OCE 495: Senior Design Project

Application of the Coastal Environment Risk Index (CERI) to Providence and the Fox Point Hurricane Barrier

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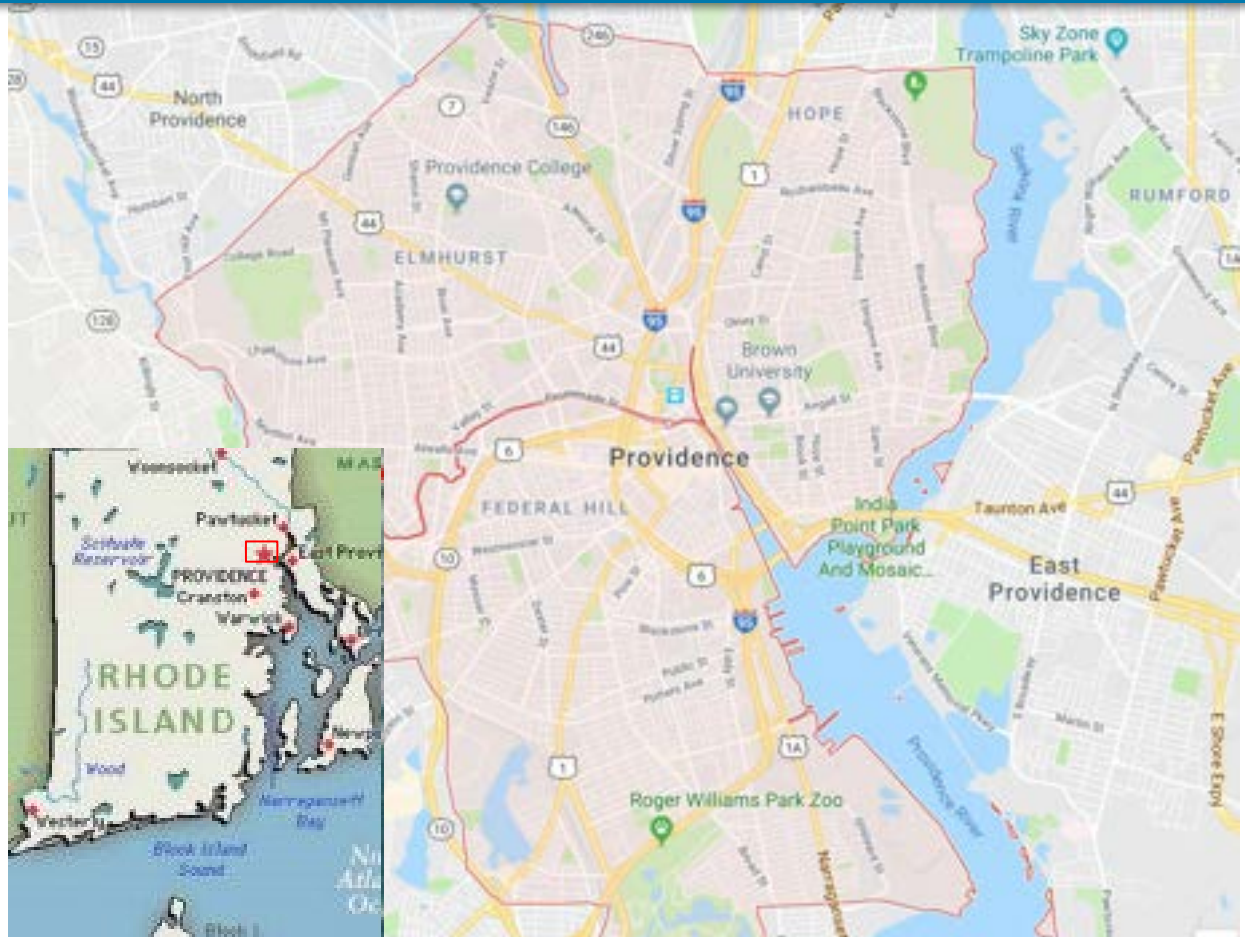
Sea Grant Rhode Island

Outline

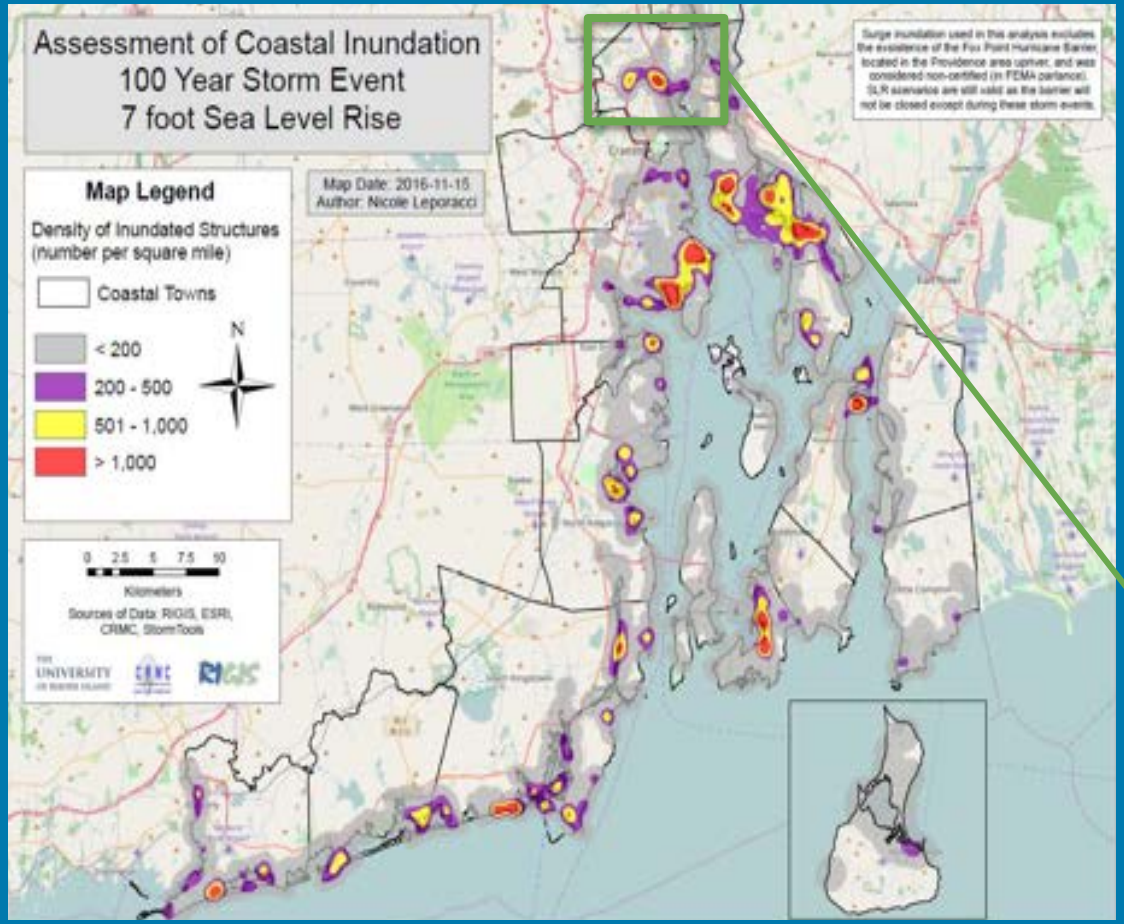
- Problem Statement
- Study Objectives
- Methodology
- Results
- Barrier Analysis
- Conclusion
- Next Semester Plans

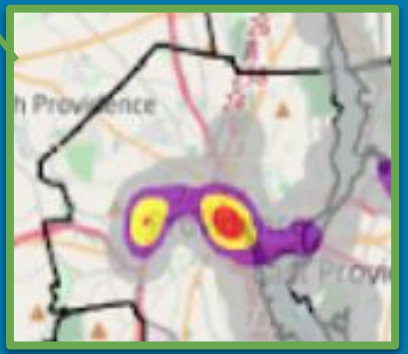


Problem Statement: Providence, RI

- Downtown Providence
- Coastal flooding has presented many problems for this low lying city in the past
  - The Hurricane of 1938 and Hurricane Carol (1954)
  - Extensive amounts of flooding
- Concern if Fox Point Hurricane Barrier provides adequate protection for future storms with increasing sea level rise

Problem Statement: Structural Density

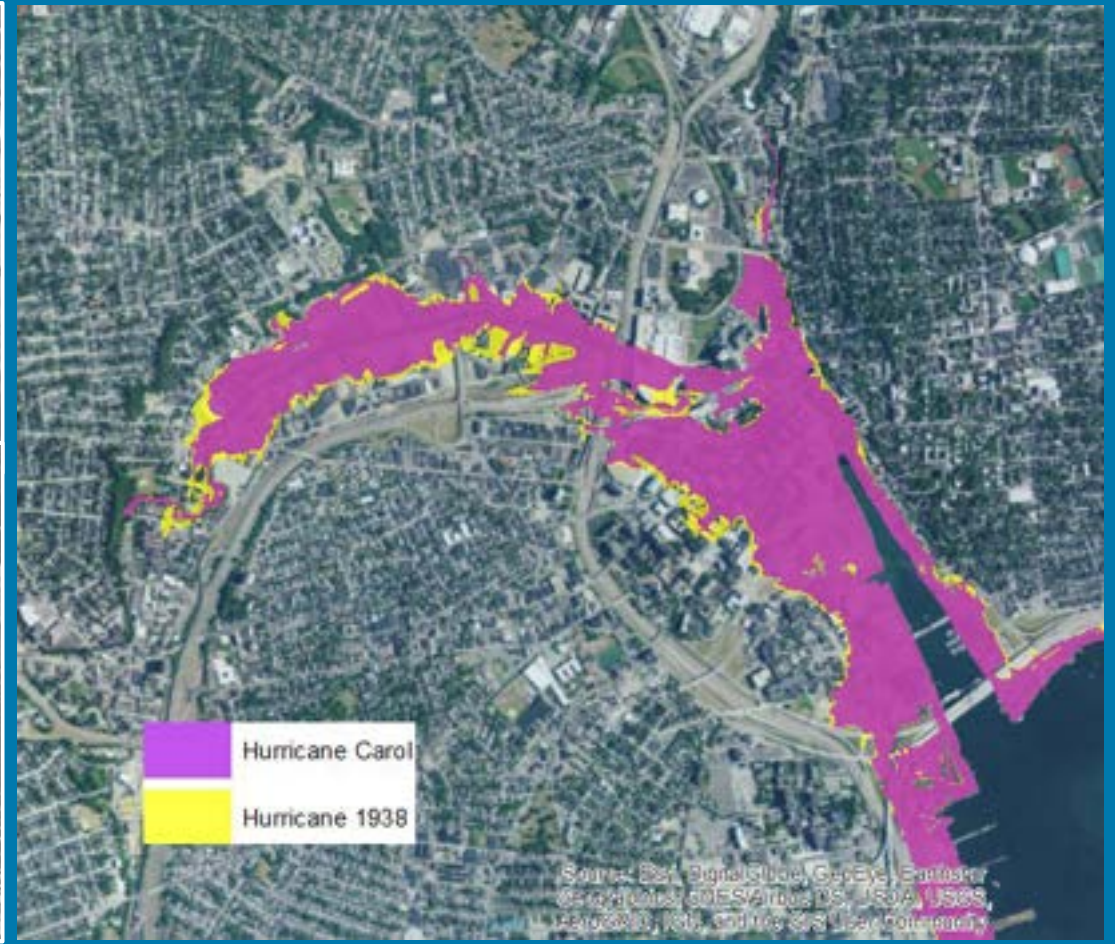




Problem Statement: Hurricanes of Providence Past

Hurricane ‘38 - 4.6 m (MSL)

Hurricane Carol - 4.3 m (MSL)



Fox Point Hurricane Barrier

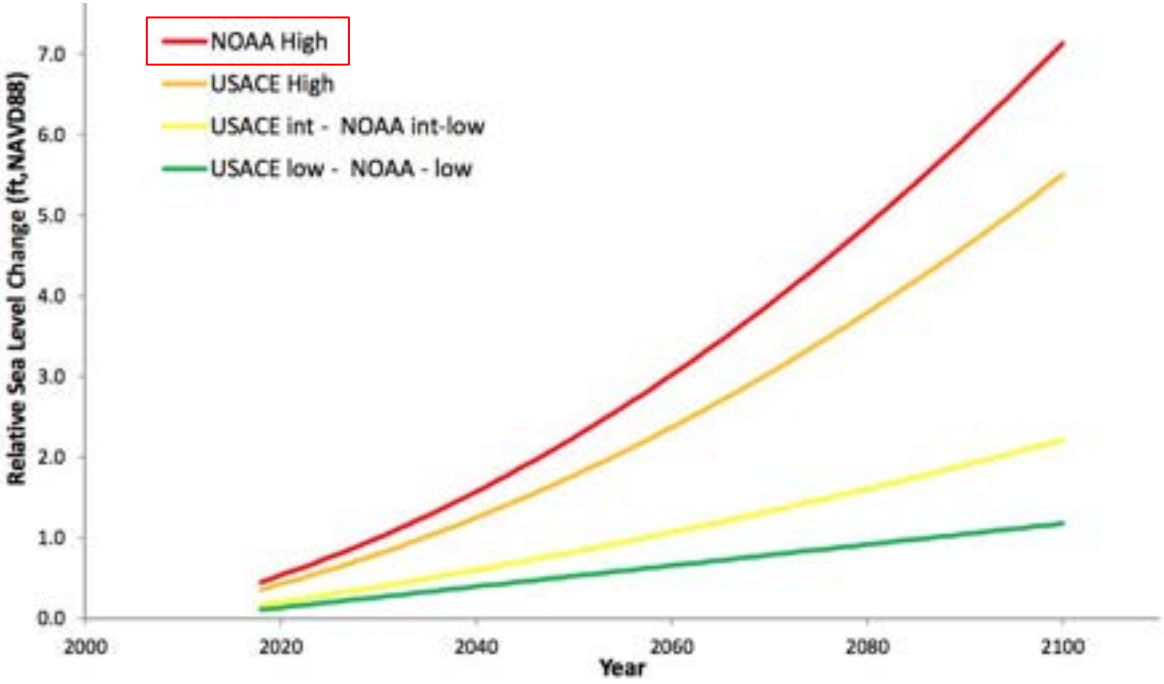
- Constructed between 1960 - 1966
- Constructed to a height of 7.62 meters
  - NAVD 88
  - 500 year storm
- Main dike includes a pump house (5 pumps), and 3 tainter gates

Fox Point Hurricane Barrier

West and east wing walls

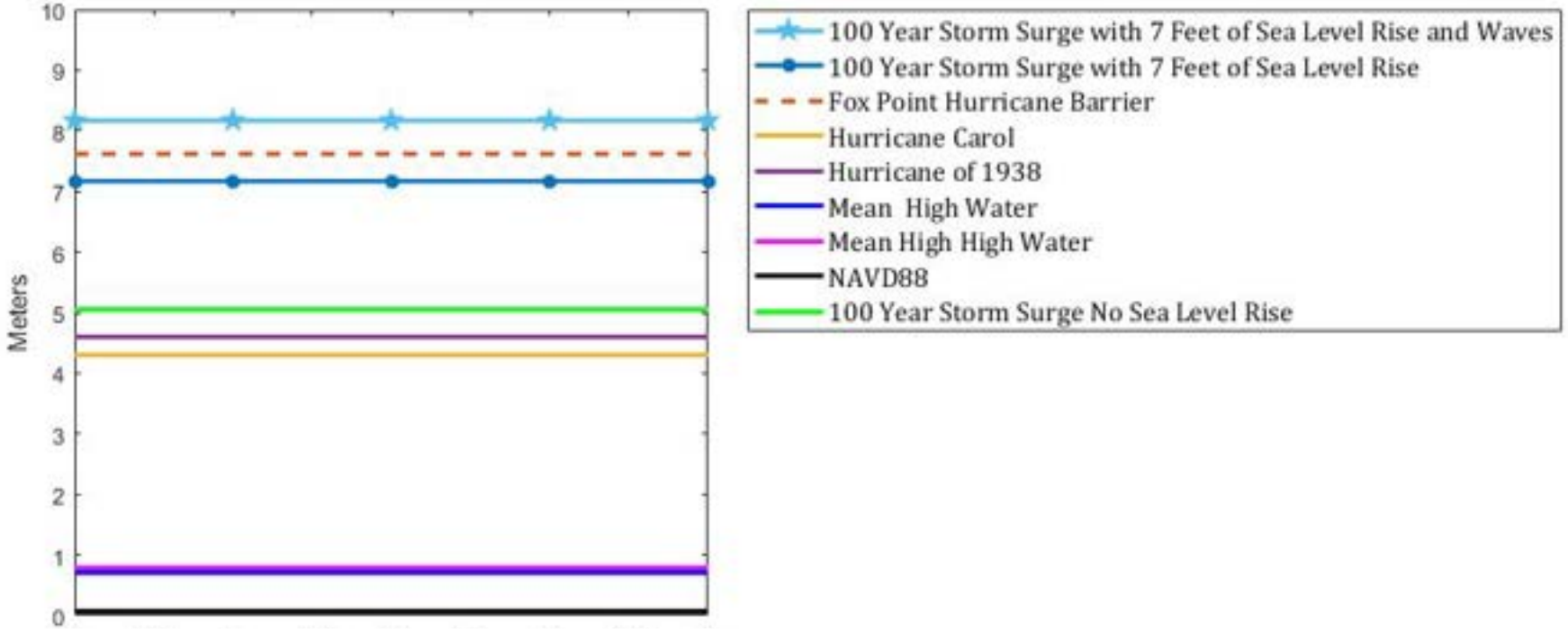
5 vehicular gates

Problem Statement: Sea Level Rise (SLR)

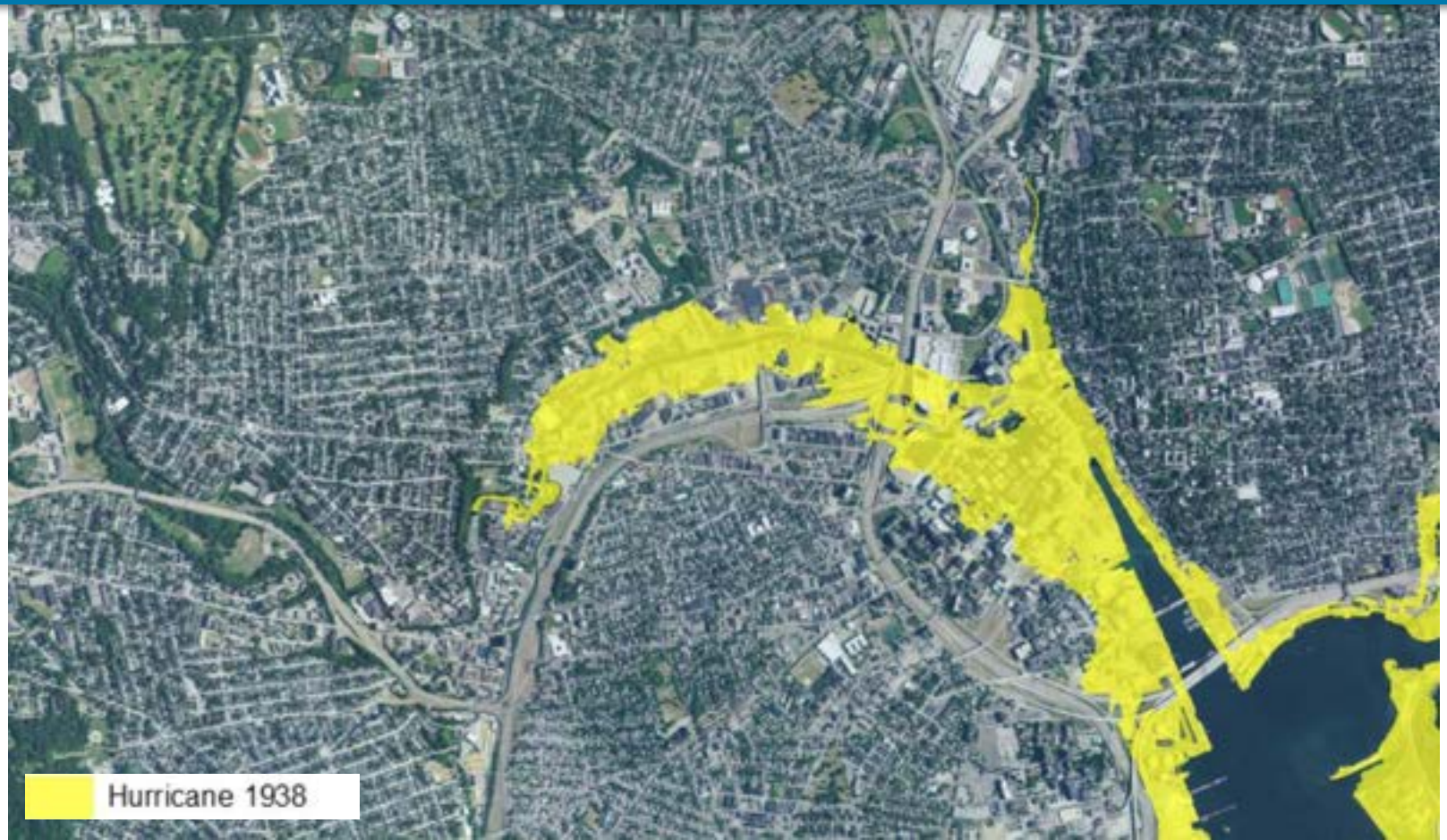


- **Sea Level Rise Projections**
  - Rhode Island Coastal Resource Management Council (RI CRMC) adopted NOAA high curve
  - NOAA high curve used for predictions as a conservative measure of future sea level rise
  - 7ft (~ 2.13 m) sea level rise

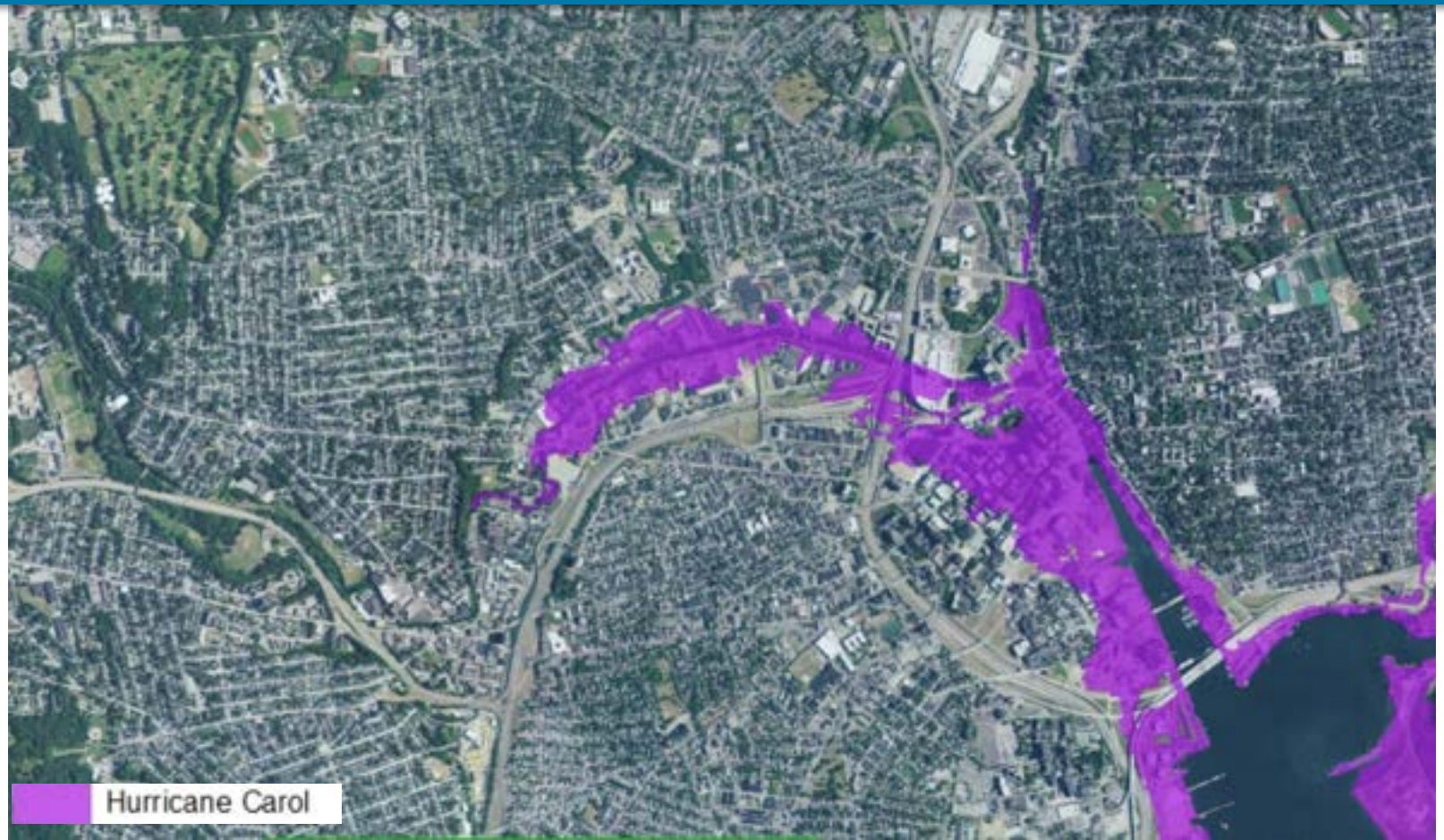
Problem Statement: Sea Level Rise (SLR)



Storm Surge Downtown Providence



Storm Surge Downtown Providence



Storm Surge Downtown Providence

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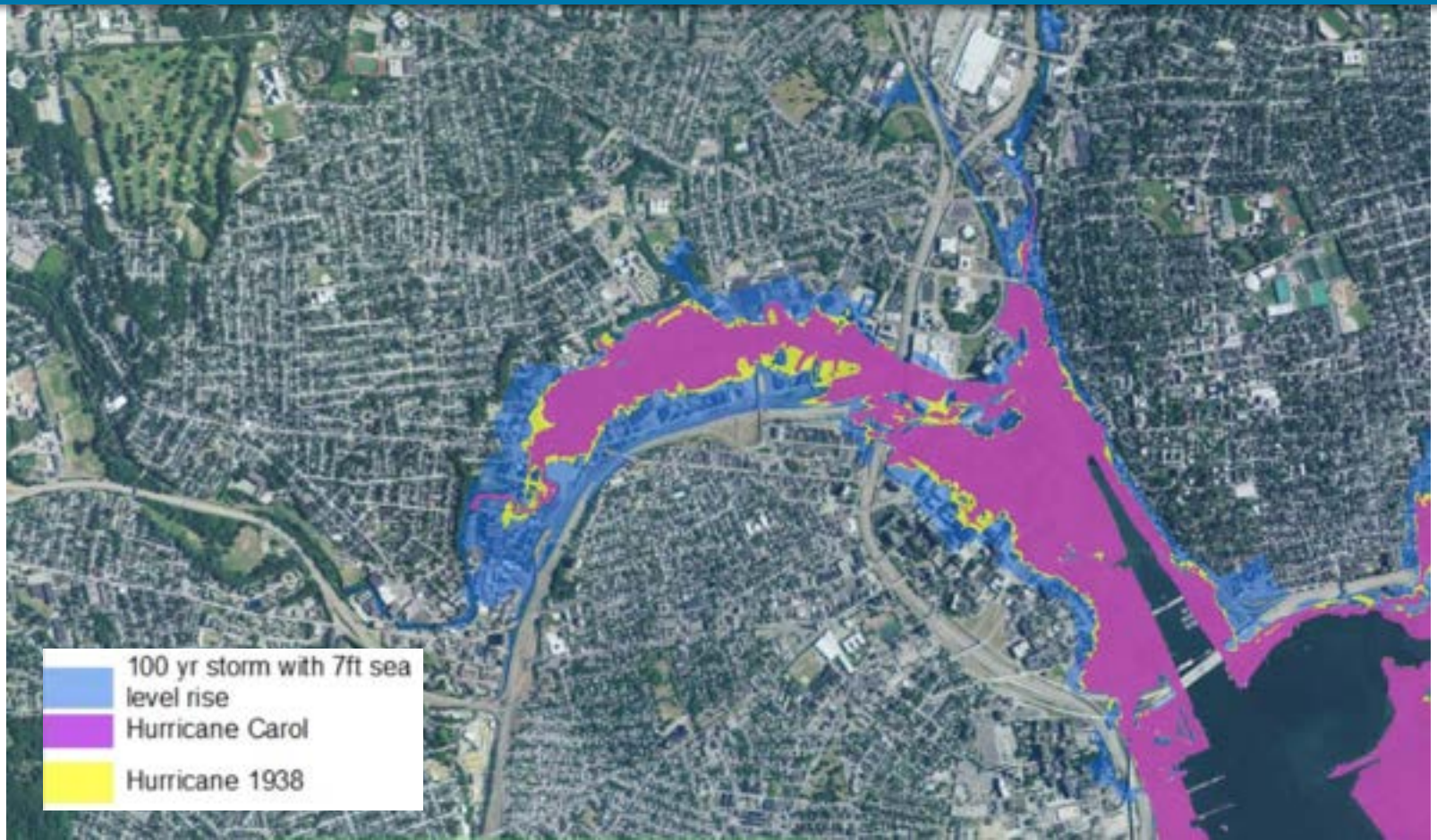
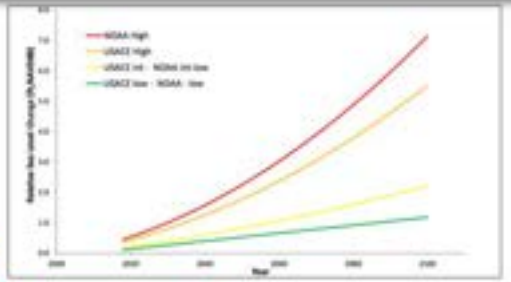


Problem Statement: Timeline



Hurricane 1638

"Gale of 1815"

Hurricane Carol

Hurricane Bob

Sea Level Rise

1638

1815

1954

1991

1635

1966

1938

1600

1800

1900

2000

2100

Great Colonial Hurricane

Great New England Hurricane 1938

Fox Point Hurricane Barrier

Problem Statement Summary

Providence is a community at risk

- Structurally dense (commercial)
- Rate of sea level rise projected to increase substantially
- High damage from large storm events
- Fox Point Barrier was not designed to account for sea level rise

Flood line of 1938 Hurricane

13 feet, 8 inches above MHW

Flood line of the Great Gale of 1815

11 feet, 9.25 inches above MHW

Objectives

- Assess flooding damage to structures in Providence due to storm surge from a 100 yr storm, with and without effects of sea level rise (7 ft, 2.13 m), without the barrier in operation.

- Determine if the Fox Point hurricane barrier provides adequate protection to downtown Providence and if not how the barrier should be modified.

Coastal Environmental Risk Index (CERI)

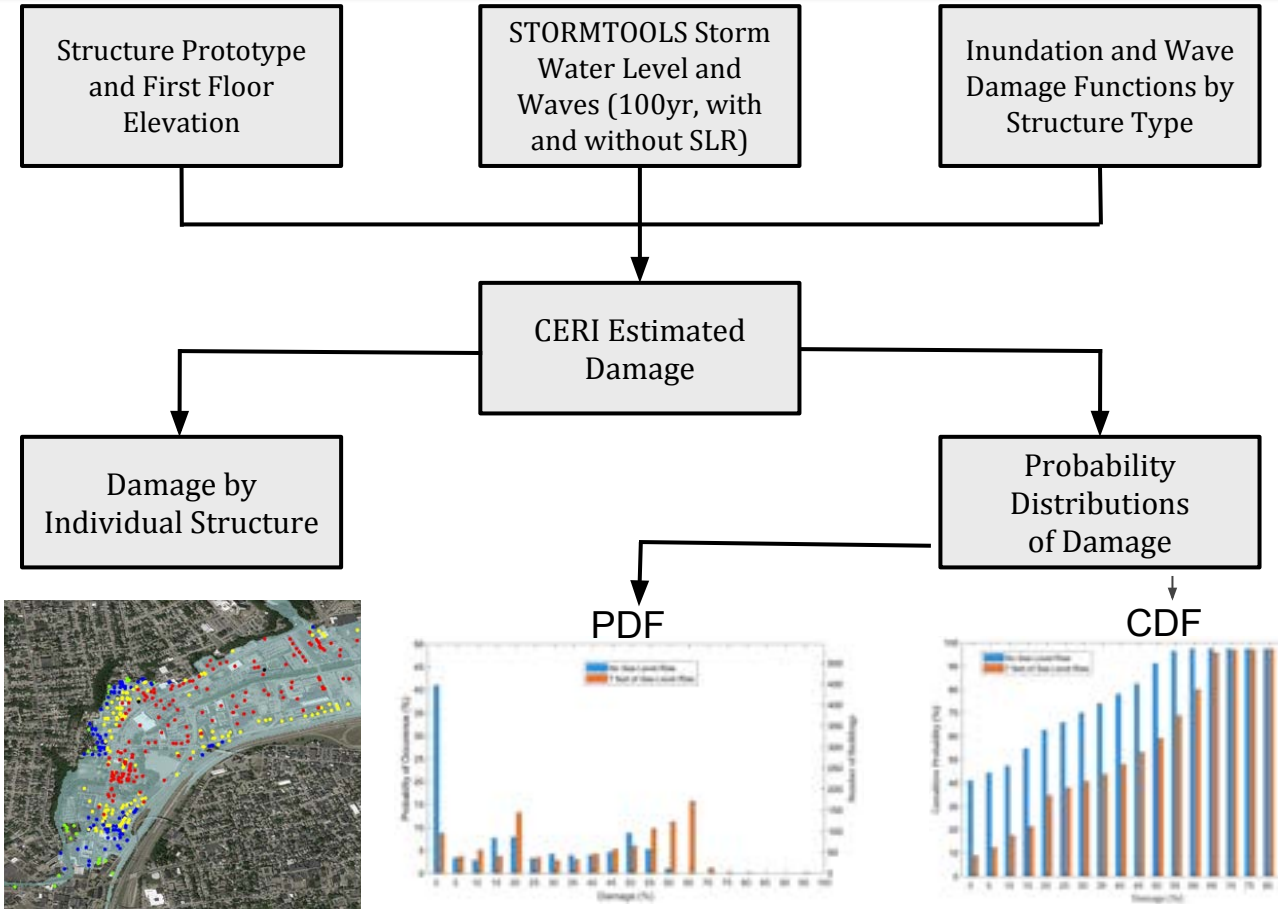
CERI application used to assess flooding damage to structures in Providence

Has been successfully applied to Matunuck, Charlestown, Warwick, and Misquamicut

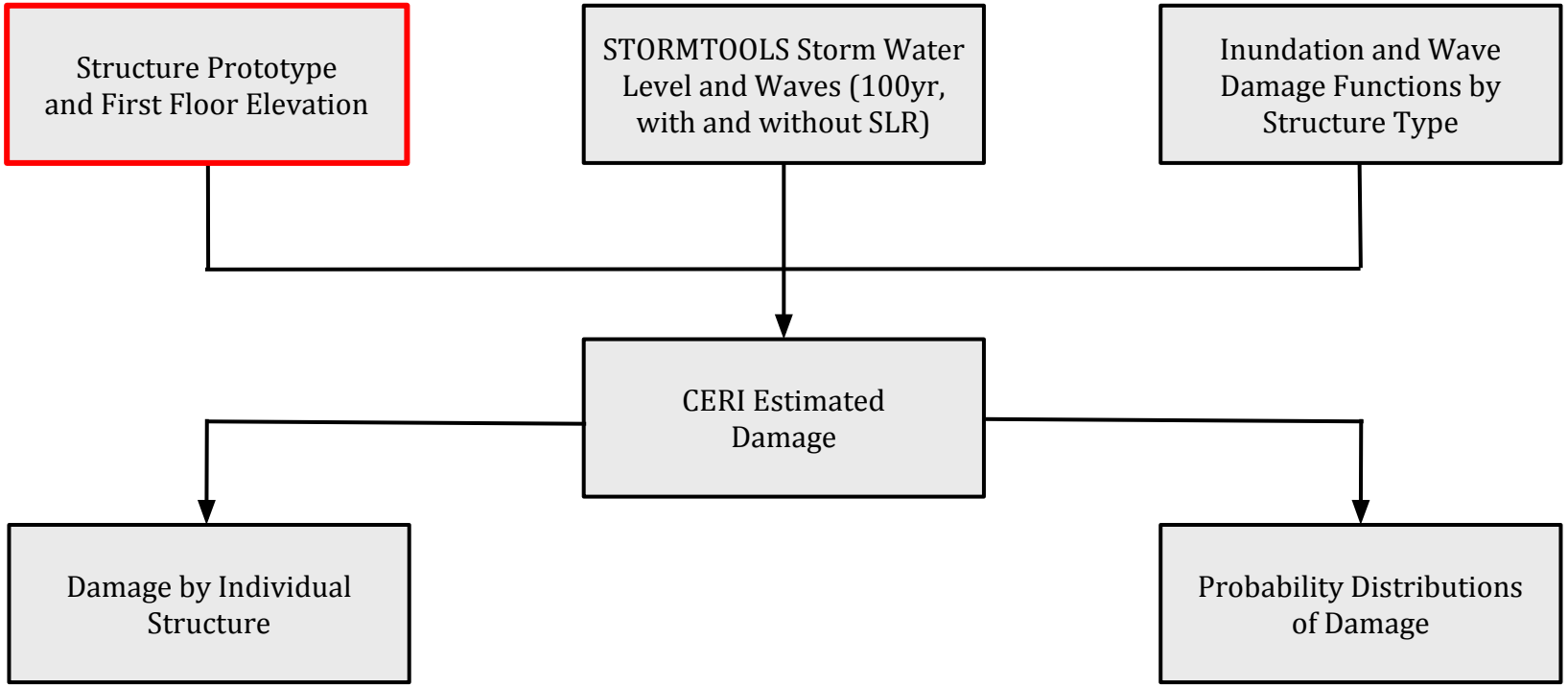
Damage Functions:
NACCS prototypes

Damage Estimates:
NACCS damage curves

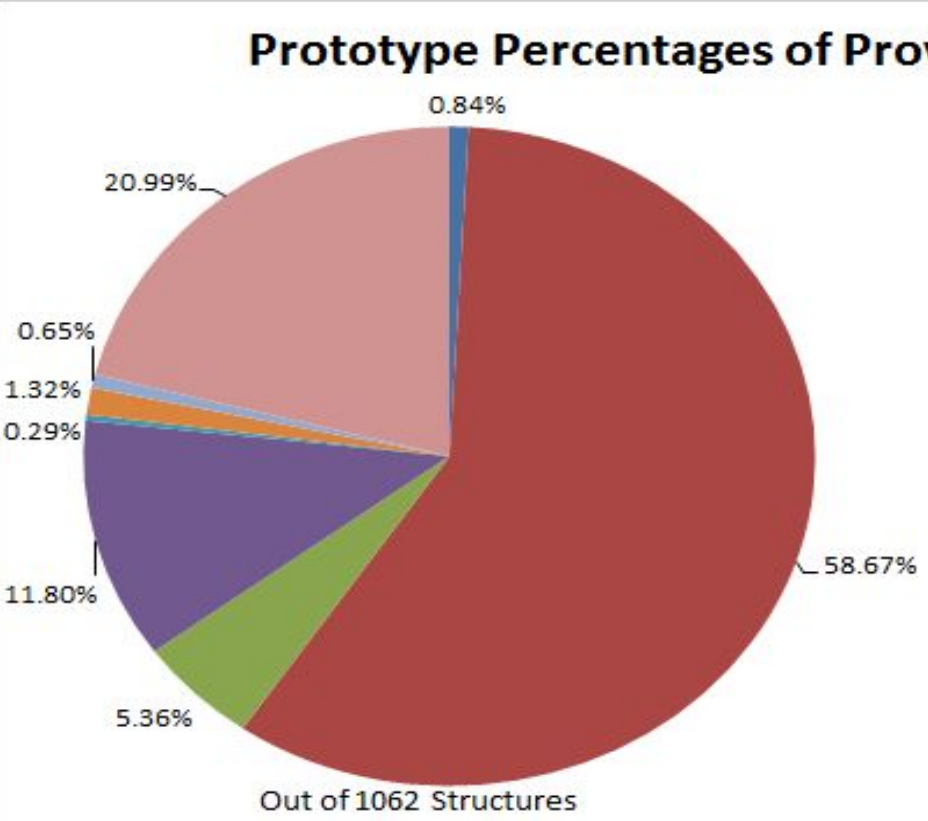
Location parameter:
E911 Database



CERI - Structures in the Study Area



Structure Prototype Results



1A-3	9 Structures
2	623 Structures
3	57 Structures
4A	126 Structures
5A	3 Structures
5B	14 Structures
6A	7 Structures
6B	223 Structures
Total	1062 Structures

Structure Prototypes - Part One

Final Prototype
Prototype 1A-1: One Story Apartment - No Basement Prototype 1A-3: Three Story Apartment - No Basement Prototype 1B-1: One Story Apartment - With Basement* Prototype 1B-3: Three Story Apartment - With Basement*
Prototype 2: Commercial - Engineered
Prototype 3: Commercial - Pre/Non-Engineered
Prototype 4A: Urban High Rise
Prototype 4B: Beach High Rise
Prototype 5A: Single Story Residence, No Basement
Prototype 5B: Two Story Residence, No Basement
Prototype 6A: Single Story Residence, With Basement
Prototype 6B: Two Story Residence, With Basement
Prototype 7A: Building With Open Pile Foundation
Prototype 7B: Building With Enclosed Pile Foundation

2: 58.67%

6B: 20.99%

4A: 11.80%

3: 5.36%

Structure Prototypes - Part Two

Final Prototype
Prototype 1A-1: One Story Apartment - No Basement
Prototype 1A-3: Three Story Apartment - No Basement
Prototype 1B-1: One Story Apartment - With Basement*
Prototype 1B-3: Three Story Apartment - With Basement*
Prototype 2: Commercial - Engineered
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Prototype 6B: Two Story Residence, With Basement
Prototype 7A: Building With Open Pile Foundation
Prototype 7B: Building With Enclosed Pile Foundation

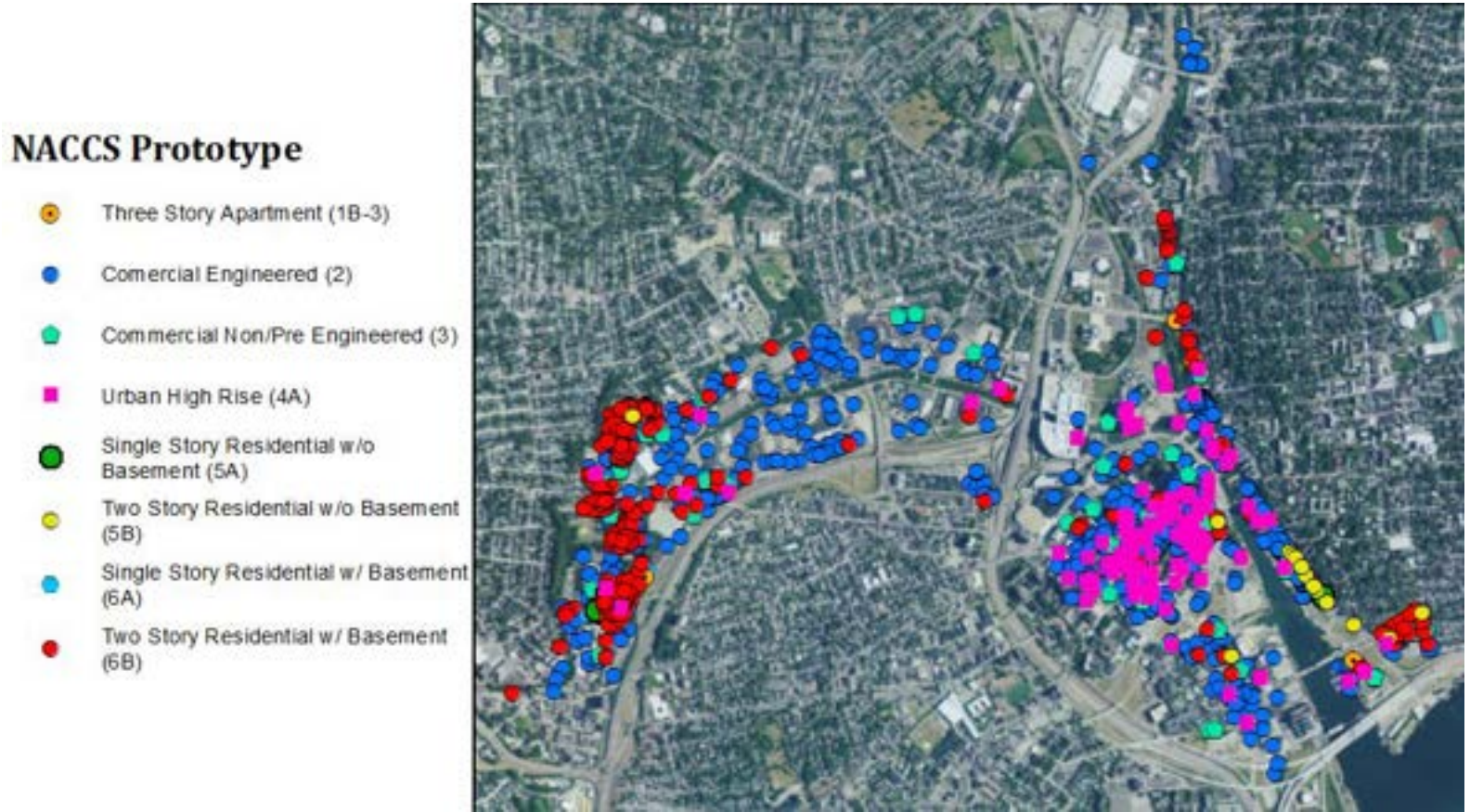
5B: 1.32%

1A-3: 0.84%

6A: 0.65%

5A: 0.29%

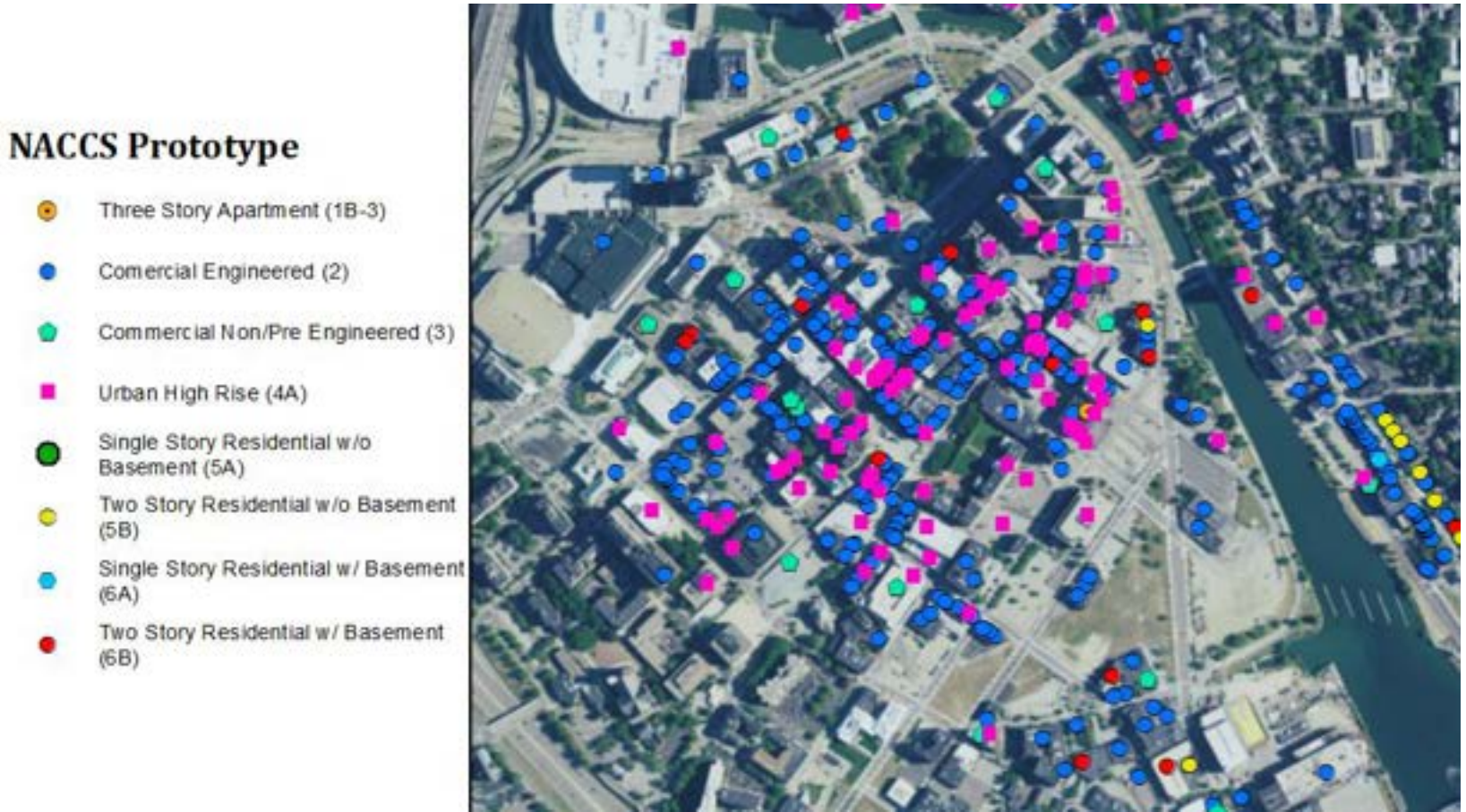
Structure Prototype Distribution



Structure Prototype Distribution

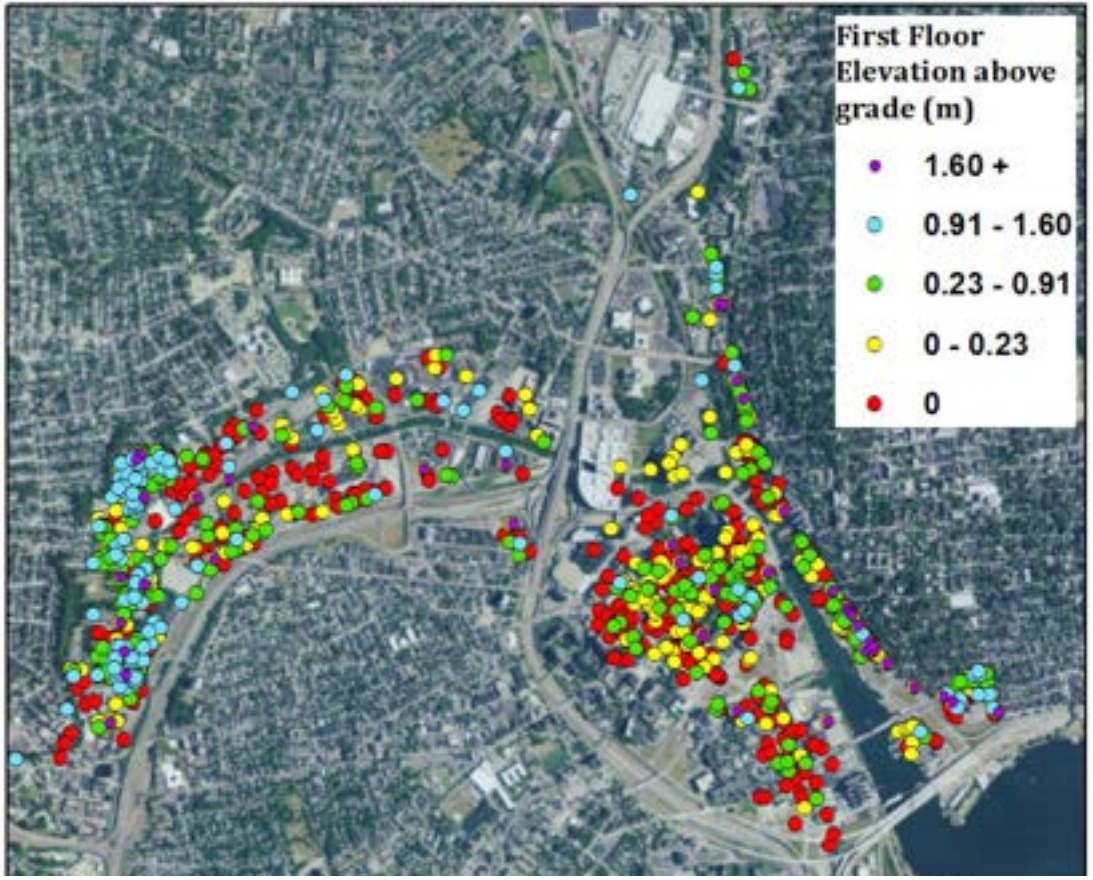
Structure Prototype Distribution : Western Residential Area

Structure Prototype Distribution: Downtown Providence

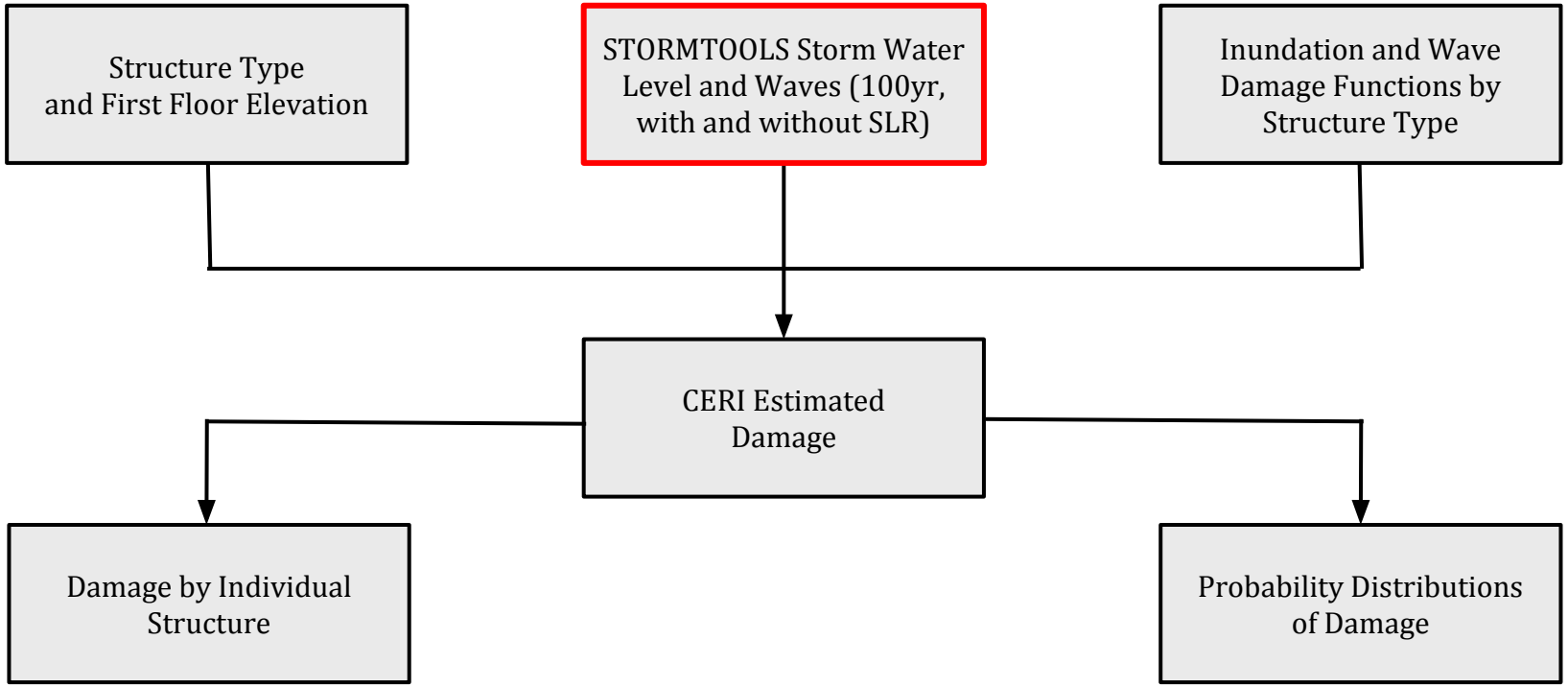


First Floor Elevation (FFE)

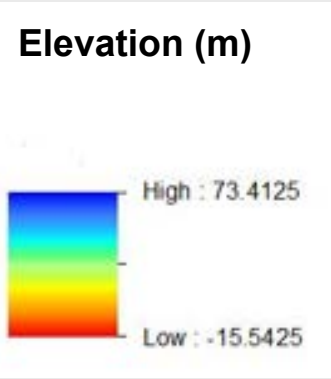
- Elevation of the first finished floor above grade
- Calculated by counting steps from ground to front door

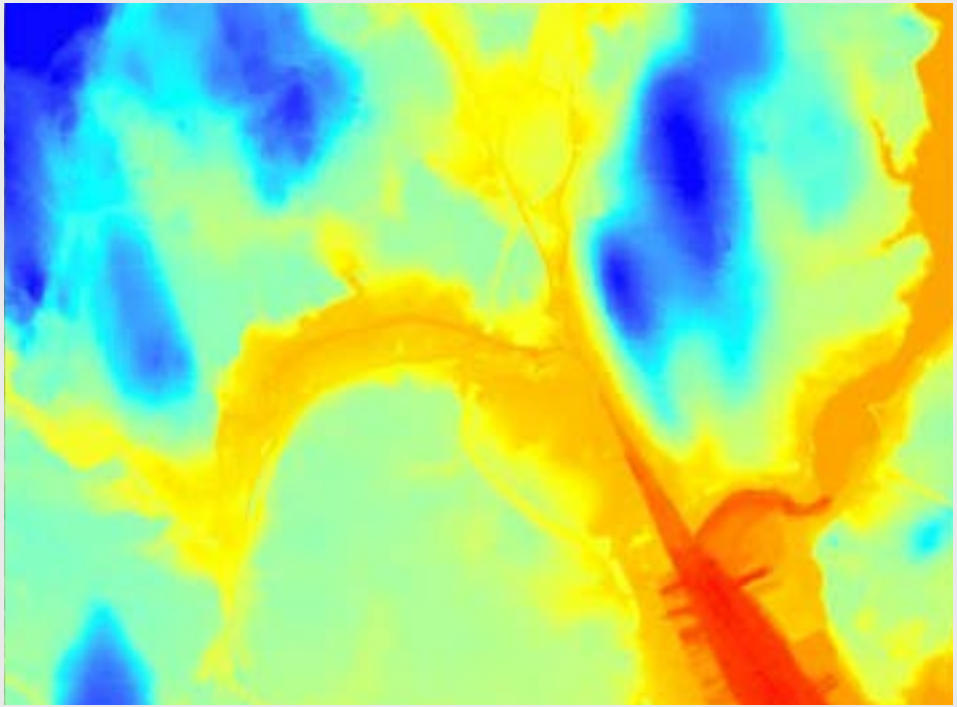


CERI - STORMTOOLS Inundation & Waves



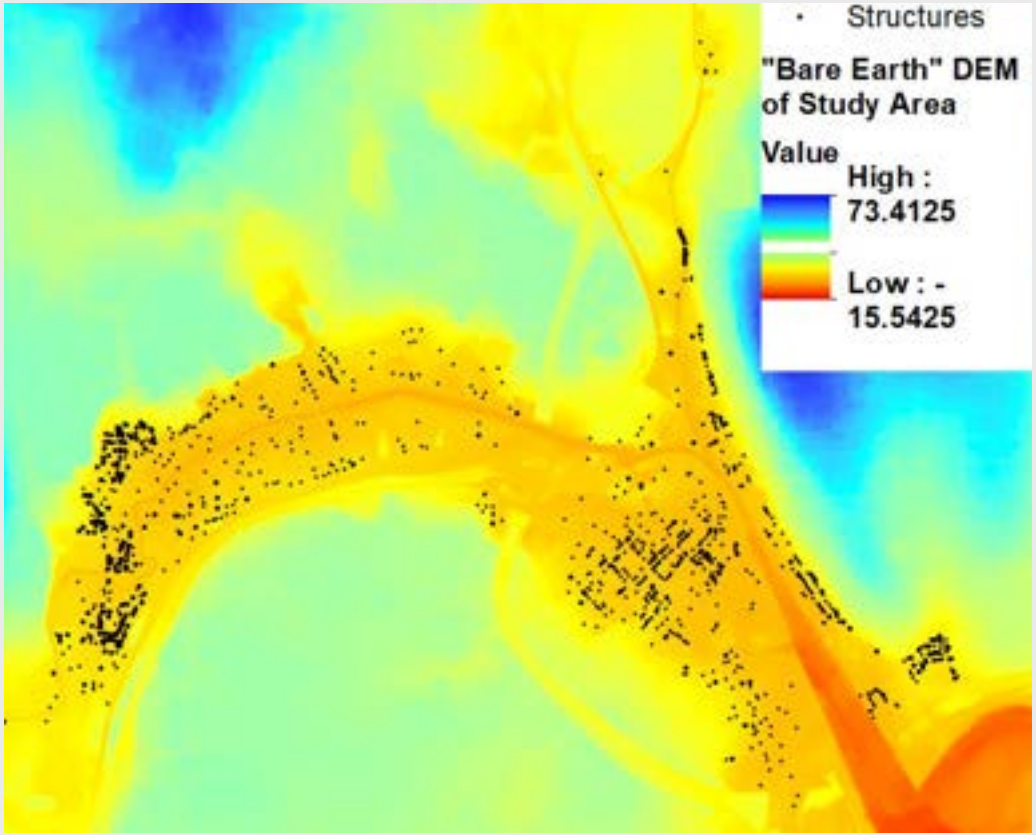
Digital Elevation Model





- Topography from 2011 LiDAR survey
  - “Bare Earth”
  - 1 meter resolution
- Bathymetry from NOAA sonar and sounding

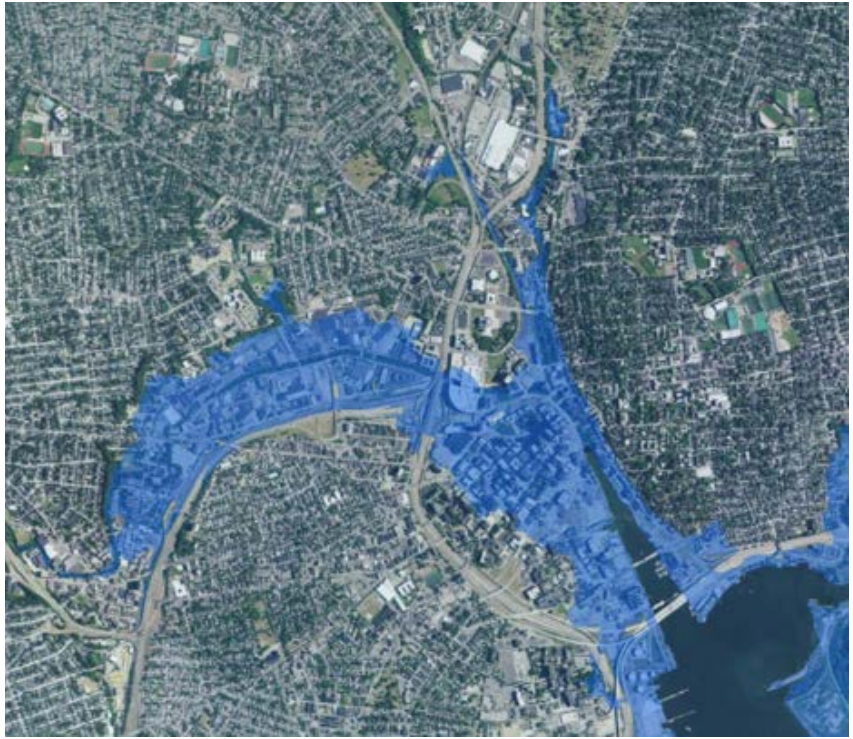
Structure Distribution



- All structures in study area
  - Downtown area, structures cluster in low lying areas

STORMTOOLS

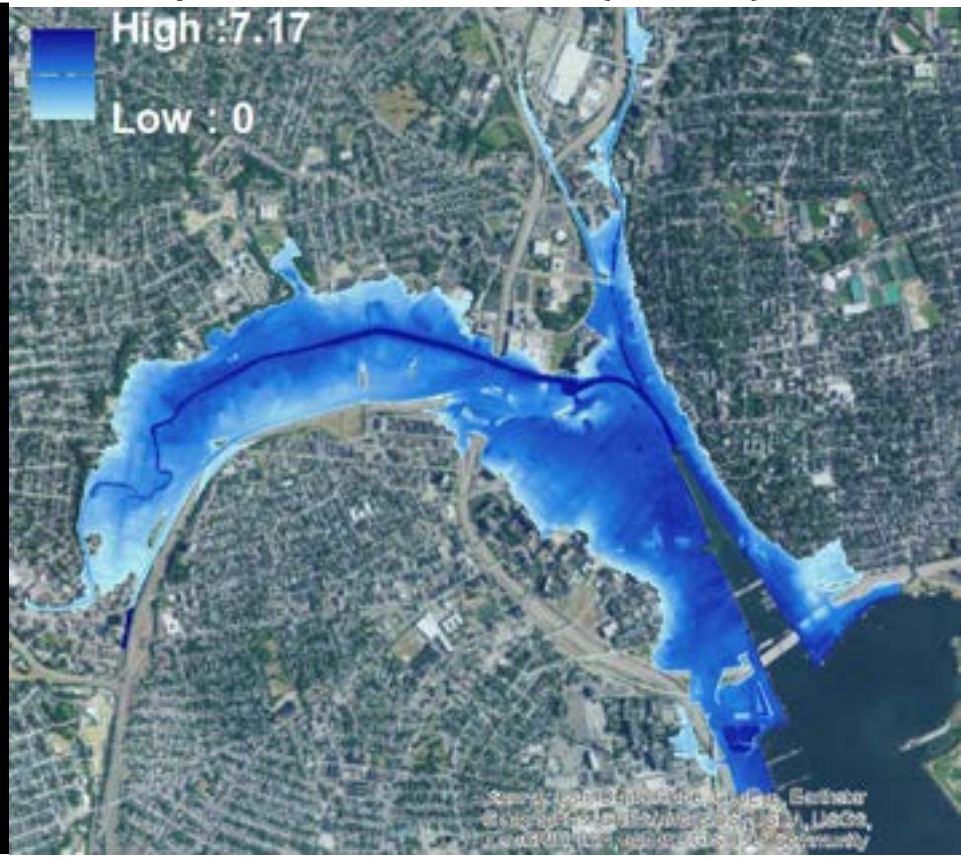
- Online database providing simplified flood inundation models for storms of various return periods with and without sea level rise
  - 25, 50, and 100 year storm
- The study area was chosen based on the 100 year storm with 7 feet (2.1 meters) of sea level rise.
  - Upper 95% confidence interval



STORMTOOLS Inundation Depth

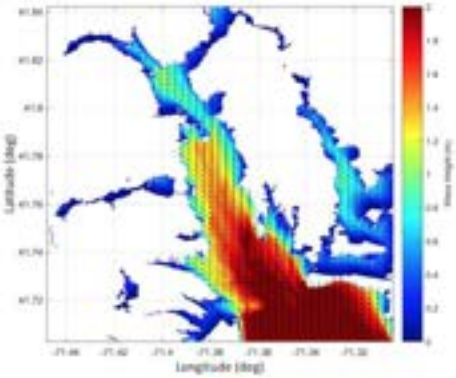
100 yr Storm without SLR

100 year storm with 7 ft (2.13 m) SLR



STWAVE (STeady state spectral WAVE)

Sources	STWAVE Inputs	STWAVE Calculation	STWAVE Results
Rhode Island Geographic Information System (RIGIS)	Bathymetry	Waves propagate from offshore	Peak wave period
Spaulding et al. 2017	Storm Surge	Wave transformation calculated by wave action equation • Depth-induced refraction • Depth-induced shoaling • Depth-induced breaking • Diffraction • Wave growth due to wind • Wave-wave interaction • White capping, redistributes and dissipates energy in a growing field	Significant wave height
NACCS Report	Offshore Significant Wave Height		Wave direction
Grilli et al. 2016	Wave Spectrum • Wave Period • Directional Spreading Factor (n) • Spectral Peak Enhancement Factor (γ)		
	Wind Speed		
Sensitivity Tests	Wind Direction		



SMS
Surface-Water Modeling System

STWAVE - Modeling Process

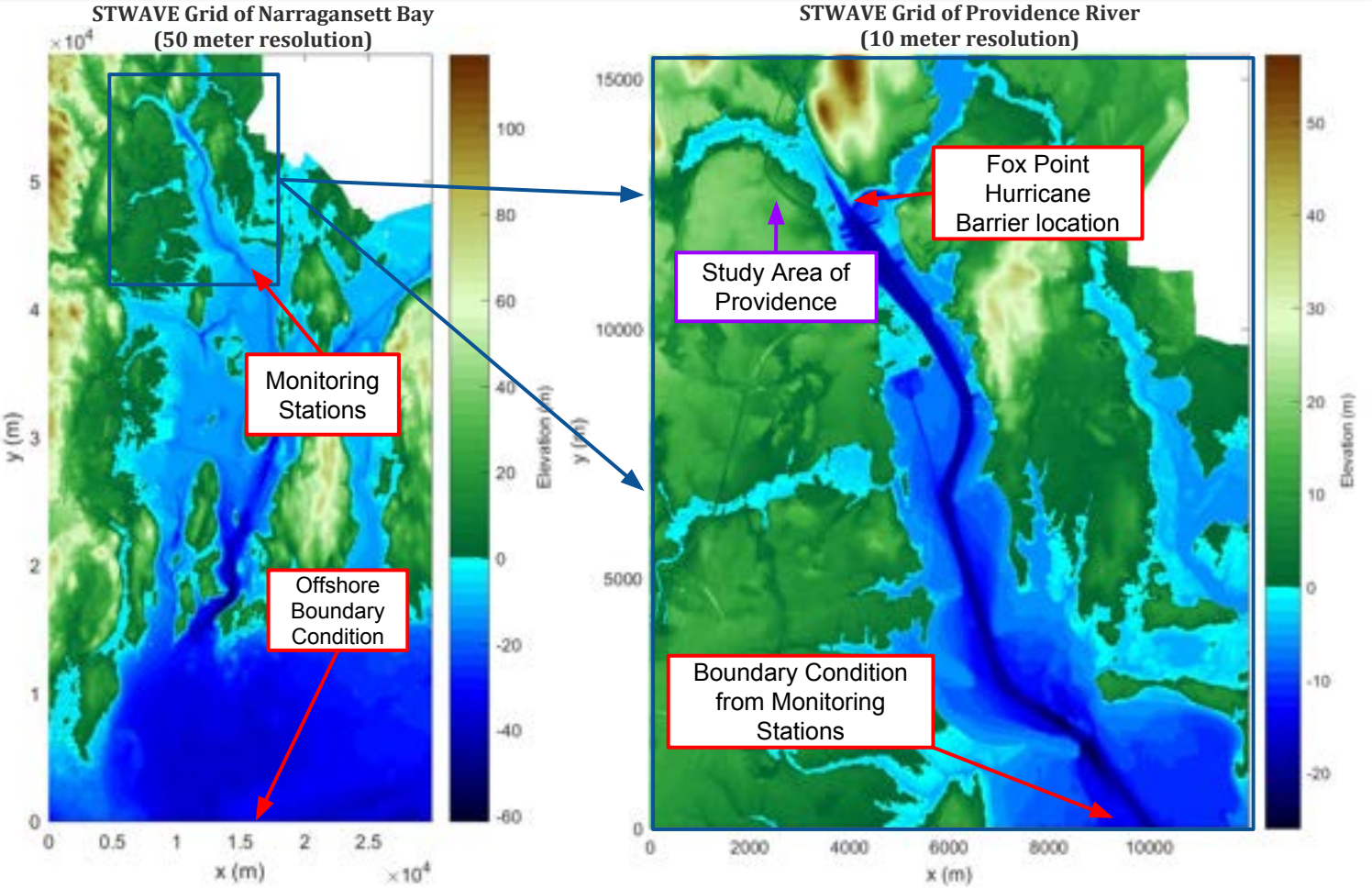
Determine Offshore Boundary Condition

STWAVE Analysis of Narragansett Bay

Record Wave Spectrum at Mouth of Providence River

STWAVE Analysis of Providence River

Record Wave Crest Height in Study Area



STWAVE - Offshore Boundary Condition

100 Year Storm Wave Parameters - Result of "NACCS Coastal Storm Simulations: Waves and Water Levels" Study.

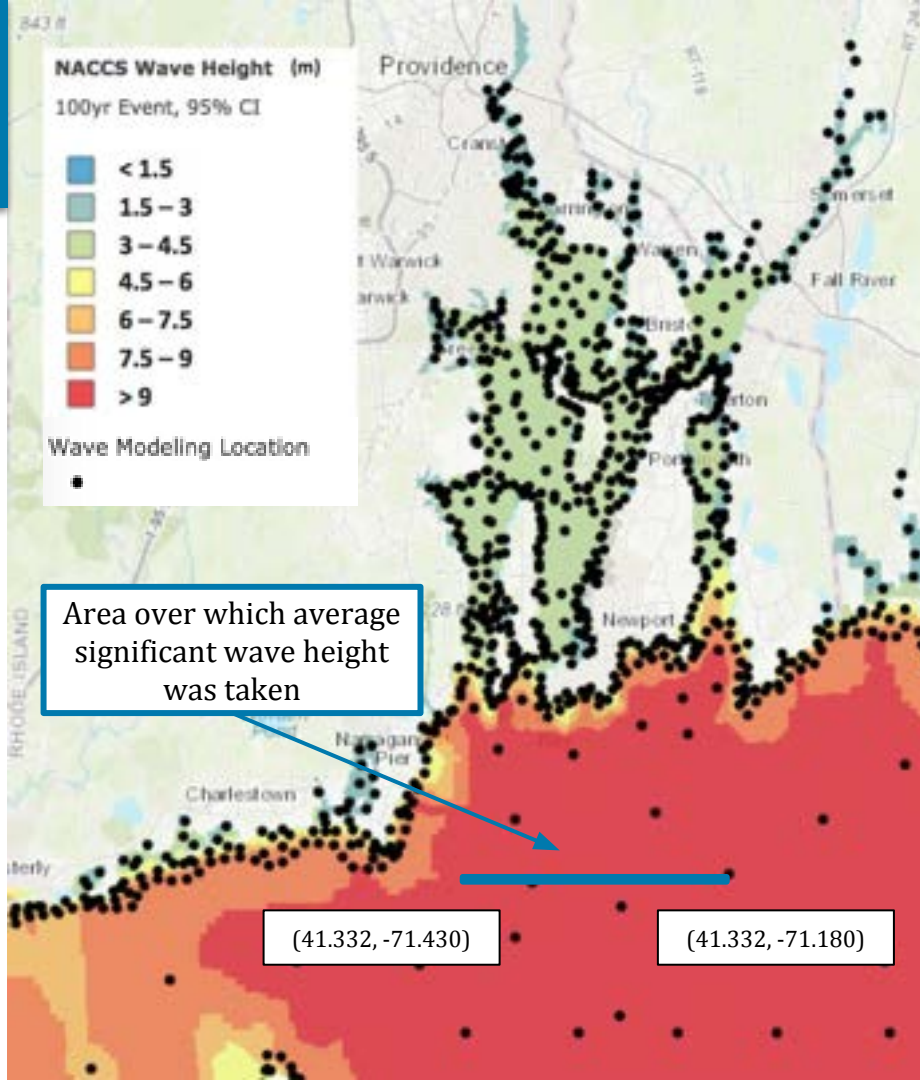
Average of significant wave height (10.5 meters) over shown area was used as the STWAVE Boundary Condition.

Peak Period (Tp), Spectral Shape Parameter (Gamma), and Spreading Coefficient (nm) determined from sources.

Wave Parameters at Boundary Condition

Hs (m)	Tp (sec)	Angle (deg)	Gamma	nm
10.5	20	90	8	20

Grilli et al. 2016



STWAVE - Wind Sensitivity Tests

Objective - To determine the wind direction that generates largest waves at both mouth of Providence River and the study area

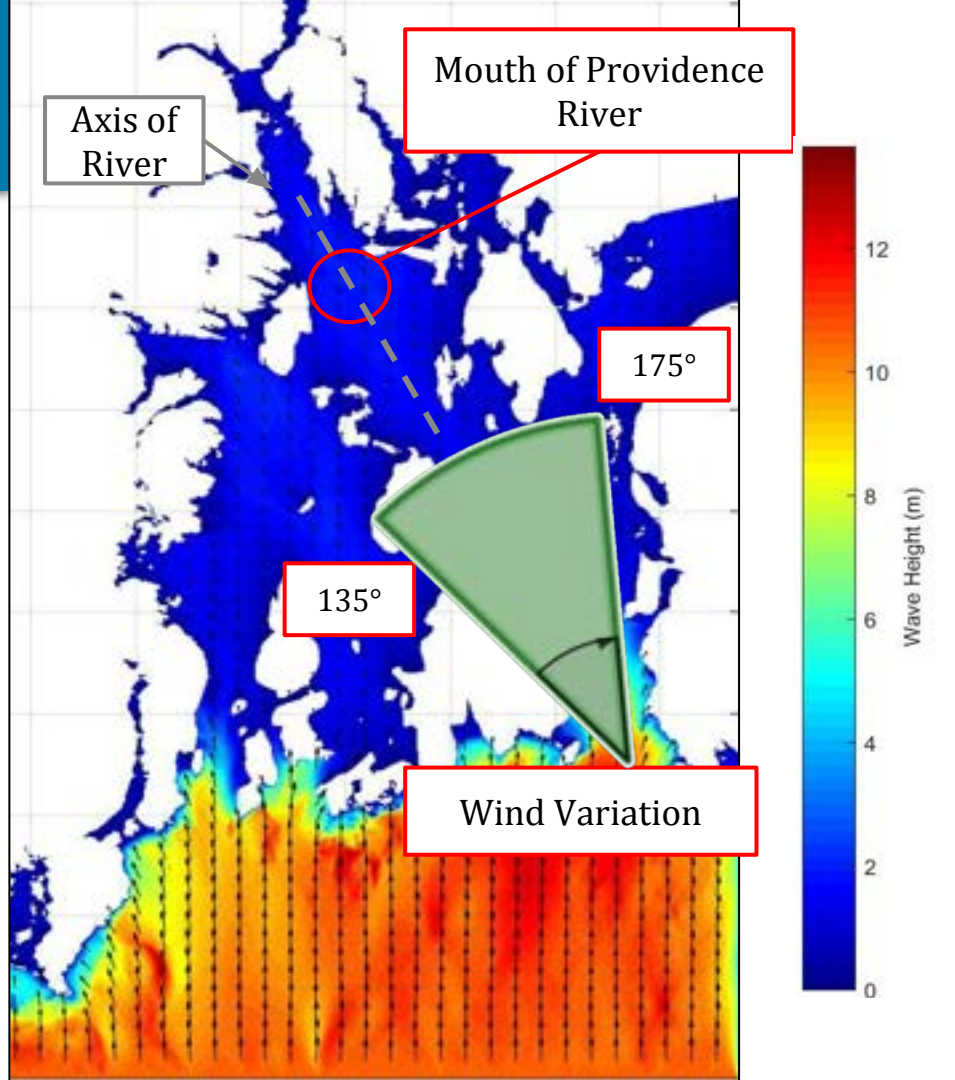
Reason - Waves in study area are a function of fetch

Process

1) Perform Narragansett Bay STWAVE analysis with varying wind directions. Record wave spectrum at mouth of Providence River. **Wind velocity kept constant at 35 m/s.**

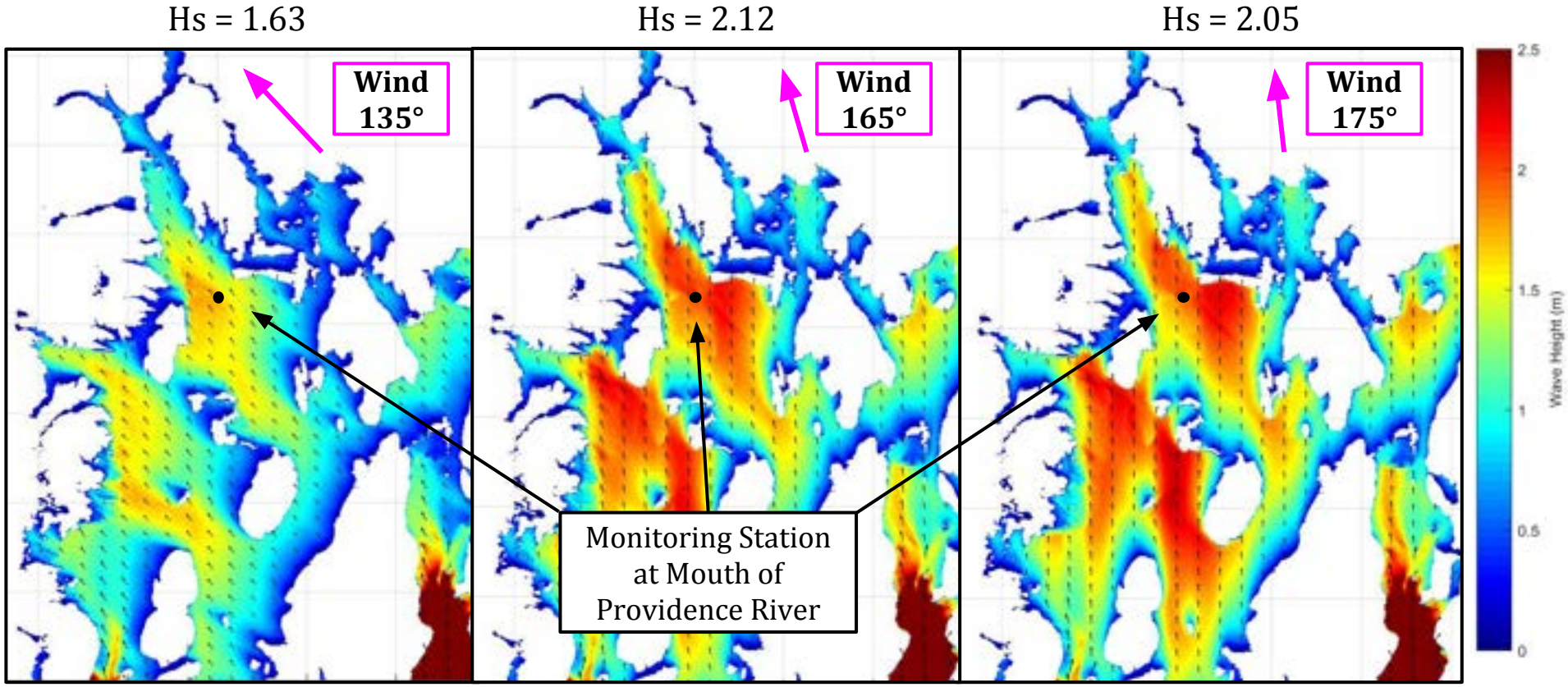
2) Perform Providence River STWAVE analysis with higher grid resolution. Use wave spectrum with highest energy from Narragansett Bay analyses.

3) Determine wind direction that produces highest significant wave heights at Fox Point Barrier.

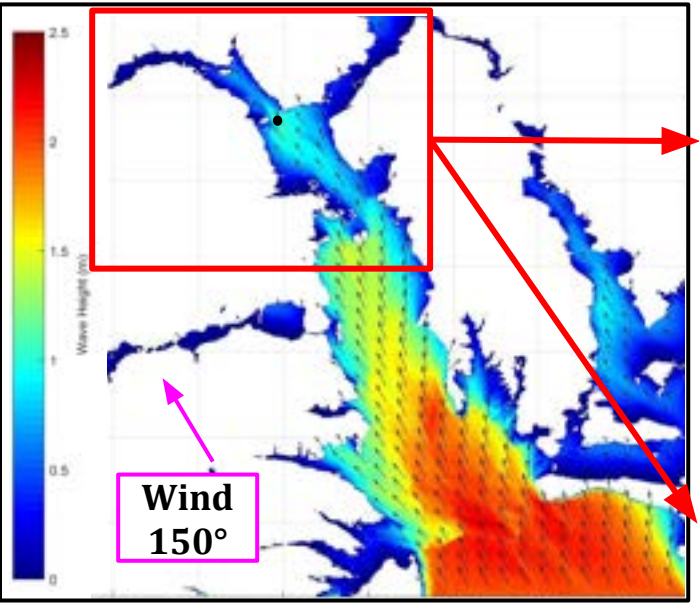


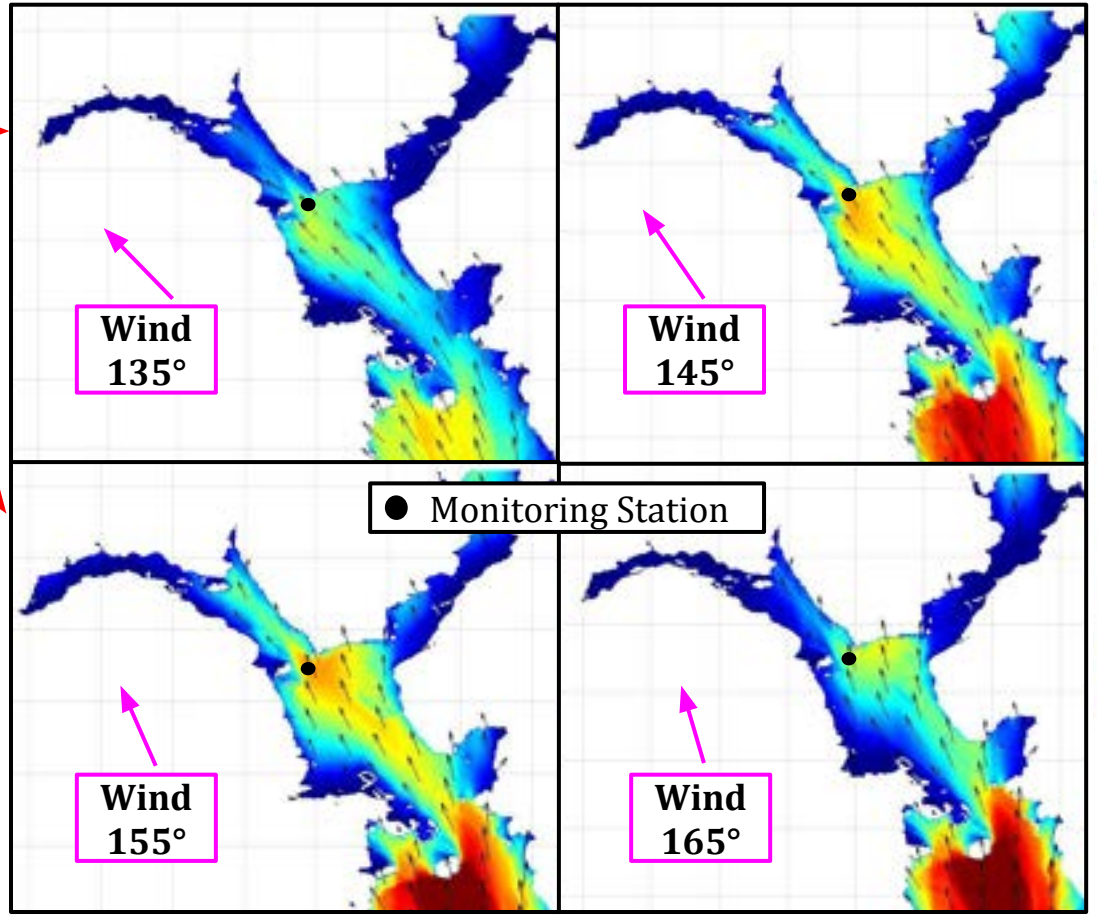
STWAVE - Narragansett Bay Wind Sensitivity Results

Significant Wave Height (Hs) at Monitoring Station:



STWAVE - Providence River Wind Sensitivity Results





Hs at Monitoring Stations:

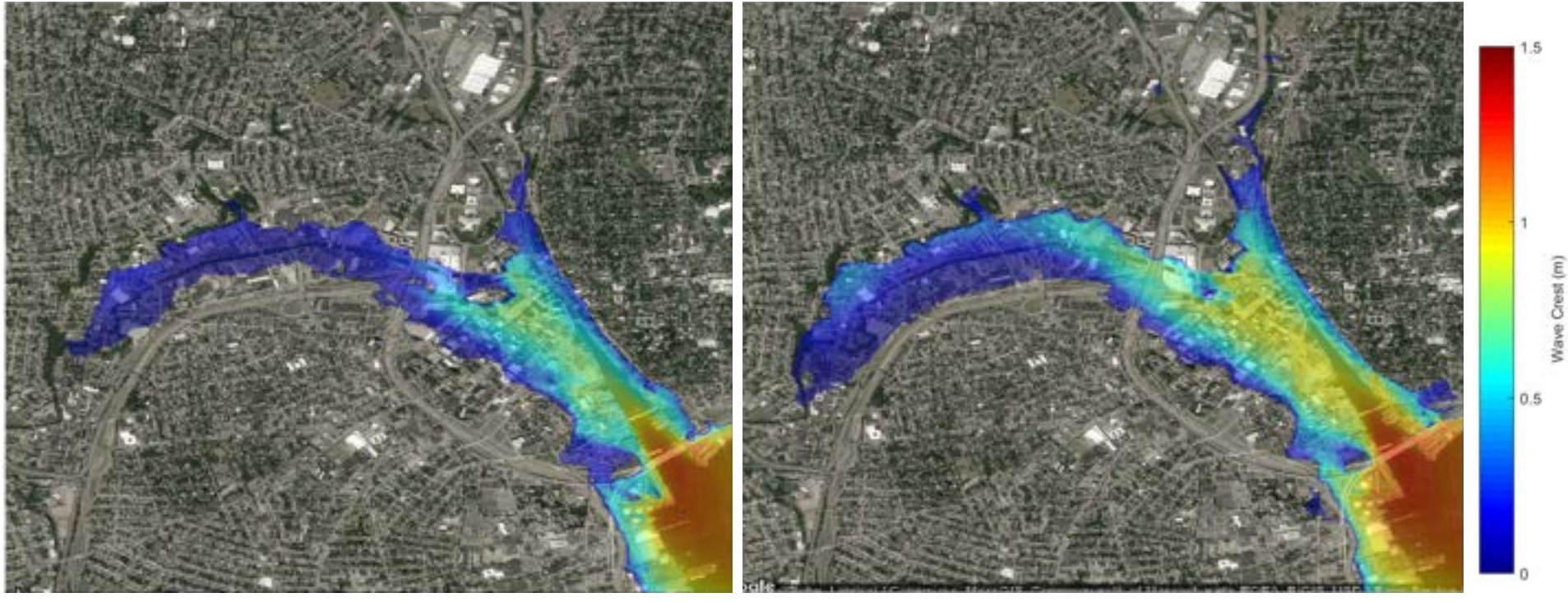
135° - 0.76 m
145° - 0.96 m
150° - 1.01 m
155° - 0.98 m
165° - 0.80 m

STWAVE - Waves in Study Area due to 100 Yr Storm

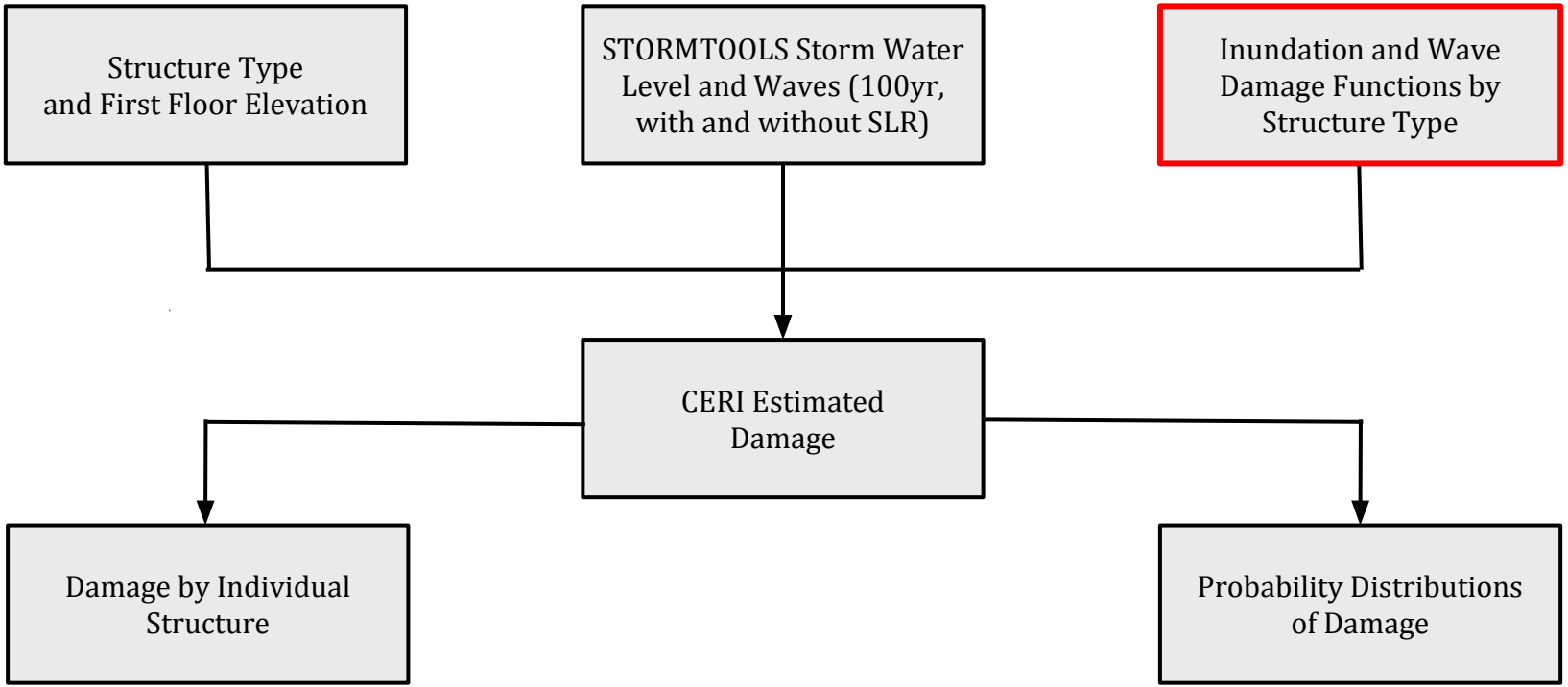
Wave Crest = 1.12 * Significant Wave Height

No SLR

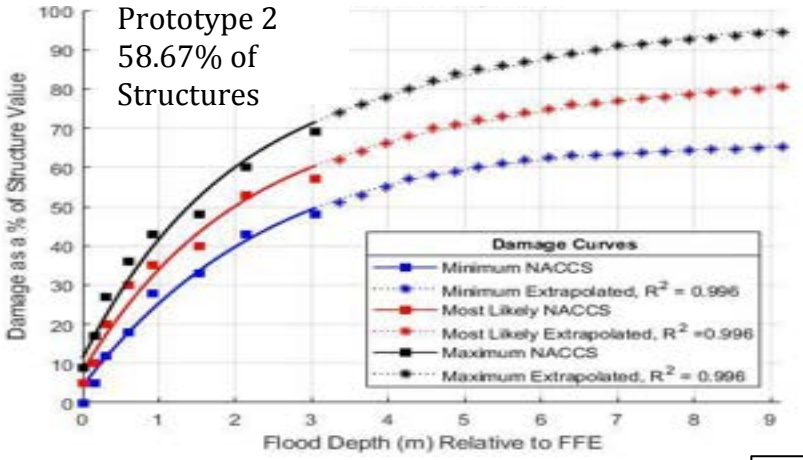
7ft of SLR



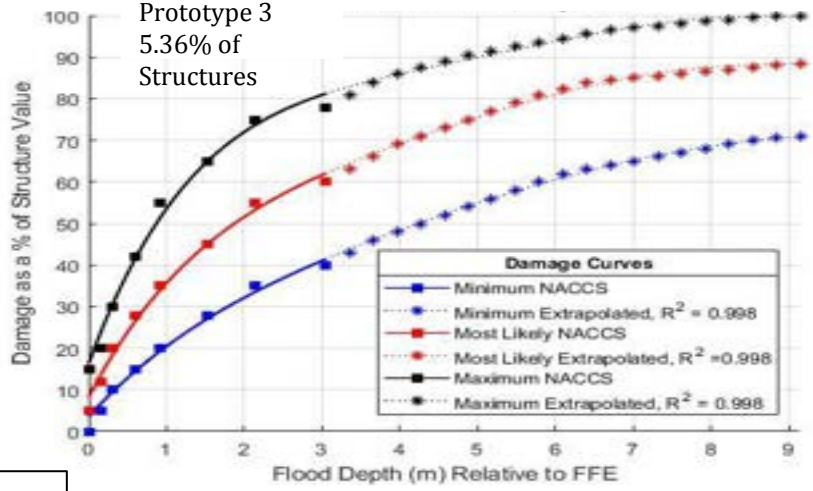
Damage Functions



Prototype 2
58.67% of
Structures

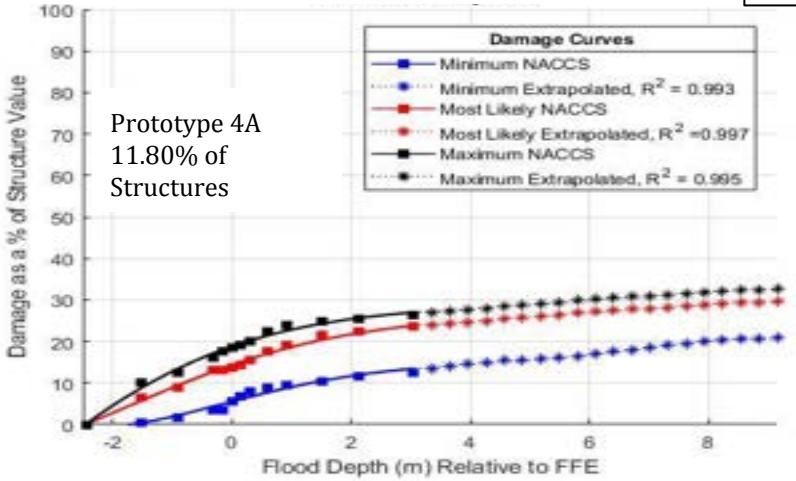


Prototype 3
5.36% of
Structures

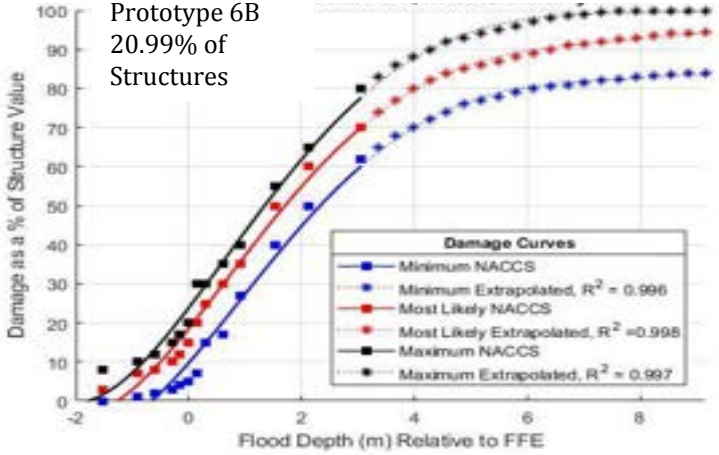


Inundation

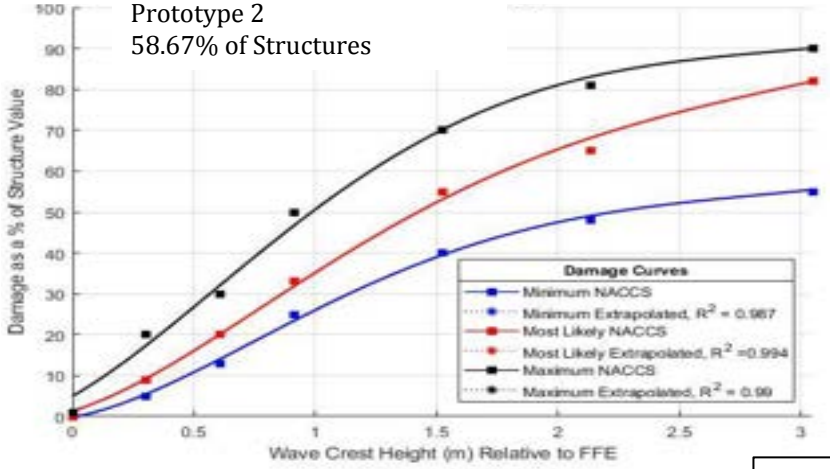
Prototype 4A
11.80% of
Structures



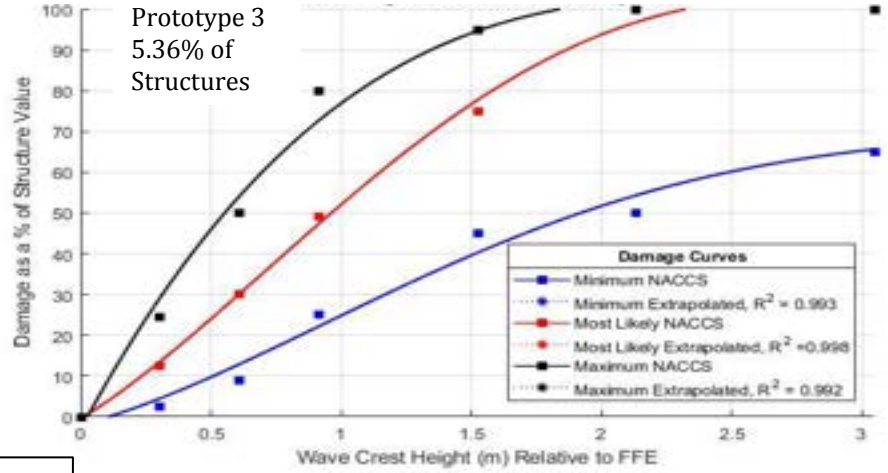
Prototype 6B
20.99% of
Structures



Prototype 2
58.67% of Structures

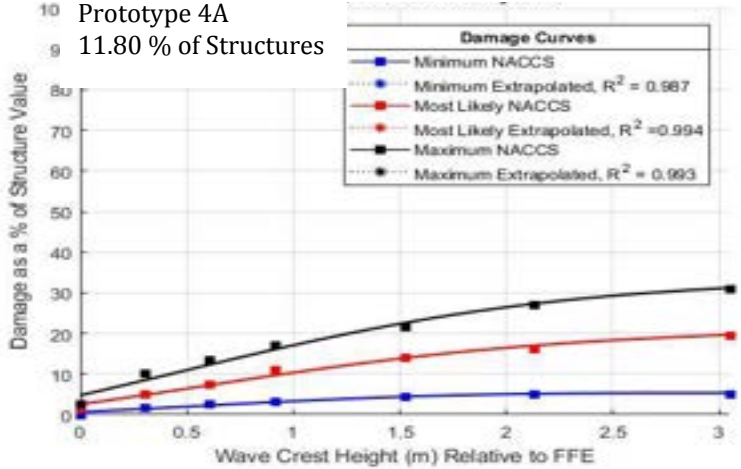


Prototype 3
5.36% of
Structures

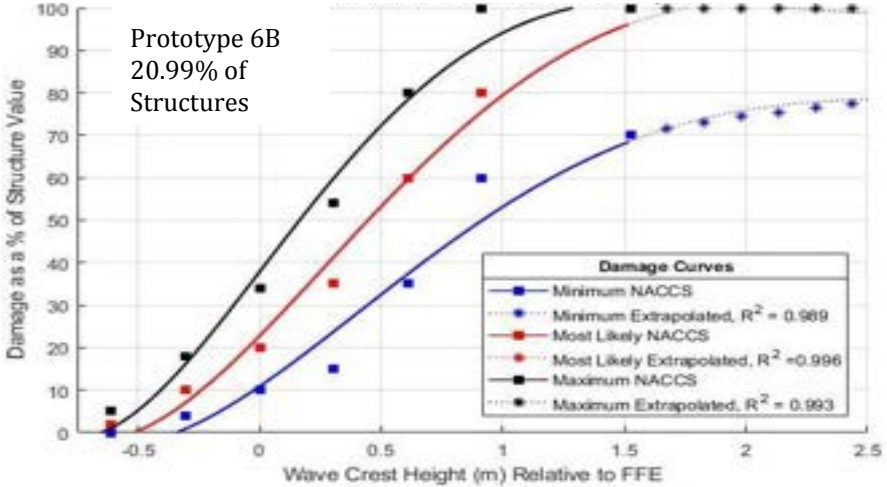


Waves

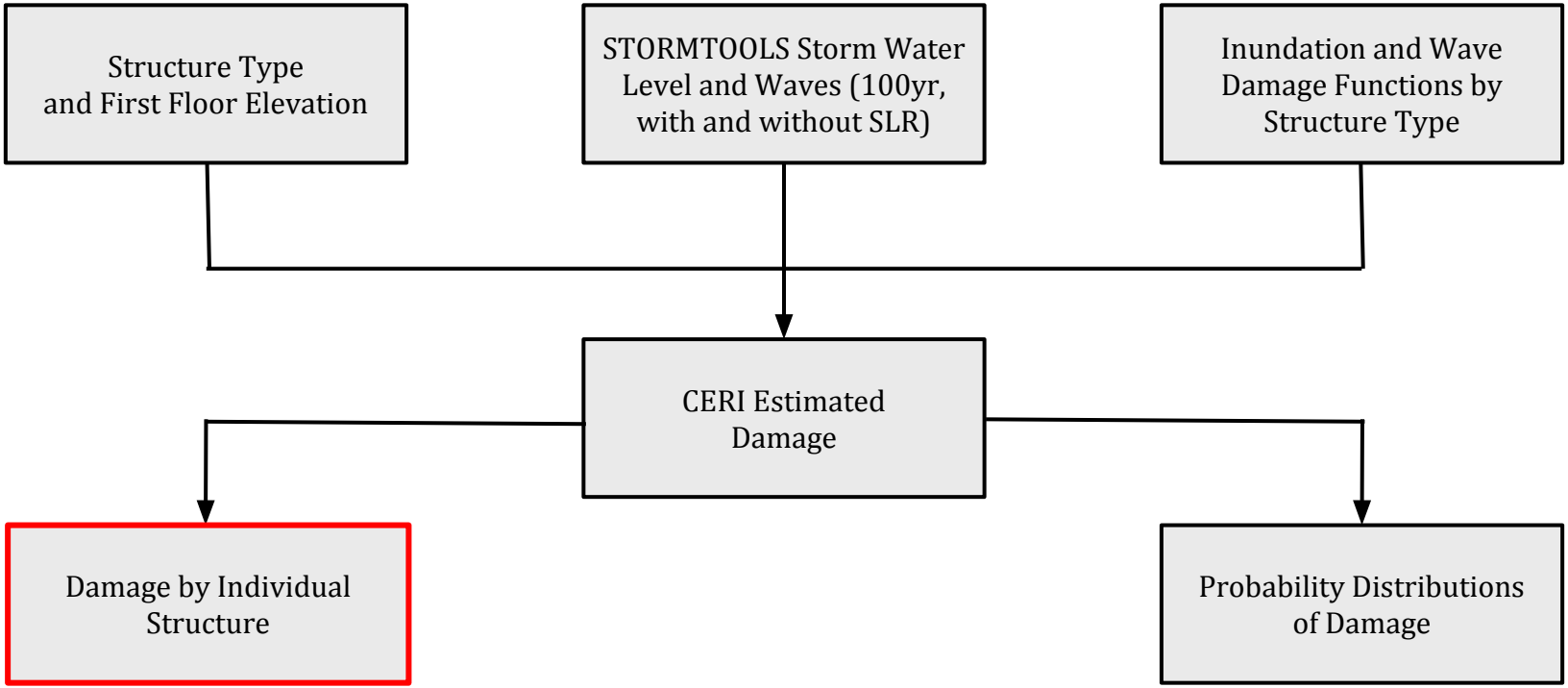
Prototype 4A
11.80 % of Structures



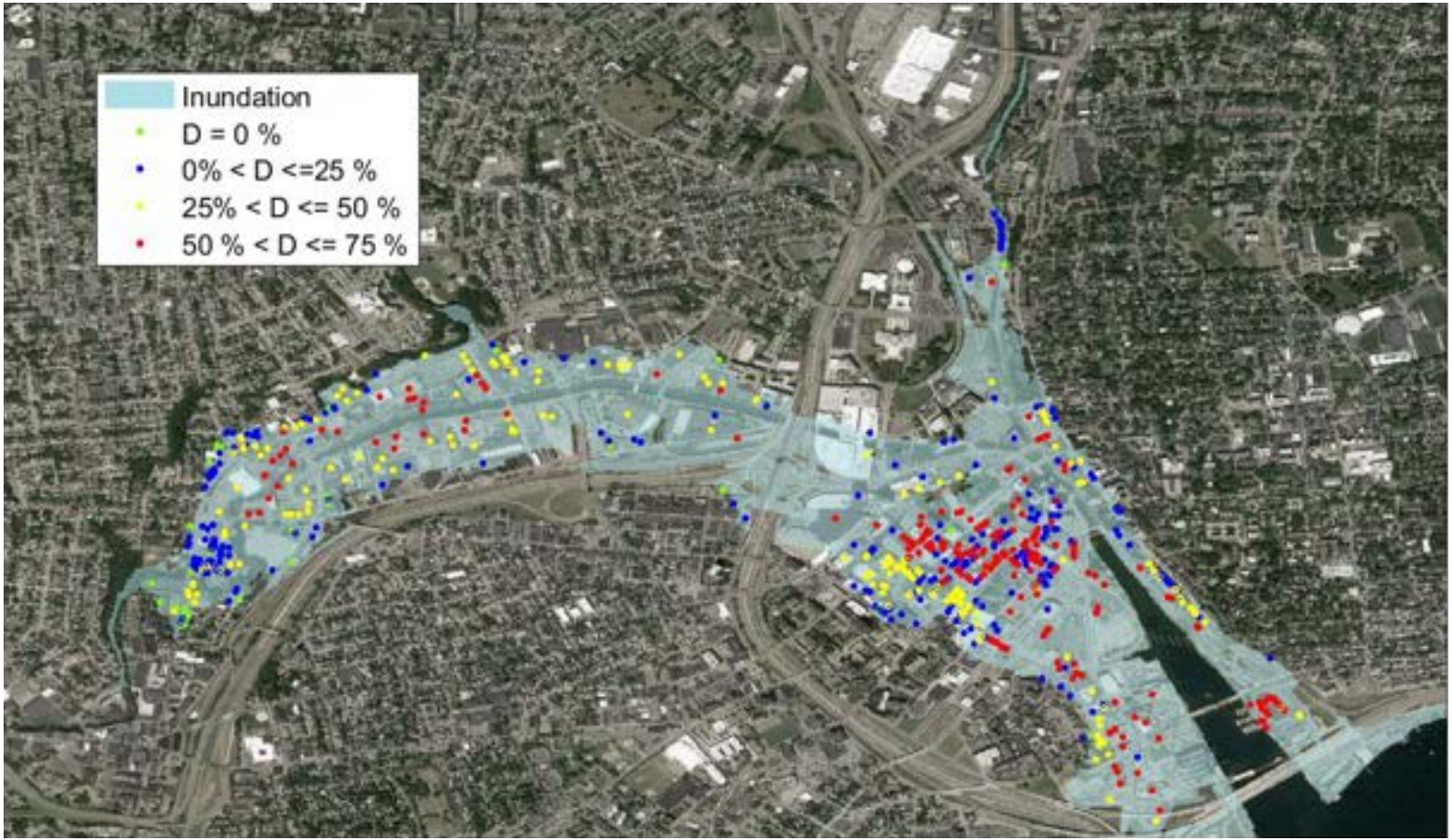
Prototype 6B
20.99% of
Structures



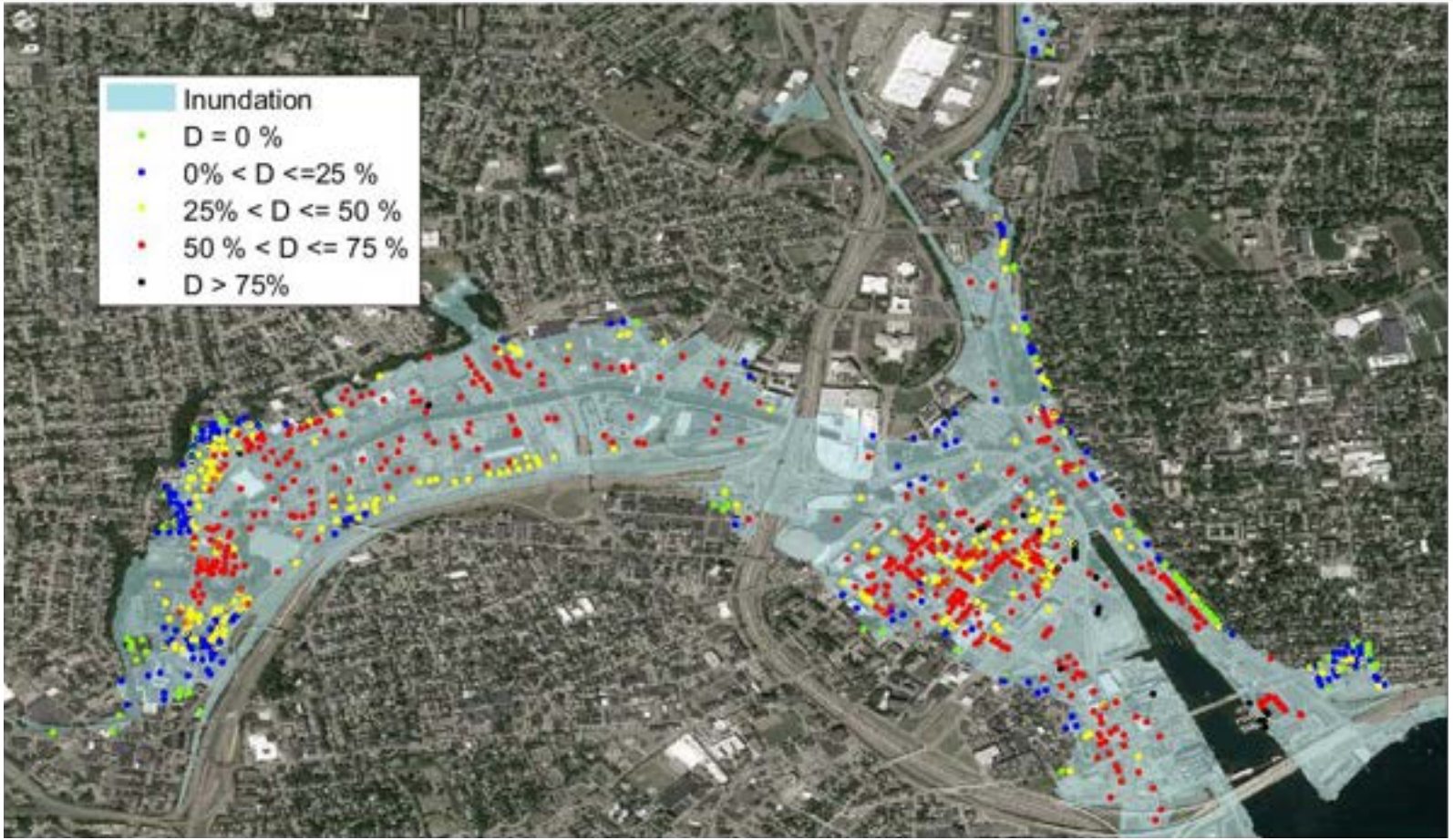
CERI -Inundation and Wave Damage



Inundation Damage - 100 Year Storm Surge without SLR



Inundation Damage - 100 Year Storm Surge with 7ft of SLR

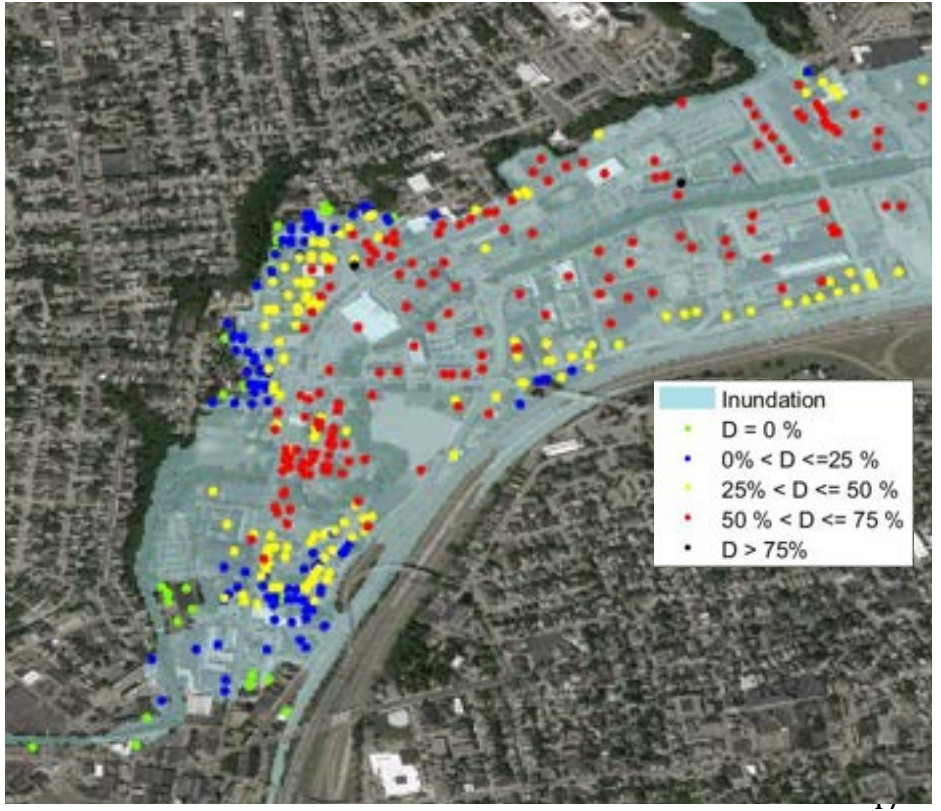


Inundation Damage - 100 Year Storm Surge with 7ft of SLR

Inundation Damage - Residential Area Comparison

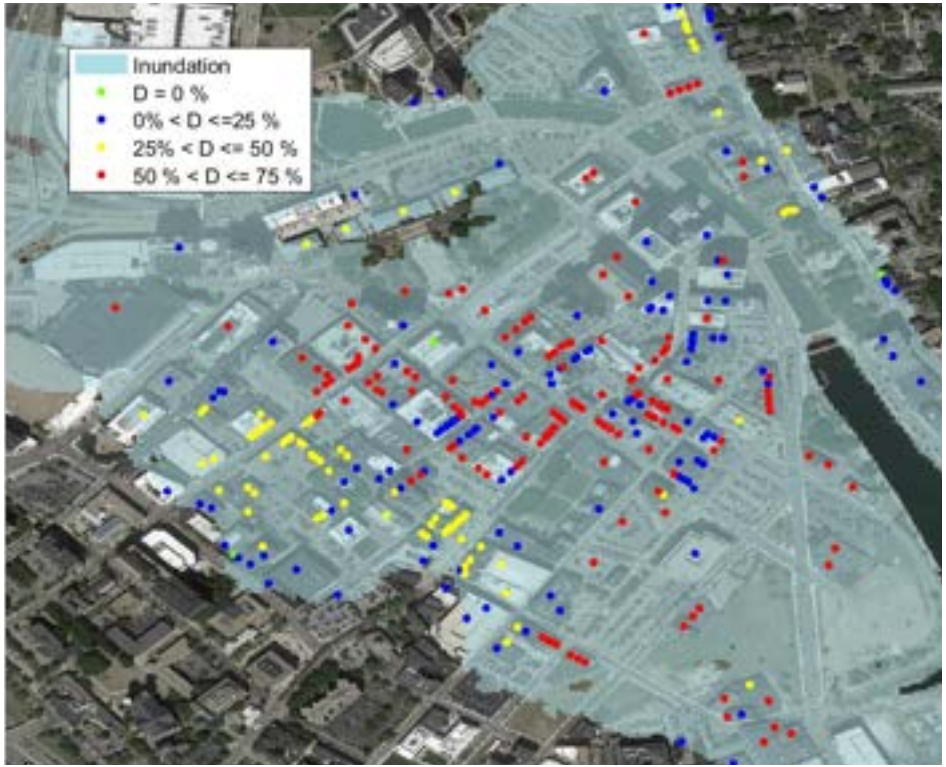
No SLR

7ft of SLR

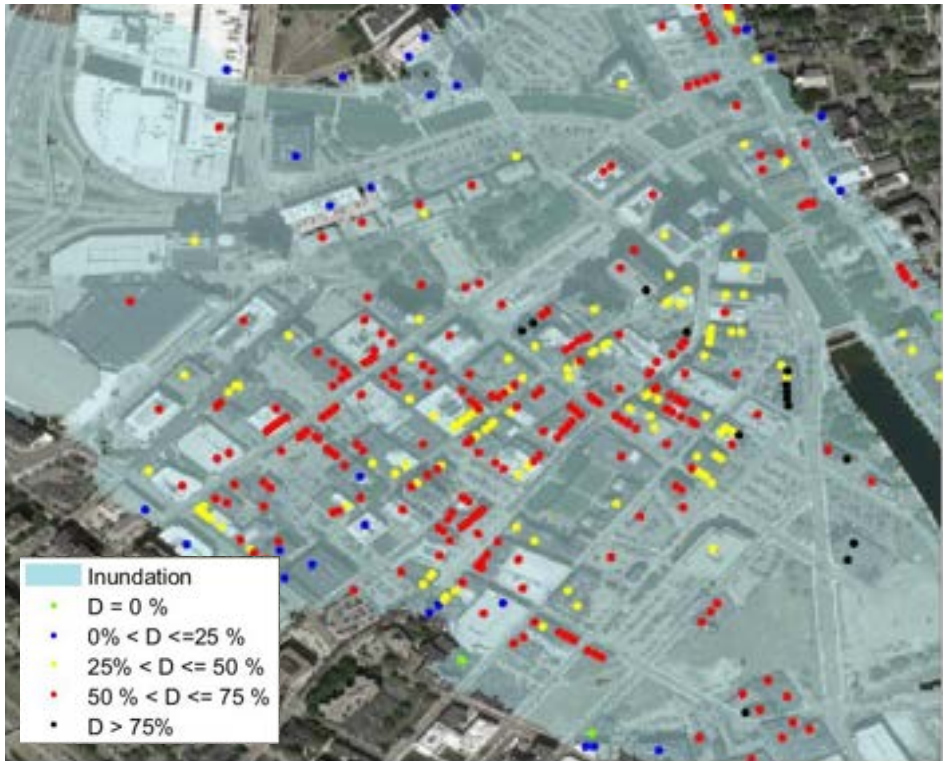


Inundation Damage - Downtown Area Comparison

No SLR



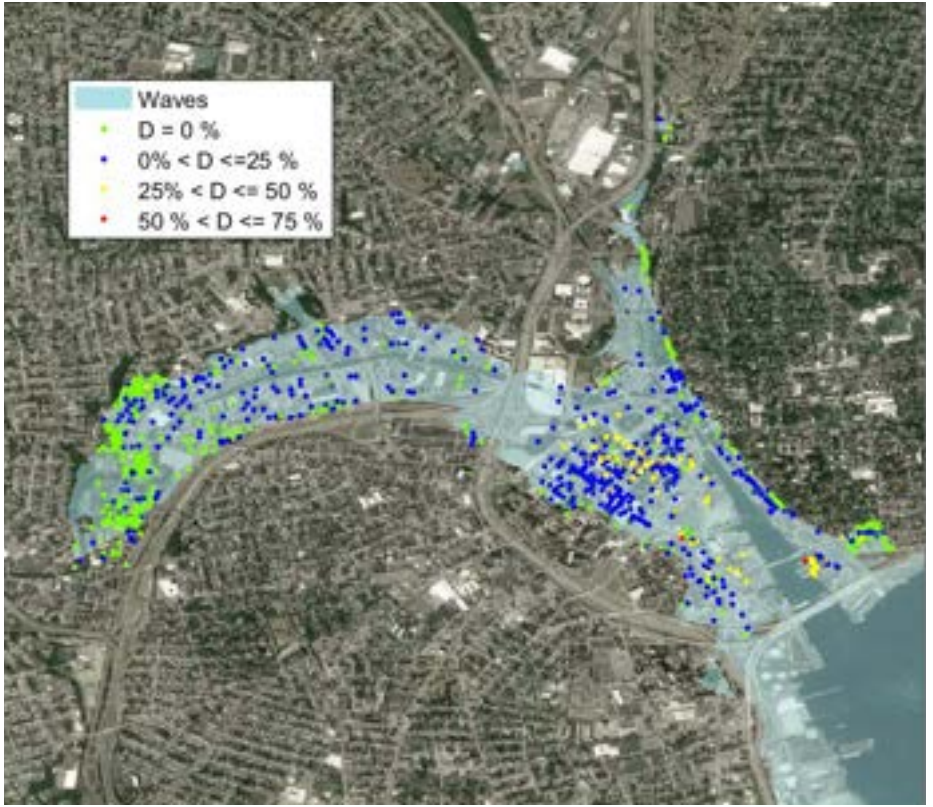
7ft of SLR



Wave Damage - 100 Year Storm

No SLR

7ft of SLR

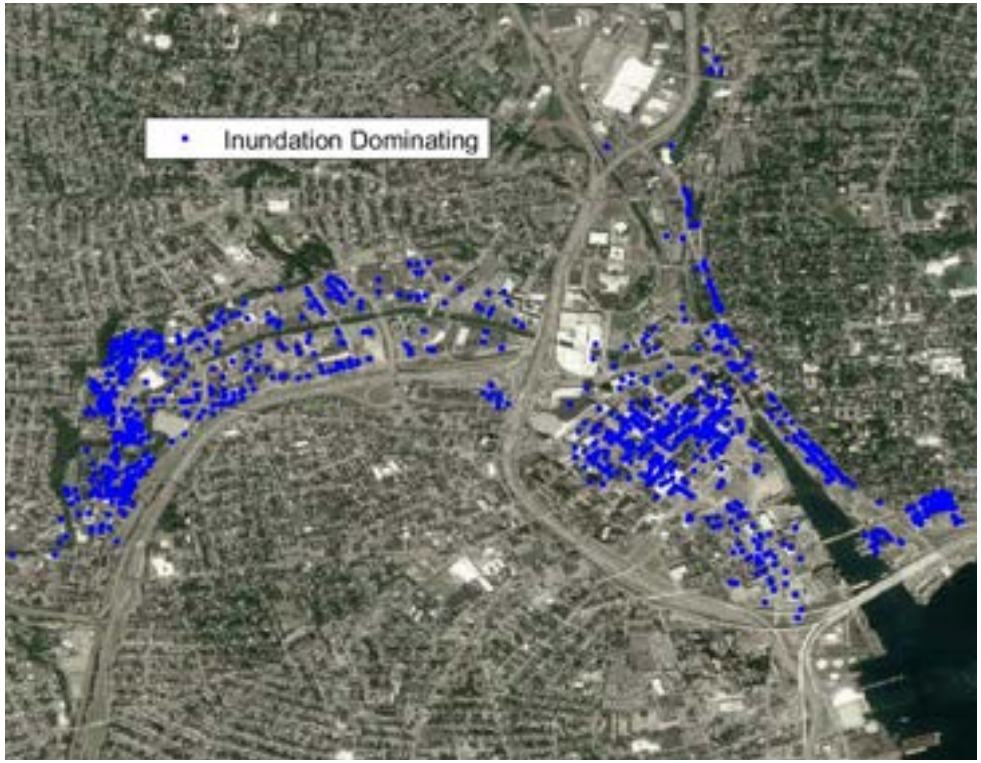


Dominating Damage

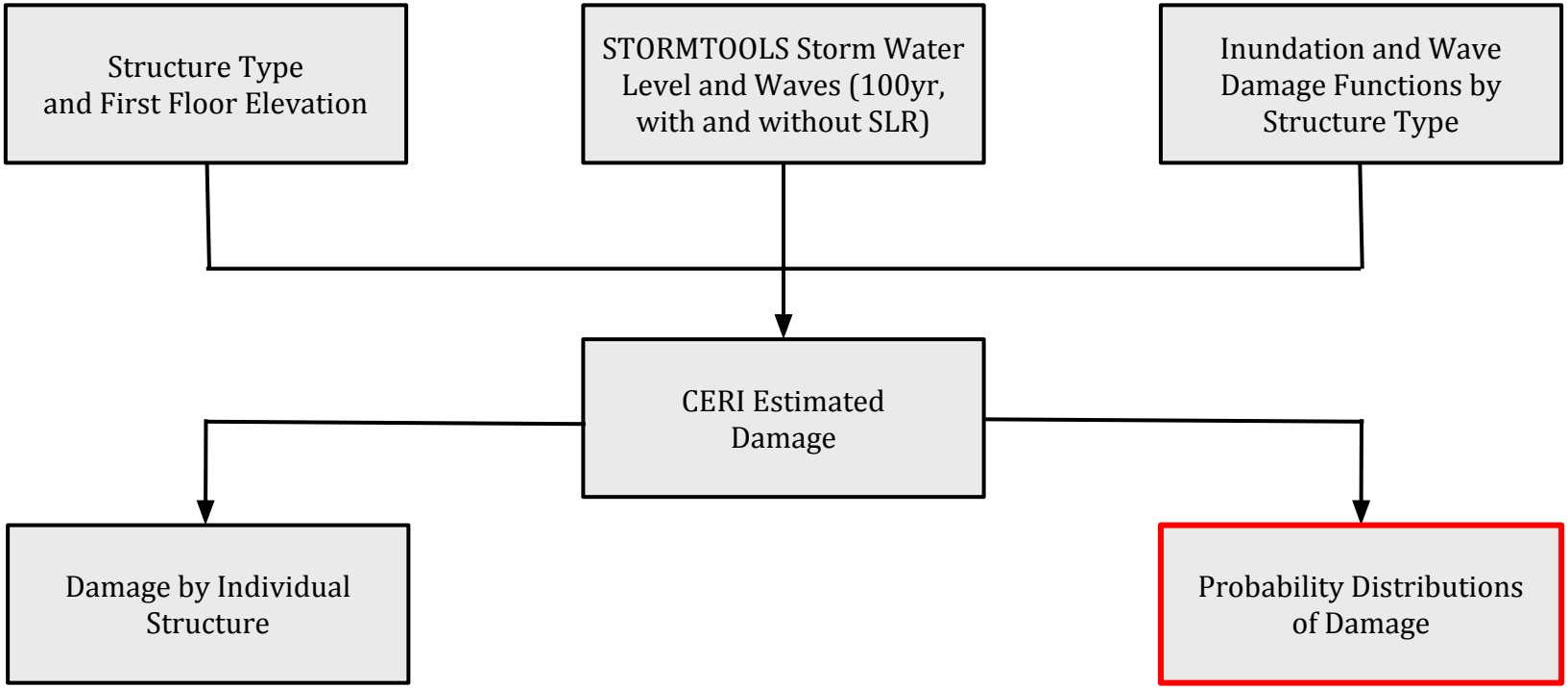
Total Damage = max (Inundation Damage, Wave Damage)

No SLR

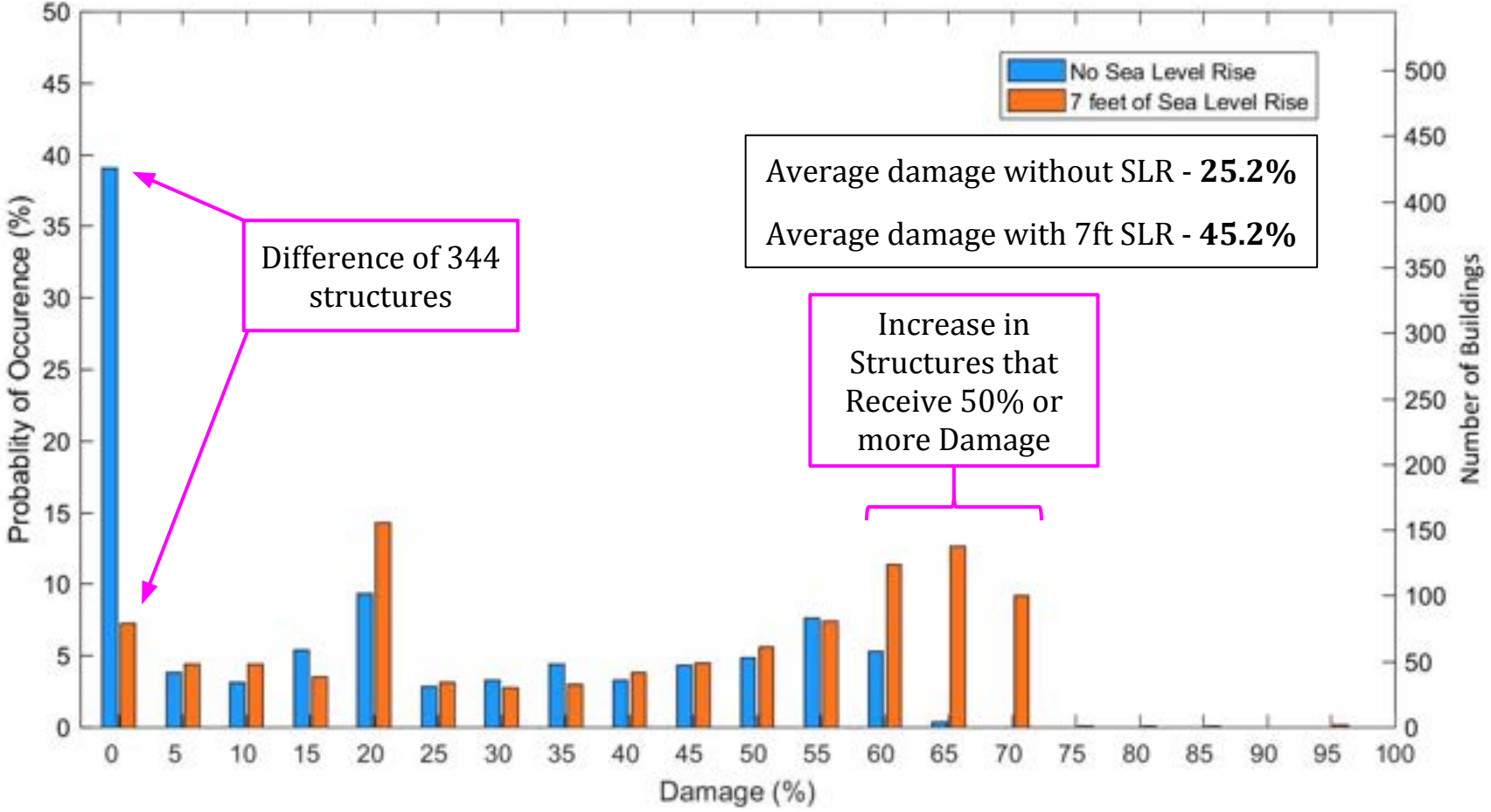
7ft of SLR



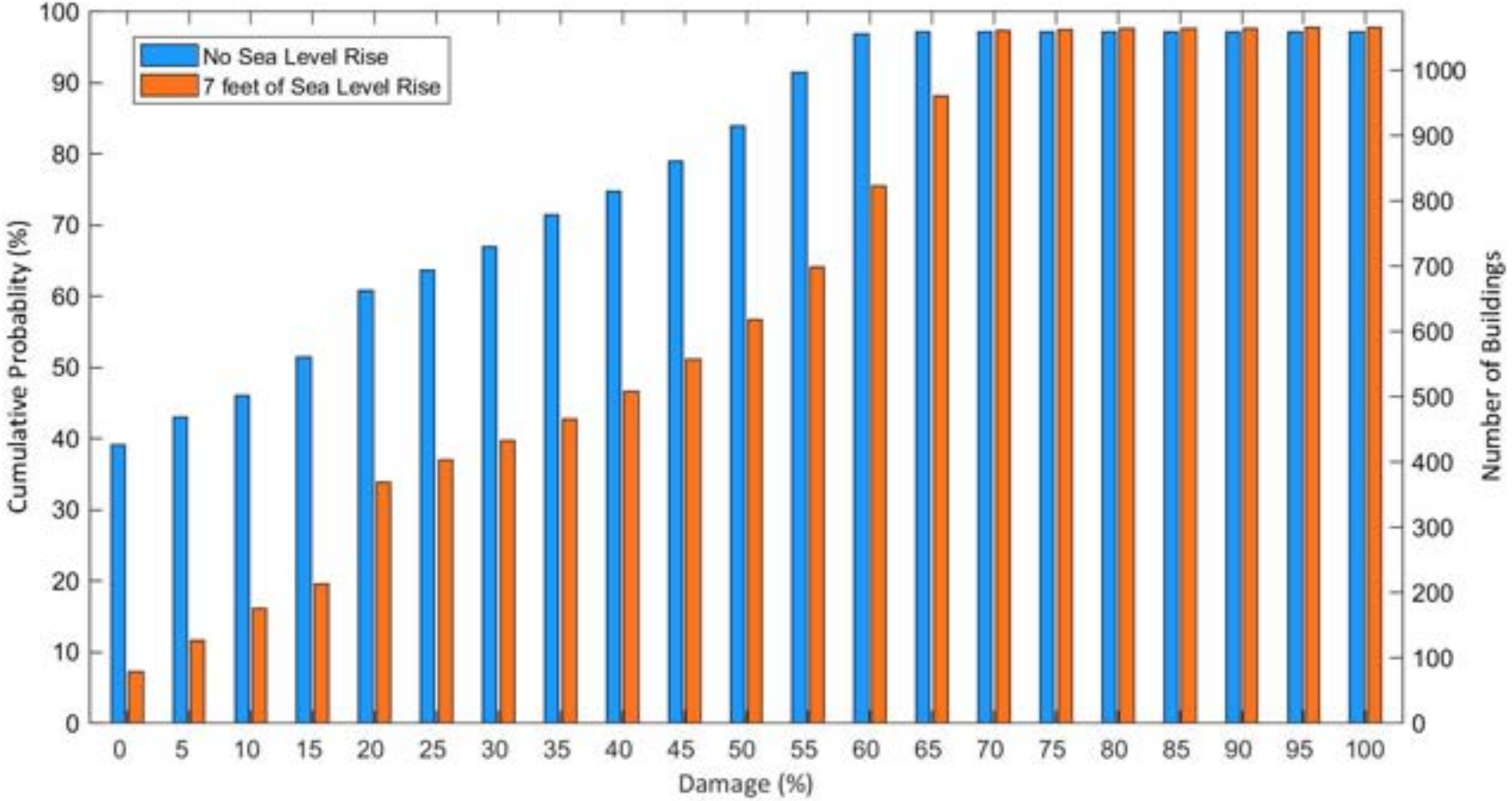
CERI - Total Damage Statistics



Total Damage: Probability Distribution (PDF)



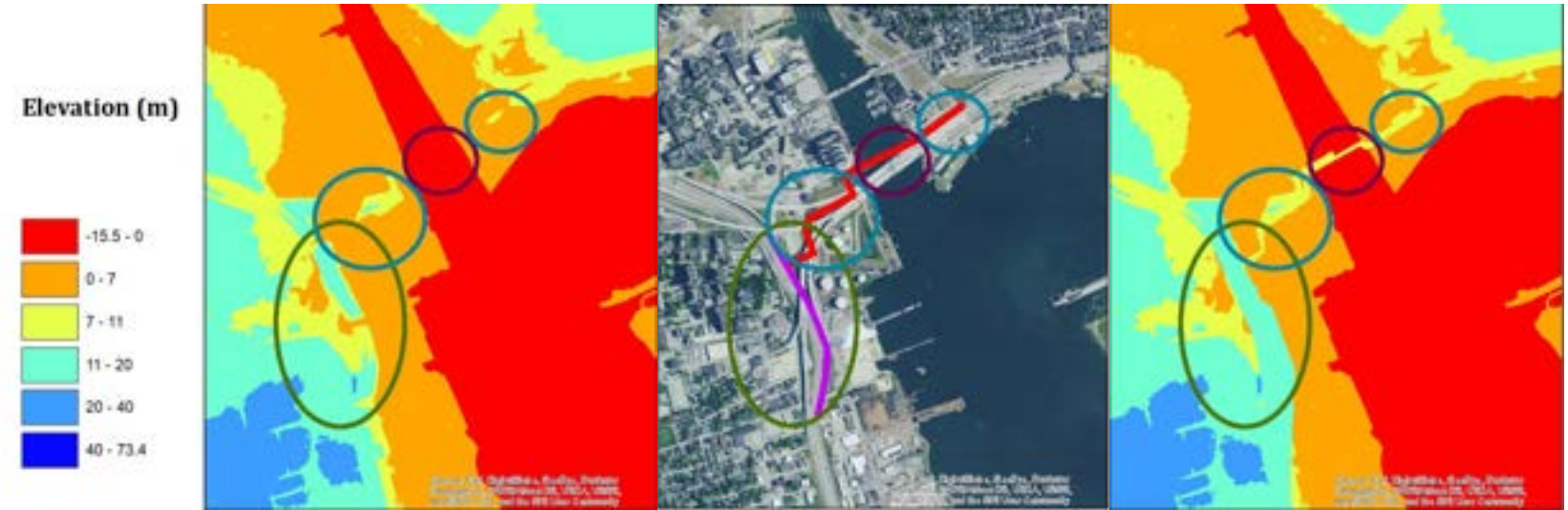
Total Damage: Cumulative Distribution (CDF)



Analysis of the Fox Point Hurricane Barrier

Editing Digital Elevation Model

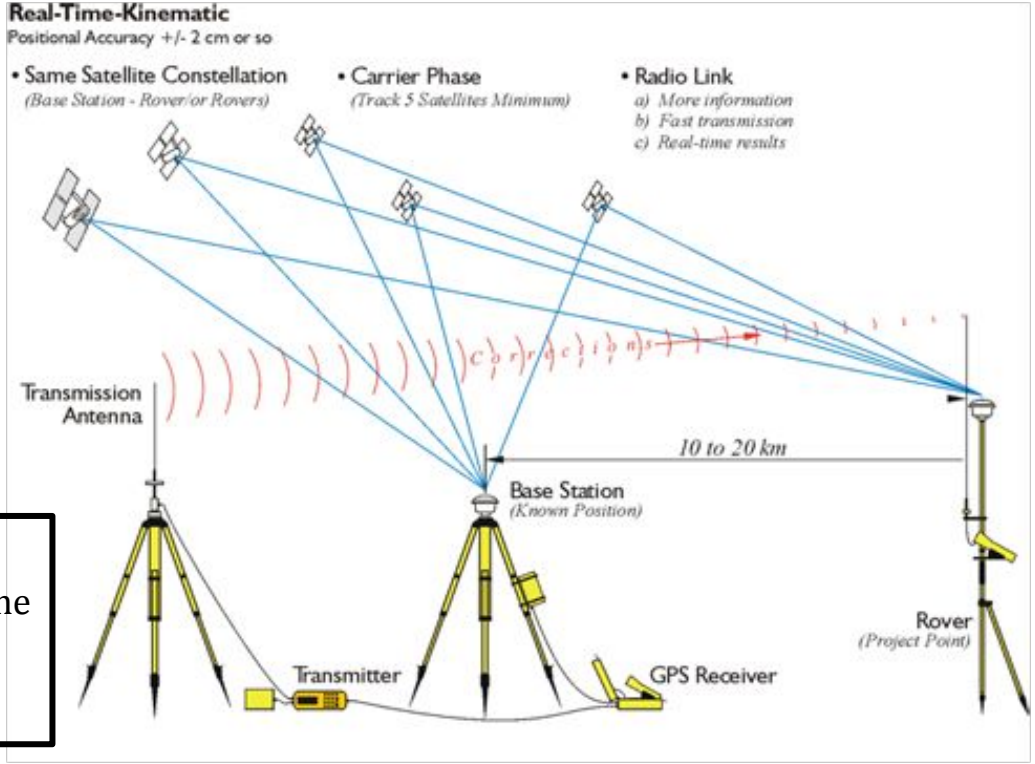
- "Bare Earth" does not include Fox Point Hurricane Barrier, wing walls, or elevation of the highway
  - Barrier and wing walls documented to be elevated 25 feet (7.62 meters) (above NAVD88) by Army Corps of Engineers
  - Highway estimated to be 39 feet (11.8 meters) by hills included in DEM and estimates made in the field



Real Time Kinematic (RTK) GPS

RTK measurements were taken of various points around the barrier to compare to to the Bare Earth DEM as well as the modified DEM

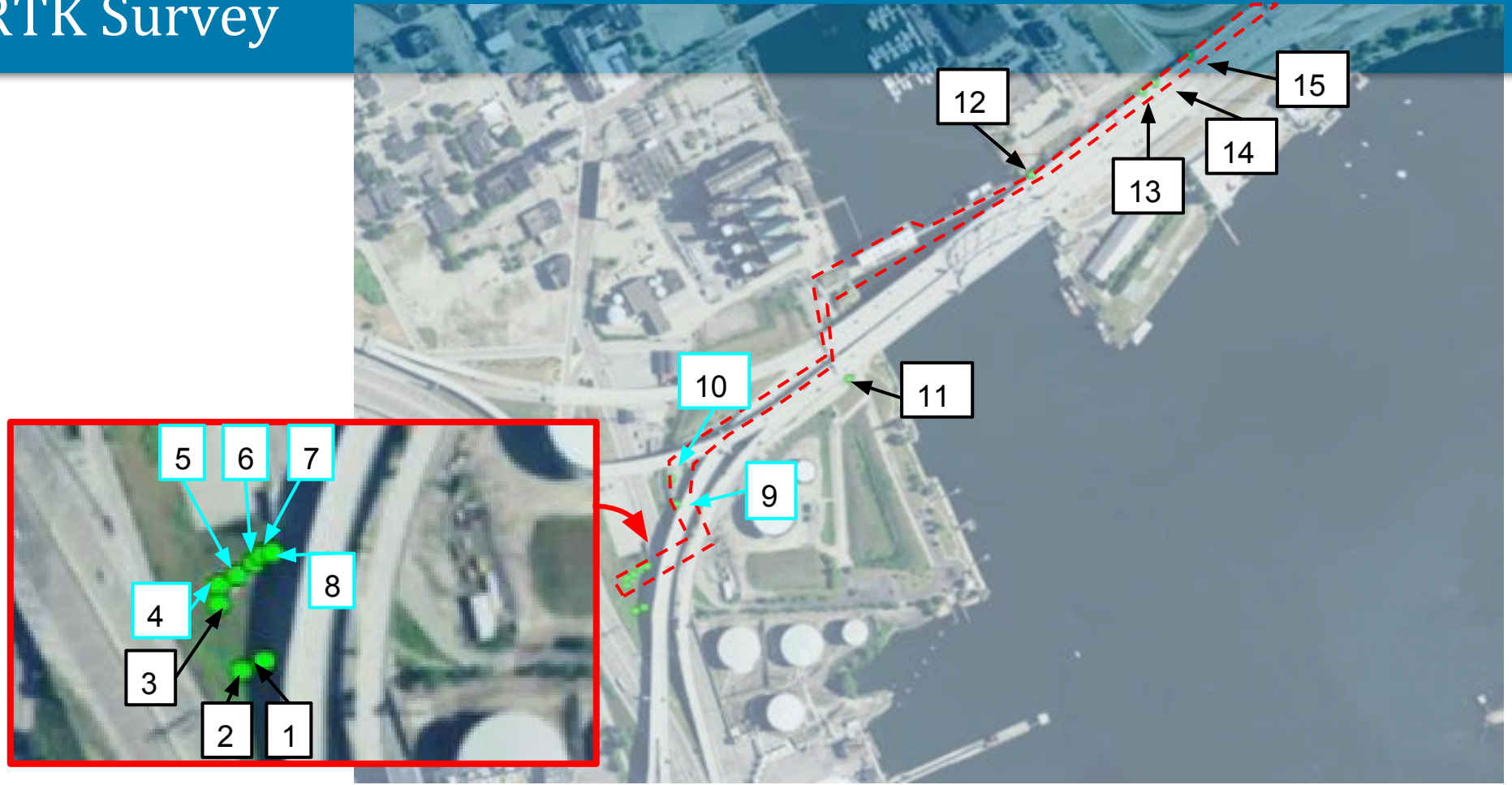
Uses a base station to transmit code from satellites to determine an instantaneous position and elevation



https://www.e-education.psu.edu/geog862/node/1828

RTK Survey

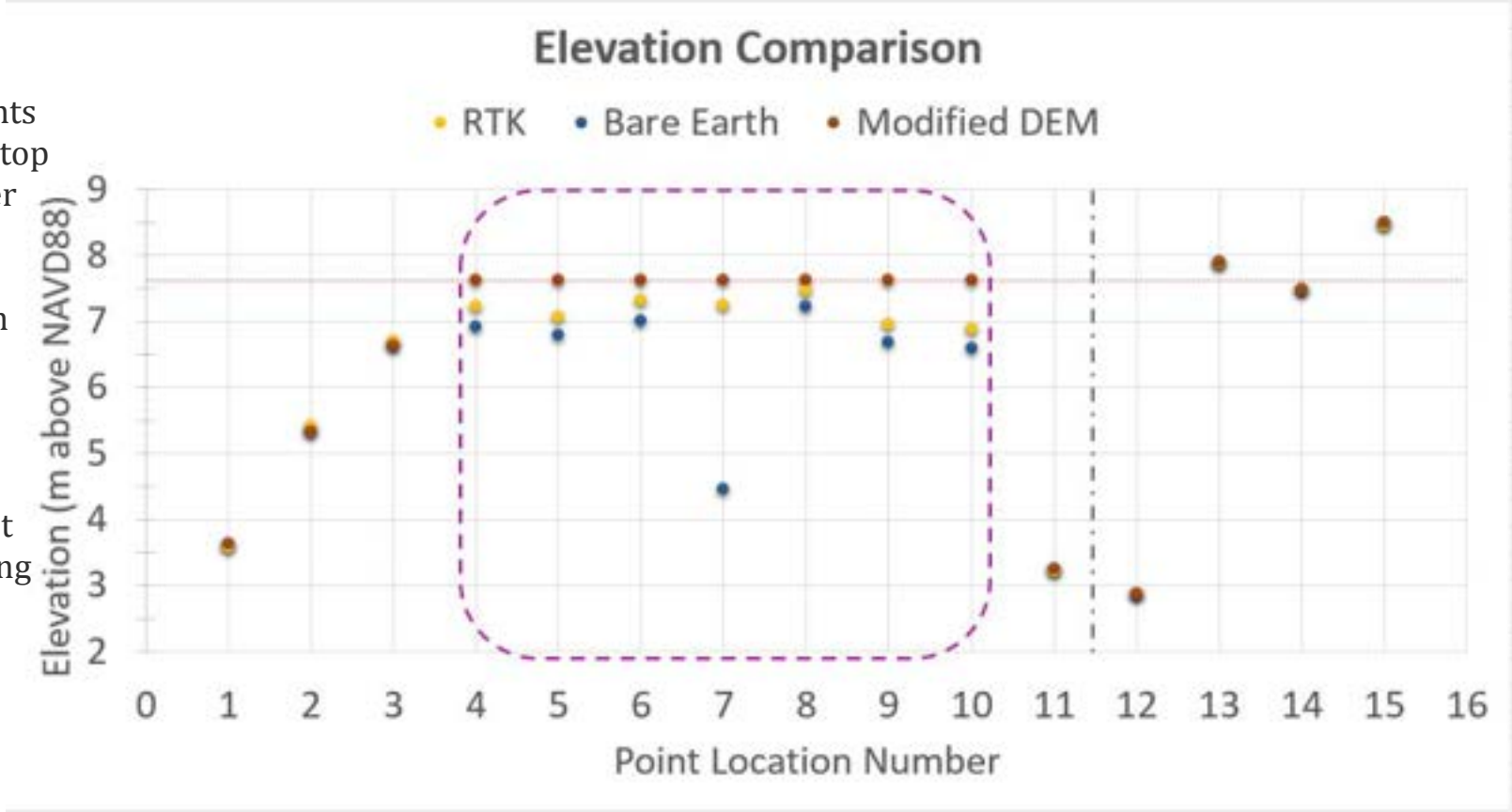
RTK Survey



Measurements taken at the top of the Barrier

Construction height of barrier

Transition between east and west wing walls

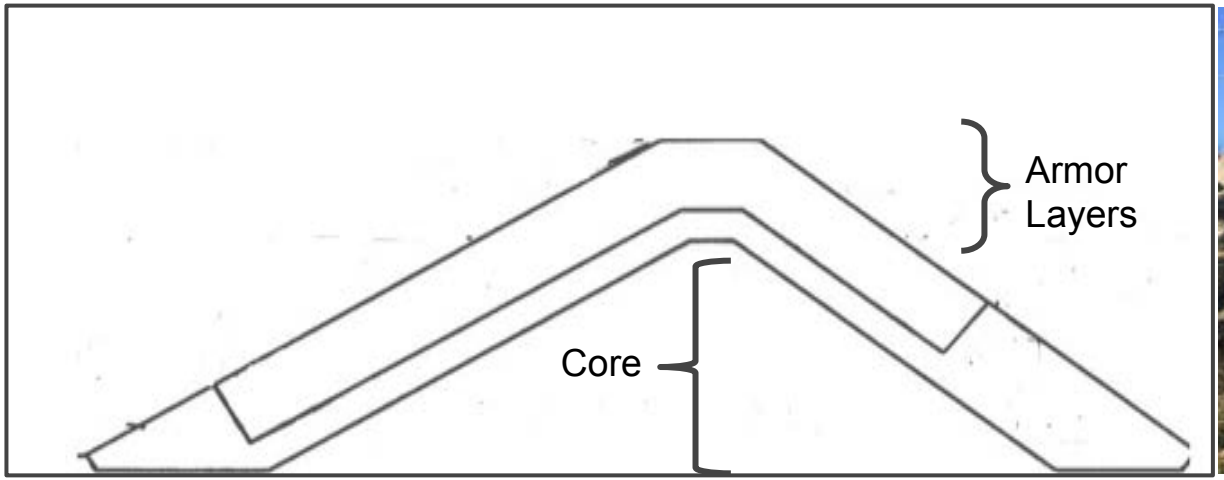


Estimating Permeability

No cross-sectional depictions of Fox Point Hurricane Barrier available

- Recently found and purchased USACE “Design of the Fox Point Barrier” for next semester

Typical design of a rubble-mound structure



Major Concerns

Permeability-
The large boulders covering shorter impermeable core may allow water through

Hydraulic gate malfunctions-
Failure to close one of the gates would compromise entire barrier

Height-
RTK measurements have shown the wing walls to be up to 0.5 m (1.6 ft) lower than expected

Conclusions

- Providence is a low lying, structurally dense, city that has a history of significant flooding due to severe storms.
- Without the Hurricane Barrier, Providence will receive significant structural damage from a 100 year storm, as determined with CERI.
    - Sea level rise will increase this damage.
- The true height and permeability over the entire Fox Point Hurricane Barrier is not consistent with its design.
- As sea levels rise, there is an increase risk of the Hurricane Barrier being overtopped from a severe storm.

Next Semester

- Analyze the design of the Fox Point Hurricane Barrier.
  - Determine permeability and effective height.
- If needed, propose alterations to the Fox Point Hurricane Barrier.
- Analyse fluvial flooding to Providence due to severe storm considering effects of climate change.
- Incorporate Artificial Intelligence into the CERI calculations.

Questions?

Appendix

Citations

Sources

(1) Grilli, A., Spaulding, M., Schambach, L.,Smith, J., Bryant, M. 'Comparing Inundation Maps developed using WHAFIS and STWAVE. A case study in Washington County, RI.' URI. OCE. USACE. 2015

(2) Spaulding, Malcolm L., et al. "Application of State of the Art Modeling Techniques to Predict Flooding and Waves for a Coastal Area within a Protected Bay." Journal of Marine Science and Engineering, vol. 5, no. 1, 2017, p. 14., doi:10.3390/jmse5010014.

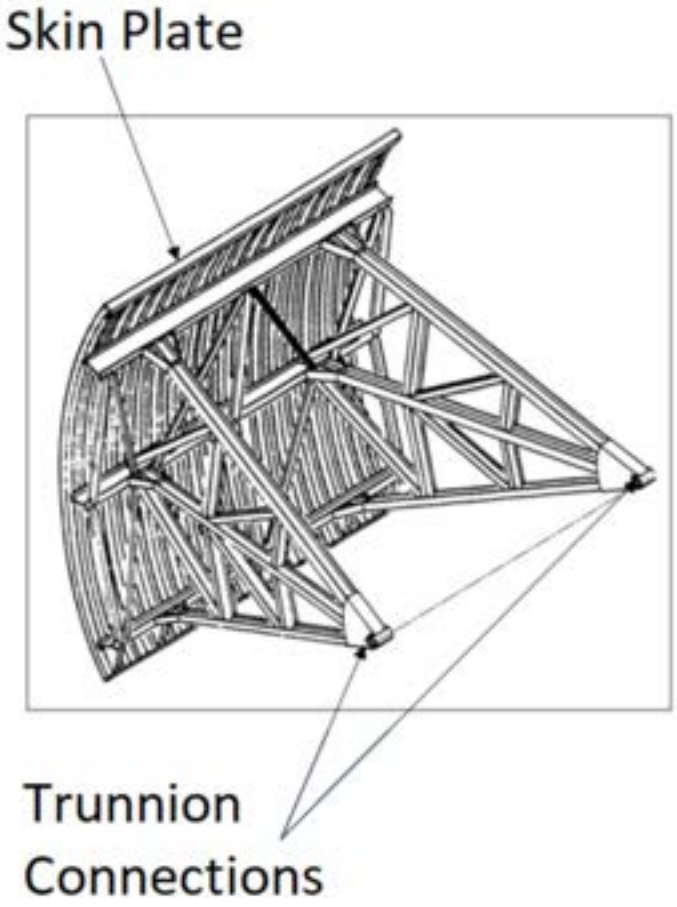
Figures

(3) https://www.google.com/search?q=flooded+providence+pictures+1954&rlz=1C1GCEA_enUS773US773&tbm=isch&source=iu&ictx=1&fir=ZdhSwRoZ0WD9YM%253A%252CP1quZb_a1Vr6vM%252C_&usg=__2sgVW8I0yfJ8mNTvhYoXdaLd3XE%3D&sa=X&ved=0ahUKEwj5m-u0nvjXAhUKY98KHUwEAHsQ9QEIKDAA#imgrc=ZdhSwRoZ0WD9YM: (Hurricane Carol Picture)

(4) http://www.nad.usace.army.mil/Portals/40/docs/NACCS/NACCS_main_report.pdf

(5) https://www.flickr.com/photos/coreywelch/8124212585

Fox Point Hurricane: Tainter Gates



- 3 tainter gates located in main dike
- Each gate is 12.2 meters by 12.2 meters, weigh 48.1 metric tons, and have low hoist capacity
- Tainter gate- radial arm floodgate rotates about the point of the pie-shaped wedge, considered a trunnion or pin connection.
- Cylindrical skin plates curved, no moment about the axis of the gate

Fox Point Hurricane Barrier: Pump House

- Pump-house contains 5 pumps with 3.3 MW capacity
- Capable of moving 11.7 million liters per minute when all pumps are operational

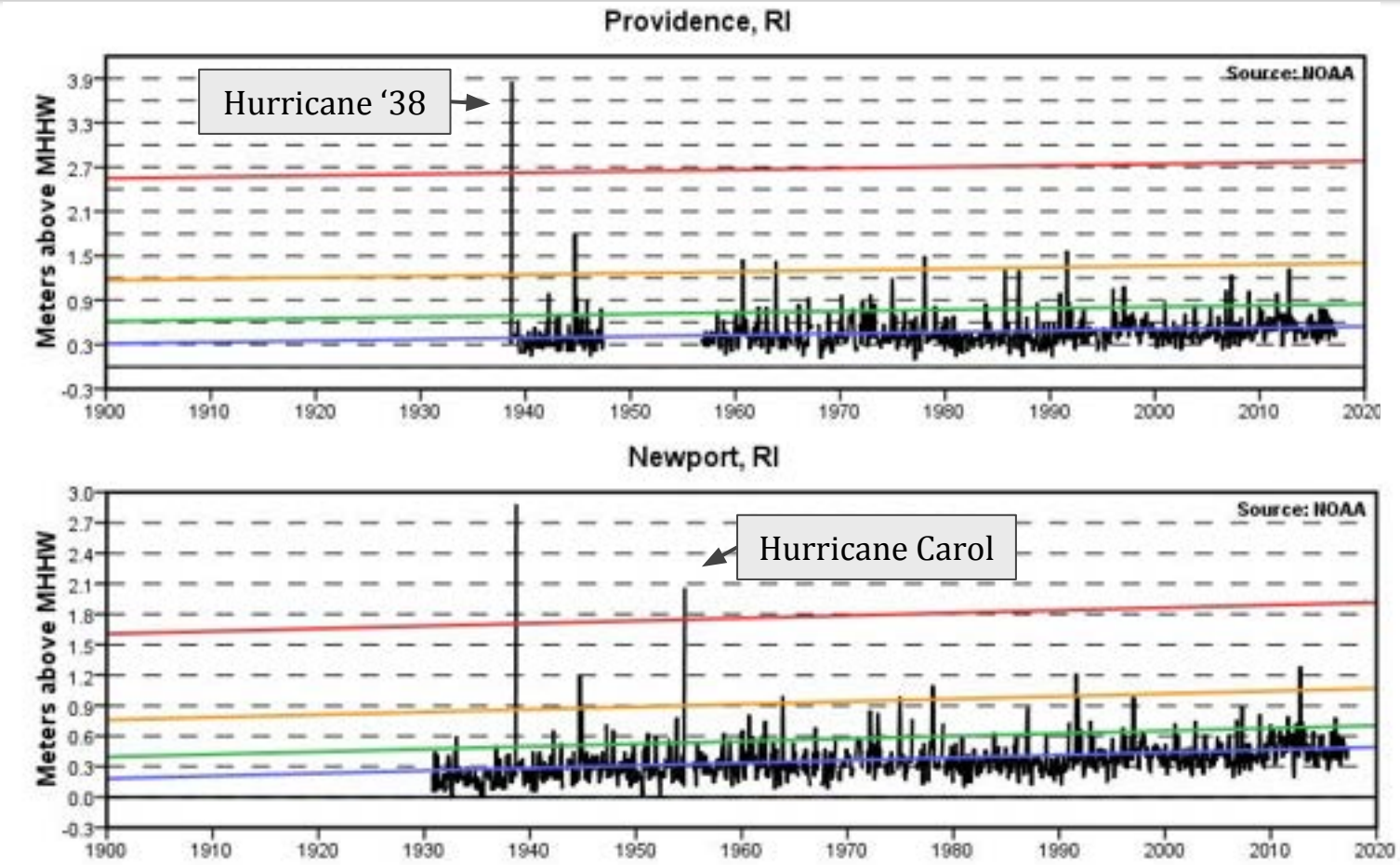
Fox Point Hurricane Barrier: Sketch

Significant Hurricanes: Providence

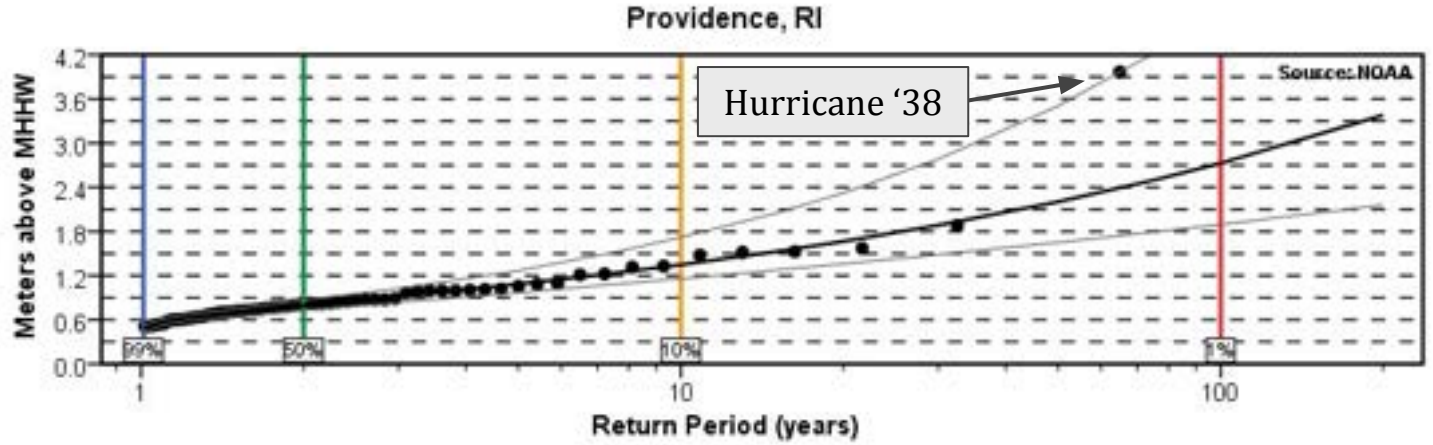
• 1635: Great Colonial Hurricane	5.0 m
• 1638: Hurricane of 1638	5.3 m
• 1815: “Gale of 1815”	4.1 m
• 1938: Hurricane of 1938	4.6 m
• 1954: Hurricane Carol	4.3 m
• 1991: Hurricane Bob	2.3 m
• 2011: Hurricane Irene	1.7 m
• 2012: Hurricane Sandy	2.1 m

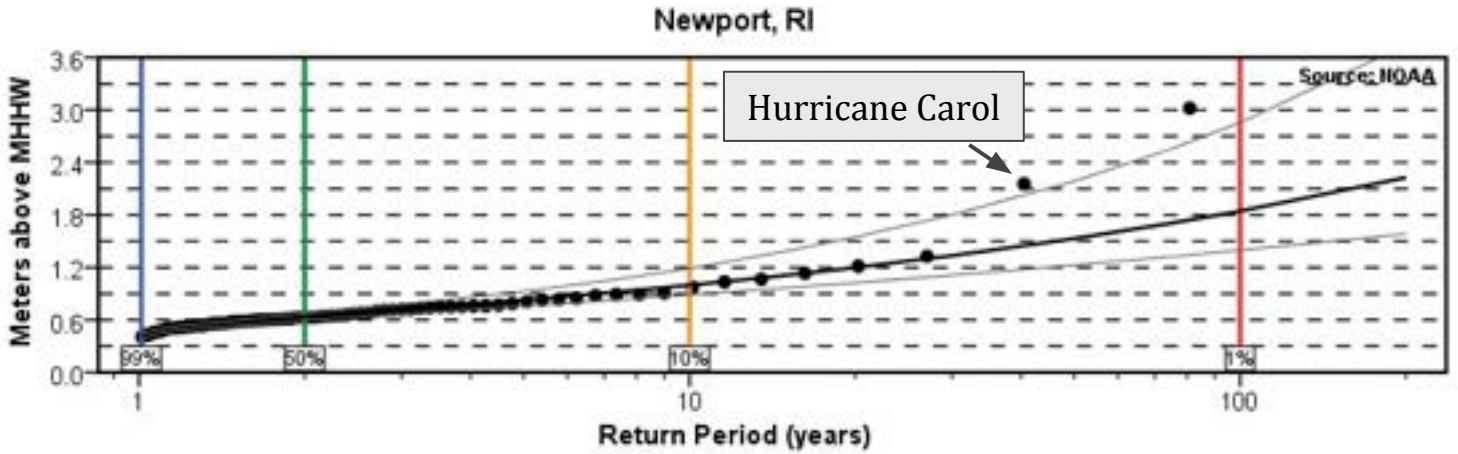
Water Levels per NAVD88 taken from Morang

Rhode Island - High Water



Rhode Island - Return Period

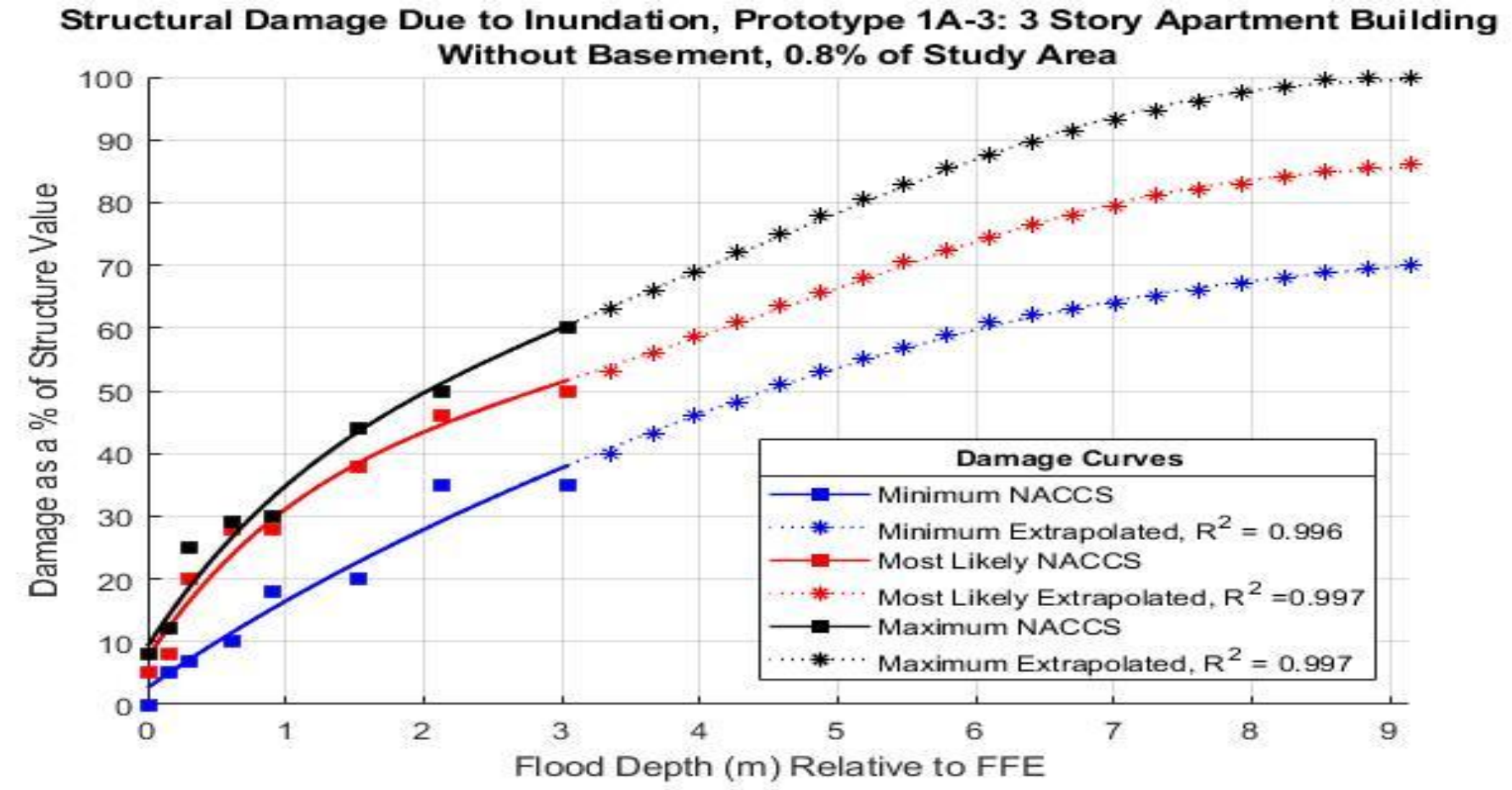




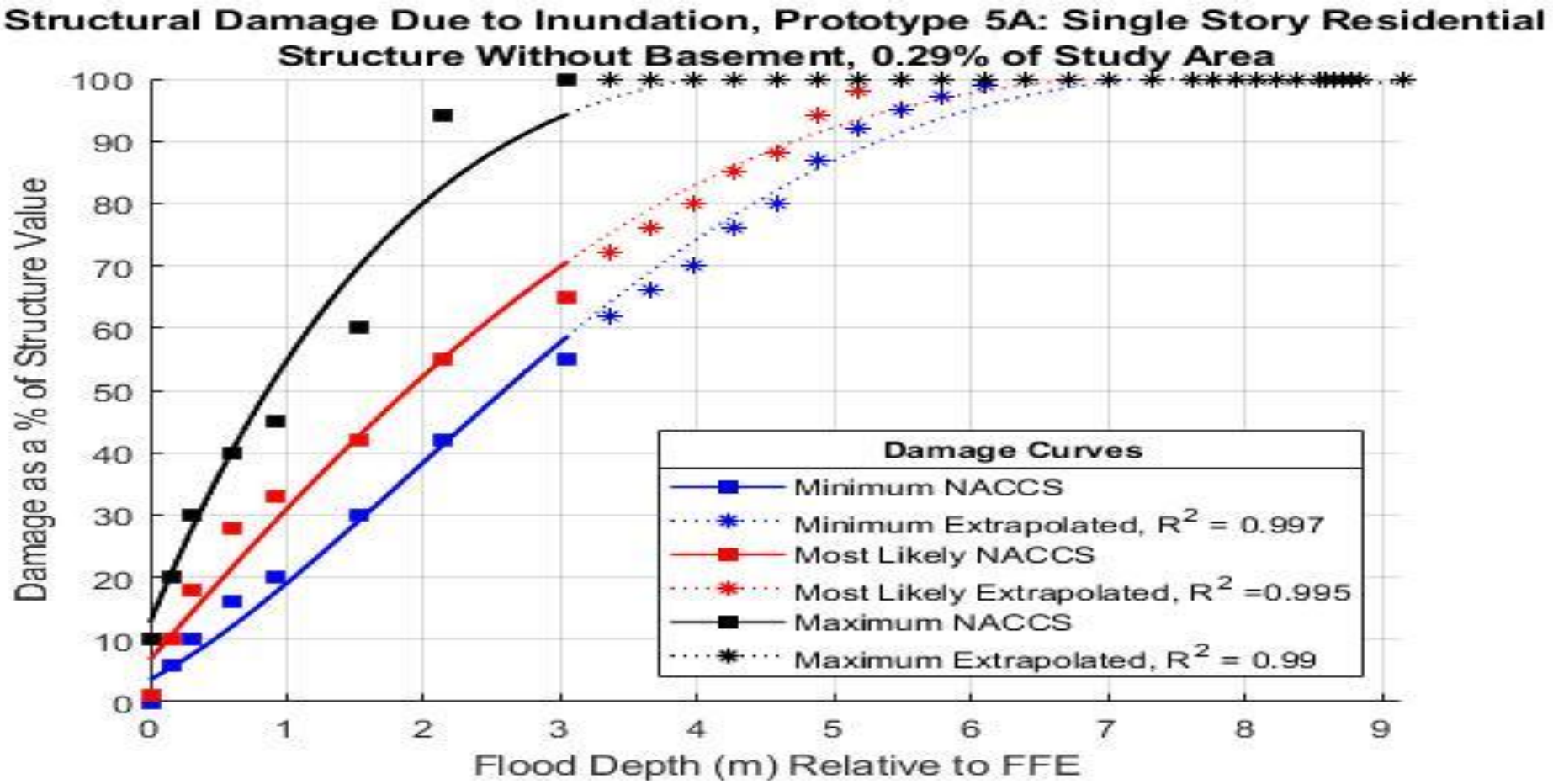
Prototyping Assumptions

1. The height of all steps was assumed to be 8 inches
   a. From OSHA standards
2. Any structure over 5 stories was classified as an Urban High Rise
3. If the structure was on sloped land, the steps to the back door and front door were averaged
4. If a building had more than one use, prototype was based on the lowest floor
5. 50% of the structures with no basement information were given basements and the other 50% were not

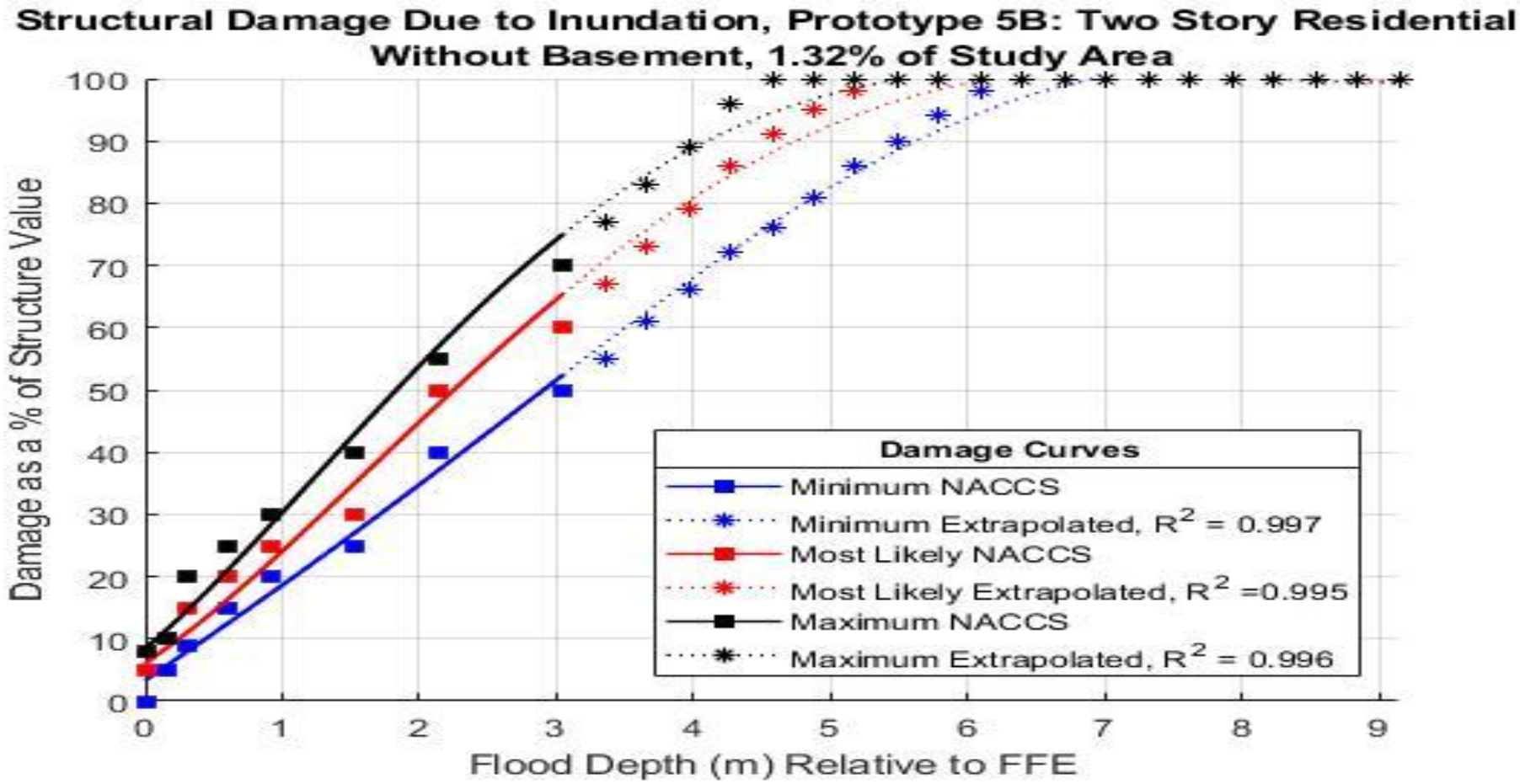
Inundation Curves - Extra



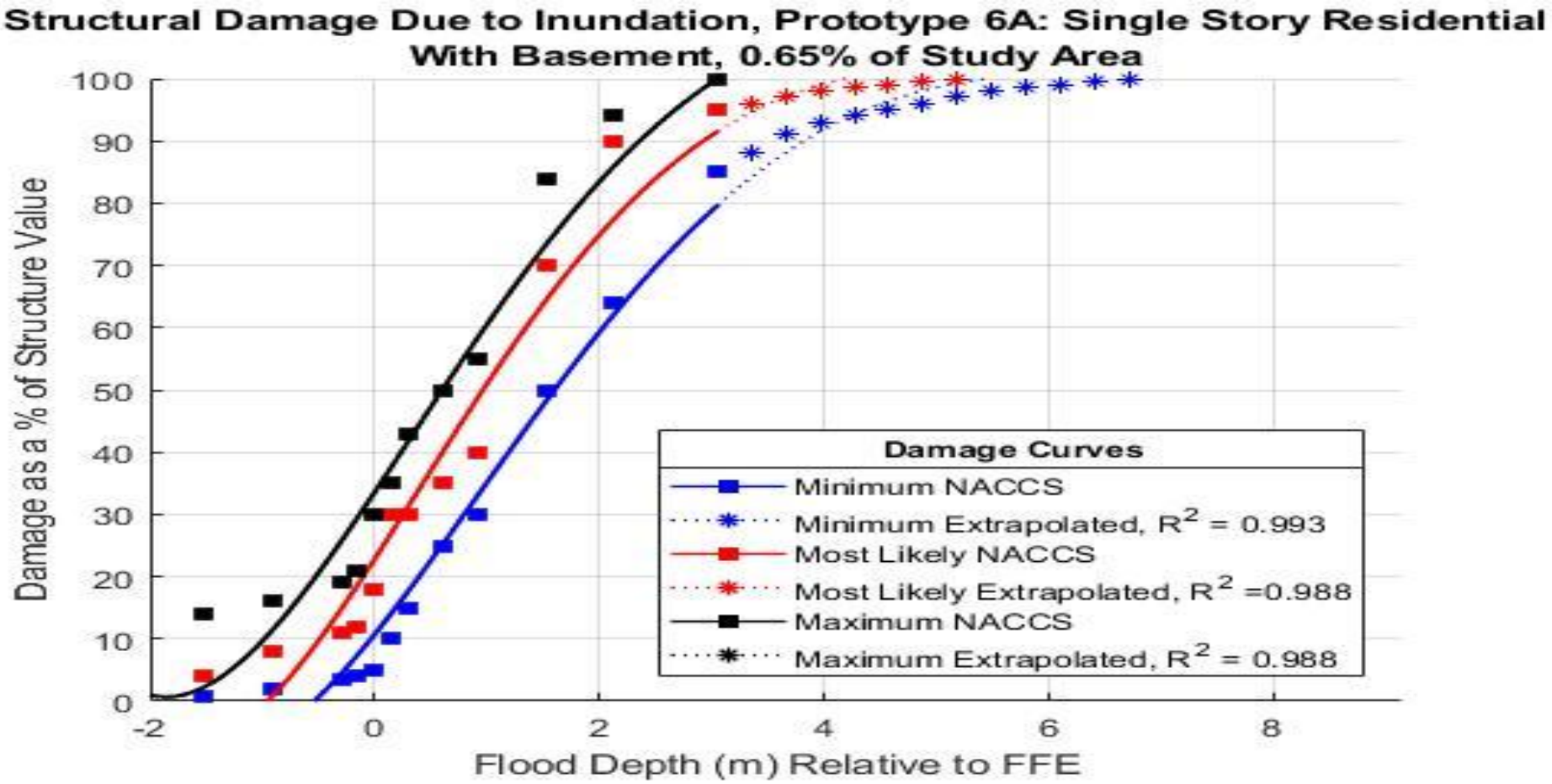
Inundation Curves - Extra



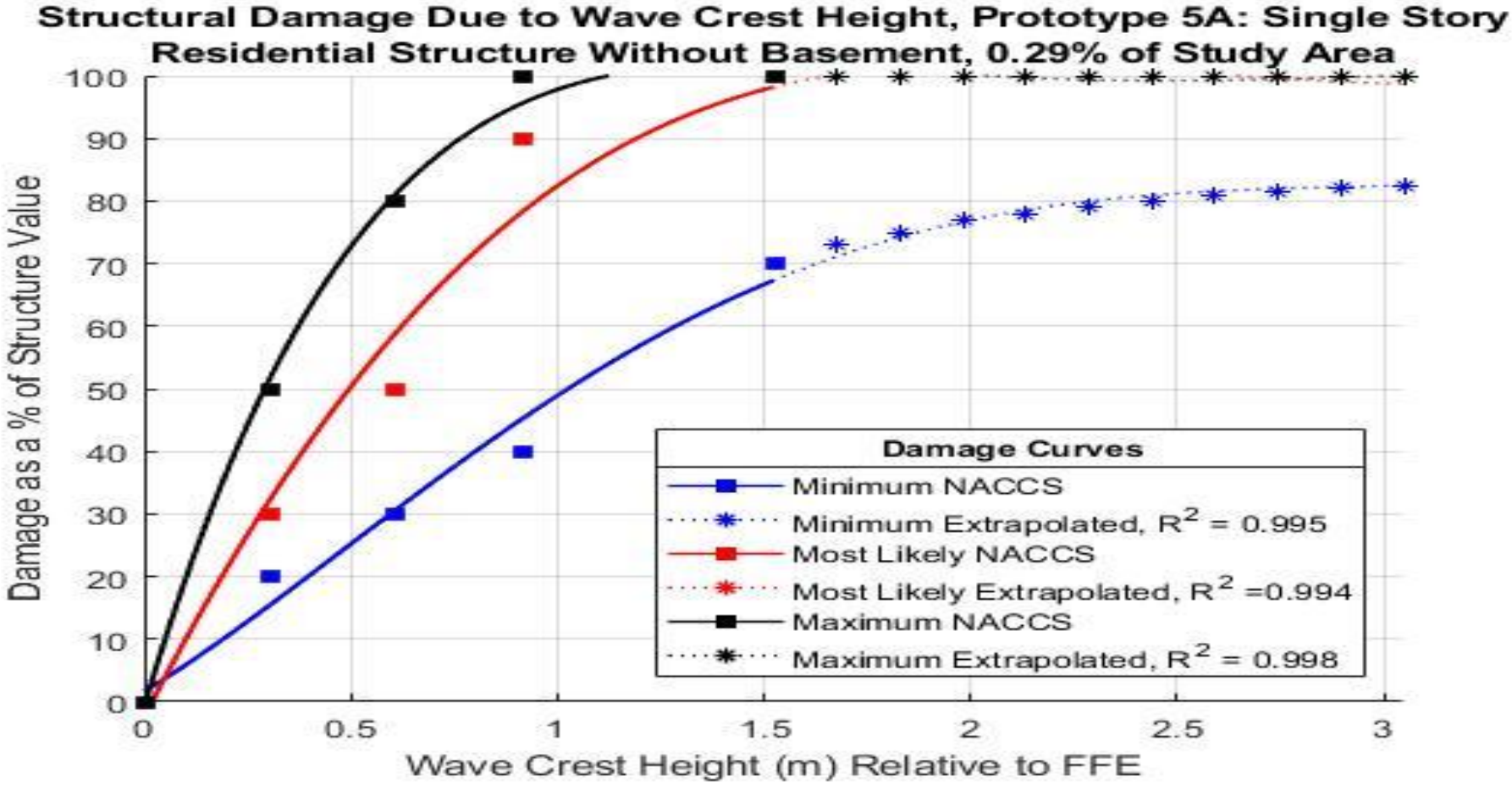
Inundation Curves - Extra



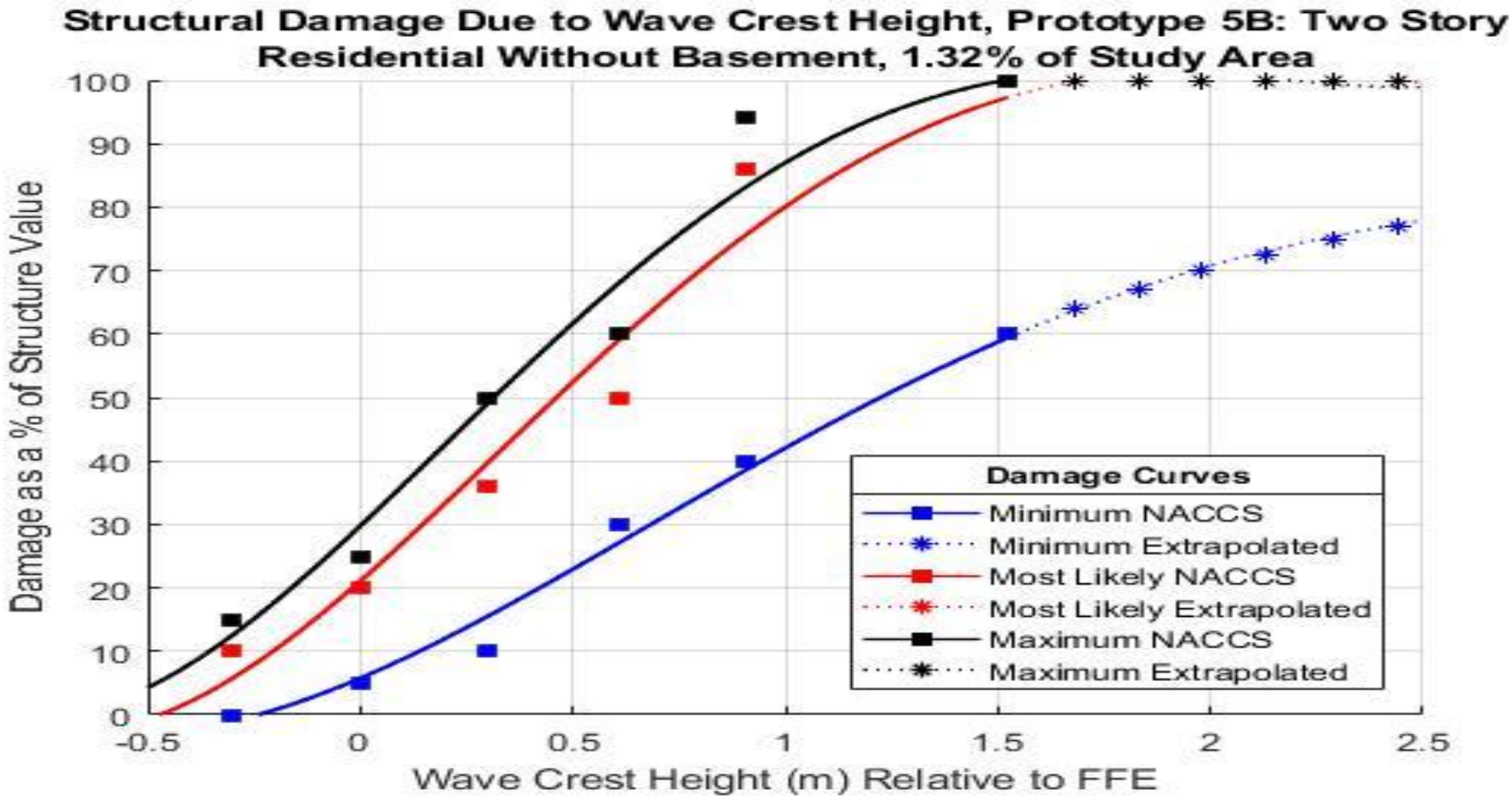
Inundation Curves - Extra



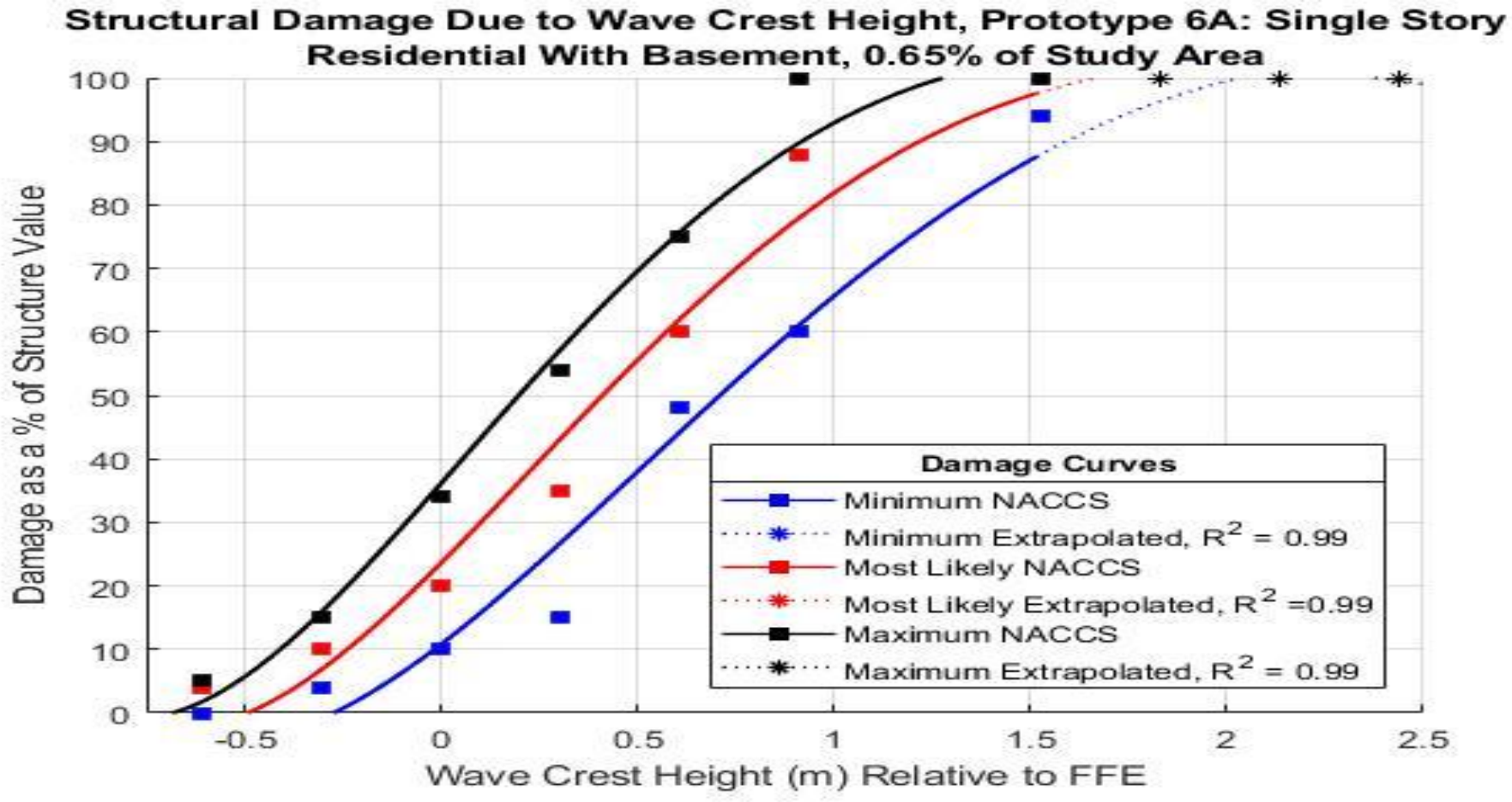
Wave Crest Damage Curves - Extra



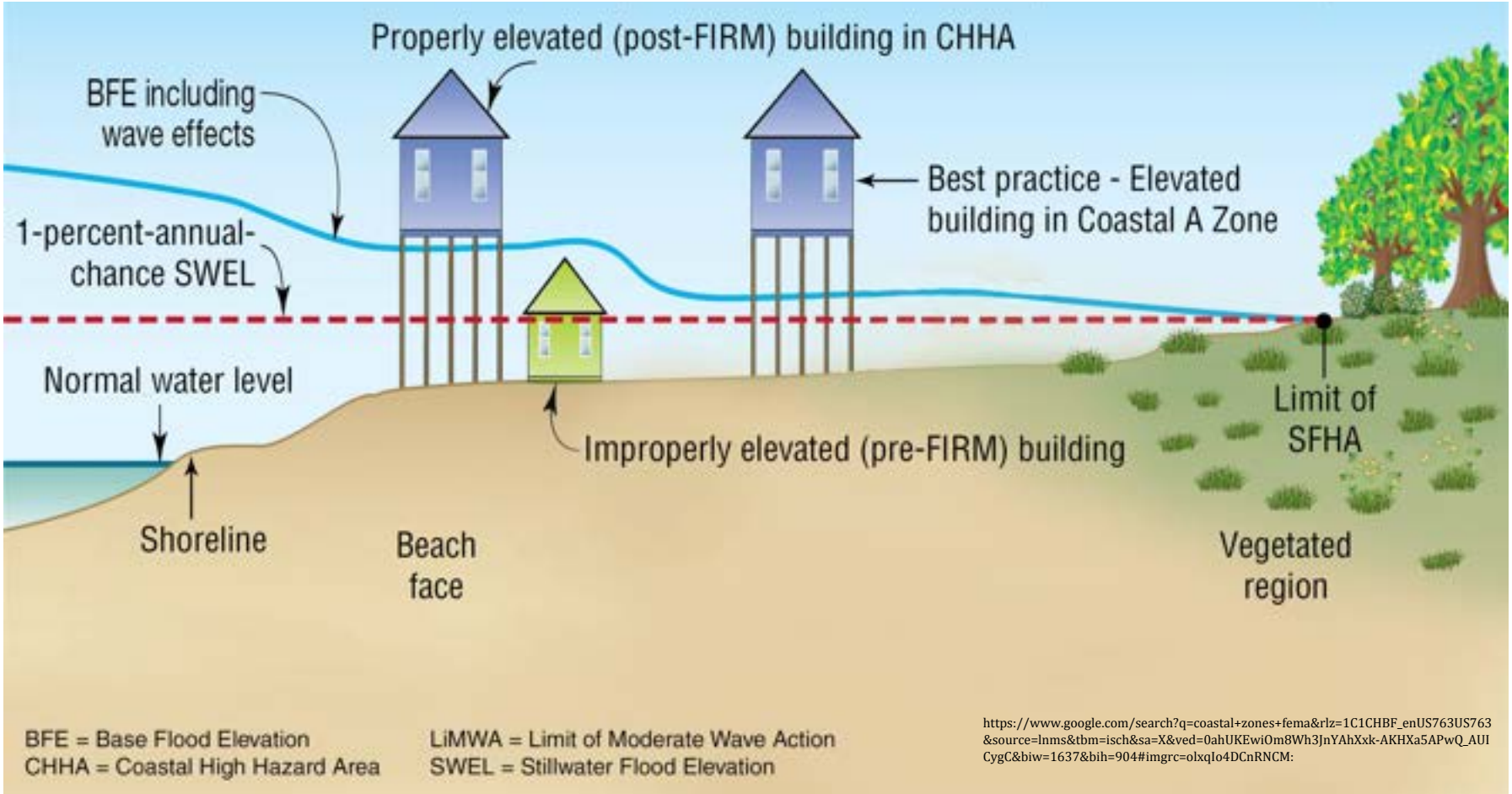
Wave Crest Damage Curves - Extra



Wave Crest Damage Curves - Extra

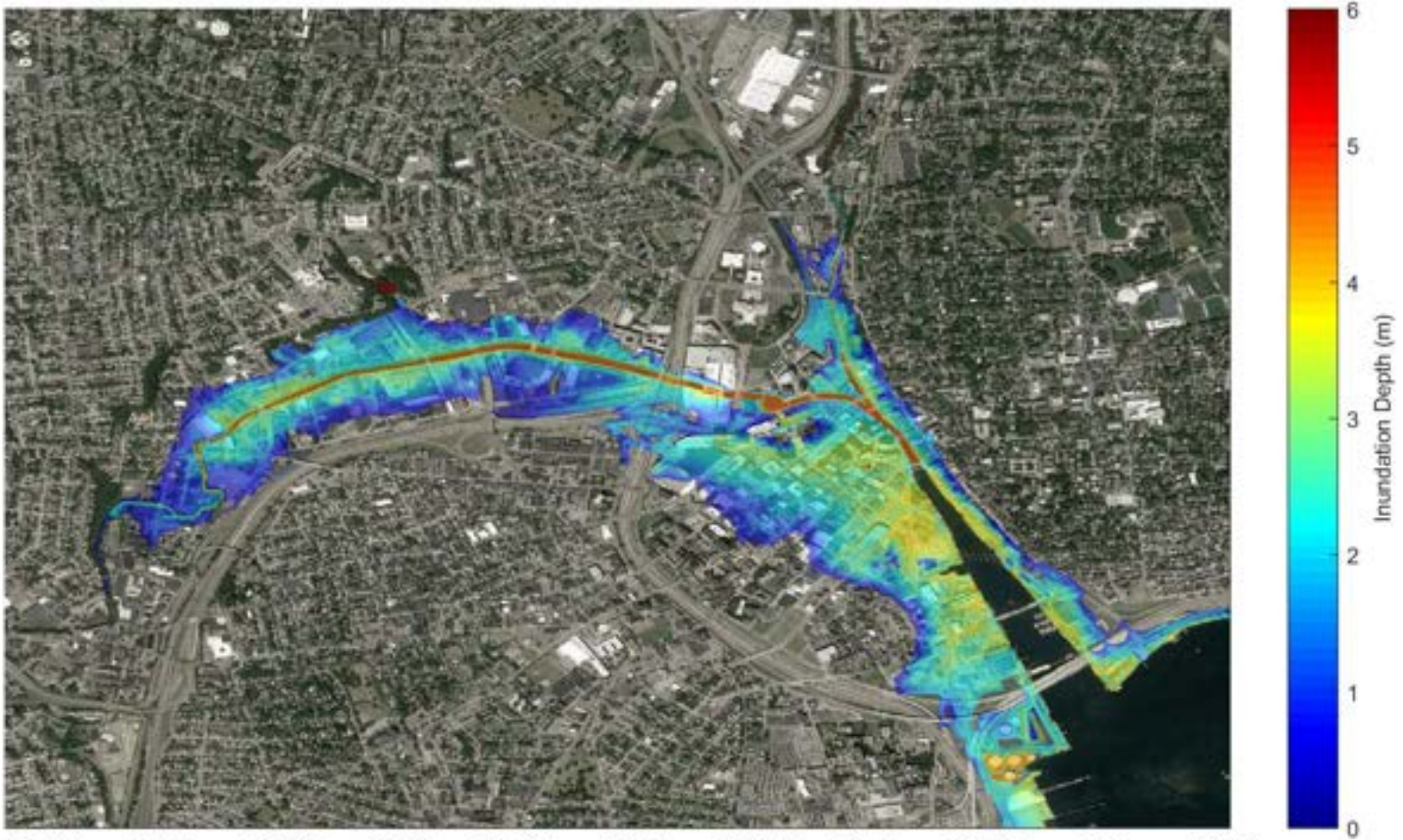


Base Flood Elevation

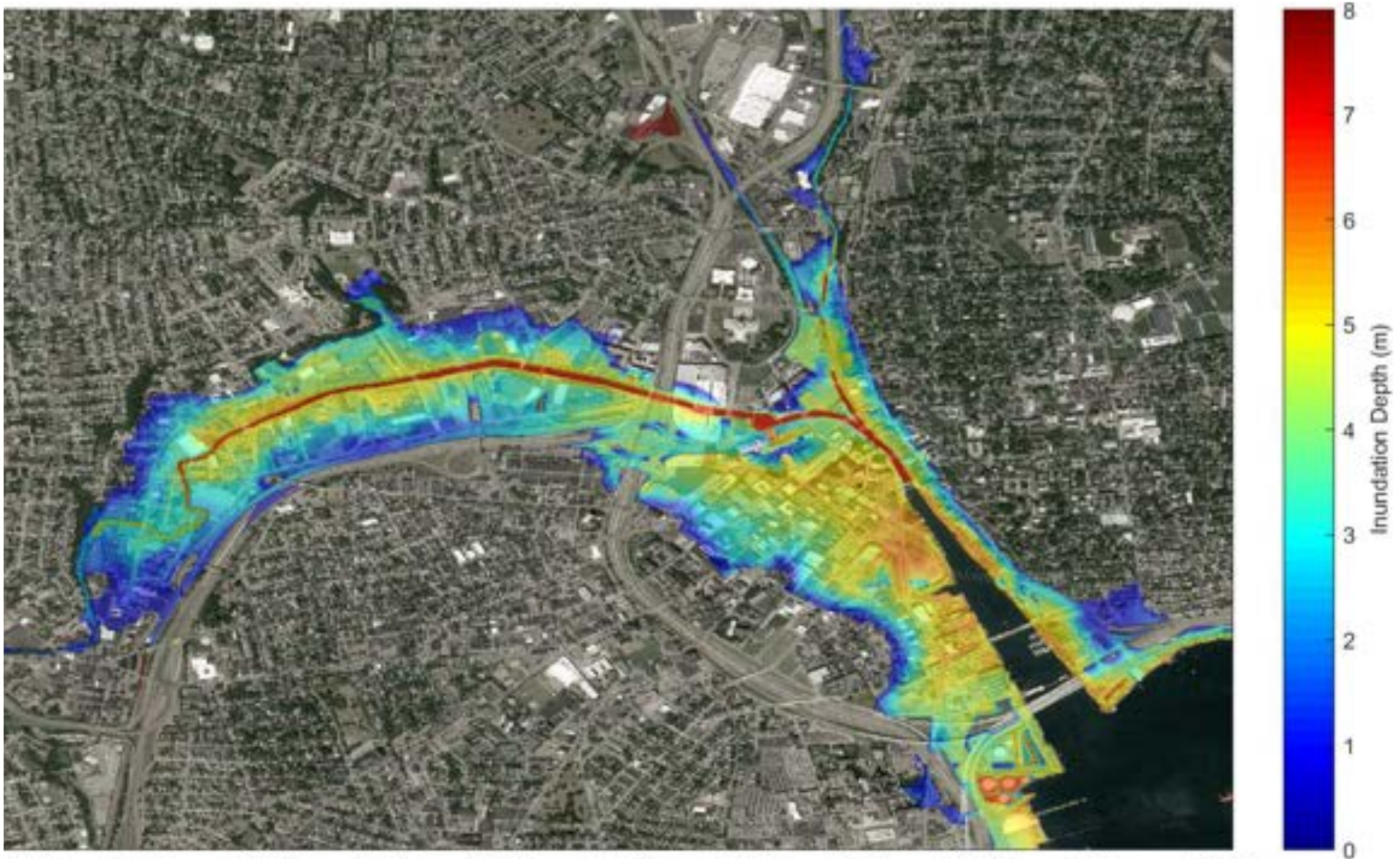


https://www.google.com/search?q=coastal+zones+fema&rlz=1C1CHBF_enUS763US763&source=lnms&tbm=isch&sa=X&ved=0ahUKEwiOm8Wh3JnYAhXxk-AKHXa5APwQ_AUICygC&biw=1637&bih=904#imgrc=olxqIo4DCnRNCM:

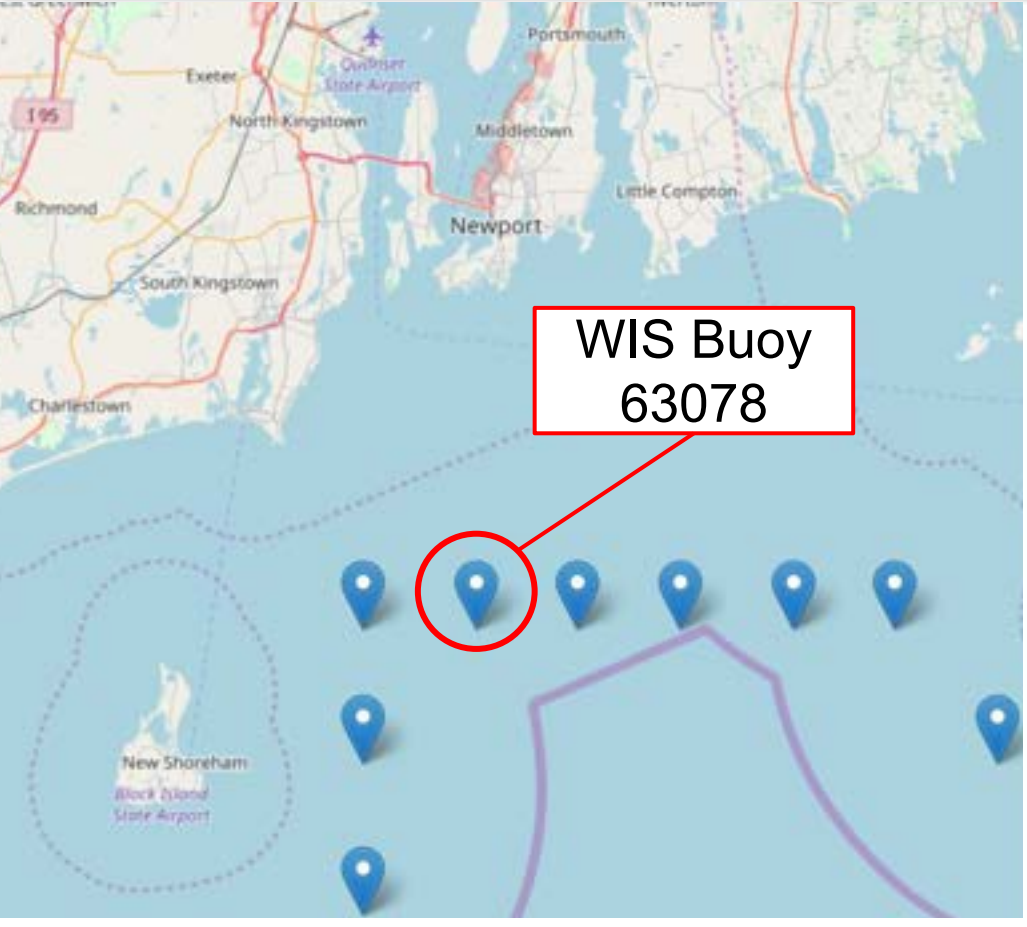
Inundation Depth (BFE) - 100 Year Storm without SLR



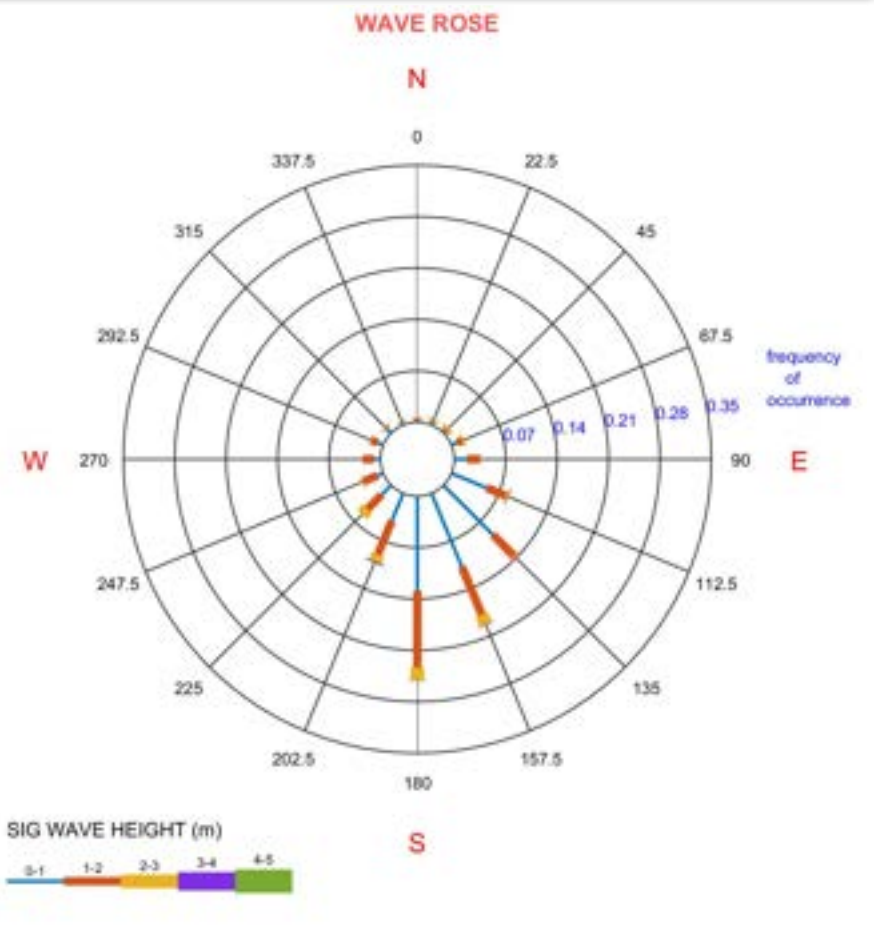
Inundation Depth (BFE) - 100 Year Storm with 7ft of SLR

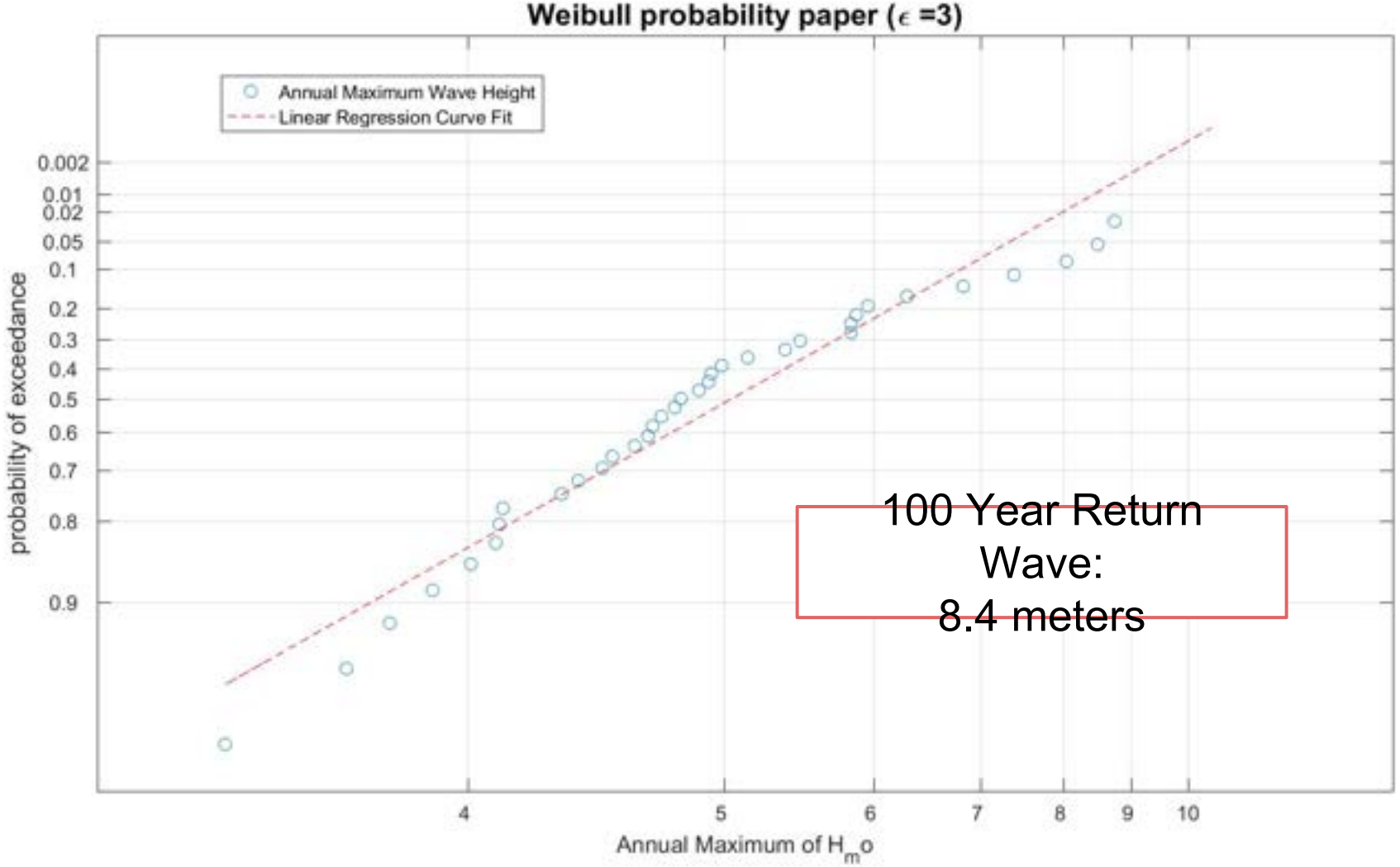


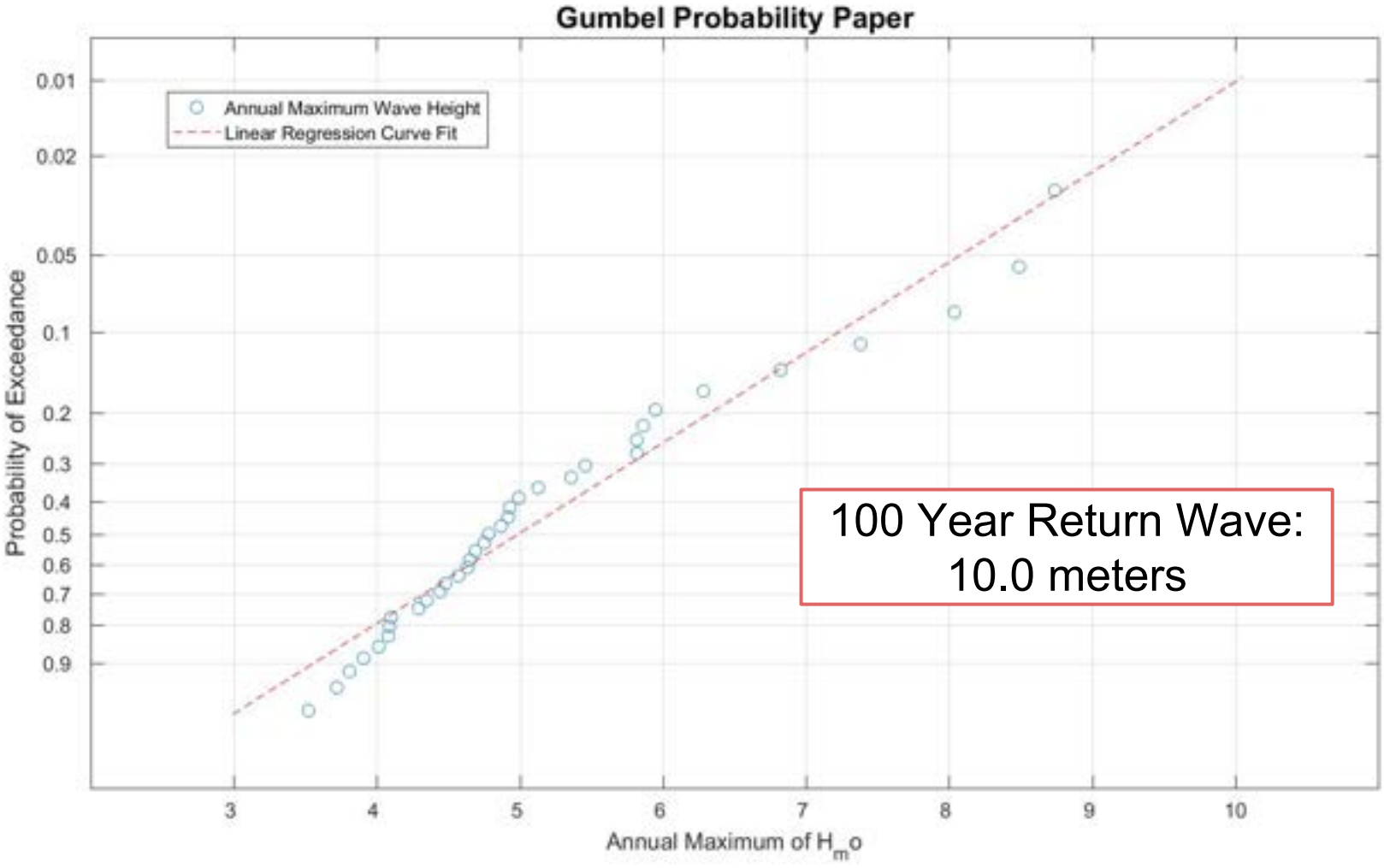
STWAVE - Validation of NACCS Wave Height Using WIS Data

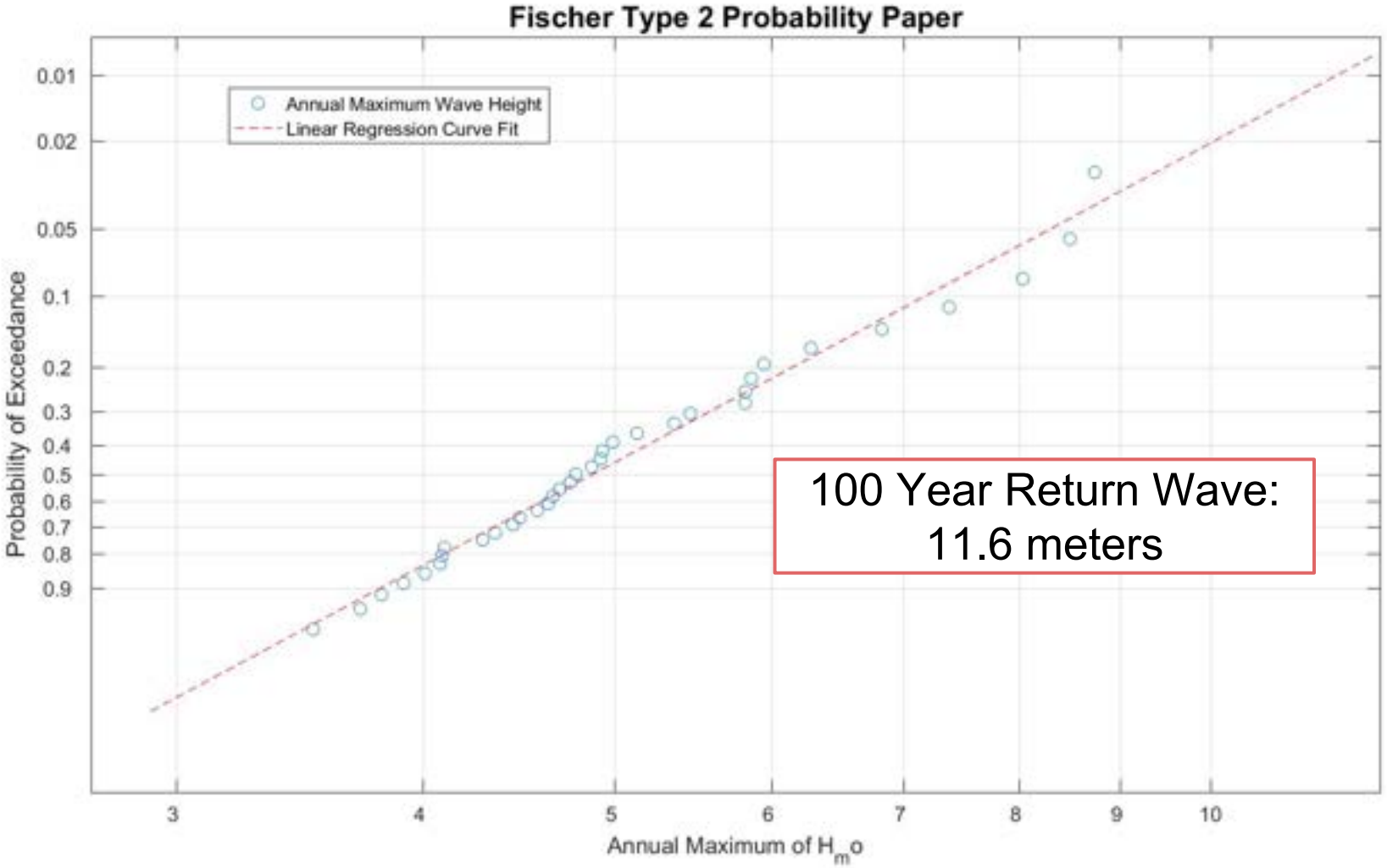


WIS Buoy 63078




Weibull probability paper (ϵ =3)
Annual Maximum Wave Height
Linear Regression Curve Fit
probability of exceedance
0.002
0.01
0.02
0.05
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
4
5
6
7
8
9
10
Annual Maximum of Hmo
100 Year Return Wave: 8.4 meters


Gumbel Probability Paper
Annual Maximum Wave Height
Linear Regression Curve Fit
Probability of Exceedance
0.01
0.02
0.05
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
3
4
5
6
7
8
9
10
Annual Maximum of $H_{m}o$
100 Year Return Wave:
10.0 meters


Fischer Type 2 Probability Paper
Annual Maximum Wave Height
Linear Regression Curve Fit
Probability of Exceedance
0.01
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0.05
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
3
4
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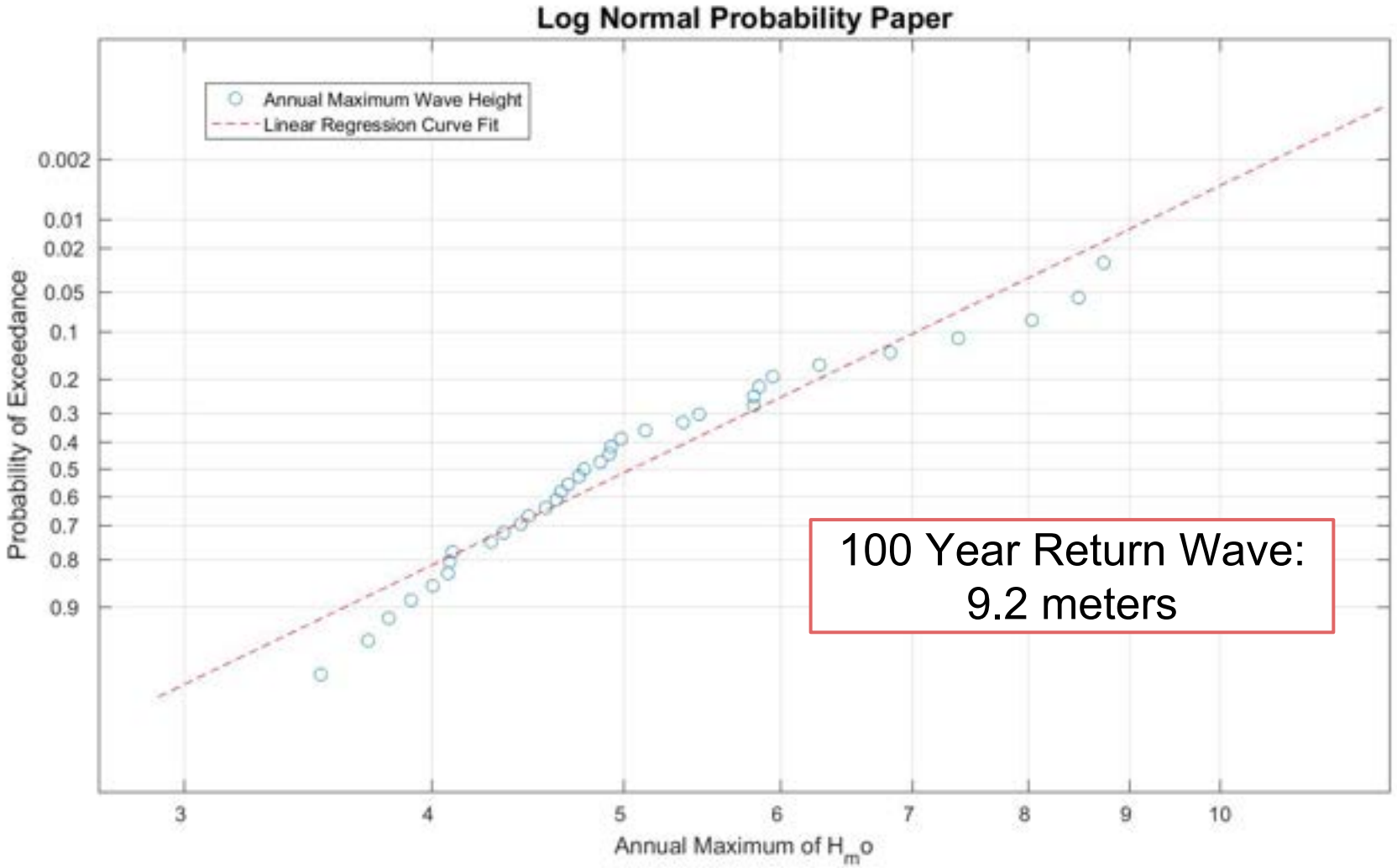
7
8
9
10
Annual Maximum of $H_m o$
100 Year Return Wave:
11.6 meters


Log Normal Probability Paper
Annual Maximum Wave Height
Linear Regression Curve Fit
Probability of Exceedance
0.002
0.01
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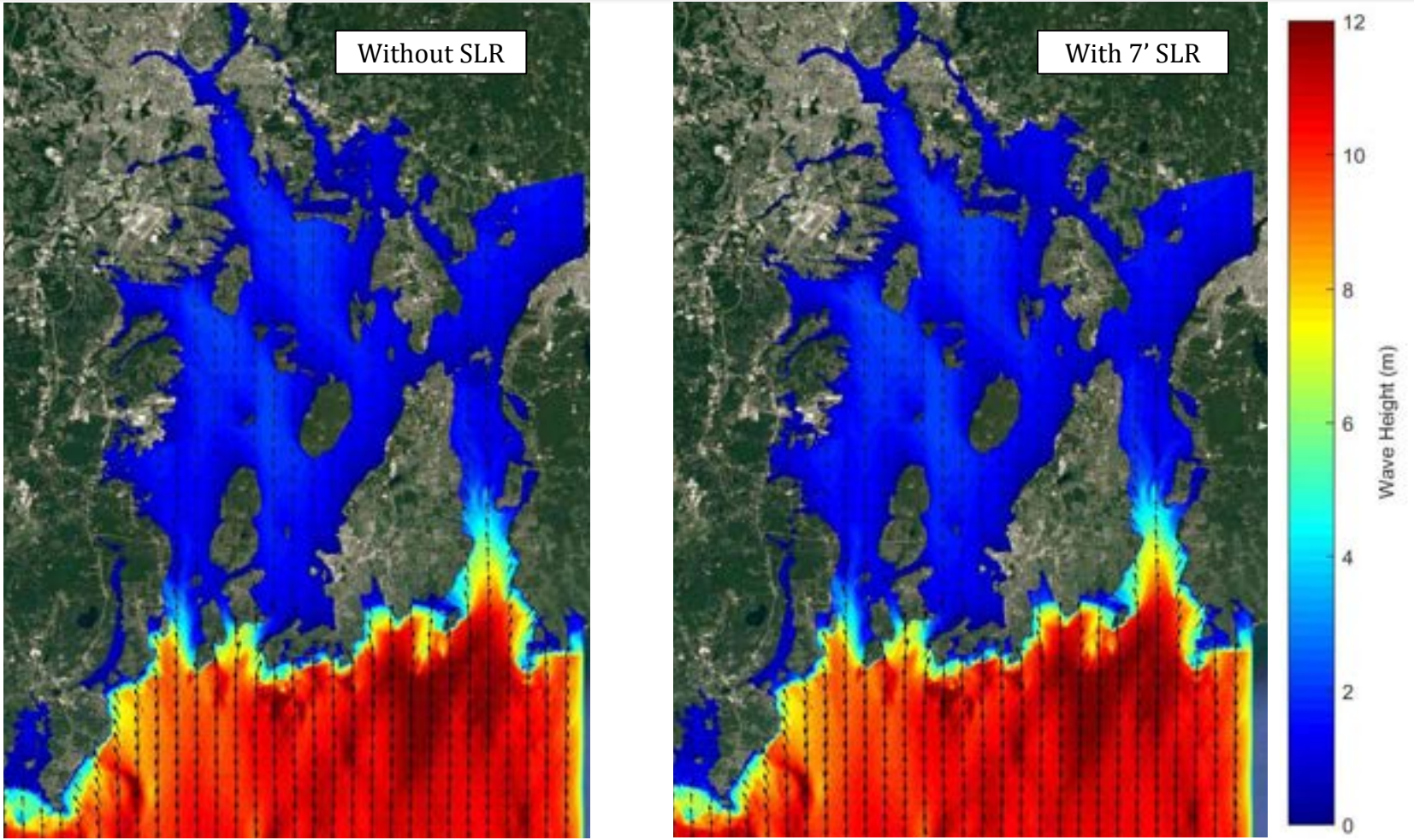
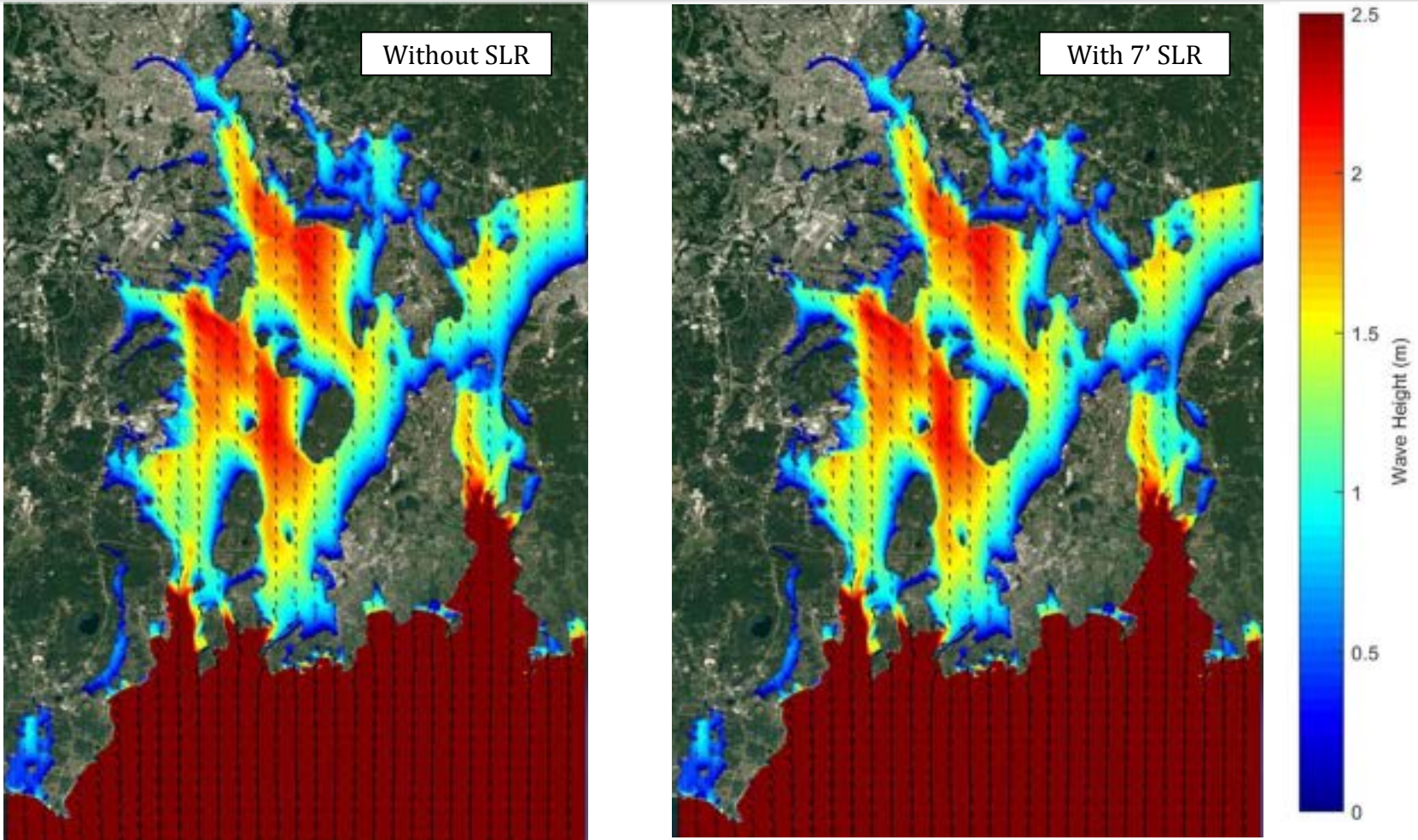
0.05
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
3
4
5
6
7
8
9
10
Annual Maximum of H_mo
100 Year Return Wave:
9.2 meters

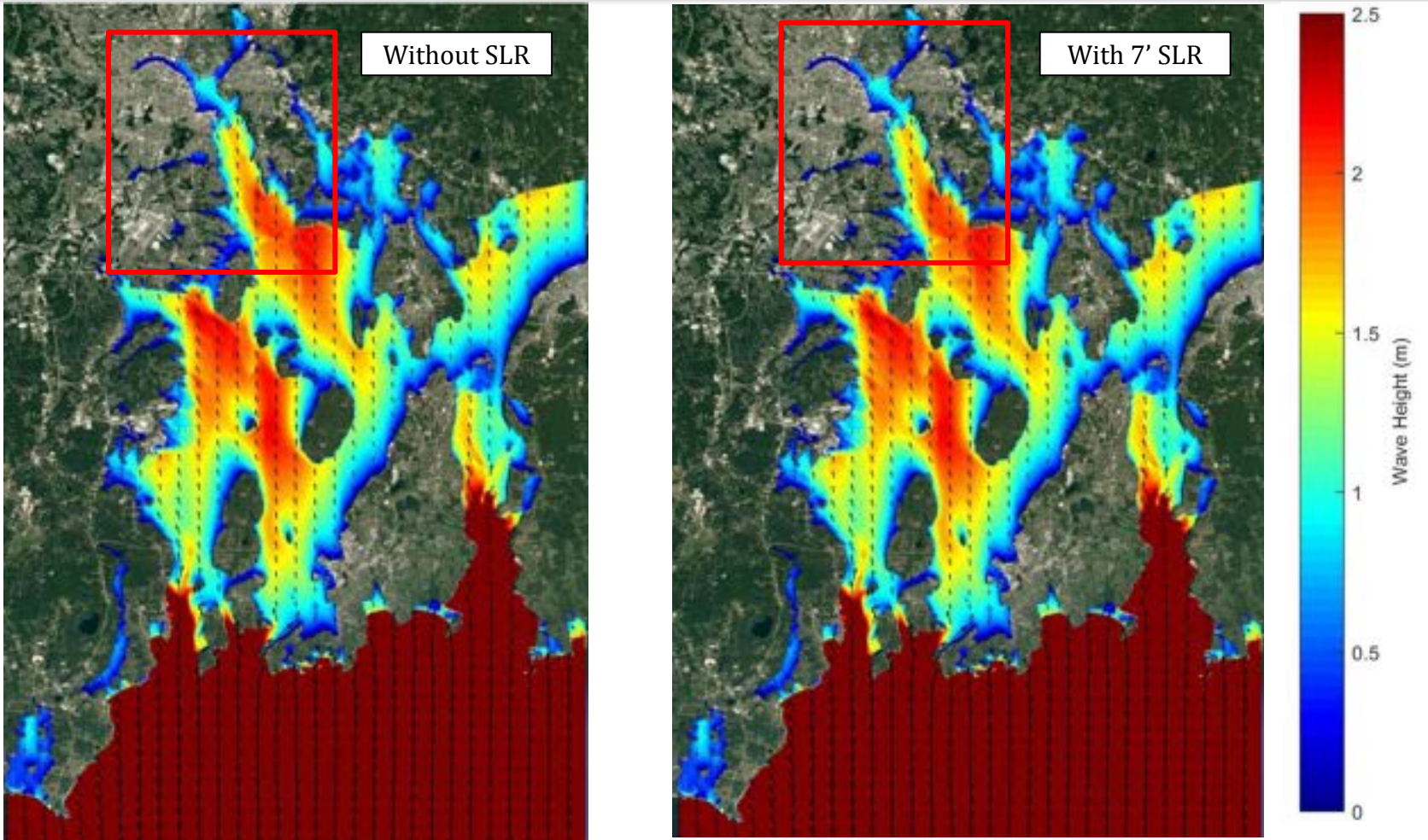
STWAVE Results - Narragansett Bay



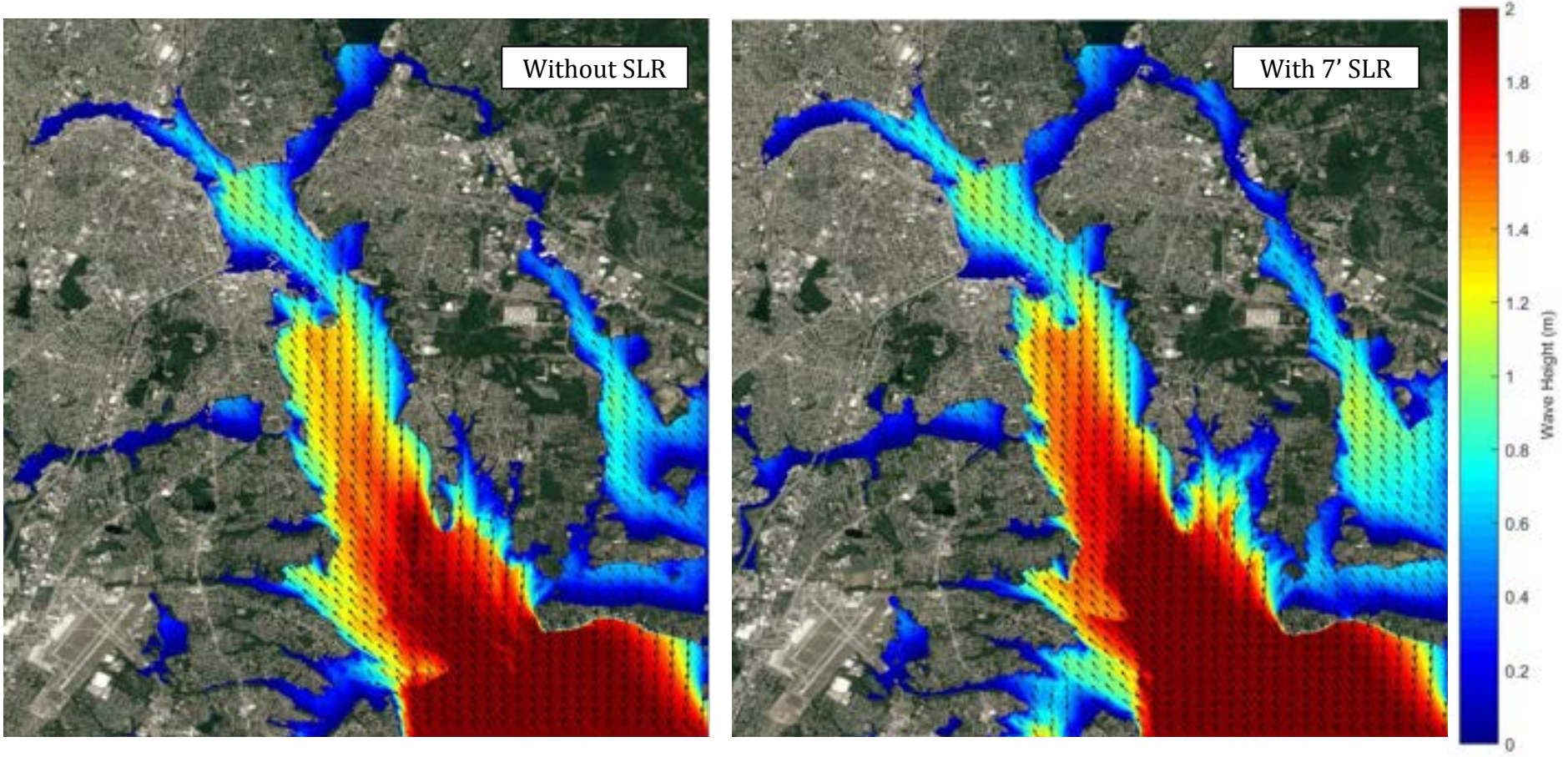
STWAVE Results - Narragansett Bay (Cont.)



STWAVE Results - Narragansett Bay (Cont.)

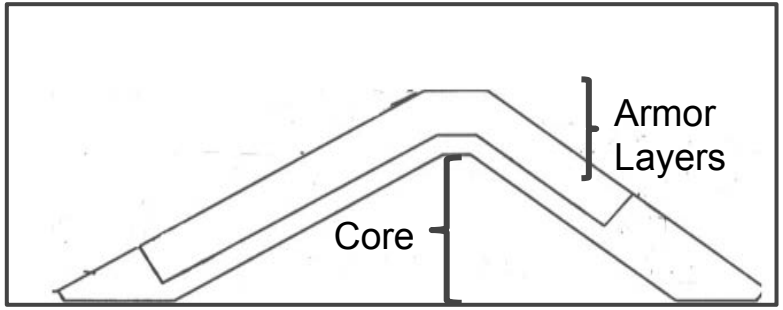


STWAVE Results - Providence River



Estimating Impermeable Core Height

- No cross-sectional depictions of Fox Point Hurricane Barrier available
- Using van der Meer equations (1988) for layer thickness of rubble mound structures, several estimates of core height



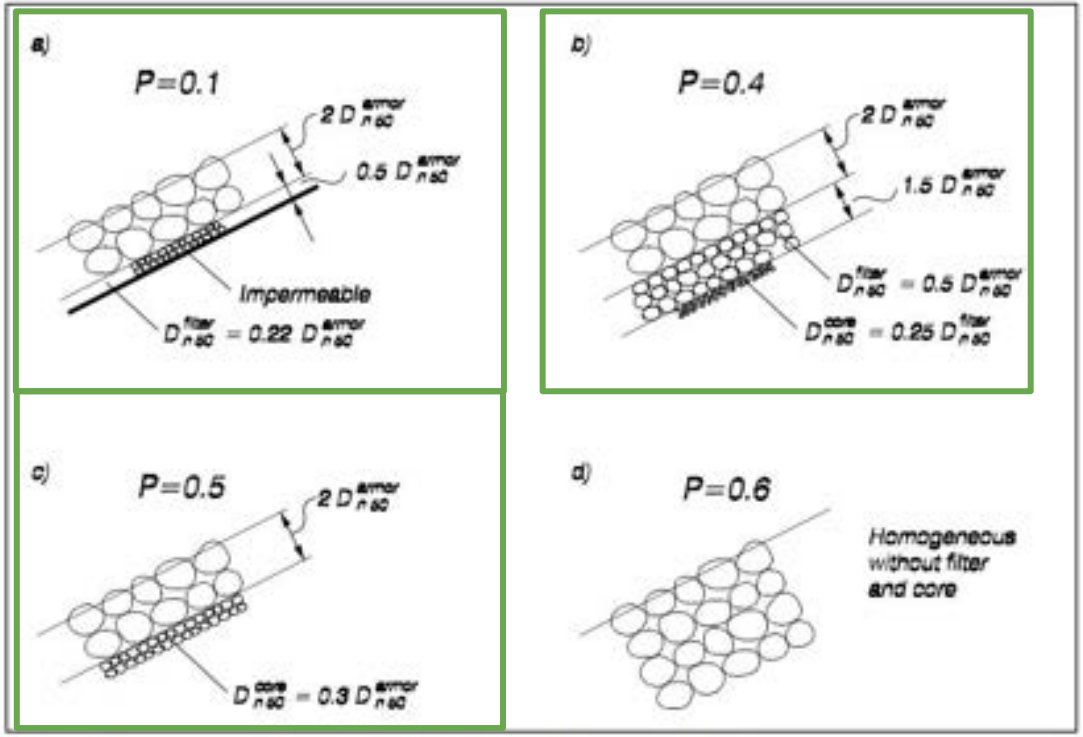
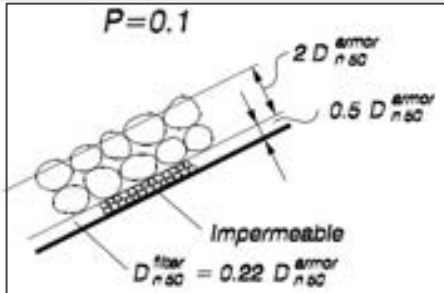


Figure VI-5-11. Notational permeability coefficients (van der Meer 1988)

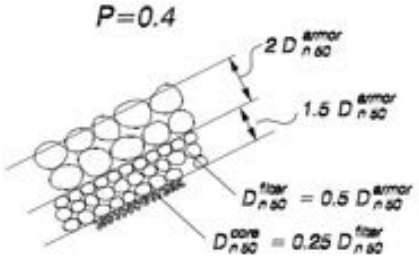
Estimating Impermeable Core Height

Assuming the average median equivalent cube length (D_{n50}) is one meter based on observation and the barrier remains at design height of 7.62 meters



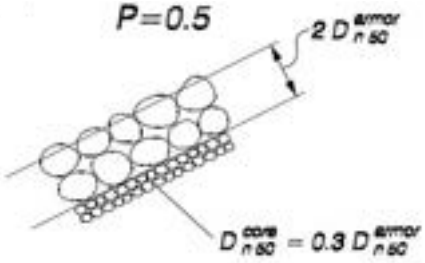
Outer Layer = 2 m
Middle Layer = 0.5 m

Core Height = 5.21 m (16.79 ft)



Outer Layer = 2 m
Middle Layer = 1.5 m

Core Height = 4.12 m (15.51 ft)



Outer Layer = 2 m

Core Height = 5.62 m (18.43 ft)

STWAVE Model Methodology and Assumptions

Methods

1) Steady-state, finite difference, spectral model based on the wave action balance equation
2) Accounts for depth-induced wave refraction and shoaling, current-induced refraction and shoaling, depth and steepness induced wave breaking, diffraction, wave growth because of wind input, and wave-wave interaction and white capping that redistribute and dissipate energy in a growing field (Reference A).

Assumptions

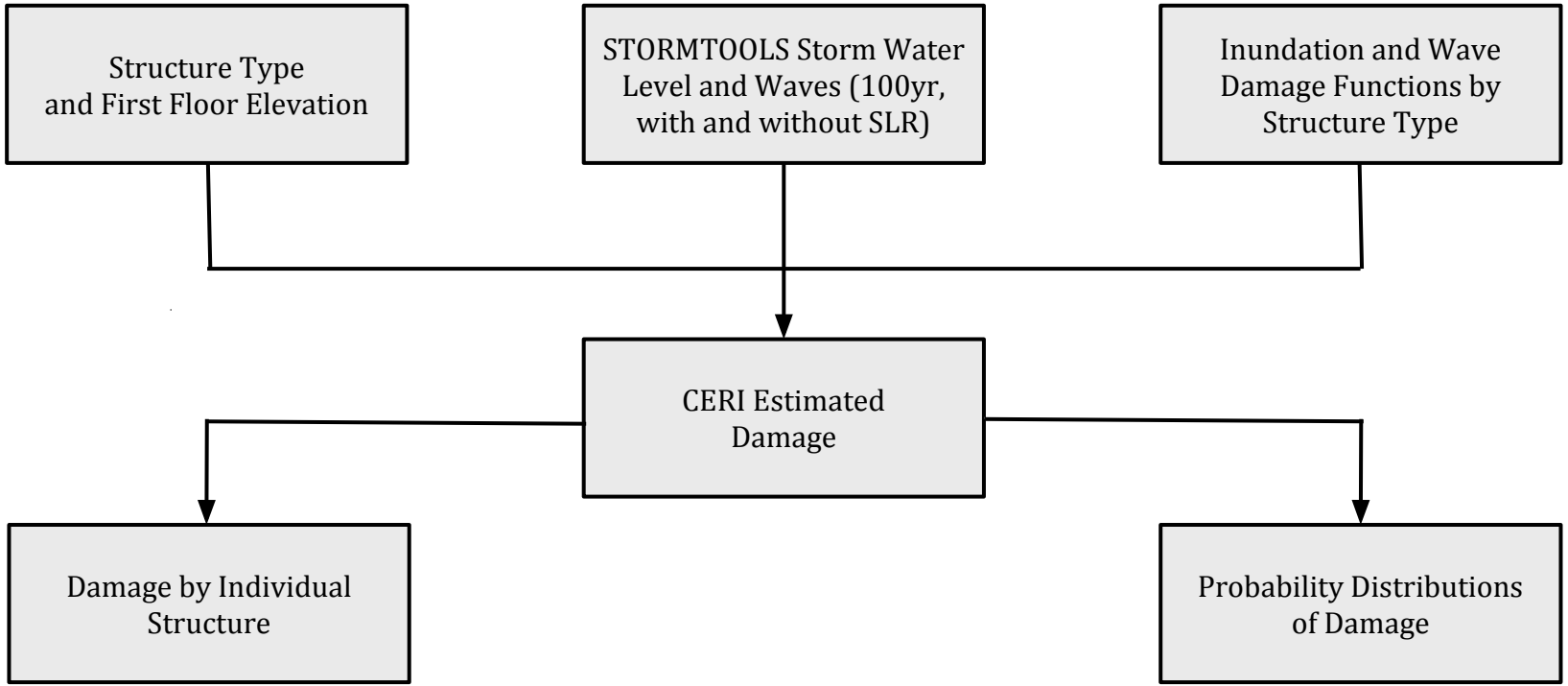
1) Phase Averaged – phases of the spectral components are random and phase information is not tracked. Therefore, an average phase is applied.
2) Mid bottom slope and negligible wave reflection – Waves reflected from the shoreline or from steep bottom features are neglected
3) Steady-state – The model is time independent
4) Linear refraction and shoaling – Does not represent wave asymmetry or other nonlinear wave features.
5) Depth-uniform current – Wave current interaction assumes a single current throughout the water column.
6) Linear radiation stress – Radiation stress is calculated based on linear wave theory.

STWAVE - Wind Sensitivity Results

Wind Direction (degrees)	Hs at mouth of Providence River (meters)	Hs at Fox Point Barrier (meters)
165	1.76	0.37
160	1.85	0.78
155	1.90	0.84
150	1.88	0.89
145	1.85	0.90
140	1.74	0.86
135	1.63	0.80

STORMTOOLS

- GIS application providing water levels due to storm surge of Rhode Island waters
- Uses water level data to generate a map representing inundation
  - Newport, RI data buoy is the reference used
  - Utilizes NOAA sea level rise protocol
- Used for all inundation levels in this study


Structure Type and First Floor Elevation
STORMTOOLS Storm Water Level and Waves (100yr, with and without SLR)
Inundation and Wave Damage Functions by Structure Type
CERI Estimated Damage
Damage by Individual Structure
Probability Distributions of Damage

Tainter gates

Radial arm floodgate used to control. water flow through hydraulic. Structures.

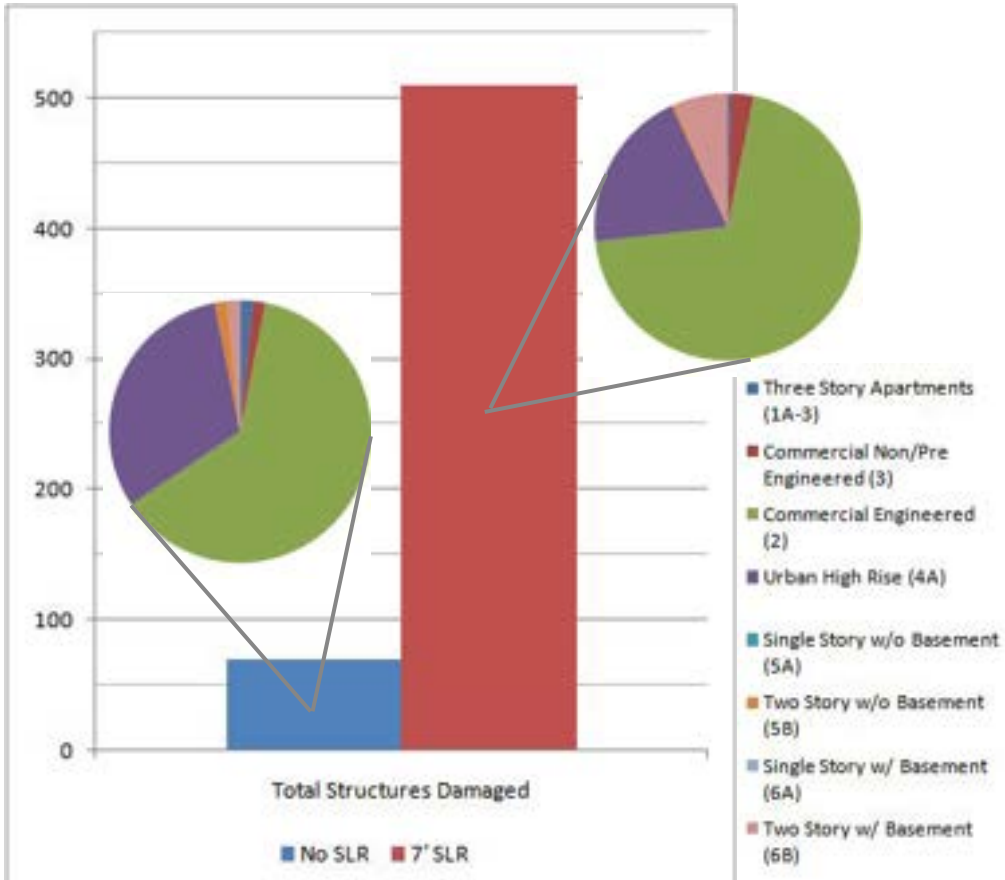
The structure
contains three tainter gates that permit passage of small
vessels but can be closed to prevent entry of a surge from
Narragansett Bay to the south. Each gate is 12 m high by 12 m
wide

Total Damage Calculations

Flooding Damage= Max(Inundation Damage, Wave Damage)

Number of houses that have 10’ or more of Inundation

Prototype	No SLR	7’ SLR
1A-3	1	2
2	40	357
3	1	14
4A	20	101
5A	0	0
5B	1	2
6A	0	0
6B	1	33
Total	**69**	**509**



Total Damage: With and Without SLR

Damage percentages to structures	Number of structures (No SLR)	Percent of structures	Number of structures (7ft SLR)	Percent of Structures	Difference
0	428	40.30	84	8	-344
0 to 25	273	25.70	240	22.60	-33
25 to 50	189	17.79	256	24.11	67
50 to 75	202	19.02	311	29.28	109
> 75	0	0	201	18.93	201