Evaluating and Improving the Resilience of Wastewater Treatment Facilities and Above Ground Storage Tanks in Upper Narragansett Bay to Coastal Flooding

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Ocean Engineering Senior Design OCE 496

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Thank You, Narragansett Bay Commission

Outline

- Problem Statement
- Study Objectives
- Methodology
- Results
- Summary and Conclusion

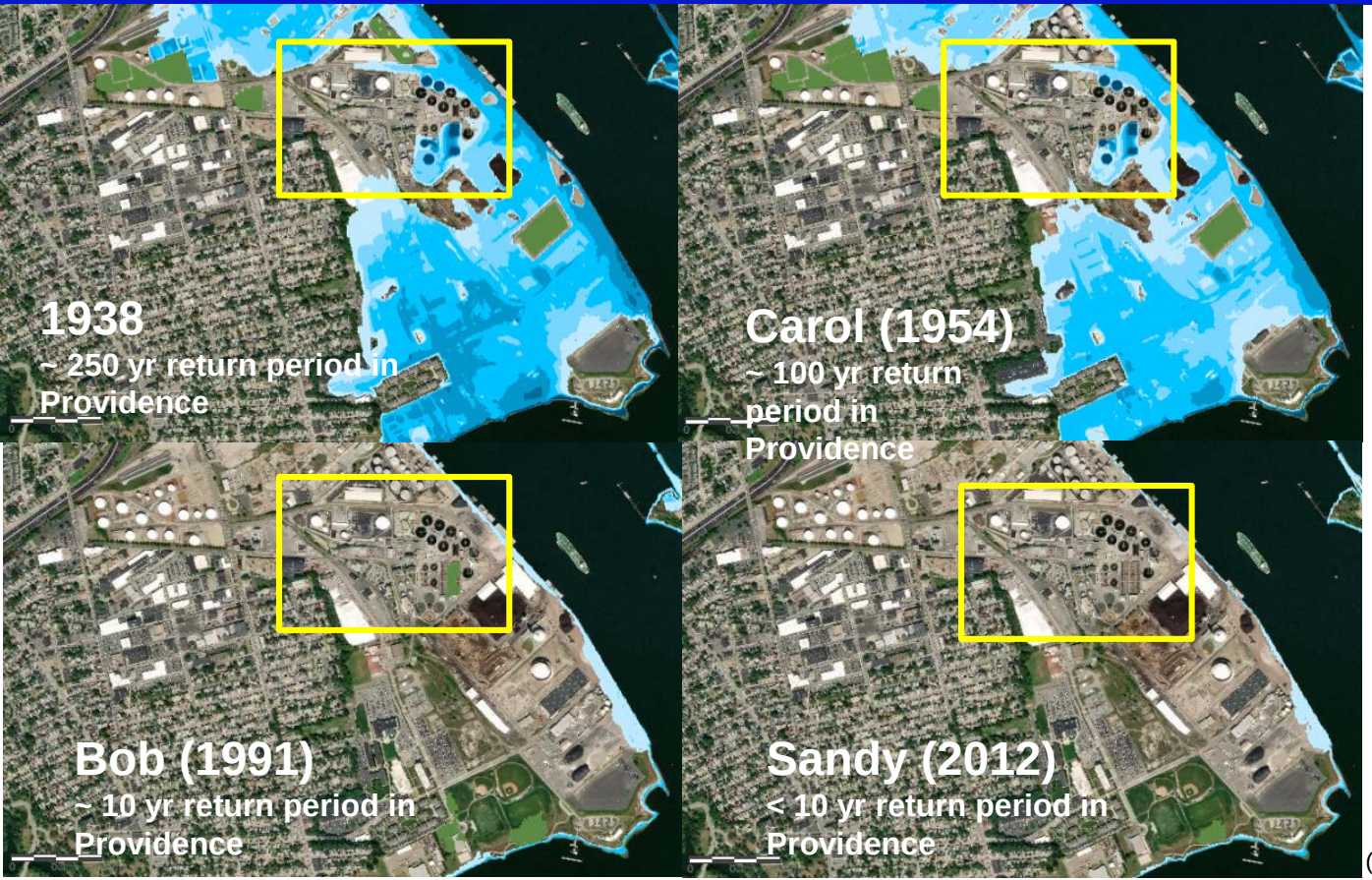
Problem Statement: Infrastructure in Providence, RI

- Infrastructure in upper Narragansett Bay are subjected to the threat of flooding from storm surge with sea level rise
- When structures/infrastructure were originally designed, sea level rise was not considered. Fields Pt. WWTF built in 1901, Bucklin Pt. WWTF built in 1954
- FEMA FIRMS, the current regulatory practice, does not account for impact of sea level rise

Flooding from the 1938 Hurricane in downtown Providence.

(Providence Journal, 2018)

Historical Storm Inundation at Fields Point

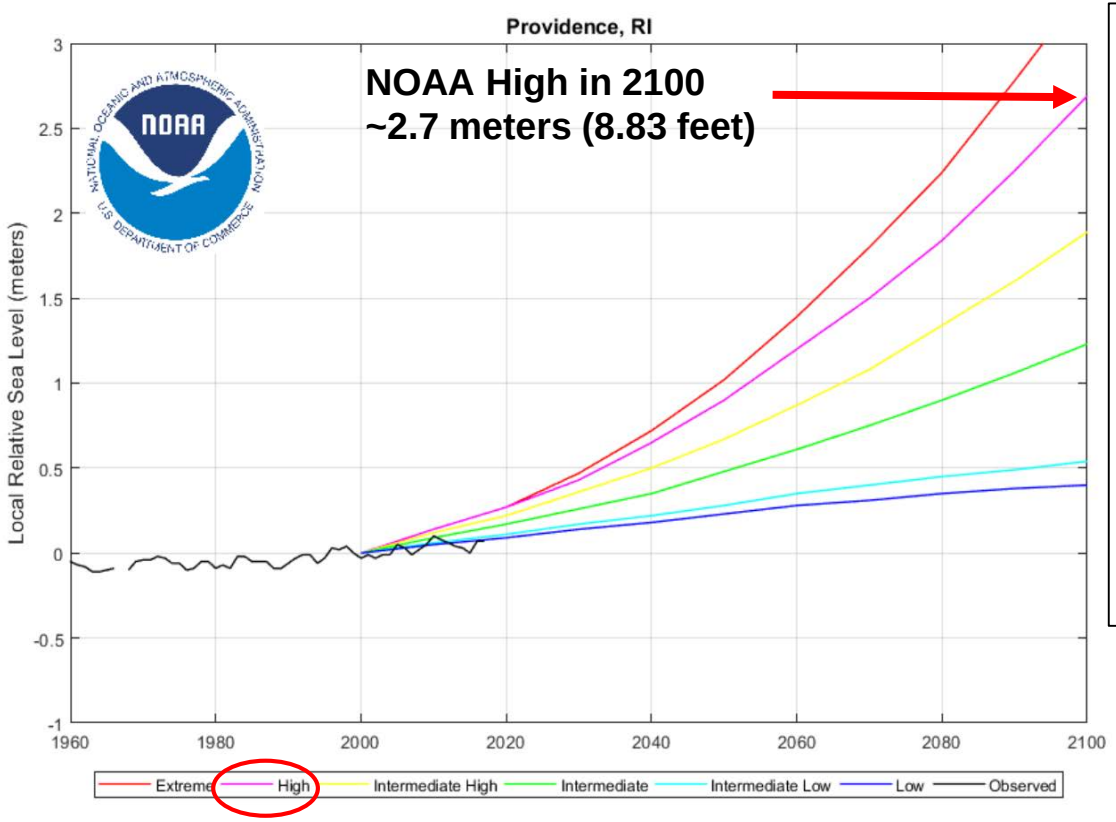


Inundation Level
(feet, depth above grade)

- <= 2
- 4
- 6
- 8
- 10
- > 10
- Lowlying

(STORMTOOLS, 2018)

Problem Statement: Sea Level Rise



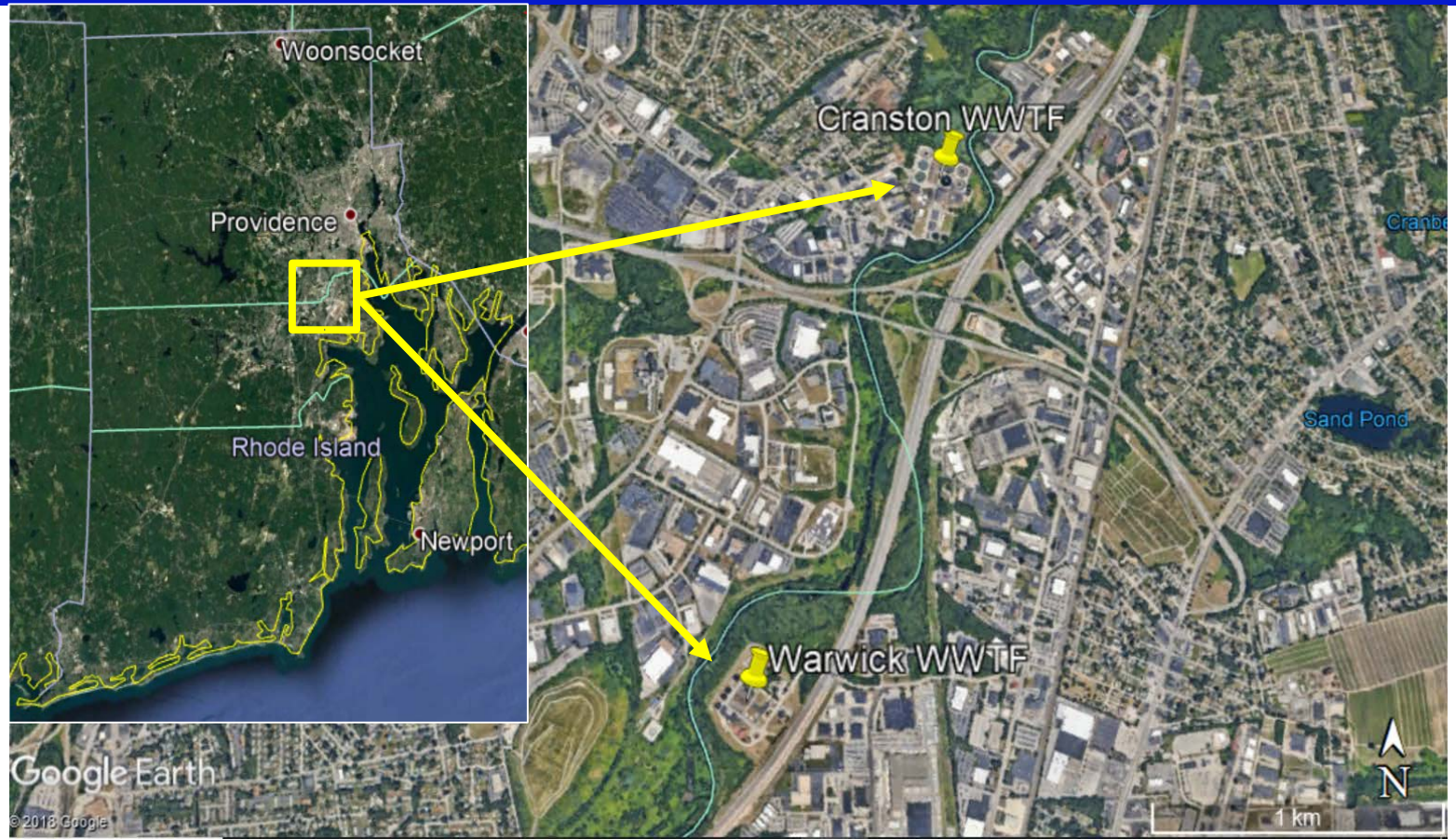
Providence
Scenarios for PROVIDENCE
NOAA2017 VLM: 0.00200 feet/yr
All values are expressed in feet

Year	NOAA2017 VLM	NOAA2017 Low	NOAA2017 Int-Low	NOAA2017 Intermediate	NOAA2017 Int-High	NOAA2017 High	NOAA2017 Extreme
2000	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2010	0.02	0.16	0.20	0.30	0.39	0.46	0.46
2020	0.04	0.30	0.36	0.56	0.72	0.89	0.89
2030	0.06	0.46	0.56	0.85	1.18	1.41	1.54
2040	0.08	0.59	0.72	1.15	1.64	2.13	2.36
2050	0.10	0.75	0.92	1.57	2.20	2.95	3.35
2060	0.12	0.92	1.15	2.00	2.85	3.94	4.56
2070	0.14	1.02	1.31	2.46	3.54	4.92	5.91
2080	0.16	1.15	1.48	2.95	4.40	6.04	7.35
2090	0.18	1.25	1.61	3.48	5.25	7.38	9.12
2100	0.20	1.31	1.77	4.04	6.20	8.83	10.96
2120	0.24	1.41	2.03	4.56	7.74	11.88	14.80
2150	0.30	1.64	2.49	6.23	11.09	17.52	22.44
2200	0.40	1.80	3.15	9.12	17.95	29.56	37.07

Since 2018, CRMC adopted the NOAA High curve for all coastal regulations

NOAA, 2017

Problem Statement: Pawtuxet River Floods Affecting Wastewater Treatment Facilities in 2010

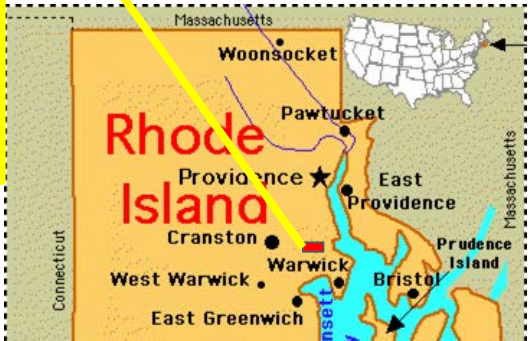


Problem Statement: Pawtuxet River Floods Affecting Wastewater Treatment Facilities in 2010

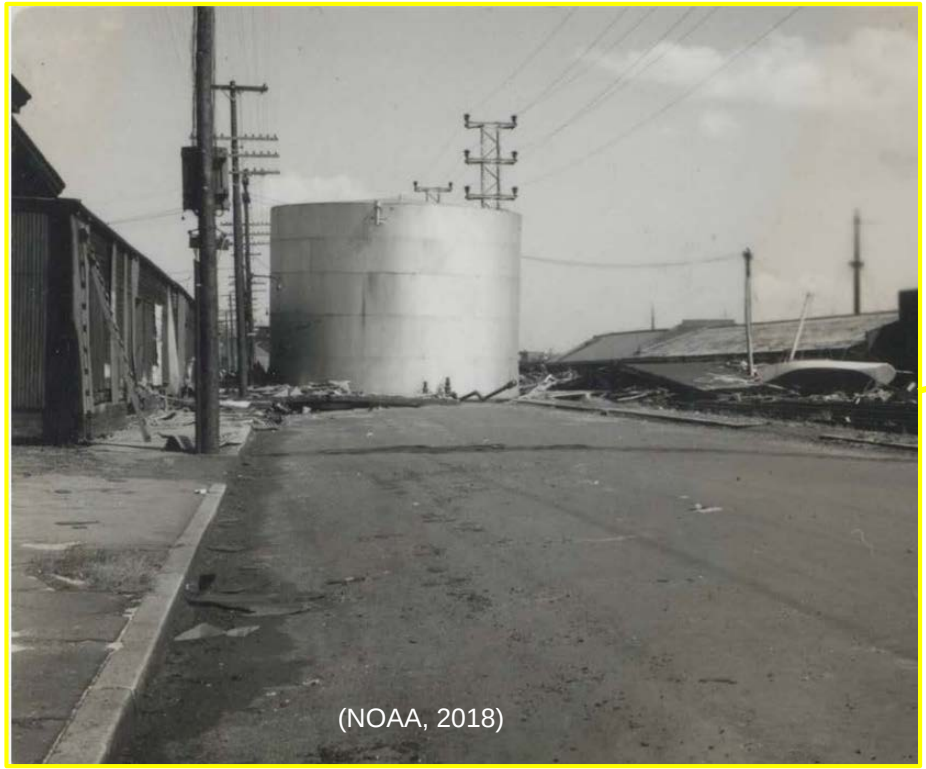
Flooded Warwick Wastewater Treatment Facility

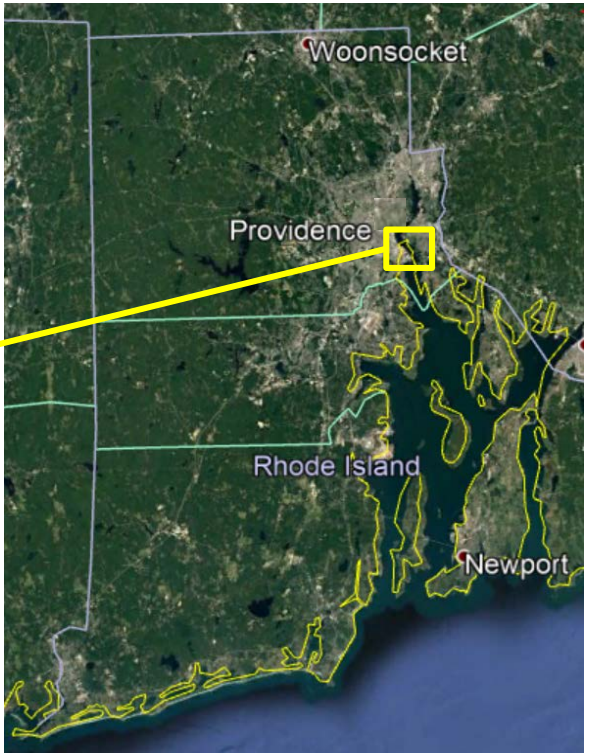
Image: (RI DEM 2018)

- 3 consecutive storms
- 500 year flood event (9” of rainfall)
- Warwick WWTF
  - 3 days: no treatment
  - 1 month: temporary disinfection
  - 3 months: biological treatment
  - 4 months: nutrient removal
- Cranston WWTF
  - 3 days pump station shut down
  - Highest flows ever recorded



Problem Statement: Inundation Affecting Past Above Ground Storage Tanks





An oil tank floated to the center of the road in East Providence during 1954 Hurricane Carol

Infrastructure (WWTFs and Tank Farms) in Upper Narragansett Bay

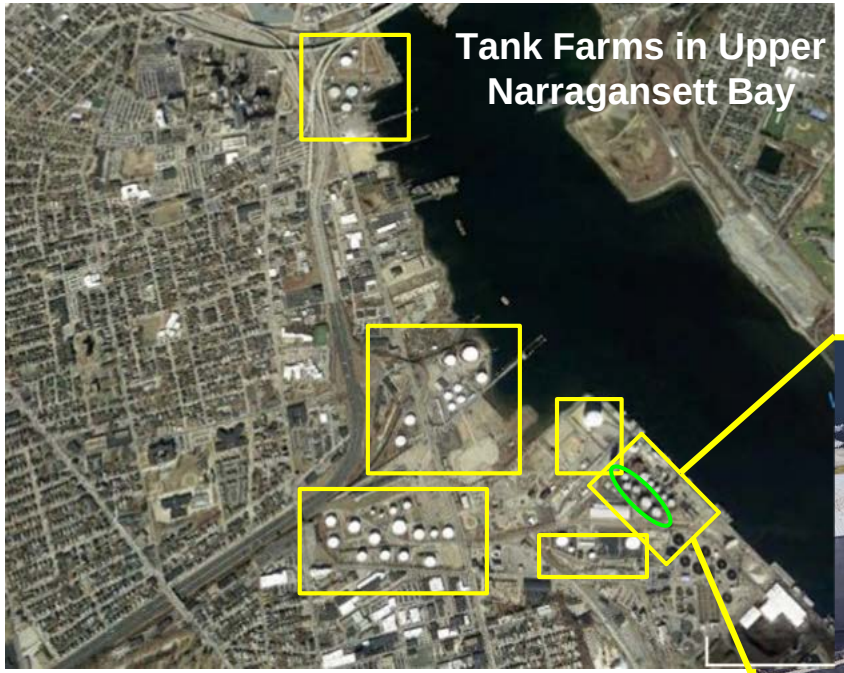
NBC Fields Pt. WWTF

NBC Bucklin Pt. WWTF

Berm → - - -

- Constructed in 1947
- Treats 46 million gallons of wastewater per day
- During a wet weather event, it can treat up to 113 million gallons per day
- Treats the wastewater of about 130,000 customers
- 12 - 18 inches added to preexisting berm in 2014

Study Area for Above Ground Storage Tanks



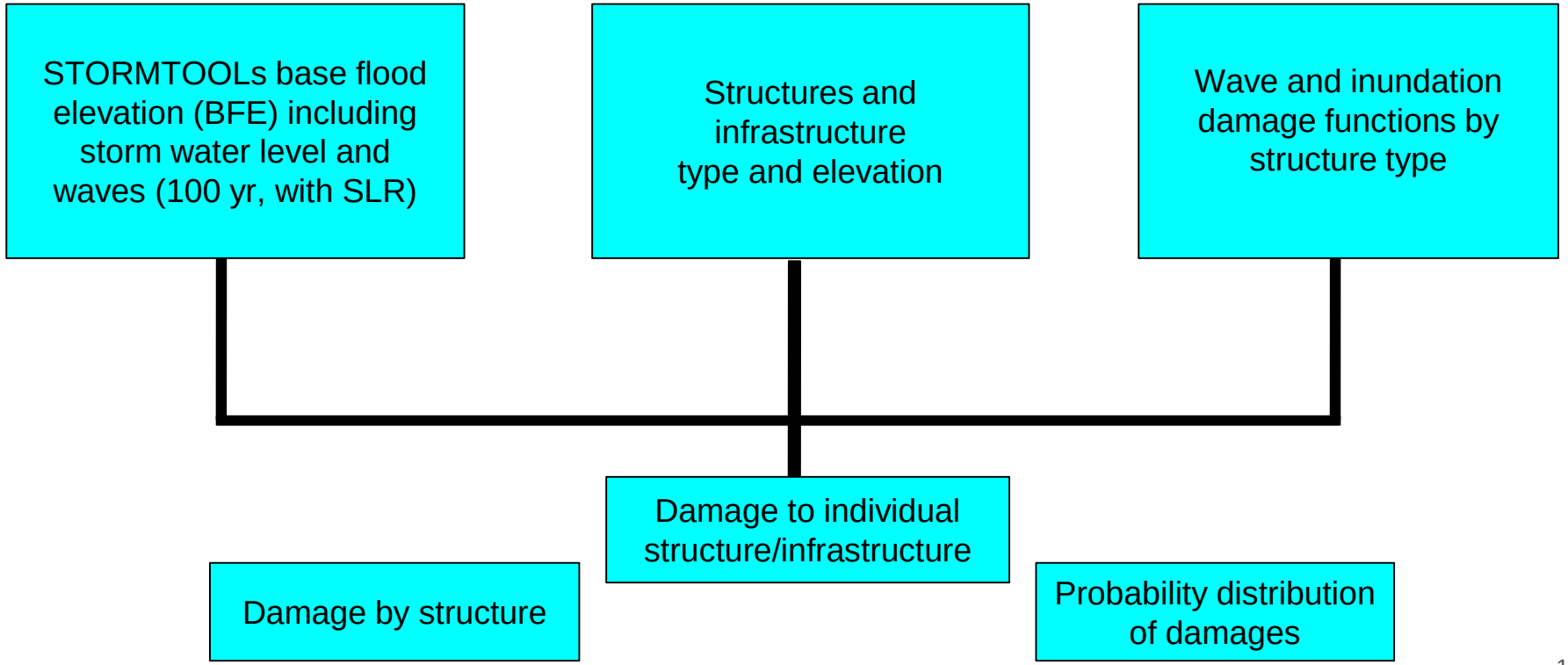
Study Objectives

- Use the Coastal Environmental Risk Index (CERI) to assess flooding damage during 100 year return period storm event with sea level rise to Fields Point and Bucklin Point Wastewater Treatment Facilities (WWTFs) and Above Ground Storage Tanks (ASTs) in upper Narragansett Bay.

- Based on the evaluation of damages to WWTFs and ASTs, propose mitigation strategies to make these systems more resilient.

Methodology

Coastal Environmental Risk Index (CERI) General Flow Chart



(Spaulding et al., 2016)

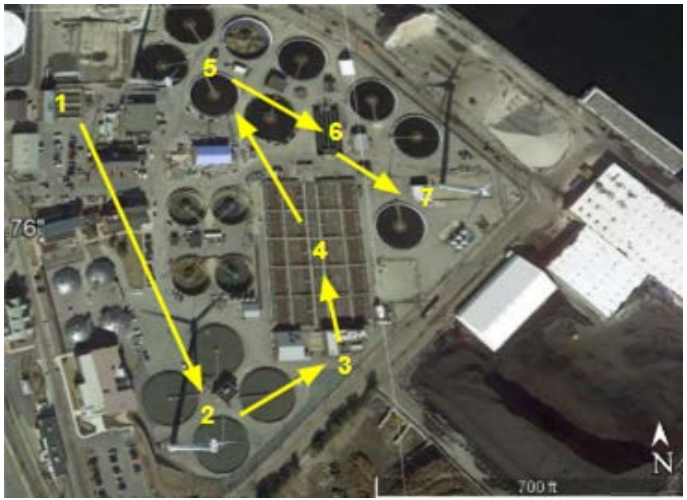
Methodology: CERI for WWTF

Fields Point & Bucklin Point Treatment Functionality Index

Water levels (surge, wave height) extracted from STORMTOOL's Design Elevation maps (SDE BFE) for 100 yr storm and sea level rise

Type and elevation of WWTF components (Critical Flood Elevation)

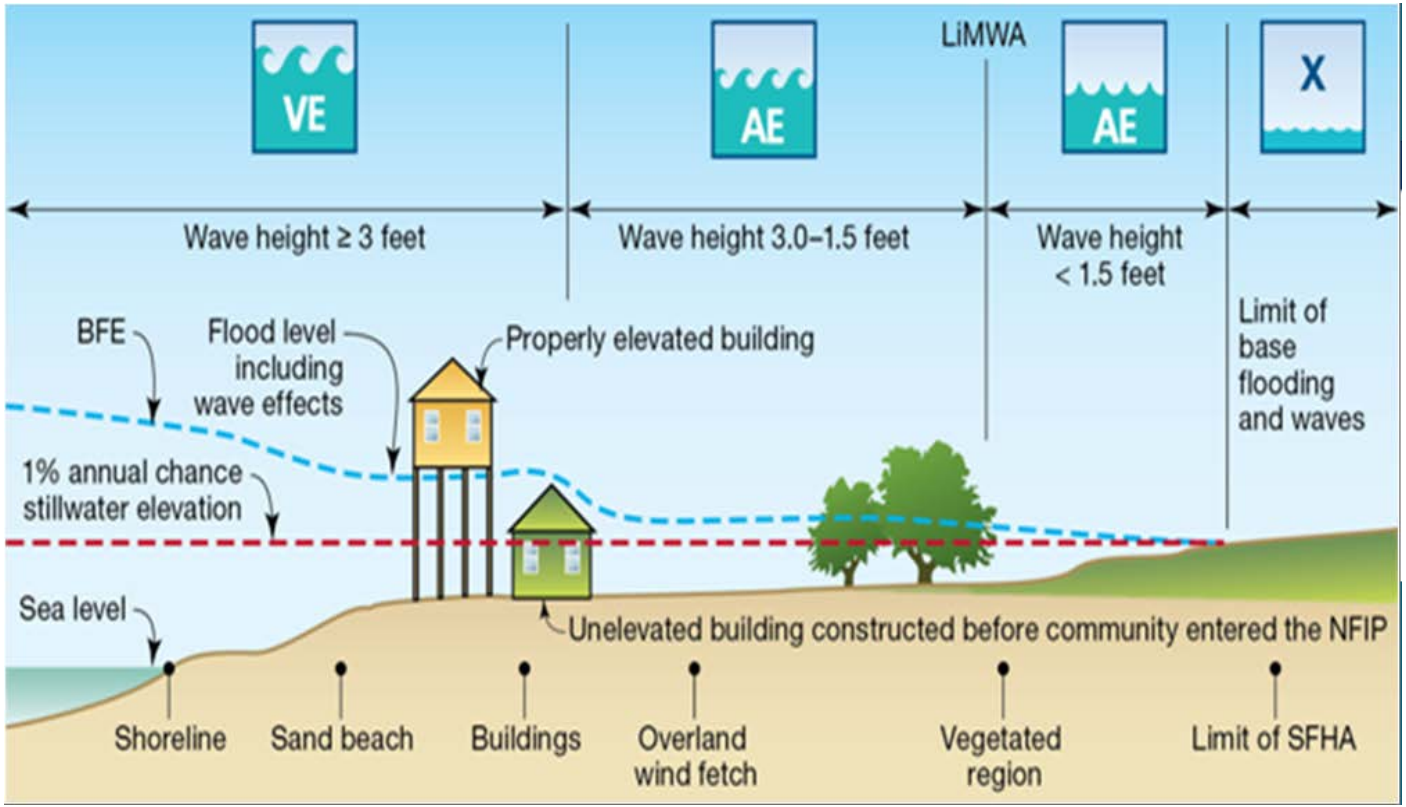
Functionality of WWTF based on primary flow path (%BOD, %Bacteria, %Nutrients)



Resulting functionality of WWTF due to storm event

1. **Screen & Grit**
2. **Primary Clarifiers**
3. **Screw Lift Pump**
4. **Aeration Tanks**
5. **Secondary Clarifiers**
6. **Chlorination**
7. **Dechlorination**

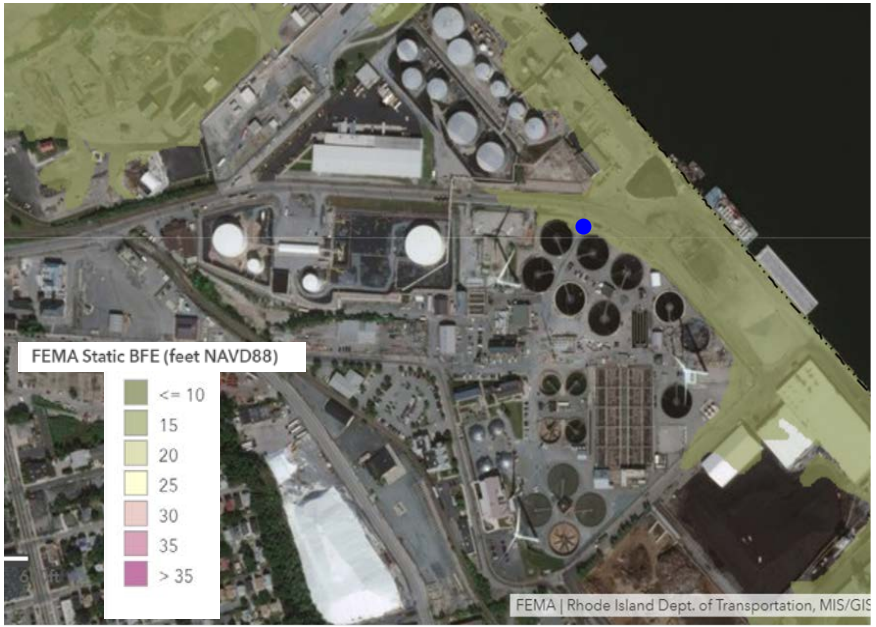
FEMA Flood Zones with Associated Water Levels and Waves



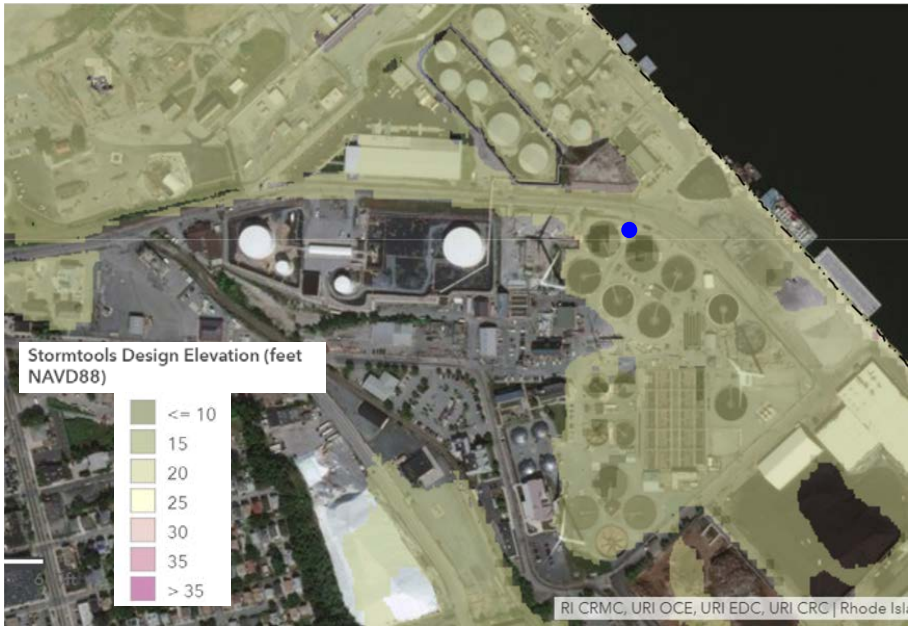
https://www.portsmouthva.gov/332/Flood-Zones

FEMA vs SDE Comparison (Fields Point)

FEMA Static BFE Map



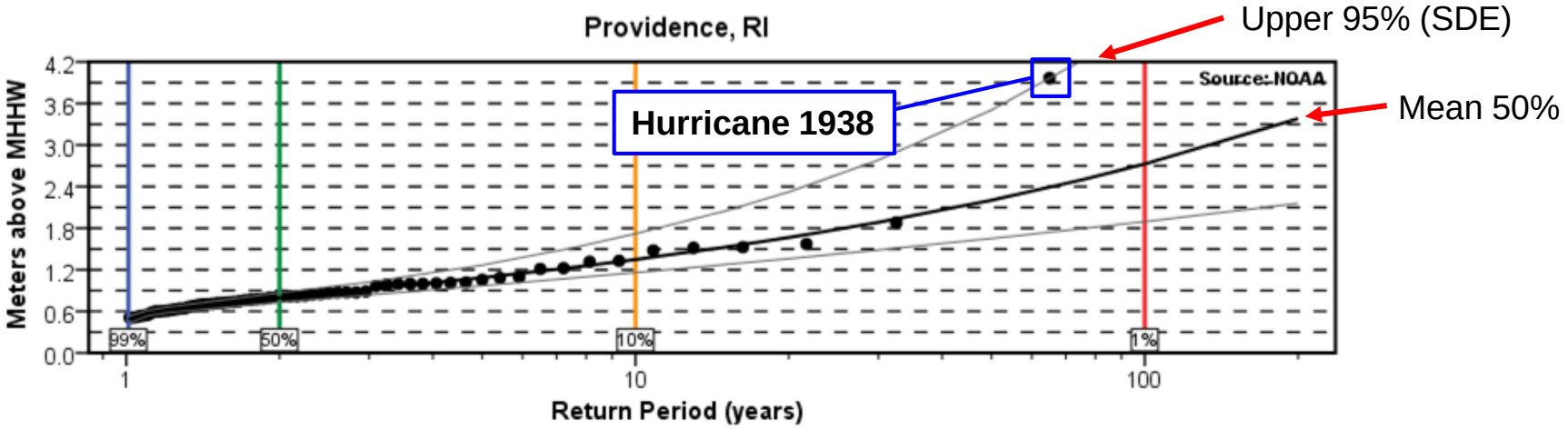
SDE BFE Map



100 year Storm Event + 0ft SLR

Inundation (ft NAVD88)
12.0 (FEMA)
17.7 (SDE)

FEMA FIRMs vs SDE Water Levels

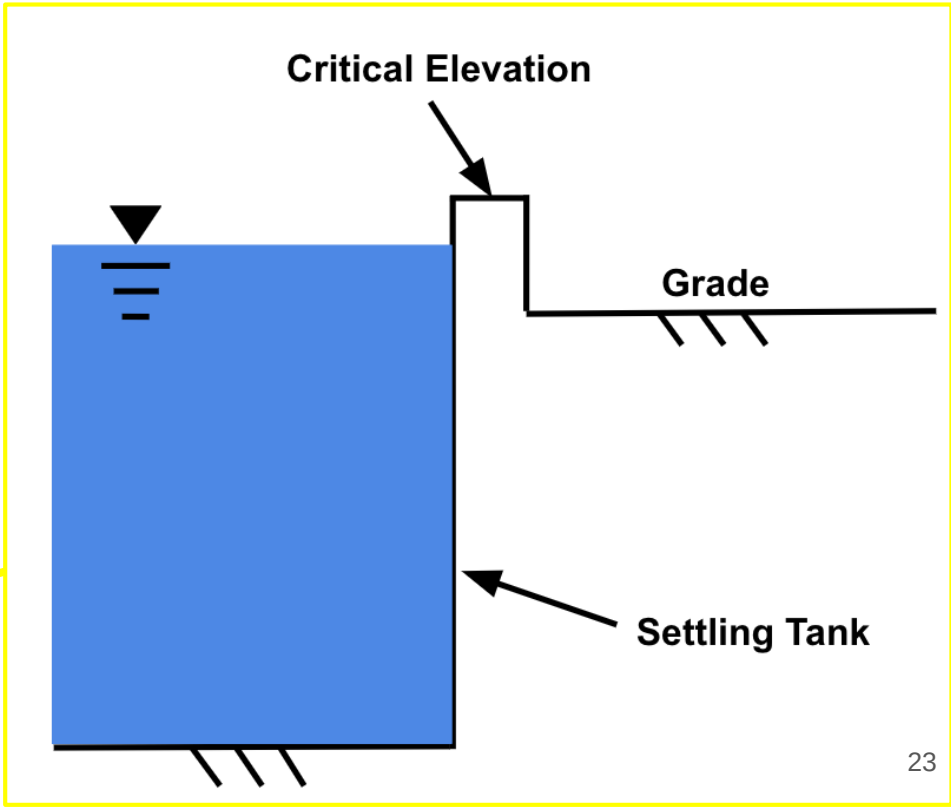


- FEMA FIRMs use 50% confidence interval
- SDE maps use upper 95% confidence interval
- Past storms follow mean water level predictions
- Hurricane of 1938 exceeds mean curve ***significantly***

Critical Flood Elevation of Different WWTF Components

Clarifying/Aeration Tanks:

Critical flood elevation (CFE) is the elevation above which flooding starts to impact the component



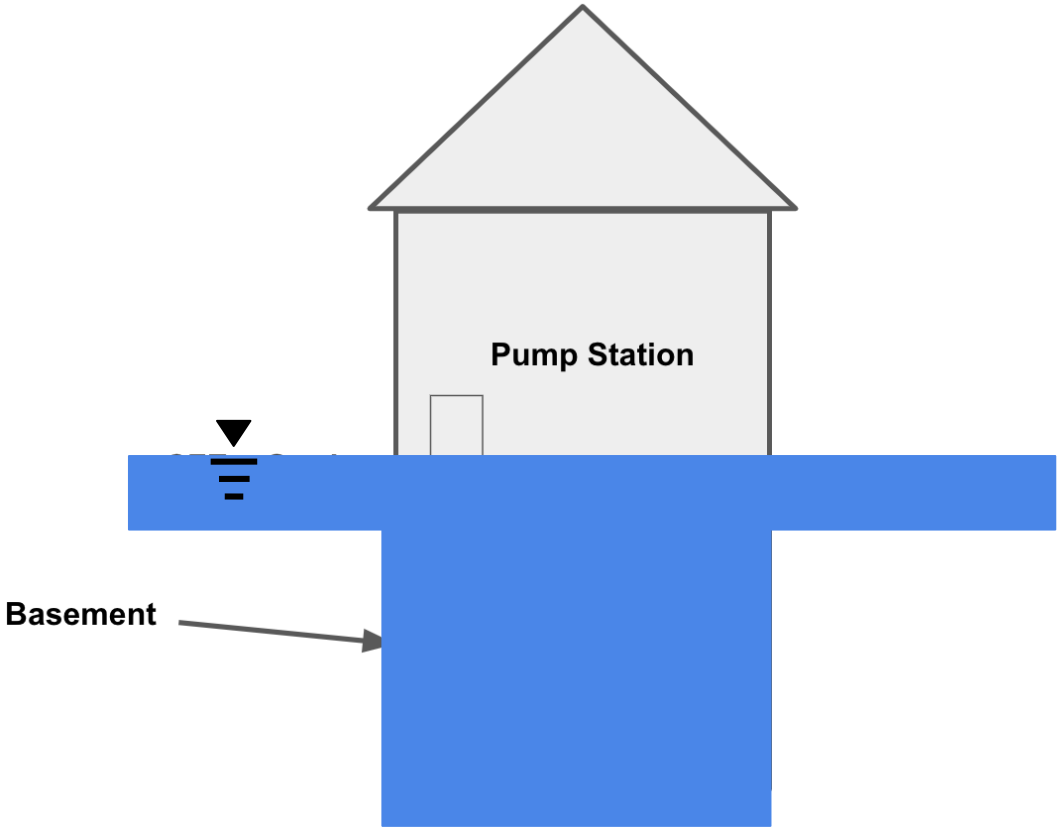
CFE of Different WWTF Components

Pump Stations/Substations:

Critical flood elevation is the elevation above which flooding starts to impact the component

CFE of Different WWTF Components

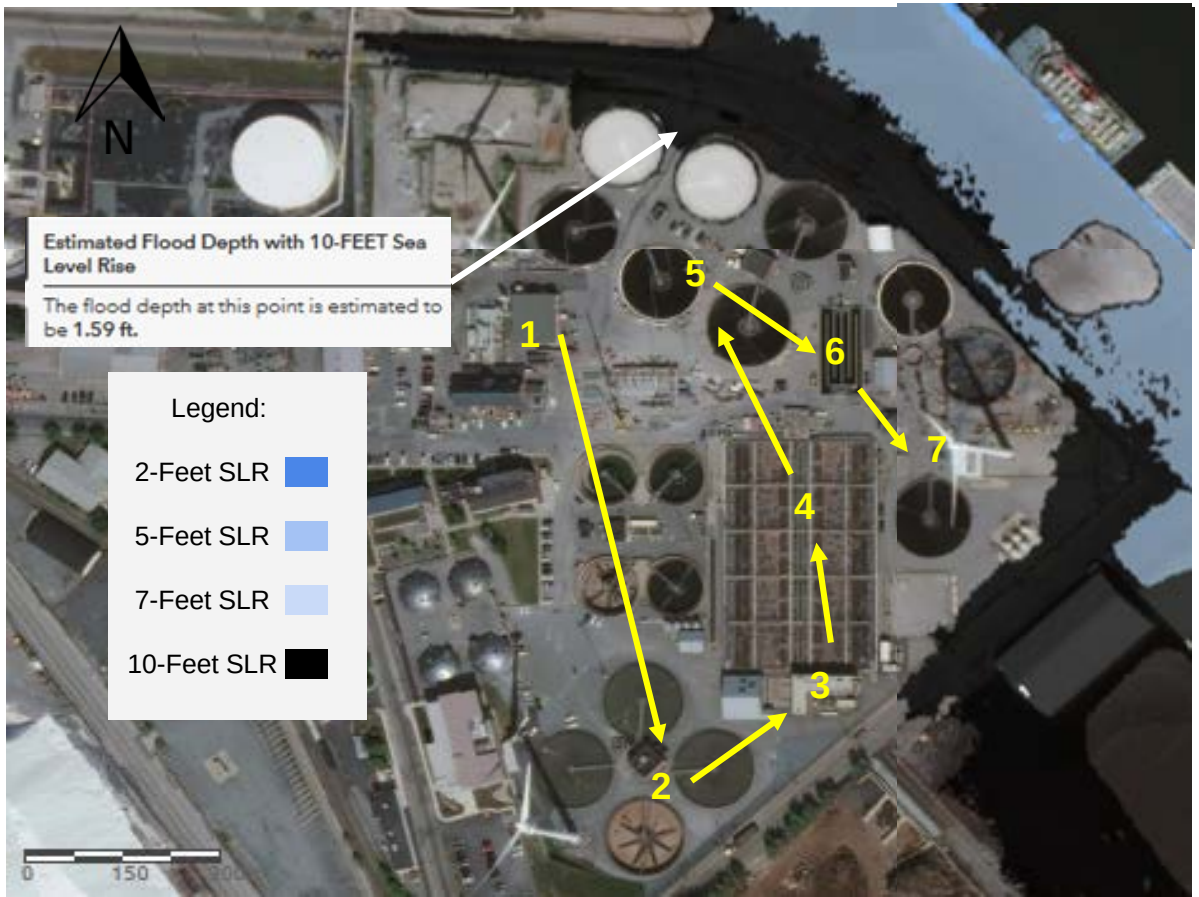
- Example of a pump substation at the Fields Point WWTF
- Pumps are located in basement of building (one story below grade)



Digital Surface Model of Fields Point

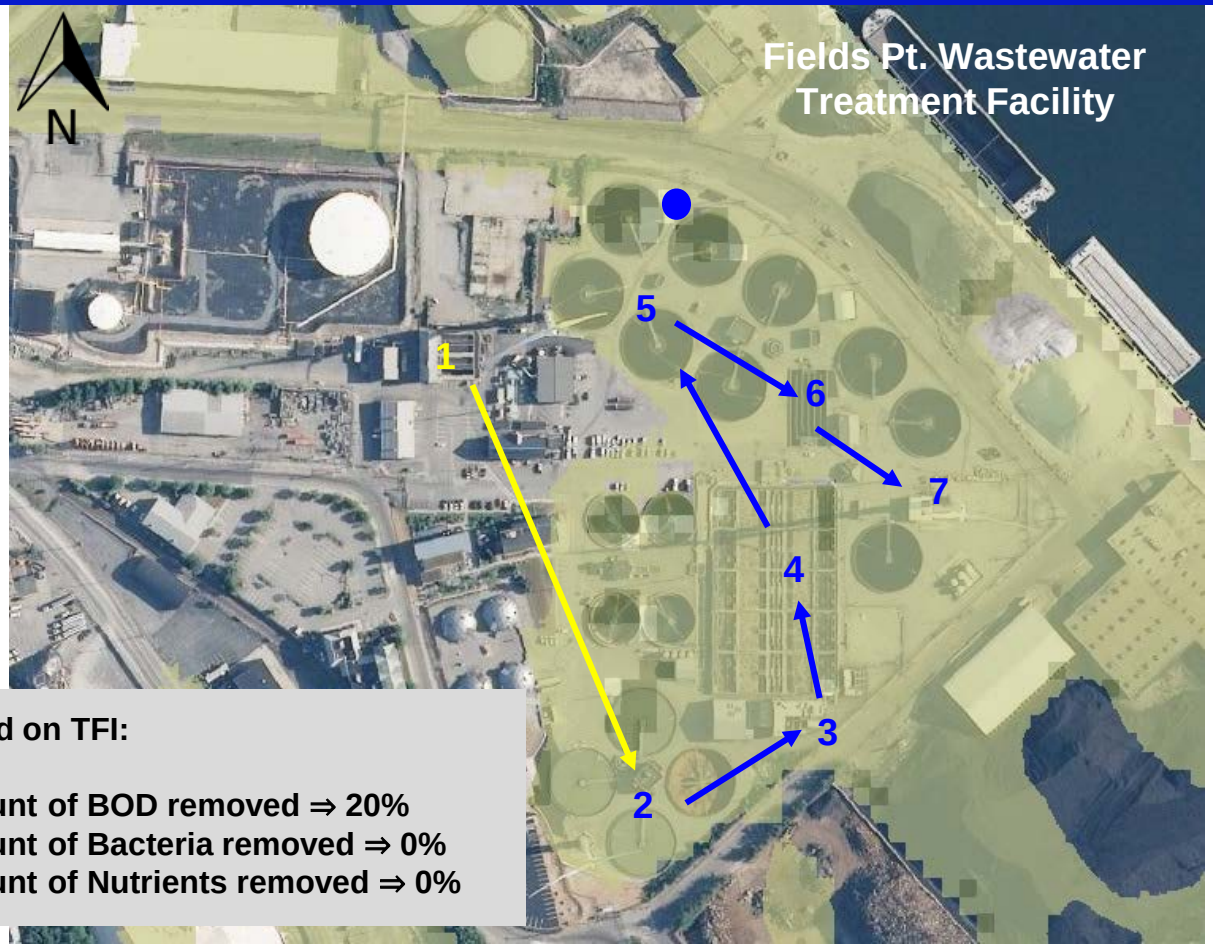
(TEL: Elevation and location of critical WWTF components)

Fields Pt. Treatment Functionality Index (Sea Level Rise Without Storm)



- No inundation to primary components of wastewater treatment facility
- All components still operational with 10 feet of sea level rise

Stormtools Design Elevation - 100 Year Storm + 0 ft SLR



Inundation (ft NAVD88)

17.7

Stormtools Design Elevation (feet NAVD88)

- <= 10
- 15
- 20
- 25
- 30
- 35
- > 35

Operational

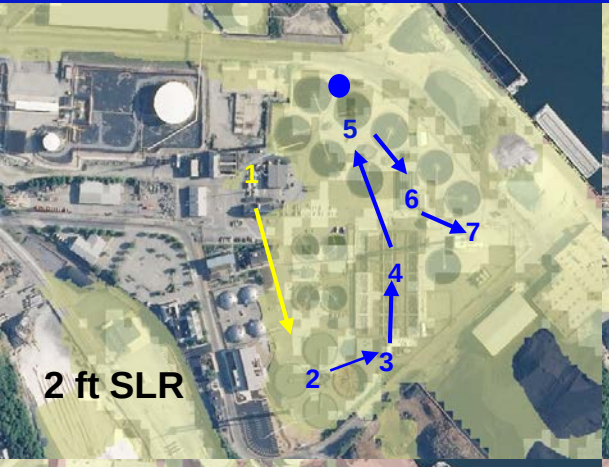
Impacted by Flooding

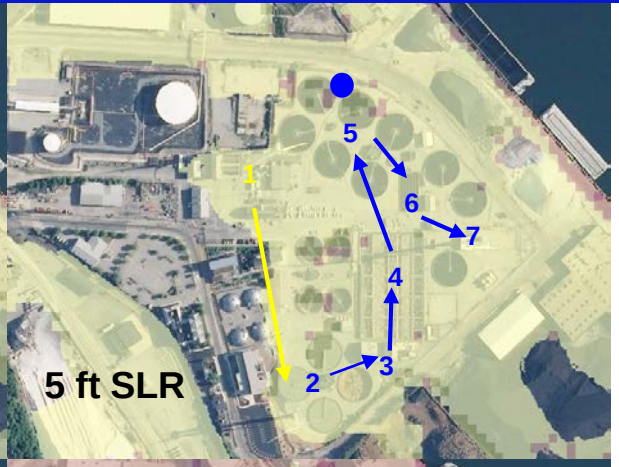
1. **Screen & Grit**
2. **Primary Clarifiers**
3. **Screw Lift Pump**
4. **Aeration Tanks**
5. **Secondary Clarifiers**
6. **Chlorination**
7. **Dechlorination**

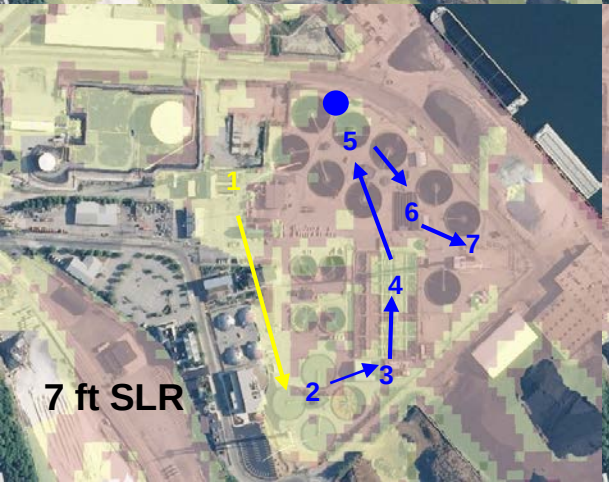
Based on TFI:

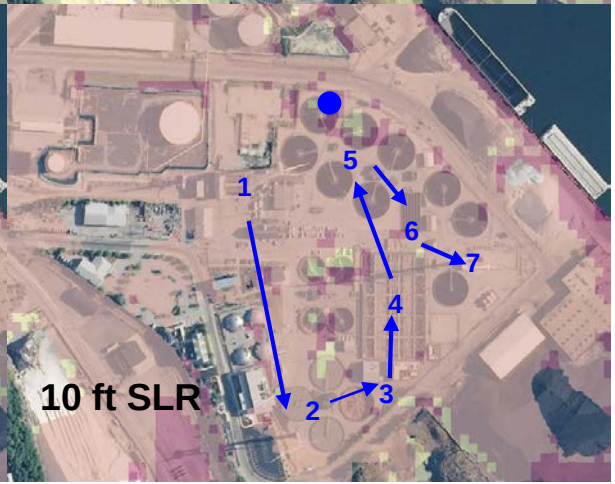
Amount of BOD removed ⇒ 20%
Amount of Bacteria removed ⇒ 0%
Amount of Nutrients removed ⇒ 0%

Stormtools Design Elevation - 100 Year Storm + SLR



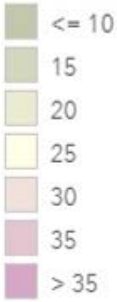






Fields Pt. Wastewater Treatment Facility

STORMTOOLS Design Elevation (feet NAVD88)



- *Inundation (ft NAVD88)*
  - *12.0 (FEMA, no SLR)*
  - 17.7 (SDE, 0 ft SLR)
  - 19.9 (SDE, 2 ft SLR)
  - 23.2 (SDE, 5 ft SLR)
  - 25.4 (SDE,7 ft SLR)
  - 28.9 (SDE,10 ft SLR)

- Based on TFI : 2ft, 5ft, 7ft SLR

Amount of BOD removed ⇒ 20%
Amount of Bacteria removed ⇒ 0%
Amount of Nutrients removed ⇒ 0%

- Based on TFI, no constituents removed in 10ft SLR case

Evaluation of Mitigation Strategies: Fields Point WWTF

Introduction to Mitigation Strategies

Hardening:

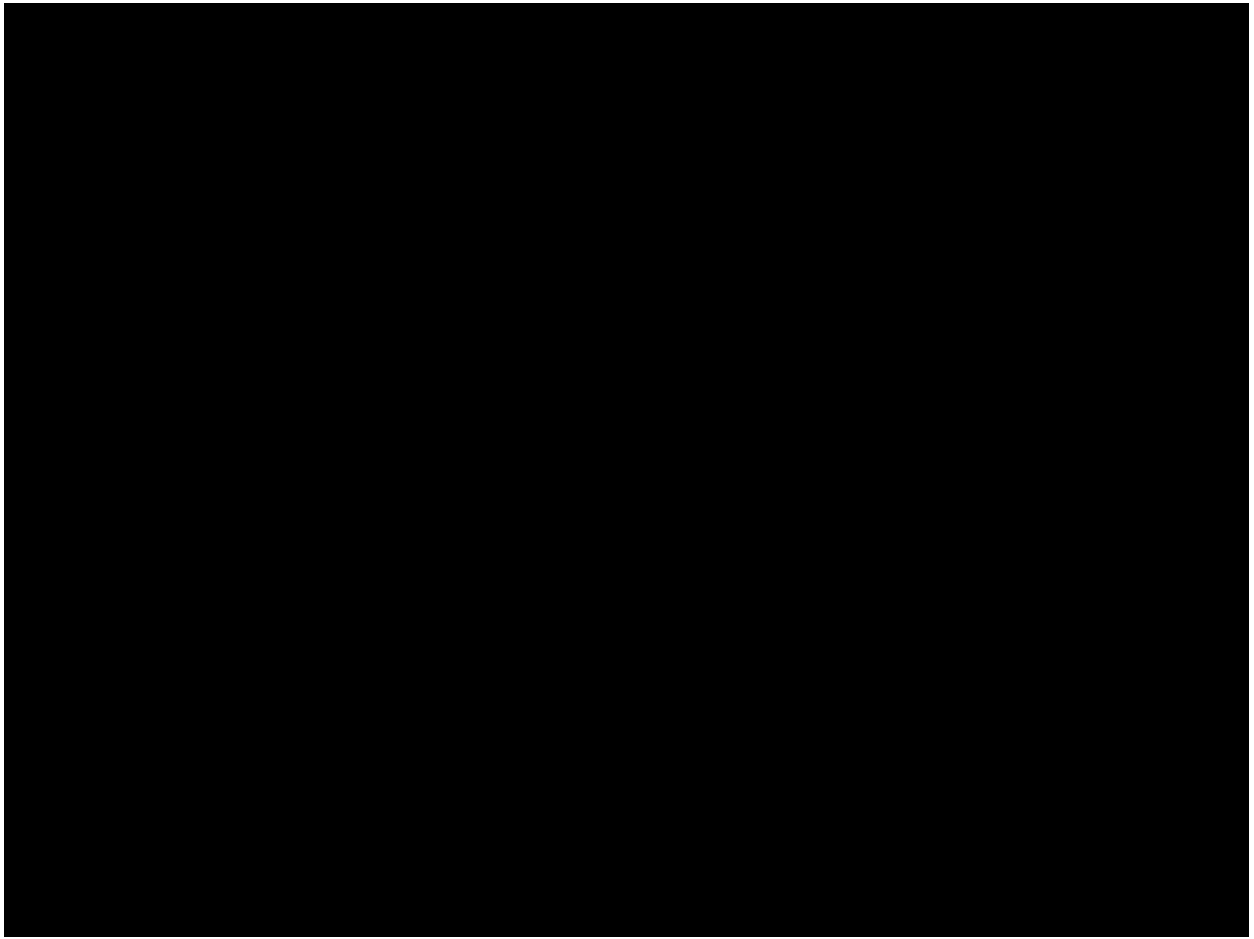
- Constructing physical barriers to block water from entering facility components (flood proof doors, temporary flood barriers)
- Waterproofing by installing submersible pumps, water resistant electrical enclosures, general waterproofing

Elevating:

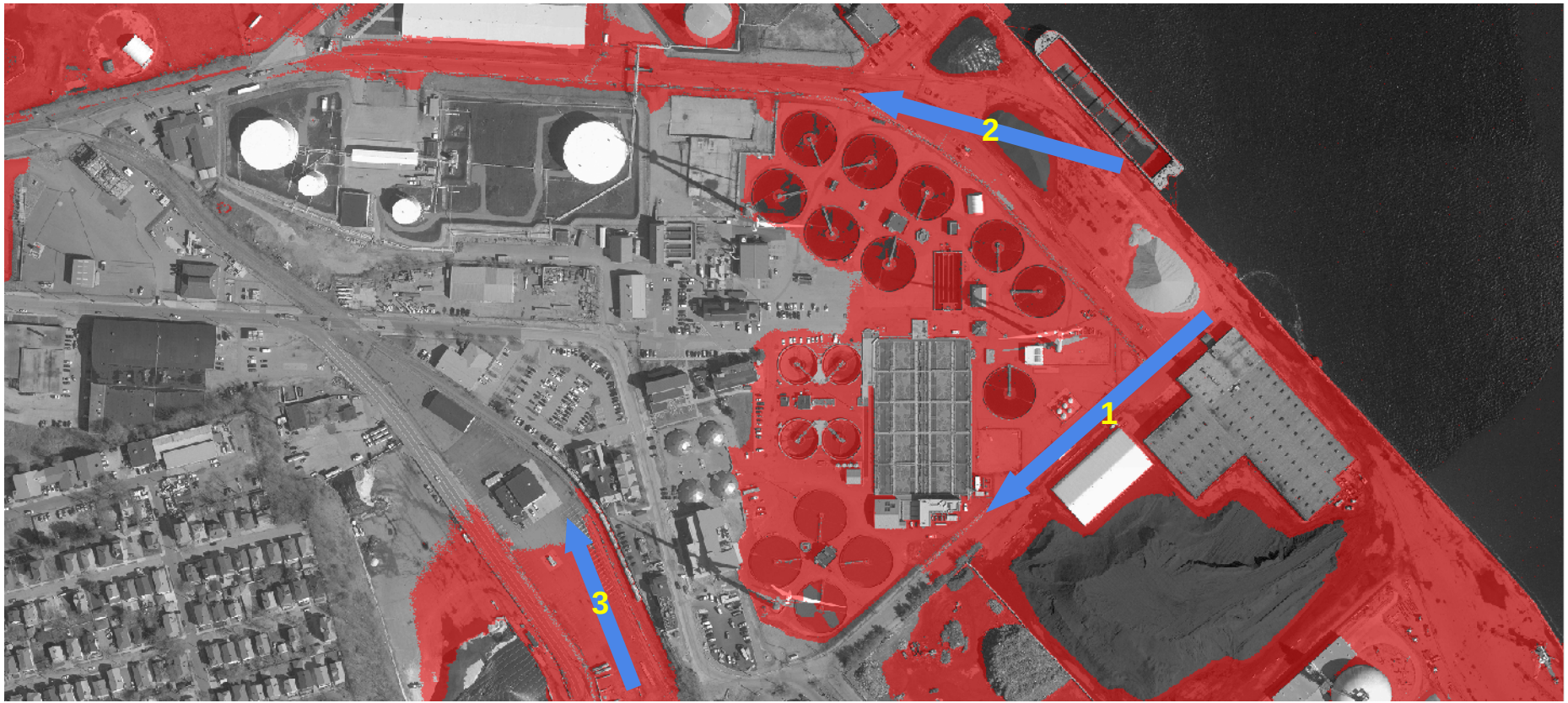
- Increasing the CFE's of different WWTF components (generators, pump houses, etc)
- Adding or increasing berms and walls

Flood Control International, 2019

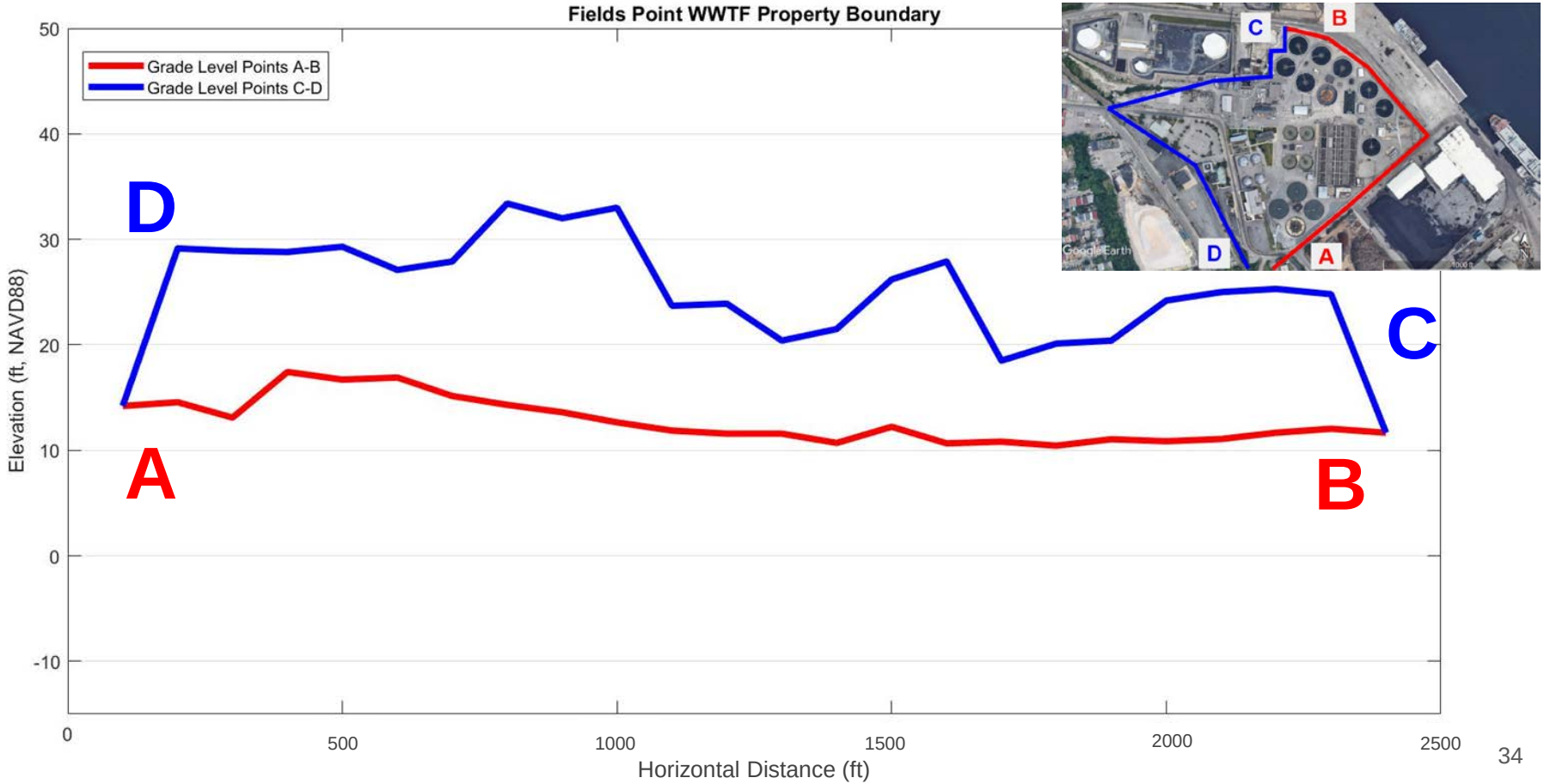
Path of Inundation @ Fields Pt. WWTF (100 Yr Storm, 10 ft SLR)



Path of Inundation @ Fields Pt. WWTF



Elevation of Property Boundary Around Fields Point WWTF



Evaluation of Mitigation Strategies: Bucklin Point WWTF

Bucklin Pt. Treatment Functionality Index (Sea Level Rise Without Storm)

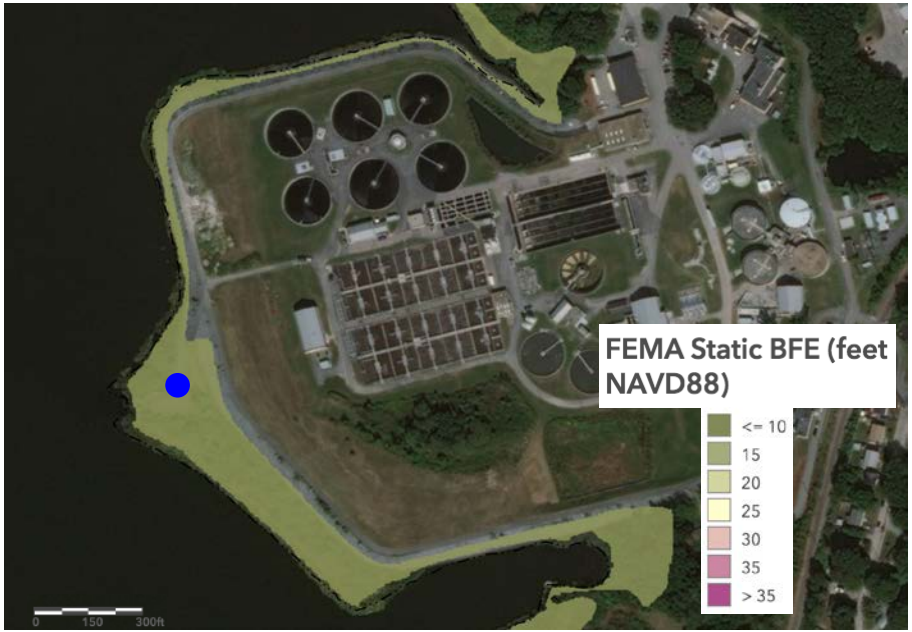
- Berm withstands SLR
- No impact to any components of wastewater treatment facility
- All components still operational with 10 feet of sea level rise

Legend:

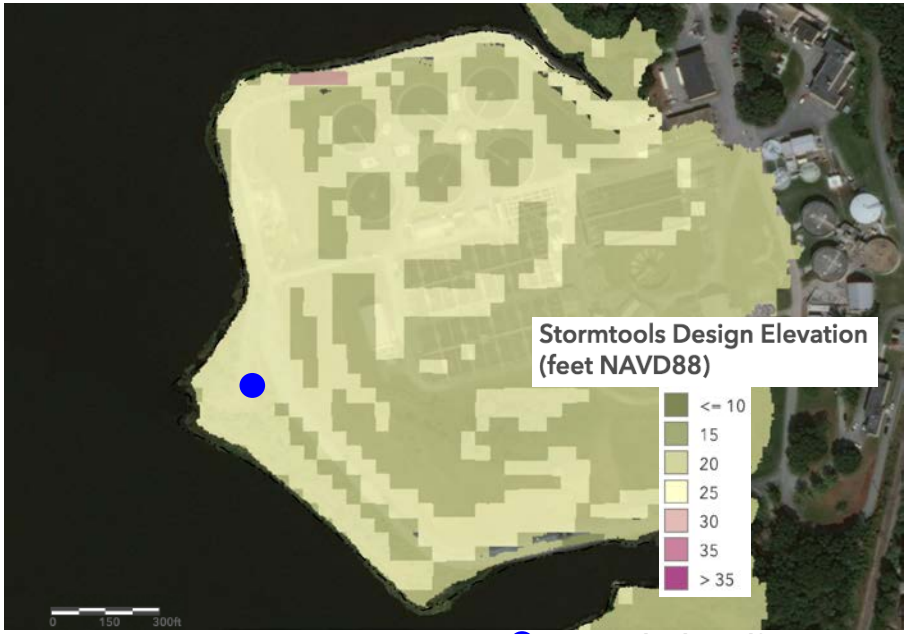
- 2-Feet SLR
- 5-Feet SLR
- 7-Feet SLR
- 10-Feet SLR

Bucklin Point FEMA FIRM Static BFE vs SDE BFE

FEMA Static BFE Map



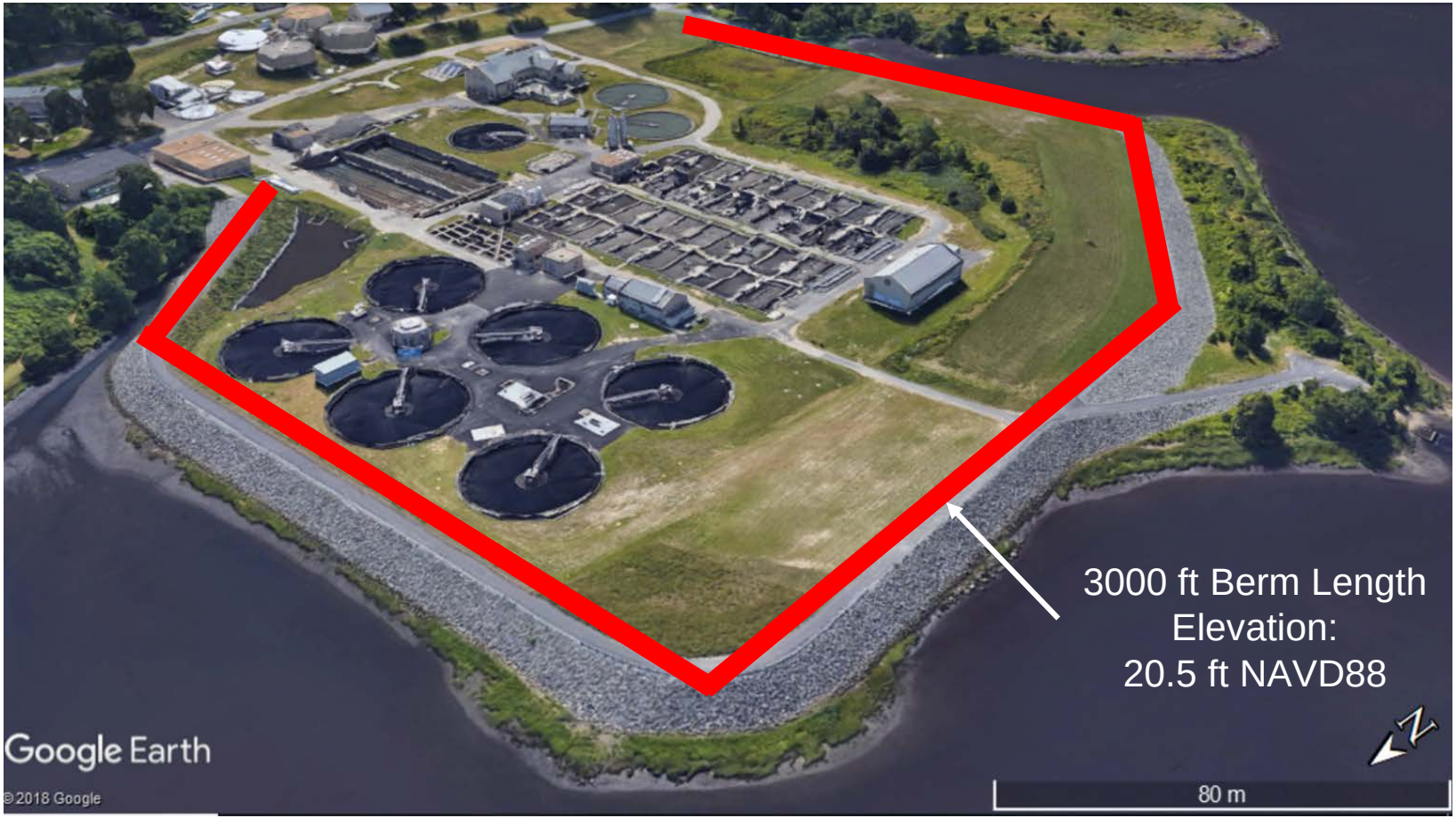
SDE BFE Map



100 year Storm Event + 0ft SLR

Inundation (ft NAVD88)
13.0 (FEMA)
20.7 (SDE)

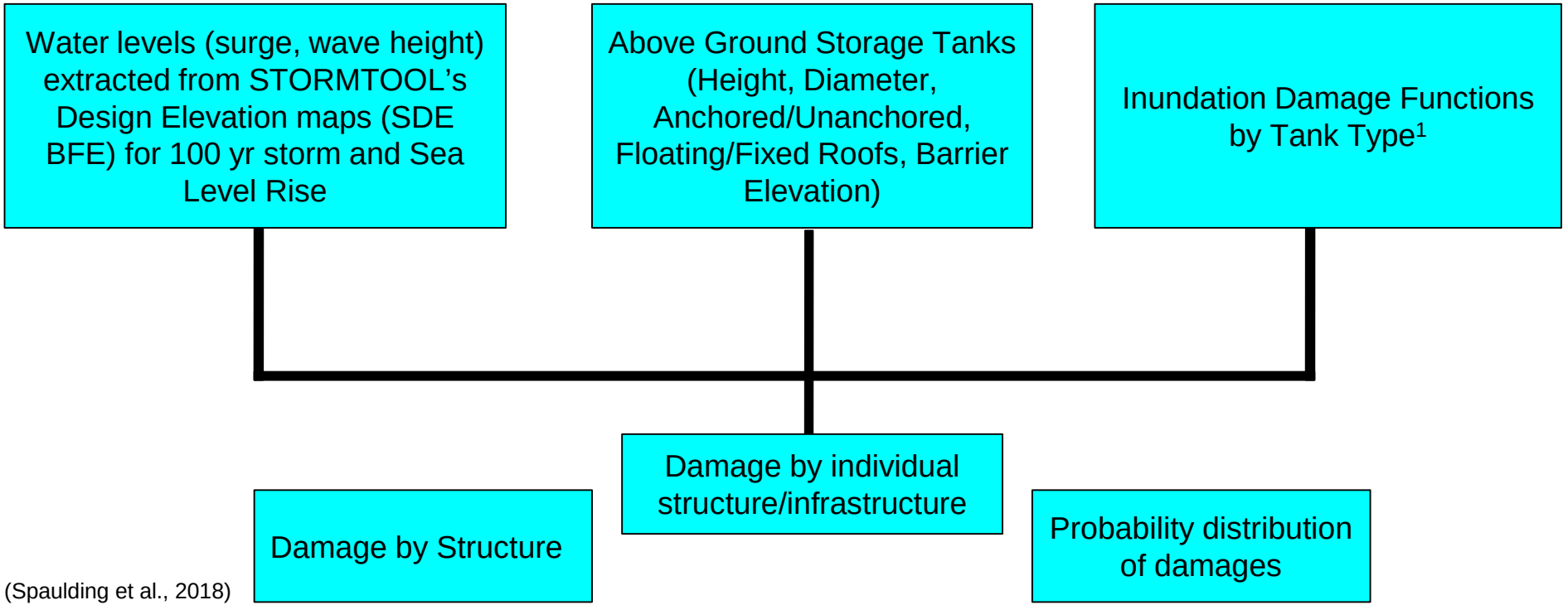
Mitigating Flood Damage to Bucklin Point



Methodology:
CERI for ASTs

Flow Chart for Coastal Environmental Risk Index

(Above Ground Storage Tanks)



(Spaulding et al., 2018)

([1]Kameshwar, S.; Padgett 2018)

Evaluation of Mitigation Strategies: AST Farm

AST Information

- All sites without containment berms are immediately inundated
- 60% AST's inundated 100 yr storm without SLR
- 98% AST's inundated 100 yr storm with 10 ft SLR

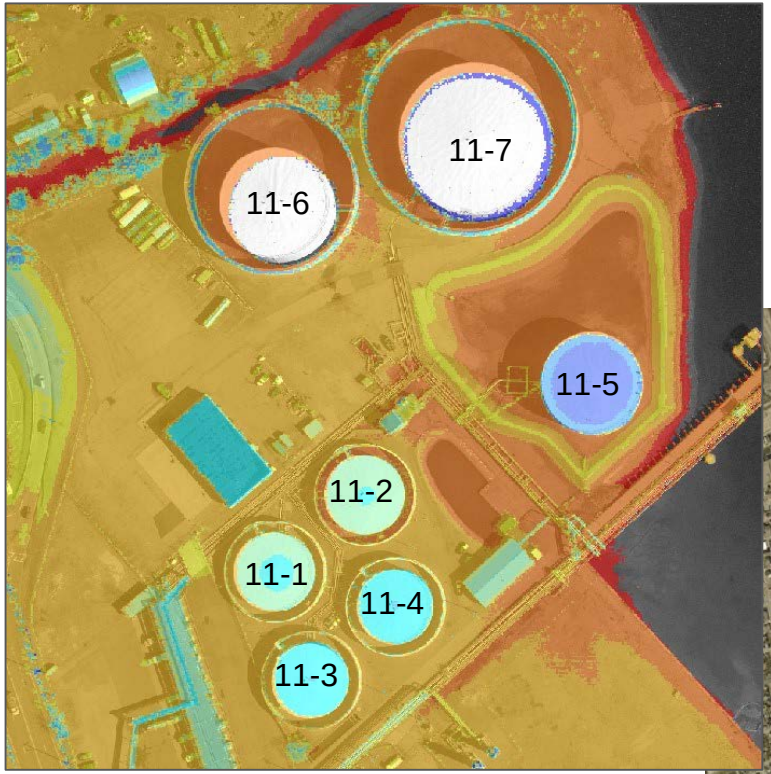
Facility	PlatLot	Name	Num_ASTs
1	PR 056-0069-LB01	HudsonTerminal Operations Bldg.	1
2	PR 056-0009	Abanequi Carriers	1
3	PR 056-0327	Univar (formerly George Mann Company)	1
4	PR 056-0005	Narragansett Electric Company	2
5	PR 101-0001	Providence Gas Co.	2
6	PR 055-0025	Motiva Enterpises (Star Enterprise)	2
7	PR 047-0655	Northland Environmental (PSC)	3
8	PR 057-0294	Motiva Enterpises (Star Enterprise)	4
9	PR 056-0346	Narragansett Electric Company	4
10	PR 056-0348	New England Petroleum Terminal LLC (NEPT)	5
11	PR 055-0016	Motiva Enterpises (Star Enterprise)	7
12	PR 046-0314	Narragansett Improvement Co.	8
13	PR 046-0160	Sprague Energy Corp.	8
14	EP 311-010-14.00	East Providence Water Pollution Control Facility	9
15	PR 101-0493	Motiva Enterpises (Star Enterprise)	12
16	PR 056-0339	New England Petroleum Terminal LLC (NEPT)	13
17	PR 056-0006	Hudson Terminal	19

(DEM 2018)

Site 11 Existing Barrier Elevation

AST CFE's (NAVD88)

- 11-1 = 23 ft (NAVD88)
- 11-2 = 23 ft (NAVD88)
- 11-3 = 27 ft (NAVD88)
- 11-4 = 27 ft (NAVD88)
- 11-5 = 15 ft (NAVD88)
- 11-6 = 38 ft (NAVD88)
- 11-7 = 37 ft (NAVD88)



DSM of Polygon 11 shown in right

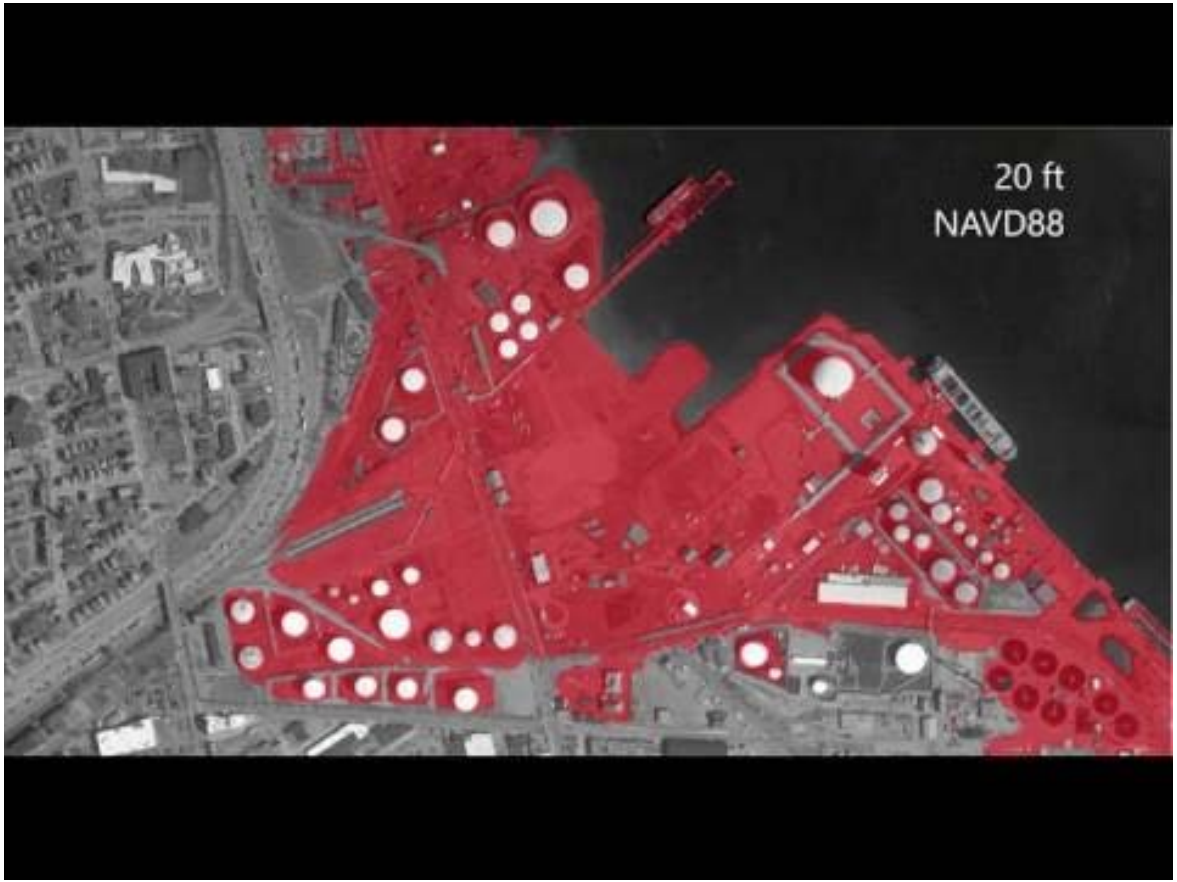
Determining Tanks Affected by Inundation

Polygon 11

		Tank 11-1	Tank 11-2	Tank 11-3	Tank 11-4	Tank 11-5	Tank 11-6	Tank 11-7
Structure Dimensions	**Berm Height (ft NAVD88)**	23.1	23.5	27.1	27.3	15.2	38.4	37.7
	Tank height	31.4	31.7	35.0	35.0	48.9	70.8	65.0
Max BFE	**100 yr (ft NAVD88)**	18.4	18.5	18.3	18.6	18.9	18.6	19.1
	100 yr + 2 SLR (ft NAVD88)	20.6	20.6	20.8	20.4	21.1	20.8	21.4
	100 yr + 5 SLR (ft NAVD88)	23.9	23.2	23.9	23.6	24.8	23.9	24.4
	100 yr + 7 SLR (ft NAVD88)	25.9	25.8	26	25.6	26.2	26.0	26.5
	100 yr +10 SLR (ft NAVD88)	29	28.9	29.1	28.7	29.3	28.9	29.5

BFE > CFE	Inundated
BFE < CFE	Protected

Inundation Path based on Digital Surface Model (DSM)



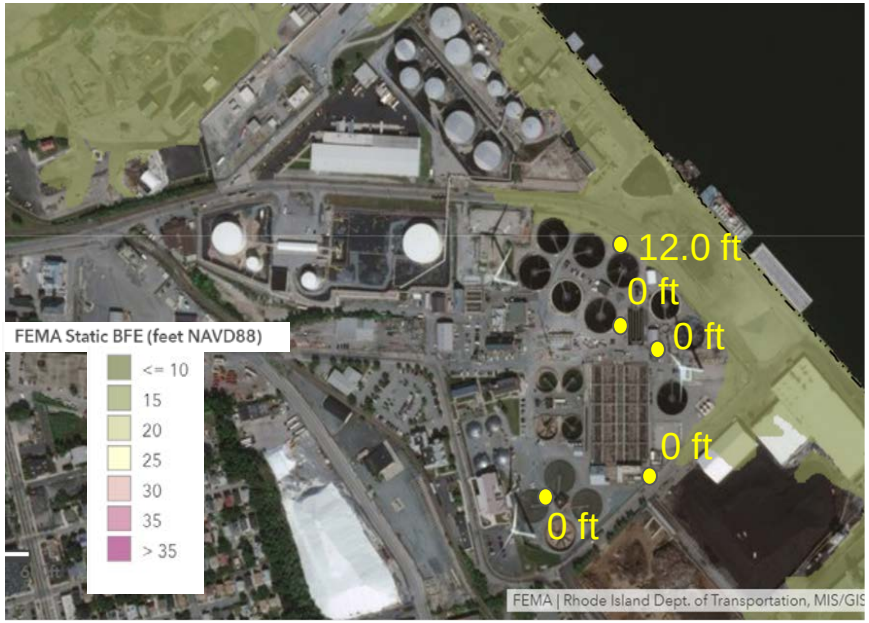
RESULTS

Fields Point: HAZUS Percent Damage

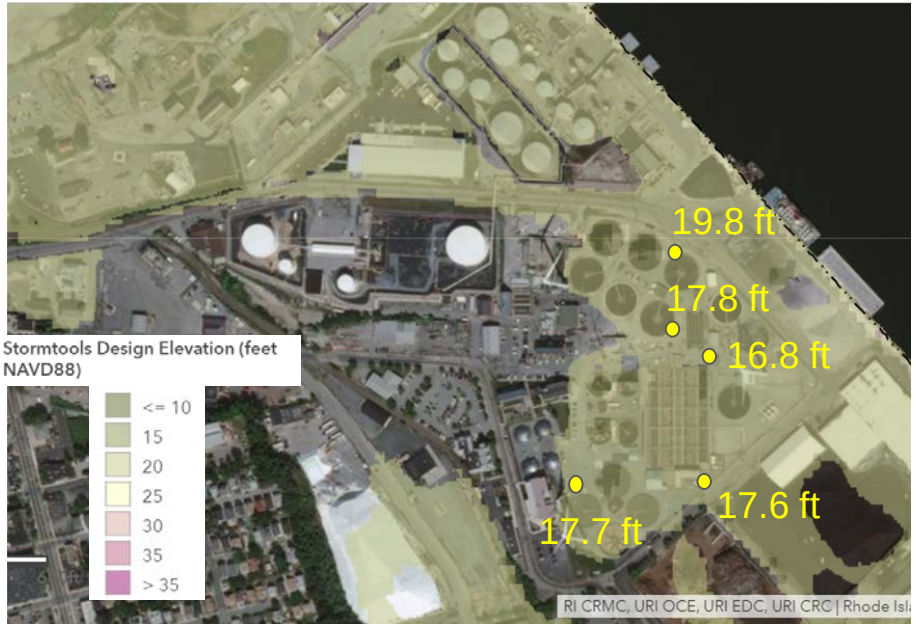
Scenario	CFE (ft NAVD88)	Inundation Level (ft NAVD88)	Depth above CFE (ft)	HAZUS percent damage (%)
SLR only: 10 ft case	12.8 **18.2** 24.5	15.2	2.4 **0** 0	8 **0** 0
100 year storm no SLR	12.8 **18.2** 24.5	17.9	5.1 **0** 0	24 **0** 0
100 year storm + 2 ft SLR	12.8 **18.2** 24.5	20.0	7.2 **1.8** 0	30 **8** 0
100 year storm + 5ft SLR	12.8 **18.2** 24.5	23.3	10.5 **5.1** 0	40+ **24** 0
100 year storm + 7ft SLR	12.8 **18.2** 24.5	25.5	12.7 **7.3** 1.0	40+ **30** 5
100 year storm + 10ft SLR	12.8 **18.2** 24.5	28.9	16.1 **10.7** 4.4	40+ **40+** 17
FEMA FIRMS	12.8 **18.2** 24.5	14.5	1.7 **0** 0	8 **0** 0

FEMA vs SDE Comparison (Fields Point)

FEMA Static BFE Map



SDE BFE Map



Fields Point CFEs

- Low: 12.8 ft (NAVD88)
- Mean: 18.2 ft (NAVD88)
- High: 24.5 ft (NAVD88)

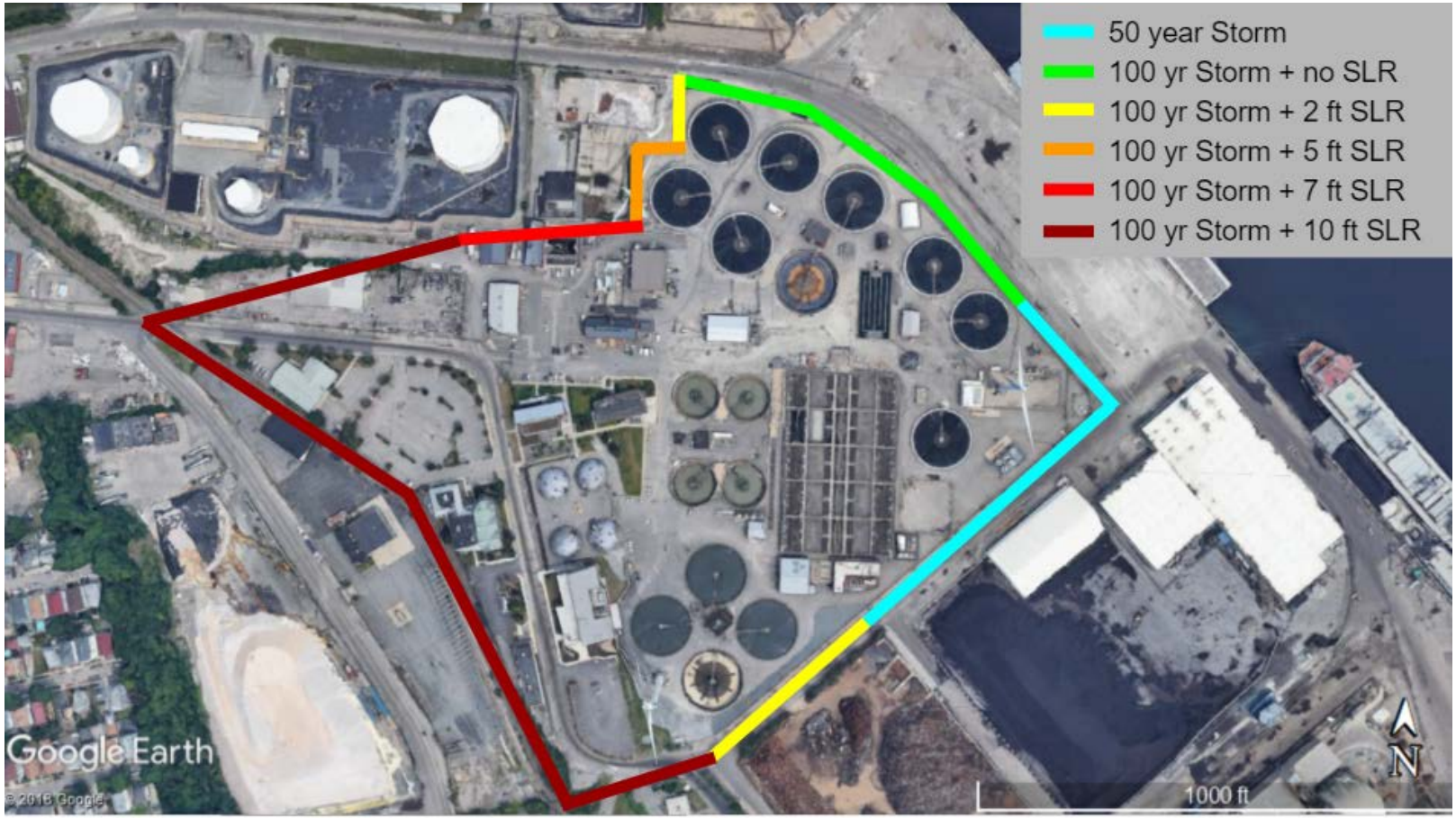
100 year Storm Event + 0ft SLR

Inundation (ft NAVD88)

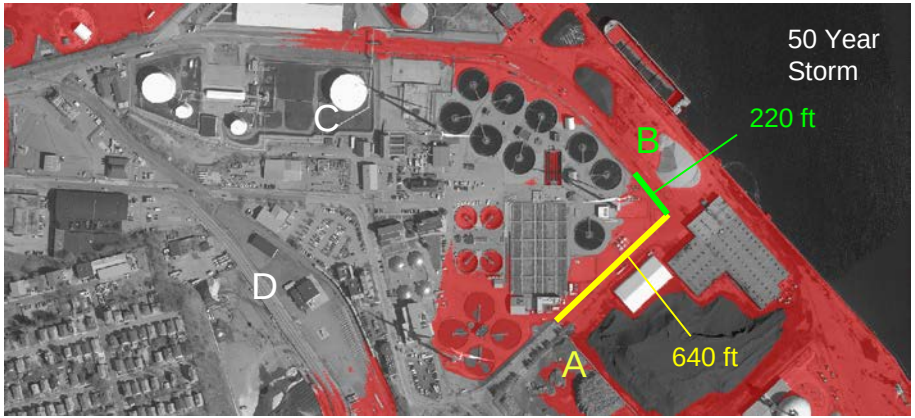
2.4 (FEMA)

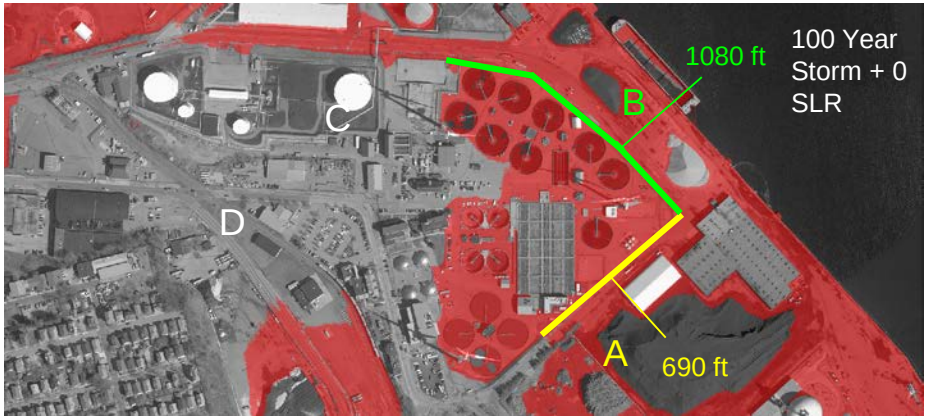
17.9 (SDE)

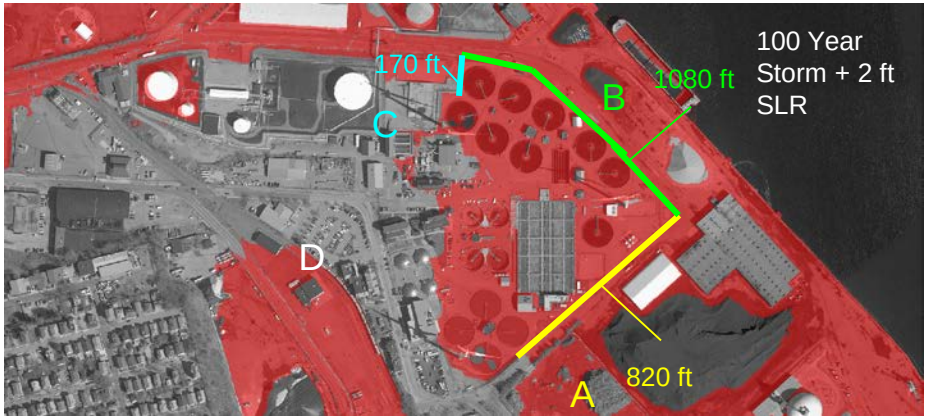
Fields Point Concrete Wall Protection for Different Storm Scenarios



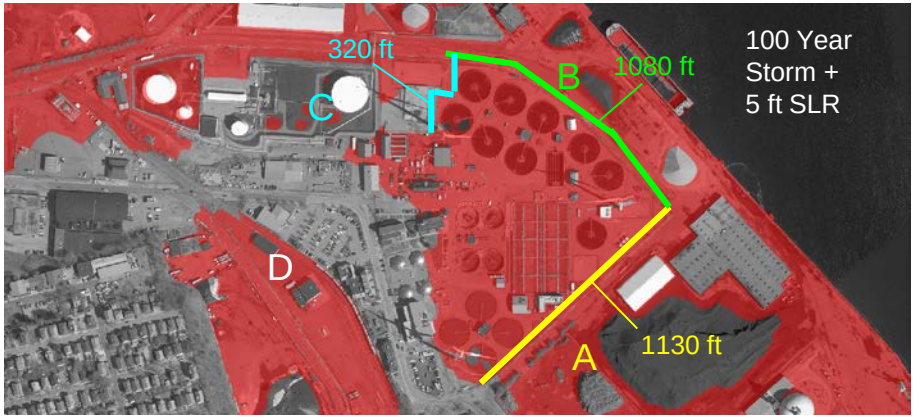
Fields Point Concrete Wall Length

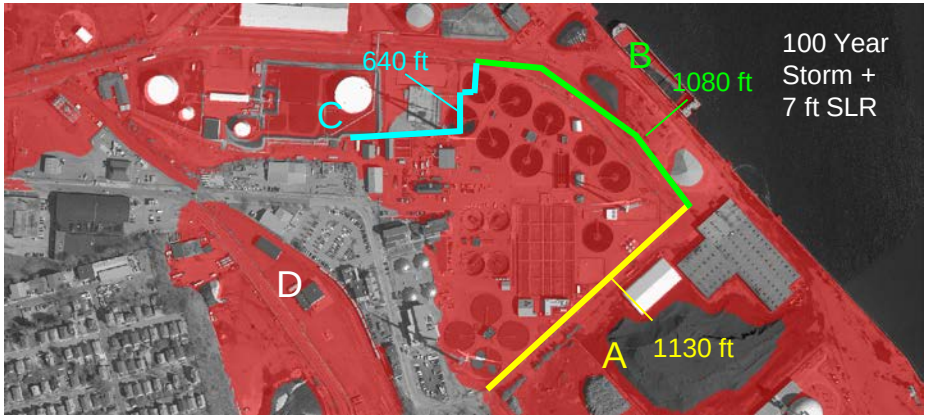


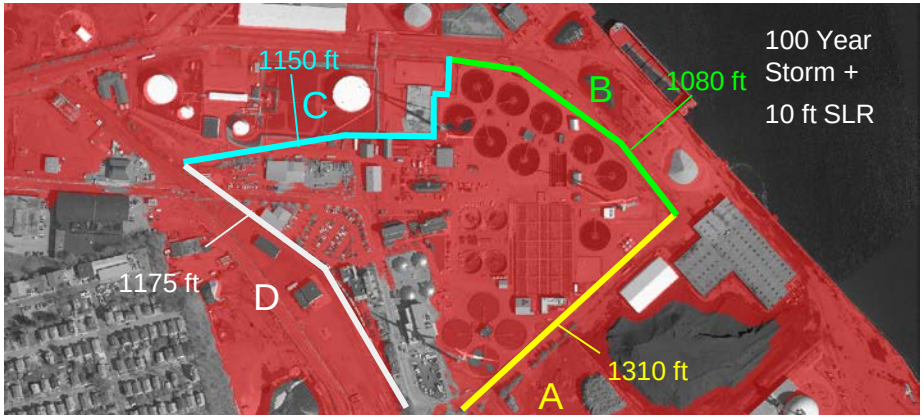




Fields Point Concrete Wall Length

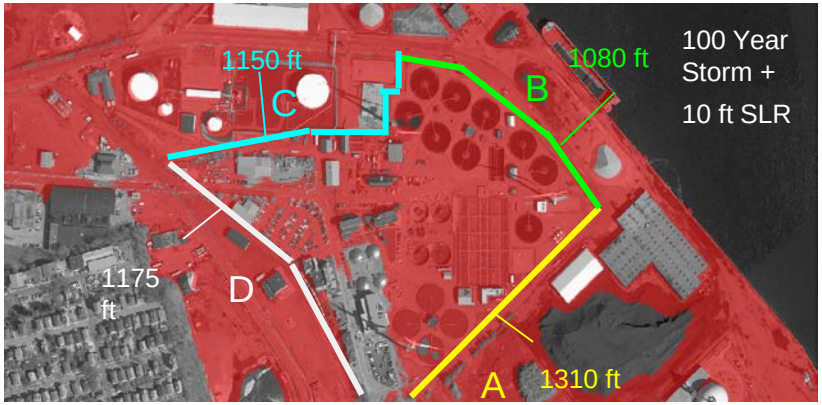




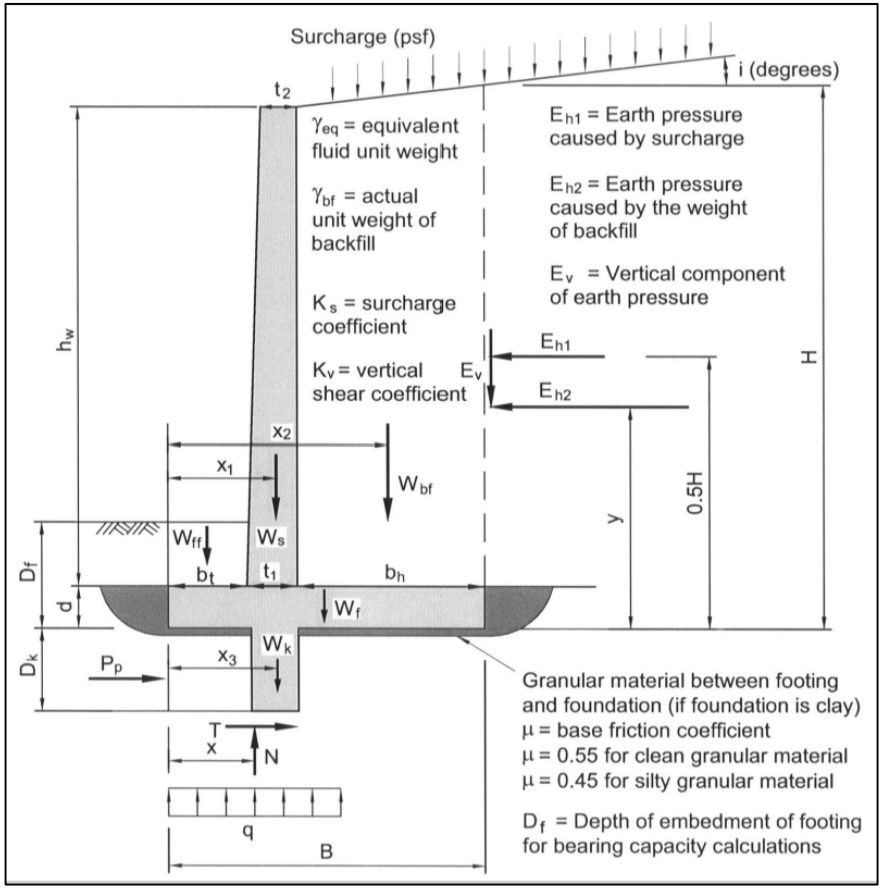


Fields Point Concrete Wall Average Height

Storm Scenario	**Wall Height A (Grade)**	**Wall Height B (Grade)**	**Wall Height C (Grade)**	**Wall Height D (Grade)**
50 Year	4 ft	4 ft	-	-
100 Year + 0 SLR	8 ft	8 ft	-	-
100 Year + 2 ft SLR	10 ft	10 ft	3 ft	-
100 Year + 5 ft SLR	13 ft	13 ft	6 ft	-
100 Year + 7 ft SLR	15 ft	15 ft	6 ft	-
100 Year + 10 ft SLR	18 ft	18 ft	6 ft	2 ft



Concrete Wall Volume Based on Storm Scenario

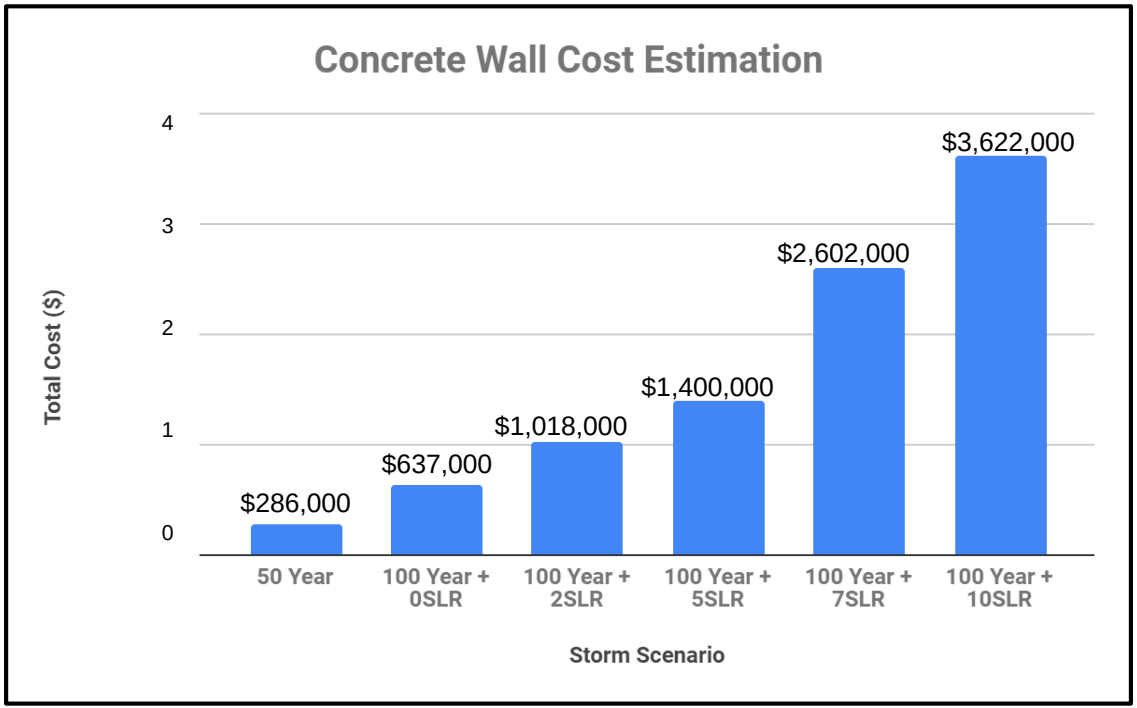


(J.M Duncan & R.L Mokwa, 1998)

Storm Scenario	Volume (ft^3/linear ft of wall)
50 Year	21.6
100 Year + 0 SLR	31.32
100 Year + 2 ft SLR	32.45
100 Year + 5 ft SLR	36.45
100 Year + 7 ft SLR	61.69
100 Year + 10 ft SLR	82.62

Field's Point: Concrete Wall Cost Estimation Based on RSMeans

- Unit cost of cast concrete retaining walls = $15.8 / ft^3
- Unit cost includes bare material, labor, equipment and overhead & profit.



Hardening Mitigation Strategies for Fields Point: Floodproofing

Both permanent and temporary barriers that can be installed to pump station/substations buildings are possible strategies to reduce the possibility of flooding.

Flood Control International, 2019

Trademark Hardware, 2019

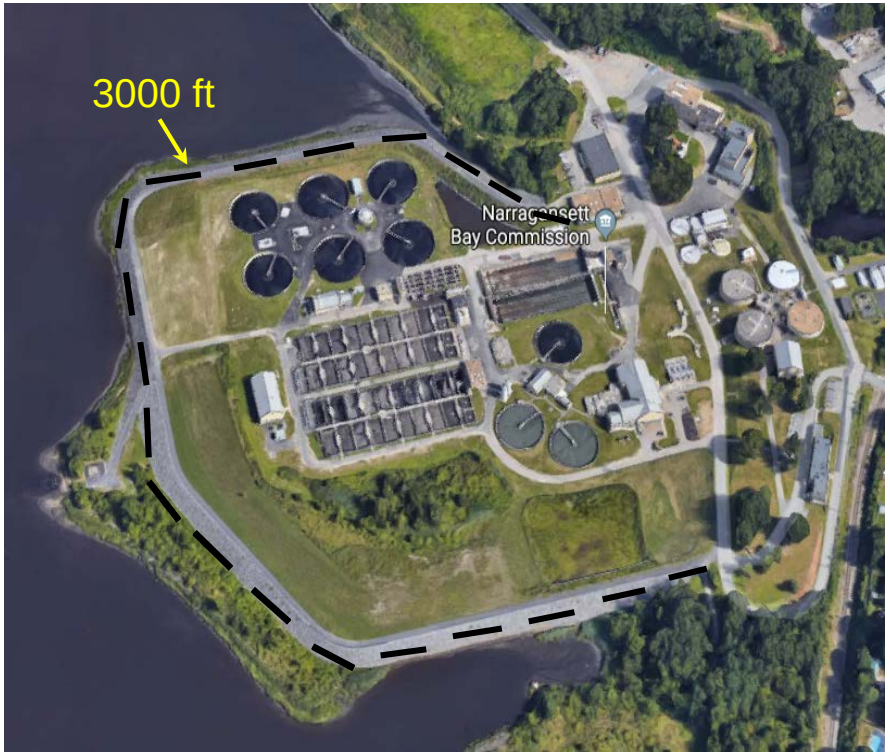
Primary Sludge Pump Station at Bucklin Point

Hardening Mitigation Strategies for Fields Point: Waterproofing

Installation of waterproof pumps and water resistant electrical enclosures are other alternative mitigation strategies when prioritizing the pump stations in the WWTF

Reiner Pump Systems, 2019

Bucklin Pt. Berm Upgrade Proposal



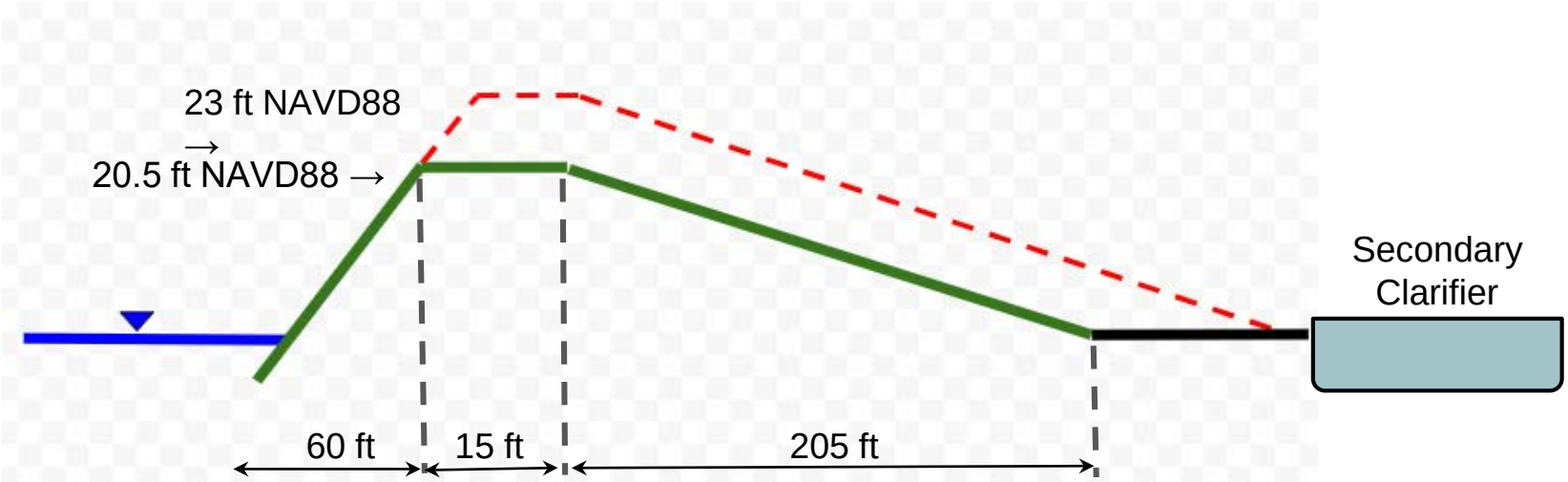
Current Berm Height approximately 20.5 ft (NAVD88)

Total Berm Length approximately 3000 ft.

Storm Scenario	Base Flood Elevation (ft NAVD88)	Berm Upgrade (ft)
Current Berm Height	20.5	-
100 Year + 0ft SLR	22	2.5
100 Year + 2ft SLR	24.1	4.6
100 Year + 3ft SLR	25.1	5.6
100 Year + 5ft SLR	27.2	7.7
100 Year + 7ft SLR	29.4	9.9
100 Year + 10ft SLR	32.6	13.1

Bucklin Berm Upgrade Cross Section

100 Year Storm, 0 ft. SLR
(All Heights in feet, NAVD88)

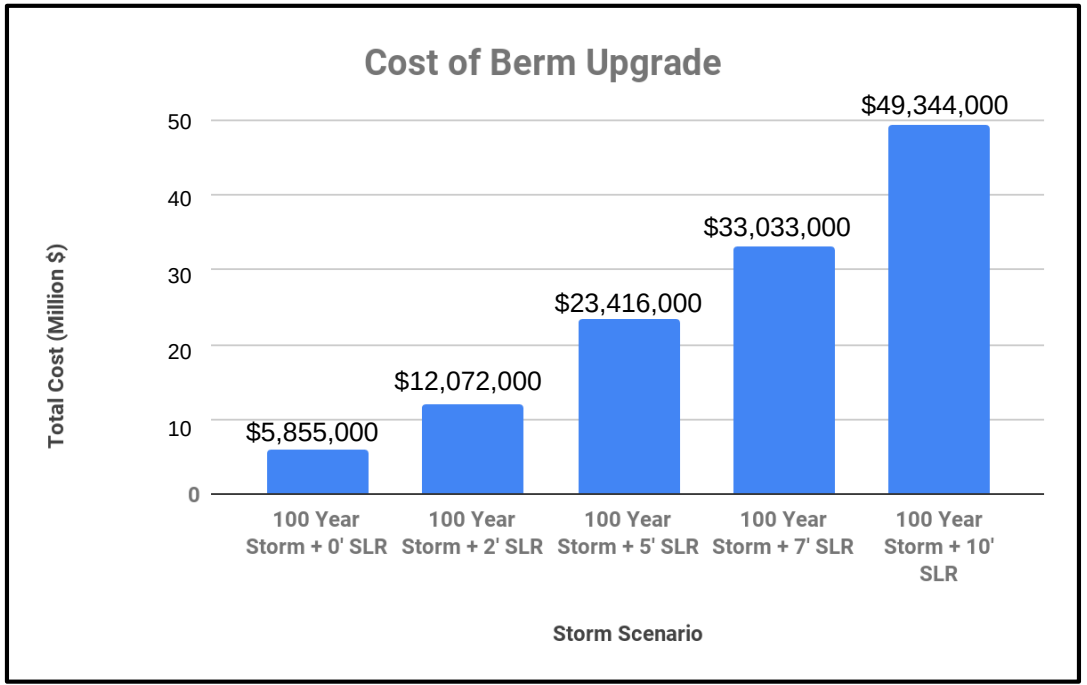


Bucklin Pt. Berm Upgrade Cost Calculation

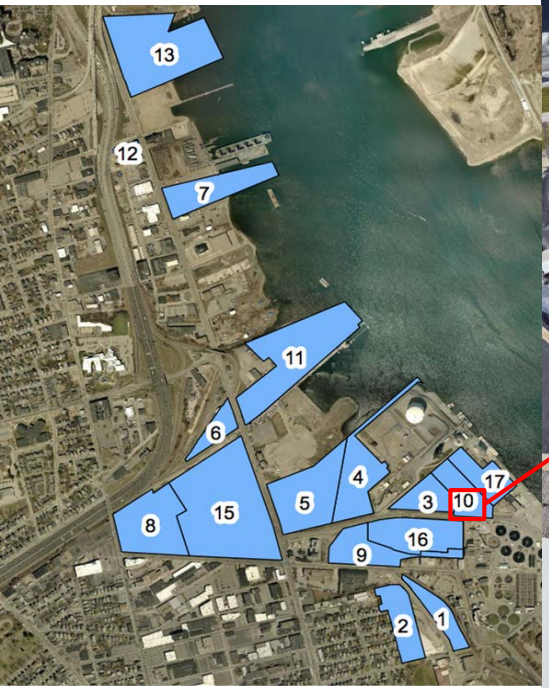
Unit cost of berm upgrade (fill soil only) = $3.04 / ft^3

Unit cost includes fill/loading ($0.83/ ft^3), spreading & compacting ($1.81/ ft^3) and hauling ($0.38/ ft^3)

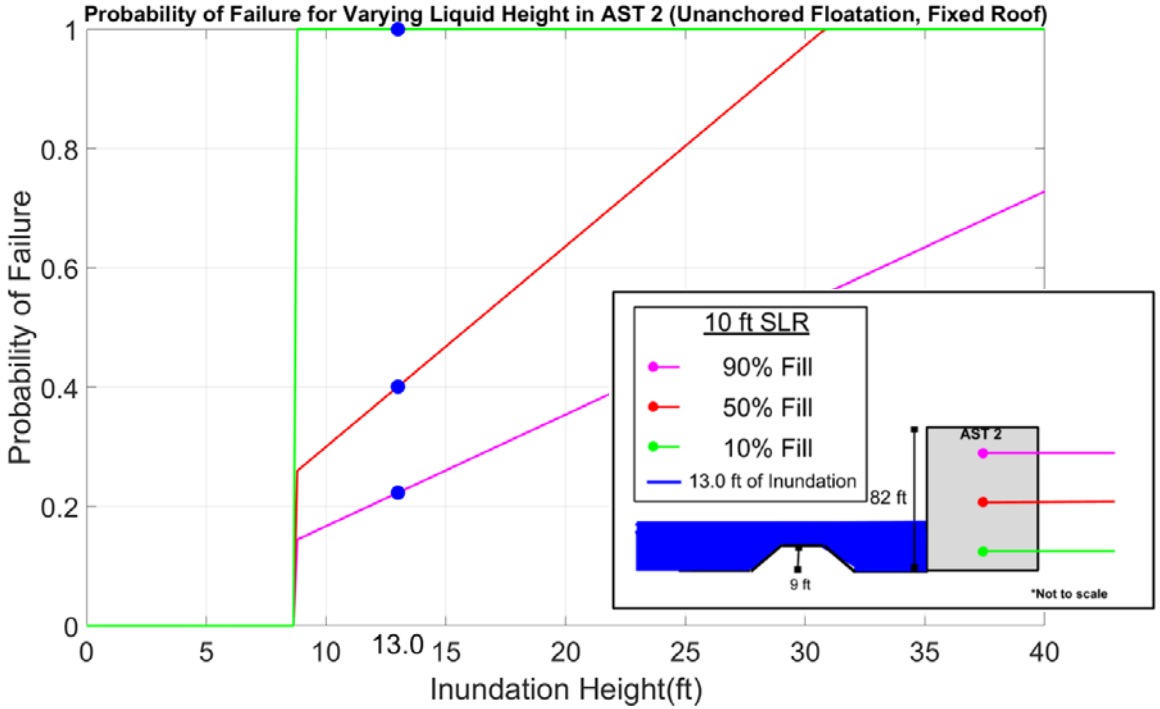
Storm Scenario	Volume (ft^3 per linear ft of berm)	Total Cost ($)
100 Year + 0 SLR	642.7	5,855,000
100 Year + 2 ft SLR	1325.03	12,072,000
100 Year + 5 ft SLR	2570.07	23,416,000
100 Year + 7 ft SLR	3625.63	33,033,000
100 Year + 10 ft SLR	5415.87	49,344,000



Damage Calculation for Selected AST: Polygon 10



Damage Probabilities for Multiple Fill Levels

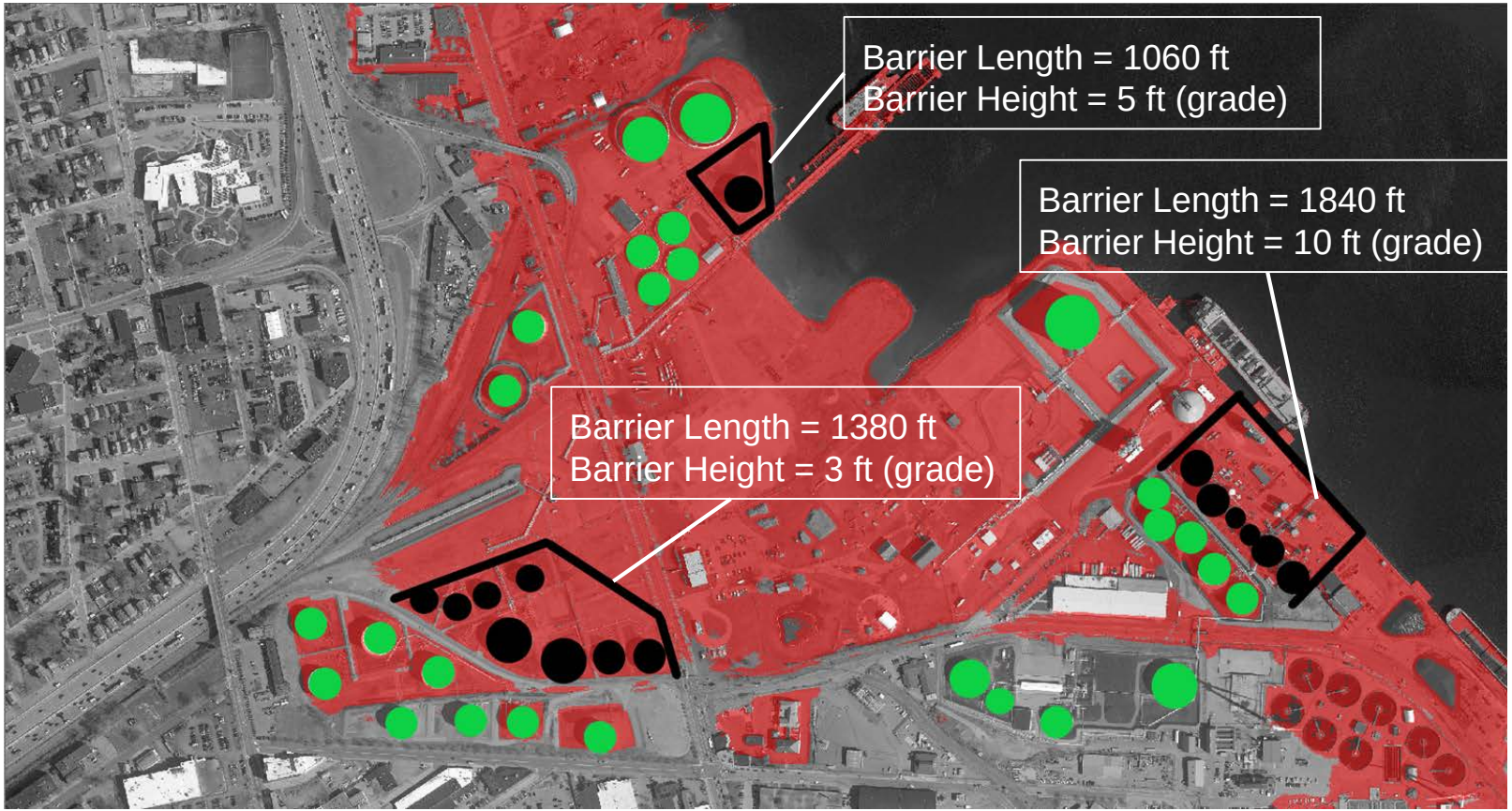


Liquid Height at 90% fill
Liquid Height at 50% fill
Liquid Height at 10% fill
Tank 2 Probability of Failure for an Inundation Height based on 100 year storm with 10 ft SLR

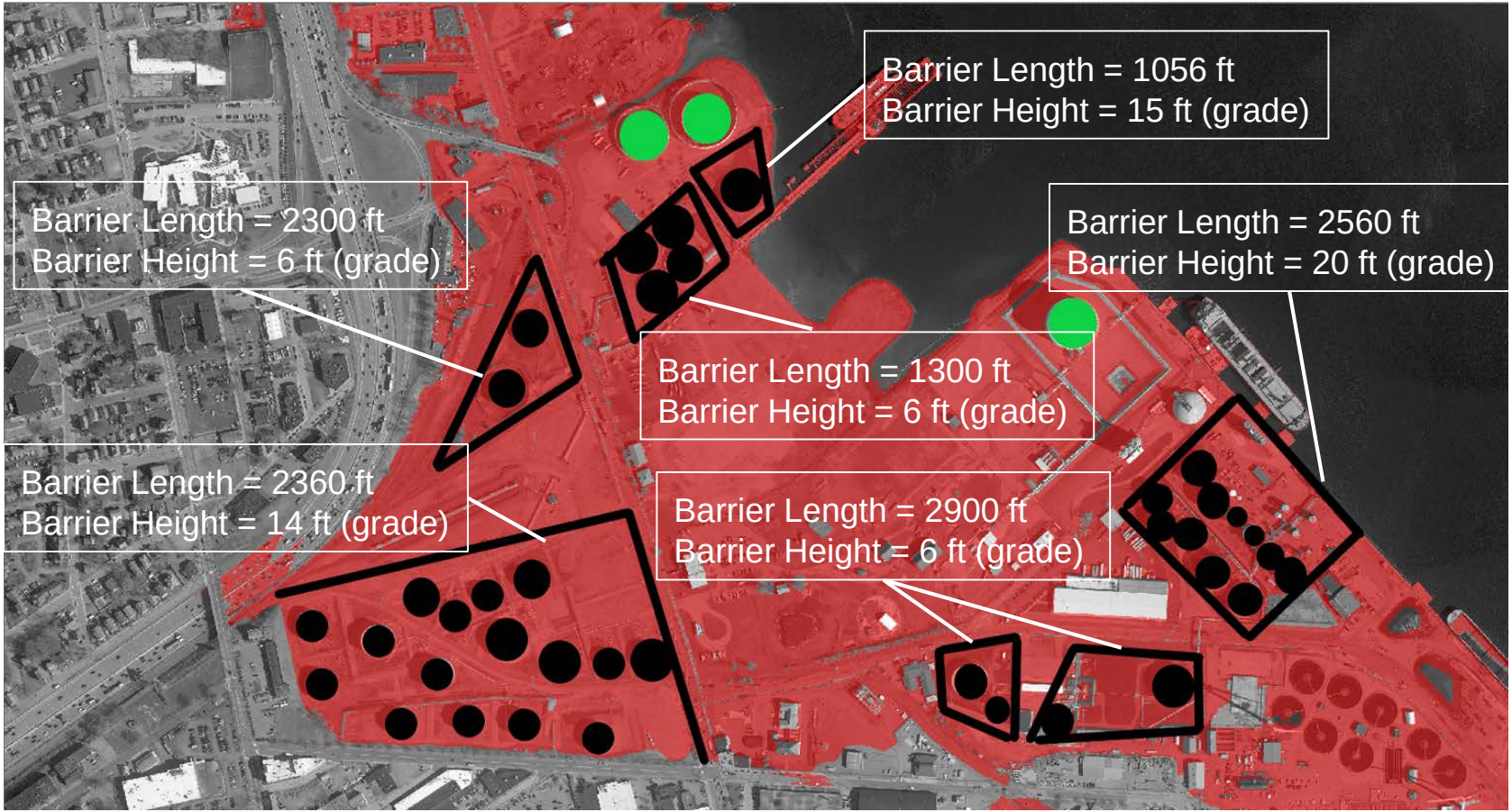
BFE - CFE


Legend
100 Year Storm + 0 ft SLR
100 Year Storm + 2 ft SLR
100 Year Storm + 5 ft SLR
100 Year Storm + 7 ft SLR
100 Year Storm + 10 ft SLR
Unaffected
Elevation Contour Lines
(ft NAVD88)
5 - 10
10 - 15
15 - 20
20 - 25
25 - 30
30 - 35
35 - 40
40 - 45
45 - 50

Proposed Barriers for ASTs - 100 Year Storm + 0 SLR



Proposed Barriers for ASTs - 100 Year Storm + 10 ft SLR



Summary

Problem Statement:

- Areas in Upper Narragansett Bay susceptible to threat of coastal flooding and sea level rise
- These areas have high concentrations of infrastructure

Study Objective:

- Use CERI to assess flooding damage during 100 year return period storm event with sea level rise to Fields Point and Bucklin Point WWTFs and ASTs in Upper Narragansett Bay.
- Based on the evaluation of damages to WWTFs and ASTs, recommend mitigation strategies to make these systems more resilient.

Conclusions: Fields Point WWTF

- Existing HAZUS risk index too general for level of our analysis
- Determined detailed amount of damage to WWTF using TFI
- All of Fields Point inundated for 100 yr storm with 10 ft of SLR
- Elevating strategies such as building a barrier or hardening strategies such as floodproofing doorways can be applied

Fields Point Wastewater Treatment Facility

Conclusions: Bucklin Point WWTF

- If berm is overtopped Bucklin Point is rendered inoperable
- All of Bucklin Point inundated for 100 yr storm with 0 ft of SLR
- Increasing existing berm height around facility best strategy for mitigating damage from coastal flooding

Bucklin Point Wastewater Treatment Facility

Conclusions: Above Ground Storage Tanks

- 60% of ASTs inundated for 100 yr storm without SLR
- 74% of ASTs inundated for 100 year with 5ft SLR
- 98% ASTs inundated for 100 yr storm with 10 ft SLR
- It is recommended that all tanks are anchored and barriers are added or height is increased

Above Ground Storage Tanks
near Fields Point

Questions?