

# consulting engineers and scientists

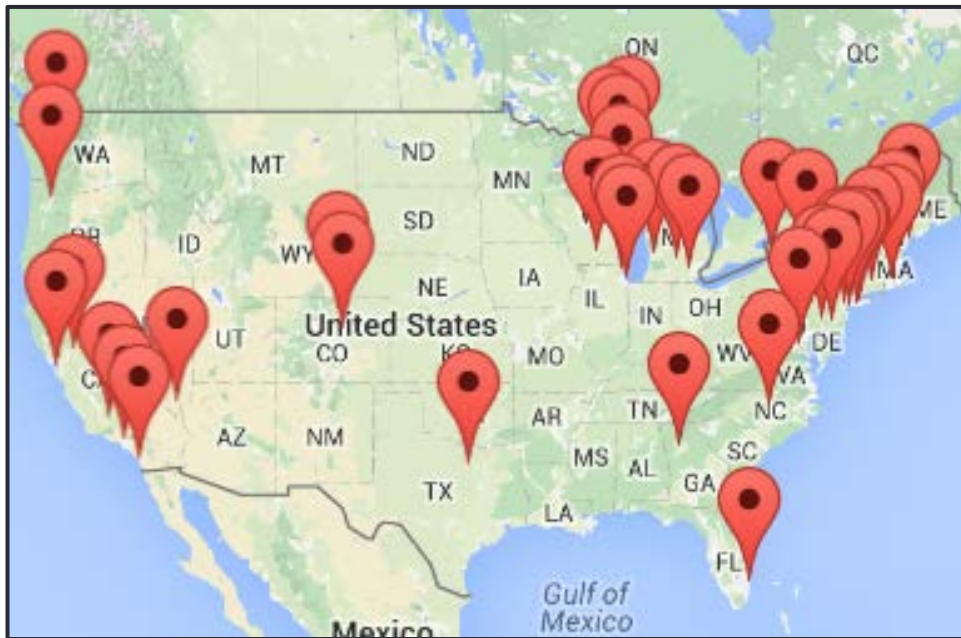


## Extreme Weather Events and Transportation Infrastructure:

### A Framework for Benefit-Cost Analysis

Samuel B. Merrill, Ph.D.  
Climate Prediction Applications  
Science Workshop, Burlington, VT  
March 24 2016

# GEI Basics



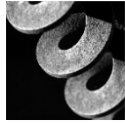
- Founded in 1970
- 750+ Employees
- 37 Offices
- 35,000+ Projects in all 50 states and 25 countries

# Technical Practice Areas



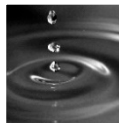
## Environmental

- Compliance
- Permitting
- Due Diligence
- Characterization
- Remediation
- Risk Assessment
- Restoration
- Asbestos
- Demolition
- Brownfields
- In-Water & Uplands



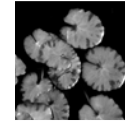
## Geotechnical

- Coastal Engineering & Planning
- Foundations
- Excavation Support
- Construction
- Tunneling
- Dams
- Embankments
- Levees
- Failure Analysis
- Geotechnical Testing



## Water Resources

- Conveyance
- Flood Control
- Water Management
- Water Supply and Storage
- Water Resources Support
- Hydropower



## Ecological

- Ecotoxicology
- Monitoring
- Water Quality
- Aquatic Ecosystems
- Environmental Impact
- Laboratory Services
- Sensory Services
- Air Quality



# US Capitol Visitor Center, Washington DC



# Goldman Sachs Building, NY

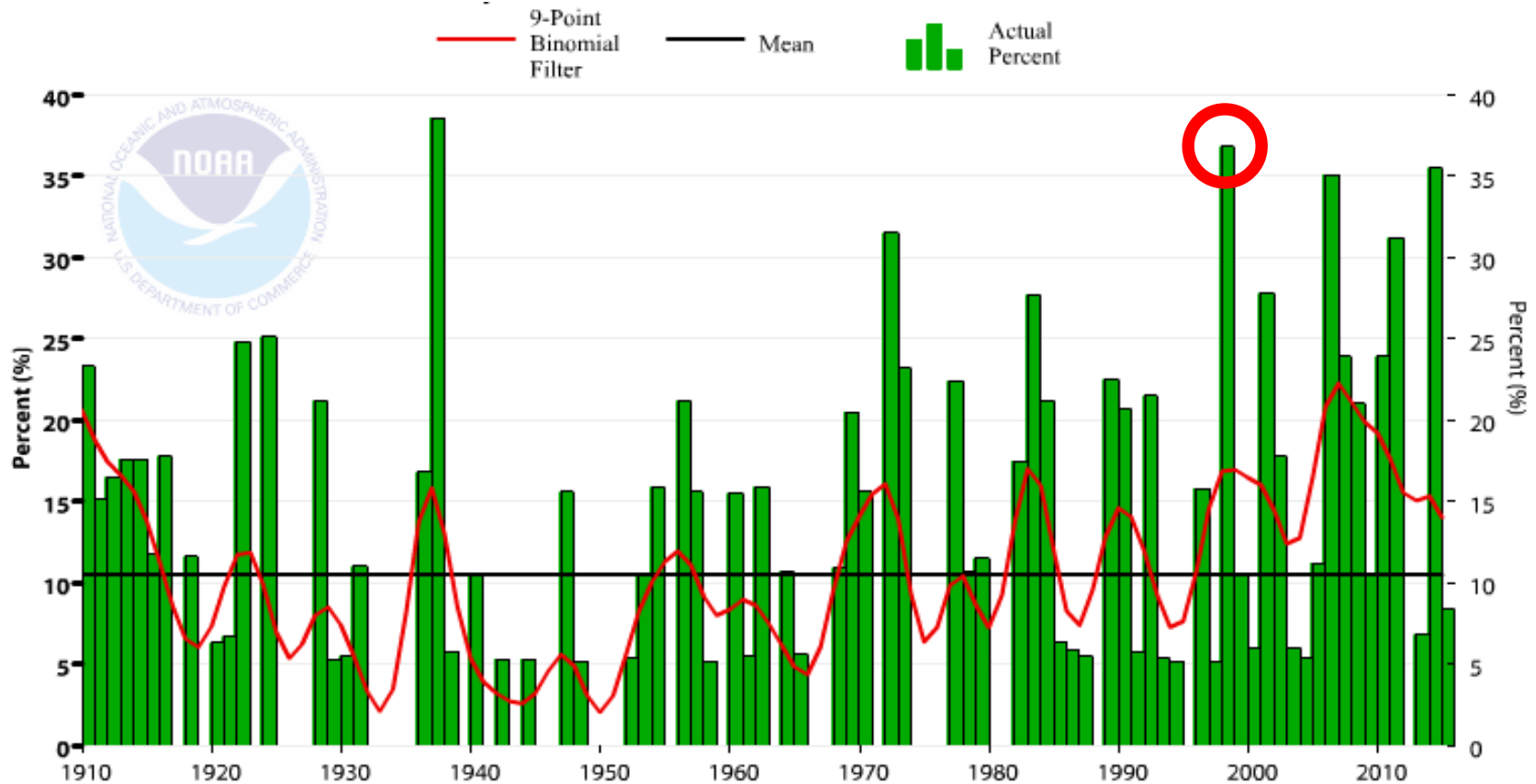




# Brickell City Centre, Miami



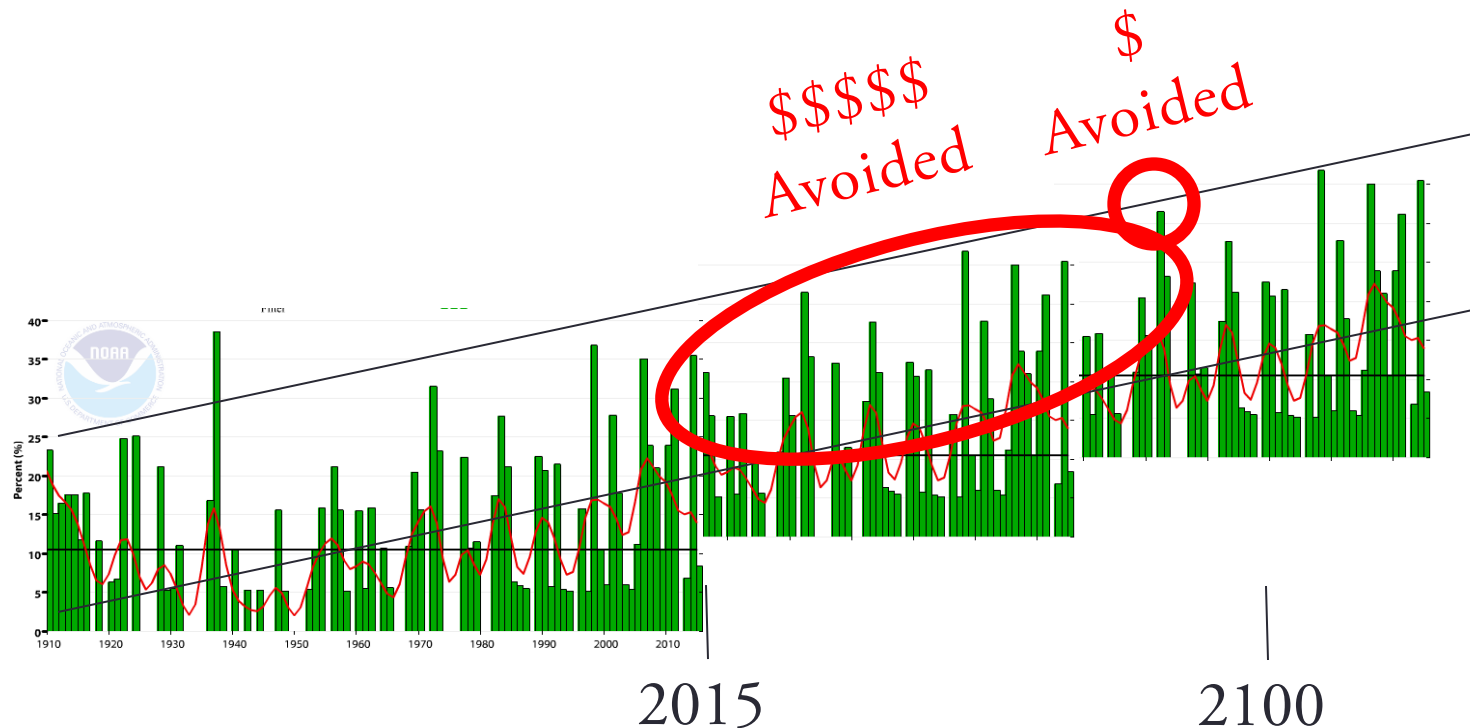
# What storm do we currently consider in our design standards?



<http://www.ncdc.noaa.gov/extremes/cei/graph/ne/4/01-12>

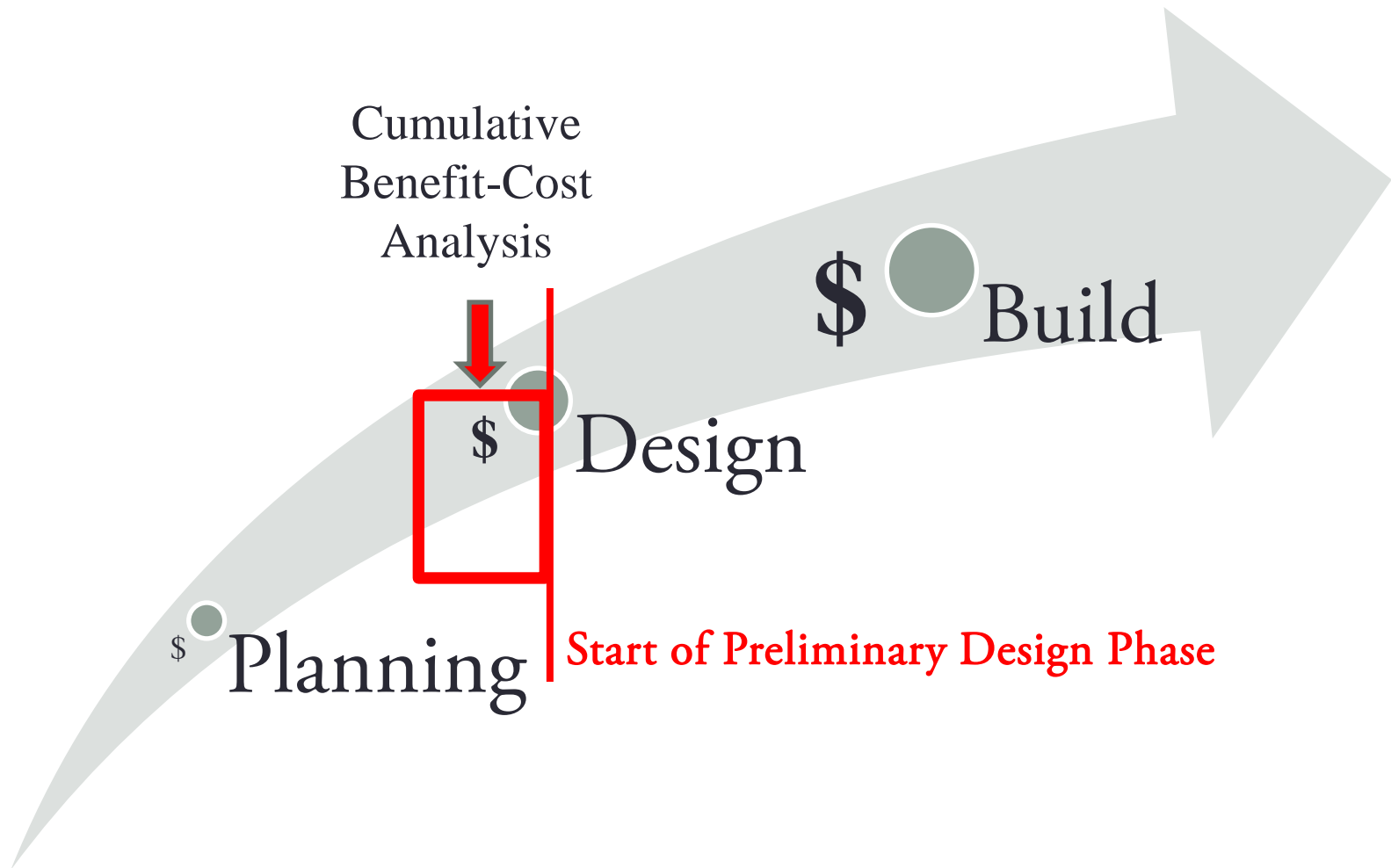
# So what do we design for?

A key measure of the value of any adaptation design investment is **cumulative avoided damage**

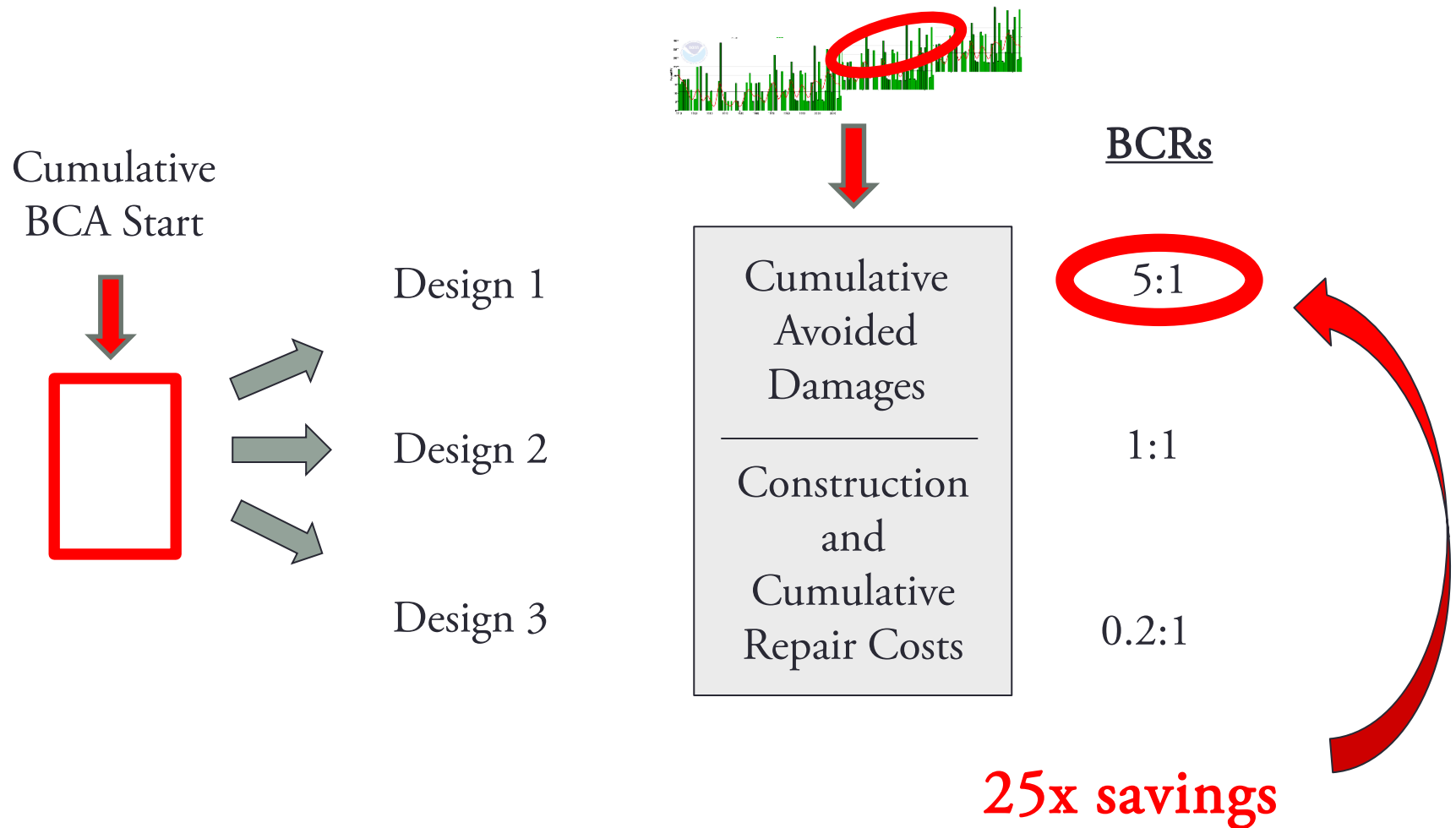




# Engineering Project Timeline



# Cumulative BCA Summary





# Lifecycle/Cumulative BCA Framework Concepts

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Methods to calculate cumulative avoided damages should:

- Track impact of events over an entire time period, not just as snapshots.

The Old Port, 10/11 at high tide (M. Craig)



Methods to calculate cumulative avoided damages should:

- Track impact of events over an entire time period, not just as snapshots.
- Account for impacts of events with different intensities, frequencies, and rates of change.
  - *and their interactions.*

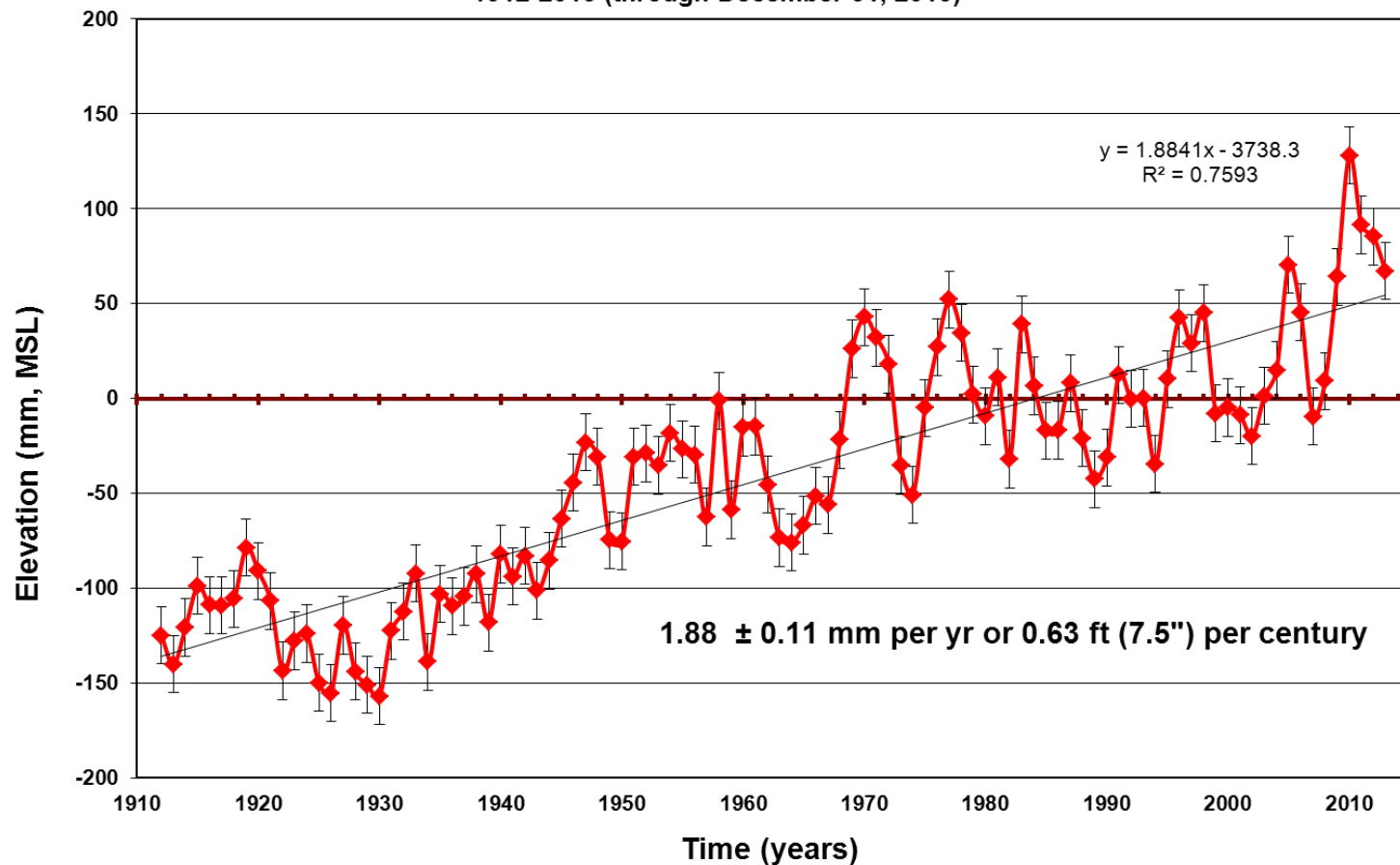
# Rates of Sea Level Rise are Increasing



# Rates of Sea Level Rise are Increasing

*Over the past 100 years, sea level rise in Portland has generally followed globally averaged long-term trends*

**Sea Level, Portland, Maine**  
1912-2013 (through December 31, 2013)



Data courtesy of NOAA CO-OPS, [www.tidesandcurrents.noaa.gov](http://www.tidesandcurrents.noaa.gov)

P.A. Slovinsky, Maine Geological Survey, January 21, 2014

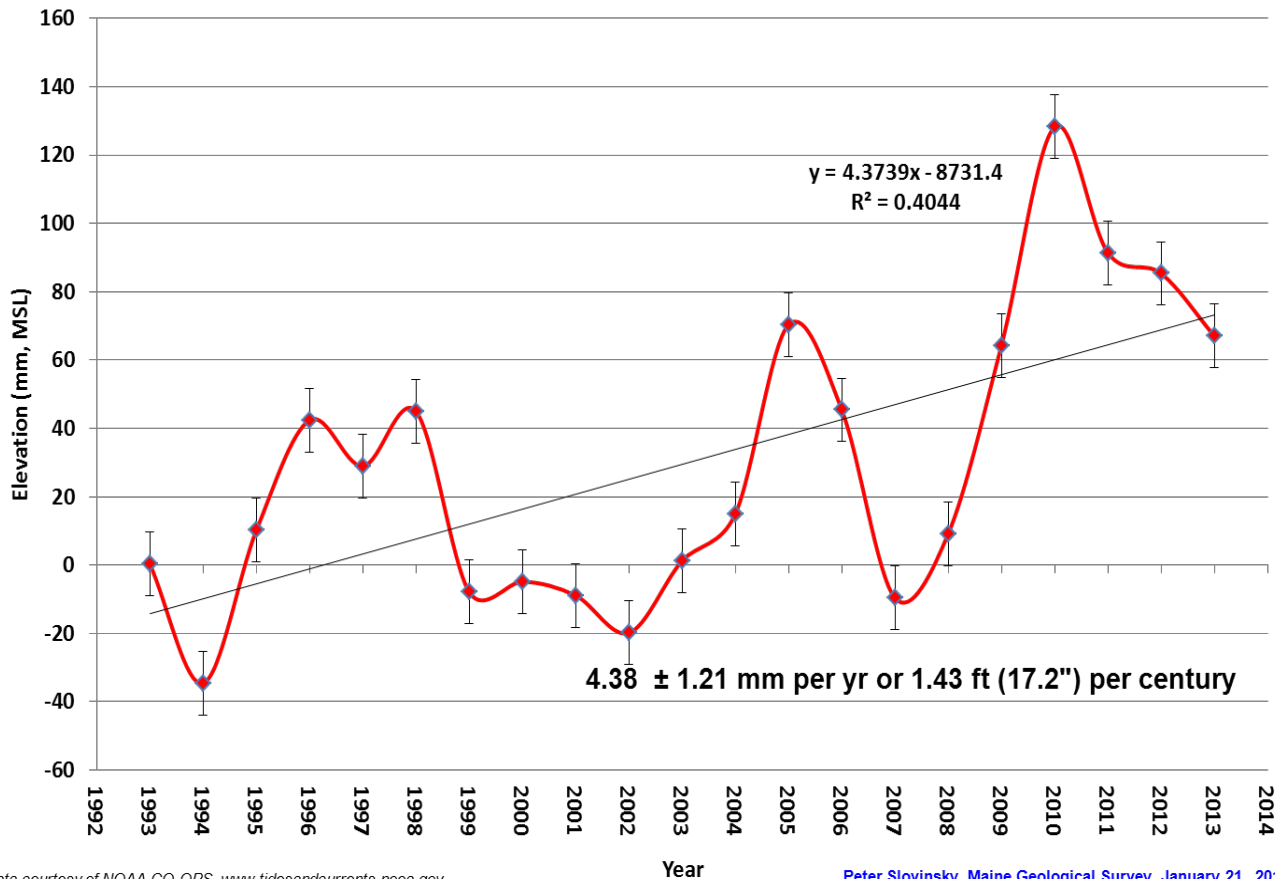




# Rates of Sea Level Rise are Increasing

*Over the past 20 years, sea levels in Portland have risen far faster than the long-term trend. This change in rate is also being seen in global measurements.*

**Sea Level, Portland, Maine**  
1993-2013 (through December 2013)



Data courtesy of NOAA CO-OPS, [www.tidesandcurrents.noaa.gov](http://www.tidesandcurrents.noaa.gov)

Peter Slovinsky, Maine Geological Survey, January 21, 2014



# Surge Events are Increasing



The Old Port, 3/10 at high tide (D. Yakovleff)

# Surge Events are Increasing



The Old Port, 10/11 at high tide (M. Craig)



# Surge Events are Increasing



East Bayside at High Tide 9/15 (Portland Press Herald 10/2/15)

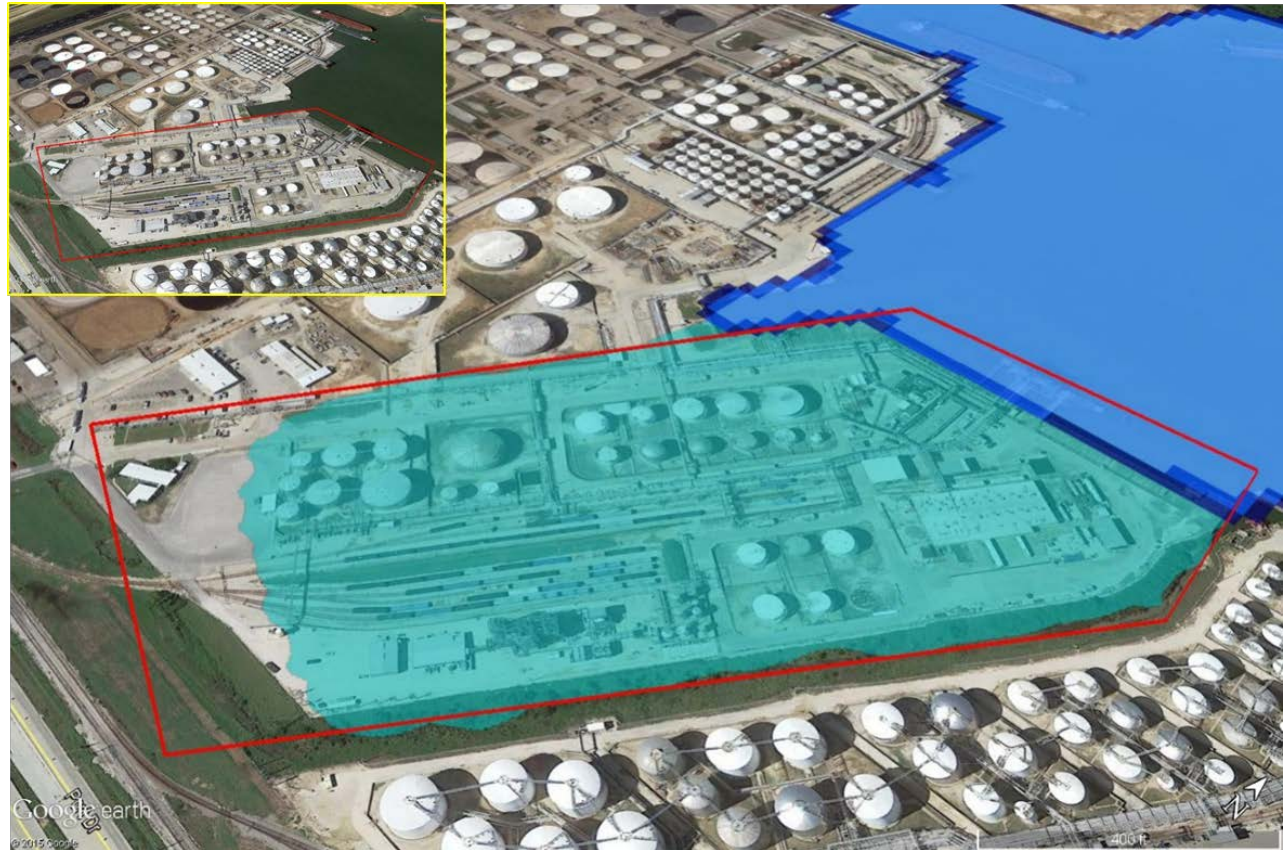
# Flood Frequency is Influenced by Sea Level

Scenario	Flood Stage (ft, MLLW)	# times inundated	% of high tides	Duration, hrs
Existing Flood	12.0	8	1.1%	8.6
+1 ft SLR	11.0	87	12.4%	121.8
+2 ft SLR	10.0	312	44.4%	575.3
+3.3 ft SLR	8.7	616	87.6%	1748.5
+6 ft SLR	6.0	702	99.9%	3816.3
<i>based on 2013 Portland tidal station data from the NOAA Inundation Analysis Tool</i>				

# Oil Refineries Will Face Increasing Vulnerability from Sea Level Rise and Storm Surge

## LEGEND

- 0 ft sea level rise
- 3 ft sea level rise
- 6 ft sea level rise
- 100-yr flood (no sea level rise)





# COAST Software (Initially US EPA)

The screenshot displays the COAST V.1.0 software interface. The main window shows a map of a coastal area with a blue body of water and surrounding land. A scale bar indicates distances from 0 to 2.0 km. Several configuration dialog boxes are open:

- Estimate Cumulative Storm Damage:** This dialog box is open on the left. It shows the 'Model Parameters' section with 'Name: portland', 'Elevation Data: BackCove\_base.tif', 'Asset Data: Portland Lots', 'Exceedance Curve: Portland Exceedance Curve', 'Eustatic SLR: VBR 2009 High', 'Base Water Level: MHHW Portland, ME', 'Local SLR: (None)', 'Adaptation: (None)', 'Discount Rate (Pct.): 0', and 'Time Period: Start Year: 2013, End Year: 2013'. The 'Output' section shows 'Damage Report File: C:\Users\PatrickCunningham\Documents\Demodata\Glob...'. Buttons for 'OK' and 'Cancel' are at the bottom.
- Estimate One-time Storm Damage:** This dialog box is open on the right. It shows the 'Model Parameters' section with 'Name: TestScenario', 'Elevation Data: BackCove\_base.tif', 'Asset Data: Portland Lots', 'Exceedance Curve: Portland Exceedance Curve', 'Eustatic SLR: VBR 2009 Low', 'Base Water Level: MHHW Portland, ME', 'Local SLR: Portland Local SLR', 'Adaptation: (None)', 'Discount Rate (Pct.): 15', and 'Time Period: Year: 2100, Recurrence Interval: 100 Y'. The 'Output' section shows 'File Name: C:\Users\PatrickCunningham\Documents\Demodata\Glob...'. Buttons for 'OK' and 'Cancel' are at the bottom.
- COAST Model Parameters:** This dialog box is open at the bottom right. It shows the 'Local Sea-Level Rise' section with 'Exceedance Curve: Portland Exceedance Curve'. The 'Definition' section shows 'Unit: FEET'. A table lists recurrence intervals, probabilities, and surge heights:

Recurrence Interval	Probability	Surge Height
500 Y	0.002	9.2
100 Y	0.01	6.5
50 Y	0.02	5.6
20 Y	0.05	4.6
10 Y	0.1	3.9


Buttons for 'Add...', 'Update...', 'Remove', 'New Curve', and 'Delete Curve' are at the bottom. 'OK', 'Cancel', and 'Apply' buttons are at the very bottom.



# BCA for Infrastructure Upgrades



Muskie School of Public Service  
University of Southern Maine



Based on numerous peer-reviewed method papers

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Climatic Change  
DOI 10.1007/s10584-011-0379-z

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## **Simplified method for scenario-based risk assessment adaptation planning in the coastal zone**

**Paul Kirshen • Samuel Merrill • Peter Slovinsky •  
Norman Richardson**

Received: 16 November 2009 / Accepted: 14 November 2011  
© Springer Science+Business Media B.V. 2011



# COAST is a means of

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- Evaluating *cumulative* vulnerability to storm surge and/or sea level rise.
  - Tailored to specific engineered structures.
- Comparing costs and benefits of candidate adaptation actions or alternative designs.

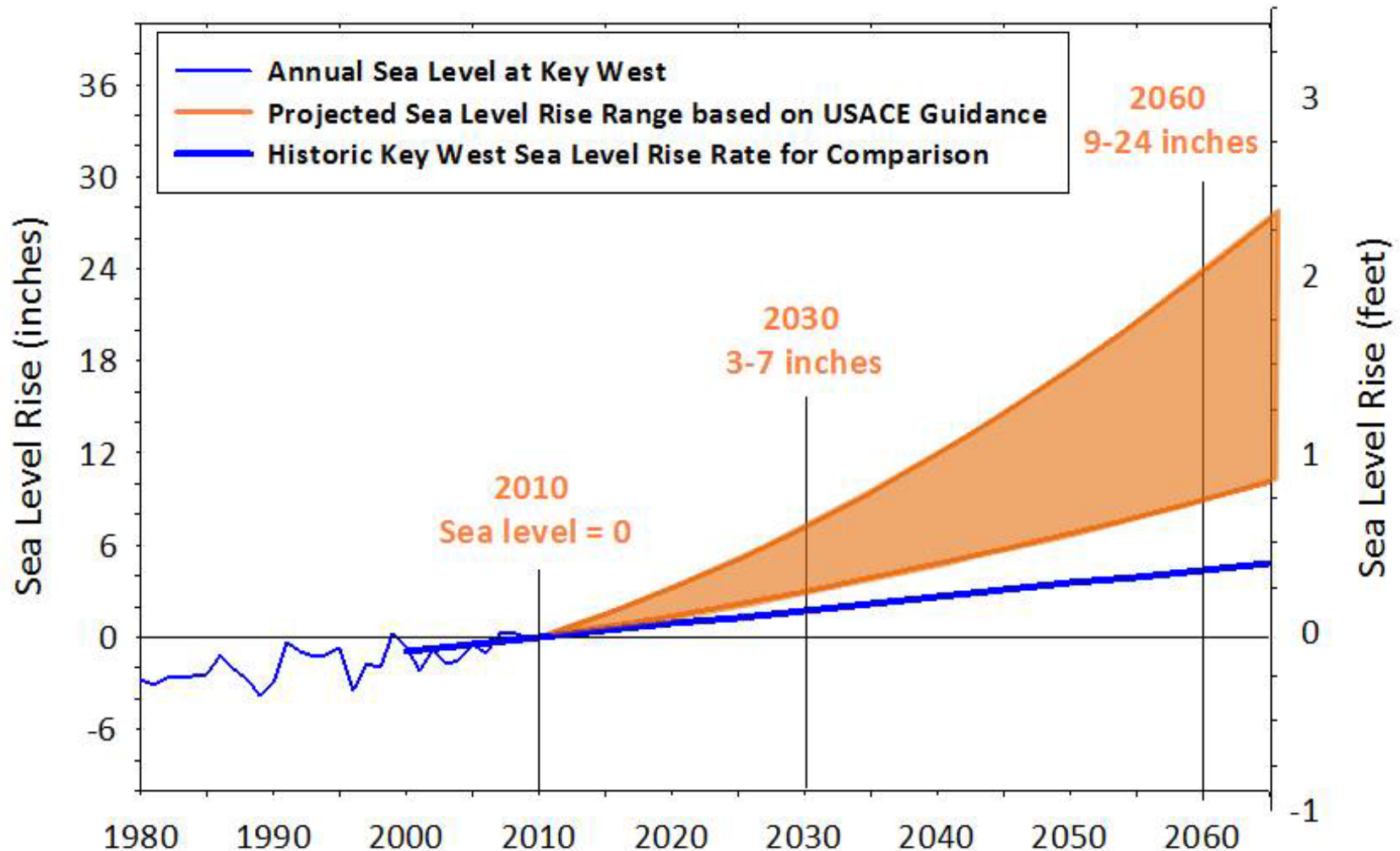
## Some Project Sites Completed or Underway

Selsey, United Kingdom  
Santos, Brazil  
Fort Lauderdale, Florida  
Key Largo, Florida  
Islamorada, Florida  
Kingston, New York  
Piermont, New York  
Catskill, New York  
Groton/Mystic, Connecticut  
Hampton, New Hampshire  
Seabrook, New Hampshire  
Hampton Falls, New Hampshire

East Machias, Maine  
Falmouth, Maine  
Portland, Maine  
Bowdoinham, Maine  
Old Orchard Beach, Maine  
Scarborough, Maine  
Bath, Maine  
Farmington, Maine  
New Sharon, Maine  
Marshfield, Massachusetts  
Duluth, Minnesota  
Rochester, Minnesota



# Input Sea Level Rise Curves



# Input Flood Elevations and Recurrence Intervals

FEMA Map Service Center - Mozilla Firefox

File Edit View History Bookmarks Tools Help

FEMA Map Service Center -

https://msc.fema.gov/webapp/wcs/stores/servlet/FemaWelcomeView?storeId=10001&catalogId=10001&langId=-1

**FEMA** Map Service Center

Product Catalog | Map Search | Quick Order | Digital Post Office | Help

**Product Search by...**

Address Map Panel ID

1) Select a Product:

Flood Maps

2) Enter an Address:

Street:

City:

State:

Zip:

Search by Street Address

**Announcements**

**NFHL Data Freeze**

The Geographic Information System (GIS) services for the Map Service Center (MSC) and the Mapping Information Platform (MIP) sites is being enhanced and updated. In order to provide these updates, the MSC will undergo several changes and outages in the coming months. National Flood Hazard Layer (NFHL) data freeze - NFHL data will freeze beginning April 24, 2013 and will end

**New to the FEMA Map Service Center**

- General Information for all Products
- General Information for Flood Insurance
- Homeowner's Riskers
- Real Estate Flood Determination Agents
- Insurance Agents
- Engineers/Surveyors
- Federal Exempt Customers

**Preliminary Flood Hazard Data**

FEMA is launching a new way to view preliminary flood hazard data - over the convenient location! Preliminary flood the public an early look at your home to flood hazards. Beginning in May 2013 search tool to find your data. For more the Preliminary Flood Hazard Data we

**Try our new Live Chat service**

Our staff is available for online chat Monday, Friday, 9:00 am to 5:00 pm Eastern Standard Time (Eastern Daylight Time). Click below

[live chat open](#)  
Powered by nGenia  
Live chat by nGenia

**What are you looking for?**

- Flood Maps
- FIRMs
- DIRM Databases
- MapViewer - Web
- Documents, Publications & Forms

More Information

Table 8: Summary

Flooding Source and Transect	FIRM Panel	10-percent-annual-chance
ATLANTIC OCEAN (continued)		
8	0567,0586	--
9	0567,0586	--
10	0559,0578	--
11	0559,0578	--
12	0559,0578	--
13	0557,0576	--

<sup>1</sup> Rounded to the nearest foot and may include effects of wave action. Base Flood Elevations shown on map may

## FLOOD INSURANCE STUDY



### BROWARD COUNTY, FLORIDA AND INCORPORATED AREAS



Community Name	Community Number
BROWARD COUNTY (UNINCORPORATED AREAS)	125093
COCONUT CREEK, CITY OF	120031
COOPER CITY, CITY OF	120032
CORAL SPRINGS, CITY OF	120033
DANIA BEACH, CITY OF	120034
DAVIE, TOWN OF	120035
DEERFIELD BEACH, CITY OF	125101
FORT LAUDERDALE, CITY OF	125105
HALLANDALE BEACH, CITY OF	125110
HILLSBORO BEACH, TOWN OF	120040
HOLLYWOOD, CITY OF	125113
LAUDERDALE-BY-THE-SEA, TOWN OF	125123
LAUDERDALE LAKES, CITY OF	120043
LAUDERHILL, CITY OF	120044
LAZY LAKE, VILLAGE OF	120045
LIGHTHOUSE POINT, CITY OF	125125
MARGATE, CITY OF	120047
MIRAMAR, CITY OF	120048
NORTH LAUDERDALE, CITY OF	120049

Community Name	Community Number
OAKLAND PARK, CITY OF	120050
PARKLAND, CITY OF	120051
PEMBROKE PARK, TOWN OF	120052
PEMBROKE PINES, CITY OF	120053
PLANTATION, CITY OF	120054
POMPANO BEACH, CITY OF	120055
SEA RANCH LAKES, VILLAGE OF	120056
SEMINOLE TRIBE OF FLORIDA	120685
SOUTHWEST RANCHES, TOWN OF	120691
SUNRISE, CITY OF	120328
TAMARAC, CITY OF	120058
WEST PARK, CITY OF	120222
WESTON, CITY OF	120678
WILTON MANORS, CITY OF	125156

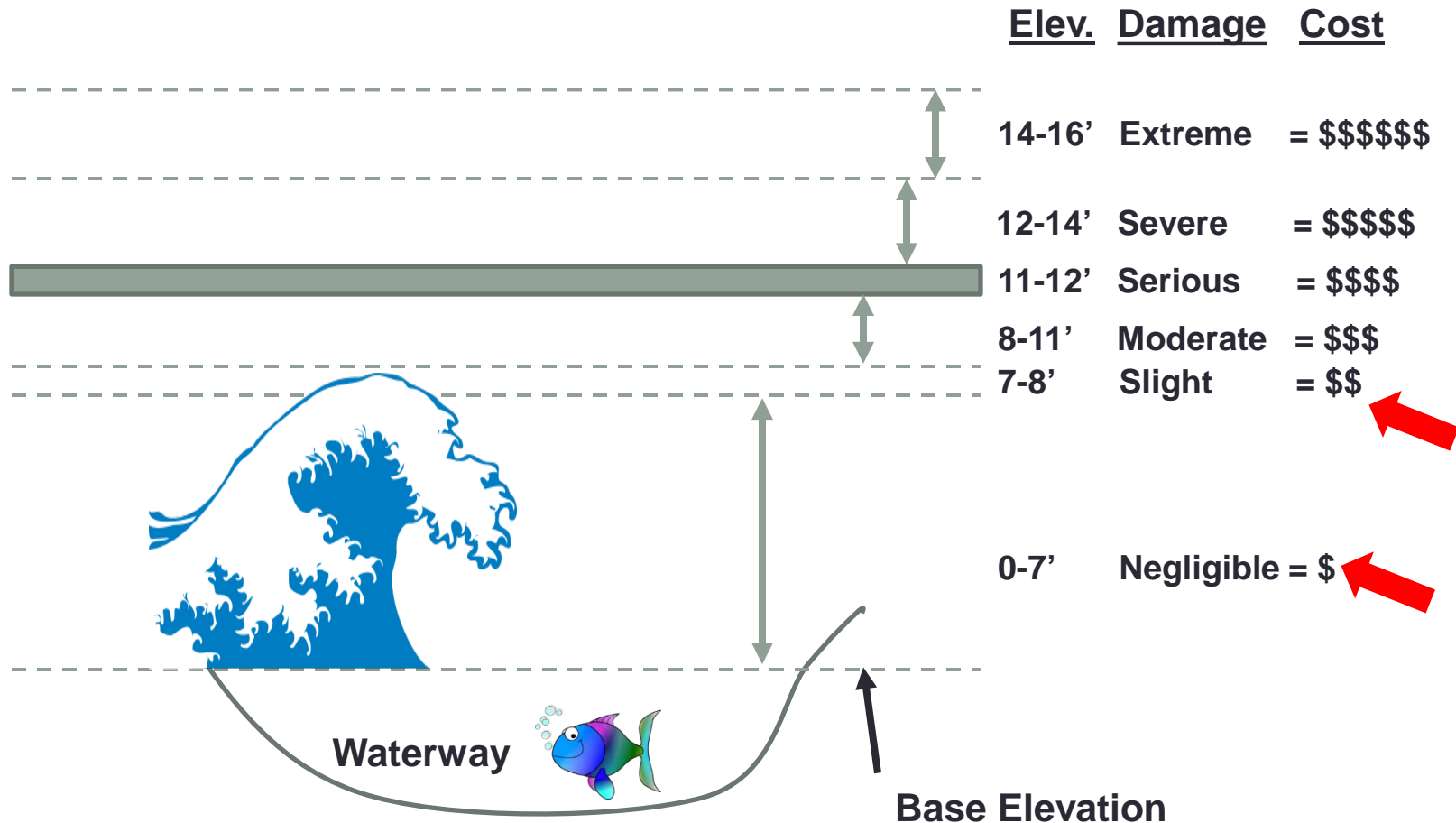
REVISED  
August 18, 2014



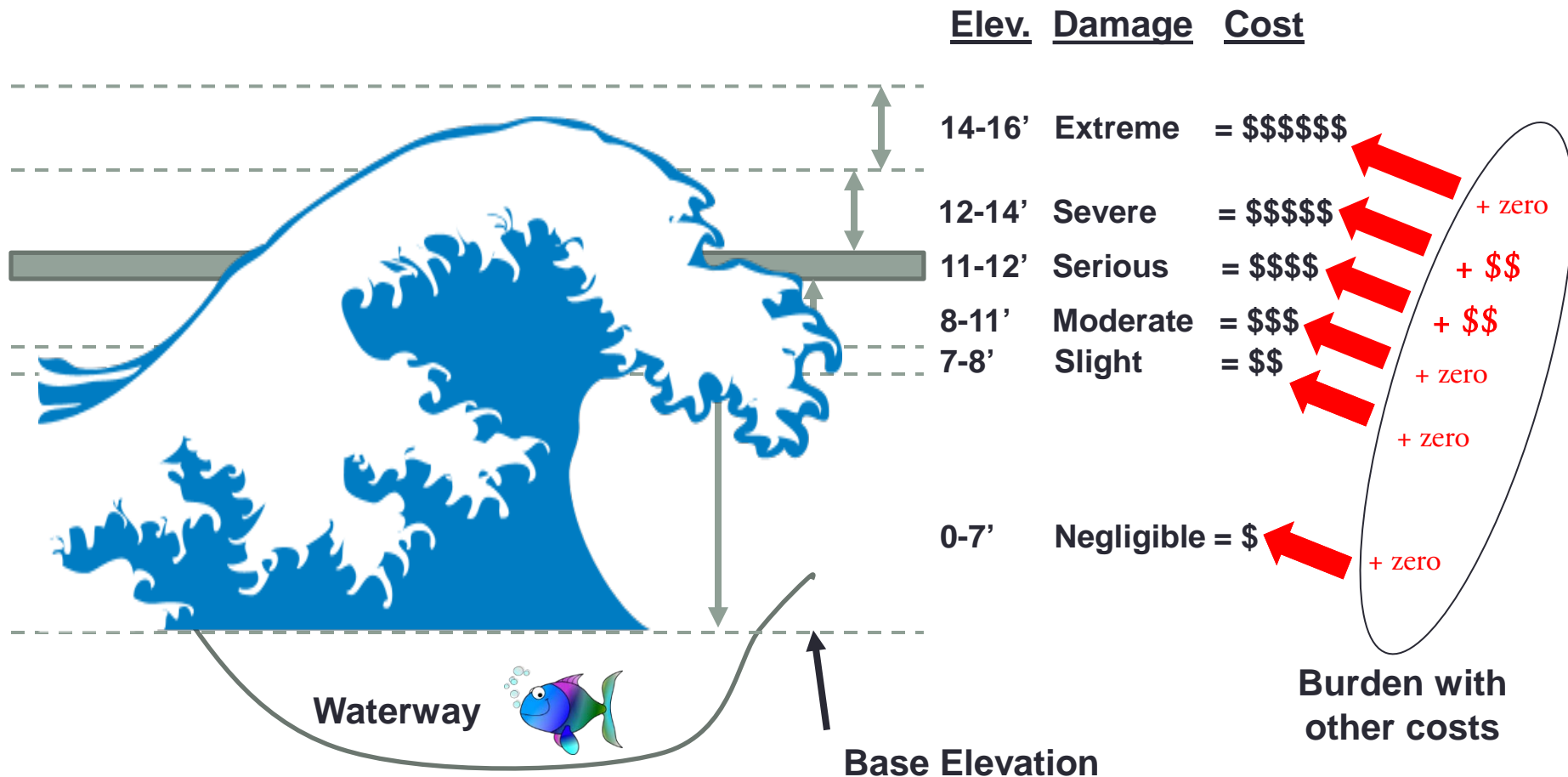
**Federal Emergency Management Agency**  
FLOOD INSURANCE STUDY NUMBER  
12011CV000A

Can also use finer resolution data from ADCIRC and other models.

# Depth Damage Functions Designed for Each Candidate Action/Structure

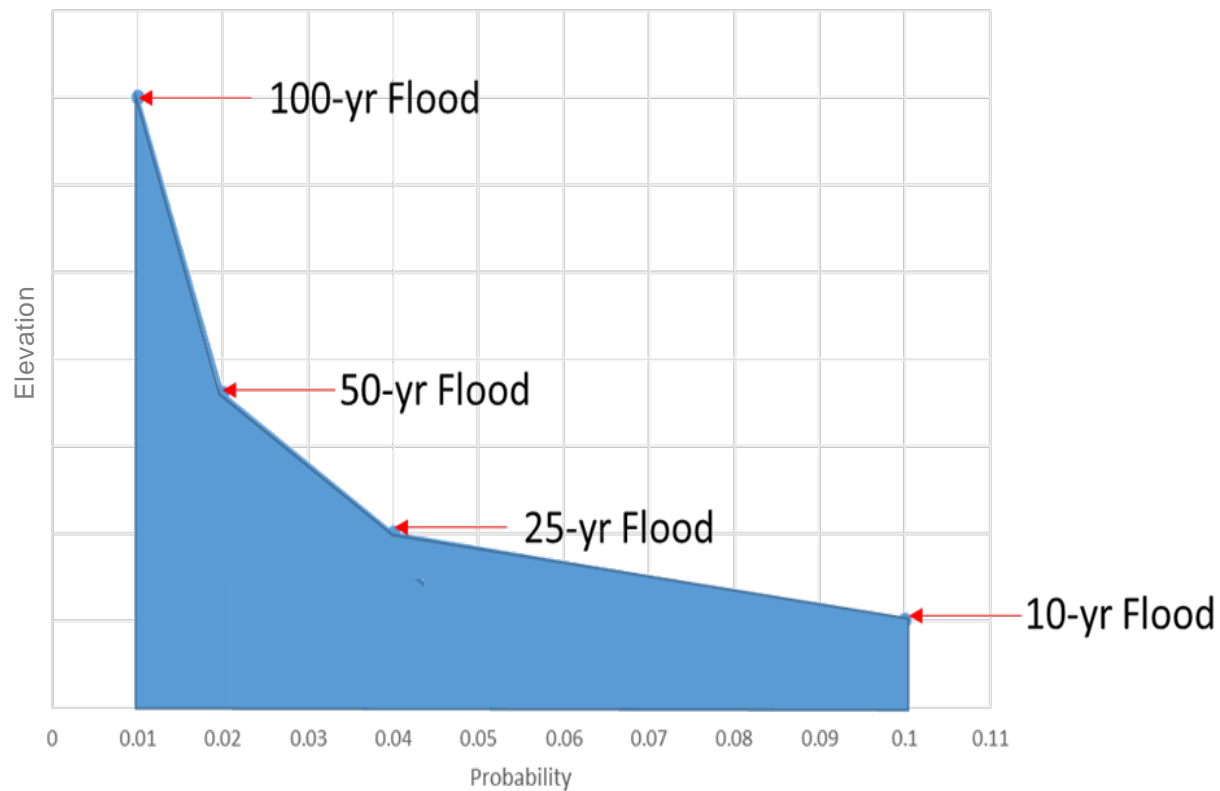


# Depth Damage Functions Designed for Each Candidate Action/Structure

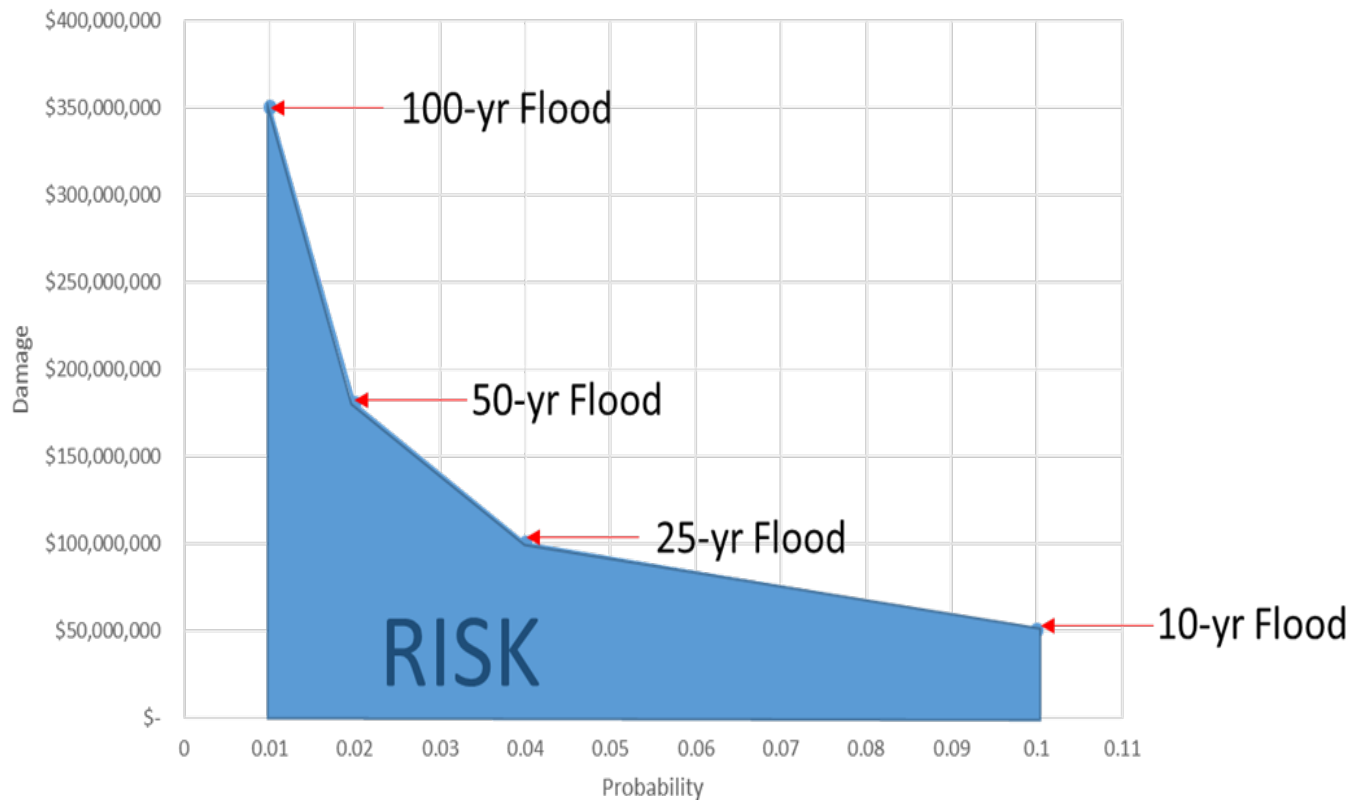




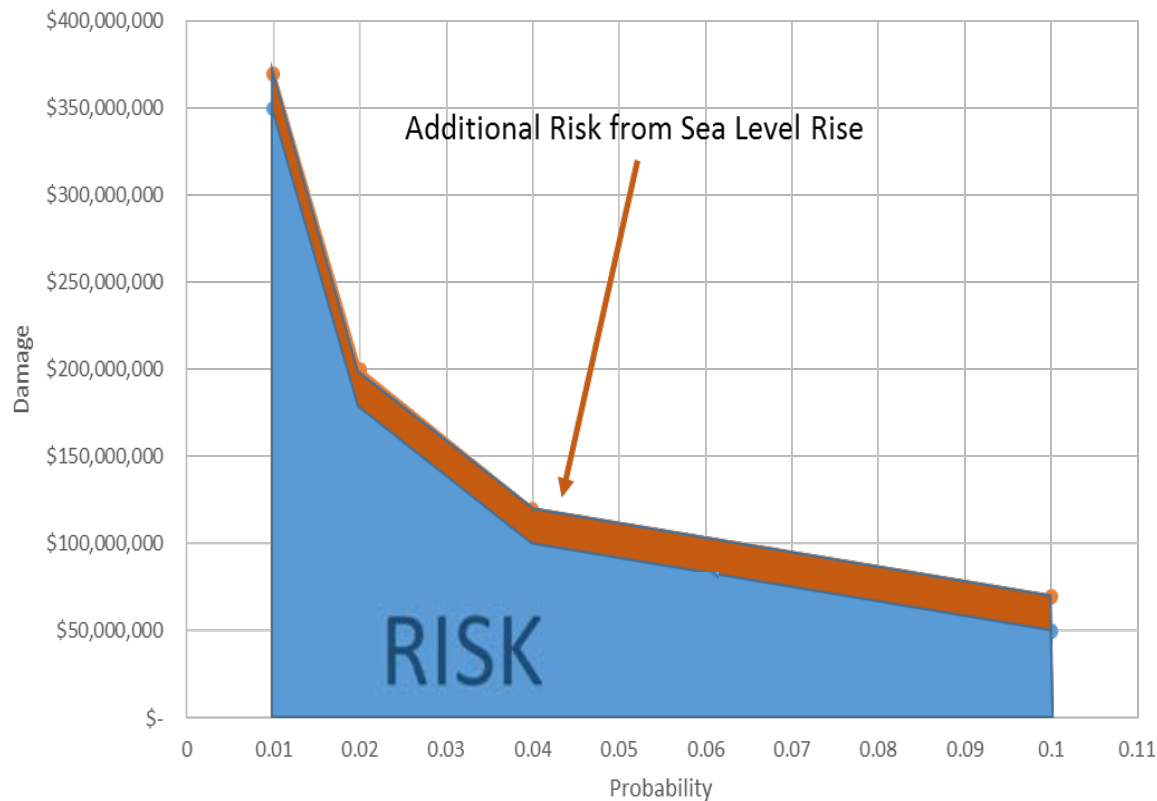
# Exceedance Curves



# How Vulnerable Are We If We Do Nothing?



# How Vulnerable Are We If We Do Nothing?



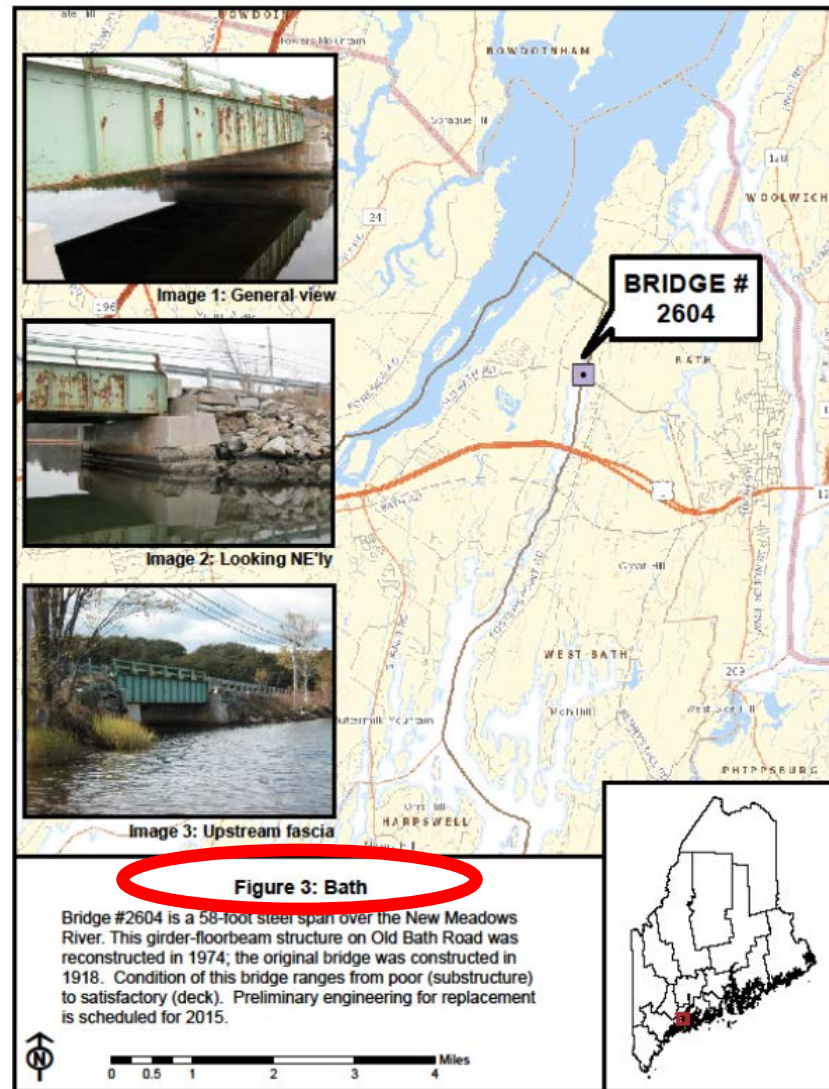
# Bridge Sensitivity to Elevated Water Levels



View of a bridge over the Sandy River on ME-41 in Farmington, an example of the types of structures that have been evaluated with the COAST software.



# Transferable Examples



# Transferable Examples

## Bath

### Low Sea Level Rise (3.3')

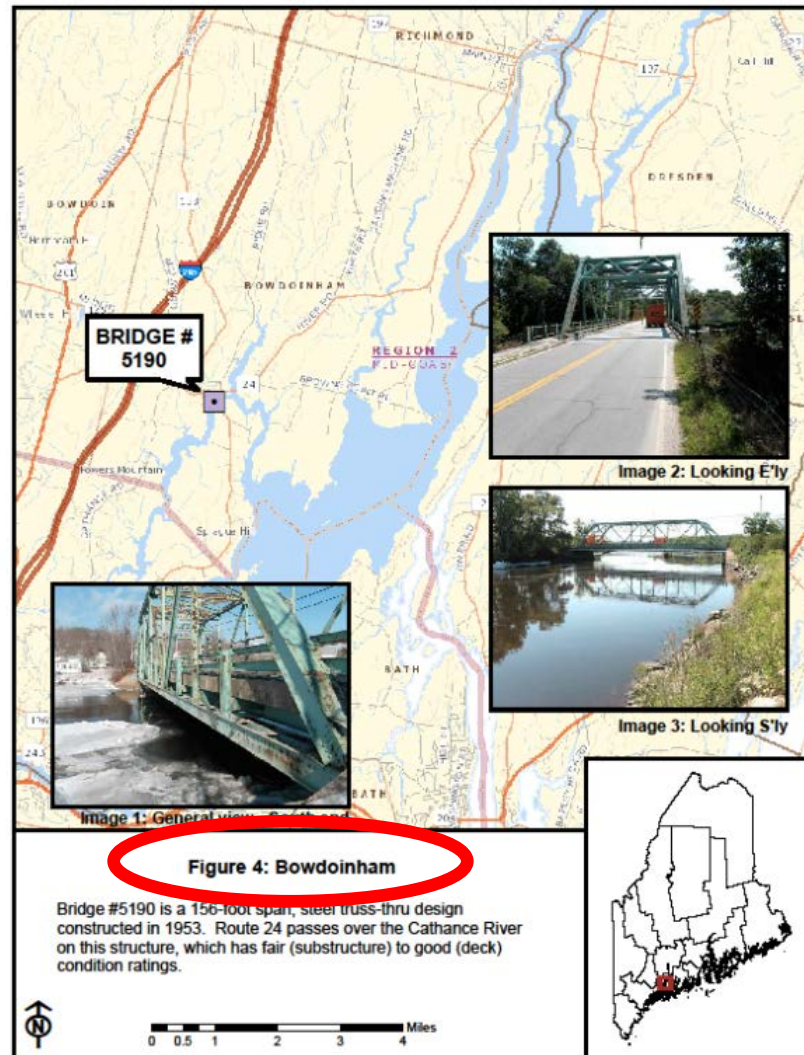
	Initial Construction Costs	Total Damage/Repair Costs by 2100	TOTAL LIFE CYCLE COST BY 2100
<b>Replace in Kind</b>	\$400,000	\$697,476	<b>\$1,097,476</b>
Replace with 3.3' SLR design	\$594,000	\$697,476	\$1,291,476
Replace with 6' SLR design	\$1,000,000	\$281,242	\$1,281,242

### High Sea Level Rise (6')

	Initial Construction Costs	Total Damage/Repair Costs by 2100	TOTAL LIFE CYCLE COST BY 2100
Replace in Kind	\$400,000	\$1,867,580	\$2,267,580
Replace with 3.3' SLR design	\$594,000	\$1,867,580	\$2,461,580
<b>Replace with 6' SLR design</b>	\$1,000,000	\$916,598	<b>\$1,916,598</b>

**Replace in Kind** was the most cost effective choice for a Low sea level rise scenario, but **Replace with 6' SLR design** was the most cost effective choice for a High sea level rise scenario.

# Transferable Examples



# Transferable Examples

## Bowdoinham

### Low Sea Level Rise (3.3')

	Initial Construction Costs	Total Damage/Repair Costs by 2100	TOTAL LIFE CYCLE COST BY 2100
Replace in Kind	\$250,000	\$1,656,830	\$1,906,830
Replace with 3.3' SLR design	\$394,000	\$1,162,080	\$1,556,080
Replace with 6' SLR design	\$491,000	\$205,159	<b>\$696,159</b>

### High Sea Level Rise (6')

	Initial Construction Costs	Total Damage/Repair Costs by 2100	TOTAL LIFE CYCLE COST BY 2100
Replace in Kind	\$250,000	\$2,163,283	\$2,413,283
Replace with 3.3' SLR design	\$394,000	\$1,900,813	\$2,294,813
Replace with 6' SLR design	\$491,000	\$908,565	<b>\$1,399,565</b>

**Replace with 6' SLR design** was the most cost effective choice for both Low and High sea level rise scenarios.

# Summary

- In terms of fiscal efficiency, there is no one right answer to the question “what design standard should we use?” Site-specific analysis is required.

Transportation Research Part D 33 (2014) 87–94



Contents lists available at [ScienceDirect](#)

Transportation Research Part D

journal homepage: [www.elsevier.com/locate/trd](http://www.elsevier.com/locate/trd)

Economic analyses of sea-level rise adaptation strategies  
in transportation considering spatial autocorrelation

Qing-Chang Lu<sup>a,\*</sup>, Zhong-Ren Peng<sup>a,b</sup>, Liye Zhang<sup>c</sup>, Zhanyong Wang<sup>a</sup>

“...The construction costs of seawall and road elevation are different for different states or situations, so **the economic analysis should be conducted based on the actual construction plan in proposed locations.**”



# But many futures are possible!

- How do we pick whether to build for a low or a high sea level rise scenario??

## Bath

### Low Sea Level Rise (3.3')

	Initial Construction Costs	Total Damage/Repair Costs by 2100	TOTAL LIFE CYCLE COST BY 2100
Replace in Kind	\$400,000	\$697,476	<b>\$1,097,476</b>
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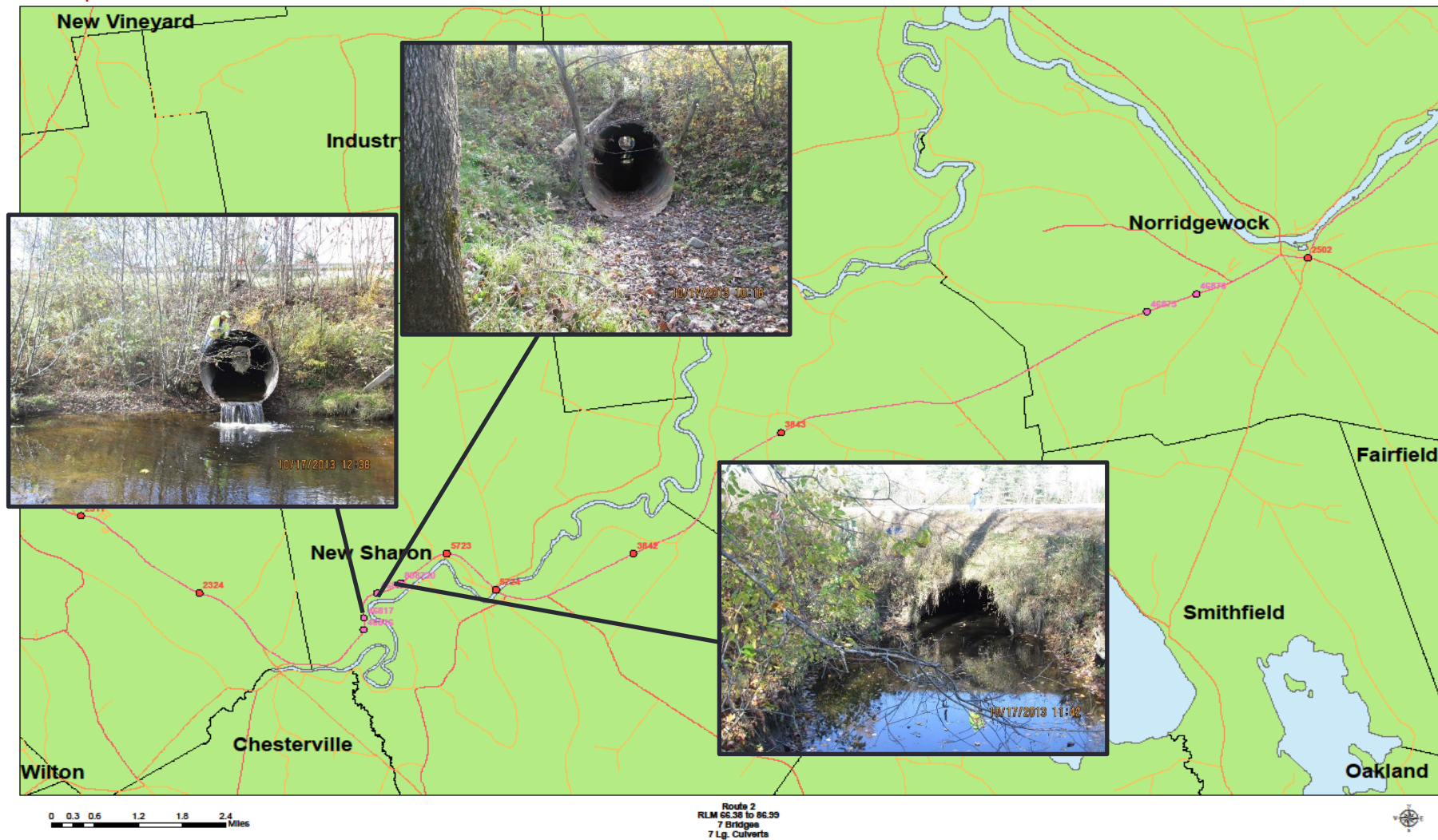


# But many futures are possible!

---

- How do we pick whether to build for a low or a high sea level rise scenario??
- Still needed is a means of selecting from candidate designs in a way that minimizes risk across modeled future scenarios.

# Transferable Example – Going Inland





# Transferable Example – Going Inland



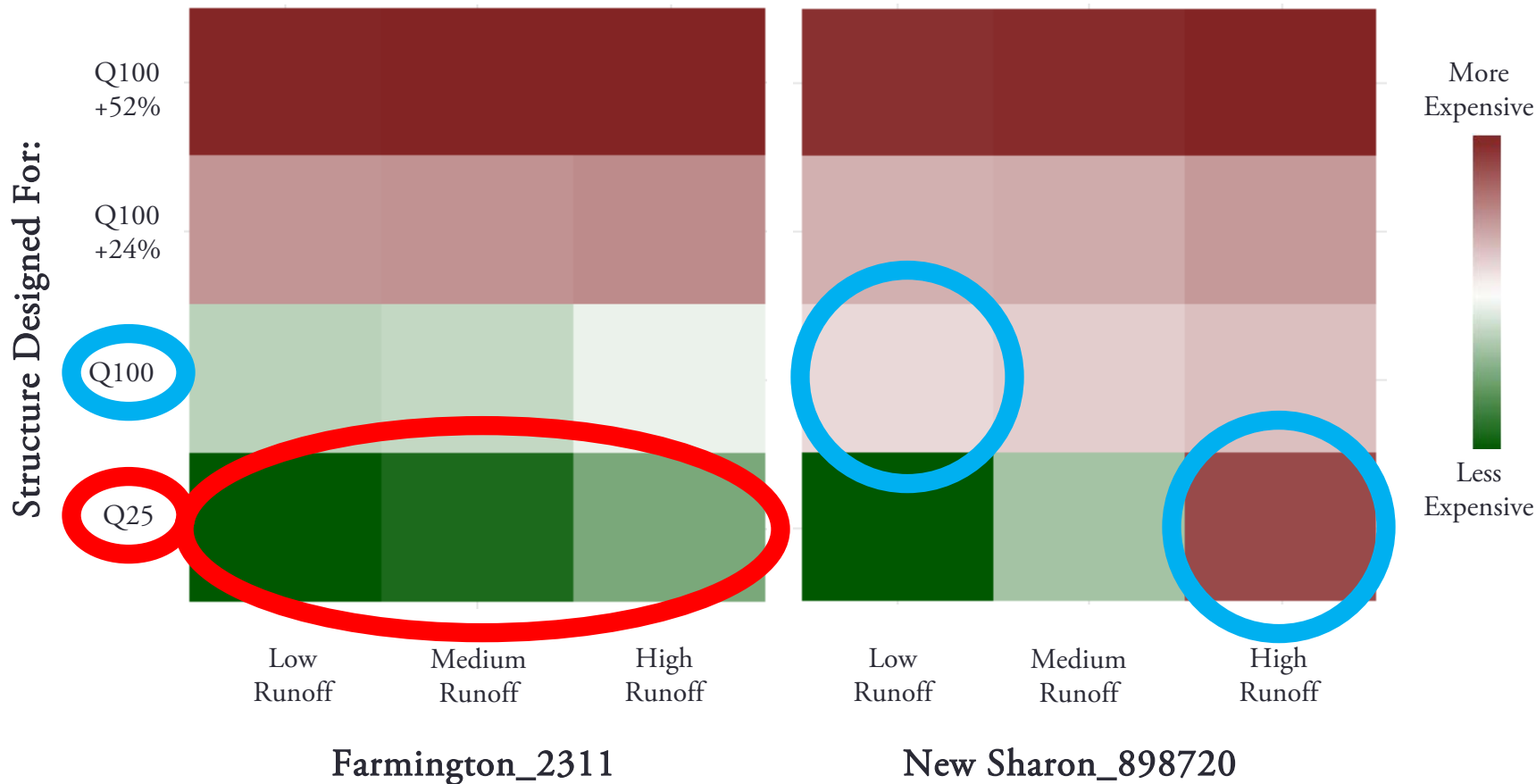
Farmington\_2311



New Sharon\_989720

# No-regrets Design Across Futures

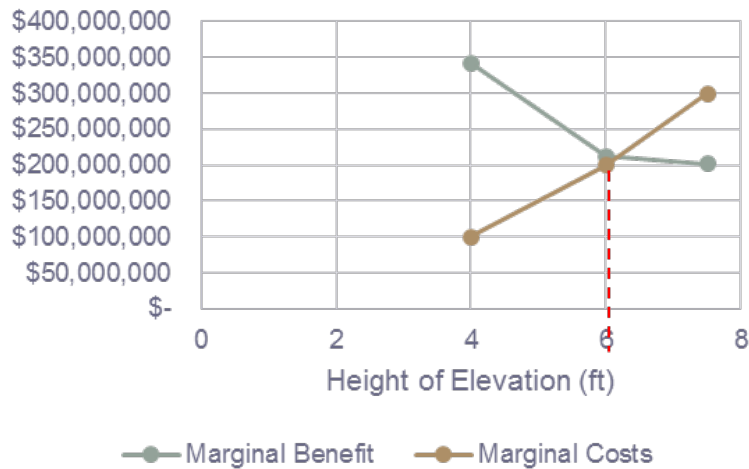
## Cumulative Burdened Life-cycle Costs



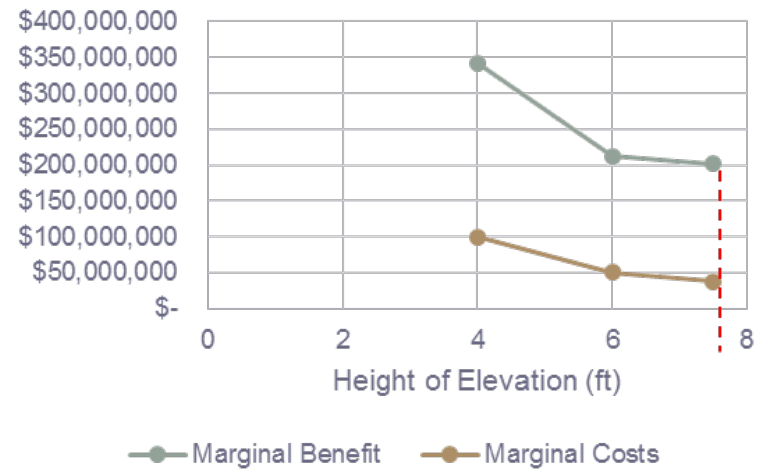


# How High Should Road or Other Elevations Be?

**Marginal Costs and Benefits of Elevation Height  
(curves cross)**



**Marginal Costs and Benefits of Elevation Height  
(curves don't cross)**



- When curves cross, appropriate height is at the curve intersection.
- When curves don't cross, appropriate height is at the best ratio between them.
- If choosing to build to a standard other than ideal, you at least have an estimate of how efficient the investment will be.



Thank You!

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[smerrill@geiconsultants.com](mailto:smerrill@geiconsultants.com)  
[www.geiconsultants.com](http://www.geiconsultants.com)

