MassDOT-FHWA Pilot Project:
Climate Change and Extreme Weather Vulnerability Assessment and Adaptation Options for the Central Artery/Tunnel, Boston, Massachusetts

First International Conference on Surface Transportation System Resilience to Climate Change and Extreme Weather Events

September 16-18, 2015

UMASS BOSTON

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University of New Hampshire

massDOT Massachusetts Department of Transportation Highway Division

U.S. Department of Transportation Federal Highway Administration

Project Team

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Project Overview

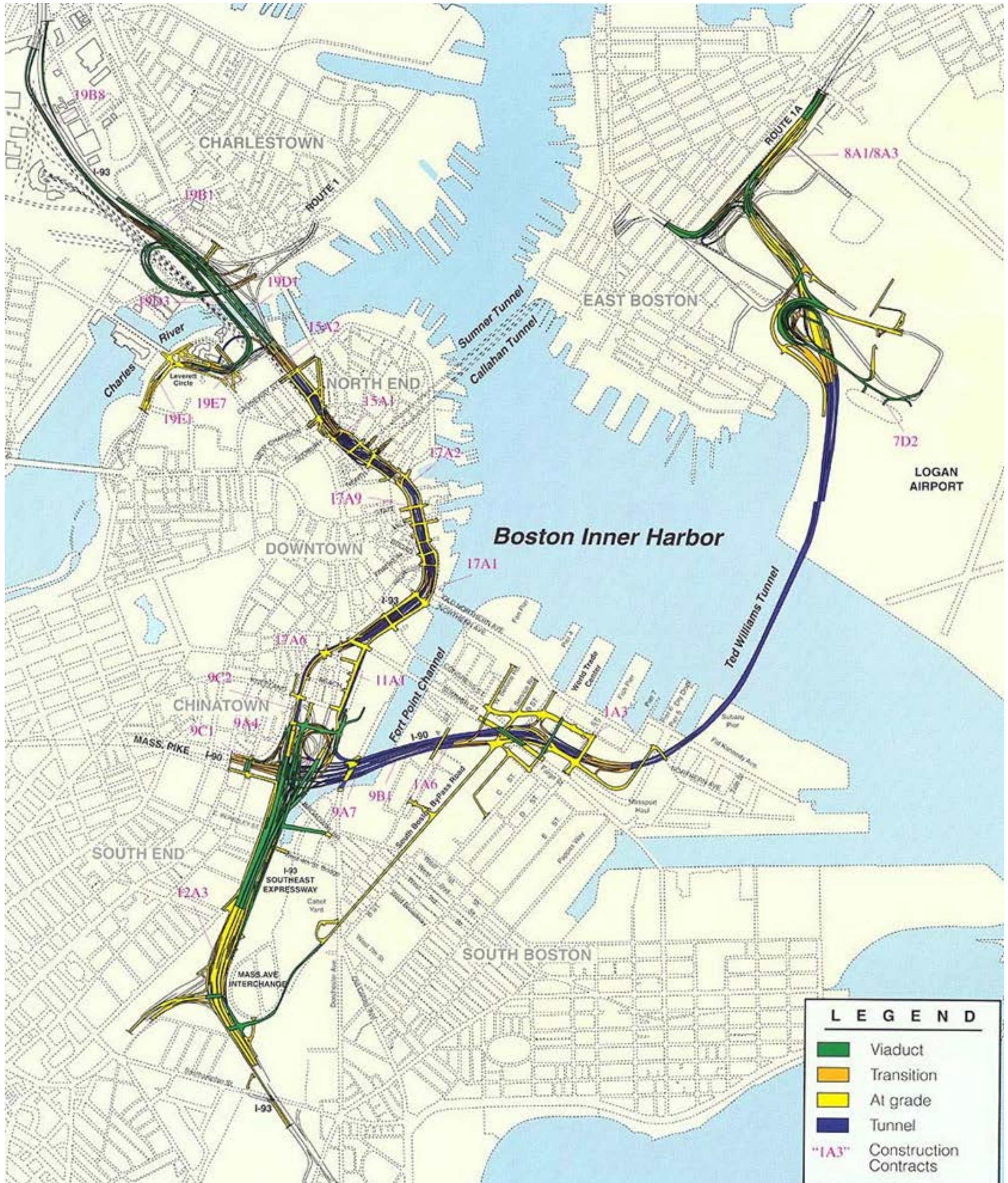
The **Central Artery/Tunnel (CA/T)** system is a critical link in regional transportation and a vitally important asset in the Boston metropolitan area. It is potentially vulnerable to flooding from an extreme coastal storm under present and future climate.

Project Objectives:

- Assess vulnerability of CA/T to present climate and future sea level rise and extreme storm events
- Investigate options to reduce identified vulnerabilities through local and regional adaptation
- Support an emergency response plan for tunnel protection and/or shut down in the event of a major storm

Project Overview

- PHASE 1: Define Geographical Scope
- PHASE 2: Inventory of Assets
- PHASE 3: Surveys of Critical Areas of Central Artery
- PHASE 4: Hydrodynamic Analysis
- PHASE 5: Vulnerability Assessment
- PHASE 6: Adaptation Strategy
- PHASE 7: Project report and presentations

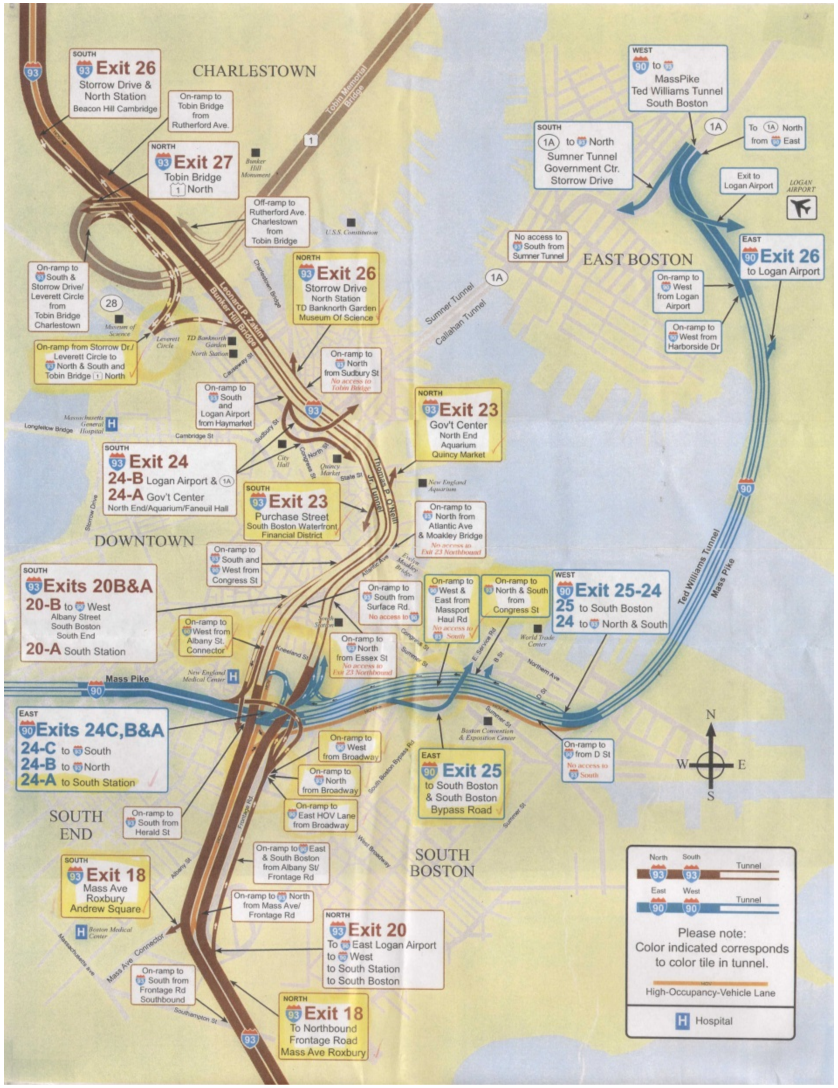

CHARLESTOWN
EAST BOSTON
NORTH END
DOWNTOWN
CHINATOWN
SOUTH END
SOUTH BOSTON
Boston Inner Harbor
LOGAN AIRPORT
Sumner Tunnel
Callahan Tunnel
Ted Williams Tunnel
Fort Point Channel
Charles River
Leverett Circle
ROUTE 1A
ROUTE 1
I-93
I-90
MASS. PIKE
I-93 SOUTHEAST EXPRESSWAY
MASS AVE INTERCHANGE
South Boston ByPass Road
World Trade Center
19B8
19B1
19D1
19D3
19E7
19E1
15A2
15A1
17A2
17A9
17A1
17A6
11A1
9C2
9C1
9A4
9B1
9A7
1A6
1A3
12A3
8A1/8A3
7D2
LEGEND
Viaduct
Transition
At grade
Tunnel
"1A3" Construction Contracts

Boston Harbor & Tip O'Neill Tunnel Exit/Entrance Ramps
http://www.flickr.com/photos/pictometry/6220376808/

Project Realities

Phase 1: Define Geographical Scope

- GIS-based delineation too unwieldy
- Redefined scope with “Institutional Knowledge” (IK) approach
  - District 6 staff provided significant insight into the CA/T
- Created “mini-pilot” project approaches to:
  - Develop preliminary vulnerability assessment methodology using a subset of tunnel assets to identify key assets
  - Field work to identify structures and measure heights of openings
  - Interacted with IK to augment field work and GIS data analysis
- “Discovered” several databases (i.e., Maximo)
  - defined a common language and identifiers across datasets and personnel.
- Final project domain defined by IK team
  - Face-to-face meetings with maps to decide what was in and what was out.


CHARLESTOWN
EAST BOSTON
DOWNTOWN
SOUTH END
SOUTH BOSTON
SOUTH Exit 26 Storrow Drive & North Station Beacon Hill Cambridge
NORTH Exit 27 Tobin Bridge 1 North
NORTH Exit 26 Storrow Drive North Station TD Banknorth Garden Museum Of Science
NORTH Exit 23 Gov't Center North End Aquarium Quincy Market
SOUTH Exit 24 24-B Logan Airport & 1A 24-A Gov't Center North End/Aquarium/Faneuil Hall
SOUTH Exit 23 Purchase Street South Boston Waterfront Financial District
SOUTH Exits 20B&A 20-B to West Albany Street South Boston South End 20-A South Station
EAST Exits 24C,B&A 24-C to South 24-B to North 24-A to South Station
WEST Exit 25-24 25 to South Boston 24 to North & South
EAST Exit 25 to South Boston & South Boston Bypass Road
EAST Exit 26 to Logan Airport
WEST 90 to 93 MassPike Ted Williams Tunnel South Boston
SOUTH 1A to 93 North Sumner Tunnel Government Ctr. Storrow Drive
SOUTH Exit 18 Mass Ave Roxbury Andrew Square
NORTH Exit 20 To 90 East Logan Airport to 90 West to South Station to South Boston
NORTH Exit 18 To Northbound Frontage Road Mass Ave Roxbury
Mass Pike
Ted Williams Tunnel
Sumner Tunnel
Callahan Tunnel
Please note: Color indicated corresponds to color tile in tunnel.
High-Occupancy-Vehicle Lane
Hospital


B 3
C 4
C 3

Project Realities

Phase 2: Inventory of Assets

- Devised GIS hierarchical framework to incorporate interconnectedness and to facilitate vulnerability analysis

<u>Structural Systems</u> ← <u>Structures</u> ← <u>Facilities</u> ← <u>Assets</u>

- Inventory limited to Structures and Facilities
- Created GIS database (CATDB) of Facilities and Structures
  - Maximo not georeferenced, locations not accurate enough for VA.
  - As-Built Record Drawings not compatible with project needs
  - Identified ~25% more structures than contained in Maximo.
  - Field work alone was ~500 man-hours or ~3 months FTE additional time.
  - IK team instrumental in this process.

Tip O’Neill Tunnel Exit & Entrance Ramps

Tip O'Neill Tunnel Exit Ramp

Vent Building 1

Vent Building 1 – Detail of Air Exchange Vent

Project Realities

- Photo Documentation of Structures and Facilities
- Found potential cross connections between MBTA and CA/T tunnels
  - Silver Line tunnel below South Station
    - Discovered sump allegedly connected to CA/T
  - Blue Line tunnel at Aquarium Station
    - Discovered Tunnel Egress not previously located
    - Dubbed “Ground Zero” for CA/T flooding vulnerability

High Resolution Hydrodynamic Modeling

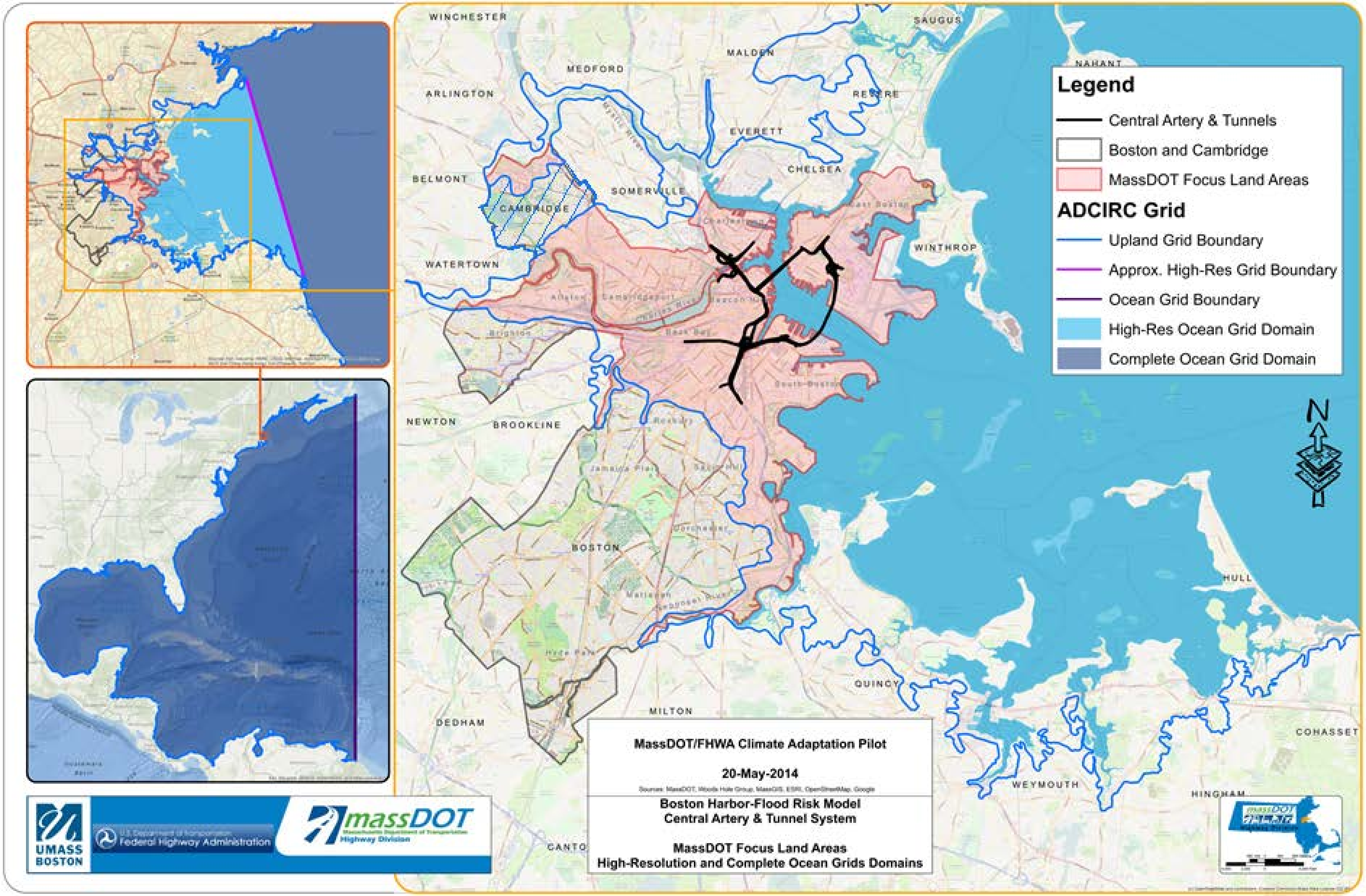
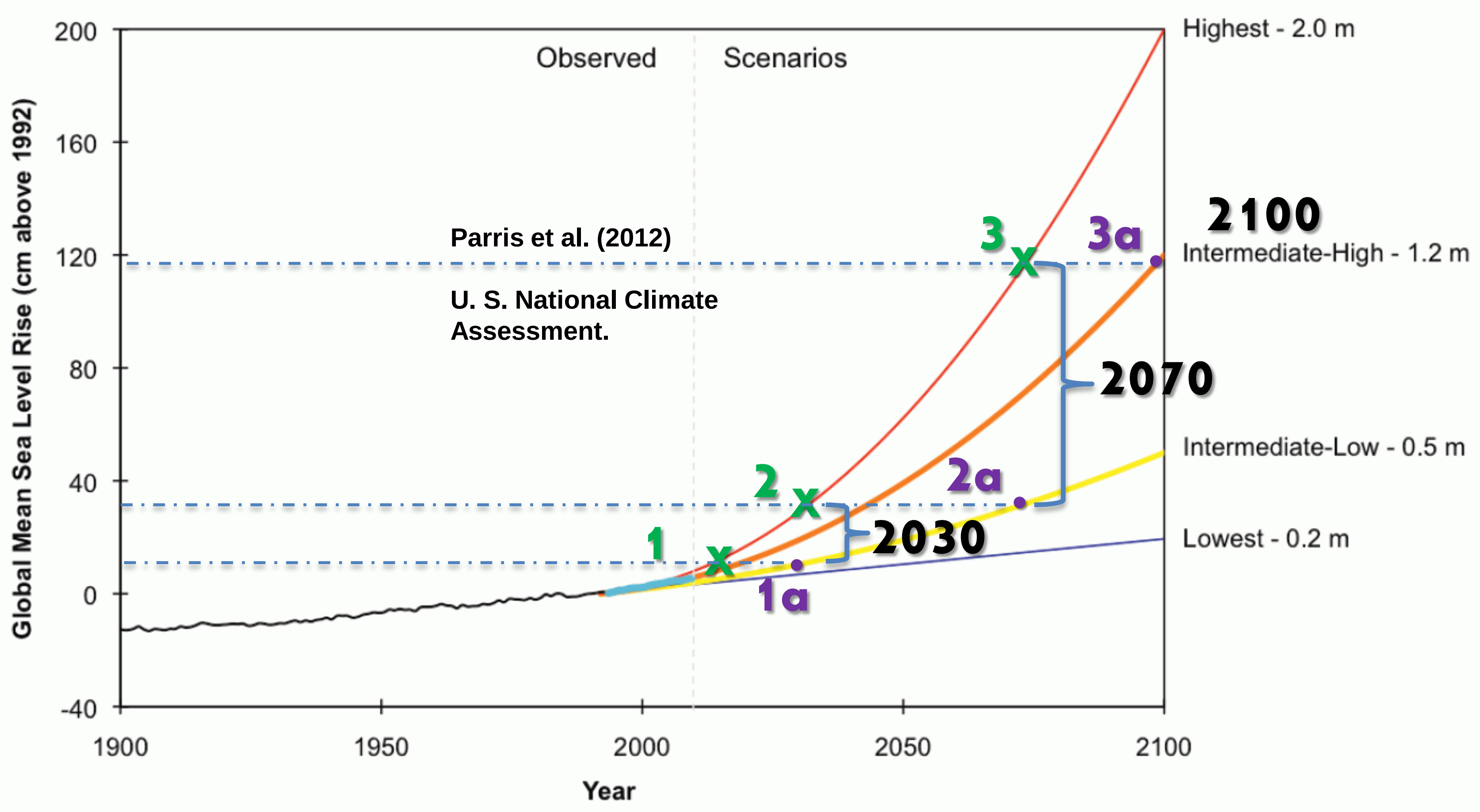



Image Landsat
Google earth

SLR Scenarios - Using Projections to Bracket Risk



Estimating annual maximum exceedance probabilities

- Model generates a series of water surface elevations (WSE) for hurricanes and for nor'easters.
  - Independent series due to Monte Carlo approach

- Estimate average annual frequency (λ) of each storm type.

  $\lambda(H)$ = 0.337 (2030 climatology)

  $\lambda(N)$ = 2.3 (historical)

- Transform PDS to AMS using:

$$p_e = 1 - \exp(-\lambda \cdot q_e)$$ HoH 18.6.3a

- Now we have the empirical annual maximum exceedance probability series (AMS) for each storm type (p_e vs WSE)

Develop composite exceedance probability distribution for WSE

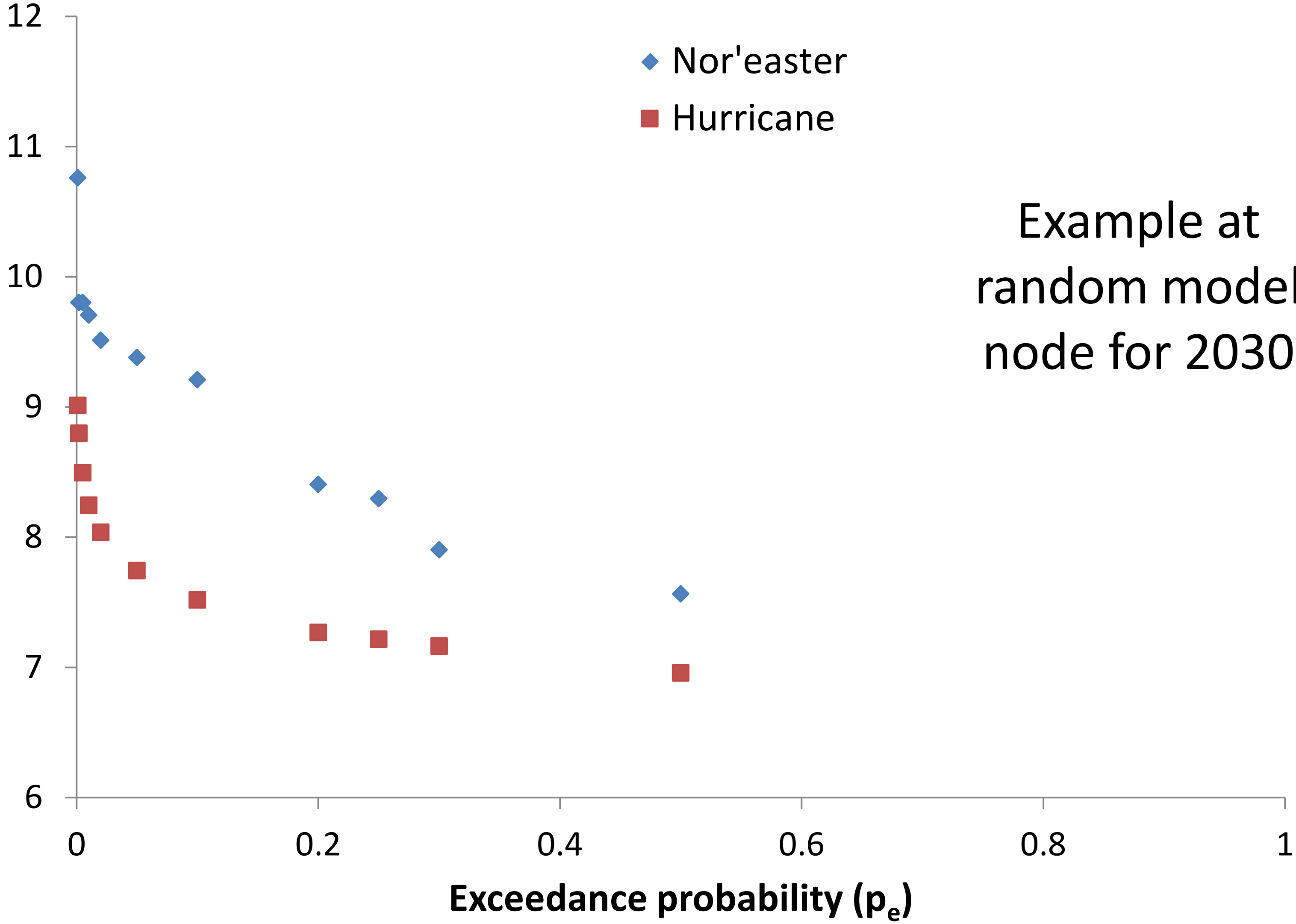
- Following Vogel and Stedinger (1984):

$$F_S(q_m) = F_H(q_m) \cdot F_N(q_m)$$

- Which is equivalent to

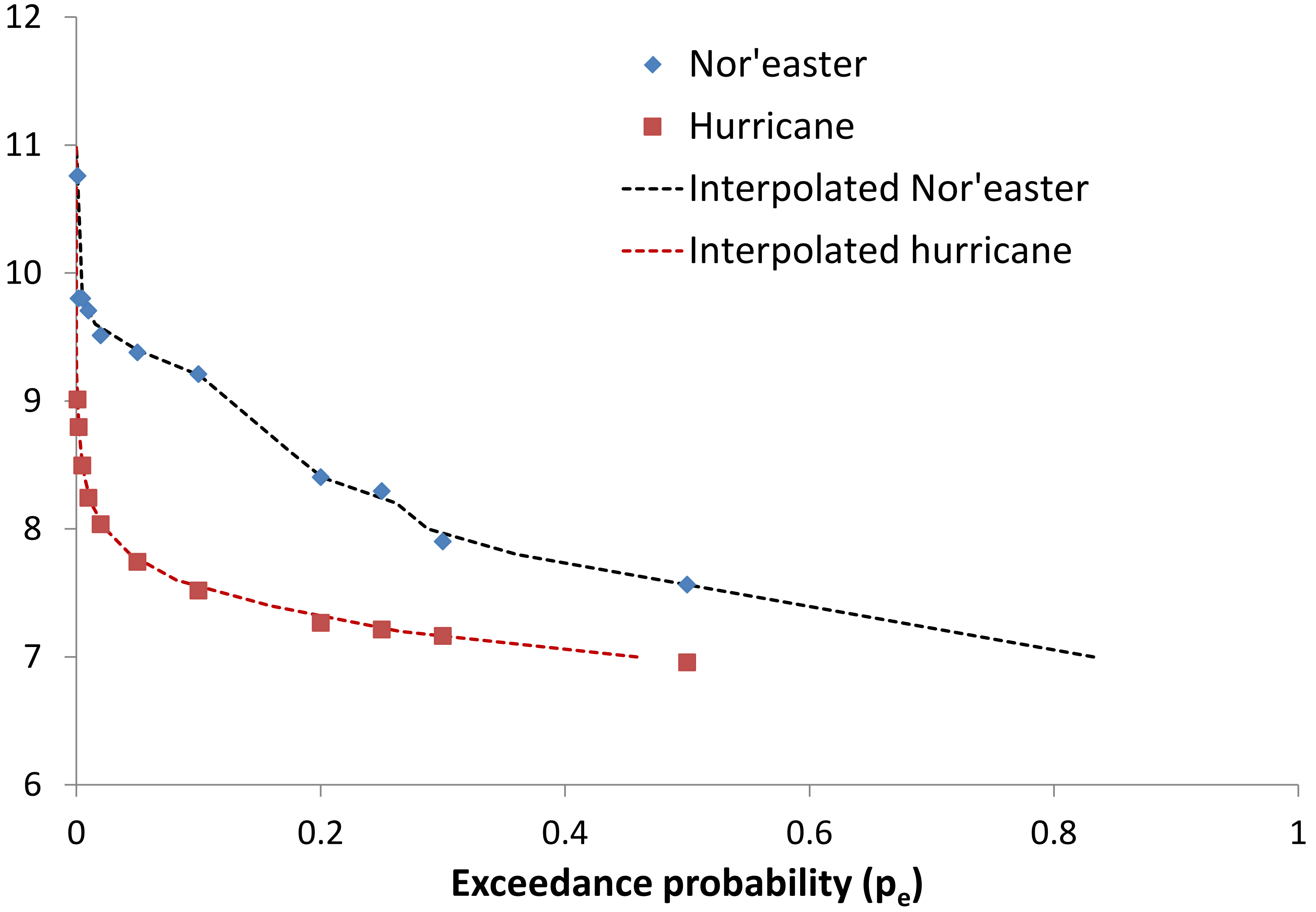
  $p_s(WSE) = p_N(WSE) + p_H(WSE) – p_N(WSE)\, p_H(WSE)$

  (Douglas, Vogel and Bosma, in preparation)

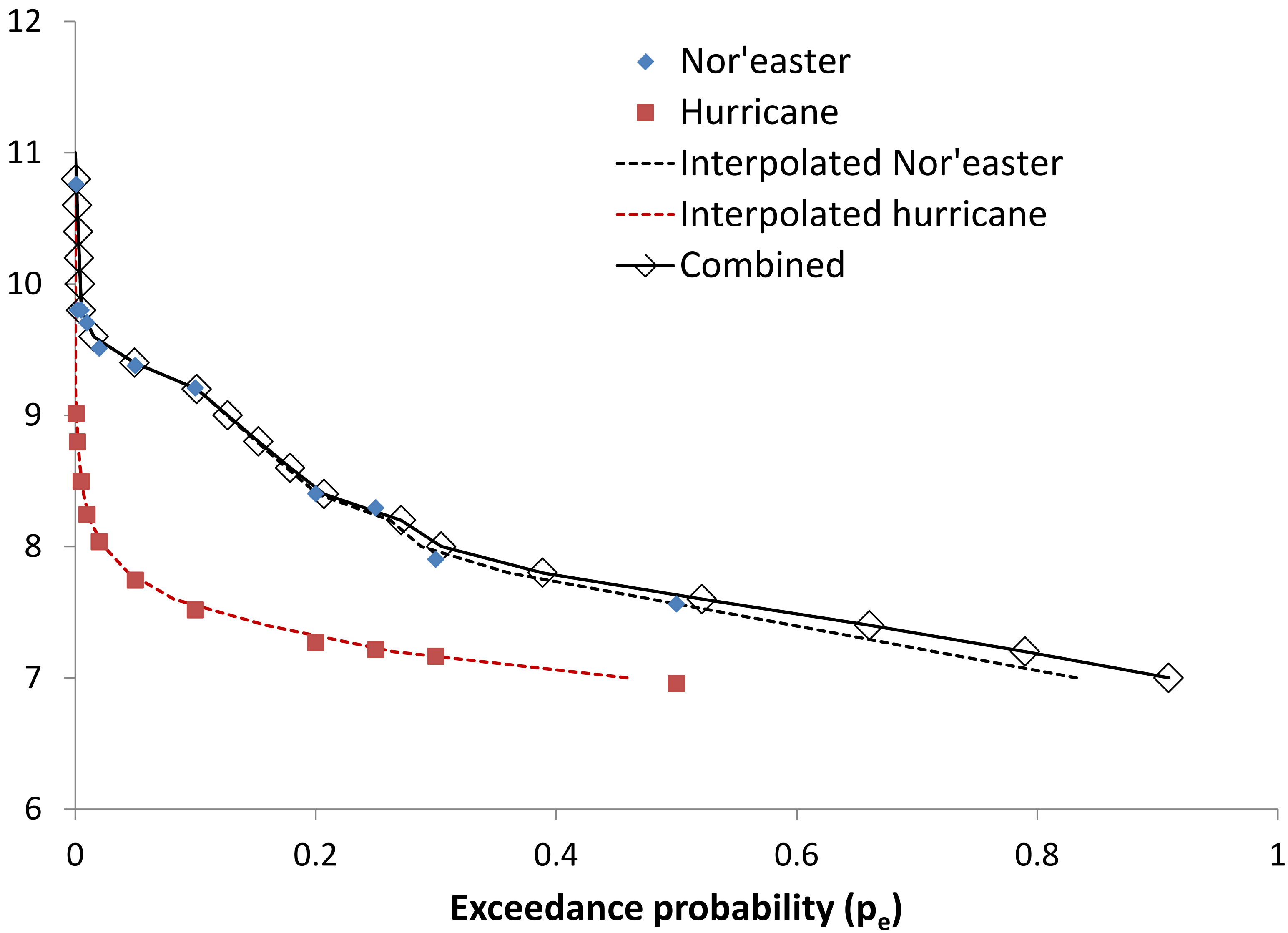


Example at random model node for 2030

(Source: Douglas, Vogel and Bosma, in preparation)

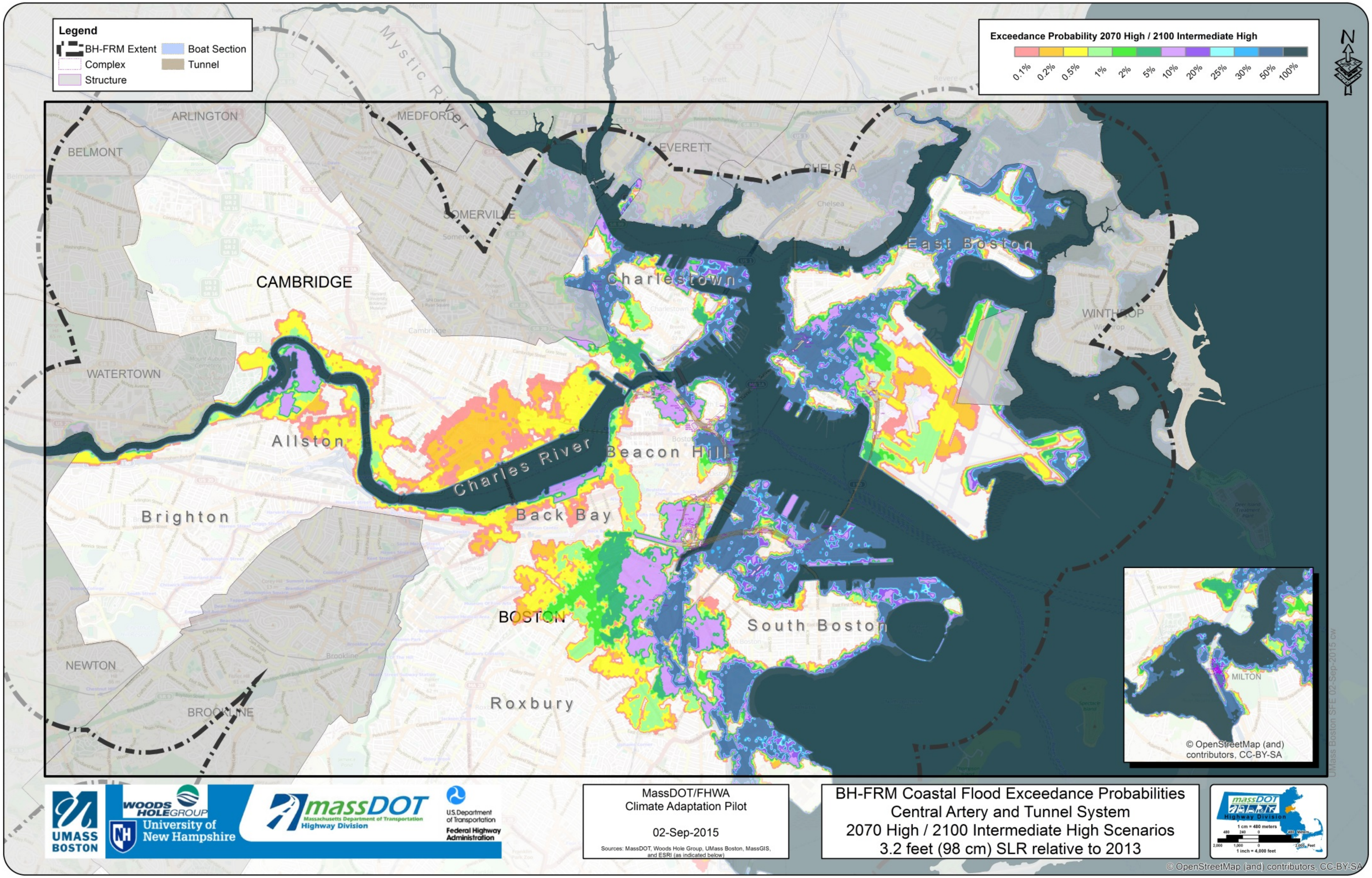


(Source: Douglas, Vogel and Bosma, in preparation)

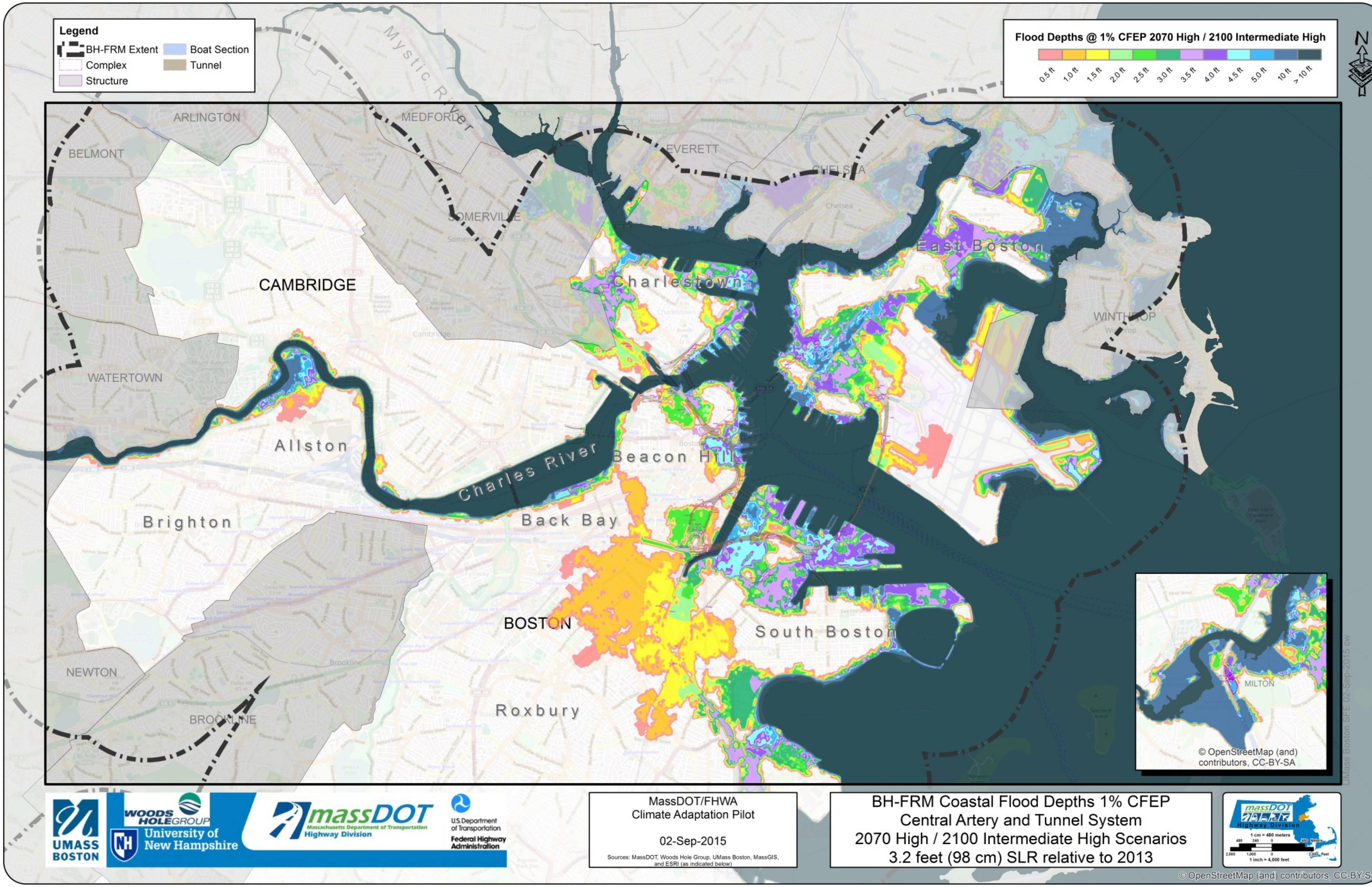


(Source: Douglas, Vogel and Bosma, in preparation)

Flood exceedance probabilities

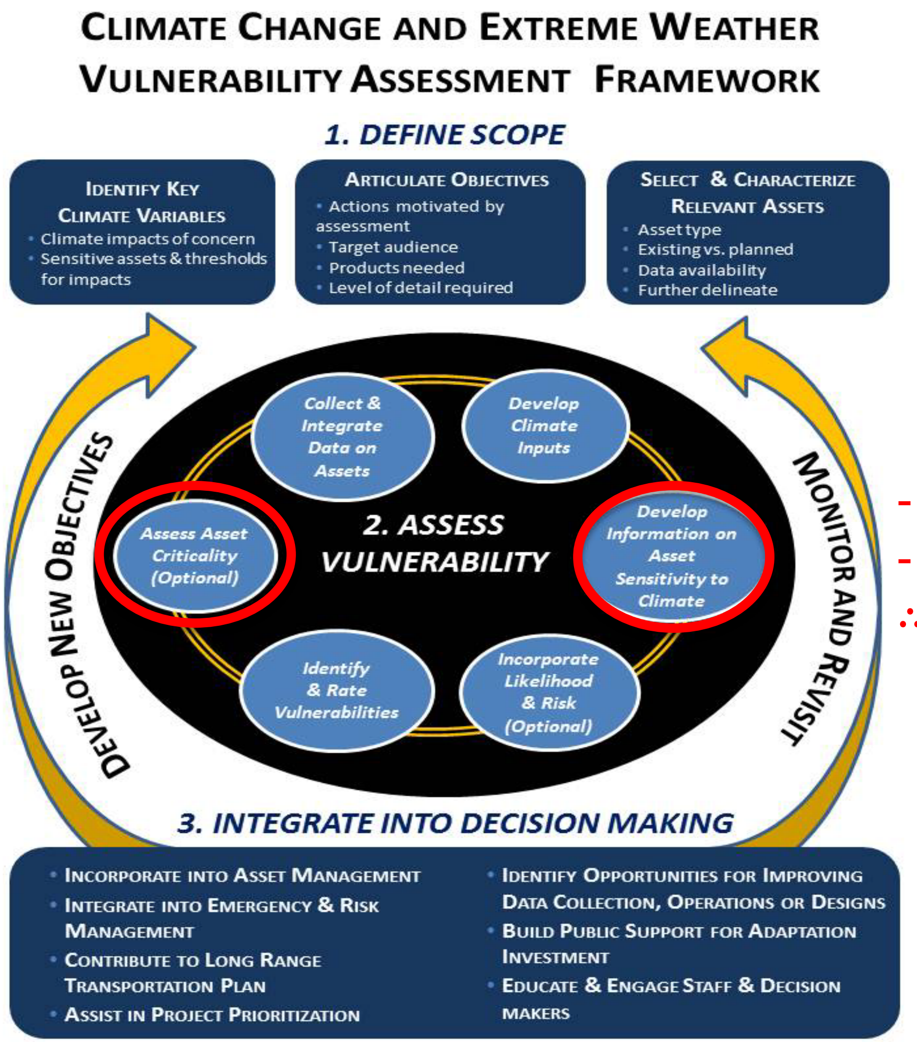


1% Flood depths



Vulnerability Assessment and Adaptation options

FHWA framework for assessing the vulnerability of transportation systems to climate change and extreme weather (Source: Fig 1 from FHWA, 2012, pg. 2)



- All components are equally critical
- Any flooding could impact system.

∴Exposure = risk of getting wet at any structure or facility

- Sensitivity = 1
- Adaptive Capacity = 0

∴ Vulnerability = Exposure

Vulnerable Structures

2013 1 % Depth (ft)	2013 to 2030 1 % Depth (ft)	2030 to 2070/2100 1 % Depth (ft)	Structure Location and Notes
0	0 to 0.1	2.2 to 3.3	Central Maintenance Facility Complex 400 D Street, South Boston - this Complex also contains *D6-CMF-FAC, D6A-D1* and *MHRML*
0	0 to 0.1	2.6 to 3.3	*Central Maintenance Facility*
0	0.1	2.7 to 2.9	*Fuel Depot CMF South Boston*
0	0.1	2.9 to 3.3	*Mass Highway Research & Materials Laboratory*
0	0 to 0.5	0.5 to 3.2	Depot-Main Complex SMF Rutherford Street, Charlestown -this Complex also contains *D6-ES10-FAC, D6-SMF-SAC* and *DA6-D3*
0	0 to 0.5	1.9 to 3.2	*Emergency Response Station 10*
0	0 to 0.5	2.2 to 3.2	*Satellite Maintenance Facility*
0	0 to 0.2	2.3 to 3.0	*SMF Fuel Depot*
0	0	0.0 to 0.7	Air Intake Structure – Atlantic Avenue, Boston
0 to 0.5	0 to 1.7	0.0 to 4.9	Depot-Main Complex 93 Granite Ave, Milton - this Complex also contains *Buildings A, B, C, D* and *D6D-D1*
0 to 0.5	0.9 to 1.7	4.0 to 4.9	*D6 Granite Ave Building B*
0	0 to 0.7	2.7 to 3.8	*D6 Granite Ave Building C*
0	0 to 0.5	2.2 to 3.2	*D6 Granite Ave Building A*
0	0	3.2 to 4.6	*D6 Granite Ave Building D*
0	0 to 1.4	0 to 3.1	*D6 Granite Ave Fuel Depot*
0	0 to 0.7	1.6 to 3.9	Complex HOC 50 Massport Haul Road, South Boston - this Complex also contains *D6-HOC-FAC, D6-ES02-FAC* and *D6-SWO4-FAC*
0	0 to 0.6	1.5 to 1.6	*Highway Operation Center*
0	0 to 0.3	1.2 to 3.0	*Emergency Response Station 2*
0	0 to 0.6	1.6 to 3.4	*Storm Water Pump Station 4* - This is the vent. Door to pump station located in boat section, upstream of BIN7J8-POR. Needs water tight door. Its vent structure is at surface grade directly above. Vent protected by wall around D6-HOC-FAC Complex.
0	0	0.0 to 1.2	Electrical Substation 2 - Albany Street, Boston
0	0	0.0 to 1.8	Electrical Substation 3 – Austin Street, Boston
0	0	2.4	Fan Chamber - Beach Street, Boston
0	0	0.0 to 1.0	Low Point Pump Station 11 – This is the street grate on Atlantic Avenue, Boston
0	0	2.5	Storm Water Pump Station 7 – Albany Street, Boston
0	0	2.4	Storm Water Pump Station 9 – Rear of Rear of 185 Kneeland Street
0	0	1.7	Storm Water Pump Station 12 – Frontage Road, Boston
0	0	2.0 to 2.9	Storm Water Pump Station 16 – Dock Square, Boston
0	0	2.0 to 2.5	Storm Water Pump Station 17 – Leverett Circle, Boston
0	0	0.0 to 1.4	Storm Water Pump Station 18 – Austin Street, Boston
0	0	0.0 to 1.2	Sumner/Callahan Administration – North Street, Boston
0	0	0	Storm Water Pump Station 25 outside (upstream) of BIN7CA-POR (Sumner Tunnel

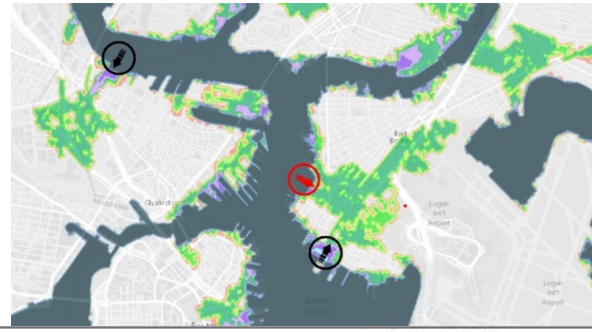
Vulnerable boat-sections

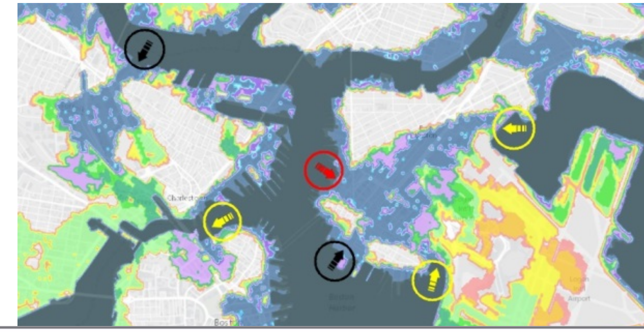
Structure_ID	2013 0.1 Depth (ft)	2013 to 2030 0.1 Depth (ft)	2030 to 2070/2100 0.1 Depth (ft)	Ramp Area or Roadway Area and Notes
BIN5UR -POR	0	0	*0 to 3.2	Ramp CS-SA Central Artery Southbound to Surface Artery
BIN5VQ-POR	0	0	*0 to 1.4	Rose Kennedy Greenway Parcel 18: Ramp A-CN Atlantic Avenue to I-93 Northbound
BIN5VA-POR	*0 to 1.0	*0 to 1.7	*0 to 4.4	Rose Kennedy Greenway Parcel 12: Ramp CN-SA Central Artery Northbound to Surface Artery
BIN59Y-POR	0	0	*0 to 2.3	Ramp CN-S Central Artery Northbound to Storrow Drive
BIN5AF-POR	0	0	*0 to 1.6	Storrow Drive Northbound entrance to Leverett Circle Tunnel
BIN5K2-POR	0	0	*0 to 1.5	Storrow Drive Northbound exit from Leverett Circle Tunnel
BIN59K-POR	0	0	*0 to 1.7	Ramp L-CS Leverett Circle to Central Artery Southbound
BIN7BC-POR	0	0	*0 to 2.8	Ramp B Massport Haul Road to I-90 Westbound
BIN7BB-POR	0	0	*2.2 to2.8	Ramp D Congress Street to I-93 from Ramp Area F
BIN7BL-POR **BIN7BM**	0	0	*0 to 2.8	Ramp L I-93 North Bound to I-90 Eastbound – includes a short underpass from BIN7BM to BIN7BL
BIN7DE-POR **BIN7D5-POR** **BIN7DX-POR** **BIN7BN-POR**	0	0	*0 to 3.4	I-90 / I-93 Interchange: Ramp D tunnel exit to I-93 Southbound, I-90 West Bound tunnel exit, I-90 East Bound tunnel entrance and Ramp C entrance to I-93 Northbound / Tip O'Neill Tunnel
BIN7GA-POR **BIN7FX-POR** **BIN7FL-POR**	0	0	*0 to 1.9	Sumner Tunnel Exit: Ramp ST-CN to Central Artery Northbound, and Ramp ST-S to Storrow Drive Also, door to D6-SW25-FAC is located in the Boat Section outside (upstream) of BIN7GA-POR
BIN7HV-POR	0	0	*0 to 3.3	I-93 Northbound entrance to Ted Williams Tunnel
BIN7EK-POR **BIN7E7-POR** **BIN7F6-POR** **BIN7FQ-POR** **BIN7FN-POR**	0	0	*0 to 3.0	Rose Kennedy Greenway Parcel 6: Ramp SA-CS Surface Artery to Central Artery South, Ramp SA-CN Surface Artery to Central Artery North, Ramp SA-CT Surface Artery to Callahan Tunnel Ramp ST-SA Sumner Tunnel to Surface Artery Ramp ST-CN Sumner Tunnel to Central Artery North
BIN6HB	0	0	*0 to 3.3	I-93 Southbound exits from Ted Williams Tunnel and I-90 Collector

Estimated Local Adaptation Costs

Structure_ID	Estimated Wall Length (ft)	Estimated Cost ($Million)	Notes
D6A-DC03	1500	5.3	Wall around Complex also protects D6-ES10-FAC, D6-SMF-FAC, D6A-D3 and yards around them.
D6D-DC01	1400	4.9	Wall around Complex also protects D6D-D1-A, D6D-D1-B, D6D-D1-C, D6D-D1-D and D6D-D1, yards around them, but not entire parking lot.
HOC-D6	1640	5.7	Wall around Complex also protects D6-HOC-FAC, D6-ES02-FAC, D6-SW04-FAC (wall protects surface vent only, also needs watertight door, see note below).
D6-SW04-FAC	n/a	n/a	Needs **watertight door**, upstream of BIN7J8-POR; **installation recommended by 2013**
D6-FCB-FAC	49	0.2	
D6-SW07-FAC	279	1.0	
D6-SW09-FAC	197	0.7	
D6-SW16-FAC	39	0.1	
D6-SW25-FAC	n/a	n/a	Needs **watertight door**, upstream of BIN7GA-POR.
D6-SW17-FAC	66	0.2	
D6-SW27-FAC	n/a	n/a	Needs **watertight door**, upstream of BINC01-POR.
D6A-DC01	2116	7.4	Wall around Complex also protects D6-CMF-FAC, D6A-D1, MHRML and yards around them.
D6-HQC	1739	6.1	Wall around Complex also protects D6-185K-FAC, parking area north of I-90/I-93 interchange Boat Sections and adjacent electric power plant owned by others.
TB03-D6	n/a	n/a	Structures ERS07 and D6-TB03-FAC are protected by walls around buildings only; vehicles in this Complex to be relocated.
D6-TB03-FAC	381	1.3	See note above re: TB03-D6 Complex
ERS07	190	0.7	See note above re: TB03-D6 Complex
TA03-D6	787	2.8	Wall around Complex also protects D6-TA03-FAC and parking lot.
D6-VB11-FAC	328	1.1	
D6-VB12-FAC	328	1.1	
D6-VB13-FAC	328	1.1	
D6-VB6-FAC	951	3.3	Wall around this Structure also protects TE061E and TE061W
D6-VB8-FAC	410	1.4	

Regional Adaptation





Regional Adaptation Planning	Regional Flood Entry Points														
	Sullivan Square			East Boston Greenway / Border Street / Wood Island / Jefferies Point			Granite Avenue			Fort Point Channel			Charles River Dam		
General Description	The regional flood entry point in the vicinity of Sullivan Square is located at the Schrafft's building and parking area, shown below. This location, downstream of the Amelia Earhart Dam on the Mystic River, is prone to potential flooding under current day storm surge conditions through a fairly well confined flood entry point, as shown in the 2013 Flood Probability results. Sea water that enters through the parking lot propagates upland and is able to inundate a significant spatial area, impacting multiple structures, roadways, and parcels. In the 2030 and 2070 (eventually flanking the Charles River Dam) projections, the extent of upland flooding increases; however, the flood entry point remains relatively confined to the same location, making this an ideal site for a regional adaptation.			This regional flood entry point is located at the East Boston Greenway adjacent to Logan International Airport. At this location, flooding initially occurs along a 1,500-2,000 linear foot stretch of the Boston Harbor shoreline, but is subsequently confined to a fairly narrow (approximately 50 foot) flood pathway (the Greenway) extending to the northeast and spreading to a larger regional area, including portions of Logan International Airport. While other potential flood pathways develop to add to the flooding of the East Boston area by 2030 and 2070, the East Boston Greenway remains confined to a fairly focused pathway and a regional solution implemented at this location would cover a wide range of storm events, including covering the more probable moderate events in future years. In 2030, flooding expands via a secondary flood pathway exists initiating at the Border Street, Liberty Plaza area that spans approximately 1,500 to 2,000 feet. In 2070, flood entry points at the Wood Island area and the Jeffries Point area that contribute to the overall flooding risk initially started at the East Boston Greenway.			The location consists of two distinct flood entry points that flood a large MassDOT parcel, but also flood local neighborhoods and roadways. The flood pathways occur on both sides of the MassDOT parcel. At this location, there is a viable threat of flooding even under current day conditions, and that threat is expanded in frequency, magnitude, and extent of flooding in the future.			This location is at the far upstream end of the Fort Point Channel. There is a railroad crossing on the western side of Fort Point Channel that resides at a lower elevation than the surrounding wall bordering the channel. This flood pathway becomes prevalent in the 2070 and 2100 time frames and represents a narrow flood entry point that produces flooding over a large urban area, including major roadways and significant MassDOT facilities.			The Charles River Dam and adjacent local flanked areas represent another regional flood pathway that impacts significant MassDOT facilities. This flood pathway occurs with dam overtopping and flanking in 2070 and 2100 scenarios. This flood entry point impacts the upstream areas of the Charles River, including Cambridge.		
Site Overview at Flood Entry Point and Flood Pathway (Black Arrows)															
MassDOT Facilities Protected by Potential Regional Adaptation	Complex D6A-DC03 and all associated Structures, D6-ESS3-FAC, D6-SW18-FAC, BINtc1-POR, BINLt1-POR,BIN-tc1-POR			BIN9BW-POR, BIN9BV-POR, BINmL2-POR, BIN9CU-POR,BIM9CT-POR, BINA07-POR, BINC00-POR, D6-TA03-FAC, D6-TB03-FAC, ERS07, D6-VB13-FAC, D6-VB11-FAC, TA03-D6, SW06			D6D-DC01, D6D-D1, D6D-D1-B, D6D-D1-A, D6D-D1-C, and D6D-D1-D			D6-FCB-FAC, D6-HQC, D6-185K-FAC, D6-SW07-FAC, D6-SW09-FAC, TE173, TE183, TE310, TE201, VG99, BIN62B-POR, BIN78N-POR, BIN7DS-POR, BIN7DE-POR, BIN7DFPOR, BIN7DX-POR, BIN7HV-POR, BINco1-POR, BIN6HD-POR & BIN9P8-POR			D6-SW17-FAC, D6-LP09-FAC, D6-SW02-FAC, D6-VB8-FAC, TE601, TE605, TE606, TE609, TE611 & TE617, BIN7UG-POR, BIN7MG-POR, BIN7GC-POR, BIN5JR-POR, BIN59Y-POR, BIN59KPOR, BIN5K2-POR, BINss3-POR, BIss1 & BISAF-POR, TE526, BIN7E7-POR, BIN7EK-POR, BIN7F6-POR, BIN7FQ-POR, BIN7FN-POR		
Adaptation Concepts	Upland Flooding Potential	Recommended Engineering Adaptations	Estimated Adaptation Cost*	Upland Flooding Potential	Recommended Engineering Adaptations	Estimated Adaptation Cost*	Upland Flooding Potential	Recommended Engineering Adaptations	Estimated Adaptation Cost*	Upland Flooding Potential	Recommended Engineering Adaptations	Estimated Adaptation Cost*	Upland Flooding Potential	Recommended Engineering Adaptations	Estimated Adaptation Cost*
2013	Flood probabilities reach 1-2% for potential flood entry into this region. Depths of 1-1.5 feet maximum in flooded areas.	Modular Seawall installation fronting the Schrafft's parking area. The solution could also be integrated with closable doors and/or elevated walkways to provide access to the shoreline. Boat ramp would be closed.	Capital Cost: $3.0-3.5 million (1,000 foot length) Annual Maintenance Costs: $15,000	Flood probabilities reach 10% along the shoreline, with 1% risk of flooding advancing down the Greenway. Depths of 1.5 feet maximum in flooded areas down the Greenway.	Redevelopment of shoreline at the Greenway, including mix of gray and green resiliency design of shoreline fronting the Greenway, and elevated entry way to the greenway from the coastline.	Broad range of costs depending on conceptual solution developed. Detailed cost to be developed in next phases of design.	Flood probabilities reach 10% at the southern parking lot, with 2% risk at the existing building structures. Depths of a maximum of 0.5 - 1 feet	Increased elevation through use of natural berms at both flood pathway locations.	Capital Cost: $1.0-1.5 million Annual Maintenance Costs: $30,000	No Flooding Expected	No Action Required	N/A	No Flooding Expected	No Action Required	N/A
2030 (High Sea Level Rise Projection)	Flood probabilities reach 20-25% for potential flood entry into this region. Depths of 2.5-3 feet maximum in flooded areas.	No modification required to 2013 solution	N/A	Flood probabilities reach 25% along the shoreline, with 2-5% risk of flooding advancing down the Greenway. A secondary flood entry point develops near Border Street. Depths of 2.5-3 feet maximum in flooded areas down the Greenway.	In addition to above: - Improved revetment and enhanced bioengineered berm along the shoreline in vicinity of Liberty Plaza and Border St. A mix of gray and green resiliency design.	Broad range of costs depending on conceptual solution developed. Detailed cost to be developed in next phases of design.	Flood probabilities reach 50% at the southern parking lot, with 10-20% risk at the existing building structures. Depths of a maximum of 1.5-2.0 feet.	No modification required to 2013 solution	N/A	No Flooding Expected	No Action Required	N/A	No Flooding Expected	No Action Required	N/A
2070 (High Sea Level Rise Projection)	Flood probabilities reach 50% (2-year return period water level) for potential flood entry into this region. Depths of 5-10 feet maximum in flooded areas.	Phased increases in elevation and length of seawall	Capital Cost: $10.0-12.0 million (3,500 ft additional length) Annual Maintenance Costs: $25,000	Flood probabilities reach 50% throughout the area, with depths reaching maximums of 10 feet. Two additional flood pathways develop at Wood Island and Jeffries Point.	In addition to above: - Marsh restoration and natural shoreline enhancement at Wood Island entry way. - Enhancement of Massport Harbor Walk along the Jefferies point region with seawall	Broad range of costs depending on conceptual solution developed. Detailed cost to be developed in next phases of design.	Flood probabilities reach 50% throughout the area, with depths reaching maximums of 5 feet.	Compliment natural berms with targeted walls in locations to reduce flood risk.	Capital Cost: $5.0-7.0 million Annual Maintenance Costs: $15,000	Flood probabilities reach 10% for potential flood entry into this region. Depths of 3-4 feet maximum in flooded areas.	Increased elevation to existing Fort Point Channel wall and design of a removable flood barrier at RR crossing	Capital Cost: $5-6 million Annual Maintenance Costs: N/A	Flood probabilities reach 10% for potential flood entry into this region. Depths of 3 flanking the dam on the south side.	Potential adaptations involve raising the dam, and designing systems to reduce potential flanking of the dam on the south side. Solutions related to the Sullivan Square flood pathway must also be included.	These costs would need to be developed based on site specific engineering development.

* = Initial Capital Costs and Operational and Maintenance costs provided are rough estimates based on costs from similar types of projects. More detailed and accurate costs would be required for actual engineering and construction. Estimated costs are based on 2015 dollar value.

\# - Depends on length of seawall installed.

Summary and Lessons learned

- Inventoried large number of CA/T Facilities & Structures
  - →Big lessons: Institutional Knowledge and field work were key allow ~3 months for "discovery"
- Assessed MassDOT's preferences for flood management and vulnerability definition
  - →Big lesson: uncertainty requires flexibility in approach
- Developed high resolution hydrodynamic model simulate the impacts of extratropical and tropical storms, freshwater inflows and flood-control dam operations
- Applied a Monte Carlo approach to estimate probability of flooding under current and future sea level rise scenarios.
  - →Big lesson: computational time grows exponentially with time

Good News and Bad News

The good news:

- Extent of flooding under current conditions is fairly limited with low exceedance probabilities. This allows MassDOT to focus their efforts on reducing the vulnerability of individual Structures and on local adaptation strategies.
- Regional adaptation can prevent flooding in some areas

The bad news:

- Vulnerable Structures under current conditions include some Tunnel Portals; the number of vulnerable Portals triples by 2070.
- Cost for protecting non-boat section structures through 2100 ~$47 million.
- Cost to protect tunnel entrances under current conditions ~$27 million, with another ~$150 million to protect through 2100.

- Final report submitted to FHWA end of May 2015.
- Report and datalayers will be available on MassDOT website soon.

QUESTIONS?