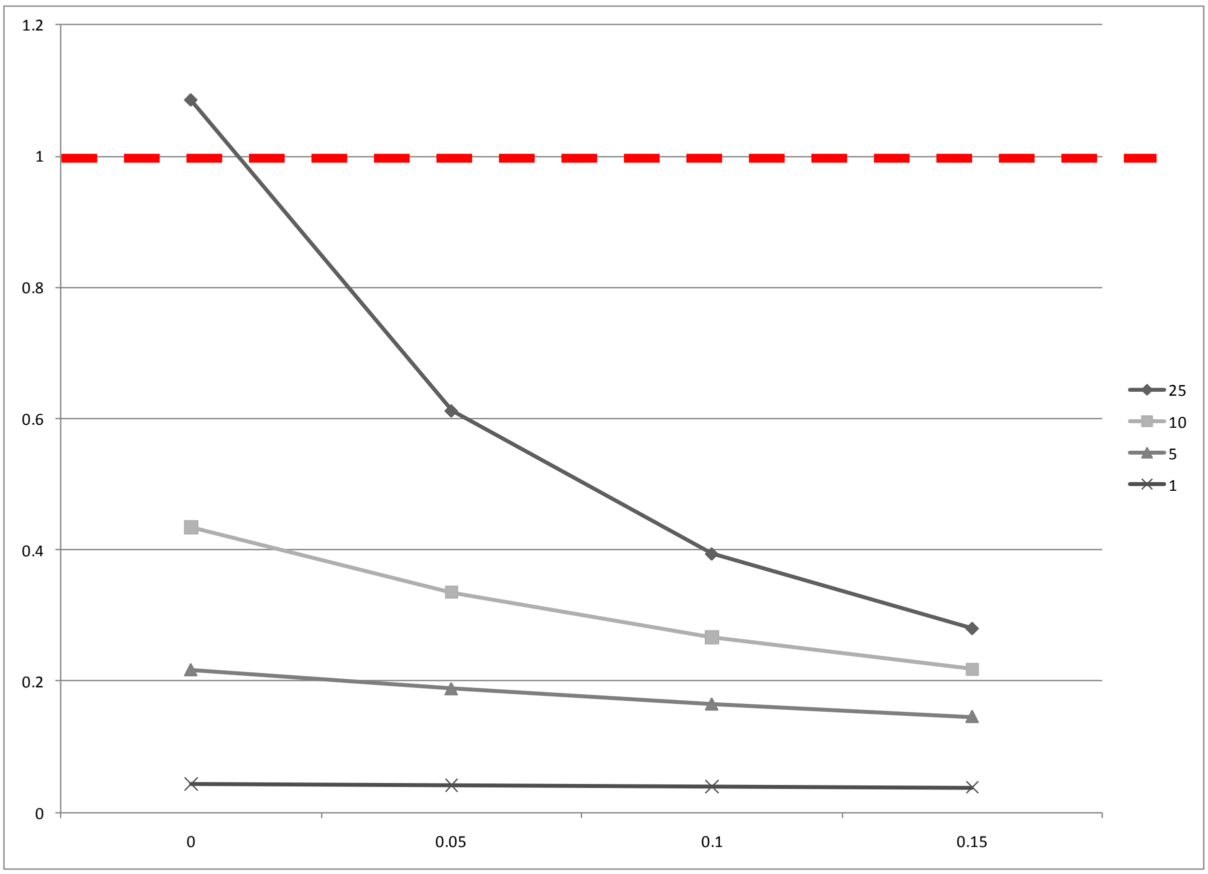

Figure 33. Travis County Benefit-Cost Ratio Best-Case Scenario for an X500 wood frame/crawlspace home elevated 8 feet. *Source: Czajkowski et al. (2012)*

The average benefit-cost ratios by flood zone for Galveston County for the two construction/foundation housing types are provided in Table 16. Again, these particular average ratios are determined assuming 25 years of benefits at a 0% discount rate. Given the discrepancy between the nominal benefit values due to elevation and the relative large costs of elevation for existing structures, it is again not surprising to find these values on average to be all less than one. However, we do see certain housing types within specific flood zones doing better than others such as V and A zone homes that are wood frame with a crawlspace.

Table 16. Galveston County Average Benefit-Cost Ratios per Level of Elevation by Flood Zone and Housing Type over 25 Years and a 0% Discount Rate. *Source: Czajkowski et al. (2012)*

House Type	FEMA Flood Zone	Average B/C Ratio 2 Feet Elevation	Average B/C Ratio 4 Feet Elevation	Average B/C Ratio 8 Feet Elevation
WOOD FRAME / CRAWLSPACE	V	0.20	0.29	0.39
	A	0.22	0.30	0.37
	X500	0.11	0.17	0.23
	X	0.07	0.10	0.12
MASONRY / SLAB-ON-GRADE	V	0.07	0.10	0.15
	A	0.07	0.11	0.14
	X500	0.04	0.06	0.09
	X	0.02	0.03	0.05

Highlights

Benefit-cost results from both counties suggest that if elevation to existing homes is to be undertaken as a flood mitigation effort, it must be done very selectively from an economic perspective due to the relatively significant costs of elevation to existing structures. However, they note that they have only calculated only the direct economic benefits stemming from elevation and not considered other direct benefits, such as reduced fatalities and injuries, or reduced damage to infrastructure and the environment. Nor have they looked at the indirect economic benefits such as the savings in the government costs of permanently relocating residents. Furthermore, elevation costs for new construction would be significantly lower than for existing construction, which could make mitigation of new homes much more appealing.

3.8.2 New York City Flood Mitigation BCA

Prompted by the occurrence of Hurricane Irene in 2011 and especially Hurricane Sandy in 2012, different flood risk reduction strategies have been proposed for New York City (NYC) by scientists, engineers, NGOs and policymakers (Aerts et al. 2013a; NYC 2013). Some measures are effective in lowering the probability of the flood hazard and protecting large parts of the city, for example, through barriers, levees, and wetland restoration or beach strengthening. However, some of these large scale engineering options have received criticism since their initial investment costs are very high, as Aerts et al. (2013a) show. Other measures lower exposure and vulnerability by linking to current policies, for example, through zoning regulations and enhancing building codes (Aerts and Botzen 2011). These measures may considerably reduce the potential damage that floods cause and entail lower investment costs than flood protection infrastructure such as storm surge barriers, but they do not prevent flood waters from entering the City.

Approach

Aerts et al. (2014) provide a comprehensive cost-benefit analysis of flood risk reduction strategies by focusing on both main strategies (preventing flooding and reducing vulnerability), and some derivatives:

1. The *Resilient Open City* strategy (*S1*) builds upon enhancing current building codes in New York City (NYC) (Aerts and Botzen 2011), by elevating or wet-or dry- flood proofing of both existing and new buildings.
2. The *Storm Surge Barrier Strategies 2a, b and c* (*S2a,b,c*) described in Aerts et al. (2013a) aim at lowering flood probabilities in NYC and parts of New Jersey (NJ), with different sets of storm surge barriers and, additionally, protective measures such as levees and beach nourishments.
    - *S2a* "*Environmental dynamics"* consists of three barriers to close off parts of NYC and NJ, while preserving the wetland dynamics of Jamaica Bay.
    - *S2a* is expanded to *S2b,* "*Bay closed"* by adding a fourth barrier that closes off Jamaica Bay.
    - *S2c*, "*NJ-NY connect"* replaces three barriers from *S2b* with one large barrier in the Outer Harbor*,* thereby protecting a larger area. The barriers systems are designed to withstand an extreme surge of 25-30ft.
3. *S3*, the "*hybrid solution"* proposed by Aerts et al. (2013a)*,* combines cost-effective building code measures of *S1* only in high risk 100-year return flood zones (defined by the U.S. Federal Emergency Management Agency, FEMA) with protection of critical infrastructure to reduce economic losses due to business interruption. *S3* includes moderate local flood protection measures, such as levees and beach nourishment that are also part of *S2c*. These building code measures and local protection measures are adjustable to future climate change as they can be upgraded if flood risk increases.

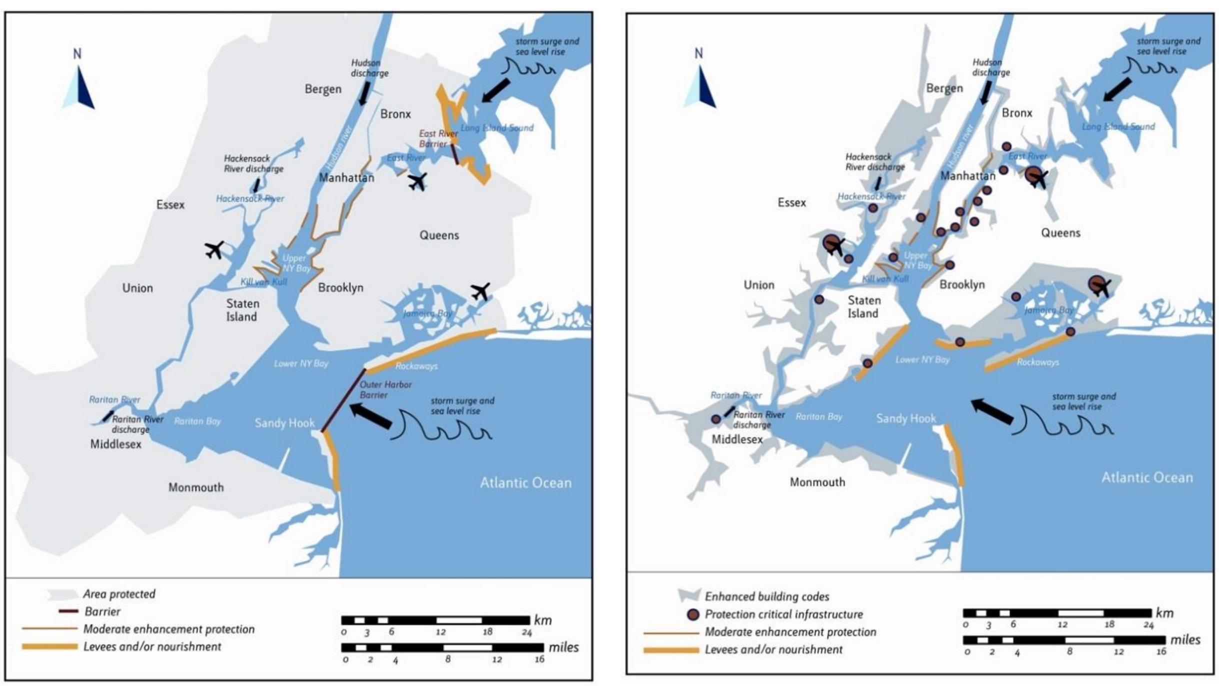

Figure 34: Left panel shows strategy S2c for NYC; right panel shows strategy S3.
Source: Aerts et al., 2014

As Aerts et al. (2014) explain: “Strategy *S2c* (left panel) reduces the length of the coastline of the NYC-NJ area as much as possible, to minimize flood protection costs. Two storm surge barriers are developed: one large barrier that connects Sandy Hook in NJ and the tip of the Rockaways in Queens, NY and a barrier in the East River. Some lower spots (bulkheads, levees, or landfill) on the inside of the protection system will be elevated to accommodate rising water levels caused by Hudson River peak discharges during a storm event. Strategy *S3* (right panel) combines cost effective flood-proofing measures with local protection measures of critical infrastructure. Such a ‘hybrid solution’ aims at keeping options open: either (a) building codes can be further enhanced in the future with additional local protection measures or (b) storm surge barriers can be developed.”

The CBAs of building code strategies for *S1* and part of *S3* pertain to three main categories of measures: elevation, wet flood proofing, and dry flood proofing. The costs and benefits of the application of each measure are estimated for 2ft, 4ft, and 6ft above the current height of existing buildings. A distinction is made for each strategy whether it applies to existing buildings or only new residential buildings. A further distinction is made between application of the measures in the 1/100 and 1/500 FEMA flood zones, based on the maps that were available in 2012. Elevation is applicable to both 1/100 high-risk named “A” and “V” zones, while wet and dry flood proofing is only analyzed for application in A zones since these stand-alone measures are less effective to cope with high velocity waves in V zones, especially if flood depths are high.

Detailed cost estimates of the building code measures are provided in Aerts et al. (2013a). These cost estimates are based on GIS information on the current and projected (until 2040), building stock in NYC flood zones. Based on the number and characteristics of these buildings and engineering cost estimates of flood proofing buildings, flood zone aggregated costs of applying a building code strategy to all buildings for which this strategy can be applicable are obtained. Aerts et al. (2013a) estimate the investment and maintenance costs of the storm surge barrier strategies based on costs of barrier designs made for NYC by engineering firms, and by checking on the reliability of these estimates by examining costs of large storm surge barrier projects conducted around the world in relation to the characteristics of their designs. In addition, the costs of additional flood protection works, such as strengthening the coastline around the barriers are included by assessing where such reinforcements are needed, and by calculating their costs based on published literature of unit prices.

The resulting cost estimates show that flood proofing existing buildings through elevation is very expensive (between $2.3bn and $2.6bn in the A zone). The total costs of dry or wet flood-proofing these buildings is lower, but nevertheless substantial (between $0.25bn and $1bn in the A zone) (Aerts et al. 2013a). Flood proofing of new buildings is cheaper. Especially, elevation is considerably less costly if it is applied to new instead of old buildings, since additional costs of elevating a building are low when this is done during construction of a building (Aerts et al. 2013a). The investment costs of the flood protection strategies *S2a,b,c* are much higher than the building code options: namely, about $19bn for *S2a,b* and $13bn for *S2c*. The hybrid solution (S3) investment costs are about $11bn.

The risk reduction benefits of the building code and flood protection strategies are estimated using a probabilistic flood risk model, which is an extension of Aerts et al. (2013b), that estimates potential flood damage on the census block level in NYC. Average annual flood damage estimates of this model are based on 549 synthetic storm surge scenarios produced by a coupled hurricane – hydrodynamic model. This model is based on the HAZUS MH4 methodology using a detailed database for NYC, and applies flood depth-damage curves to calculate potential damage to buildings and vehicles, for each of the particular 549 inundation scenarios. The risk to other categories (like infrastructure), and indirect economic effects (business interruption) have been added to the model damage output based on observed consequences of Hurricane Sandy (Aerts et al.

2013a). The coupled hurricane model also simulates the effects on surge heights of increased storminess due to climate change. Therefore, future risk and avoided flood damage by each strategy was also simulated using different climate change conditions, related to both sea level rise and storminess. This resulted in three climate change scenarios which built on the Global Climate Model simulations used by Lin et al. (2012) and sea level rise projections for NYC produced by Horton et al. (2010). Another future scenario represents the increase in urban exposure, due to new construction in flood zones until the year 2040. It should be noted that those benefit-cost ratio (BCR) and (Net Present Value) NPV estimates include only reduced annual flood risk to building stock as benefit (including business interruption and infrastructure losses).

Results

Aerts et al. (2014) present the results of an extensive cost-benefit analysis of the aforementioned strategies which was conducted over a 100 year period. A time horizon of 150 years has also been used for the flood protection strategies, but these results are very similar to the calculations with a 100-year time horizon. Sensitivity of the results to the discount rate is examined by conducting all cost-benefit analyses using a low (4%) and high (7%) value of the discount rate. Moreover, all cost-benefit analyses are conducted using an interval of a lower (-22%) and upper (+17%) value of the avoided flood damage estimate which reflects the 95% confidence interval of the water level caused by a storm and uncertainty in the resulting damage estimate (and thus risk reduction of a strategy). Finally, the influence on the results of delaying the investment in flood protection infrastructure by 25 years is examined.

None of *S2a,b,c* nor *S3* is economically beneficial under current levels of flood risk and the low climate change scenario, although the proposed *S3* by Aerts et al. (2014) shows the highest Net Present Value (NPV) and benefit cost ratio. Under the middle climate change scenario and high discount rate (7%) *S3* is the only strategy that would make sense economically. When a low 4% discount rate is considered, all strategies make economic sense if sea level rise occurs and climate change increases storminess. In that case, *S2c* results in the highest NPV. All storm surge barriers are economically feasible if flood risk develops according to the high rapid ice melt scenario. Since trends in flood risks are still highly uncertain (Lin et al. 2012), flood management strategies for coastal cities must also be flexible to allow for a change in policy when more detailed and reliable information becomes available on, for example, sea level rise. Therefore, Aerts et al. (2014) propose to start with implementing building code measures that are part of *S3* which are already cost effective under current climate conditions: namely, elevating new buildings +6ft in V zones and +4ft in A zones. Moreover, critical infrastructure should be protected against flooding by mainstreaming adaptation measures into recovery and repair works. If climate develops according to the middle climate change scenario – meaning that storminess increases – then NYC should consider investing in storm surge barrier *S2c*.

Highlights

Overall, this study by Aerts et al. (2014) shows that a comprehensive and spatially detailed flood risk analysis on a metropolis scale can provide a robust cost-benefit evaluation for policy makers, despite the modelling of large uncertainties related to discounting, risk estimates, time horizons of investments, and future scenarios of development of flood risk. Future work could aim to integrate reduction of casualties, health risks, and environmental impacts of the flood protection strategies.

In conclusion, the Texas study similarly finds that if elevation to existing homes is to be undertaken as a flood mitigation effort, it must be done very selectively from an economic perspective due to the relatively significant costs of elevation to existing structures. In New York, none of the storm surge barrier nor hybrid approaches analyzed is economically beneficial under current levels of flood risk and the low climate change scenario. However, they find when a low 4% discount rate is considered, all strategies make economic sense if sea level rise occurs and climate change increases storminess. In Pensacola, similar relaxations of discount rates and higher sea-level risk scenarios lead to more favorable BCRs.

4.0 Moving Beyond the Economic Effectiveness of Individual Property Mitigation

Chapter 4 Summary

As we have shown, mitigating individual homes against surge risks can be economically effective in particular circumstances; for example, single-family homes with low first-floor elevations and open foundations in the 10% or 4% annual chance surge zones are economically effective to elevate. However, examining the economic effectiveness of individual home mitigation cannot capture community-level benefits, as mitigating individual properties eventually translates into better neighborhood- and community-level resilience to flooding. Therefore, we advocate that the broader benefits of flood risk mitigation beyond an individual property owner must be analyzed and ultimately incorporated into a mitigation economic effectiveness analysis. These additional broader benefits include but are not limited to emergency response/rescue services, frequent damage to exterior property improvements (like fences, sheds, pools, playsets, etc.), damage to vehicles, and recurring damage from foundation and crawlspace flooding.

To better understand the linkages between individual and community level flood mitigation, in this chapter we discuss the Flood Risk Reduction and Risk Assessment (RA/RR) Plan from the Charlotte Mecklenburg Storm Water Services (CMSWS) Department, and the Community Rating System (CRS) of the National Flood Insurance Program (NFIP). Both the Flood RA/RR Plan and the CRS are comprehensive community-based approaches to flood risk mitigation that have a connection from mitigation benefits of individual structures to that of communities, with the goal of enhancing communities' resilience to flood risks.

The Flood RA/RR plan provides an alternative to the implementation of property flood not solely limited to an individual property mitigation BCR > 1, but used in conjunction with this criteria and including broader benefits to the property. Importantly, this methodology is also built upon economic principles relating to the capturing of indirect and intangible benefits of the flood risk mitigation effort relevant to include in a BCA. And given that these indirect and intangible disaster losses are difficult to identify and quantify, and hence are seldom considered in BCAs, we advocate that the Flood RA/RR Plan should be investigated for other communities to implement its principles, such as those we examined in Escambia County, Florida.

In Escambia County there are three separate communities that participate in the CRS – the City of Pensacola, Pensacola Beach, and unincorporated Escambia County. Previous research has generated the benefits from avoided losses due the CRS activities of Escambia County. However, from economic effectiveness standpoint, the costs of implementing the CRS program in Escambia County have not been ascertained. We initiated a pilot study in Escambia to collect this information. As an existing CRS cost study in Virginia has also found, this important cost information is difficult to collect. We provide an overview of our approach and lessons learned, with CRS cost information pending as of the date of this report. Key findings from the pilot study include: costs of managing the CRS are not regularly tracked by the CRS coordinators; basing the costs on the percentage of total points earned is a good starting point but not wholly reflective of total costs; given the external connections of the CRS to other departments and program, costs external to the CRS need to be collected; and while the existing costs of managing the program are certainly helpful, understanding the cost to improve CRS rankings would be very useful.

4.1 Assessing Flood Mitigation from the Charlotte Mecklenburg Storm Water Services Department and the Flood Risk Assessment/Risk Reduction Plan

Charlotte-Mecklenburg Storm Water Services (CMSWS) manages and maintains the regulated floodplains within the City of Charlotte, the towns of Cornelius, Davidson, Huntersville, Matthews, Mint Hill, and Pineville, and the unincorporated areas of Mecklenburg County. They are responsible for over 4,000 buildings and accessory structures in approximately 350 miles of regulated the floodplain within the County. Their goal is to reduce the potential for loss of life and property due to flooding, while enhancing the natural and beneficial functions of the floodplain.. CMSWS aims to reduce flood risk to people and property through a variety of programmatic strategies, including: enforcing floodplain regulations, maintaining floodplain maps, providing advanced flood notification to emergency responders, assessing flood risk, developing mitigation plans, and *implementing flood hazard mitigation projects.* CMSWS provided us background information on the development of their 2012 Flood Risk Assessment and Risk Reduction (RA/RR) Plan (CMSWS, 2012) and historic data on their flood mitigation activities in Charlotte Mecklenburg, North Carolina.

In Figure 35 below, we show data on acquisition and demolition projects implemented by CMSWS from 2000 to 2011. Figure 35 shows the counts of each type of structure that were acquired and demolished by CMSWS, classified by whether the BCR was under 1 or equal or greater than 1. For these various property types, what this data shows is that **most of the structures that had been acquired and demolished had a BCR less than 1**, especially for single-family residences.

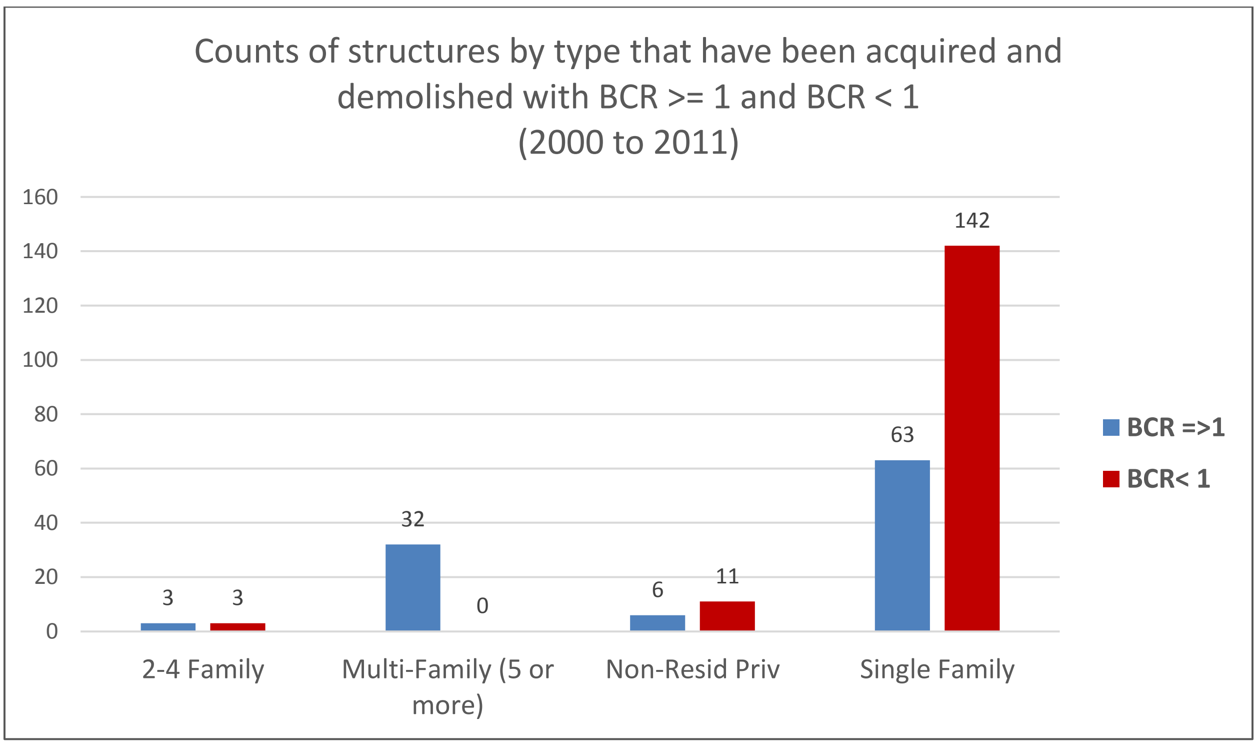

Figure 35. Counts of structures by structure type that were acquired and demolished from 2000 to 2011 by CMSWS, classified according to whether the BCR for each structure was equal or greater than one (blue bars), or less than one (red bars).

Our Escambia County analysis has been built upon the methodological premise that by definition, a BCR of 1 means that the expected discounted benefit of implementing the mitigation equals its cost. Any measure where a BCR is greater (less) than 1 is considered to be economically-effective (not economically effective) and should (should not) be implemented as the benefits exceed (do not exceed) costs and a project thus adds (does not add) value to society – mostly from a financial perspective. In Charlotte-Mecklenburg, it's clear that the BCR does not solely limit the implementation of mitigation efforts. How does this happen?

Recognizing that FEMA's approach to assessing overall effectiveness of flood mitigation techniques with the BCA Toolkit has what they deem substantial limitations, CMSWS began developing their Flood RA/RR Plan (CMSWS, 2012)[27]. This plan focused on flood risk to the property (probabilities and consequences) instead of solely benefits of mitigating losses to the building. One identified limitation is that FEMA BCA and most BCAs in general tend to favor high-value property, as losses avoided from floods are a percentage of building values. Currently the RA/RR Plan purposely neglects monetary values of what is impacted by flooding in order to normalize values. For example, all homes, cars, electrical and mechanical equipment at risk to flooding and evaluated for mitigation have the same values that are derived from average values of these things in Charlotte Mecklenburg County. Another key limitation according to CMSWS is that "it is also commonly noted that the BCA Tool's definition of benefits, which is limited to future property losses prevented or reduced, is too narrow in scope and doesn't take into account additional benefits to society and/or community values that are often realized at the local level" (CMSWS, 2012 pg. 50). These additional benefits include but are not limited to emergency response/rescue services, frequent damage to exterior property improvements (like fences, sheds, pools, playsets, etc.), damage to vehicles, and recurring damage from foundation and crawlspace flooding. In addition to the community-based benefits, there are other community needs that CMSWS considers in their flood mitigation scoring System. These items are described in more detail below (e.g., expanding or connecting publicly owned lands, greenway trails, sanitary sewer routes and water quality buffers). CMSWS has determined that multi-benefit mitigation efforts garner more support from elected official and the community. From an economic perspective these would be considered indirect and intangible (i.e., external) benefits stemming from the mitigation, but still relevant to include in a BCA (Mechler et al., 2014). Both the Texas and New York City studies presented in Section 3.8 above discuss the potential inclusion of these additional benefits. However, as Mechler et al. (2014) discuss, indirect and intangible disaster losses are difficult to identify and quantify and hence are seldom considered in BCAs.

CMSWS limits the emphasis and influence of the BCA Tool in its risk reduction recommendations. Rather, their Flood RA/RR plan has developed an approach to evaluating flood risk and associated mitigation technique for each flood-prone property from a more comprehensive, holistic, and multi-disciplinary risk-based approach to risk assessment and risk reduction. Specifically, the purpose of the Flood RA/RR Plan is to "recommend a more comprehensive range of specific flood mitigation techniques at the building/parcel level and to assist private property owners and local government officials in making informed decisions about flood mitigation strategies. In short, the purpose of the Flood RA/RR Plan is to assist in identifying, prioritizing, and planning future flood mitigation projects" (CMSWS, 2012 pg. 7). [It is important to note that in Figure 41 we presented BCR data from 2001 to 2011. The determination of these flood mitigation actions was therefore done prior to the 2012 Flood RA/RR Plan that we describe in detail here. However, similar indirect benefits were utilized for the Figure 41 data although not quite as extensive as the 2012 plan. For example, "…Charlotte-Mecklenburg completed engineering studies that evaluated flood hazard mitigation strategies in 10 of the County's most urbanized

[27] CMWSW Flood Risk Assessment/Risk Reduction (RA/RR) Plan can be found at http://charlottenc.gov/StormWater/Flooding/Documents/Flood_RARR_Plan-Final.pdf#search=RA%2FRR%20plan.

watersheds. This study primarily used two sets of criteria to evaluate the different improvement alternatives—location in relation to the Community Encroachment Area Boundary (0.1' Floodway) and cost effectiveness (Benefit-Cost Ratio). As a secondary consideration, the study also evaluated flood mitigation techniques for flood reduction capability, constructability, social/environmental impacts, and hydraulic impacts in a broad sense." (CMSWS 2012, pg. 6). Thus, these mitigation decisions still incorporated indirect and intangible impacts, being the forerunner to the even more comprehensive 2012 plan – "The successful implementation of the buyout strategy in the previous Flood Hazard Mitigation Plan, coupled with FEMA's narrow view of the financial "benefits" of mitigation, has created an opportunity to reprioritize remaining flood-prone buildings and re-evaluate strategies to reduce the flood risk." – CMSWS, 2012 pg. 6]

The CMSWS RA/RR Plan is comprised of three primary elements: (1) flood risk property score, (2) risk reduction recommendations, and (3) flood mitigation priority scores. The flood risk property score is the foundational part of the plan. The assessment of flood risk for an individual property utilizes 1) flood hazard data (examples: flood event probabilities, flood depths, FEMA flood zone and BFE, high velocity zones, floodways, and 2) damage/impacts data (examples: FFE of structures, foundation and frame types of structures, elevation certificate data, vehicle parking areas, types of exterior property improvements, history of damaging events, and other pertinent data.

Part of the flood risk property score uses three additional location-based factors. Each location-based factor has a multiplier that is applied to the flood risk property score. The first location based factor is whether a property is in a high or medium depth-velocity danger zone. If the property is in a high depth-velocity danger zone as modeled by CMSWS, a multiplier of 1.5 is applied to the flood risk property score. If the property is in a medium depth-velocity danger zone, a multiplier of 1.3 is applied. The second location-based factor is whether property is near a storm drainage overflow area. If the property is near an area impacted by storm drainage overflows, which are not part of FEMA DFIRMs, then a multiplier of 1.3 is applied to the flood risk property score. Storm drainage overflows are usually adjacent to areas of low elevation on streets, between streams and storm drain inlets. Areas with storm drainage overflow risks can be mapped in a GIS using street areas, elevation data, and storm water drain inlets, and assessing adjacency to potential flood mitigation candidate properties. The third location-based factor is if the property is in a community encroachment area, for which a multiplier of 1.1 is applied. Community encroachment areas are delineated by CMSWS and are areas where floodplain management ordinances apply. Once the flood risk property score and the location-based factors and multipliers are assessed, then the risk reduction recommendations are made for each property.

Once the flood risk property score is determined, risk reduction recommendations are made based on a list of 19 different mitigation activities (See Table 17) which have been deemed potentially effective in the Charlotte-Mecklenburg area. Each of the 19 mitigation options is evaluated for every candidate property and rated with four different options as shown in Table 17: highly effective and recommended, effective, further evaluation needed, and not recommended. The methodology behind these planning level recommendations is based on a floodplain management vision supported by various guidance documents and plans approved by elected officials.

Table 17. The flood mitigation techniques that are evaluated for each candidate property to be mitigation as part of the CMSWS RA/RR Plan, and the potential effectiveness rating for each mitigation technique. (From page 47 of the CMSWS RA/RR Plan.)

Num-ber	Mitigation Technique	Highly Effective, Recommended	Effective	Further Evaluation Needed	Not Recommended
1	**Buyout (demolition/ acquisition)***	X	X	X	X
2	Demolition/ Rebuild	X	X	X	X
3	**Demolition/ relocation***	X	X	X	X
4	**Buyout (acquisition, demolition or relocation) and resale***	X	X	X	X
5	**Elevation***	X	X	X	X
6	Fill Basement	X	X	X	X
7	**Dry Floodproofing***	X	X	X	X
8	**Wet Floodproofing***	X	X	X	X
9	Audible Warning	X	X	X	
10	Detention (e.g., ponds)			X	X
11	Flood Control (e.g., culvert and bridge modifications)			X	X
12	Flood Information & Notification System (FINS)	X			
13	Public Education	X			
14	Flood Insurance	X			
15	Levee			X	X
16	Protecting Equipment	X	X	X	
17	Partial Dry Floodproofing			X	X
18	Partial Wet Floodproofing			X	X
19	Ring Levee			X	X

Note: Mitigation techniques in bold font and followed with an asterisk are evaluated with the BCA Toolkit if these techniques are deemed “highly effective” or “effective” for a structure.

There are also watershed-level mitigation activities assessed in flood risk property scoring, such storm water detention facilities such as ponds, and storm water system controls such as the modification of bridges or culverts to mitigate higher floodwaters. Storm water system control projects are designed to reduce flood risks due to “backwater”: backwater is flooding caused by increased upstream flood elevations that are caused by undersized bridges or culverts. Both storm water detention facilities and storm water system controls can be funded by government. For example in Charlotte Mecklenburg, the North Carolina Department of Transportation (NCDOT) maintain bridges and culverts therefore they fund storm water system control projects. A Flood Information & Notification System (FINS) is another community-level mitigation technique: this is a network of automated rain and stream gauges placed in flood-prone areas that is designed to alert emergency personnel of a flood threat.

The third component of the Plan, flood mitigation priority scores, is designed to assess non-risk based community benefits and other indirect benefits that cannot be accounted for in the flood risk property score. The flood mitigation priority scores are used to prioritize individual properties as well as project areas for mitigation. The history of success of acquisition and demolition projects implemented in Charlotte Mecklenburg demonstrated that the view of economic benefits as assessed by FEMA with the BCA Toolkit is too narrow in scope for CMSWS’s floodplain program. The limitations of FEMA’s BCA approach and the added value of collaborative mitigation projects are the primary motivations for the priority scores within the RA/RR Plan.

In Table 18, we show the RA/RR Plan Flood Mitigation Score Factors Summary (see Table 5 of the RA/RR Plan, pages 53-54). Each mitigation technique listed in Table 17 that is deemed highly effective or effective for a property or project area is assessed in terms of each priority factor listed in Table 18. Each priority factor is scored according to the criteria listed in Table 18. Six of the 19 mitigation techniques used in the RA/RR Plan can be evaluated with the BCA Toolkit (we have looked at three of these in Escambia). In Table 17, techniques in bold font and an asterisk immediately after their name are evaluated with the BCA Toolkit if they are deemed “highly effective” or “effective” options for a property. Again, in relation to our Escambia County analysis, it is important to note that the BCRs of these 6 mitigation techniques, as calculated with the Toolkit, do not have to be 1 or greater to qualify for points with the flood mitigation priority scoring system. As noted in Table 17, if one of these six techniques for a property or project area has a BCR according to the Toolkit between 0.5 and 1, it gets 75 points. In other words, a BCR > 1 is not the only determinant for mitigating an individual property.[28]

Table 18. Flood mitigation score factors summary (Table 5, pg. 53-54 of RA/RR Plan). The number and name of the priority factor is listed with the possible numbers of points for each criterion and the possible mitigation techniques applicable for each priority factor.

#	**Priority Factor**	**Points**	**Criteria**	**Mitigation Techniques That Apply**	
1	Life and human safety	150	Project involves the permanent removal of habitable structure from flood hazard area	Property Acquisition and Structure Demolition Property Acquisition and Structure Relocation Property Acquisition, Demolition/Relocation, and Re-sale	

[28] Through personal communication with CMSWS although a BCR > 1 is not main determining factor for flood mitigation priority, it is safe to assume that if any mitigation action had a BCR > 1 and there was no other extenuating circumstance for not mitigating the home such as property owner lack of participation, very complicated real estate transaction, etc., this property would eventually be mitigated. In other words, economically efficient mitigation efforts are not being disregarded.

#	Priority Factor	Points	Criteria	Mitigation Techniques That Apply	
2	Cost effectiveness (Benefit-Cost Ratio)	150 75 0	BCR ≥ 1.0 0.5 ≤ BCR < 1.0 BCR < 0.5	Property Acquisition and Structure Demolition Property Acquisition and Structure Relocation Property Acquisition, Demolition/Relocation, and Re-sale Structure Elevation Dry Floodproofing of Structures Wet Floodproofing of Structures	
3	Proximity to other mitigation projects	125	Project is located within 1,000 feet of other previously implemented or planned mitigation projects	Property Acquisition and Structure Demolition Structure Demolition and Rebuild Property Acquisition and Structure Relocation Property Acquisition, Demolition/ Relocation, and Re-sale Structure Elevation	
4	Property added to flood zone	100	Property was not located in a mapped floodplain at the time of purchase by current owner	Any	
5	Repetitive loss structure	100 50 0	Severe Repetitive Loss Structure Repetitive Loss Structure N/A	Any	
6	Property adjacent to publicly owned land	50	Property touches publicly owned land	Property Acquisition and Structure Demolition Property Acquisition and Structure Relocation Property Acquisition, Demolition/ Relocation, and Re-sale	
7	Property located on five-year planned greenway trail	50	Property intersects with five-year planned greenway trail	Property Acquisition and Structure Demolition Property Acquisition and Structure Relocation Property Acquisition, Demolition/ Relocation, and Re-sale	
8	Property located on five-year planned sanitary sewer route	50	Property intersects with five-year planned sanitary sewer route	Property Acquisition and Structure Demolition Property Acquisition and Structure Relocation Property Acquisition, Demolition/ Relocation, and Re-sale	
9	Property intersects with water quality buffer	50	Property intersects with County's comprehensive stream buffers	Property Acquisition and Structure Demolition Property Acquisition and Structure Relocation	

#	Priority Factor	Points	Criteria	Mitigation Techniques That Apply	
10	Property located in an Environmental Focus Area	50	Property located in one of the County's top ten impacted watersheds	Property Acquisition and Structure Demolition Property Acquisition and Structure Relocation	
11	Property covered by NFIP policy	30	Property address included in FEMA's NFIP policy database	Any	
12	Historic preservation and cultural asset protection	30	Property includes historic structure(s) or is in proximity to areas of historic or cultural significance	Property Acquisition and Structure Relocation Structure Elevation Dry Floodproofing of Structures Wet Floodproofing of Structures	
13	Other	150 100 50	High Medium Low	Any	

CMSWS developed the framework of the RA/RR Plan and performed pilot testing to adapt the initial methodology in some areas. But importantly, beyond the quantitative development of the tool, successful implementation ultimately needed input and support from the community. Thus, the second phase involved a Citizen's Review Committee (CRC) who met 9 times during year 2011. The CRC was comprised of 12 vocal residents who own flood-prone properties in different neighborhoods. The CRC discussed ideas for improvement as the Plan was being developed and helped define the impacts to life and property. Engaging people that experienced the routine flood damage, especially damage not included in traditional FEMA BCA methods, was a critical part of creating a valid Plan that could be broadly supported.

In conclusion, this Flood RA/RR plan provides an alternative to the implementation of property flood mitigation beyond a BCR > 1. Importantly, this methodology is also built upon economic principles relating to the capturing of indirect and intangible benefits of the flood risk mitigation effort relevant to include in a BCA (Mechler et al., 2014). And given that these indirect and intangible disaster losses are difficult to identify and quantify, and hence are seldom considered in BCAs, we advocate that the Flood RA/RR Plan should be investigated for other communities to implement its principles, such as those we examined in Escambia County, Florida.

4.2 Community Mitigation via FEMA's Community Rating System (CRS)

4.2.1 CRS Overview

Given the existing and increasing risks from flooding, not only is there a growing interest in enhancing individual homeowner ex-ante preparedness and resilience for such events, but also enhancing community ex-ante preparedness and resilience to these events as well. A recent review of residential flood insurance markets in more than 25 countries[29] (Atreya et al., 2014) reveals that only the United States has a national program that systematically encourages communities to better prepare for flood events, quantitatively scores communities across a number of flood resilience activities and links scores to reduction of insurance premiums for residents in those active communities. This is the Community Rating System (CRS), which is managed by the NFIP under FEMA. The CRS is a voluntary national program that since 1990 systematically encourages communities to better prepare for flood events, quantitatively scores communities across 19 high-level flood mitigation activities, and links scores to reduction of flood insurance premiums for NFIP policyholders in those approximately 1,300 active CRS communities. For each activity the community undertakes, and depending on the level of achievement within that activity, the community obtains points. The more points, the better the community is rated (from 10 to 1, 10 being the lowest rating and 1 the highest). And the better the rating, the larger is the premium discount (up to 45 percent) to eligible policyholders within the community. Today, while the number of communities that participate in the CRS program is small in relative terms (1300 out of 20,000 plus NFIP participating communities), they represent an estimated two-thirds of the total flood insurance policies sold by the NFIP across the United States.

<u>CRS Operational Background</u>

The goals of the Community Rating System (CRS) are to reduce flood damages to insurable property, strengthen and support the role flood insurance can play in this regard, and encourage communities to adopt a more comprehensive and coordinated approach to floodplain management. The CRS provides economic incentives in the form of premium discounts for eligible NFIP policyholders in communities that go beyond the minimum floodplain management requirement. The 19 creditable activities in the CRS are organized under four main categories (called "series"): Public Information, Mapping and Regulation, Flood Damage Reduction, and Flood Preparedness.[30] All NFIP participating communities start with a class 10 rating (no discounts) and once a community applies to the CRS and its implementation of activities is verified, the communities move up in CRS class based upon the credit points they earn. Table 19 presents the creditable activities with their associated maximum possible points that can be earned for that activity (in brackets) and the number of elements in each activity.

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[29] Austria, Australia, Belgium, Canada, Czech Republic, Germany, Finland, France, Hungary, Iceland, Indonesia, Japan, Mexico, Morocco, Nepal, Netherlands, Norway, Peru, Poland, Romania, Slovakia, Spain, Switzerland, the United Kingdom, and the United States of America.

[30] A detailed description of these activities is described in the official CRS's coordinator manual, available at: https://www.fema.gov/media-library/assets/documents/8768?id=2434. Note that the manual is organized such that it starts with an introduction (section 1), then goes to describing the CRS procedure (section 2), then the public information activities (section 3). This is why the first CRS activities series is 300.

Table 19. CRS Activities, Associated Maximum Possible Points and the Number of Elements in Each Activity

Series	**Activities**	Max Possible Points	Number of Elements
	Public Information		
310	Elevation Certificate	116	3
320	Map Information Service	90	7
330	Outreach Projects	350	4
340	Hazard Disclosure	80	4
350	Flood Protection Information	125	3
360	Flood Protection Assistance	110	4
370	Flood Insurance Promotion	110	4
	Mapping and Regulations		
410	Floodplain Mapping	802	7
420	Open space Preservation	2020	7
430	Higher Regulatory Standards	2042	15
440	Flood Data Maintenance	222	4
450	Stormwater Management	755	4
	Flood Damage Reduction		
510	Floodplain Management Planning	622	3
520	Acquisition and Relocation	2250	5
530	Flood Protection	1600	3
540	Drainage System Maintenance	570	6
	Warning and Response		
610	Flood Warning and Response	395	6
620	Levees	235	5
630	Dams	160	5
Total	**19**	**12,654**	**99**

Note: Data based on FEMA coordinator's manual FIA-15/2013

In general, series 300 (Public Information) credits programs that advise people about the flood hazard, encourage the purchase of flood insurance, and provide information about ways to reduce flood damage. These activities also generate data needed by insurance agents for accurate flood insurance rating. Series 400 (Mapping and Regulations) credits programs that provide increased protection to new development. Series 500 (Flood Damage Reduction) credits programs for areas in which there is some protection effort for existing development at risk. And series 600 (Warning and Response) provides credit for measures that protect life and property during a flood, through flood warnings and response programs.

As indicated in Table 2, each activity has several elements for which a community can achieve points. For example, in series 300 *Elevation Certificates,* the participating communities can earn credit for maintaining elevation certificates for pre-FIRM and post-FIRM buildings separately. *Map Information Services* provide information about the local flood hazard and about flood-prone areas that need special protection. *Outreach Projects* provide the public with information needed to increase flood hazard awareness. *Hazard Disclosure* requires disclosure of a property's potential flood hazard to prospective buyers before a lender notifies them of the need for flood insurance. *Flood Protection Information* establishes additional ways to provide the public with information, such as through local public libraries and flood protection websites. *Flood Protection Assistance* provides one-on-one help to people who are interested in protecting their property from flooding. *Flood Insurance Promotion* is most recent activity added to the CRS in 2013 and provides communities credit for first assessing their existing insurance coverage and then acting on how this can be enhanced.

In series 400, *Floodplain Mapping* provides credit for developing regulatory maps and flood data for floodplain management purposes in areas where FEMA did not provide such data, or for mapping to a higher standard than that required by FEMA. *Open Space Preservation* keeps the flood-prone lands free of development and protects the natural functions of the floodplain. *Higher Regulatory Standard* credits regulations to protect existing and future development and natural floodplain functions that exceed the minimum criteria of the NFIP. *Flood Data Maintenance* credits a community for additional map data, maintenance of FIRMs (Flood Insurance Rate Maps), and erosion data. *Stormwater Management* prevents future development from increasing flood hazards to existing development and to maintain and improve water quality.

In series 500, *Floodplain Management Planning* credits the production of an overall strategy of programs, projects and measures that will reduce the adverse impact of the hazard. *Acquisition and Relocation* encourage communities to acquire, relocate, or otherwise clear existing buildings out of the flood hazard area. *Flood Protection* credits communities for retrofitting buildings and constructing flood control projects that reduce the risk of flood waters reaching the buildings. *Drainage System Maintenance* ensures that the community keeps its water run-off channels and storage basins clear of debris.

In series 600, the activity *Flood Warning and Response* encourages communities to ensure timely identification of impending flood threats, disseminate warnings to appropriate floodplain occupants, and coordinate flood response activities to reduce the threat to life and property. *Levees* activity encourages communities to "properly inspect and maintain levees and to identify impending levee failures in a timely manner, disseminate warnings to appropriate floodplain occupants, and coordinate emergency response activities to reduce the threat to life and property." *Dams* activity encourage states to provide dam safety information to communities where dams have been built.

As we see in Table 2, the most CRS points to be earned are in the series 400 (Mapping and Regulations) and series 500 (Flood Damage Reduction). Specifically, activities 420 – open space preservation; 430 – higher regulatory standards; 520 – acquisition and relocation; and 530 – flood protection represent 63 percent of the total possible 12,654 points to be earned.

Based on community activities and total points collected, flood insurance premium rates are discounted in increments of 5 percent up to a maximum of 45 percent for eligible insured properties in the high risk SFHAs, and between 5 percent and 10 percent for eligible insured properties outside of the SFHAs. Table 20 below shows the credit points earned, classification awarded and premium reductions given for CRS communities. From Table 3 we also see the number of communities per CRS class (data as per May 2014), where 75 percent of the participating communities only achieve a CRS rating of 7, 8, or 9.

Table 20. Ten CRS Classes, Associated Point Range and NFIP Premium Discounts

CRS Class	Credit points	Premium reduction for residences in SFHA	Premium reduction for residences outside SFHA	Number of CRS communities benefitting
1	> 4,500	45%	10%	1
2	4,000-4,499	40%	10%	3
3	3,500-3,999	35%	10%	1
4	3,000-3,499	30%	10%	7
5	2,500-2,999	25%	10%	85
6	2,000-2,499	20%	10%	218
7	1,500-1,999	15%	5%	299
8	1,000-1,499	10%	5%	468
9	500-999	5%	5%	203
10	0-499	0	0	All remaining

Note: data as of May 2014. SFHA: Special Flood Hazard Areas, considered as high risk of flooding by FEMA.

As per May 2014, there were 1,285 communities participating in the CRS implementing local mitigation, floodplain management, and outreach activities that exceeded the minimum NFIP requirements. Figure 36 depicts the distribution of the number of active CRS communities across the 50 states in the United States. Not surprising given their high number of NFIP policies-in-force, Florida, California, Texas, New Jersey and North Carolina have among the highest number of active communities.

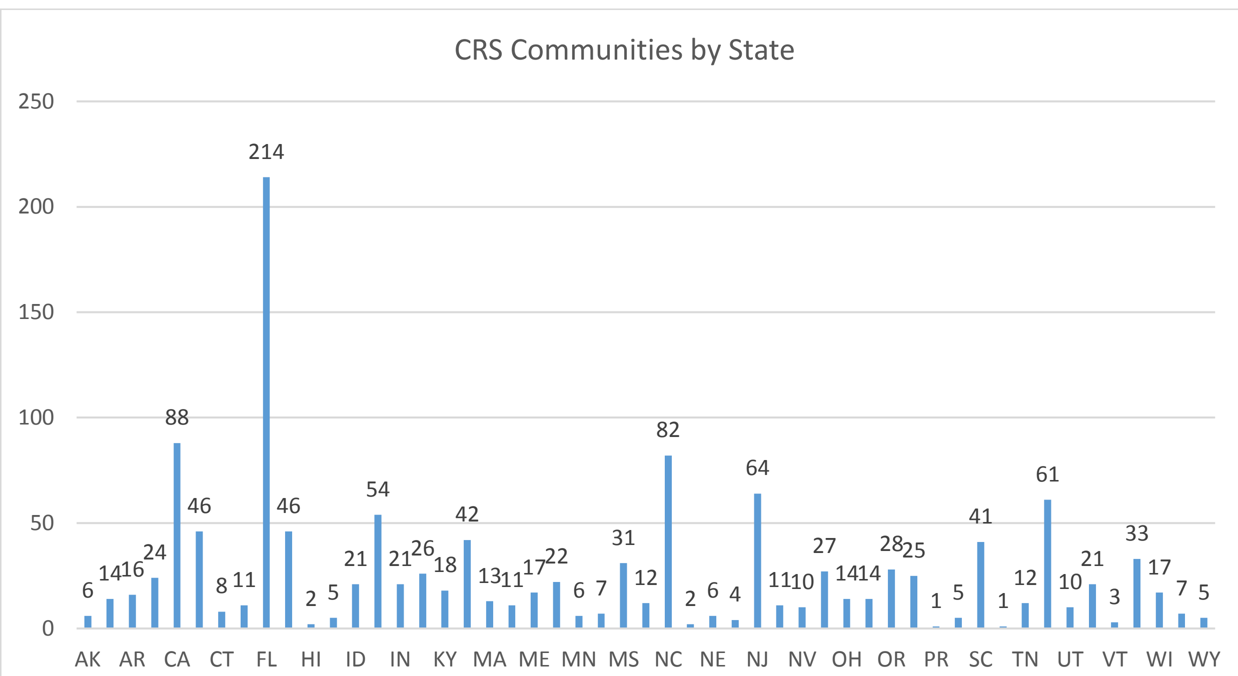


Figure 36. Number of Active CRS Communities by State (data as per 2014)

CRS in Florida

In Figure 37 the dots represent the CRS classes achieved by all of the participating CRS communities nationwide and a darker state color indicates a larger number of participating CRS communities in each state as a percentage of total NFIP communities in the state (participating and non-participating CRS communities). Not only does Florida have the largest number of participating communities, they also have the largest proportion of participating CRS communities per state.

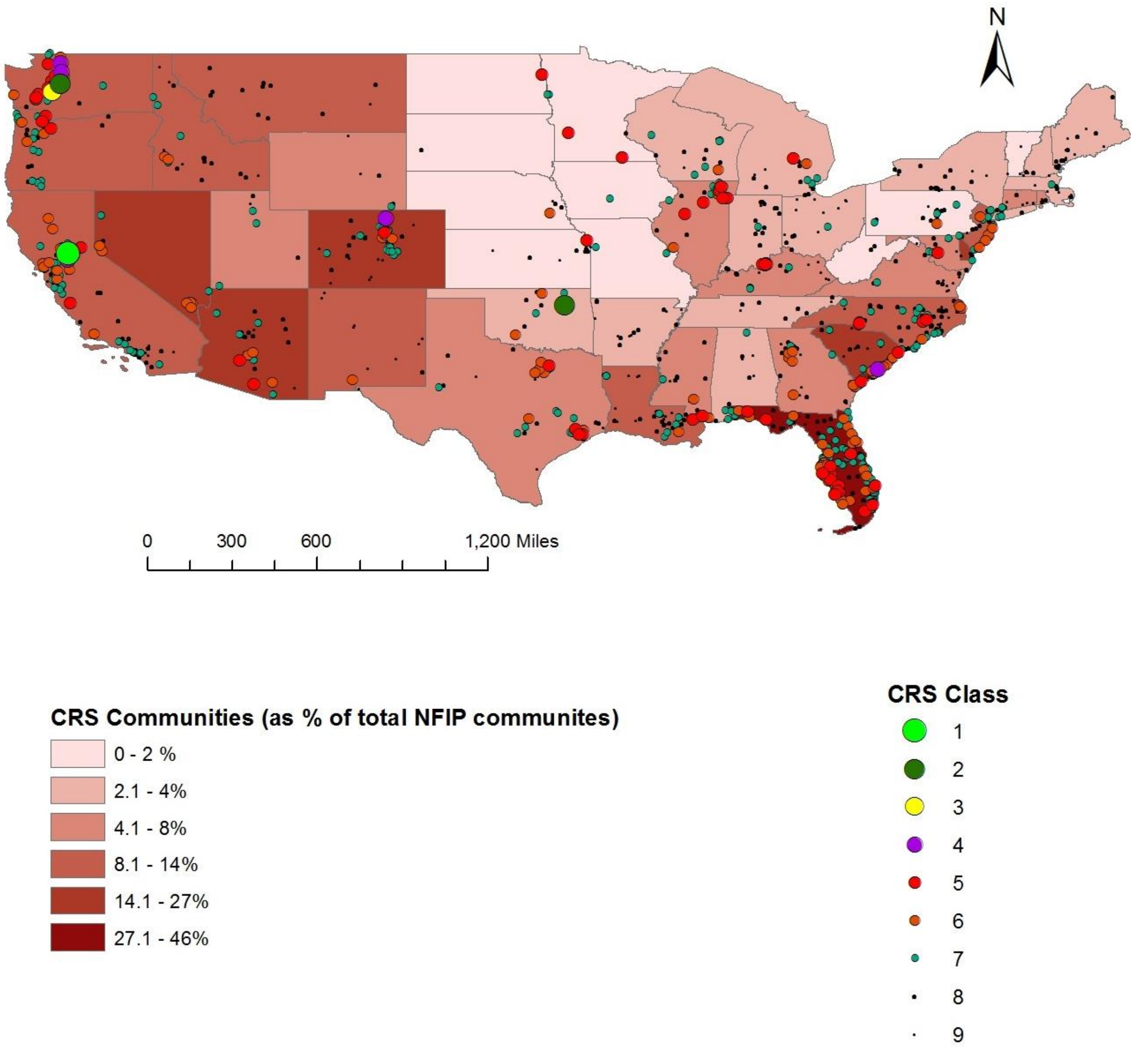


Figure 37: Geographic Distribution of CRS classes (data as per 2011)

There are a total of 480 NFIP participating communities in Florida, with 214 of these participating in the CRS (45 percent) as per 2014. Figure 38 illustrates that 8 percent of FL CRS communities achieve a CRC class of 5, followed by 30 percent class 6, 38 percent class 7, 21 percent class 8, and 3 percent class 9. So although the most participating CRS communities are in Florida, the highest performing communities are not.

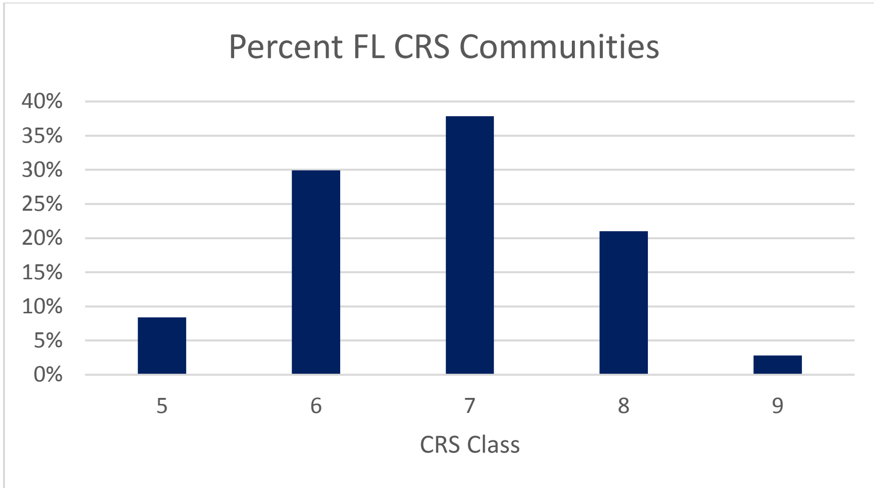
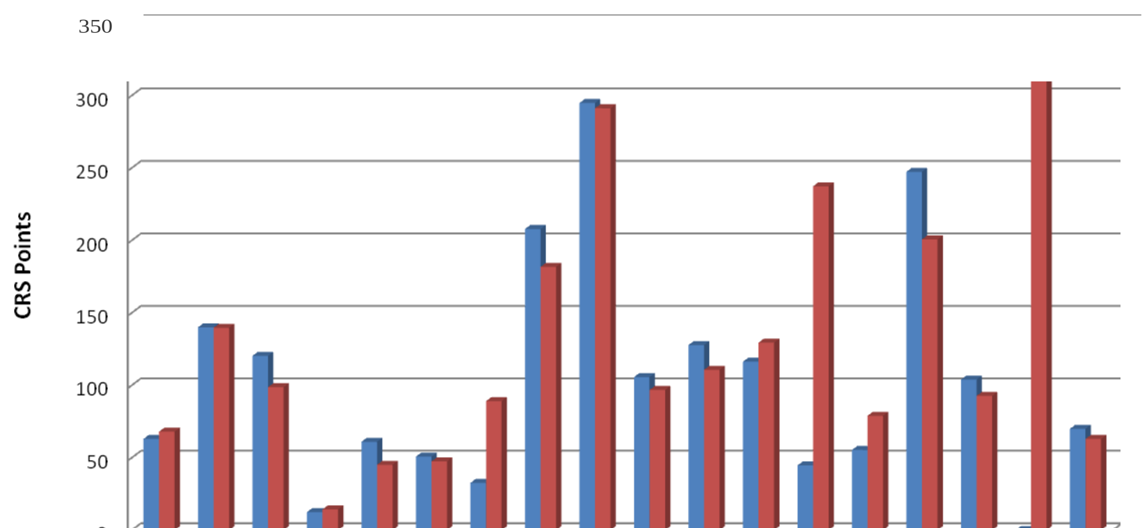


Figure 38: Florida CRS Community Ratings (data as per 2014)

As per the 2013 Florida CRS State Profile (https://crsresources.org/200-2/), 1.9 million policies are located in these CRS participating communities with their CRS activity generating $176 million in premium savings. This compares to only 154,766 policies in the 266 non-CRS participating communities in Florida. Finally, from an overall activity perspective, Figure 39 illustrates that the average CRS community in Florida obtains more points than the average CRS community nationwide in activities 330 (outreach), 350 (flood protection information), 360 (flood protection assistance), all 400 series activities except for 410 (floodplain mapping), 540 (Drainage system maintenance), and 610 (flood warning).



	c310	c320	c330	c340	c350	c360	c410	c420	c430	c440	c450	c510	c520	c530	c540	c610	c620	c630
Florida Average Credit	63	140	120	12	61	51	33	208	295	106	128	116	45	55	247	104	0	70
National Average Credit	68	140	99	14	45	47	89	182	291	97	111	129	237	79	201	93	312	63

Figure 39: Florida Average CRS credits vs National Average Credits (data as per 2013). *Source: Florida CRS State Summary* (https://crsresources.org/200-2/),

4.2.2 CRS Community Flood Mitigation and Flood Loss Reduction

While the CRS has become an established program based on known non-structural mitigation techniques, relatively little research exists on its overall effectiveness. There have, however, been single-state studies at the county level on the observed effects of participation in the CRS. When correlating the class rating of participating CRS jurisdictions with reported property damage on a per-flood basis (while controlling for multiple natural environment, built environment, and socioeconomic contextual characteristics), this line of research found that communities implementing mitigation activities through the CRS experienced significant flood damage reduction in both states. In Florida, results showed a real unit change in CRS class (moving in increments of 5 percent) equaled a $303,525 decrease in the average amount of damage per flood. The CRS rating in this state was more than twice more effective than the number of dams as an indicator of measures that reduce flood damage. Putting these results into a climatological context, the property damage saved by a 5 percent increase in the CRS discount for insurance premiums was roughly equal to the added amount of property damage associated with 2 inches of precipitation (see Brody et al., 2007 for more details). Overall, the statistical effect of the CRS on reducing flood damage was one of the most powerful predictors among all variables analyzed.

Results from the Texas study revealed a similar pattern of flood damage reduction. Among coastal counties in Texas, from 1997 to 2001, a real unit increase in CRS class equaled a $38,989 reduction in the average property damage per flood. Theoretically, if every jurisdiction in the study area had maximized their CRS rating (e.g. achieved a class of 1), the cost of floods would have been less than a quarter of the $320 million catalogued (Brody et al., 2008). While it is not likely all coastal counties in Texas will ever achieve the highest possible CRS class, it demonstrates the effectiveness of non-structural flood mitigation techniques in terms of reducing the severity of flood damage over time.

Building on these regional studies examining CRS classes, Highfield and Brody (2013) conducted a study on the flood loss-reducing effect of specific CRS activities by tracking point totals on a yearly basis over an eleven-year period from 1999 to 2009. Two avoidance-based mitigation activities were found to be most effective in reducing observed flood losses: freeboard (vertical avoidance) and open space protection (horizontal avoidance). The total dollar savings of a one-point increase in the freeboard element (elevation of a structure above BFE) for total losses was equivalent to, on average, nearly $8,300 per community per year. Taking into account the average amount of credit points communities in the sample received for each activity in 2009 (the final year of the study period), freeboard requirements led to the highest overall reduction in flood damages with an estimated average of $800,000 per year. Concurrently, the dollar savings of a one-point increase in the activity for protecting open space in the floodplain was equal to, on average, $3,532 per community, per year. Considering the average amount of points accrued for open space protection among communities in the study sample, the total savings per year for this activity was equivalent to, approximately $591,436.

Empirical evidence also supports the notion that CRS-based mitigation activities at the community level significantly reduce losses incurred at the household level (Highfield et al., 2014). In a study of the Clear Creek watershed south of Houston, TX, the authors found that structures located within CRS-participating communities experience nearly an 88 percent reduction in mean damage than those not under the program. For every point increase in the CRS point total for a community, there is a significant reduction of 0.06% in property damage realized at the parcel level. In particular, public information and outreach activities (series 300) under the CRS had a strong effect on reduced flood losses among property owners. These actions may range from moving contents to a second floor to flood-proofing bottom floors and basements, once the hazard risk is better understood. Other research evaluating the CRS at the community-level has yielded similar results. Michael-Kerjan and Kousky (2010), for example, found that Class 5 CRS communities in Florida had lower flood damage claim amounts compared to CRS communities in the class 6 – 9 range. The CRS program has also shown significant flood damage reductions when evaluated based on pre/post event analyses. For example, following the Fort Collins flood of 1997, CRS-based mitigation activities resulted in between $2.8 and $5.5 million dollars of flood damage reduction (Grigg et. al., 1999). Finally, recent national-level figures indicate that in addition to receiving discounts on insurance premium rates, communities that participate in the CRS experienced a 41.6% overall average reduction in flood claims relative to communities with similar characteristics that do not participate (Highfield and Brody, 2017).

While the existing research has shown the reduced property loss benefits to a number of these specific activities, significantly there has been little corresponding identification of the costs to implementing these activities. Stiff (2017) is an exception to this where she estimated that CRS coordinators in Virginia cost an average of $11,570 to implement the CRS in 21 communities in the state. This overall CRS cost was based upon the estimated median staff time spent specific to the CRS across various positions. And given the importance of the mitigation BCR as we have already presented, generating this information is critical for community-level flood mitigation decision-making and prioritization.

4.2.3 CRS in Escambia – Communities, Points Earned, and Avoided Flood Losses

In Escambia County, there are four communities that participate in the NFIP, and three that participate in CRS (Table 21). For the three that participate in the CRS – Escambia County, Pensacola Beach, and the City of Pensacola – CRS ratings of 6, 5, and 7 have been achieved respectively as per 2016. Thus, two of these three communities are at the higher end of the rating scale (5 & 6) in comparison to the overall CRS ratings achieved for all Florida CRS communities, and in the middle of the Florida CRS range for the City of Pensacola (7).

Table 21. Numbers of single-family homes in Escambia County by NFIP community name and year that the community entered the NFIP, based on 2015 parcel data from the ECPA, and Community Rating System dates, classes, and discounts for insurance premiums. The year that the community entered the NFIP is used to determine whether a home is pre- or post-FIRM for NFIP rating and premium calculations.

NFIP Community Name	Community ID number	Year entering NFIP (determines pre- or post-FIRM bldgs.)	Count of single family homes	CRS Entry Date	CRS Effective Date	Current CRS Class	% Discount for SFHA policies	% Discount for non-SFHA policies
CENTURY, CITY OF	120084	8/4/1987	689	n/a	n/a	n/a	n/a	n/a
ESCAMBIA COUNTY	120080	9/30/1977	77,357	10/1/91	05/1/11	6	20	10
PENSACOLA BEACH-SANTA ROSA ISLAND AUTHORITY	125138	9/28/1973	819	10/1/91	10/1/16	5	25	10
PENSACOLA, CITY OF	120082	9/15/1977	22,513	10/1/02	10/1/12	7	15	5

For these three CRS communities, Table 22 presents the specific points earned per each of the 18 activities as per 2014 CRS data (activity 370 was new as per 2013 with no points being earned by any communities at this time and Pensacola Beach's total points in 2014 equated to a CRS rating of 7 compared to their CRS class rating of 5 from 2016 points). And for comparison purposes, the Florida and National CRS averages are also included.

Table 22.. CRS Points Per Activity in Escambia

Series	Activities	Escambia County	Pensacola Beach	City of Pensacola	Florida CRS Average	National Average
	Public Information					
310	Elevation Certificate	62	56	56	63	68
320	Map Information Service	140	140	140	140	140
330	Outreach Projects	107	143	55	120	99
340	Hazard Disclosure	15	15	10	12	14
350	Flood Protection Information	84	9	32	61	45
360	Flood Protection Assistance	0	0	0	51	47
	Mapping and Regulations					
410	Floodplain Mapping	41	0	0	33	89
420	Open space Preservation	195	338	154	208	182
430	Higher Regulatory Standards	514	329	294	295	291
440	Flood Data Maintenance	144	24	108	106	97
450	Stormwater Management	125	106	119	128	111
	Flood Damage Reduction					
510	Floodplain Management Planning	135	135	135	116	129
520	Acquisition and Relocation	5	0	0	45	237
530	Flood Protection	8	4	0	55	79
540	Drainage System Maintenance	263	0	280	247	201
	Warning and Response					
610	Flood Warning and Response	153	150	70	104	93
620	Levees	0	0	0	0	312
630	Dams	71	71	71	70	63
Total	**18 Activities**	**2062**	**1520**	**1524**		

From the CRS data, we see similarities and difference in terms of the focus of their community mitigation activities. For example, all three communities score relatively the same in terms of elevation certificates (310), map information services (320), hazard disclosure (340), stormwater management (450), floodplain management planning (510), and dams (630). Furthermore, these scores are all in-line compared to the Florida and national CRS averages. It is also interesting to note that all three communities do very little regarding flood protection assistance (360), floodplain mapping (410), acquisition and relocation (520), flood protection (530), and levees (620). These activities are generally well below the Florida and national CRS averages. In relation to the other two communities, Escambia County places more of an emphasis on flood protection information (350) and higher regulatory standards (430); Pensacola Beach on outreach (330) and open space preservation (420); and the City of Pensacola on drainage system maintenance (540)

At a national CRS scale, Highfield and Brody (2013) conducted a study on the flood loss-reducing effect of specific CRS activities by tracking point totals on a yearly basis over an eleven-year period from 1999 to 2009. In particular, two avoidance-based mitigation activities were found to be most effective in reducing observed flood losses: freeboard (vertical avoidance) and open space protection (horizontal avoidance). The total dollar savings of a one-point increase in the freeboard element (elevation of a structure above BFE) for total losses was equivalent to, on average, nearly $8,300 per community per year. Taking into account the average amount of credit points communities in the sample received for each activity in 2009 (the final year of the study period), freeboard requirements led to the highest overall reduction in flood damages with an estimated average of $800,000 per year. Concurrently, the dollar savings of a one-point increase in the activity for protecting open space in the floodplain was equal to, on average, $3,532 per community, per year. Considering the average amount of points accrued for open space protection among communities in the study sample, the total savings per year for this activity was equivalent to, approximately $591,436.

These particular national loss reduction results were also "downscaled" to Escambia County Florida where it was found that the implementation of several CRS activities in Escambia County could result in significant reductions in insured flood losses. Downscaling in the Highfield and Brody (2013) study involved applying the statistical model estimated on a national level to estimate the savings in avoided flood losses from implementing CRS activities in Escambia County. For example, if Escambia received the CRS national average for freeboard during 2009, losses would have been reduced by over 20 percent overall and over 17 percent for structures within the Special Flood Hazard Area (SFHA). Also, open space protection efforts in 2009 reduced flood losses in Escambia County by almost 39 percent overall and over 40 percent for damage within the SFHA.

Again, while existing research has shown the reduced property loss benefits to a number of these specific activities, significantly there has been no corresponding identification of the costs to implementing these activities. Using Escambia County as a pilot, our goal was to identify these CRS mitigation costs by activity in order to then utilize them to determine the relative economic effectiveness of a suite of flood mitigation activities in relation to flood losses avoided. We hypothesize that this economic effectiveness information may be useful for decision making regarding where to focus community mitigation efforts. As noted above, Pensacola Beach as per 2016 has achieved a CRS class 5 rating. Below we present the points per CRS activity between 2014 and 2016 for Pensacola Beach. While clearly there are a number of activities where their point accrual increased significantly (outreach, open space, regulatory standards, flood data maintenance), what is interesting to see from the points achieved is that there are also a number of activities where the points simultaneously decreased over time (elevation certificates, map information services, stormwater management, flooplain management planning). In order to improve the overall Pensacola Beach CRS rating, these point increases in certain activities and decreases in others over time indicate that trade-offs are being made between the 19 activities in regard to where to allocate CRS time and resources. We believe that the additional BCR economic effectiveness data of individual activities would help facilitate these type of trade-off decisions and subsequent CRS point allocation amongst the 19 activities.

Table 23. Pensacola Beach CRS Points 2014 and 2016

Series	Activities	Pensacola Beach (2014)	Pensacola Beach (2016)
	Public Information		
310	Elevation Certificate	56	27
320	Map Information Service	140	0
330	Outreach Projects	143	302
340	Hazard Disclosure	15	15
350	Flood Protection Information	9	80
360	Flood Protection Assistance	0	85
370	Flood Insurance Promotion	N/A	90
	Mapping and Regulations		
410	Floodplain Mapping	0	10
420	Open space Preservation	338	781
430	Higher Regulatory Standards	329	696
440	Flood Data Maintenance	24	163
450	Stormwater Management	106	61
	Flood Damage Reduction		
510	Floodplain Management Planning	135	50
520	Acquisition and Relocation	0	0
530	Flood Protection	4	65
540	Drainage System Maintenance	0	0
	Warning and Response		
610	Flood Warning and Response	150	258
620	Levees	0	0
630	Dams	71	0
Total	**18 Activities**	**1520**	**2683**

4.2.4 CRS Costs in Escambia – CRS Costs Pilot Study

Using the three CRS communities of Escambia County as a pilot, our goal was to identify their relevant CRS mitigation costs by activity. Firstly, there are a few overall cost categories to consider in regard to the costs of the program: the costs of initial enrollment[31]; the costs to manage and maintain the program year to year including annual certifications as well as 5 year cycle review; indirect costs like training, certifications etc.; and the costs to improve points and class rankings which could involve the upfront costs to improve as well as increased year over year management and maintenance costs at the established higher CRS rating. Moreover,

[31] CRS has an existing "quick-check" document to assist in whether their existing management activities warrant at least 500 CRS credit point to enter the CRS program

the costs of operating the CRS program are not necessarily limited to the CRS department itself (if that even exists within a particular CRS community), but also likely carry over into other related government departments (local and state), other community entities, and individual homeowners themselves. Therefore, when attempting to measure the costs of operationalizing the CRS in a community, all of these costs should be considered. In our pilot process we decided as a first step to concentrate on attempting to collect the costs related to manage and maintain the program as well as how much these costs are internal or external to the CRS program. This initial focus was mutually agreed upon by the CRS personnel we spoke to.

In order to capture this CRS cost information we reached out to all three CRS coordinators of Escambia County communities with the below information: i) CRS point summary information worksheet per community at the activity level; ii) a cost component allocation worksheet; and iii) open-ended cost questions that were the same set utilized by Stiff (2017) in her Virginia CRS cost study. Responses to these three items will be triangulated to ascertain a CRS cost estimate per activity.

For example, the goal of the community point summary worksheet was to verify whether the points as a percent of the total points reflect actual time and resources of the CRS program. For example, in Escambia County, 25 percent of their points come from activity 430 – Higher Regulatory Standards. Therefore, from the Escambia County CRS coordinator, we want to understand whether considering the overall resources dedicated to managing and maintaining the CRS in this community, is this activity point percentage reflective of the actual percent of the overall CRS resource use, i.e., 25 percent? For all CRS activities, in relation to the total point earned percentage for each of the activities, CRS coordinators were asked to adjust these time/resource percentages up or down using the worksheet. Then, once the overall costs are obtained from items iii) and potentially ii), they can be allocated across the various activities on the allocated percentage basis. Relatedly for the cost component allocation worksheet, the percent of each activity whether it is internal to the CRS program or external to it will be indicated. Thus, for external percentages, it will be necessary to reach across the external entities to collect related time spent and cost figures for items i) and iii) respectively.

i) 2014 CRS Point Summary – As a Percent of Total Community Points Earned

ESCAMBIA COUNTY

Series	**Activities**	**Year 2014 Points per Activity**	**Percentage of Total Community Points Earned**	**Year 2014 Points per Series**	**Percentage of Total Community Points Earned**
	Public Information			**408**	**20%**
310	Elevation Certificate	62	3%		
320	Map Information Service	140	7%		
330	Outreach Projects	107	5%		
340	Hazard Disclosure	15	1%		
350	Flood Protection Information	84	4%		
360	Flood Protection Assistance	0	0%		
	Mapping and Regulations			**1019**	**49%**
410	Floodplain Mapping	41	2%		
420	Open space Preservation	195	9%		
430	Higher Regulatory Standards	514	25%		
440	Flood Data Maintenance	144	7%		
450	Stormwater Management	125	6%		
	Flood Damage Reduction			**411**	**20%**
510	Floodplain Management Planning	135	7%		
520	Acquisition and Relocation	5	0%		
530	Flood Protection	8	0%		
540	Drainage System Maintenance	263	13%		
	Warning and Response			**224**	**11%**
610	Flood Warning and Response	153	7%		
620	Levees	0	0%		
630	Dams	71	3%		
Total	**18 Activities**	**2062**	**100%**	**2062**	**100%**

* Series 400 scores are County Growth Adjusted

PENSACOLA BEACH-SANTA ROSA ISLAND AUTHORITY
(* These points are not reflective of the 2016 CRS = 5 rating)

Series	Activities	Year 2014 Points per Activity	Percentage of Total Community Points Earned	Year 2014 Points per Series	Percentage of Total Community Points Earned
	Public Information			**363**	**24%**
310	Elevation Certificate	56	4%		
320	Map Information Service	140	9%		
330	Outreach Projects	143	9%		
340	Hazard Disclosure	15	1%		
350	Flood Protection Information	9	1%		
360	Flood Protection Assistance	0	0%		
	Mapping and Regulations			**797**	**52%**
410	Floodplain Mapping	0	0%		
420	Open space Preservation	338	22%		
430	Higher Regulatory Standards	329	22%		
440	Flood Data Maintenance	24	2%		
450	Stormwater Management	106	7%		
	Flood Damage Reduction			**139**	**9%**
510	Floodplain Management Planning	135	9%		
520	Acquisition and Relocation	0	0%		
530	Flood Protection	4	0%		
540	Drainage System Maintenance	0	0%		
	Warning and Response			**221**	**15%**
610	Flood Warning and Response	150	10%		
620	Levees	0	0%		
630	Dams	71	5%		
Total	**18 Activities**	**1520**	**100%**	**1520**	**100%**

* Series 400 scores are County Growth Adjusted

PENSACOLA, CITY OF

Series	Activities	Year 2014 Points per Activity	Percentage of Total Community Points Earned	Year 2014 Points per Series	Percentage of Total Community Points Earned
	Public Information			**293**	**19%**
310	Elevation Certificate	56	4%		
320	Map Information Service	140	9%		
330	Outreach Projects	55	4%		
340	Hazard Disclosure	10	1%		
350	Flood Protection Information	32	2%		
360	Flood Protection Assistance	0	0%		
	Mapping and Regulations			**675**	**44%**
410	Floodplain Mapping	0	0%		
420	Open space Preservation	154	10%		
430	Higher Regulatory Standards	294	19%		
440	Flood Data Maintenance	108	7%		
450	Stormwater Management	119	8%		
	Flood Damage Reduction			**415**	**27%**
510	Floodplain Management Planning	135	9%		
520	Acquisition and Relocation	0	0%		
530	Flood Protection	0	0%		
540	Drainage System Maintenance	280	18%		
	Warning and Response			**141**	**9%**
610	Flood Warning and Response	70	5%		
620	Levees	0	0%		
630	Dams	71	5%		
Total	**18 Activities**	**1524**	**100%**	**1524**	**100%**

* Series 400 scores are County Growth Adjusted

ii) 2014 CRS Point Summary – Cost Components Internal or External

By percentage please indicate whether the CRS costs are internal to the program or allocated across other entities

Series	**Activities**	**CRS Administrative**	**Other Department Admin**	**Community Property Owners**	**Other Community Entity**
	Public Information				
310	Elevation Certificate				
320	Map Information Service				
330	Outreach Projects				
340	Hazard Disclosure				
350	Flood Protection Information				
360	Flood Protection Assistance				
	Mapping and Regulations				
410	Floodplain Mapping				
420	Open space Preservation				
430	Higher Regulatory Standards				
440	Flood Data Maintenance				
450	Stormwater Management				
	Flood Damage Reduction				
510	Floodplain Management Planning				
520	Acquisition and Relocation				
530	Flood Protection				
540	Drainage System Maintenance				
	Warning and Response				
610	Flood Warning and Response				
620	Levees				
630	Dams				
Total	**18 Activities**				

iii) Open-Ended Cost Survey

Overall CRS Management and Maintenance Costs:

1. What amount or percentage of time does the Coordinator spend on the CRS exclusively? (Ex: by week, month, or year)

2. How many locality staff contribute to CRS efforts?

3. There are few direct costs of implementing the CRS program, the list below captures what I understand to be the only direct costs. Are there any additional direct costs that you can identify?

   a. Staff Time

   b. Outreach initiatives (postage, printing, etc.)

4. Are there any administrative staff that support the program (making copies, stuffing envelopes, etc.)? If so, how many?

5. Have the costs of participating in the CRS prohibited success in the CRS?

Cost Pilot Implementation and Lessons Learned

Detailed phone conversations were held with two members of the Escambia County CRS teams concerning the objective of the cost study as well as items i) to iii) that were provided to them. Preliminary phone conversation concerning the cost study and the provided materials was also undertaken with the CRS coordinator of Pensacola Beach. The CRS coordinator of the City of Pensacola could not be reached via phone, although several email attempts were made. Additionally, detailed phone conversations concerning the study and associated materials were held with the ISO coordinator for these communities.[32] She then separately made several attempts to encourage the CRS coordinators to participate in the pilot process. Lastly, detailed phone conversations regarding the study and the associated materials were also undertaken with the author of the VA CRS cost study, the CRS coordinator for Hillsborough County in Florida (facilitated through our ISO contact), and the CRS coordinator of Lambertville NJ.

As of the writing of this report we are awaiting the high-level cost information from Escambia. In our discussions with them, they agreed that the information was useful and its collection would be very helpful for their upcoming ISO 5 year cycle visit. The CRS coordinator for Pensacola Beach also believed the study was a worthwhile effort, but had limited time to dedicate to collecting the cost information until the summer beach season was over.

Through our various conversations, the key lessons learned from this cost collection process include:

- Collecting this type of cost information is not something the CRS coordinators typically do as part of their CRS management, although they all believe the data would be very useful for them.
- The approach of collecting the cost information at the activity level in terms of time spent and internal and external components is a good one. One even argued for going to the element level.
- Given the external connections of the CRS system, collecting all of the relevant CRS cost information is likely a complex endeavor.
- While the existing costs of managing the program are certainly helpful, understanding the cost to improve rankings would be very useful.
- Beyond the costs, a better understanding of the avoided flood losses will also be useful for the CRS coordinators. Premium reductions are the typical benefit consideration.

[32] ISO is responsible for administering and validating the CRS points for FEMA.

5.0 Discussion and Conclusions

We have analyzed the economic effectiveness of elevating homes, demolishing and acquiring homes, and building floodwalls around homes to mitigate the risks of storm surge. Our analyses were possible because we employed granular storm surge data comprised of five different annual chances with corresponding surge elevations. We analyzed single-family homes in three NFIP communities in northwest Florida, at risk to surge from the Gulf of Mexico: unincorporated Escambia County, the City of Pensacola, and Pensacola Beach.

We analyzed economic effectiveness of our three mitigation activities by analyzing a sample of 39 homes with the FEMA BCA Toolkit in unincorporated Escambia County, the City of Pensacola, and Pensacola Beach. We also analyzed 6,820 homes at risk to surge in unincorporated Escambia County, the City of Pensacola, and Pensacola Beach with a method that accounts for different sea level rise scenarios that are unique to the Pensacola area. Main findings across both data sets include:

- homes with low FFEs in 10% and 4% annual chance surge zones are most economically effective to mitigate
- demolition/acquisition is very rarely cost effective
- slab homes might be best mitigated with floodwalls, while open foundation homes should be elevated
- despite the differences in methods, results from the Toolkit are similar to those obtained in bulk analyses without the Toolkit

We also compare our mitigation BCR results to those from previous studies in Texas and New York. The Texas study similarly finds that if elevation to existing homes is to be undertaken as a flood mitigation effort, it must be done very selectively from an economic perspective due to the relatively significant costs of elevation to existing structures. In New York, none of the storm surge barrier nor hybrid (i.e., building codes and critical infrastructure protection) approaches analyzed is economically beneficial under current levels of flood risk and the low climate change scenario (30 cm sea-level rise). However, they find when a low 4% discount rate is considered, all strategies make economic sense if sea level rise occurs and climate change increases the frequency of storms. In Pensacola, similar relaxations of discount rates and higher sea-level risk scenarios lead to more favorable BCRs.

As we have shown, mitigating individual homes against surge risks can be economically effective in particular circumstances, but not necessarily at scale within a community. For example, 12 percent of properties analyzed in the bulk analysis had a BCR > 1 with any of the three mitigation methods. Therefore, we advocate that the broader benefits of flood risk mitigation beyond an individual property owner must be analyzed and ultimately incorporated into a mitigation economic effectiveness analysis. These additional broader benefits include but are not limited to emergency response/rescue services, frequent damage to exterior property improvements, damage to vehicles, and recurring damage from foundation and crawlspace flooding. To better understand the linkages between individual and community level flood mitigation, we discuss the Flood Risk Reduction and Risk Assessment (RA/RR) Plan from the Charlotte Mecklenburg Storm Water Services (CMSWS) Department, and the Community Rating System (CRS) of the national Flood Insurance Program (NFIP). Both the Flood RA/RR Plan and the CRS are comprehensive community-based approaches to flood risk mitigation that have a connection from mitigation benefits of individual structures to that of communities, with the goal of enhancing communities' resilience to flood risks.

The CMSWS RA/RR Plan has potential to improve the economic effectiveness of flood mitigation approaches and enhance community resilience to flood risks in other places. It could be applied in communities of Escambia County Florida, for example, but we note the importance of the Citizen's Review Committee in the success of the CMSWS Plan. Involving residents of a community in flood mitigation planning ensures procedural fairness in the implementation of such plans, and fosters a sense of community in the management of natural hazards.

Nevertheless, there are some ways that ideas from the CMSWS RA/RR Plan could be implemented in Escambia County, and other communities, even before developing a plan to involve residents. For example, examining location-based factors of candidate properties for flood mitigation could be done in a GIS. To locate properties adjacent to flood velocity zones would require fine-scale hydrologic and hydrodynamic modeling to delineate flood velocity zones. But, areas adjacent to storm water overflow areas could be identified with elevation data, street areas, and locations of storm water drain inlets. The GIS departments of Escambia County and the City of Pensacola have these GIS data layers. Encroachment areas could be delineated by County and City engineering personnel, to identify areas at risk to flooding and then enforce floodplain regulations within these areas. Mapping and enforcement flood encroachment areas would go beyond the floodplain mapping requirements of the NFIP and therefore probably be a creditable activity under the CRS.

Of the 465 NFIP participating communities in Florida, 47 percent participate in the CRS (FLDEM, 2018). In addition to making the CRS participating community more resilient to future flood damage, an estimated $183 million in insurance premiums is saved annually in these CRS communities (FLDEM, 2018). And while compared to communities in other parts of the U.S., Florida has a higher percentage of communities participating in the CRS, and higher levels of relative achievement in mitigation activities, there is still much work to be done. Firstly, while 47 percent of communities participate in the CRS, that means more than half do not. Further, of those communities that do participate in the CRS, flood risk reduction benefits are being left on the table as the vast majority of communities are rated toward the lower end of the 1 (the best) to 10 CRS scale, i.e., rated 7 or greater.

We will leverage our CRS research piloted here to measure the costs associated with implementing community based resilience-enhancing activities. For CRS communities in Florida beyond Escambia we will conduct a cost-benefit analysis (CBA) across various community flood mitigation investments, which for communities: 1) is critical for an optimal economic allocation of mitigation financial resources and effective policy implementation over the long term; and 2) has not been previously estimated and thus fills an important community mitigation investment decision-making gap. By having determined the relative economic effectiveness of flood mitigation activities we can then compare this optimal ranking to any current mitigation investment allocation to identify divergences between the two. Where differences exist, the drivers of such differences will be explored including the potential non-economic drivers of flood mitigation investment. Therefore the benefit of our approach will not only produce the first of its kind optimal allocation of community flood mitigation investment, but also the potential barriers to achieving this. Moreover, by providing proponents of pre-event mitigation investment with a reliable cost effectiveness estimate, the case for increased investment becomes easier to make with economic value clearly demonstrated.

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APPENDIX A: Detailed procedures used in the FEMA BCA Toolkit

A-1 BCA Toolkit Specifications and home characteristics for elevating homes

In this section we explain how we use the BCA Toolkit Flood Module to obtain BCRs for each sample home for each type of mitigation project. We have outlined in detail which radio buttons, drop-down menu options, and inputs we made in every portion of the user interface within the Toolkit.

A-1.1 Starting a new flood mitigation project for a structure

In the BCA Toolkit, select the radio button for "start a new mitigation: Flood". Damage-frequency Assessment is another option to assess flood mitigation activities, but it is quite limited in what it can analyze since it is intended for mitigation projects that are lacking flood hazard data with different return periods.

Select the type of wizard "Flood Mitigation Project (Short Form)". The other option is Flood Mitigation Project with "all the data necessary for an official submittal to FEMA as part of the grant application process". We do not select this option because it requires flood hazard data from either a Flood Insurance Study (FIS) or a Hydrology & Hydraulic (H&H) study. The data from the FIS accompanying the Escambia County 2006 effective DFIRM is very limited with respect to where the representative homes are located. We do not have any H&H study data. Without data from a FIS or H&H study, the longer form would require several assumptions that could not be properly justified. Therefore, we use the surge risk data as inputs into the Short Form.

For all mitigation projects:

- use the **default discount rate of 7%**[33]
- source of flooding is **coastal** (since everything is based on surge risk data)
    - select **coastal A flooding** for sample homes that are in surge zones and any A zone (i.e., within A, AE, AO, AH zones in the Escambia County 2006 effective DFIRM)
    - select **coastal V flooding** for sample homes that are in surge zones and VE zones (according to the Escambia County 2006 effective DFIRM)

A-1.2 Structure tab of the BCA Toolkit

The inputs of the Structure tab of the Toolkit are the same for all types of flood mitigation projects.

Building replacement value = improvements value from 2015 parcel data

Total size of building (square feet) = heated square feet from parcel data

- Since only 1-story homes are selected, heated square footage should be fairly close to building footprint area. As stated above, the heated area of the Pensacola Beach 2-story home is very close in value to the area of the building footprint so we treat it as a 1-story home.

[33] See Appendix C of the BCA Reference Guide, located online at https://www.fema.gov/media-library-data/20130726-1736-25045-7076/bca_reference_guide.pdf (accessed 25 June 2018).

- Building footprint area might be more accurate than heated area because building footprint areas would include open attached carports and porches, but some building footprints are multipart features (e.g., a shed or detached garage). For multipart features, building footprint area would lead to an overestimate of the area to be elevated and therefore the cost of elevation. Additionally, the slab an attached carport would most probably not be elevated along with the rest of the home, but open carports would be included in the area of building footprints. We also do not know if parts of building footprints include closed garages or open carports, since the building footprints are based on building rooftops.

Value of building ($/sq ft) = heated square foot area / improvements value (from 2015 parcel data)
Demolition damage threshold (%) = default value of 50%

Building type = 1-story

Foundation type (choices are slab, pier or pile). For crawlspace and subfloor foundations, we select pier foundation.

Does basement exist? No. This is an easy assumption to defend since there are very few homes anywhere in Escambia County with basements because the water table is very close to the ground surface.

Is there an obstruction? No (also select No for Pensacola Beach homes in VE zones on piles, which is an assumption).

A-1.3 Mitigation tab: Elevation

Type = Elevation

Project useful life = 30 years

Mitigation project cost ($) = based on type of foundation and frame types, rates per square foot to be elevated are based on FEMA P-312 (2009) for elevating homes by 2', 4', 6', and 8'. To estimate costs of elevating homes by 6', we used the average of the rates for elevating by 4' and 8' (after Aerts et al. 2013, Cost estimates for flood resilience and protection strategies in New York City). The estimated costs of elevating homes according to FEMA P-312 (2009) can be found in the Appendix.

Depth-damage function type (select Default radio button, not Library): for homes that are at risk to Coastal A flooding, the USACE generic - 1 story w/o basement function or the FEMA FIA function is chosen. For homes in VE zones, use FEMA FIA function or Expert Panel function. The USACE generic, FEMA FIA, and Expert Panel depth-damage functions are the only options we used throughout this research. When choosing the Library radio button, the only option is FEMA FIA function consistently for every type of mitigation activity we examine.

We do not include any costs for affected populations, which are the fields on the right side of the Mitigation tab.

A-1.4 Flood Profile tab: Elevation

First floor elevation (FFE): for homes that lack an elevation certificate, the average ground elevation within the building footprint, based on the 2006 lidar digital elevation model for Escambia County, is the FFE for slab foundation homes.

For crawlspace/pier homes, we added 3’ to the average lidar-derived ground elevation within the building footprint. For homes on pilings, we added 6’ to the average lidar-derived ground elevation within the building footprint.

For the three Pensacola Beach homes for which we have an elevation certificate, we used the FFE information from the elevation certificate.

The foundation types are based on the 2015 parcel data from ECPA.

How many feet is the first floor being raised? We assess elevation by 2’, 4’, 6’, and 8’.

Base flood elevation or 100-year elevation including wave action (in feet): 13.92’. This is the stillwater surge height for the 1% annual chance surge event based on the U-Surge data. We use 13.92’ for all representative homes. The Toolkit allows input of 4 flood recurrence intervals (in years) with percent annual chance, and flood elevations before mitigation for each recurrence interval. The default annual chances are 10%, 2%, 1%, and 0.2%. We input the below observations shown in Table 4 based on the U-Surge data for each annual chance event. It is a shortcoming of the Toolkit that four annual chance floods and corresponding flood heights is the maximum number that can be input, especially since our U-Surge data have five annual chances with flood heights.

Table A-1. Stillwater surge elevations in feet for each probability event for Pensacola relative to NAVD88 (North Atlantic Vertical Datum of 1988) for year 2017. Storm tide return levels based on observed data from 1900-2016 (117 years) for the Pensacola area. (Source: U-Surge. 2017 Marine Weather & Climate https://www.u-surge.net/pensacola.html). These are the inputs for the flood risk data of the BCA Toolkit.

Annual probabilities of surge events (surge risk zone)	Recurrence interval (years)	Stillwater surge elevation (feet)
10%	10	4.91
2%	50	11.21
1%	100	13.92
0.2%	500	20.21

Ground Surface Elevation: for homes without a building certificate, we input the average lidar-derived ground elevation within the building footprint. For beach homes with elevation certificates, we use the lowest adjacent grade (LAG) from the elevation certificate.

For elevation before mitigation (ft) for each recurrence interval, we use the default recurrence intervals shown in Table A-1: 10-year, 50-year, 100-year, and 500-year.

Once we have input all the above data into the Toolkit, the "Save and Continue" button is clicked and the last screen shows the figures of the benefit-cost analysis and the BC ratio. For each representative home, we redo this procedure to assess home elevation by 2', 4', 6', and 8'.

A-2 BCA Toolkit Specifications and home characteristics for acquisitions

Acquisition of homes herein specially means the demolition of homes and buy-out at market value, with the purchased property becoming deed-restricted and maintained as open space in perpetuity for purposes of recreation or wetlands management[34] To estimate the costs of acquiring homes and land parcels, we used a spreadsheet from the Engineering & Mitigation Program of the Charlotte-Mecklenburg Storm Water Services department that is used by the State of North Carolina for their Hazard Mitigation Assistance (HMA) grant applications to FEMA. This spreadsheet is particularly helpful to estimate costs of acquiring homes because it includes costs of appraisal, closing, title work, asbestos survey, demolition, moving costs, and other costs.

In addition to the building and land values from the ECPA data, the NC HMA grant spreadsheet includes the following soft costs, for a total of $5,030 for each home:
Int. Interview: $650
Appraisal: $600
Offer to Purchase: $500
Pre-Closing: $500
Closing: $500
Title Work: $250
Recording Fee: $30
Pre-Mitigation Survey: $800
Asbestos Inspection: $1200

The costs of demolition are $6.50 per square foot of structure, as indicated in the NC HMA grant spreadsheet, and we used the heated square footage from the ECPA parcel data for the total area of the home. Although this does not include areas such as open porches and attached garages, we feel that it is more accurate than the area of the building footprint, which is actually the area of the rooftop of the home. Demolition costs also include $9,000 for asbestos abatement. We assumed that every home was owner-occupied so that tenant relocation costs were not applicable. However, moving costs were $1,500 for every home; and project management costs were another 5% of the total cost of acquiring owner-occupied homes.

In the Toolkit, users select Acquisition from the mitigation type drop-down menu, the project useful life is the standard 100 years, and costs are based on the spreadsheet from the Mecklenburg Storm Water Services department as described above.

[34] From FEMA Hazard Mitigation Assistance Guidance Addendum, located online at https://www.fema.gov/media-library-data/1424983165449-38f5dfc69c0bd4ea8a161e8bb7b79553/HMA_Addendum_022715_508.pdf.

A-3 BCA Toolkit Specifications and home characteristics for building floodwalls

The option to select in the Toolkit to examine building floodwalls around homes is called “Drainage Improvement”. The costs are based on the perimeter of the building footprints for building floodwalls that are either two or four feet high. The height of floodwalls is input into the Toolkit by adding the height of the floodwall (i.e., 2’ or 4’) to the ground elevation to fill in the blank next to the question: “at what elevation will flood water overtop the barrier?” The estimated costs for building floodwalls according to FEMA P-312 (2009) can be found in Appendix B. We assumed that three closures would be incorporated into the floodwalls, and we did not include costs for reseeding disturbed areas. The total costs to build floodwalls are therefore based on the perimeter of building footprints around which to build floodwalls that are either two or four feet high, $375 for three closures, and the lump sum of $7,200 for an interior drainage system.

A-4 Project Useful Life Summary, from FEMA BCA Reference Guide Appendix D

APPENDIX D
Project Useful Life Summary

Project Type	Useful Life (years)		Comment
	Standard Value	Acceptable Limits (documentation required)	
Acquisition/Relocation			
All Structures	100	100	
Elevation			
Residential Building	30	30–50	
Non-Residential Building	25	25–50	
Public Building	50	50–100	
Historic Buildings	50	50–100	
Structural/Non-Structural Building Project			
Residential Building Retrofit	30	30	
Non-Residential Building Retrofit	25	25–50	
Public Building Retrofit	50	50–100	
Historic Building Retrofit	50	50–100	
Roof Diaphragm Retrofit	30	30	Roof hardening and roof clips
Tornado Safe Room – Residential	30	30	
Tornado Safe Room – Community	30	30–50	Retrofit or small community safe room ≤ 16 people (30 yr), New (50 yr)
Non-Structural Building Elements	30	30	Ceilings, electrical cabinets, generators, parapet walls, or chimneys
Non-Structural Major Equipment	15	15–30	Elevators, HVAC, sprinklers
Non-Structural Minor Equipment	5	5–20	Generic contents, racks, shelves

APPENDIX B: COST ESTIMATES USED TO CALCULATE TOTAL COSTS OF ELEVATING SINGLE-FAMILY HOMES TO MITIGATE FLOOD RISKS

Approximate Square Foot Costs of Elevating a Home

Construction Type	Existing Foundation	Elevate on Continuous Foundation Walls or Open Foundation	Cost (per square foot of house footprint)
Frame (for frame house with brick veneer on walls, add 10 percent)	Basement or Crawlspace	2 feet	$29
		4 feet	$32
		8 feet	$37
	Slab-on-Grade	2 feet	$80
		4 feet	$83
		8 feet	$88
Masonry	Basement or Crawlspace	2 feet	$60
		4 feet	$63
		8 feet	$68
	Slab-on-Grade	2 feet	$88
		4 feet	$91
		8 feet	$96

Source: Modified from Table 3-3, page 3-20. Homeowner's Guide to Retrofitting Six Ways to Protect Your Home From Flooding. FEMA P-312, Second Edition / December 2009.

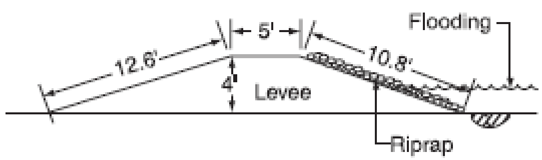
Note: for estimating the costs of elevating homes by 6', we took the average of the costs to elevate by 4' and 8'.

APPENDIX C: COST ESTIMATES USED TO CALCULATE TOTAL COSTS OF CONSTRUCTING FLOODWALLS AROUND SINGLE-FAMILY HOMES TO MITIGATE FLOOD RISKS

Approximate Costs of building levees and floodwalls around homes. We have not examined levees herein because they require a very large lot. For example, refer to this figure below from FEMA P-312 page 3-37. This example levee that is 4' high with a slope of 2.5:1 would require 12.6' + 5' + 10.8' = 28.4 feet of space between the home and the end of the lot.

Cross-Section Showing Dimensions of a 4-Foot-High Levee

With a height of 4 feet and a slope of 2.5:1 the face of the levee on the water side would span 10.8 feet



In table C-1 below, the components and costs in bold font are those employed in the estimation of floodwall costs in this report.

Table C-1. Levee and floodwall components and costs per unit used in the estimation of construction costs.

Component	Height above ground	Cost	Per
Levee	2 feet	$63	Linear foot
	4 feet	$118	Linear foot
	6 feet	$197	Linear foot
Floodwall	**2 feet**	**$145**	**Linear foot**
	4 feet	**$212**	**Linear foot**
Levee riprap	n/a	$53	Cubic yard
Interior drainage system	**n/a**	**$7,200**	**Lump sum**
Closure (each)	**n/a**	**$125**	**Square foot of closure area**
Seeding of disturbed area	n/a	$0.10	Square foot of ground area

Source: Modified from Table 3-14, page 3-37. Homeowner's Guide to Retrofitting Six Ways to Protect Your Home From Flooding. FEMA P-312, Second Edition / December 2009.

APPENDIX D: SCREEN SHOTS OF DEPTH-DAMAGE TABLES AND AVERAGE EXPECTED LOSSES FROM THE BCA TOOLKIT

Table D-1. Flood depths and expected percentages of building and contents values lost to flooding. The depth-damage function is called the USACE IWR res-1 in Hazus, for residential single-story homes without a basement. In the BCA Toolkit, the depth-damage function is called USACE generic for 1-story homes without a basement.

flood depth in home (feet)	Building value % damage			Contents value % damage		
	BCA Toolkit	Hazus	BCA Toolkit rounded	BCA Toolkit	Hazus	BCA Toolkit rounded
-2	0.0	0	0	0.0	0	0
-1	2.5	3	3	2.4	4	2
0	13.4	13	13	8.1	16	8
1	23.3	23	23	13.3	26	13
2	32.1	32	32	17.9	36	18
3	40.1	40	40	22.0	44	22
4	47.1	47	47	25.7	52	26
5	53.2	53	53	28.8	58	29
6	58.6	59	59	31.5	64	32
7	63.2	63	63	33.8	68	34
8	67.2	67	67	35.7	72	36
9	70.5	71	71	37.2	74	37
10	73.2	73	73	38.4	76	38
11	75.4	75	75	39.2	78	39
12	77.2	77	77	39.7	80	40
13	78.5	79	79	40.0	80	40
14	79.5	80	80	40.0	80	40
15	80.2	81	80	40.0	80	40
16	80.7	81	81	40.0	80	40

Percentages of building and contents values from the Toolkit are given in tenths of percentages, while those exported from Hazus are given in whole numbers (integers). However, the percentages from the Toolkit for building losses are the same as those from Hazus when rounded to the nearest whole number.

The percentages of contents values lost to flooding from the Toolkit are half of the corresponding percentage contents values lost according to the Hazus function. Interestingly, for estimating contents values in our procedure without the Toolkit we assumed that contents values are half of building values, following Kunreuther et al. (2018) and Montgomery and Kunreuther (in press, 2018). When using the long form of the Toolkit, we observed that the assumed contents values are 100% of building values Thus these depth-damage functions from the Toolkit and Hazus generally result in the same estimated losses from floods.

However, the damage calculation table below (Figure AC-1) is quite different from the AAL equation from Hazus that we used.

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Damage Calculation Table

Damages Before Mitigation | Damages After Mitigation

Flood De	Recurrence Inter	Building	Contents
-6.583	1.111	$0.00	$0.00
-5.507	2.000	$0.00	$0.00
-3.666	5.000	$0.00	$0.00
-2.537	8.000	$0.00	$0.00
-2.140	9.314	$0.00	$0.00
-2.000	9.814	$0.00	$0.00
0.000	19.336	$13.29	$7.99
0.109	20.000	$185.23	$107.56
1.490	30.000	$147.14	$82.06
2.555	40.000	$191.77	$105.18
4.160	59.631	$2.76	$1.50
4.186	60.000	$91.92	$36.11
4.847	70.000	$99.27	$28.93
5.439	80.000	$77.21	$23.71
5.977	90.000	$106.50	$34.56
6.870	108.751	$233.22	$83.66
10.012	200.000	$92.65	$36.23
12.342	300.000	$23.32	$9.30
13.160	343.187	$23.01	$9.20
14.119	400.000	$138.97	$138.97
	9999999.000		
		$1,426.24	$704.97

Total Annualized Damages = $2,131.21

frmBcarDialogTemplate

Damage Calculation Table

Damages Before Mitigation | Damages After Mitigation

Flood Depth (	Recurrence In	Building	Contents
-10.583	1.111	$0.00	$0.00
-9.507	2.000	$0.00	$0.00
-7.666	5.000	$0.00	$0.00
-6.537	8.000	$0.00	$0.00
-6.140	9.314	$0.00	$0.00
-3.891	20.000	$0.00	$0.00
-2.510	30.000	$0.00	$0.00
-2.000	34.517	$0.00	$0.00
-1.445	40.000	$18.17	$13.84
0.000	57.397	$5.14	$3.09
0.160	59.631	$0.87	$0.52
0.186	60.000	$24.12	$14.09
0.847	70.000	$24.15	$13.74
1.439	80.000	$22.73	$12.75
1.977	90.000	$37.59	$20.81
2.870	108.751	$145.76	$60.67
6.012	200.000	$92.65	$31.31
8.342	300.000	$23.32	$8.58
9.160	343.187	$23.01	$8.73
10.119	400.000	$138.97	$138.97
	9999999.000		
		$556.46	$327.09

Total Annualized Damages = $883.55

Figure D-1. Screen shots from the long form of the FEMA BCA Toolkit showing the depths of flood water, recurrence intervals, and values of building and contents lost to flooding. On the left side of Figure AC-1 is the table for damages before mitigation, and on the right side is the table for damages after mitigation, which is elevating this sample home by 4'.

The sample home analyzed in Figure AC-1 is P-c-10-4 (refer to table 3 in Section 2.3).

This damage calculation table shown in Figure AC-1 is based on the USACE generic depth-damage function in the Toolkit for a home on crawlspace/pier foundation.

The AAL equation from the Hazus Technical Manual (version 2.1, page 14-38) is:

$$AAL = [(f_{10} - f_{25}) * ((L_{10} + L_{25}) /2)] + [(f_{25} - f_{50}) * ((L_{25} + L_{50}) /2)] + [(f_{50} - f_{100}) * ((L_{50} + L_{100}) /2)] +$$

$$[(f_{100} - f_{500}) * ((L_{100} + L_{500}) /2)] + (f_{500} * L_{500})$$

where $f_x = 1/x$ (frequency/probability of an x-year flood event) and L_x are the losses attributable to the x-year event (expressed as percentages of building and contents) where x=10, 25, 50,100 and 500.

The AAL equation from Hazus takes the average of the differences between two consecutive flood annual probabilities, therefore it is a rougher approximation of the AALs. The annualized damages table from the Toolkit shown in Figure AC-1 includes interpolated flood depths and recurrence intervals for several more flood events than the four annual probability events we input to the Toolkit (as shown in Table 4 in Section 2.4.5). As the AAL equation from Hazus shows above, we include up to five annual probability surge events and corresponding flood depths in homes.

APPENDIX E: FIGURES SUMMARIZING THE RESULTS OF BULK ANALYSES OF ELEVATING HOMES BY 8' TO MITIGATE SURGE RISKS

In Figures E-1 through E-4, we show the results of elevating homes with box plots for the homes in each study area with no SLR, NOAA Low SLR, NOAA Intermeidate-High SLR, and NOAA High SLR scenarios. In all figures showing box plots, the dark line within the blue or green boxes represents the median of the data, the bottom of each box is the 25th percentile and top of each box is the 75th percentile. If the data are distributed normally, approximately 95% of the data are expected to lie between the bottom and top T-bars, or fences. Circular points outside of the T-bars are outliers, and asterisks represent extreme outliers.

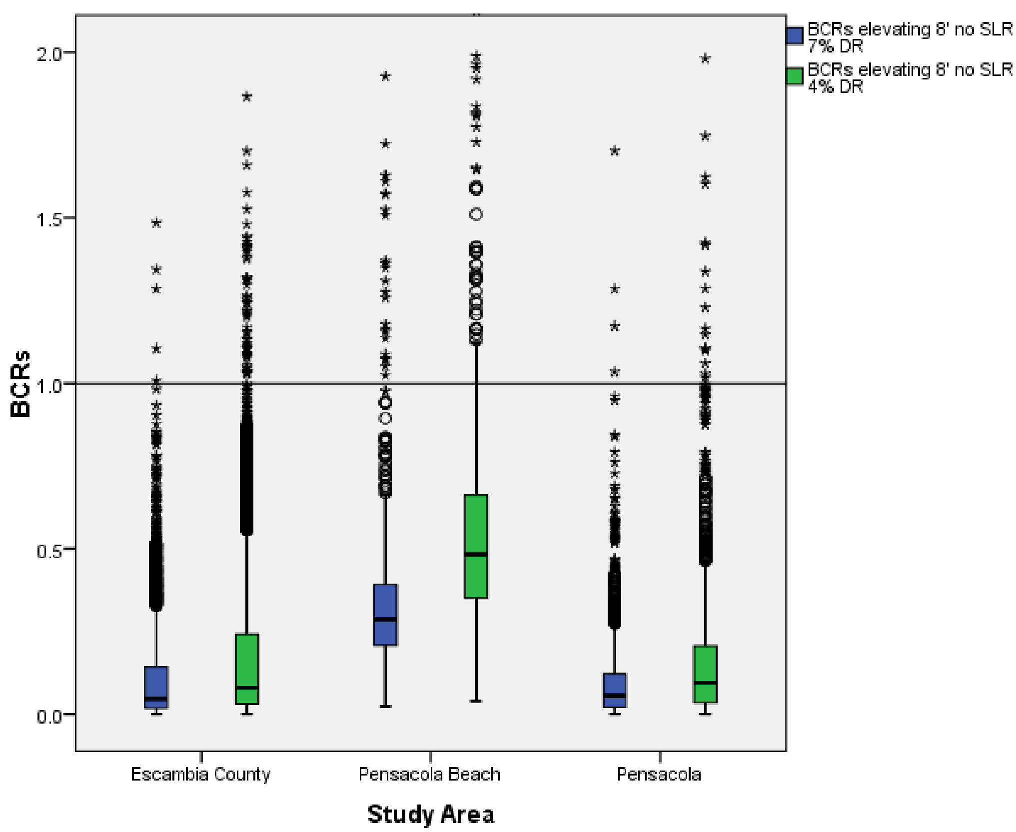

Figure E-1. Boxplots depicting statistics of benefit-cost ratios (BCRs) by study area for elevating homes by 8' with no sea level rise (SLR) and 7% and 4% discount rates (DR).

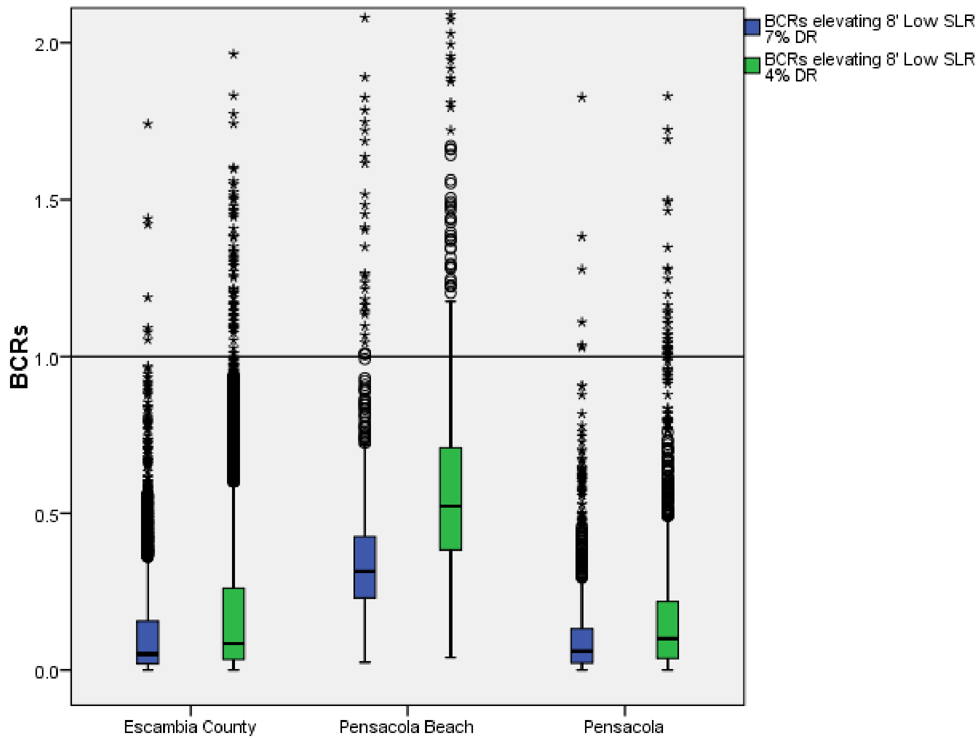

Figure E-2. Boxplots depicting statistics of benefit-cost ratios (BCRs) by study area for elevating homes by 8’ with the NOAA Low sea level rise (SLR) scenario and 7% and 4% discount rates (DR).

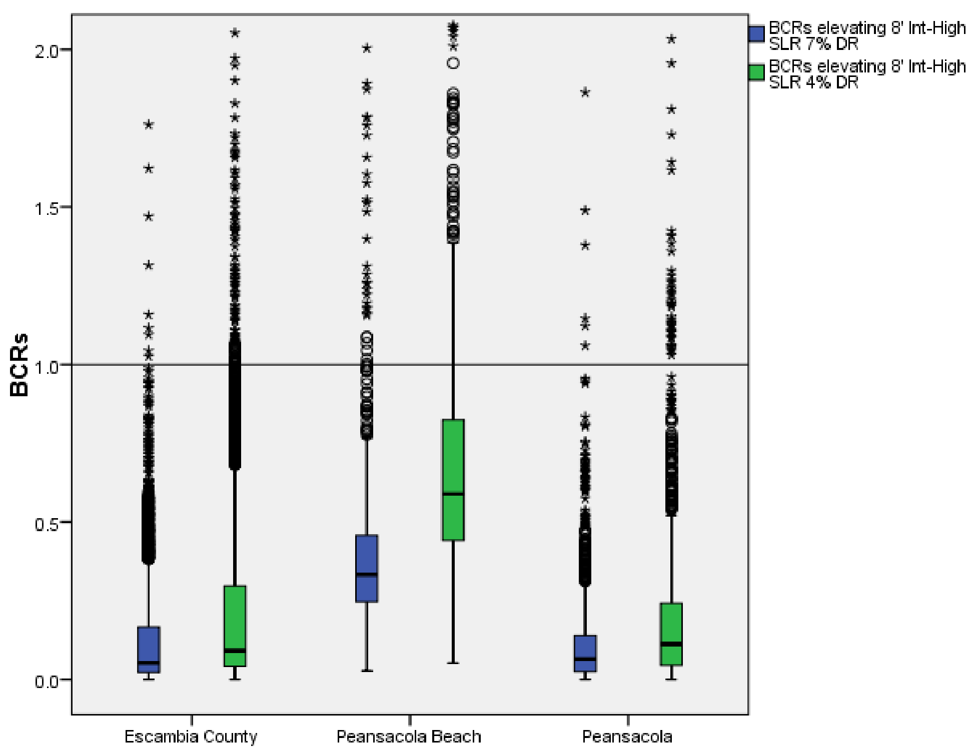

Figure E-3. Boxplots depicting statistics of benefit-cost ratios (BCRs) by study area for elevating homes by 8’ with the NOAA Intermediate (Int)-High sea level rise (SLR) scenario and 7% and 4% discount rates (DR).

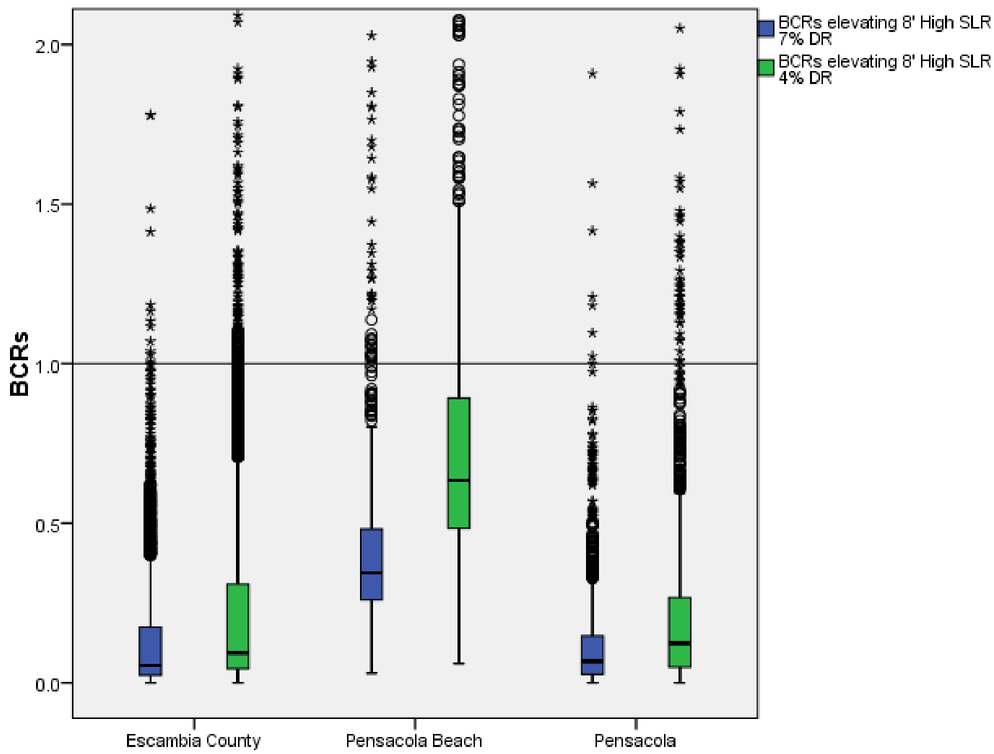

Figure E-4. Boxplots depicting statistics of benefit-cost ratios (BCRs) by study area for elevating homes by 8’ with the NOAA High sea level rise (SLR) scenario and 7% and 4% discount rates (DR).

APPENDIX F: FIGURES SUMMARIZING THE RESULTS OF BULK ANALYSES OF DEMOLITION AND ACQUISITION TO MITIGATE SURGE RISKS

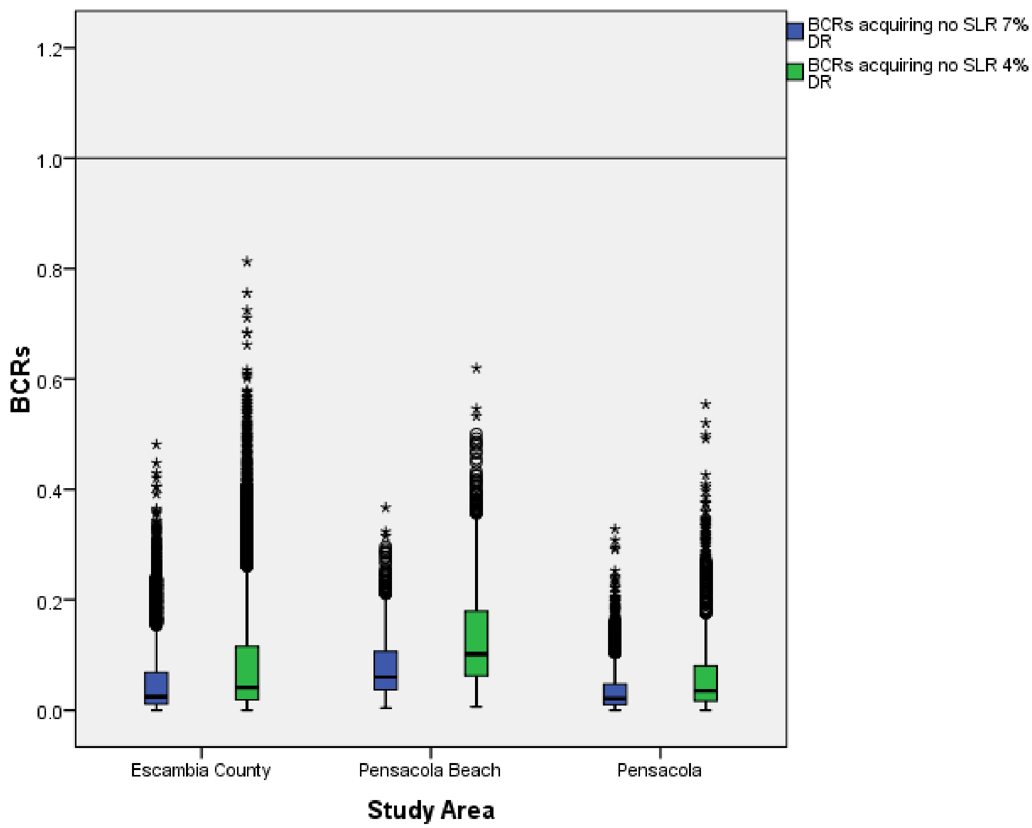

Figure F-1. Boxplots depicting statistics of benefit-cost ratios (BCRs) by study area for demolishing and acquiring homes with no sea level rise (SLR) and 7% and 4% discount rates (DR).

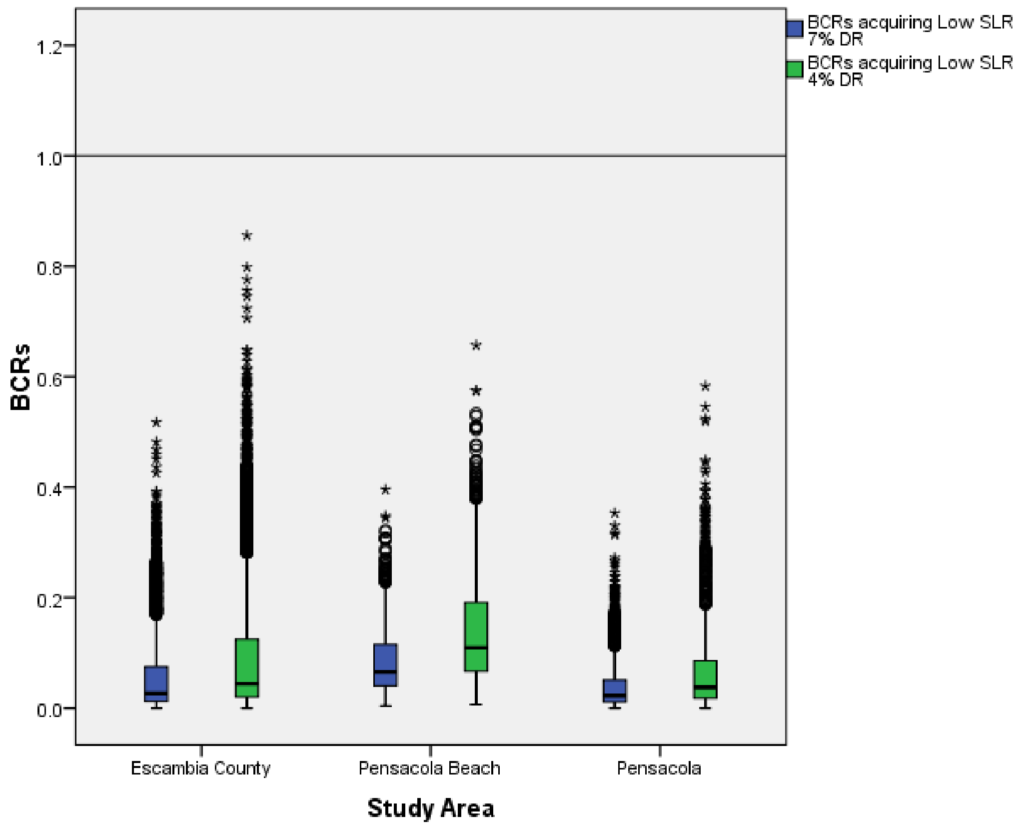

Figure F-2. Boxplots depicting statistics of benefit-cost ratios (BCRs) by study area for demolishing and acquiring homes with the NOAA Low sea level rise (SLR) scenario and 7% and 4% discount rates (DR).

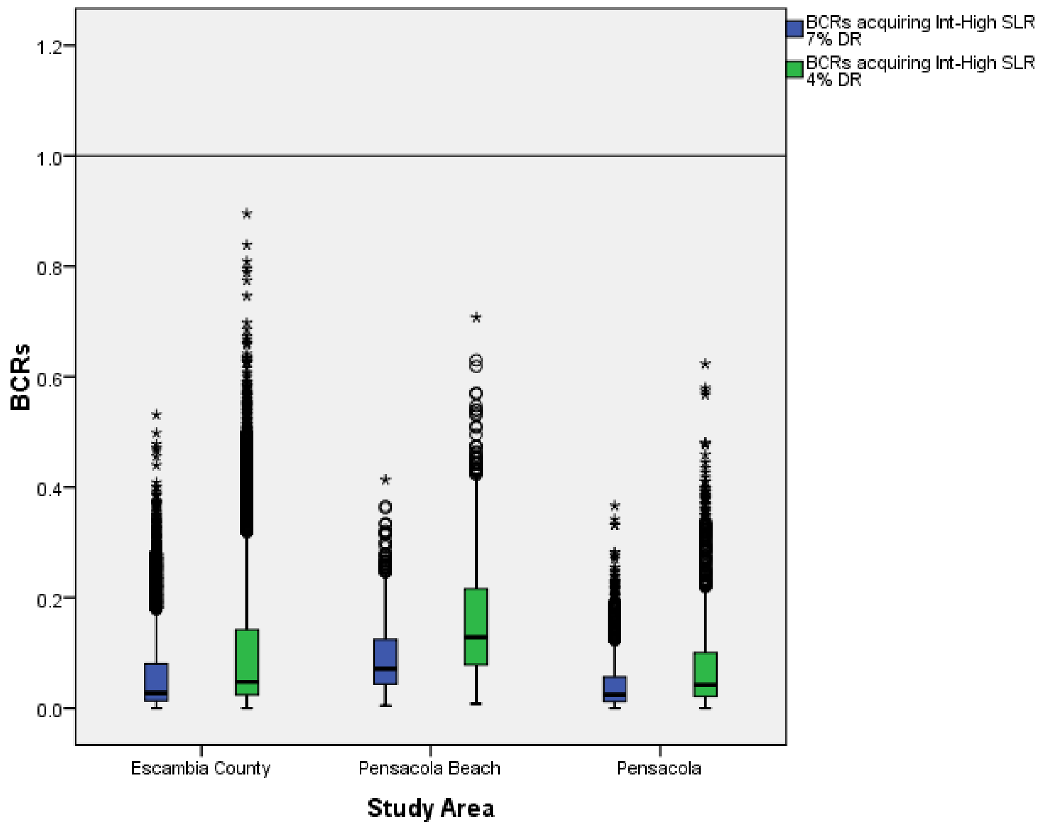

Figure F-3. Boxplots depicting statistics of benefit-cost ratios (BCRs) by study area for demolishing and acquiring homes with the NOAA Intermediate (Int)-High sea level rise (SLR) scenario and 7% and 4% discount rates (DR).

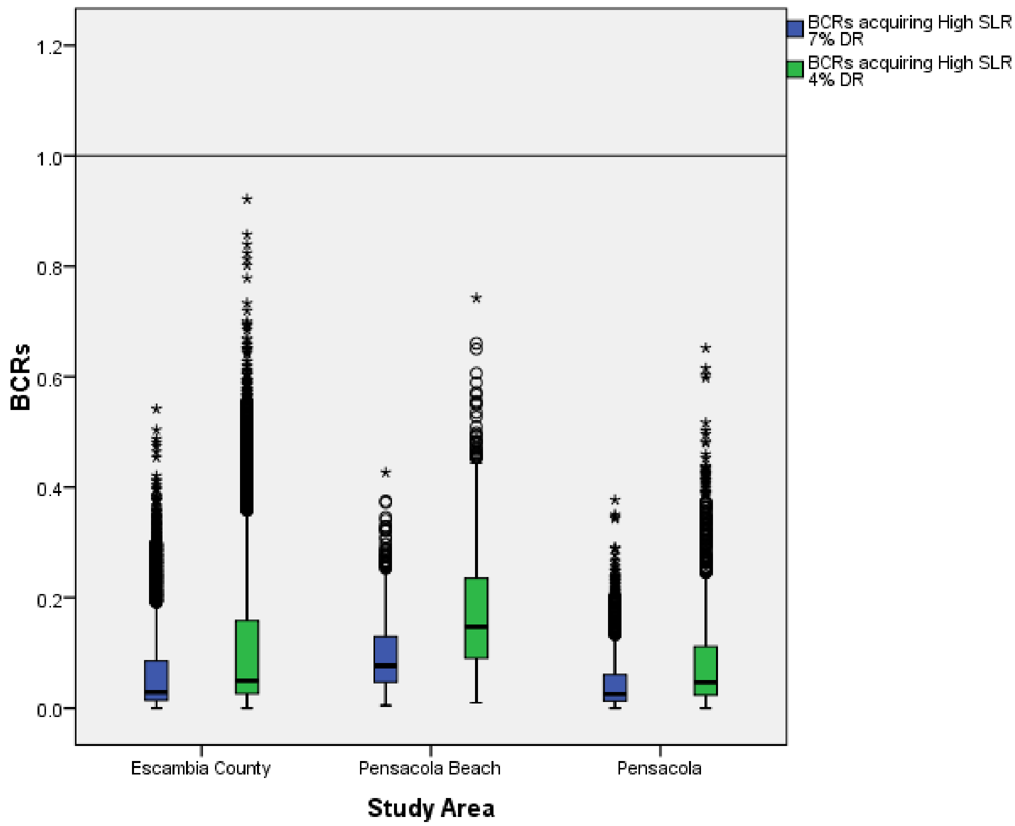

Figure F-4. Boxplots depicting statistics of benefit-cost ratios (BCRs) by study area for demolishing and acquiring homes with the NOAA High sea level rise (SLR) scenario and 7% and 4% discount rates (DR).

APPENDIX G: FIGURES SUMMARIZING THE RESULTS OF BULK ANALYSES OF BUILDING 4' HIGH FLOODWALLS AROUND HOMES TO MITIGATE SURGE RISKS

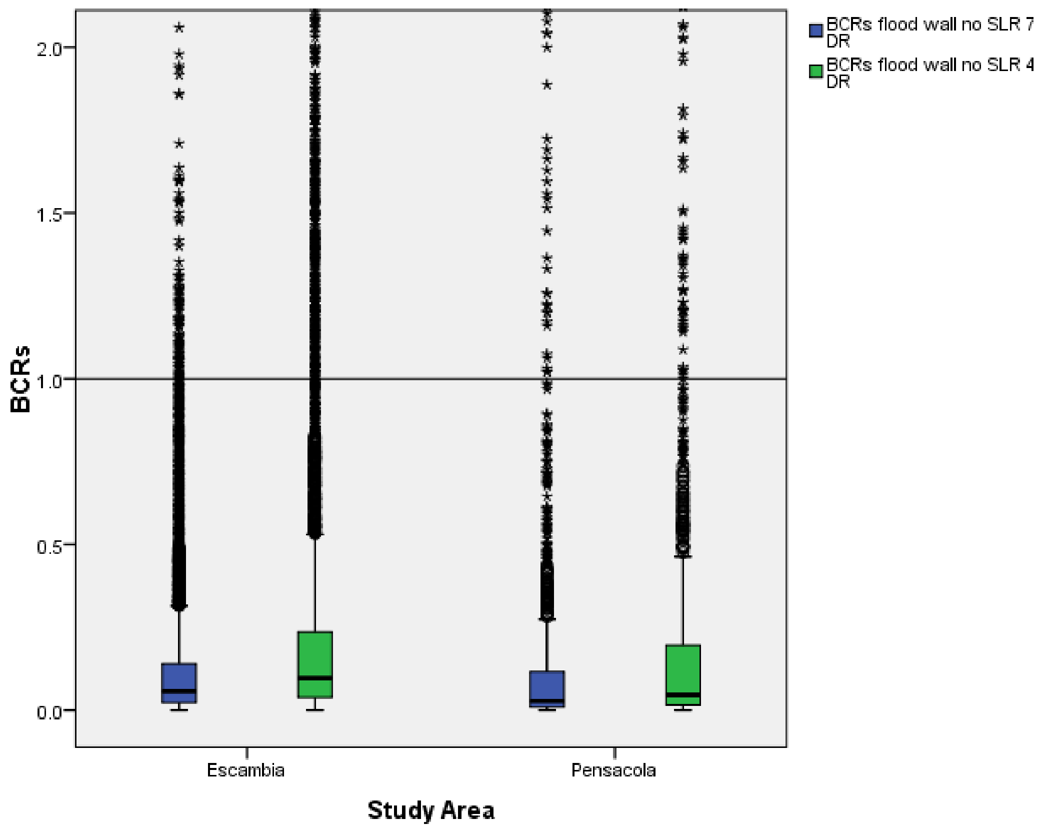

Figure G-1. Boxplots depicting statistics of benefit-cost ratios (BCRs) by study area for building 4' floodwalls around homes with no sea level rise (SLR) and 7% and 4% discount rates (DR).

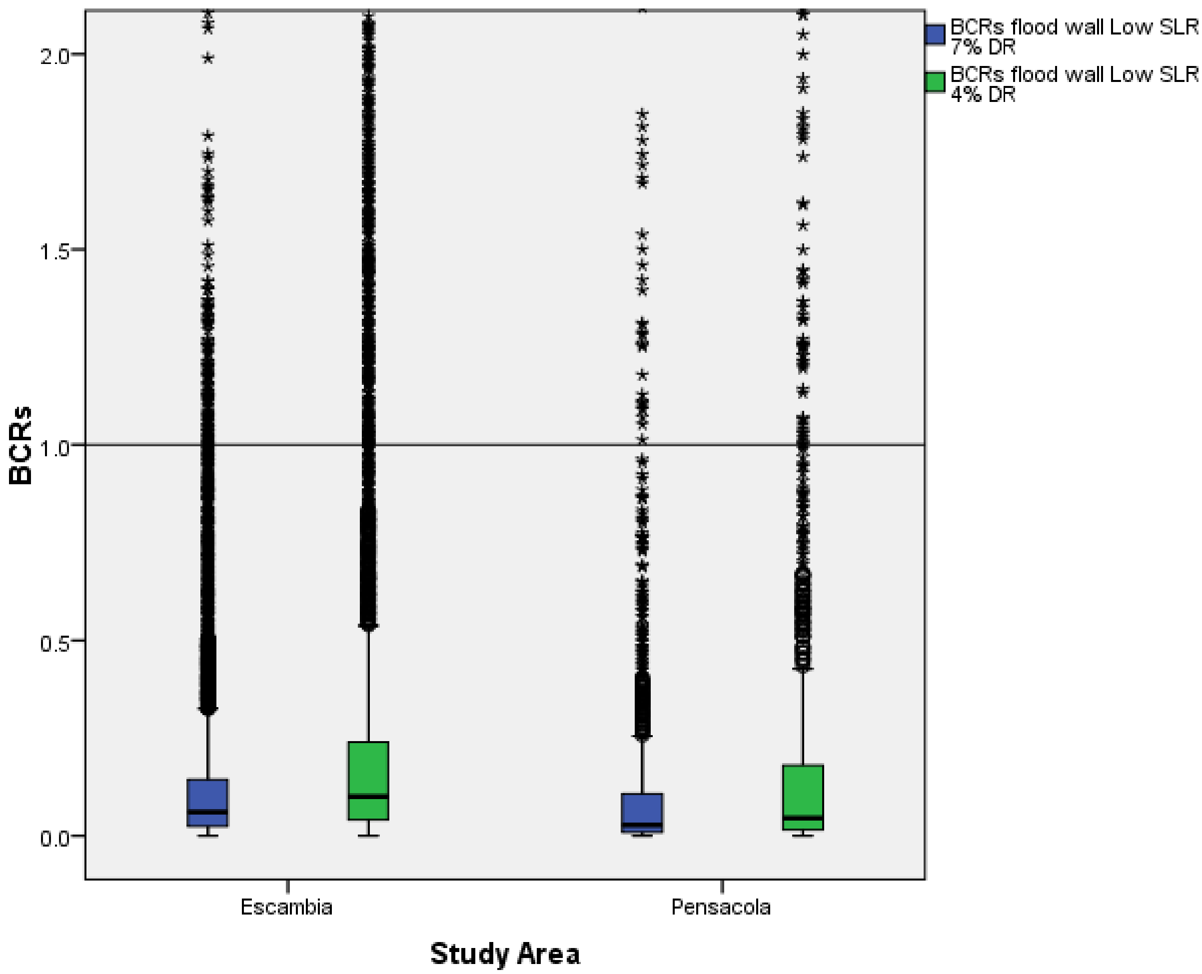

Figure G-2. Boxplots depicting statistics of benefit-cost ratios (BCRs) by study area for building 4' floodwalls around homes with NOAA Low sea level rise (SLR) scenario and 7% and 4% discount rates (DR).

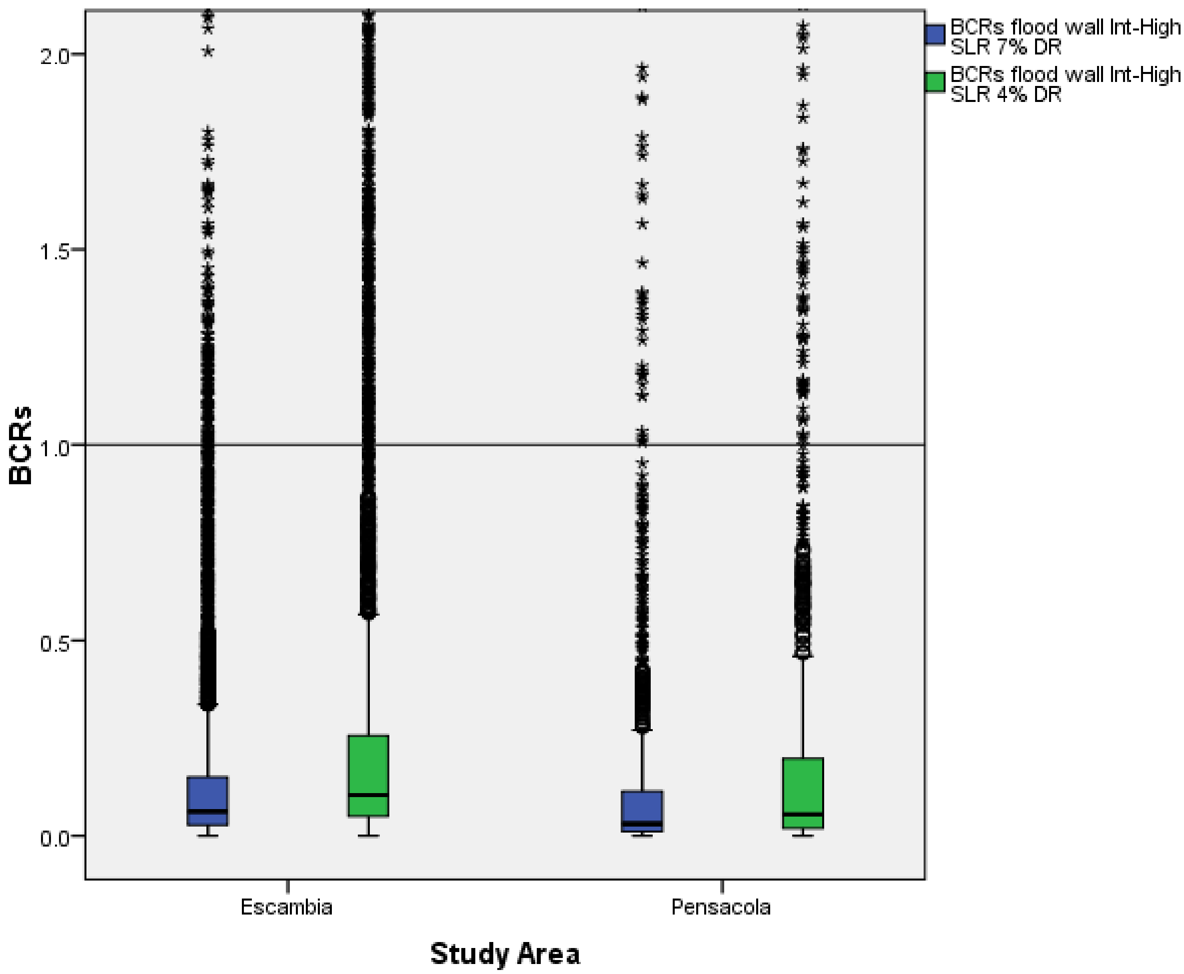

Figure G-3. Boxplots depicting statistics of benefit-cost ratios (BCRs) by study area for building 4' floodwalls around homes with NOAA Intermediate (Int)-High sea level rise (SLR) scenario and 7% and 4% discount rates (DR).

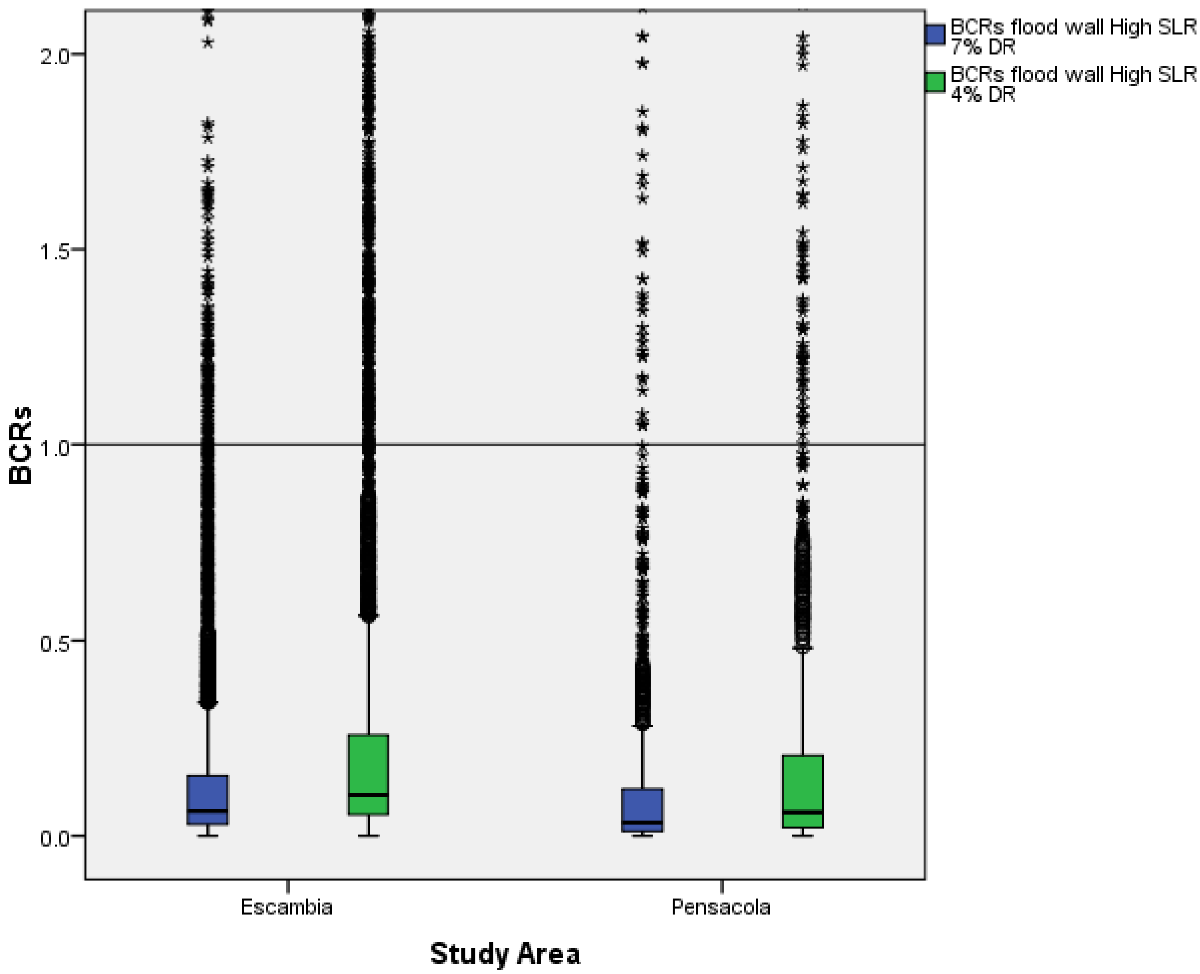

Figure G-4. Boxplots depicting statistics of benefit-cost ratios (BCRs) by study area for building 4' floodwalls around homes with NOAA Intermediate (Int)-High sea level rise (SLR) scenario and 7% and 4% discount rates (DR).

APPENDIX H: TABULAR PRESENTATION OF RESULTS OF BULK ANALYSES OF ECONOMIC EFFECTIVENESS OF MITIGATIING HOMES AGAINST SURGE RISKS

Table H-1. Elevating homes at risk to surge: summary statistics of results by study area

Summary statistics for BC ratios for elevating homes at risk to surge by 8' in unincorporated Escambia County, City of Pensacola, and Pensacola Beach.

Escambia County	**BCRs elevating 8' no SLR 7% DR**	**BCRs elevating 8' no SLR 4% DR**	**BCRs elevating 8' Low SLR 7% DR**	**BCRs elevating 8' Low SLR 4% DR**	**BCRs elevating 8' Int-High SLR 7% DR**	**BCRs elevating 8' Int-High SLR 4% DR**	**BCRs elevating 8' High SLR 7% DR**	**BCRs elevating 8' High SLR 4% DR**
Mean	0.11	0.19	0.12	0.20	0.13	0.23	0.13	0.24
Median	0.05	0.08	0.05	0.08	0.05	0.09	0.05	0.09
Std. Dev.	0.14	0.24	0.16	0.26	0.17	0.30	0.17	0.31
Min.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Max.	1.49	2.51	1.74	2.89	1.76	3.04	1.78	3.30
25th percentile	0.02	0.03	0.02	0.03	0.02	0.04	0.02	0.04
75th percentile	0.14	0.24	0.16	0.26	0.17	0.30	0.17	0.31
City of Pensacola								
Mean	0.11	0.18	0.12	0.19	0.12	0.22	0.13	0.24
Median	0.06	0.09	0.06	0.10	0.06	0.11	0.07	0.12
Std. Dev.	0.16	0.27	0.17	0.29	0.18	0.32	0.19	0.35
Min.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Max.	2.20	3.71	2.37	3.93	2.52	4.41	2.63	4.73
25th percentile	0.02	0.03	0.02	0.04	0.02	0.04	0.03	0.05
75th percentile	0.12	0.21	0.13	0.22	0.14	0.24	0.15	0.27
Pensacola Beach								
Mean	0.34	0.58	0.37	0.62	0.40	0.72	0.42	0.77
Median	0.29	0.48	0.31	0.52	0.33	0.59	0.34	0.63
Std. Dev.	0.25	0.43	0.27	0.46	0.29	0.51	0.30	0.53
Min.	0.02	0.04	0.02	0.04	0.03	0.05	0.03	0.06
Max.	2.40	4.05	2.57	4.23	2.64	4.57	2.70	4.61
25th percentile	0.21	0.35	0.23	0.38	0.25	0.44	0.26	0.48
75th percentile	0.39	0.66	0.43	0.71	0.46	0.83	0.48	0.89

N = 4,600 homes in Escambia County
N = 1,337 homes in City of Pensacola

N = 883 homes in Pensacola Beach

Table H-2 Demolishing and acquiring homes at risk to surge: summary statistics of results by study area

Summary statistics for BC ratios for demolishing and acquiring homes at risk to surge in unincorporated Escambia County, City of Pensacola, and Pensacola Beach.

Escambia County	BCRs acquiring no SLR 7% DR	BCRs acquiring no SLR 4% DR	BCRs acquiring Low SLR 7% DR	BCRs acquiring Low SLR 4% DR	BCRs acquiring Int-High SLR 7% DR	BCRs acquiring Int-High SLR 4% DR	BCRs acquiring High SLR 7% DR	BCRs acquiring High SLR 4% DR
Mean	0.05	0.09	0.06	0.10	0.06	0.11	0.06	0.12
Median	0.02	0.04	0.03	0.04	0.03	0.05	0.03	0.05
Std. Dev.	0.07	0.12	0.07	0.12	0.08	0.13	0.08	0.14
Min.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Max.	0.48	0.81	0.52	0.86	0.53	0.90	0.54	0.92
25th percentile	0.01	0.02	0.01	0.02	0.01	0.02	0.01	0.03
75th percentile	0.07	0.12	0.08	0.12	0.08	0.14	0.09	0.16
City of Pensacola								
Mean	0.04	0.06	0.04	0.07	0.05	0.08	0.05	0.09
Median	0.02	0.04	0.02	0.04	0.02	0.04	0.03	0.05
Std. Dev.	0.05	0.08	0.05	0.09	0.05	0.10	0.06	0.10
Min.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Max.	0.33	0.55	0.35	0.58	0.37	0.62	0.38	0.65
25th percentile	0.01	0.02	0.01	0.02	0.01	0.02	0.01	0.02
75th percentile	0.05	0.08	0.05	0.09	0.06	0.10	0.06	0.11
Pensacola Beach								
Mean	0.08	0.14	0.09	0.15	0.09	0.16	0.10	0.18
Median	0.06	0.10	0.07	0.11	0.07	0.13	0.08	0.15
Std. Dev.	0.06	0.11	0.07	0.11	0.07	0.12	0.07	0.12
Min.	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01
Max.	0.37	0.62	0.40	0.66	0.41	0.71	0.43	0.74
25th percentile	0.04	0.06	0.04	0.07	0.04	0.08	0.05	0.09
75th percentile	0.11	0.18	0.12	0.19	0.12	0.22	0.13	0.24

N = 4,600 homes in Escambia County

N = 1,337 homes in City of Pensacola

N = 883 homes in Pensacola Beach

Table H-3 Building 4' high flood walls around homes: results (tabular) by study area

Summary statistics for BC ratios for building 4' flood walls around homes at risk to surge in unincorporated Escambia County and City of Pensacola. Pensacola Beach homes omitted from analyses of flood walls.

Escambia County	BCRs flood wall no SLR 7% DR	BCRs flood wall no SLR 4% DR	BCRs flood wall Low SLR 7% DR	BCRs flood wall Low SLR 4% DR	BCRs flood wall Int-High SLR 7% DR	BCRs flood wall Int-High SLR 4% DR	BCRs flood wall High SLR 7% DR	BCRs flood wall High SLR 4% DR
Mean	0.17	0.28	0.18	0.29	0.18	0.30	0.18	0.31
Median	0.06	0.10	0.06	0.10	0.06	0.11	0.06	0.10
Std. Dev.	0.32	0.53	0.33	0.55	0.34	0.57	0.34	0.57
Min.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Max.	7.50	12.67	8.16	13.64	8.50	14.16	8.49	14.09
25th percentile	0.02	0.04	0.02	0.04	0.03	0.05	0.03	0.05
75th percentile	0.14	0.24	0.14	0.24	0.15	0.26	0.15	0.26
City of Pensacola								
Mean	0.14	0.23	0.14	0.23	0.15	0.26	0.16	0.27
Median	0.03	0.05	0.03	0.05	0.03	0.05	0.03	0.06
Std. Dev.	0.35	0.59	0.33	0.55	0.35	0.60	0.36	0.63
Min.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Max.	5.80	9.79	3.49	5.72	3.59	6.09	3.67	6.22
25th percentile	0.01	0.02	0.01	0.02	0.01	0.02	0.01	0.02
75th percentile	0.12	0.20	0.11	0.18	0.12	0.20	0.12	0.21

N = 4,341 homes in Escambia County (missing 259 homes with pilings)

N = 1,333 homes in City of Pensacola (missing 4 homes with pilings)

Table H-4 Summary statistics tables for all homes at risk to surge: (a) elevating by 8', (b) demolishing and acquiring, and (c) building 4' floodwalls

(a) Summary statistics for benefit-cost ratios for **elevating** all homes at risk to surge by 8'. (n=6820)

	BCRs elevating 8' no SLR 7% DR	BCRs elevating 8' no SLR 4% DR	BCRs elevating 8' Low SLR 7% DR	BCRs elevating 8' Low SLR 4% DR	BCRs elevating 8' Int-High SLR 7% DR	BCRs elevating 8' Int-High SLR 4% DR	BCRs elevating 8' High SLR 7% DR	BCRs elevating 8' High SLR 4% DR
Mean	0.14	0.24	0.15	0.25	0.16	0.29	0.17	0.31
Median	0.07	0.11	0.07	0.12	0.08	0.13	0.08	0.14
Std. Dev.	0.18	0.31	0.20	0.33	0.21	0.38	0.22	0.40
Min.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Max.	2.40	4.05	2.57	4.23	2.64	4.57	2.70	4.73
25th percentile	0.02	0.04	0.02	0.04	0.03	0.05	0.03	0.05
75th percentile	0.21	0.35	0.23	0.38	0.24	0.44	0.26	0.47

(b) Summary statistics for benefit-cost ratios for **demolishing and acquiring** all homes at risk to surge. (n=6820)

	BCRs acquiring no SLR 7% DR	BCRs acquiring no SLR 4% DR	BCRs acquiring Low SLR 7% DR	BCRs acquiring Low SLR 4% DR	BCRs acquiring Int-High SLR 7% DR	BCRs acquiring Int-High SLR 4% DR	BCRs acquiring High SLR 7% DR	BCRs acquiring High SLR 4% DR
Mean	0.05	0.09	0.06	0.10	0.06	0.11	0.07	0.12
Median	0.03	0.05	0.03	0.05	0.03	0.05	0.03	0.06
Std. Dev.	0.07	0.11	0.07	0.12	0.07	0.13	0.08	0.13
Min.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Max.	0.48	0.81	0.52	0.86	0.53	0.90	0.54	0.92
25th percentile	0.01	0.02	0.01	0.02	0.01	0.03	0.02	0.03
75th percentile	0.07	0.12	0.08	0.13	0.08	0.15	0.09	0.17

(c) Summary statistics for benefit-cost ratios for **building 4' floodwalls** around all homes at risk to surge. (n=4341; 1146 homes missing floodwall BCRs that are either on Pensacola Beach or homes with pilings foundations)

	BCRs flood wall no SLR 7% DR	BCRs flood wall no SLR 4% DR	BCRs flood wall Low SLR 7% DR	BCRs flood wall Low SLR 4% DR	BCRs flood wall Int-High SLR 7% DR	BCRs flood wall Int-High SLR 4% DR	BCRs flood wall High SLR 7% DR	BCRs flood wall High SLR 4% DR
Mean	0.17	0.28	0.18	0.29	0.18	0.30	0.18	0.31
Median	0.06	0.10	0.06	0.10	0.06	0.11	0.06	0.10
Std. Dev.	0.32	0.53	0.33	0.55	0.34	0.57	0.34	0.57
Min.	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Max.	7.50	12.67	8.16	13.64	8.50	14.16	8.49	14.09
25th percentile	0.02	0.04	0.02	0.04	0.03	0.05	0.03	0.05
75th percentile	0.14	0.24	0.14	0.24	0.15	0.26	0.15	0.26

Table H-5: Summary statistics by study and surge/flood zone

Costs of elevating homes, demolishing and acquiring, and building 4’ floodwalls by study area and surge/flood zone

			Cost for elevating homes by 8'	Total demolition/ acquisition costs	Cost for 4' floodwall
				Mean	
Escambia County	annual chance surge zone	10%	$121,321	$445,716	$55,707
		4%	$147,511	$362,174	$57,892
		2%	$129,501	$275,561	$54,240
		1%	$126,786	$245,763	$53,669
		0.2%	$120,921	$208,039	$52,265
Pensacola		10%	$152,137	$599,503	$58,391
		4%	$154,629	$545,155	$60,080
		2%	$111,617	$352,845	$57,003
		1%	$116,475	$371,086	$55,530
		0.2%	$117,406	$311,074	$53,735
Pensacola Beach		10%	$113,416	$579,038	
		4%	$121,141	$646,263	
		2%	$125,154	$1,161,973	
		1%	$137,233	$1,511,269	
				Mean	
Escambia County	FEMA flood zone (2006 DFIRM or EC where applicable)	A	$140,587	$214,022	$55,015
		AE	$127,899	$376,915	$54,417
		AO	$142,269	$708,111	$52,664
		VE	$168,827	$613,556	$63,048
		X	$126,549	$229,817	$53,557
Pensacola		AE	$144,630	$508,268	$58,887
		VE	$350,863	$2,280,177	$61,929
		X	$117,592	$345,589	$55,345
Pensacola Beach		AE	$118,746	$580,972	
		VE	$116,572	$962,675	

Table H-6: Aggregate BCRs of bulk analysis by annual chance surge risk zones and FEMA flood zones for elevating by 8’

		aggregate BCRs for elevating 8' by annual chance surge zone							
		No SLR		Low SLR		Int-High SLR		High SLR	
		4% discount rate	7% discount rate	4% discount rate	7% discount rate	4% discount rate	7% discount rate	4% discount rate	7% discount rate
annual chance surge zone	10%	0.74	0.44	0.80	0.48	0.91	0.51	0.96	0.53
	4%	0.50	0.30	0.53	0.32	0.60	0.34	0.63	0.35
	2%	0.21	0.12	0.22	0.13	0.25	0.14	0.26	0.15
	1%	0.11	0.06	0.11	0.07	0.12	0.07	0.13	0.07
	0.2%	0.04	0.02	0.04	0.02	0.05	0.03	0.05	0.03

		aggregate BCRs for elevating 8' by FEMA flood zone							
		No SLR		Low SLR		Int-High SLR		High SLR	
		4% discount rate	7% discount rate	4% discount rate	7% discount rate	4% discount rate	7% discount rate	4% discount rate	7% discount rate
FEMA flood zone (2006 DFIRM or EC where applicable)	A	0.13	0.08	0.14	0.08	0.15	0.09	0.15	0.09
	AE	0.51	0.30	0.55	0.33	0.62	0.35	0.66	0.37
	AO	0.42	0.25	0.45	0.27	0.52	0.29	0.56	0.30
	VE	0.55	0.33	0.59	0.35	0.68	0.38	0.72	0.40
	X	0.13	0.08	0.14	0.08	0.15	0.09	0.16	0.09

Table H-7: Aggregate BCRs of bulk analysis by annual chance surge risk zones and FEMA flood zones for demolishing and acquiring

		aggregate BCRs for demolishing & acquiring by annual chance surge zone							
		No SLR		Low SLR		Int-High SLR		High SLR	
		4% discount rate	7% discount rate	4% discount rate	7% discount rate	4% discount rate	7% discount rate	4% discount rate	7% discount rate
annual chance surge zone	0.10	0.19	0.11	0.21	0.13	0.23	0.13	0.25	0.14
	0.04	0.17	0.10	0.18	0.11	0.20	0.12	0.22	0.12
	0.02	0.08	0.05	0.08	0.05	0.09	0.05	0.10	0.06
	0.01	0.05	0.03	0.05	0.03	0.06	0.03	0.06	0.03
	0.00	0.02	0.01	0.02	0.01	0.02	0.01	0.03	0.01

		aggregate BCRs by FEMA flood zone							
		No SLR		Low SLR		Int-High SLR		High SLR	
		4% discount rate	7% discount rate	4% discount rate	7% discount rate	4% discount rate	7% discount rate	4% discount rate	7% discount rate
FEMA flood zone (2006 DFIRM or EC where applicable)	A	0.09	0.06	0.10	0.06	0.11	0.06	0.12	0.07
	AE	0.16	0.09	0.17	0.10	0.19	0.11	0.21	0.11
	AO	0.10	0.06	0.10	0.06	0.12	0.07	0.13	0.07
	VE	0.09	0.05	0.09	0.06	0.10	0.06	0.12	0.06
	X	0.07	0.04	0.07	0.04	0.08	0.05	0.09	0.05

Table H-8: Aggregate BCRs of bulk analysis by annual chance surge risk zones and FEMA flood zones for building 4' floodwalls around homes

		aggregate BCRs for building 4' floodwalls by annual chance surge risk zone							
		No SLR		Low SLR		Int-High SLR		High SLR	
		4% discount rate	7% discount rate	4% discount rate	7% discount rate	4% discount rate	7% discount rate	4% discount rate	7% discount rate
annual chance surge zone	10%	1.07	0.63	1.67	1.00	1.89	1.07	2.07	1.13
	4%	0.88	0.52	0.74	0.44	0.86	0.48	0.98	0.52
	2%	0.28	0.16	0.27	0.16	0.31	0.17	0.35	0.19
	1%	0.13	0.08	0.13	0.08	0.15	0.09	0.17	0.09
	0.2%	0.06	0.04	0.02	0.01	0.03	0.02	0.04	0.02

		aggregate BCRs for building 4' floodwalls by FEMA flood zone							
		No SLR		Low SLR		Int-High SLR		High SLR	
		4% discount rate	7% discount rate	4% discount rate	7% discount rate	4% discount rate	7% discount rate	4% discount rate	7% discount rate
FEMA flood zone (2006 DFIRM or EC where applicable)	A	0.23	0.14	0.15	0.09	0.18	0.10	0.20	0.10
	AE	0.69	0.41	0.80	0.48	0.92	0.52	1.03	0.55
	AO	0.94	0.55	0.75	0.45	0.88	0.49	1.01	0.53
	VE	1.10	0.65	1.05	0.63	1.20	0.68	1.33	0.72
	X	0.20	0.12	0.14	0.09	0.17	0.09	0.20	0.10

APPENDIX I: FEMA standard benefits of mitigation projects

FEMA has computed average national-level benefits of residential acquisitions, elevations[35], and demolition and rebuild projects[36] in SFHAs; and no BC analyses are needed if projects costs are equal or less than:

- $276,000 for demolition and acquisition
- $175,000 for elevation
- $150,000 for demolition and rebuild

Demolition and rebuild generally applies to structures that are not suitable for elevation; and any replacement structure must be within 110% of the size of the original structure, and elevated according to current code and ordinance standards.

The costs listed above can be funded through FEMA's Hazard Mitigation Grant Program, Pre-Disaster Mitigation Program, and Flood Mitigation Assistance Program (FEMA 2015; FY15 Hazard Mitigation Assistance Guidance and FY15 Hazard Mitigation Assistance Guidance Addendum[37]).

Another piece of data that could make flood mitigation projects more economically effective is NFIP claims data. If a structure has repetitive losses costing more than a flood mitigation technique, then it would be cost-effective to mitigate this structure using the BCA Toolkit.

[35] See https://www.fema.gov/media-library-data/2cd22ac644e67fe1960b08c82bf05af0/Cost_Effectiveness_for_Acquisitions_and_Elevations_web.pdf
[36] See page 60 Section D 2.2 of https://www.fema.gov/media-library-data/1424983165449-38f5dfc69c0bd4ea8a161e8bb7b79553/HMA_Addendum_022715_508.pdf
[37] https://www.fema.gov/media-library/assets/documents/103279

A Resource for the State of Florida

SECTION 8

Education and Outreach Programs to Convey the Benefits of Various Hurricane Loss Mitigation Devices and Techniques

A Report Submitted to:
The State of Florida Division of Emergency Management

Prepared By:
Erik Salna
Consultant: Jamie Edwards

The International Hurricane Research Center (IHRC)
Florida International University

August 13, 2018

Research Area 7: Education and Outreach Programs to Convey the Benefits of Various Hurricane Loss Mitigation Devices and Techniques (PI: Erik Salna)

Executive Summary:

Erik Salna, FIU International Hurricane Research Center Associate Director, with assistance from consultant Jamie Edwards, developed and coordinated education and outreach activities to build on the foundation of previous work under this grant and showcased the hurricane-loss mitigation objectives of the RCMP.

For the 2017-2018 performance period, the below mentioned educational partnerships, community events, and outreach programs were developed:

Wall of Wind Mitigation Challenge (WOW! Challenge): Wednesday, May 23rd, 2018
The International Hurricane Research Center (IHRC), located on the campus of Florida International University (FIU), has developed the Wall of Wind Mitigation Challenge (WOW! Challenge), a judged competition for South Florida high school students. As the next generation of engineers to address natural hazards and extreme weather, this STEM education event features a competition between high school teams to develop innovative wind mitigation concepts and real-life human safety and property protection solutions. The mitigation concepts are tested live at the FIU NHERI Wall of Wind (WOW) Experimental Facility (EF), located on FIU's Engineering Campus.

- The objective for the 2018 Wall of Wind Mitigation Challenge was for students to improve a building's aerodynamic performance.
- Over 125 attendees participated in the event, including teams from six South Florida high schools, involving 100 students and 12 teachers.
- First Place was awarded to Miami Coral Park Senior High School.
- Second Place was awarded to Florida Christian High School.
- Third Place was awarded to Booker T. Washington Senior High School.

Eye of the Storm (Science, Mitigation & Preparedness) Event: May 19th, 2018
The Museum of Discovery & Science (MODS), located in Fort Lauderdale, FL, assisted the IHRC in planning, coordinating and facilitating this free admission public education event that showcased special hands-on, interactive activities and demonstrations teaching hurricane science, mitigation and preparedness.

- Over 2,800 people attended Eye of the Storm.
- Dozens of South Florida agencies and organizations participated.
- Total Social Media Impressions: 15,637

NOAA Hurricane Awareness Tour – May 11th, 2018
In conjunction with NOAA's National Hurricane Preparedness Week, the IHRC's Erik Salna participated with NOAA's National Hurricane Center (NHC) on the 2018 Hurricane Hunter Awareness Tour at the Lakeland Linder Regional Airport in Lakeland, Florida.

- As part of its efforts to build a Weather-Ready Nation, the IHRC and other hurricane experts raised awareness about the importance for preparing for the upcoming hurricane season with public officials, school groups, local residents and media.
- NOAA's Gulfstream IV-SP (G-IV) "Hurricane Hunter" aircraft and a U.S. Air Force Reserve WC-130J "Hurricane Hunter" aircraft were on display and toured by 389 students and approximately 800 public residents.

Get Ready, Florida! The National Hurricane Survival Initiative:
The IHRC's Erik Salna collaborated with the National Hurricane Survival Initiative (NHSI) and their annual hurricane preparedness campaign to make hurricane safety a year-round culture in Florida. The IHRC contributed hurricane mitigation and preparedness information for protecting your family, home and business. For 2018, the NHSI focused on Florida, with a 30 minute TV program, Get Ready, Florida!

- The TV program has aired in Florida's top ten media markets.
- Over 367,000 Florida residents have viewed the TV program.
- Total Publicity Value is over $1.4M.

Education and Outreach Programs:

Wall of Wind Mitigation Challenge (WOW! Challenge): Wednesday, May 23rd, 2018
The International Hurricane Research Center (IHRC), located on the campus of Florida International University (FIU), has developed the Wall of Wind Mitigation Challenge (WOW! Challenge), a judged competition for South Florida high school students. As the next generation of engineers to address natural hazards and extreme weather, this STEM education event features a competition between high school teams to develop innovative wind mitigation concepts and real-life human safety and property protection solutions. The student teams prepare three components for the competition: a physical test, an oral presentation, and a written technical paper. The mitigation concepts are tested live at the FIU NHERI Wall of Wind (WOW) Experimental Facility (EF), located on FIU's Engineering Campus.

The WOW! Challenge requires problem solving, teamwork, and creativity, and it includes aspects of science, technology, engineering, mathematics, architectural design, and business entrepreneurship. The high school students are inspired to pursue STEM education and careers in wind engineering and hurricane mitigation. The competition has real world applications and benefits society as a whole by developing hurricane mitigation techniques that can lead to enhanced human safety, property loss reduction, insurance cost reduction, and a culture of hurricane preparedness. There is no other competition like it in the entire country, and it's a once in a lifetime opportunity for the high school students – an experience they never forget.

The objective for the 2018 Wall of Wind Mitigation Challenge was for students to improve a building's aerodynamic performance. Each team constructed a building model and was tasked to develop a mitigation solution that would improve its aerodynamic performance through shape optimization by minimizing aerodynamic drag. The goal was for the building model to remain upright to as high a wind speed as possible. The building models were tested by the FIU NHERI Wall of Wind Experimental Facility to evaluate their effectiveness. Safety was paramount during the competition and wind testing. Safety guidelines were described to all student teams.

Over 125 attendees participated in the event, including teams from six South Florida high schools, involving 100 students and 12 teachers. The six teams were from Miami Coral Park Senior High School, Booker T. Washington High School, North Miami Senior High School, Robert Morgan Education Center, G. Holmes Braddock High School and Florida Christian High School.

An informational workshop detailing this year's WOW! Challenge was conducted for teachers and students before the actual competition. It was recorded and the video and workshop PowerPoint were made available on the WOW! Challenge web page. All of the details of rules and guidelines for the three required components are also found on the WOW! Challenge web page located at: http://www.ihrc.fiu.edu/outreach-education/wall-of-wind-challenge/.

The Physical Test Description:

- The building model had to be a minimum of 32 inches high (i.e. total height), which included a gold painted wooden base (8x8x2 inches) which was provided for each team; see Figure 1.
- Above the lowest 2 inches of the building model, which is the gold painted wooden base, and up to at least 30 inches above the base, the building model had to have a minimum solid width of 8 inches, or wider; see Figure 1.
- Any shape, above the lowest two inches of the gold base, could be used as long as it always had a minimum solid width of 8 inches when viewed from any and all directions; see Figure 2 for shape examples.
- All building models were tested for two wind directions at 90 degrees to each other; see Figure 2 for wind directions on various shapes. The building model was prevented from sliding during the wind tests by a small ½ inch high stop that was placed at the back and side edges of the gold base.
- The goal was to have a building model shape that has the least tendency to be blown over by the wind when tested for the two directions at 90 degrees to each other. The wind speed for each of the two directions were gradually increased until the model blew over. The higher the wind speed at which this happened, resulted in a higher score for the team.
- The weight of the building model was to be no greater than 40 lbs. The center of gravity had to be directly above the center of the 8 inch square gold base (within 0.05 inches) and be within 1 inch of the mid-height of the model building.

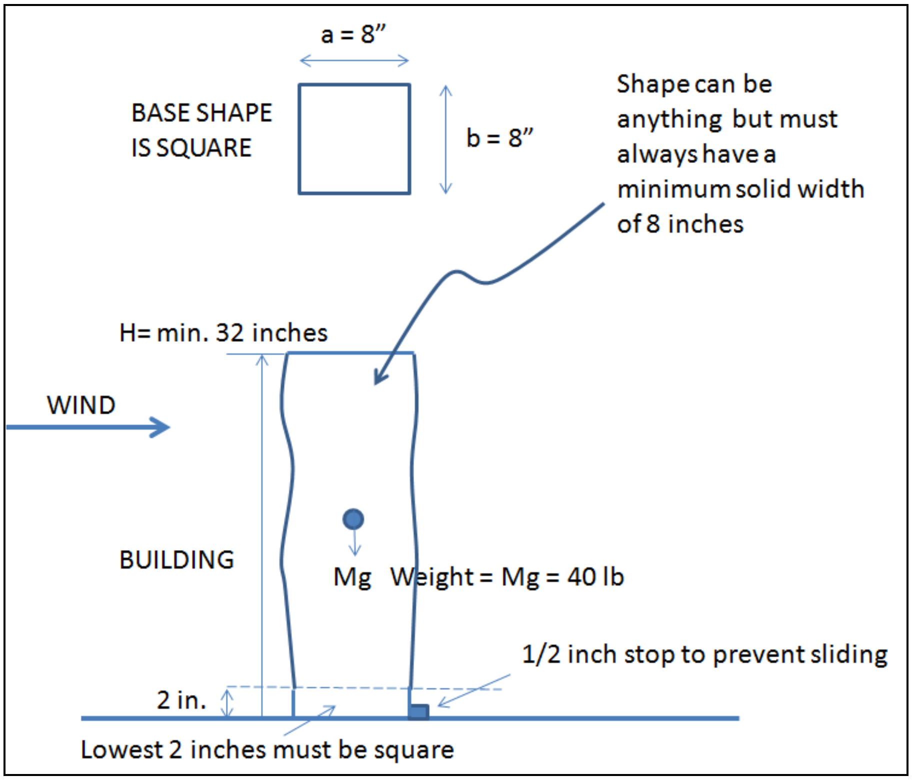

Figure 1: Schematic diagram of the building model, showing dimensions of side and plan views.

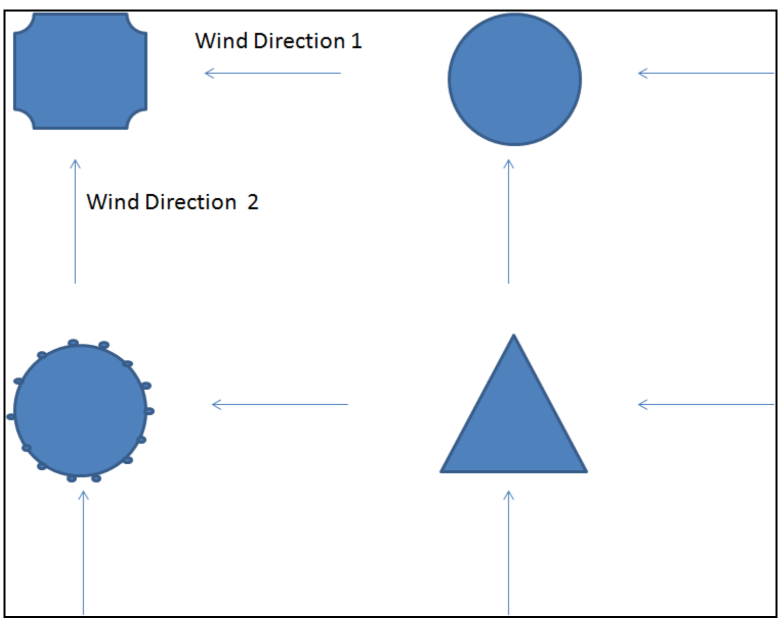

Figure 2: Examples of allowable cross-section shapes and wind directions tested by the FIU NHERI Wall of Wind Experimental Facility.

The Oral Presentation Description:

- Oral presentations were done live at FIU to a panel of Judges who then computed a score for the Team.
- Oral presentations were to be no more than 7 minutes and were strictly timed by Judges.
- Each Team had some follow-up questions from the Judges after their oral presentation.
- Oral presentations were to communicate some scientific process or analysis involved with the development of the building model.

Oral presentations were to consider these items:

- How is hurricane wind mitigation being addressed with your building model?
- What is hurricane wind mitigation?
- What is the importance of hurricane wind mitigation?
- Oral presentations could also include disciplines such as architecture, business, economics, finance, geosciences, insurance, political science, sociology, and urban planning when discussing hurricane wind mitigation and their building model.

Written technical papers were to address these items:

- Written technical papers should include any scientific or mathematical process and analysis involved with the development of their building model.
- Is hurricane wind mitigation being addressed by your building model?
- What is hurricane wind mitigation?
- What is the importance of hurricane wind mitigation?
- Written technical papers may also include disciplines such as architecture, business, economics, finance, geosciences, insurance, political science, sociology, and urban planning when discussing hurricane wind mitigation and their building model.

All three required components of the competition were judged and scored by a combination of IHRC academia and a panel of experts.

The judges were:

- Arindam Gan Chowdhury, PhD, PI and Director, NHERI Wall of Wind (WOW) Experimental Facility (EF), Co-Director, Lab. Wind Engineering Research, Extreme Events Institute, an FIU Preeminent Program, Professor, Dept. of Civil & Environ. Engineering, Florida International University
- Amal Elawady, PhD, Assistant Professor, Department of Civil & Environmental Engineering, College of Engineering and Computing, International Hurricane Research Center, Extreme Events Institute, an FIU Preeminent Program, Florida International University
- Marc Jean, Assistant Director, Department of Emergency Management, Florida International University
- Luis A. Silva, PE, Principal (FIU Engineering Alum), Aluces Corporation, Miami, Florida
- Ioannis Zisis, PhD, Assistant Professor, Dept. of Civil & Environ. Engineering, Co-Director, Lab. Wind Engineering Research, Extreme Events Institute, an FIU Preeminent Program, Florida International University

The scores from the judging for all three required components were added up for a cumulative total and were used to determine the top three teams; the final results were as follows:

- *First Place* was awarded to Miami Coral Park Senior High School.
- *Second Place* was awarded to Florida Christian High School.
- *Third Place* was awarded to Booker T. Washington Senior High School.

A complete scoring summary can be found on the following link:
http://www.ihrc.fiu.edu/wp-content/uploads/2018/08/2018_WOW_CHALLENGE_RESULTS_SUMMARY.pdf

Once again the Wall of Wind Mitigation Challenge was supported by local media. This media exposure results in great positive visibility in the community for the IHRC, FIU and FDEM's message of mitigation. The following media representatives participated:

- FIU News: https://news.fiu.edu/2018/06/wall-of-wind-challenge-attracts-next-generation-of-engineers/123393

All pictures of the 2018 WOW! Challenge can be found on the following link:
https://www.flickr.com/photos/fiu/sets/72157694069130632/

Students observing a physical test.

Students observing a physical test.

Student Team with their building model.

Student Team with their building model.

Student Team with their building model.

Student Team with their building model.

The building models.

Dr. Chowdhury congratulating the students.

The WOW! Challenge trophies.

1st Place: North Miami Senior H.S.

2nd Place: Miami Coral Park Sr. H.S. *3rd Place: Miami Northwestern H.S.*

Eye of the Storm (Science, Mitigation & Preparedness) Event: May 19th, 2018

The Museum of Discovery & Science (MODS), located in Fort Lauderdale, FL, assisted the IHRC in planning, coordinating and facilitating this free admission public education event. Over 2,800 people attended Eye of the Storm, showcasing special hands-on, interactive activities and demonstrations teaching hurricane science, mitigation and preparedness. This included special learning activities for parents and children providing family fun throughout the day. This collaborative community education outreach project partnered the IHRC with the Florida Division of Emergency Management, Broward County Emergency Management, City of Fort Lauderdale Emergency Management, NOAA's National Hurricane Center, NOAA's Miami Office of the National Weather Service and NOAA's Atlantic Oceanographic and Meteorological Laboratory-Hurricane Research Division. Great support was provided by Miami Dade College, the International Hurricane Protection Association (IHPA), local media and dozens of South Florida agencies and organizations, including the local American Red Cross.

Special interactive exhibits and demonstrations included:

- Live Air Cannon Debris Impact Testing of Shutters
- How the Weather Works Live Weather Education Demonstrations
- Weather Jeopardy Game
- TV Hurricane Broadcast Center provided by Miami Dade College
- Live Tropical Weather Briefings by NOAA's National Hurricane Center and National Weather Service
- FIU Wall of Wind Exhibit

Various distinguished hurricane experts participated:

- Daniel Brown, Senior Hurricane Specialist, NOAA's National Hurricane Center
- John Cangialosi, Hurricane Specialist, NOAA's National Hurricane Center
- Dr. Pablo Santos, Meteorologist In Charge, National Weather Service-Miami
- Dr. Frank D. Marks, Director of Hurricane Research Division, NOAA/AOML/HRD
- Neal Dorst, Hurricane Researcher, NOAA/AOML/HRD
- Stanley B. Goldenberg, Research Meteorologist, NOAA/AOML/HRD
- Erica Rule, Communications and Outreach, NOAA/AOML/HRD

Special guests and presentations:

- Broward County Emergency Management
- Hurricane Hunter Researchers – NOAA's AOML-HRD
- Broward County CERT Teams
- NOAA/NWS Owlie Skywarn Mascot
- Florida International University's Mascot Roary
- City of Fort Lauderdale Emergency Management Sparky the Fire Dog Mascot
- Museum of Discovery and Science Joey the Otter Mascot

Special live interactive theater presentations:

- NOAA/NWS Owlie Skywarn Live Weather Education Theater Shows
- Tsunami Tim Live Weather Education Theater Shows

The Eye of the Storm received great attendance and coverage by the local South Florida media. This resulted in great positive visibility in the community for IHRC, FIU and FDEM's message of mitigation.

The following local South Florida media representatives participated in person:

- Craig Setzer, Chief Meteorologist, CBS4, WFOR-TV
- Betty Davis, Chief Meteorologist, Local 10 News, WPLG-TV (ABC)

The following local South Florida media representatives provided coverage:

- Channel 7, WSVN-TV, FOX News
  https://wsvn.com/news/local/museum-of-discovery-and-science-opens-rescue-exhibit/
- Local 10 News, WPLG-TV (ABC)
  https://www1.newsdataservice.com//Player?ClipId=,S,201805,DECC52FF-AF3E-418D-9CF9-864114AFF23E&ReqServer=NDS5%5cNDS5&QueryName=Portal&Offset=1229&rai=91629e00-4f88-11d7-80a6-00b0d020616e&ran=&roi=91629e00-4f88-11d7-80a6-00b0d020616e&ron=&run=discovery&rut=Portal%20Login&Clip=Y&LRP=Y&AHR=Y&AHD=N&pbp=N&PortalId=efa6f7fe-28d8-4dd0-bcda-ddcead197989&PortalLogin=5000346d-bb77-45f0-af87-8127c0d950f1&Priority=2

Total Social Media Impressions: 15,637

- Facebook: 17,008 people reached
- Twitter: 2,374 impressions
- Instagram: 4,294 impressions

CERT Team and American Red Cross Vehicles

NOAA/NWS Owlie Skywarn Live Theater Show

FIU Wall of Wind Exhibit and FIU's Roary

Meet the NOAA-AOML Hurricane Hunters

Pet Therapy and Preparedness

Tsunami Tim Live Weather Theater Show

Local Celebrity TV Weathercasters

IHPA Live Air Cannon Missile Demonstrations

Mitigation Education: Simpson Strong-Tie

Mitigation Education: PGT Windows & Doors

NOAA Hurricane Awareness Tour – May 11th, 2018

In conjunction with NOAA's National Hurricane Preparedness Week, the IHRC's Erik Salna participated with NOAA's National Hurricane Center (NHC) on the 2018 Hurricane Hunter Awareness Tour at the Lakeland Linder Regional Airport in Lakeland, Florida. As part of its efforts to build a Weather-Ready Nation, the IHRC and other hurricane experts raised awareness about the importance for preparing for the upcoming hurricane season with public officials, school groups, local residents and media. NOAA's Gulfstream IV-SP (G-IV) "Hurricane Hunter" aircraft and a U.S. Air Force Reserve WC-130J "Hurricane Hunter" aircraft were on display and toured by 389 students and approximately 800 public residents. The IHRC showcased special interactive activities and demonstrations teaching hurricane science, mitigation and preparedness. This collaborative community education outreach activity also involved the Florida Division of Emergency Management, local Emergency Management and the Tampa office of the National Weather Service. (https://www.weather.gov/tbw/hat)

NOAA's WP-3D Orion Hurricane Hunter　　*U.S.A.F. Reserve WC-130J Hurricane Hunter*

Public touring Hurricane Hunter aircraft.　　*NHC Director Ken Graham & Erik Salna, IHRC*

Get Ready, Florida! The National Hurricane Survival Initiative:
The IHRC's Erik Salna collaborated with the National Hurricane Survival Initiative (NHSI) and their annual hurricane preparedness campaign. The IHRC contributed hurricane mitigation and preparedness information for protecting your family, home and business. (http://hurricanesafety.org/)

For 2018, the NHSI focused on Florida, with a 30 minute TV program, Get Ready, Florida! The goal is to make hurricane safety a year-round culture in Florida. The TV program looked at the damage and destruction wrought by the record-breaking 2017 Atlantic hurricane season and offered tips to prepare Floridians and their families for the 2018 season. This partnership is an ongoing effort to spur awareness, involvement, and action by millions of Floridians to take personal and collective responsibility for being prepared before, during, and after hurricane season. (http://hurricanesafety.org/get-ready-florida/)

Get Ready, Florida! TV Publicity Value

Get Ready, Florida! Participating TV Stations