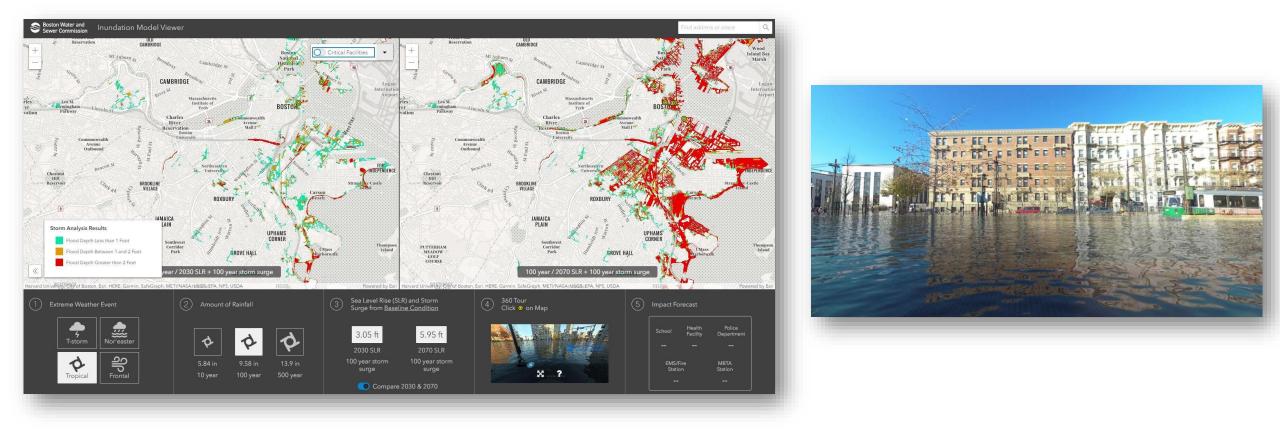
Simulating, Evaluating, and Visualizing Extreme Storm Flooding in

Boston Using Spatial Rainfall and 2D Flood Modeling





Charlie Jewell – Director of Planning and Sustainability, Boston Water and Sewer Commission Ben Agrawal, PE – Principal Engineer, Hazen and Sawyer Charles Wilson, PE – Associate Vice President, Hazen and Sawyer

### Agenda

- Background
- Storm event development
- Model development
- Demonstration of visualization tools
- Conclusions

nundation Overview	2		Neighbort	All	$\sim$	8	Ha	azer
	2	070						
Storm Summary				Population Impacted	Critical Facilities Map	ping		
Storm	Population Impacted	Critical Facilities Impacted	Cumulative Facilities Risk Level	OTotal Population   Population Impacted		ge		Dithro
Tropical (500-yr w/ 2070 SLR & 500-yr surge)	155,693	318	33052		Matschusen	4050	n (-	-) DEEL
Nor'easter (100-yr w/ 2070 SLR & 500-yr surge)	140,387	315	33645		Bost	XEX		
Nor'easter (50-yr w/ 2070 SLR & 100-yr surge)	128,242	261	24103		Charles and the second s	Part -	C)	
Tropical (500-yr w/ 2030 SLR & 500-yr surge)	105,138	210	17809		Brookline	COP.	BOSTON	E V
June 1998 Event (2070 SLR)	90,832	178	9974			200	HARBOR	
Thunderstorm (10-yr w/ 2070 SLR)	100,707	177	9674			200	-	
Fropical (100-yr w/ 2070 SLR & 100-yr surge)	80,989	166	15965			04	1950	
hunderstorm (10-yr w/ 2030 SLR)	72,053	113	2357	- 634.2K (100%)	HIGHLAND	at	Qu	incy Ba
Thunderstorm (2-yr w/ 2070 SLR)	54,673	107	7769	— 634.2K (100%)	Bing 2020 TomTom @ 2020 HERE	E. @ 2020 Micros	oft Corporation	Terms
June 1998 Event (2030 SLR)	60,841	106	1991	Critical Facility Impacts			_	
September 1999 Event (2070 SLR)	65,041	104	8183					
September 1999 Event (2010 SER)			0105	Critical Encility	Aug Duration (bro)	Max	Aug	May P
	50,138	102	And a second sec	Critical Facility	Avg Duration (hrs)			Max R
Frontal (50-yr w/ 2070 SLR)			8154	Critical Facility	Avg Duration (hrs)	Depth	Depth	Max R
Frontal (50-yr w/ 2070 SLR) Tropical (10-yr w/ 2070 SLR & 10-yr surge)	50,138	102	8154 8296			Depth (ft)	Depth (ft)	Max R
Frontal (50-yr w/ 2070 SLR) Fropical (10-yr w/ 2070 SLR & 10-yr surge) August 2017 Event (2070 SLR)	50,138 50,097	102	8154 8296 7643	EMS/Fire Stn	- 15.8	Depth (ft) 14.7	Depth (ft) 3.2	Max R
Frontal (50-yr w/ 2070 SLR) Tropical (10-yr w/ 2070 SLR & 10-yr surge) August 2017 Event (2070 SLR) Frontal (10-yr w/ 2070 SLR)	50,138 50,097 56,695 45,861	102 102 98	8154 8296 7643 8016	EMS/Fire Stn Engine Co. 9_2	• 15.8 36.1	Depth (ft) 14.7 14.4	Depth (ft) 3.2 6.1	Max R
Frontal (50-yr w/ 2070 SLR) Fropical (10-yr w/ 2070 SLR & 10-yr surge) August 2017 Event (2070 SLR) Frontal (10-yr w/ 2070 SLR) Nor'easter (100-yr w/ 2030 SLR & 100-yr surge)	50,138 50,097 56,695 45,861	102 102 98 96	8154 8296 7643 8016 5493	EMS/Fire Stn Engine Co. 9_2 Engine Co. 20	<b>15.8</b> 36.1 28.1	Depth (ft) 14.7 14.4 12.0	Depth (ft) 3.2 6.1 3.4	Max R
Frontal (50-yr w/ 2070 SLR) Tropical (10-yr w/ 2070 SLR & 10-yr surge) August 2017 Event (2070 SLR) Frontal (10-yr w/ 2070 SLR) Nor'easter (100-yr w/ 2030 SLR & 100-yr surge) Nor'easter (10-yr w/ 2070 SLR)	50,138 50,097 56,695 45,861 41,392	102 102 98 96 87	8154 8296 7643 8016 5493 4765	EMS/Fire Stn Engine Co. 9_2 Engine Co. 20 Fire Alarm	<b>15.8</b> 36.1 28.1 18.8	Depth (ft) 14.7 14.4 12.0 11.2	Depth (ft) <b>3.2</b> 6.1 3.4 3.4 3.4	Max R
Frontal (50-yr w/ 2070 SLR) Tropical (10-yr w/ 2070 SLR & 10-yr surge) August 2017 Event (2070 SLR) Frontal (10-yr w/ 2070 SLR) Nor'easter (100-yr w/ 2030 SLR & 100-yr surge) Nor'easter (10-yr w/ 2030 SLR & 100-yr surge)	50,138 50,097 56,695 45,861 41,392 45,772	102 102 98 96 87 87 87	8154 8296 7643 8016 5493 4765 5393	EMS/Fire Stn Engine Co. 9_2 Engine Co. 20 Fire Alarm Station 14 Ambulance 14	<b>15.8</b> 36.1 28.1	Depth (ft) 14.7 14.4 12.0	Depth (ft) 3.2 6.1 3.4 3.4 3.4 2.3	Max R
Frontal (50-yr w/ 2070 SLR) Tropical (10-yr w/ 2070 SLR & 10-yr surge) August 2017 Event (2070 SLR) Frontal (10-yr w/ 2070 SLR) Nor'easter (10-yr w/ 2030 SLR & 100-yr surge) Nor'easter (50-yr w/ 2030 SLR & 100-yr surge) Tropical (100-yr w/ 2030 SLR & 100-yr surge)	50,138 50,097 56,695 45,861 41,392 45,772 38,708	102 102 98 96 87 87 87 87 87	8154 8296 7643 8016 5493 4765 5393 3698	EMS/Fire Stn Engine Co. 9_2 Engine Co. 20 Fire Alarm	<b>15.8</b> 36.1 28.1 18.8	Depth (ft) 14.7 14.4 12.0 11.2	Depth (ft) <b>3.2</b> 6.1 3.4 3.4 3.4	Max R
Frontal (50-yr w/ 2070 SLR) Fropical (10-yr w/ 2070 SLR & 10-yr surge) August 2017 Event (2070 SLR) Frontal (10-yr w/ 2070 SLR) Nor'easter (100-yr w/ 2030 SLR & 100-yr surge) Nor'easter (50-yr w/ 2030 SLR & 100-yr surge) Fropical (100-yr w/ 2030 SLR & 100-yr surge) September 1999 Event (2030 SLR)	50,138 50,097 56,695 45,861 41,392 45,772 38,708 39,121	102 102 98 96 87 87 87 87 87 87 83 83 83	8154 8296 7643 8016 5493 4765 5393 3698 1043	EMS/Fire Stn Engine Co. 9_2 Engine Co. 20 Fire Alarm Station 14 Ambulance 14	<b>15.8</b> 36.1 28.1 18.8 18.3	Depth (ft) 14.7 14.4 12.0 11.2 6.1	Depth (ft) 3.2 6.1 3.4 3.4 3.4 2.3	Max R
Frontal (50-yr w/ 2070 SLR) Fropical (10-yr w/ 2070 SLR & 10-yr surge) August 2017 Event (2070 SLR) Frontal (10-yr w/ 2070 SLR) Nor'easter (10-yr w/ 2030 SLR & 100-yr surge) Nor'easter (50-yr w/ 2030 SLR & 100-yr surge) Tropical (100-yr w/ 2030 SLR & 100-yr surge) September 1999 Event (2030 SLR) Fhunderstorm (2-yr w/ 2030 SLR)	50,138 50,097 56,695 45,861 41,392 45,772 38,708 39,121 28,546	102 102 98 96 87 87 87 87 87 87 83 83 83	8154 8296 7643 8016 5493 4765 5393 3698 1043 848	EMS/Fire Stn Engine Co. 9_2 Engine Co. 20 Fire Alarm Station 14 Ambulance 14 Engine Co. 37_26	<b>15.8</b> 36.1 28.1 18.8 18.3 15.5	Depth (ft) 14.7 14.4 12.0 11.2 6.1 3.1	Depth (ft) <b>3.2</b> 6.1 3.4 3.4 2.3 1.2	Max R
Frontal (50-yr w/ 2070 SLR) Fropical (10-yr w/ 2070 SLR & 10-yr surge) August 2017 Event (2070 SLR) Frontal (10-yr w/ 2070 SLR) Nor'easter (10-yr w/ 2030 SLR & 100-yr surge) Nor'easter (50-yr w/ 2030 SLR & 100-yr surge) Fropical (100-yr w/ 2030 SLR & 100-yr surge) September 1999 Event (2030 SLR) Fhunderstorm (2-yr w/ 2030 SLR) Hurricane Dorian	50,138 50,097 56,695 45,861 41,392 45,772 38,708 39,121 28,546 20,848	102 102 98 96 87 87 87 87 87 83 83 83 5 35	8154 8296 7643 8016 5493 4765 5393 3698 1043 848 983	EMS/Fire Stn Engine Co. 9_2 Engine Co. 20 Fire Alarm Station 14 Ambulance 14 Engine Co. 37_26 Station 16 Ambulance 16	<b>15.8</b> 36.1 28.1 18.8 18.3 15.5 14.8	Depth (ft) 14.7 14.4 12.0 11.2 6.1 3.1 7.6	Depth (ft) 3.2 6.1 3.4 2.3 1.2 2.7	Max R
Frontal (50-yr w/ 2070 SLR) Fropical (10-yr w/ 2070 SLR & 10-yr surge) August 2017 Event (2070 SLR) Frontal (10-yr w/ 2070 SLR) Nor'easter (10-yr w/ 2030 SLR & 100-yr surge) Nor'easter (10-yr w/ 2030 SLR & 100-yr surge) Fropical (100-yr w/ 2030 SLR & 100-yr surge) September 1999 Event (2030 SLR) Thunderstorm (2-yr w/ 2030 SLR) Hurricane Dorian Nor'easter (50-yr w/ 2070 SLR)	50,138 50,097 56,695 45,861 41,392 45,772 38,708 39,121 28,546 20,848 24,221	102 102 98 96 87 87 87 87 87 83 83 83 83 83 83 83 83 83 83 83 83 83	8154 8296 7643 8016 5493 4765 5393 3698 1043 848 983 1412	EMS/Fire Stn Engine Co. 9_2 Engine Co. 20 Fire Alarm Station 14 Ambulance 14 Engine Co. 37_26 Station 16 Ambulance 16 Station 15 Ambulance 15	<b>15.8</b> 36.1 28.1 18.8 18.3 15.5 14.8 14.8	Depth (ft) 14.7 14.4 12.0 11.2 6.1 3.1 7.6 9.0	Depth (ft) 3.2 6.1 3.4 2.3 1.2 2.7 3.1	Max R
Frontal (50-yr w/ 2070 SLR) Fropical (10-yr w/ 2070 SLR & 10-yr surge) August 2017 Event (2070 SLR) Frontal (10-yr w/ 2070 SLR) Nor'easter (100-yr w/ 2030 SLR & 100-yr surge) Nor'easter (50-yr w/ 2030 SLR & 100-yr surge) Fropical (100-yr w/ 2030 SLR & 100-yr surge) September 1999 Event (2030 SLR) Fhunderstorm (2-yr w/ 2030 SLR) Hurricane Dorian Nor'easter (50-yr w/ 2070 SLR) August 2017 Event (2030 SLR)	50,138 50,097 56,695 45,861 41,392 45,772 38,708 39,121 28,546 20,848 24,221 45,021	102 98 96 87 87 87 87 83 35 34 34 32 27 27 25	8154 8296 7643 8016 5493 4765 5393 3698 1043 848 983 1412 751	EMS/Fire Stn Engine Co. 9_2 Engine Co. 20 Fire Alarm Station 14 Ambulance 14 Engine Co. 37_26 Station 16 Ambulance 16 Station 15 Ambulance 15 Engine Co. 33_15	▼	Depth (ft) 14.7 14.4 12.0 11.2 6.1 3.1 7.6 9.0 1.2	Depth (ft) 3.2 6.1 3.4 2.3 1.2 2.7 3.1 1.0	Max F
September 1935 Letti (2010 SLR) Frontal (50-yr w/ 2070 SLR) Tropical (10-yr w/ 2070 SLR & 10-yr surge) August 2017 Event (2070 SLR) Frontal (10-yr w/ 2030 SLR & 100-yr surge) Nor'easter (100-yr w/ 2030 SLR & 100-yr surge) Nor'easter (50-yr w/ 2030 SLR & 100-yr surge) September 1999 Event (2030 SLR) Thunderstorm (2-yr w/ 2030 SLR) Hurricane Dorian Nor'easter (50-yr w/ 2070 SLR) August 2017 Event (2030 SLR) Frontal (50-yr w/ 2030 SLR) Nor'easter (50-yr w/ 2030 SLR)	50,138 50,097 56,695 45,861 41,392 45,772 38,708 39,121 28,546 20,848 24,221 45,021 19,749	102 98 96 87 87 87 87 83 35 34 34 32 27 27 25	8154 8296 7643 8016 5493 4765 5393 3698 1043 848 983 1412 751 926	EMS/Fire Stn Engine Co. 9_2 Engine Co. 20 Fire Alarm Station 14 Ambulance 14 Engine Co. 37_26 Station 16 Ambulance 16 Station 15 Ambulance 15 Engine Co. 33_15 Station 11 Ambulance 11	▼ 15.8 36.1 28.1 18.8 18.3 15.5 14.8 14.8 8.6 7.5	Depth (ft) 14.4 12.0 11.2 6.1 3.1 7.6 9.0 1.2 5.8	Depth (ft) 3.2 6.1 3.4 2.3 1.2 2.7 3.1 1.0 1.8	Max R

### Background

- Hurricane Harvey
  (Texas, 2017)
- Develop tool and understanding of risks for emergency planning
- Identify where flooding occurs, how long, and who and what is impacted
- Communicate flood impacts to nontechnical stakeholders

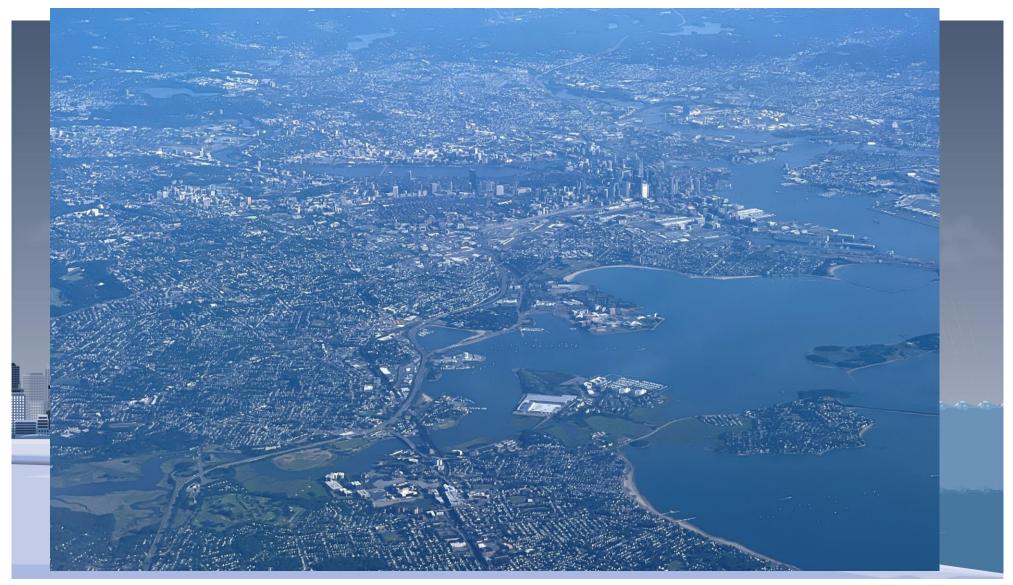




## Inundation Model - Project Overview

- 1. Develop 2D model that will estimate and graphically display inundation information using most current projections available.
- 2. Model will allow identification of land area, buildings and roads impacted by major events.
- 3. Model can be used as an early warning tool to pre-evacuate potentially impacted areas.
- 4. Estimate the projected depth and duration of inundation
- 5. Estimate potential population impacted
- 6. Identify critical facilities impacted by inundation
- 7. Utilize model as a collaboration tool with other agencies with data available and accepted by other entities
- 8. Have the information Peer Reviewed by outside entity.

### **Boston – Coastal and Stormwater Flooding**

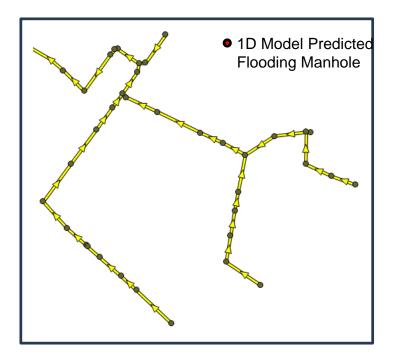


The Inundation Model considers the impact of coastal flooding and inland stormwater flooding

### 1D vs. 2D Modeling

#### **1D Modeling**

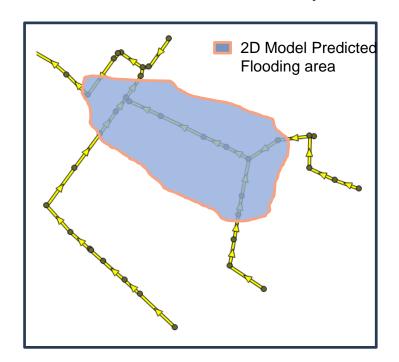
- Flows are limited in pipes
- No predicted flow movement once water leaves piping network





#### **2D Modeling**

- 2D mesh for surface flow
- Flow not limited to pipes
- Surface flows are predicted once water leaves piping network or enters from coastal boundary



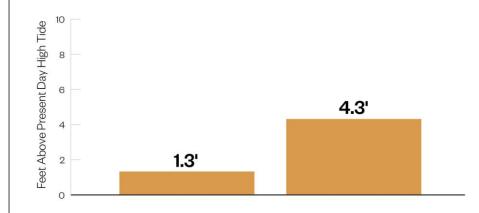
## Thunderstorm

#### **Storm Motion**

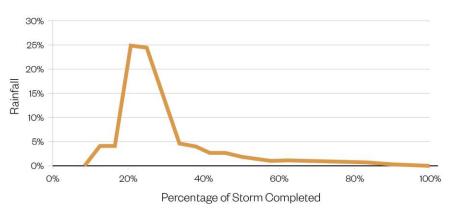


Storm Direction: **66.0 degrees | Northeast** Speed: **25 miles per hour** 

#### Sea Level Rise (SLR)



#### **Storm Accumulation**



#### Rainfall

- Logan Airport Rain Gauge: 3,100 Events
- May 1948 May 2018
- Develop parameters for characteristic rainfall distributions and motions

#### **Coastal Boundary Conditions**

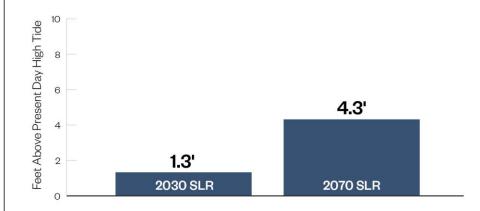
- Massachusetts Coast Flood Risk Model
- Hydrodynamic model
- Sea level rise and storm surge predictions for 2030 and 2070

## Frontal

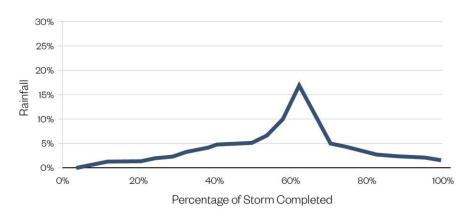


Storm Direction: **56.3 degrees | Northeast** Speed: **26.4 miles per hour** 

#### Sea Level Rise (SLR)



#### **Storm Accumulation**



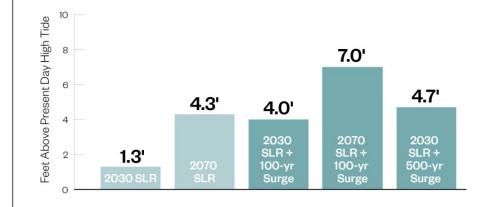
## Nor'easter

#### **Storm Motion**

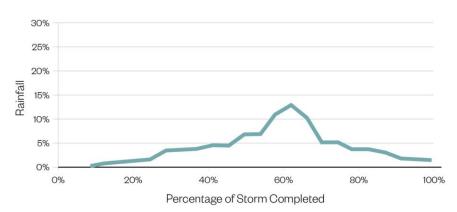


Storm Direction: 270.0 Degrees | West Speed: 21.1 miles per hour

#### Sea Level Rise (SLR) and Storm Surge



#### **Storm Accumulation**



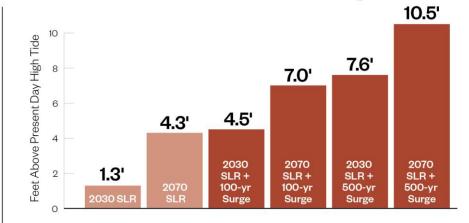
## Tropical

#### **Storm Motion**

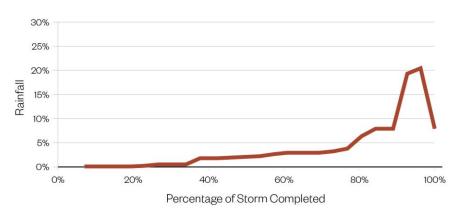


Storm Direction: **270.0 Degrees | West** Speed: **24.8 miles per hour** 

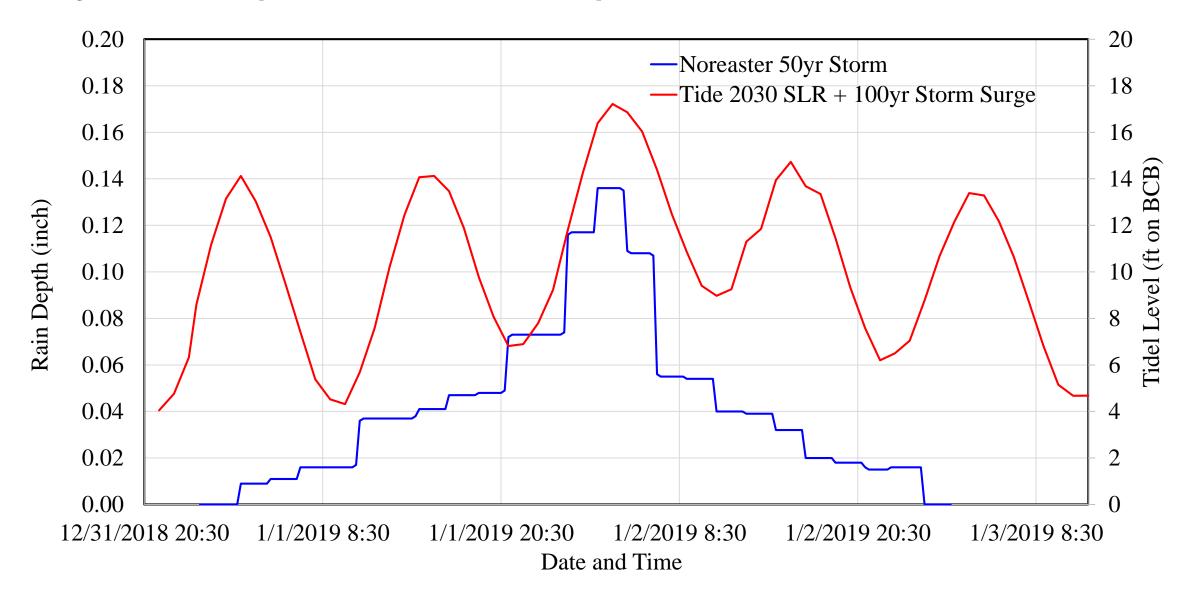
#### Sea Level Rise (SLR) and Storm Surge



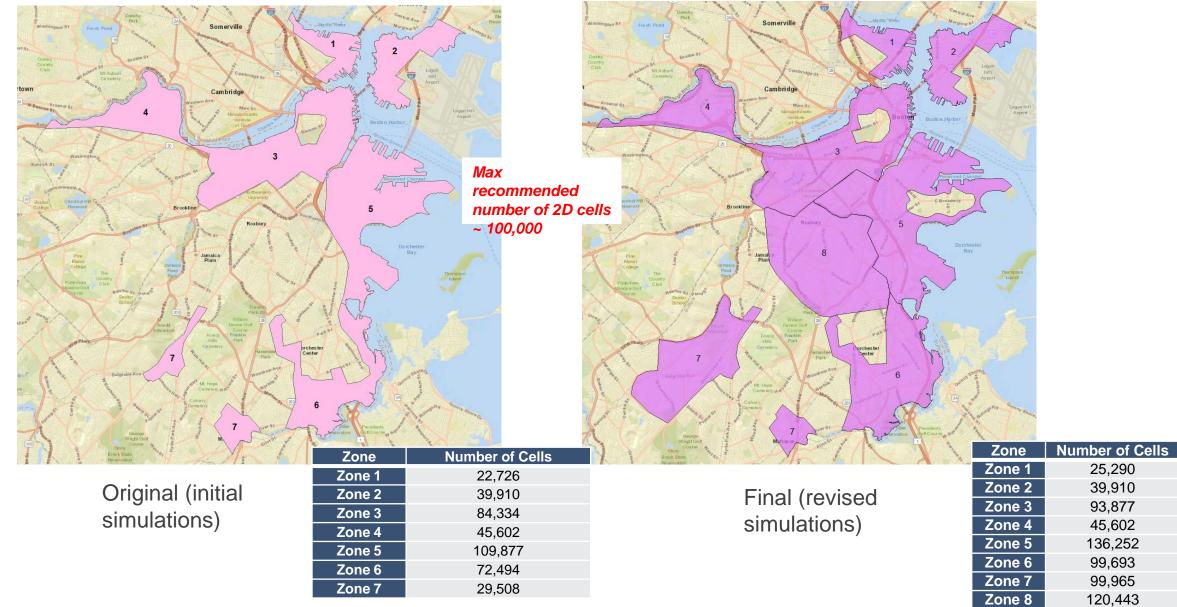
#### **Storm Accumulation**



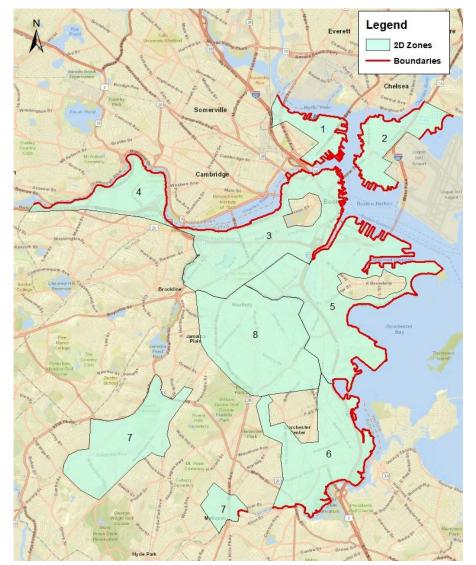
### **Tide Cycle & Precipitation – Model Example**

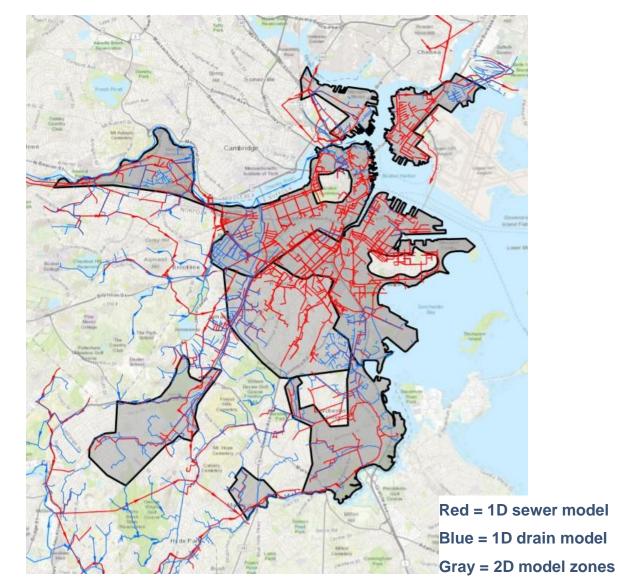


### **2D Zones – Citywide**



### **Combined Sewer, Drain, and 2D Model**





### **Baseline Simulations Completed**

Model Scenario	Dur. (hr)	Depth (in)	Return Period (yr)	Speed (mph)	Hyetograph Shape	Coastal Boundary Condition #1	Coastal Boundary Condition #2	
1) Airmass	6	1.83	2	25.0		2030 SLR	2070 SLR	
2) Airmass	6	3.20	10	25.0		2030 SLR	2070 SLR	
3) Nor'easter	48	5.84	10	21.1		2030 SLR	2070 SLR	
4) Nor'easter	48	8.46	50	21.1	-	2030 SLR	2070 SLR	
5) Nor'easter	48	8.46	50	21.1		100-year storm surge + 2030 SLR	100-year storm surge + 2070 SLR	
6) Nor'easter	48	9.58	100	21.1		100-year storm surge + 2030 SLR	500-year storm surge + 2070 SLR	
7) Frontal	72	6.34	10	26.4		2030 SLR	2070 SLR	
8) Frontal	72	9.15	50	26.4		2070 SLR	2070 SLR	
9) Tropical	48	5.84	10	24.8		2030 SLR	2070 SLR	
10) Tropical	48	9.58	100	24.8		100-year storm surge + 2030 SLR	100-year storm surge + 2070 SLR	
11) Tropical	48	13.9	500	24.8		500-year storm surge + 2030 SLR	500-year storm surge + 2070 SLR	
12) August 2, 2017	9	3.44	200 <sup>2</sup>	N/A <sup>1</sup>		2030 SLR	2070 SLR	
13) June 12, 1998	43	6.77	10	N/A <sup>1</sup>		2030 SLR	2070 SLR	
14) September 10, 1999	17	4.7	10	N/A <sup>1</sup>		2030 SLR	2070 SLR	
15) Dorian	33	10.41				2030 SLR		

240+2D simulations completed

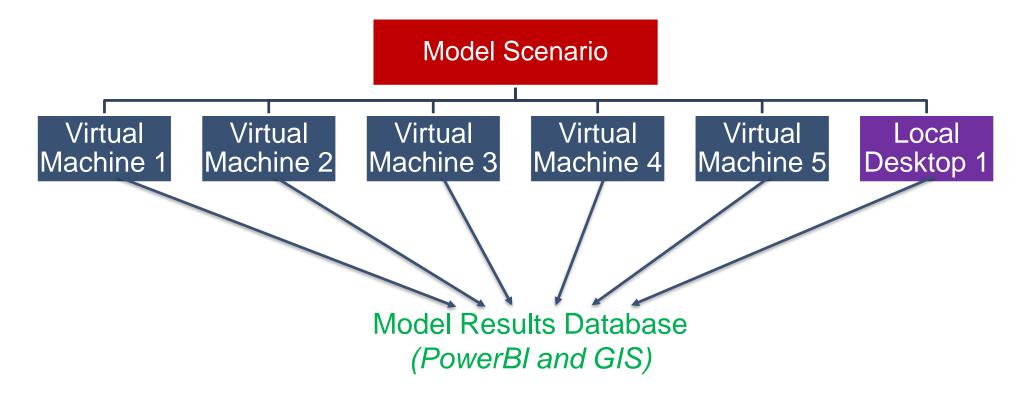
### **Simulation Strategy**

#### **Challenges:**

- Model Run Time Simulating a 48-hour storm requires almost 5 days
- Huge amount of data generated

#### Solutions:

- Utilize multiple virtual machines to run different 2D models simultaneously avoided over 365 days of continuous model simulation time!
- Develop database for data management

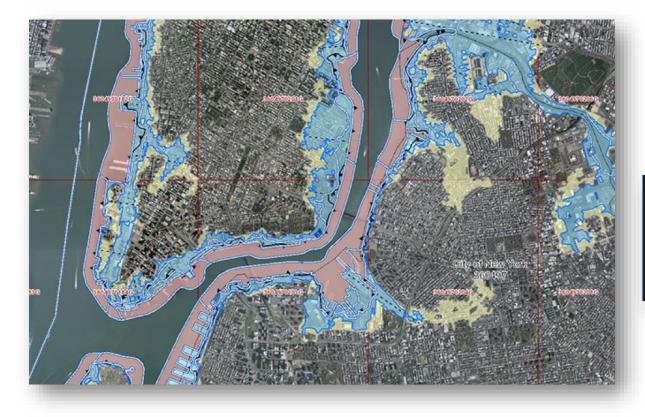


### **Interpretation of Model Results & Demonstrations**

Science News

from research organizations

New climate modeling predicts increasing occurrences of flash flooding across most of the U.S.

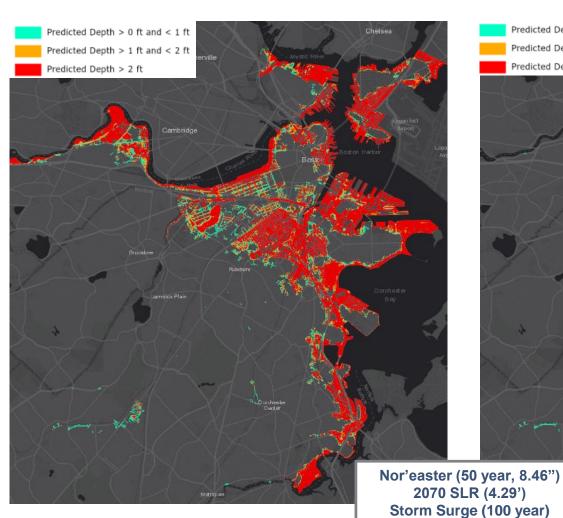


# In worst case climate, rain and storm surge combine often for extreme flooding

A study published Thursday found that the changing nature of storms like hurricanes could play a larger part than scientists had expected in worsening floods.

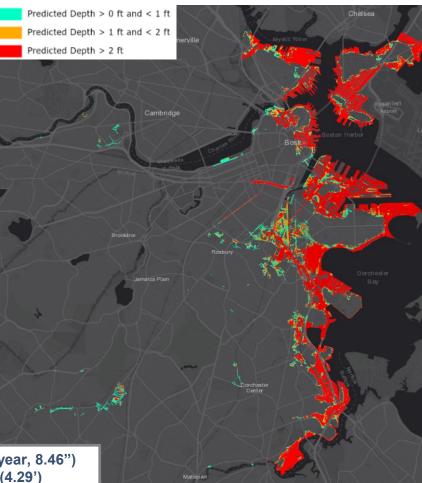
### Conclusions

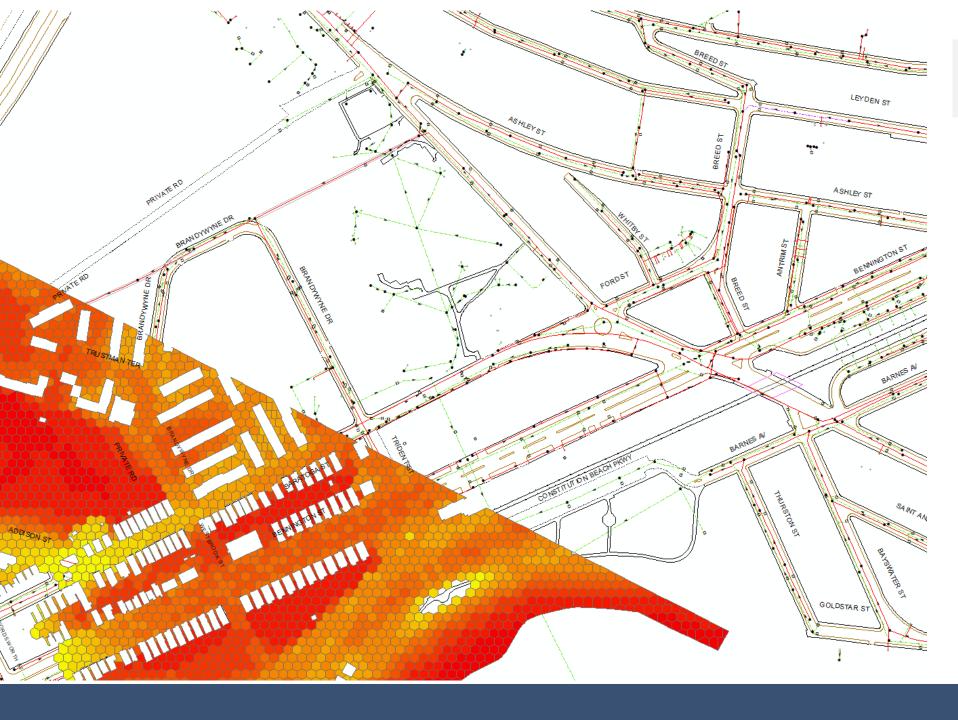
- Identify "citywide" vulnerabilities
- Collaboration
- Plan for continuous
  improvement/evolvement



No Action Scenario

#### Fort Point Channel & Charles River Dam Protection

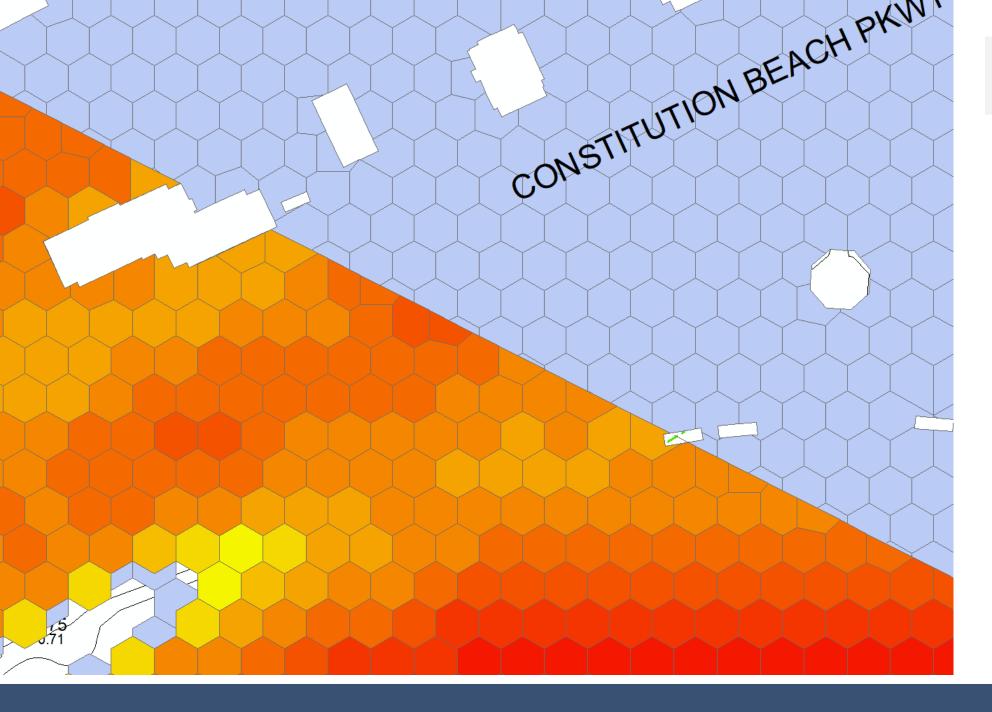




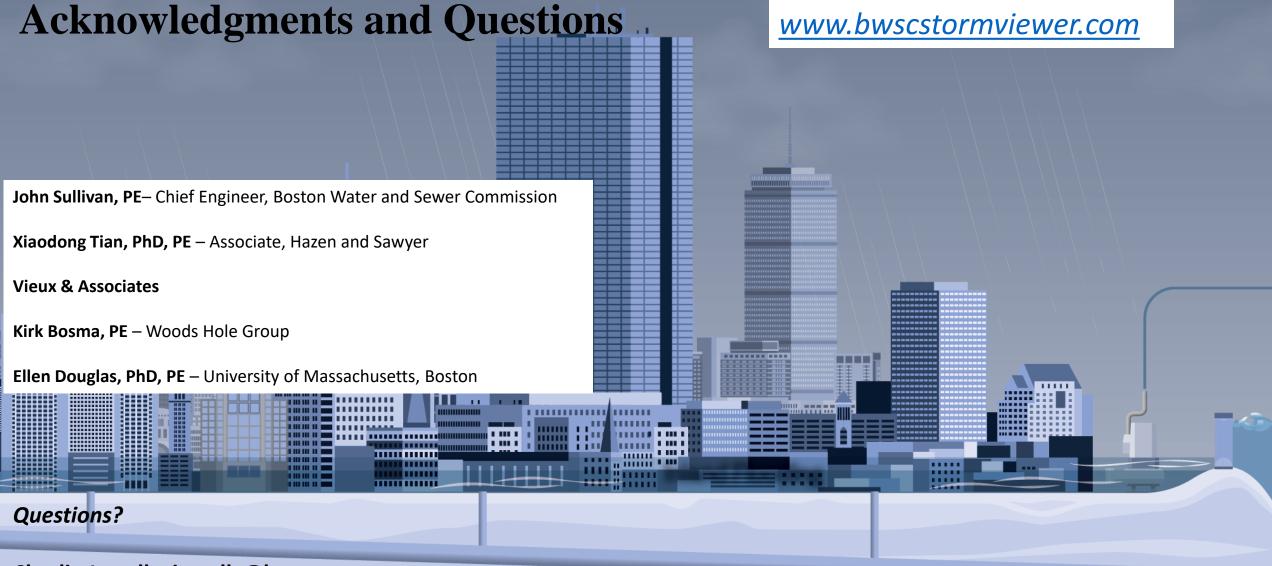
Nor'easter – 2070 – 100 year storm with Sea Level Rise and Storm Surge



Nor'easter – 2070 – 100 year storm with Sea Level Rise and Storm Surge



Nor'easter – 2070 – 100 year storm with Sea Level Rise and Storm Surge



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Chuck Wilson, PE – cwilson@hazenandsawer.com



