

Sea Level and Storm Surge Exposure of Coastal Energy Assets:

Insights from Port and Water Infrastructure
Assessments from Norfolk to Charleston

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“We live in a world designed for an environment that no longer exists.”

- Richard Sork, co-founder, Jupiter Intelligence

- Risks posed to critical infrastructures as a result of **climate change** are relatively unexplored.
- Climate Central’s ***Surging Seas*** report and tools inventory sites within projected elevations of sea level rise, a measure of **exposure** (Strauss and Ziemplinski 2012)
 - Lacking site-specific scale of analysis, **hardening**, and hence, **susceptibility**.
 - Local defensive **mitigation** and **retreat** from such locations has been recommended when planning future infrastructure Holly (2012).

Mainstreaming Resilience

“Exposure”

- Operationalized as a quantitative measure of assets, infrastructure, or population where a coastal flood may occur, a necessary first step to quantifying resilience (Karamouz et al., 2016).

“Susceptibility”

- Degree to which a system is open, liable, or sensitive to climate stimuli, like sensitivity, with connotations toward damage and/or disruption or reduced level of service or function (c.f. Cardona et al., 2012).

“Vulnerability”

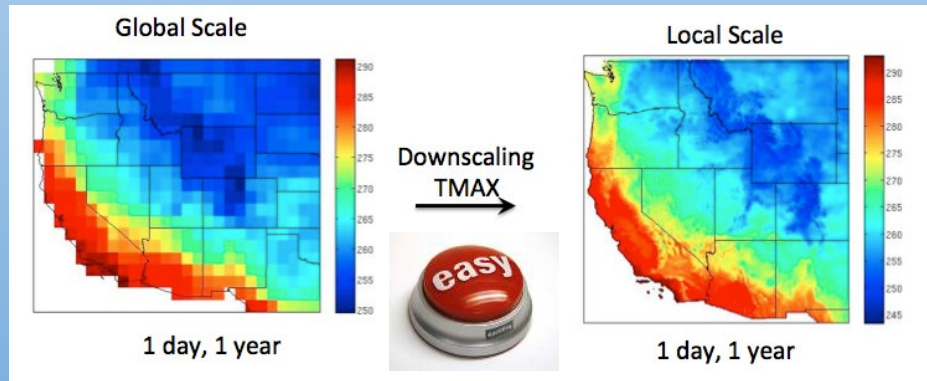
- Degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes—a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity (Melillo, Richmond, & Yohe, 2014, p. 672). In the process of our risk mapping and application to a tabletop exercise,

“Resiliency”

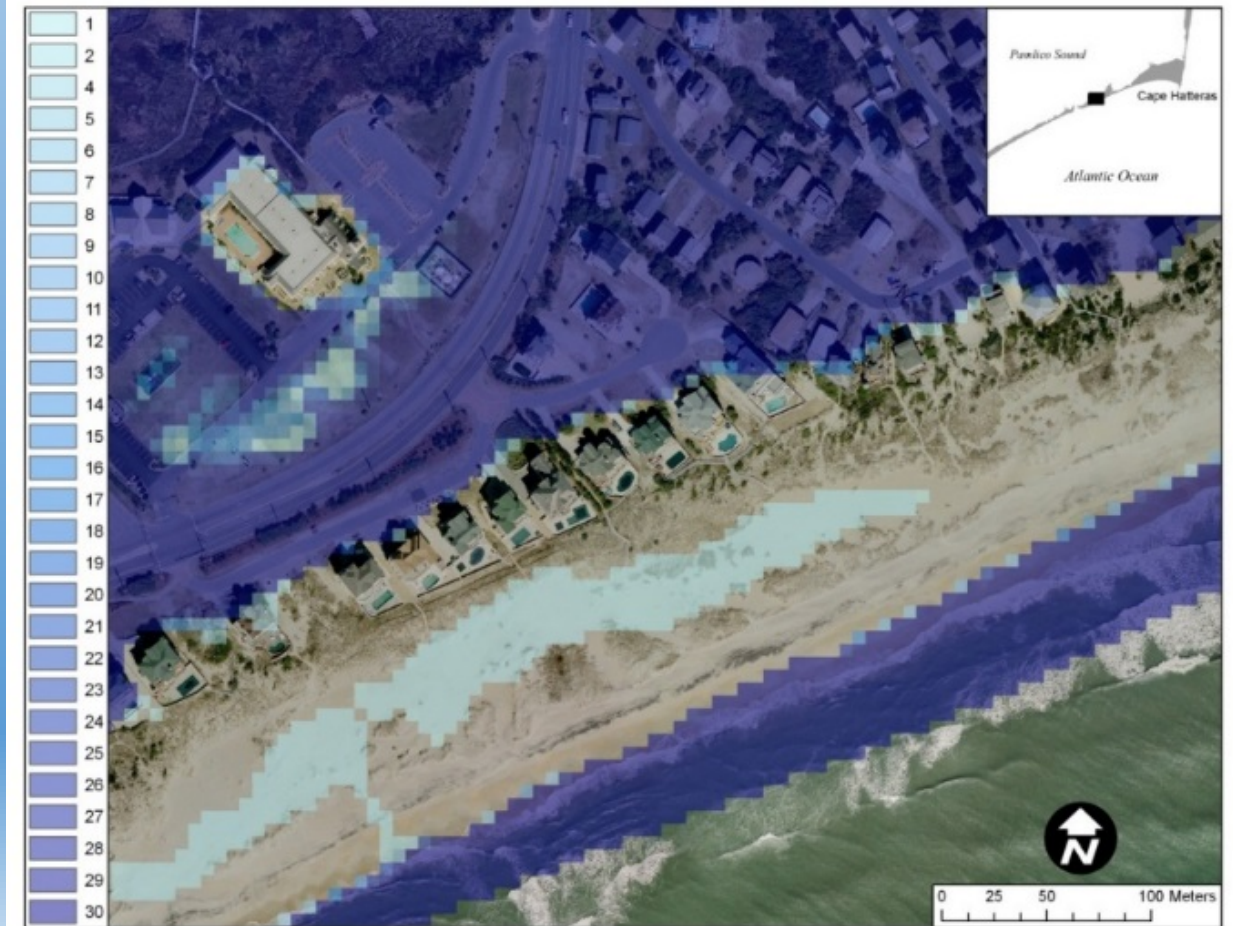
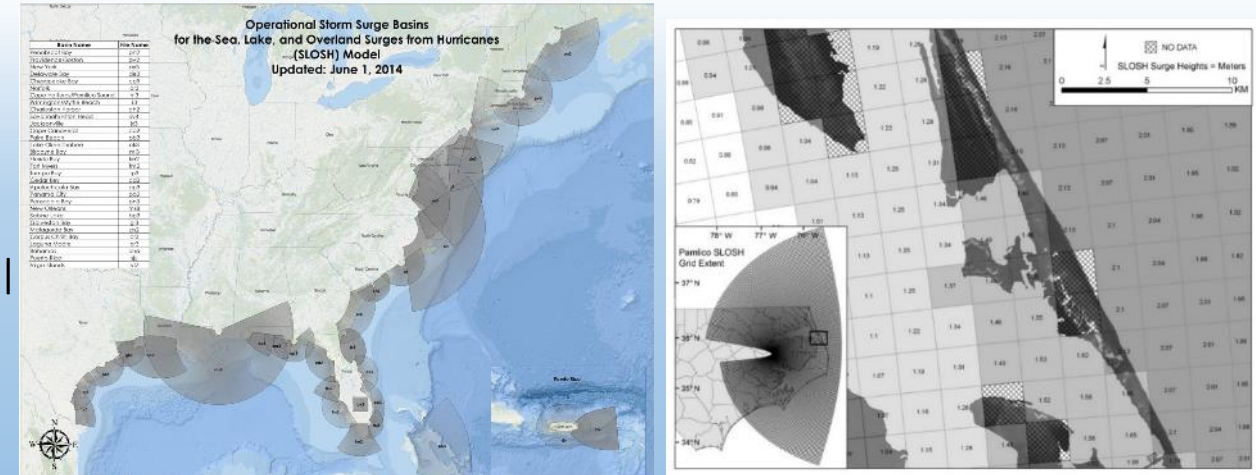
- Capability to anticipate, prepare for, respond to, and recover from significant multihazard threats with minimum damage to social wellbeing, the economy, and the environment (Melillo et al., 2014, p. 672).

Scale is a Challenge

Downscaling: Transforming a coarse resolution model to higher resolution e.g., GCM climate models

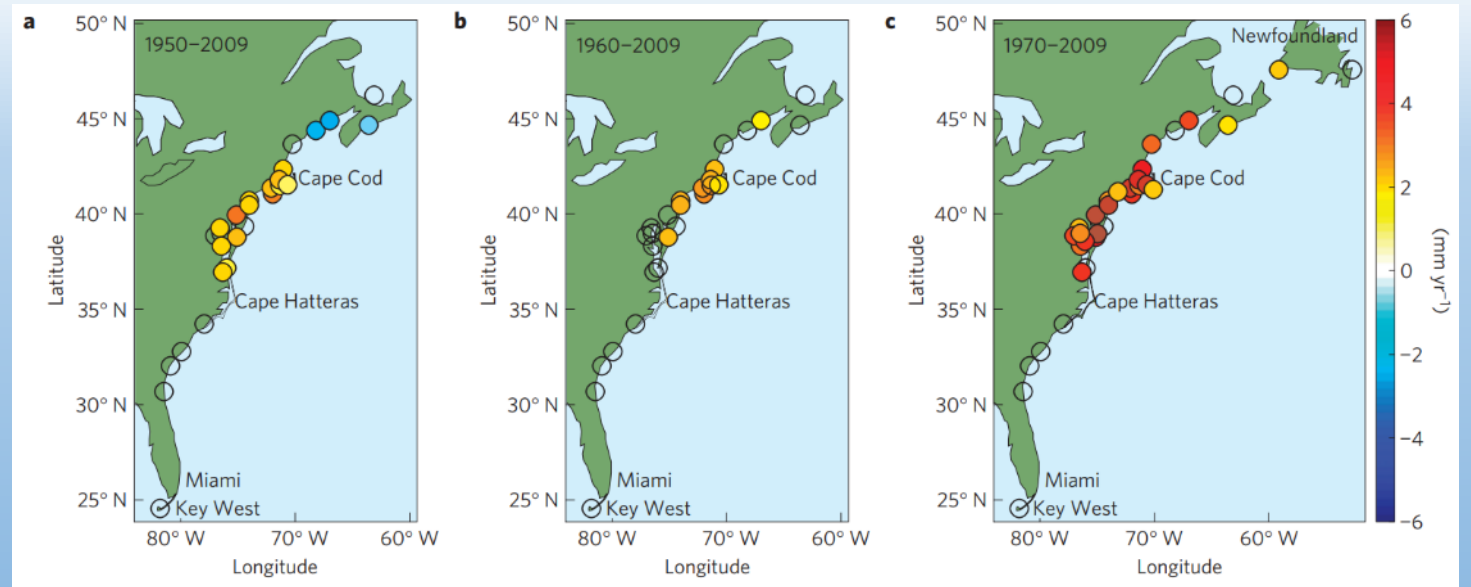


- Easy, but fraught with error...
- Consider uncertainty, error sources, and mapping “confidence,” risk tolerance, thresholds, and opportunities to optimize capital investment at junctures of infrastructure obsolescence

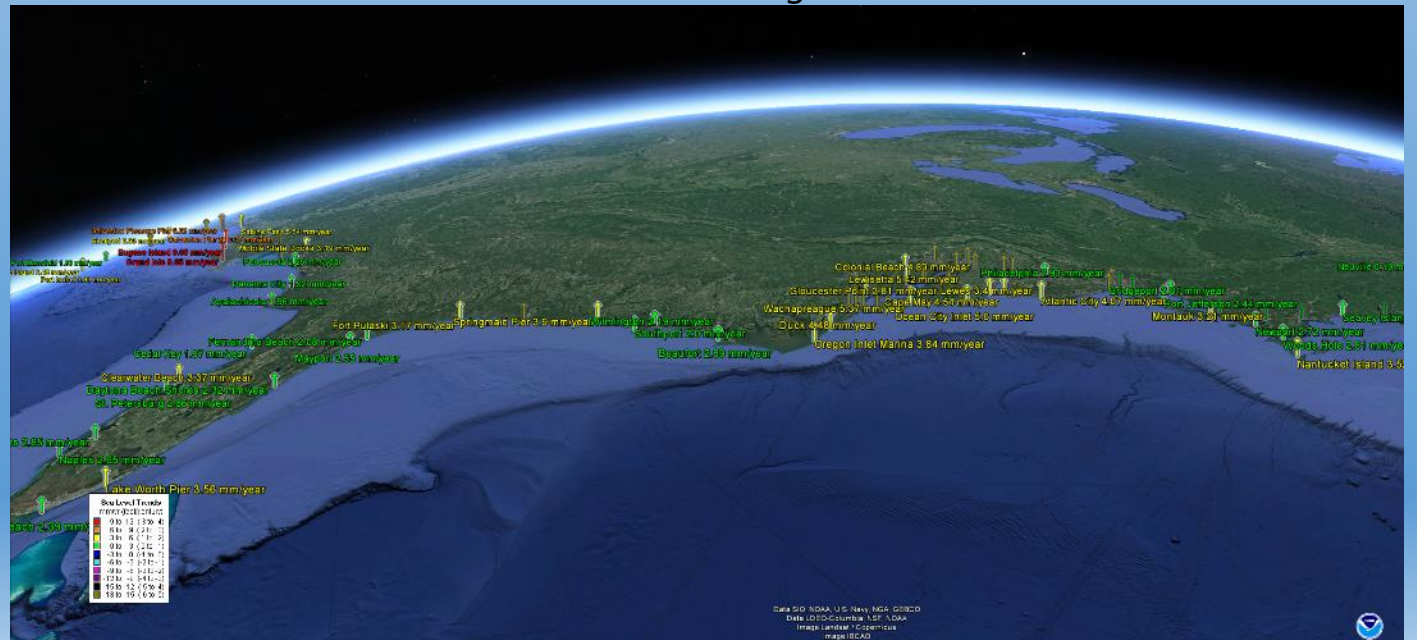


Sea Level Rise Hot Spots

- SLR rates in the northeast and Mid-Atlantic are 3-4X higher than the global average
- Warming/freshening subpolar North Atlantic
- Inhibits deep convection of Atlantic Meridional Overturning Circulation
- Gulf Stream slows down...



Sallenger et al. (2012) Hotspot of accelerated sea-level rise on the Atlantic coast of North America. *Nature Climate Change*.

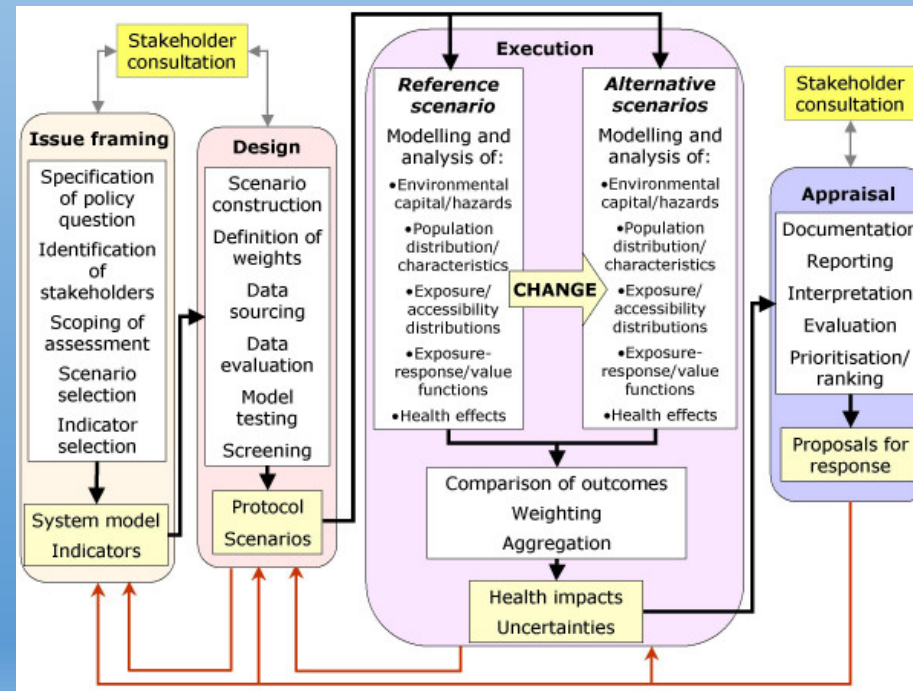


NOAA Sea Level Trends <https://tidesandcurrents.noaa.gov/sltrends/sltrends.html>

Steps to Resilience

US Climate Resilience Toolkit <https://toolkit.climate.gov/>

1. Explore Hazards
2. Assess Vulnerability & Risks
3. Investigate Options
4. Prioritize & Plan
5. Take Action



Briggs (2008) *Integrated Environmental Health Impact Assessment*

Case Studies

- NOAA Climate Program Office
 - Coastal Ocean Community Adaptation
 - Comparative study
 - Water + Health
 - Charleston, SC
 - Morehead City, NC
- Port of Virginia
 - Norfolk Intl. Marine Terminal

Public Health Risk Assessment for Water Infrastructure, Charleston

Population and Health Care

Water Infrastructure

Storm Surges

Sea Level Rise and Future Nuisance Flooding

Rainfall Runoff and Nuisance Tidal Flooding

All Layers Interactive

with Web AppBuilder for ArcGIS

Use this interactive map for visual risk assessment.

The layer list button at far upper right allows selecting layers for display, adjusting drawing order and transparency, or accessing detailed attributes. Use the legend button to see layer categories.



Legend



CHS_sewer - Chas_SewerLines



CHS_infrastructure - Chas_WaterTreatmentFacilities



CHS_infrastructure - Chas_WaterWells



CHS_infrastructure - Chas_WaterLines



Vulnerability Field Sites



CHS_SLOSH_cat2

SLOSH MOM downscale

cat2

2

Population Density (persons per acre)

g_popden

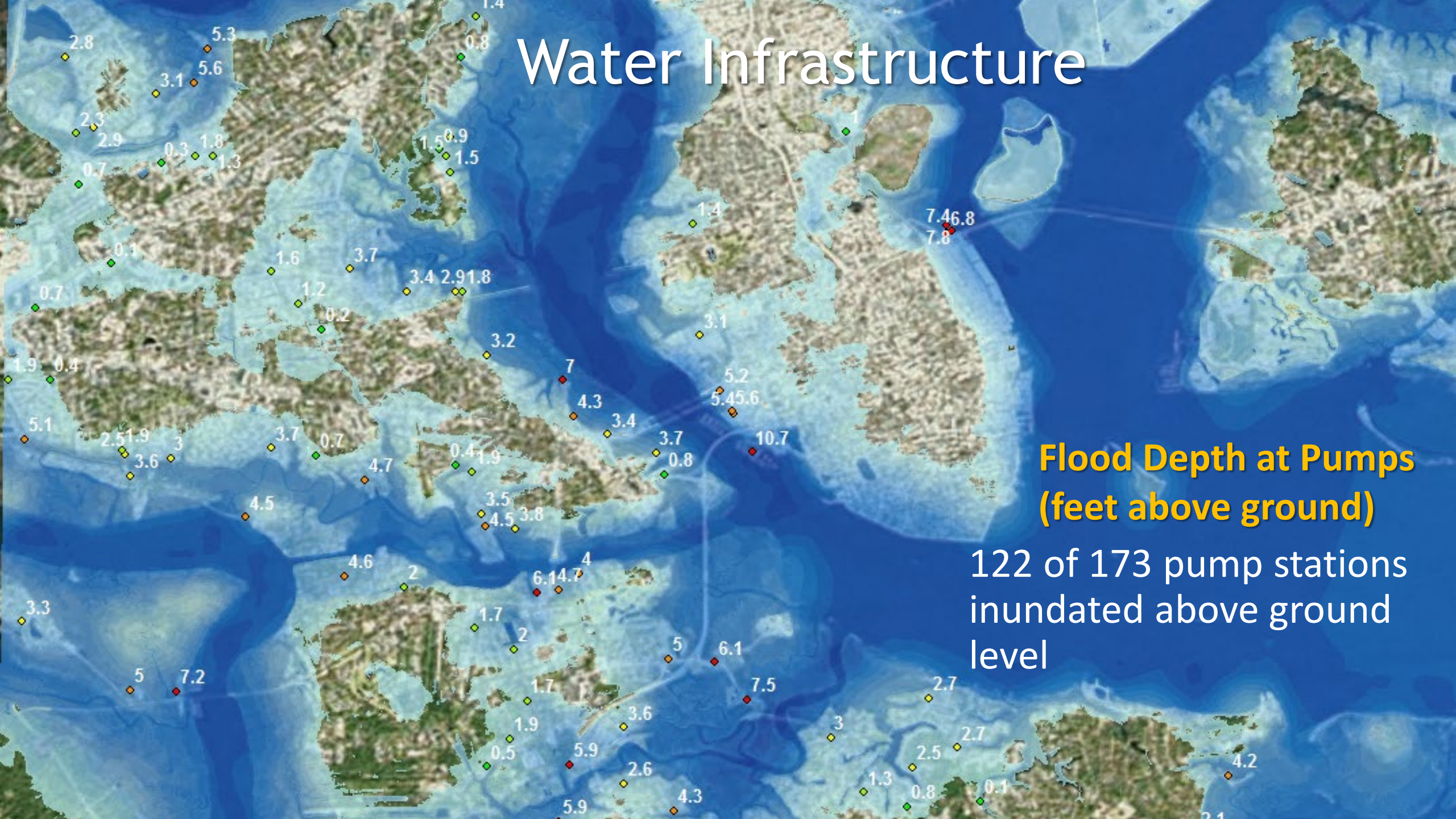
0.2 - 5

5.1 - 10

10.1 - 20

20.1 - 40

Water Infrastructure



**Flood Depth at Pumps
(feet above ground)**

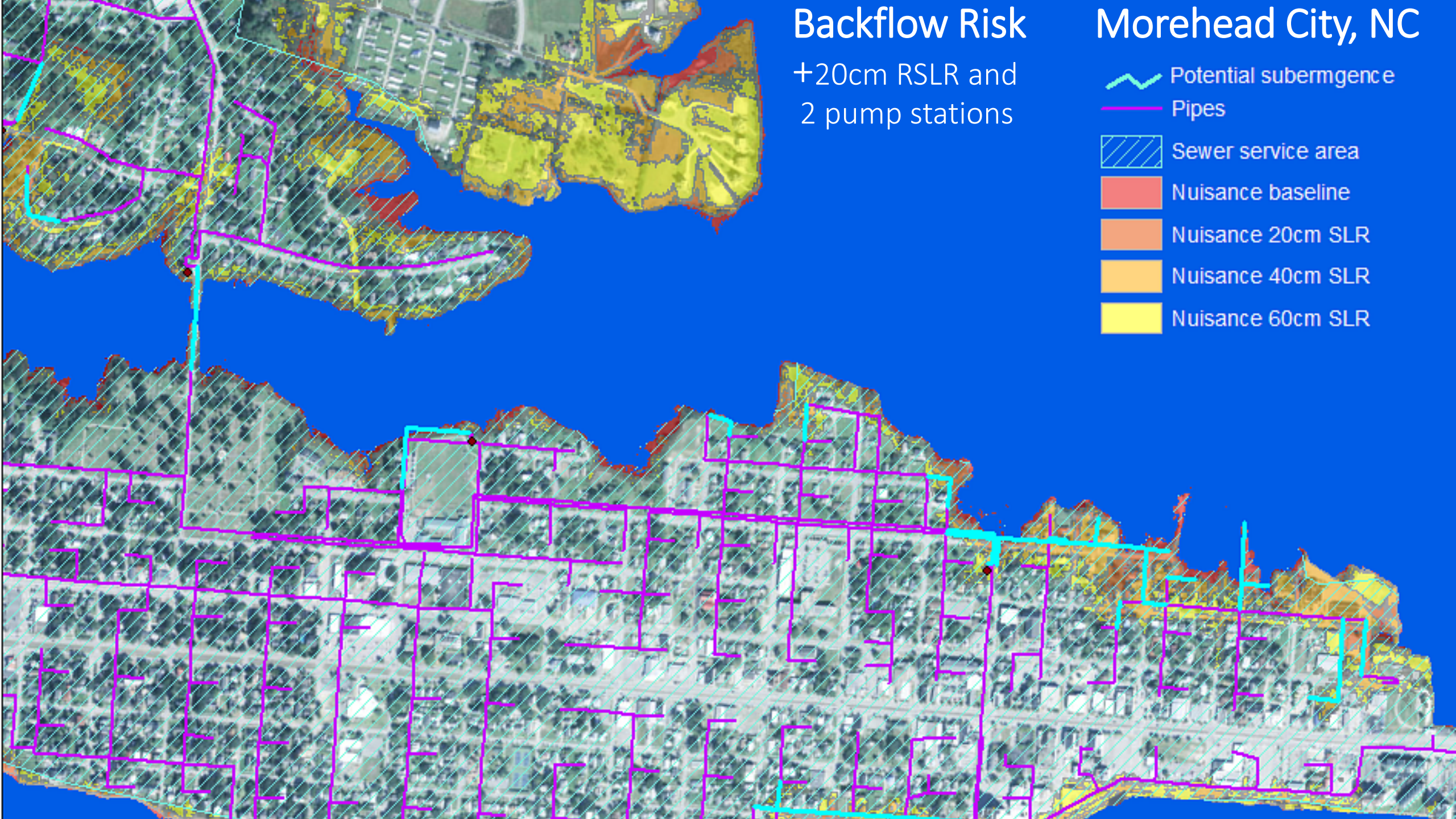
122 of 173 pump stations
inundated above ground
level

Backflow Risk

+20cm RSLR and
2 pump stations

Morehead City, NC

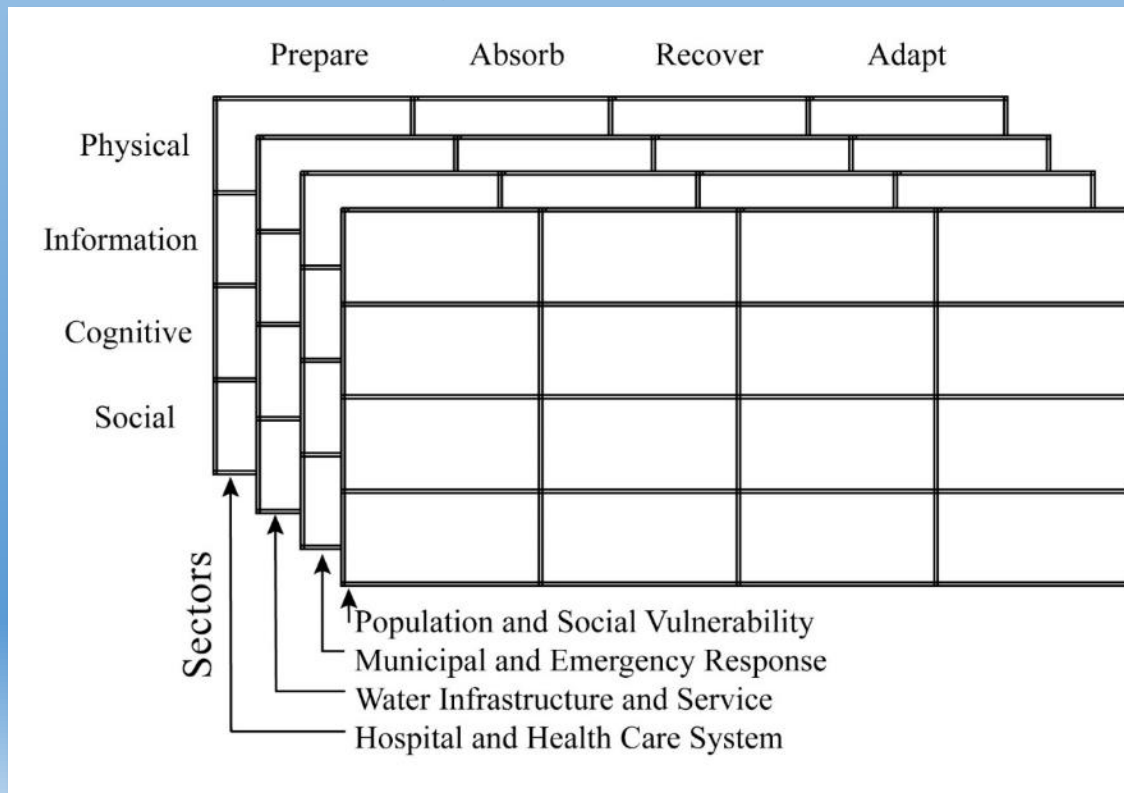
- Potential submergence
- Pipes
- Sewer service area
- Nuisance baseline
- Nuisance 20cm SLR
- Nuisance 40cm SLR
- Nuisance 60cm SLR



Charleston Work Implemented a *Resilience Matrix Framework*

Resilience Framework for Charleston Water Infrastructure and Public Health

Integrated & Multi-Sector



Resilience Analysis Process

- Probability of consequence X given threat Y
- Metrics of service interruption and recovery are well developed, but are cascading impacts and resiliency?
- ...are they available for future climate-sensitive threats?
 - E.g., damage to support services industry in Hurricanes Katrina and Rita contributed to prolonged oil and gas disruptions (DOE 2006)
 - Loss of electric power
 - → No fuel for boats, helicopters, ground transportation vital to recovery



Port of Virginia Sea Level Rise Assessment



<https://www.floodingresiliency.org/>



<http://www.portofvirginia.com/>



<https://oduadaptationandresilience.org/>



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Norfolk International Terminal

Sea Level Rising is Accelerating

- Future storm surges will reach higher than historic events.

Tidal Flooding Poses an Emerging Threat

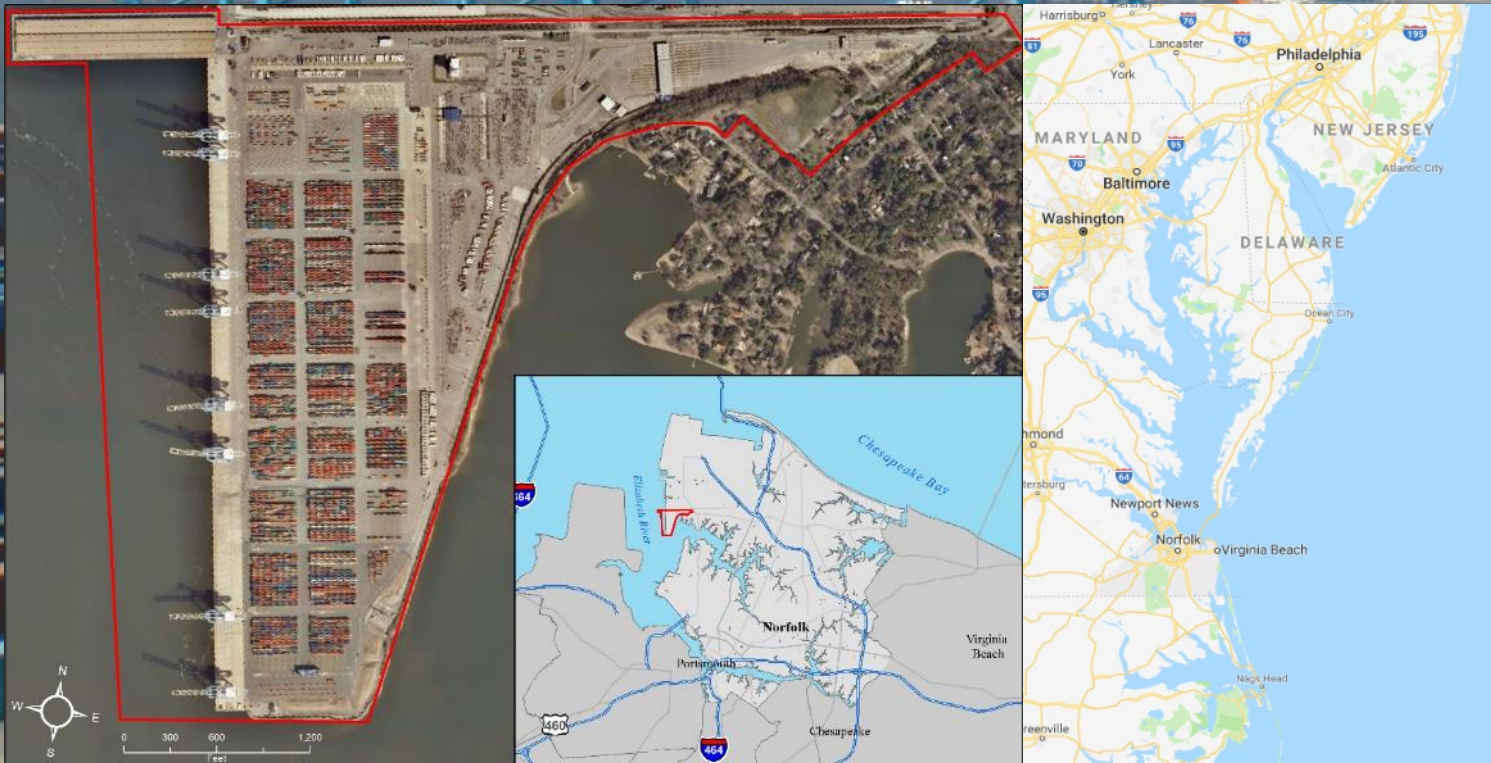
- Today's extreme high tide will be future mean high tide.
- Nuisance flooding will recur with chronic regularity.

Sustainable Operations

- Disruption to supply chain
- Efficiency
- Profitability
- Competitiveness

Broader Effort

- To inform timing & placement of planned assets at NIT South, NIT North, & VIG.
- Compatible with future optimization work.



Scenarios and Uncertainty

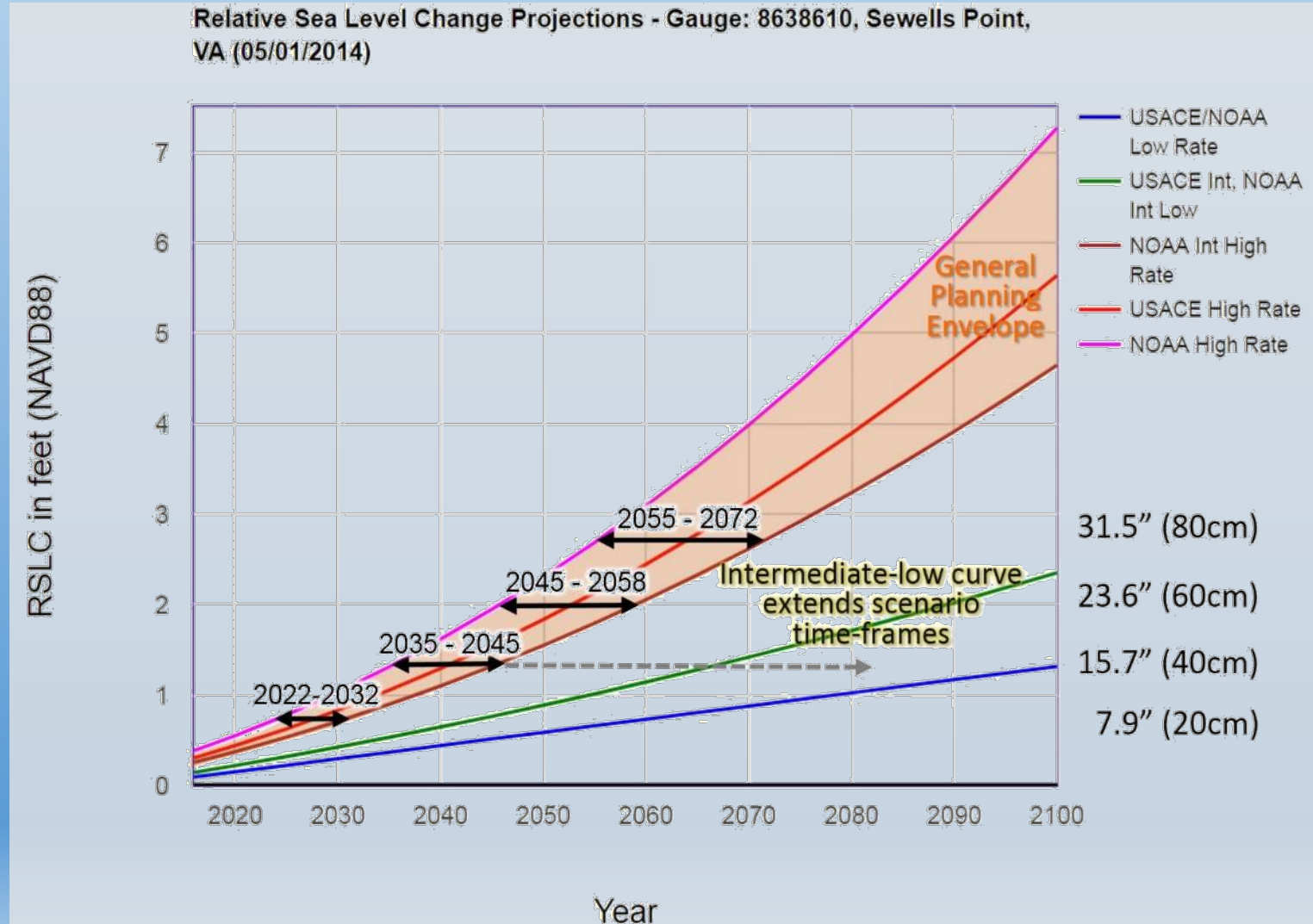
Sea Level Rise Scenarios

- NOAA 2017 and USACE Sea Level Calculations
- Vertical land motion (subsidence) included
- Modeling scenarios (intermediate-high RSLR curve for timeline)

SLR amount

Est. 1st impact

+7.9" (20cm)		~2022-2032
+15.7" (40cm)		~2035-2045
+23.6" (60cm)		~2045-2058
+31.5" (80cm)		~2055-2072

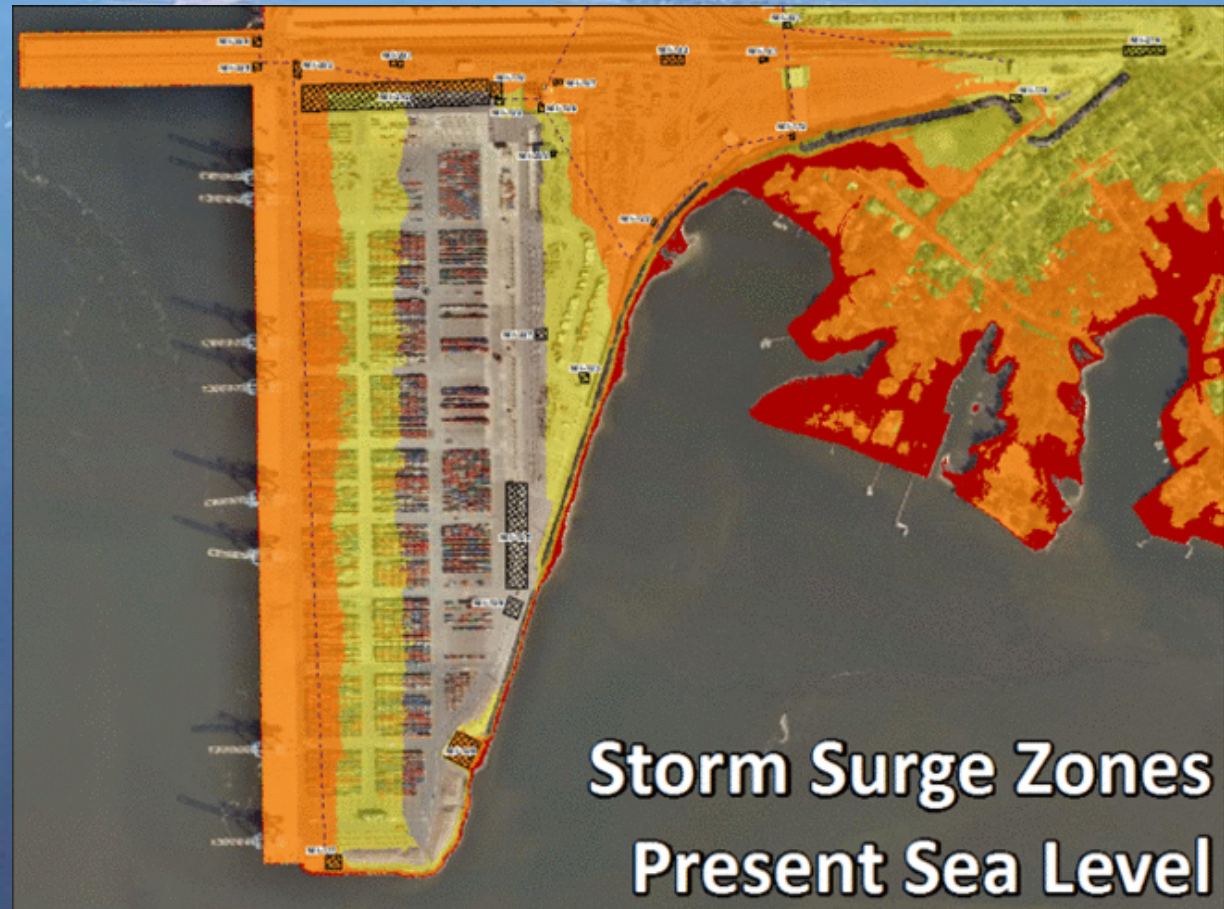
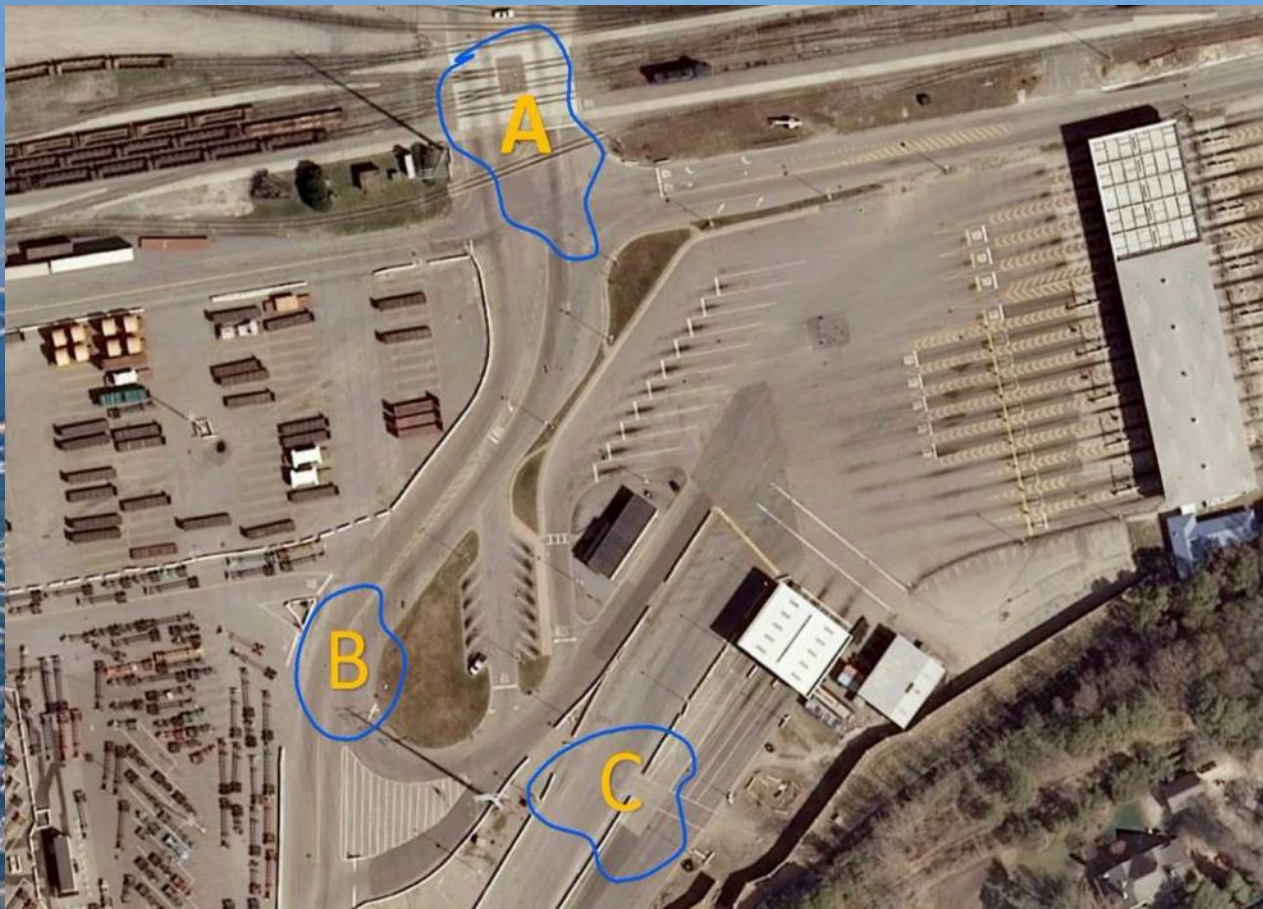


Sea Level Rise Models

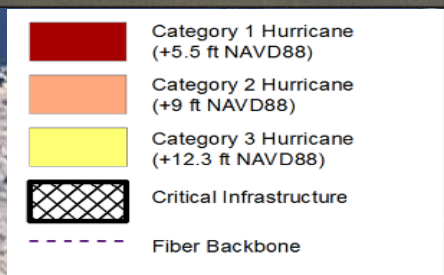
- GCMs and CoastClim (Warrick 2006)
- NOAA Sea-Level Rise Rectification Program (NOAA SLRRP 2017; Keim et al. 2008)
- USACE Sea Level Rise Calculator (USACE 2015)
- Potsdam Temperature-based sea-level rise model Rahmstorf (2007)
- Varying by
 - Appropriate scale
 - Spatial resolution
 - Temporal scale
 - Input and output parameters

Geospatial Sea-Level Rise Mapping Tools

- Increasingly accessible and used for decision support
- USGS Sea Level Rise Animations
- NOAA Digital Coast Sea Level Rise Viewer
- Climate Central Surging Seas
- The Nature Conservancy Coastal Resilience Tools

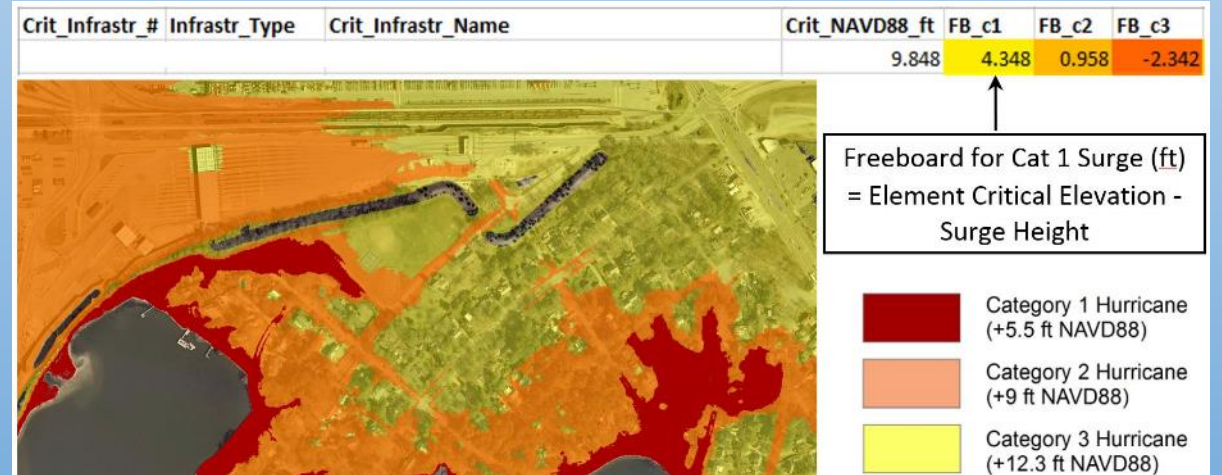


**Storm Surge Zones
Present Sea Level**



Inundation Risk Maps and Prioritization

Infrastructure risk tables detail the freeboard elevation between the surge and the structure's critical elevation. Positive values indicate critical elevation is not submerged and negative values indicate potential inundation depth.



Present day (baseline) vulnerability of storm surge for NIT South structures sorted by elevation risk within infrastructure type.

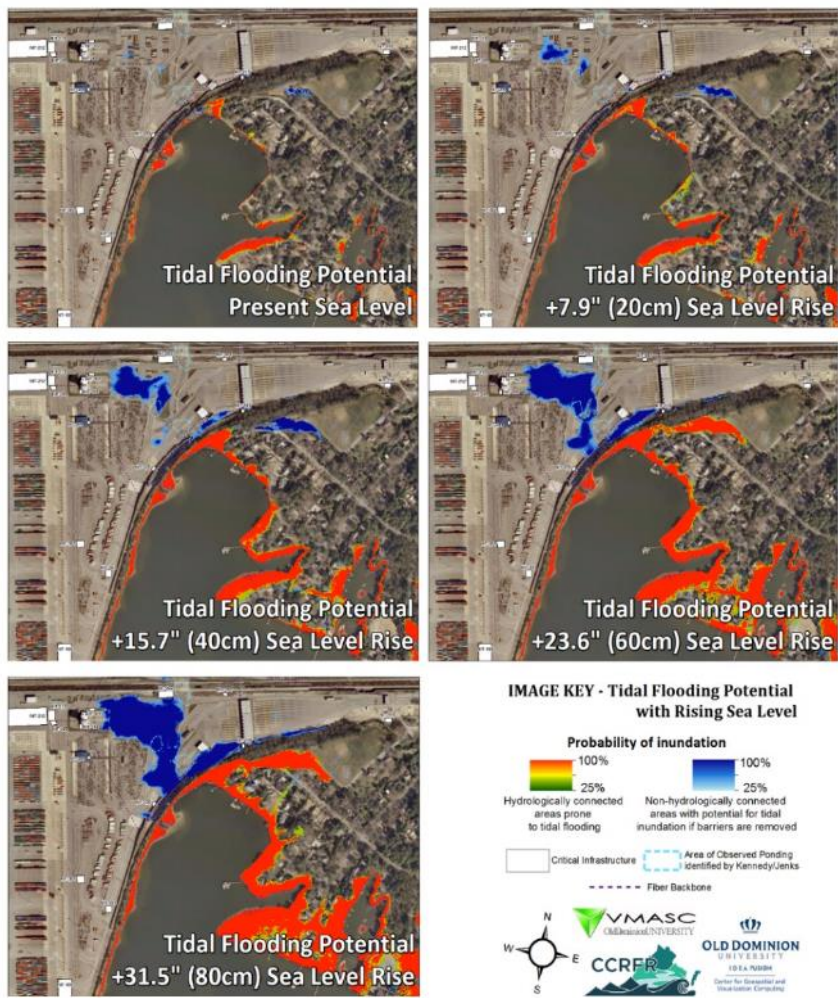
Dependency on elevation and asset mapping, SLR, and surge modeling.

Crit_Infrastr_#	Infrastr_Type	Crit_Infrastr_Name	Crit_NAVD88_ft	FB_c1	FB_c2	FB_c3
214	Electrical	Terminal Boulevard Power Feed	9.848	4.348	0.958	-2.342
120	Electrical	OCR Portal Generator	10.551	5.151	1.551	-1.749
106	Electrical	Tanners Point Substation	10.741	5.241	1.851	-1.559
107	Electrical	Control Tower Transformer	11.151	5.751	2.151	-1.149
201	Electrical	CRY Customs Area Generator	11.201	5.801	2.201	-1.099
119	Electrical	Staff Interchange Building Generator	11.341	5.941	2.451	-0.849
102	Electrical	Pump House Switch	11.851	6.451	2.851	-0.449
108	Electrical	Tower Generator	11.951	6.551	2.951	-0.349
209	Electrical	CSA Generator	12.151	6.751	3.151	-0.149
110	Electrical	Open Air Substation Reefer Row South	12.241	6.841	3.241	-0.059
101	Electrical	Terminal Boulevard Switch	13.051	7.651	4.051	0.751
118	Electrical	South Gate Front Generator	14.251	8.751	5.361	2.061
104	Electrical	Open Air Substation NIT South	14.251	8.751	5.361	1.951
103	Electrical	Tanners Point Switch	15.531	10.131	6.531	3.231

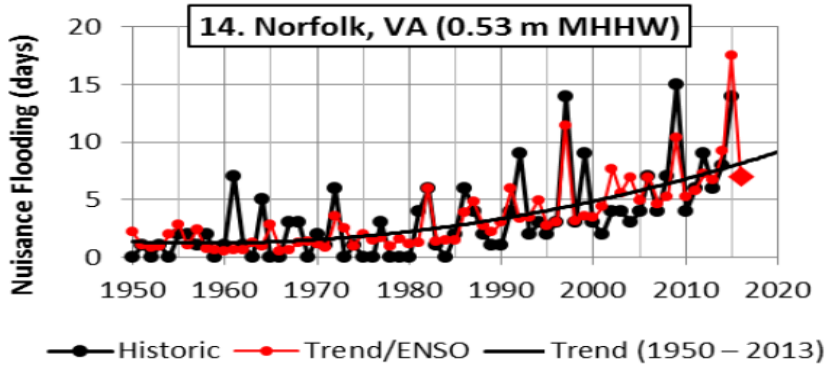
Tidal Flooding

“Today’s extreme becomes tomorrow’s mean...” Sweet and Marra (2016)

- Increased “nuisance” flooding is obvious at street-level
- Frequency *and* severity of impacts will increase
- Hence, high tide flooding is a shifting baseline as well.
- Deeper channel dredging to accommodate ever larger ships may increase upstream flooding
- Subsurface soil, fill, and stormwater require attention for backflow and tailwater flooding as hydraulic head decreases with SLR



Location Name	Nuisance Level	Historic Record	1995 Flood Days	----- 2015 Flood Days -----			----- 2016 Outlook -----	
	(above MHHW)	Yearly Floods (Days)	Trend ¹	Trend ¹	w/ El Nino ^{1,2}	Observed	Trend ¹	w/ La Nina ^{1,2}
14 Norfolk, VA	0.53	15	4	8±3	18±2	14	8	7



Strategic Site and Asset Recommendations

1. Ensure Accurate Elevation Surveys

- All critical assets, infrastructure, defenses, and LiDAR elevation models
- Adopt GIS and reference vertical and freeboard as well as horizontally e.g., RTK GPS survey, terrestrial laser scanning, UAV mapping

2. Systemic Risk or Cascading Failures

- Assess potential, utilities, employees, transport, external effects

3. Assess Hydrologic Connectivity (including subsurface)

- Investigate subsurface soil, groundwater, and storm water
- Backflow and tailwater

4. Integrate data

- Enterprise GIS or similar spatial database information system

Planning Actions to Improve Resilience

1. Explore Wider Systemic Vulnerabilities

- Transportation corridors, electric distribution, multi-modal linkages, in collaboration.

2. Include Monitoring of Sea Level & Flood Hazards

- Every 5 years...

3. Disaster Response and Emergency Management

- Incorporate vulnerabilities into port planning
- Assess workforce hazard exposure

4. Engage with Wider Community

- Risk assessment, adaptation, and mitigation projects, HR Adaptation Forum

5. Follow Strategic Developments

- Industry, government, and peer-reviewed literature.
- Integrated risk management (to include transportation, supply chains, regional disaster response and recovery, and staff exposure to impacts.)

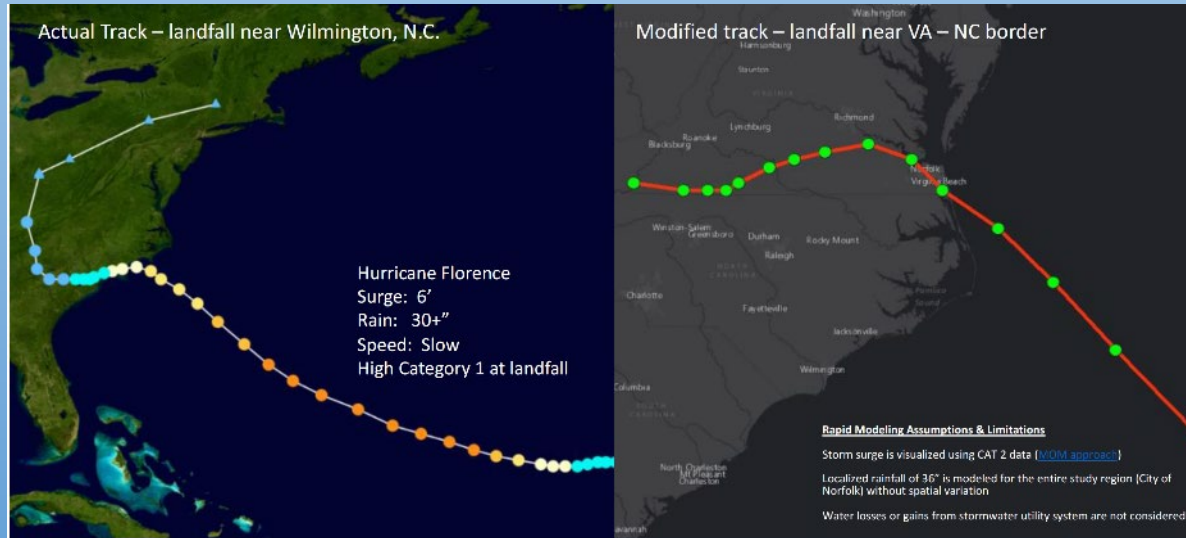
6. Track Other Ports' Resiliency Activities

- Regionally, nationally, and internationally

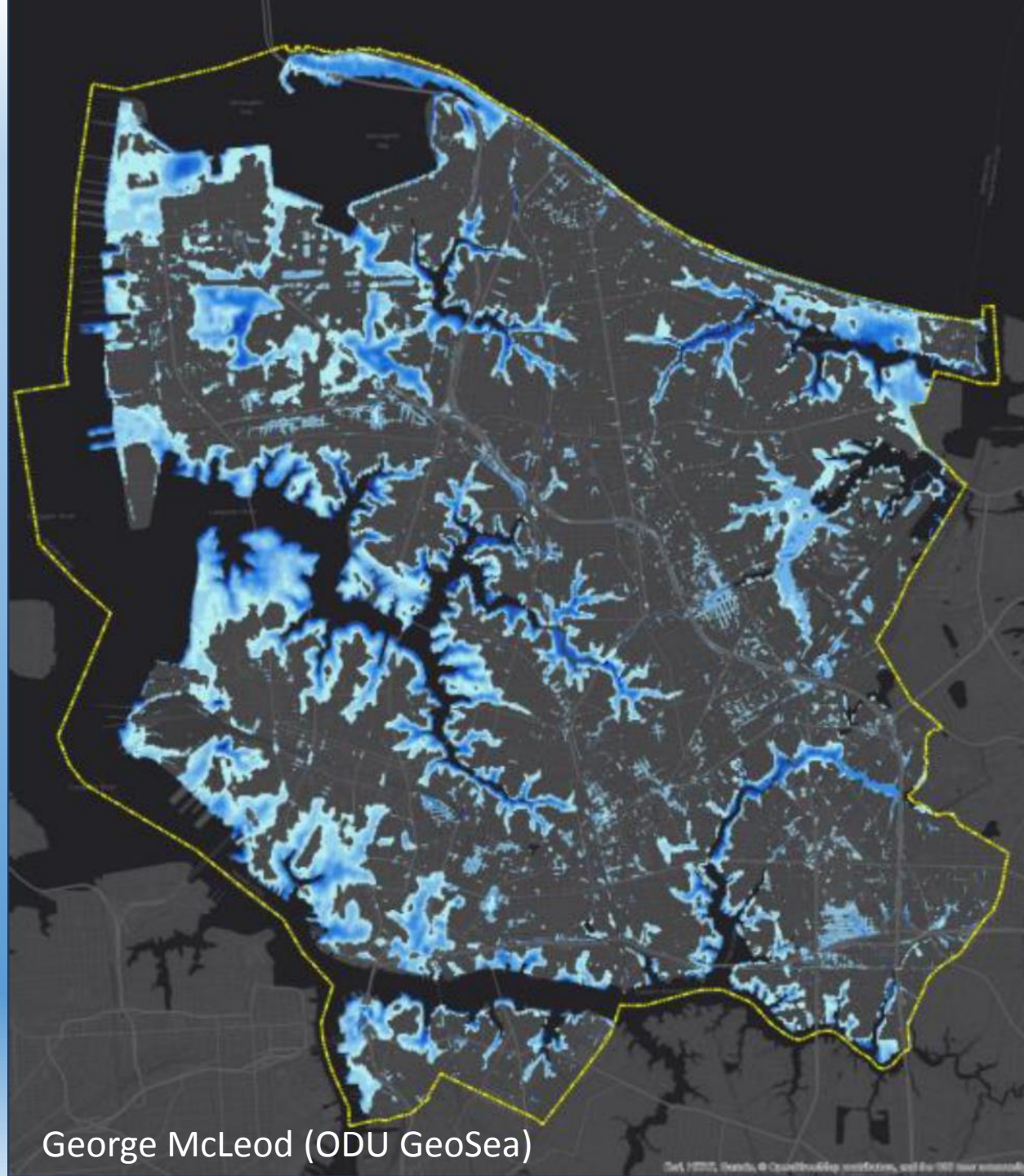
Combined Hazards

Hurricane Florence “What If?” Scenario for Norfolk, VA

- What if Hurricane Florence 2018 had struck Hampton Roads?



- Virginia Governor Northam issued A zone evacuation
- Catastrophic flooding could have happened



George McLeod (ODU GeoSea)

NASA Disasters Demo Study <http://arcg.is/0q1yn0>

Mid-Atlantic Resiliency Demo Study



Communities and Areas at Intensive Risk (CAIR): Mid-Atlantic Coastal Risk Demonstration

Coastal Risk and Resilience

<https://disasters.nasa.gov/resilience/cair>

Tropical storms are complex threats, comprising a range of risks to coastal development including storm surges, severe wind, extreme rainfall, and recurrent tidal flooding. Severe storms, sea level rise, and land subsidence coupled with increasing populations and densely populated, aging critical infrastructure often leave coastal regions and their communities extremely vulnerable.

The 2017 hurricane season saw 17 tropical storms, 10 of which evolved into hurricanes. Hurricane Harvey struck Texas in late August, leaving more than 50 inches of rainfall, roughly 200,000 damaged homes and over 80 deaths. Some estimates found damage from the 2017 hurricane season alone exceeded \$200 billion. Research from the scientific community suggests this was not an anomaly and more intense tropical storms will occur more frequently in the future.

NASA CAIR

NASA and the wider scientific community have a strong record of

1/2 Mid-Atlantic CAIR





Mid-Atlantic CAIR

Translating Compounding Hazards to Societal Risk



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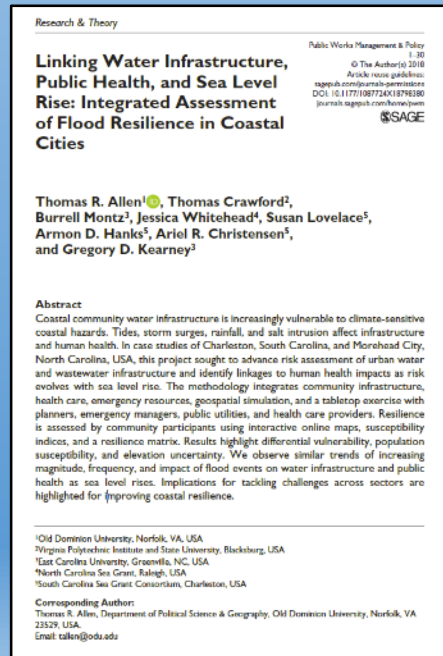
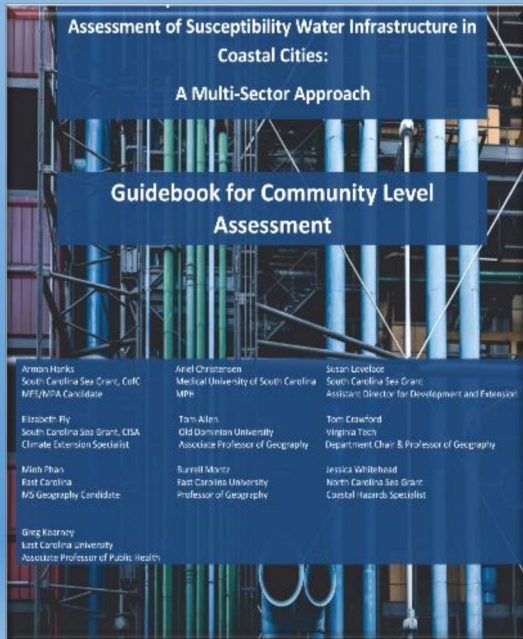
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Models for Specific or Multiple Sectors

- EPA <https://www.epa.gov/crwu>
- NOAA COCA Community Water & Public Health Assessment





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Creating Resilient Water Utilities (CRWU)

EPA's CRWU initiative provides drinking water, wastewater and stormwater utilities with practical tools, training and technical assistance needed to increase resilience to extreme weather events. Through a comprehensive planning process, CRWU assists water utilities by promoting a clear understanding of potential long-term adaptation options.

Resources to Plan for Extreme Weather



- [Use the Adaptation Strategies Guide](#)
- [Conduct a planning workshop](#)
- [Explore and share case studies](#)

Tools to Assess Risks of Extreme Weather



- [Conduct a risk assessment](#)
- [View coastal storm surge scenarios](#)

Videos: Adaptation Planning in Action

- [Camden, NJ](#)
- [Faribault, MN](#)
- [Fredericktown, MO](#)
- [Harrisburg, PA](#)
- [Los Angeles, CA](#)
- [Manchester-by-the-Sea, MA](#)
- [Waynesboro, TN](#)

Related Topics

On [epa.gov](https://www.epa.gov):

- [Water Resilience](#)
- [Effective Utility Management Practices](#)

Energy Infrastructure

- Among critical infrastructures, energy infrastructures are *uniquely vital* given the enabling functions they provide all other infrastructures. Watson et al. (2014)
- Almeidi and Mostafavi (2016) reviewed 47 articles on sea level rise and critical infrastructure and found:
 - **Top impacts** to energy infrastructure include 1) Coastal flooding, 2) Salt intrusion, 3) Coastal erosion and 4) Increased energy demand.
 - **Deficiencies** include: 1) Limited capital improvement investment, 2) Uncertainty on sea level rise projections, 3) Costs of adaptation

Viavattene et al. (2018) Selecting coastal hotspots to storm impacts at the regional scale: A Coastal Risk Assessment Framework. *Coastal Engineering*. 134:33-47.

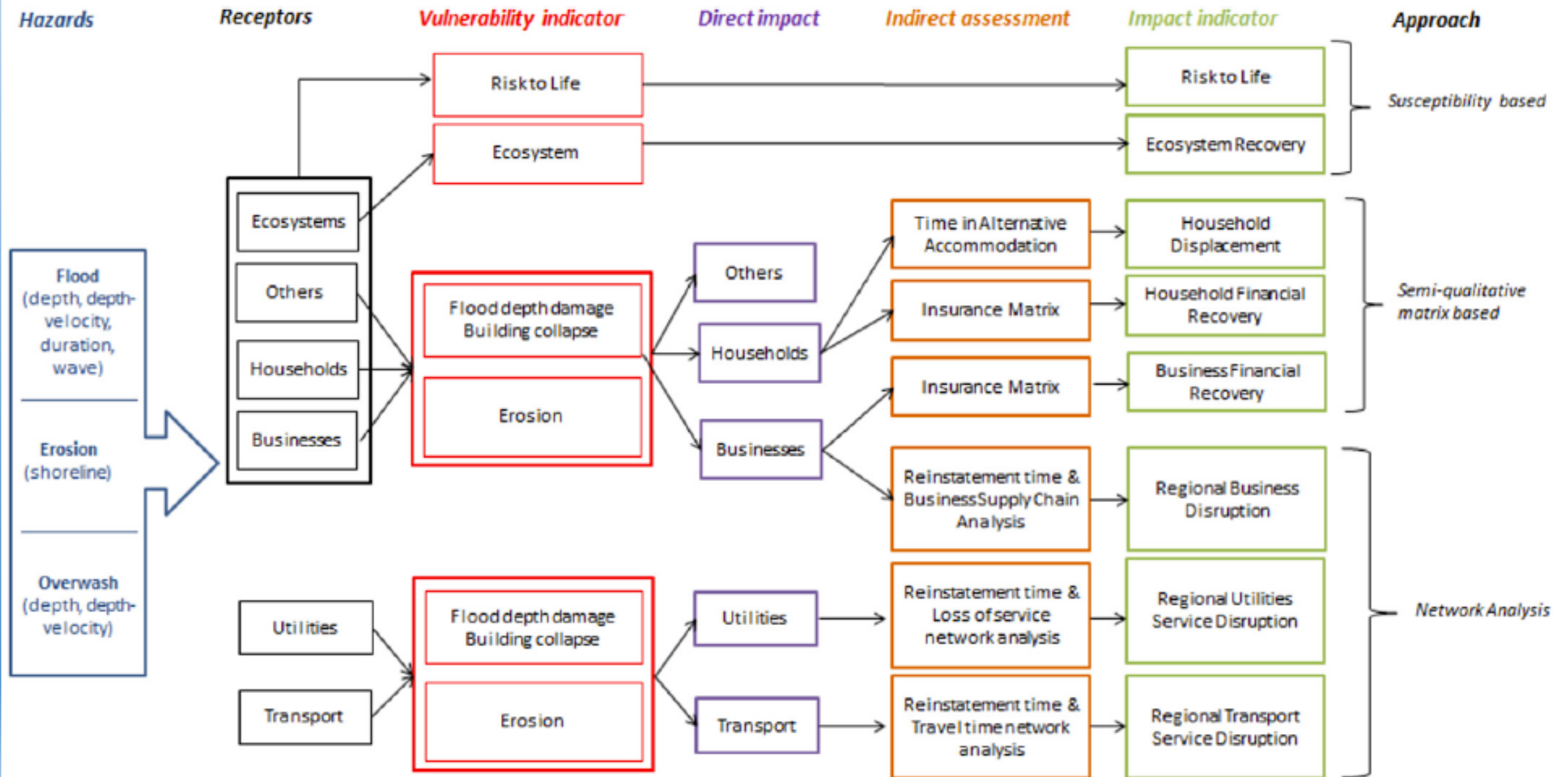
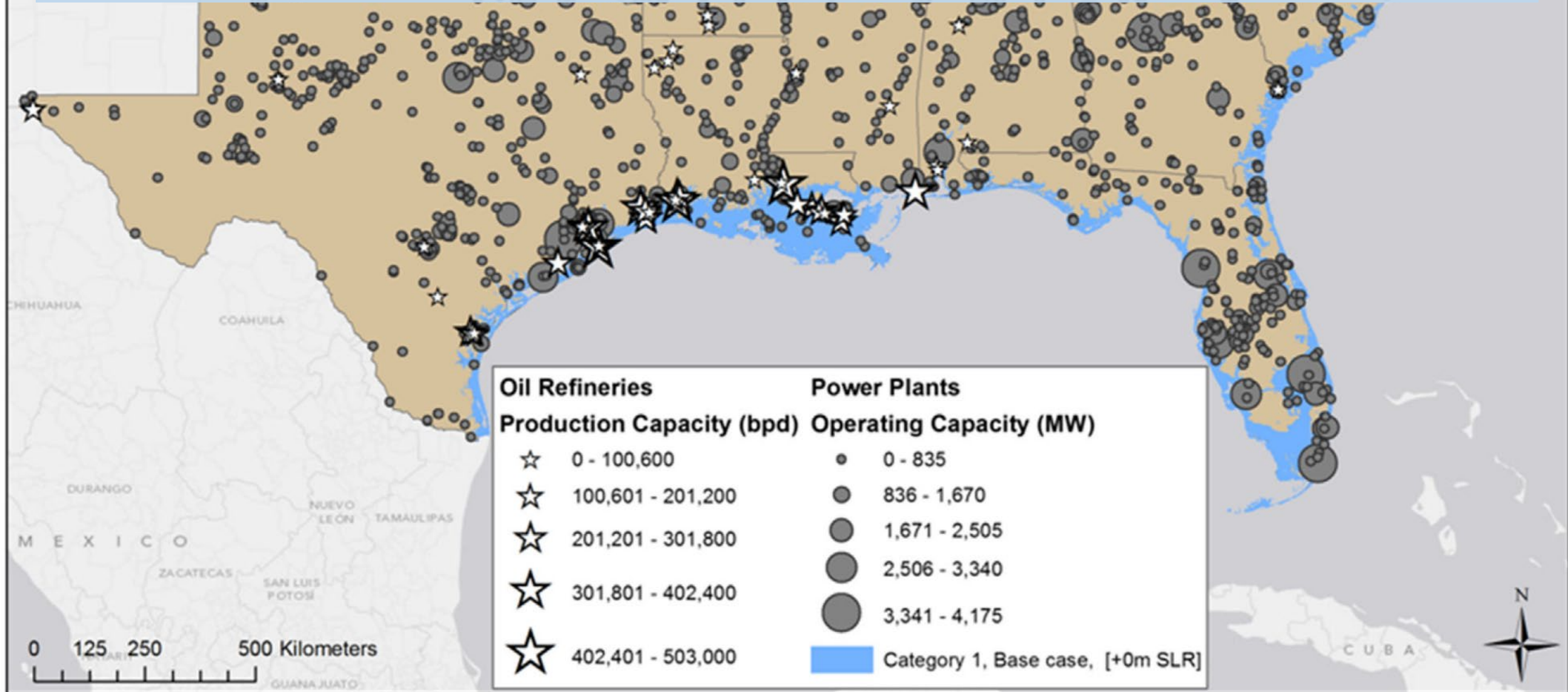
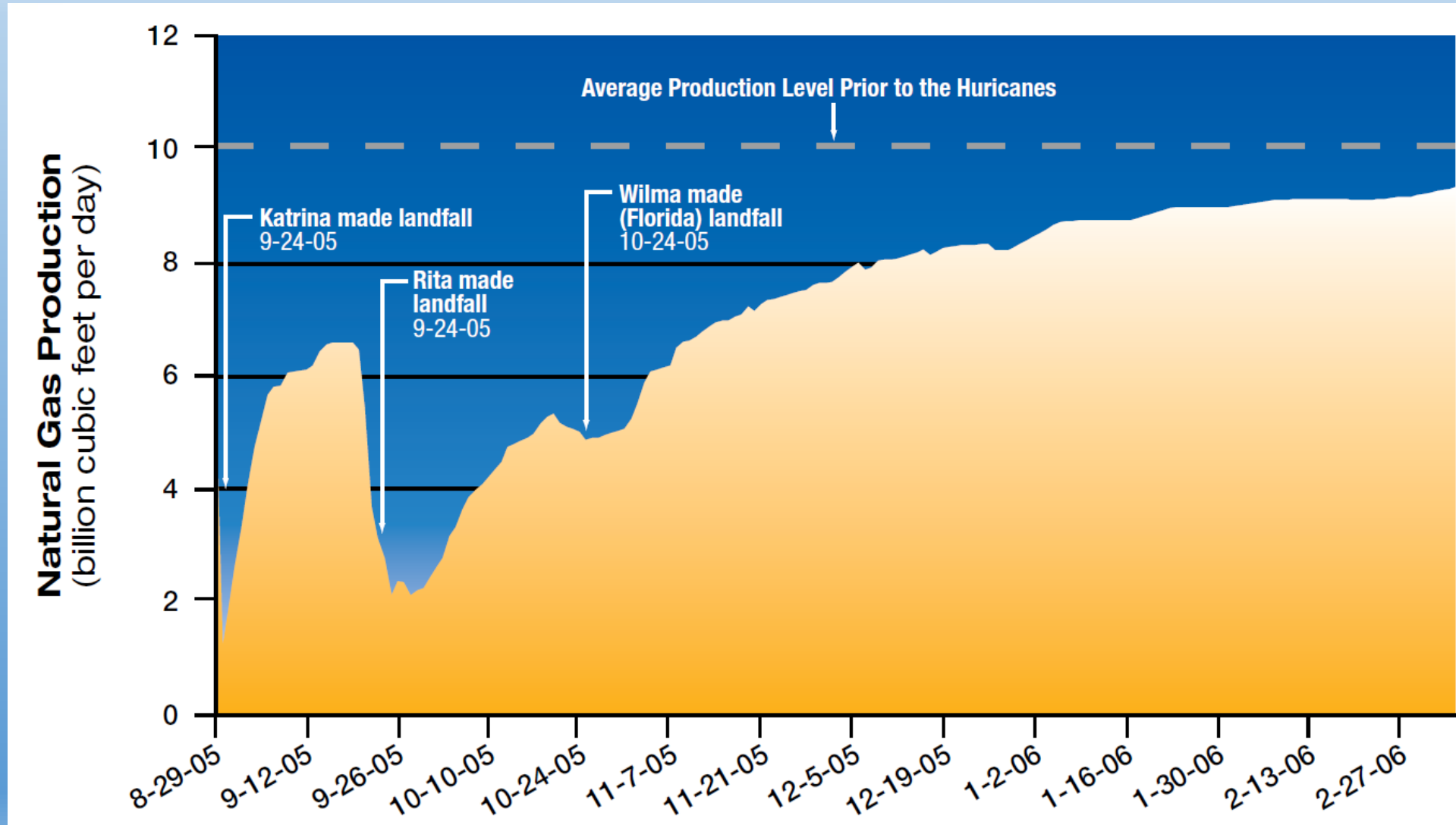


Fig. 5. Impact assessment process.

“...more precise methods are needed to evaluate exposure and vulnerability on a site-specific basis. Nevertheless, the locations of existing infrastructure represent a potential vulnerability to the U.S. energy system and future siting and investment decisions will have to accommodate the changing nature of coastal hazards and risk in future decades.” Maloney and Preston (2014) *Climate Risk Mgt.*



Federal Offshore Gulf of Mexico Natural Gas Production Recovery after the 2005 Hurricanes



US DOE Impacts of the 2005 Hurricanes on the Natural Gas Industry in the Gulf of Mexico Region

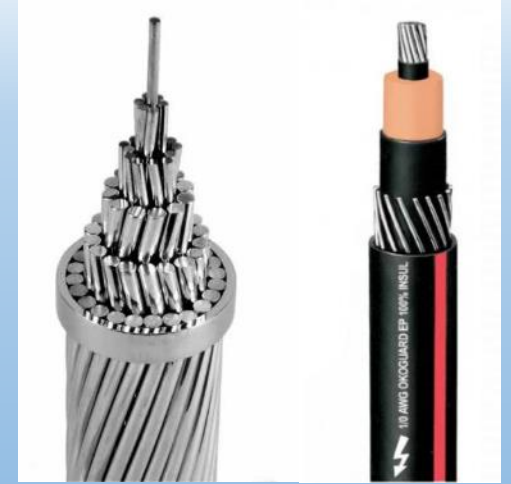
Adaptation Measures

- Protective actions
 - Seawall and natural/nature-based infrastructure
 - Hardening and undergrounding
- Accommodation
 - Increased power generation and/or distribution capacity
- Retreat
 - Elevating equipment (e.g., freeboard from storm surges or water table rise)
 - Relocating submersed underground equipment
 - Switching to renewable sources

Adaptations

Utilities are increasing investments in underground utilities (*Undergrounding*), particularly in distribution

UG distribution may allow restoration of power (temporarily), even as repairs are made...but underground transmission and distribution are expensive. Pinpointing faults can be difficult.



Linemen repair distribution lines in Hurricane Irma (Miami Herald)

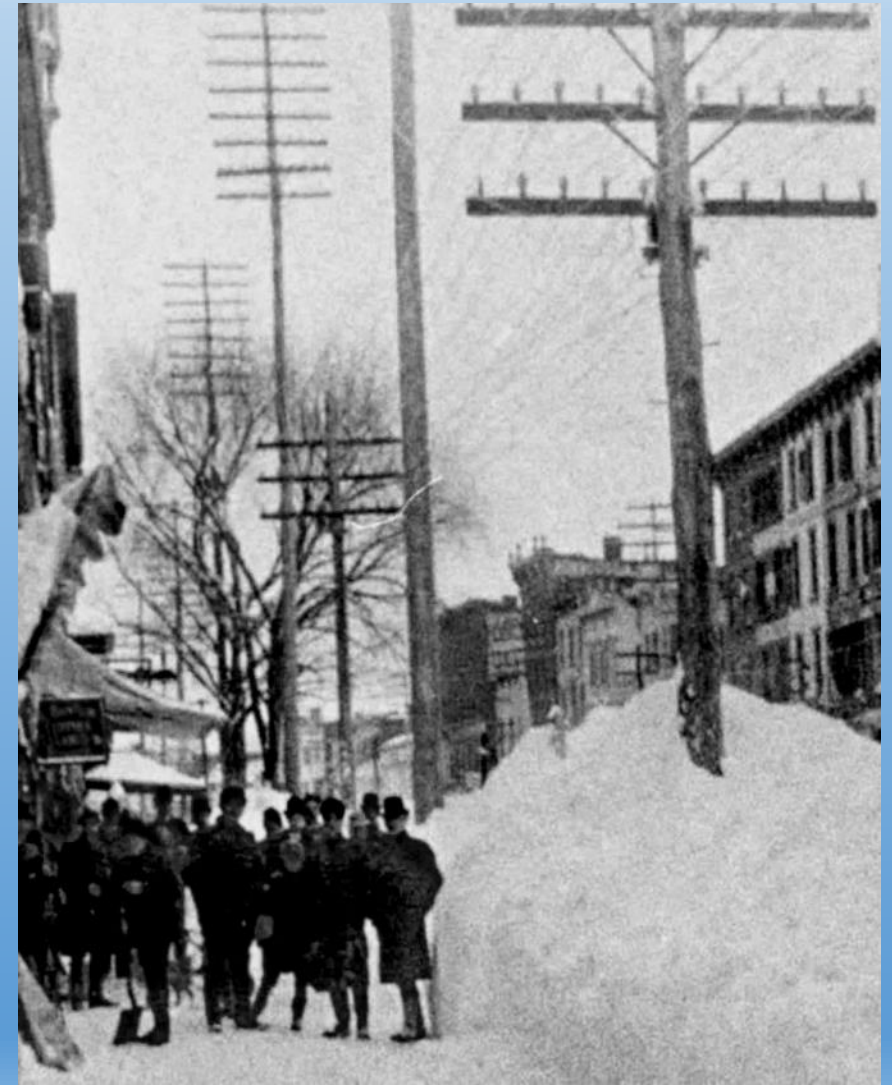
Increasing *freeboard*
Raising home utilities to BFEs



Limits to Resiliency

- Porous Florida bedrock
- Salinization of shallow groundwater and salt intrusion
- Repairs to underground infrastructure can be more complex and time-consuming...*prolonged recovery times*
- Submersed transformers pose new safety hazards
- Do cost-benefits of continuing overhead (OH) distribution accurately reflect economic losses owing to outages (and increasing storm severity)?
- UG-OH still have interdependencies (e.g., transmission, substations, to distribution)
- Costs of conversion (upfront capital) OH to UG is enormous

NYC Late 1800s (Edison Electric Institute)



Great blizzard of 1888 (PoughkeepsieJournal.com)

Conclusions

- Some needs for research and translation
 - As critical infrastructures approach obsolescence, prepare to precisely map site risk
 - Scale is a critical factor to understand hazard exposure and susceptibility
 - Sectoral risk tolerance varies, but cascading impacts and dependencies urge multi-sector/integrated assessments
 - Regional to local scale (and comparative research) may be valuable for resilience
 - Encourage nascent resilience communities of practice
 - Accept that “...uncertainty is an intrinsic property of complex knowledge and not just a flaw that needs to be excised.” Couclelis (2003)
 - Uncertainty, error and accuracy rigor in GIScience and engineering can be applied to SLR and hydrodynamic modeling

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