Quantifying Coastal Storm and Sea Level Rise Risks to Naval Station Norfolk

Dr. Kelly A. Burks-Copes

Environmental Laboratory
US Army Engineer Research and Development Center
Vicksburg, MS

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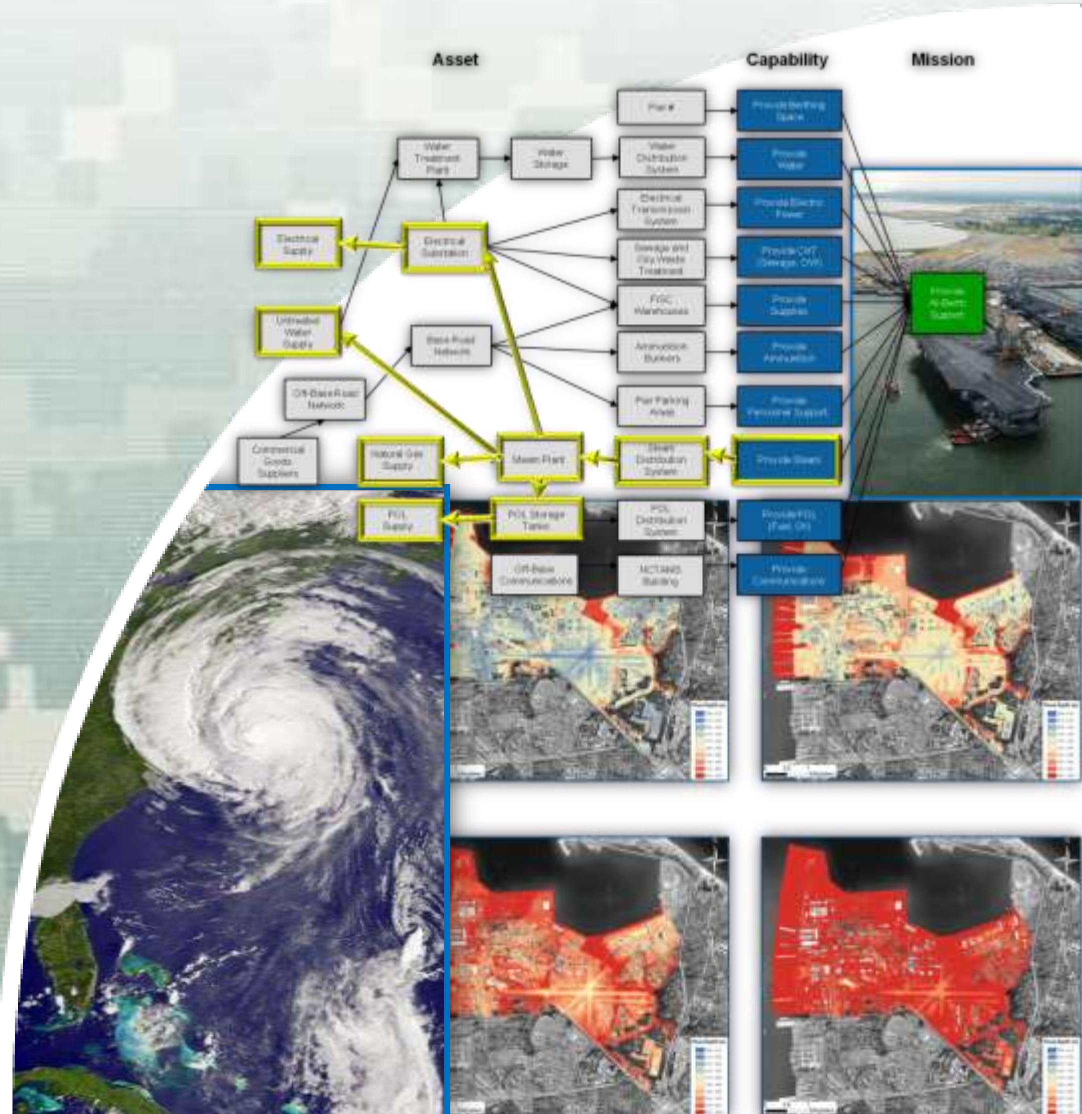

ERDC

US Army Corps of Engineers
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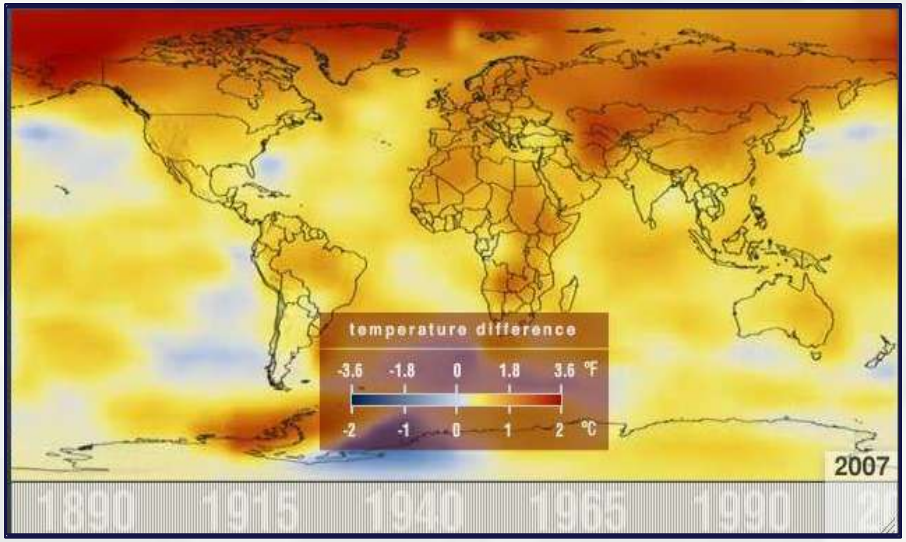
Why We're Here

- The best available scientific evidence indicates that increasing atmospheric concentrations of greenhouse gases are warming the atmosphere and the oceans at an accelerated rate – this is unequivocal (IPCC 2013).

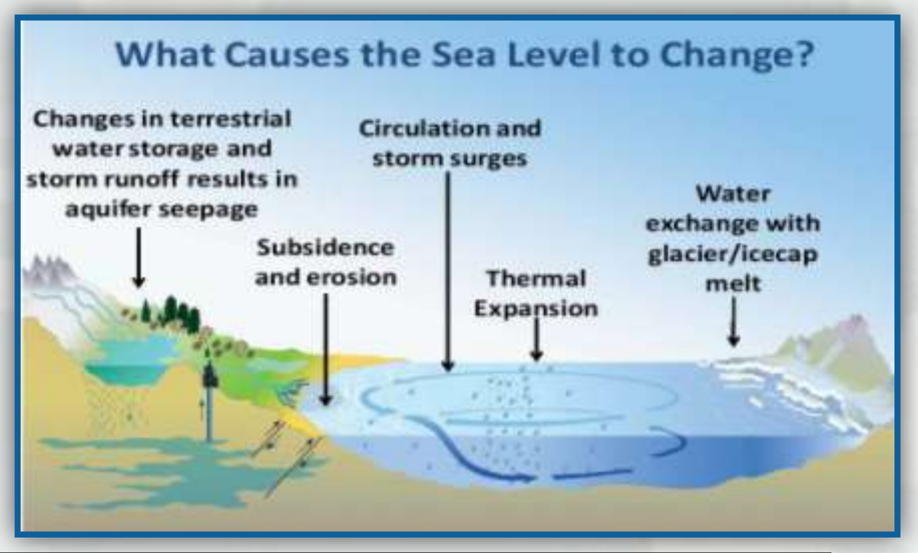
- As they warm, oceans expand and glaciers melt, resulting in an overall increase in ocean volume.

- At the same time, many coastal shorelines are eroding and subsiding, contributing to the overall rise in these sea levels.

- Unfortunately for many coastal military installations, sea level is rising at an unprecedented rate (IPCC 2013)

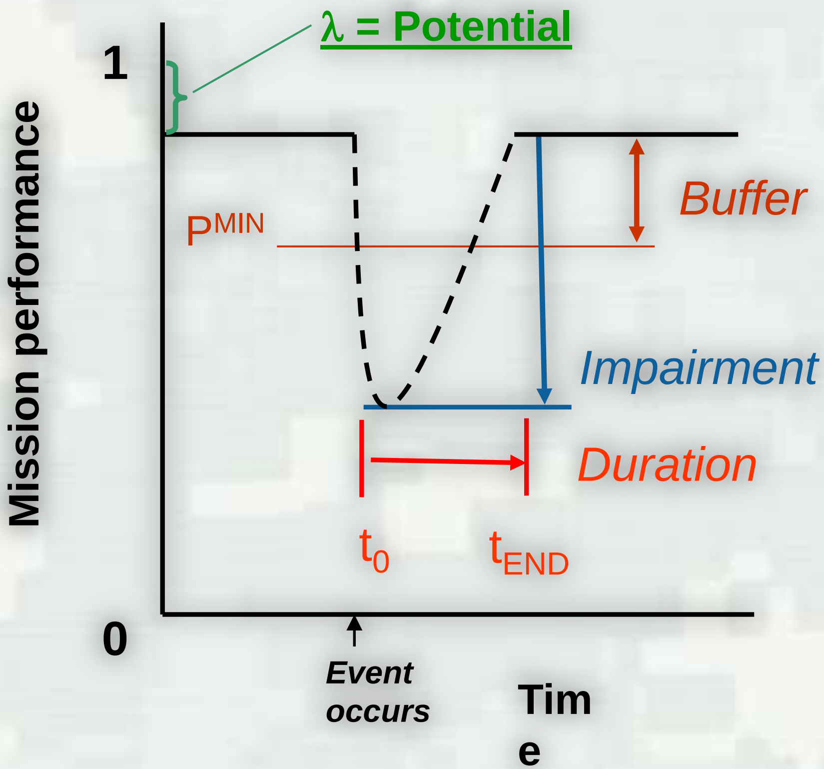


Images courtesy of NASA's Climate Time Machine - This color-coded map shows a progression of changing global surface temperatures from 1885 to 2007. Dark blue indicates areas cooler than average. Dark red indicates areas warmer than average. (Credit: NASA/Goddard Scientific Visualization Studio, http://climate.nasa.gov/ClimateTimeMachine/climateTimeMachine.cfm))



The Problem

Natural hazards (specifically coastal storms) can impair mission performance . . .



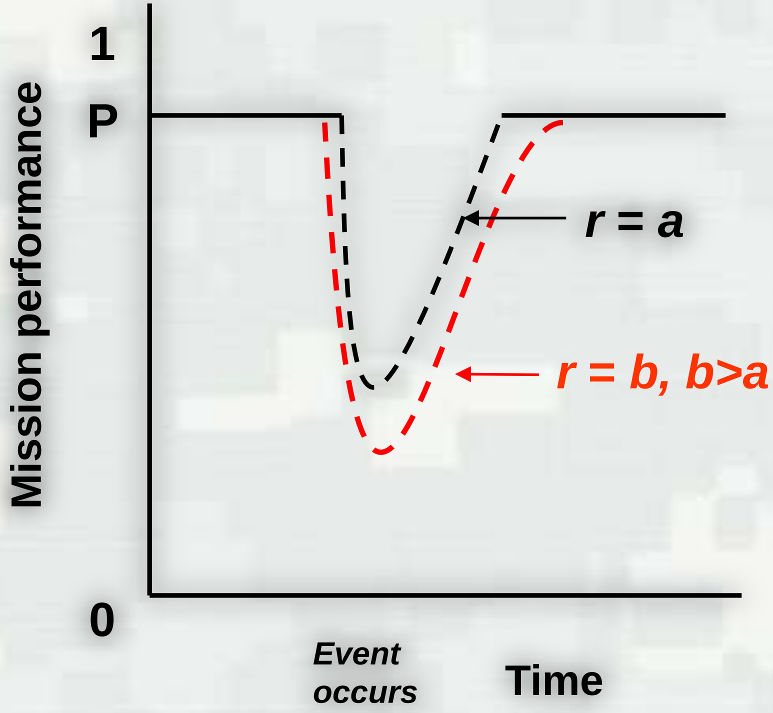
$$P_t = P - g(\lambda, h(r, \mathbf{x}))_t$$

- **Absolute maximum = 1.0**
- **Surge potential = λ**
- **Mission impairment =** $g(\lambda, h(\mathrm{x}))_t$
- **Change in sea-level =** r
- **Event severity =** $h(r, \mathrm{x})$
- **Determinants of severity =** x
  - **Pressure, Radius, Speed, *etc.***
- **Duration,** $d = t_{END} - t_0$
  - **Duration >> Event duration**

Loss is a time-weighted impairment: $$L = \sum_t g(\lambda, h(r, x))_t$$

The Problem

Sea level rise (SLR) acts as a THREAT MULTIPLIER, generating more intense storms, and leading to an INCREASE in both mission impairment and duration

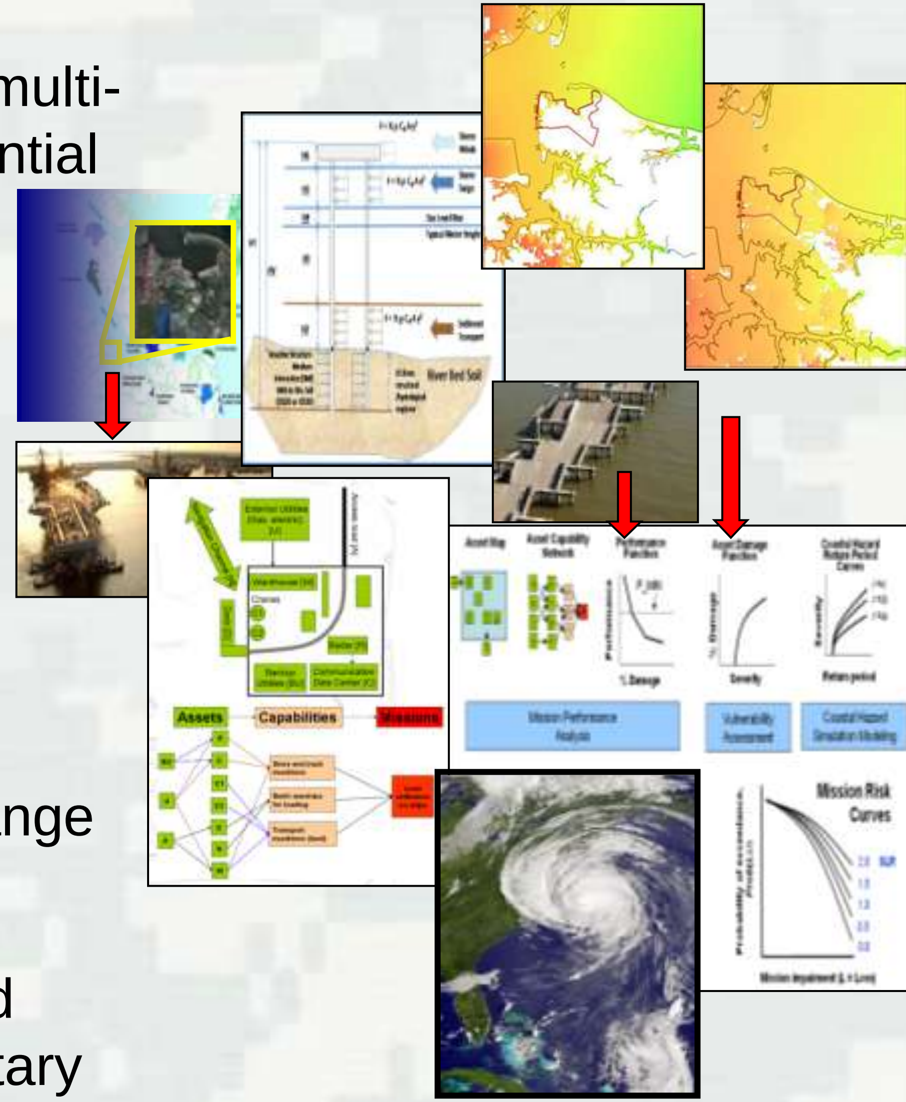


$$P_t = 1 - g\left(\lambda, h\left(r, \mathbf{x}\right)\right)_t$$

- Effect of climate change = *r*
  - {*a*,*b*} are realizations of *r*
  - *r* = sea-level rise

What Is Needed

- **“Systems Thinking”** focused on multi-hazard risks under a range of potential global change futures
- Comprehensive, integrated, and science-based approach
- Vulnerabilities identification
- Quantification of systems-scale operational risks
- Consideration of driving global change uncertainties
- Risk reduction for transforming and sustaining a highly responsive military installation portfolio



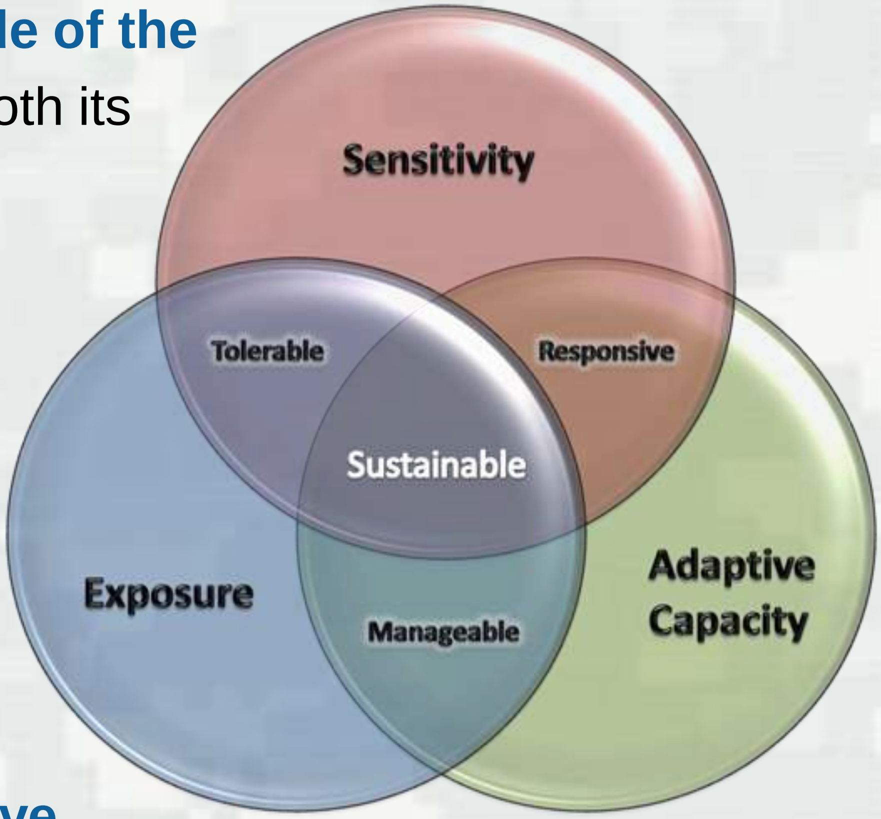
Multi-layered Risk Management

- **Employ a SMART strategy that drills down using portfolio investments to manage regrets and make decisions based on return on investment with a focus on:**
- **RESILIENCY and SUSTAINABILITY**

Specific	What?	Goals and Objectives
	Why?	Intent and Purpose
	Who?	Stakeholders
	Where?	At what scale (local, regional, national, global)
	Which?	Opportunities and constraints
Measureable	How much is enough?	
	To what level of confidence?	
Actionable	Will the results be meaningful and useful?	
Relevant	Does the effort match the return on investment?	
Time-based	What should be done immediately?	
	What can we wait on?	
	How long before the threat becomes critical?	

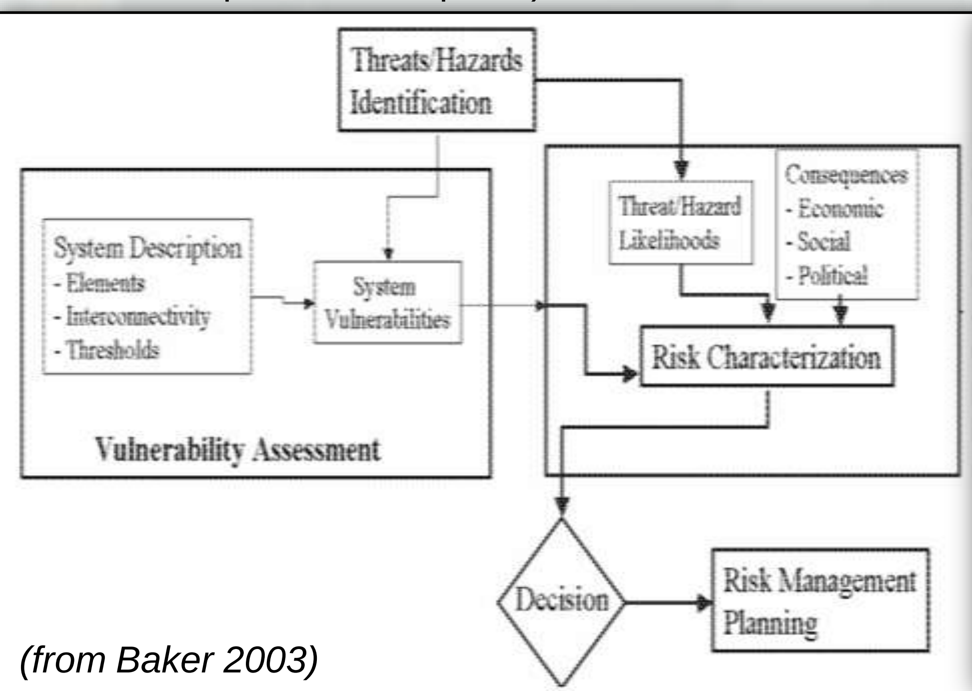
Vulnerability & Risk Assessment 101: Basic Lexicon

- **Exposure -**
  - Describes the **nature and magnitude of the hazards** that threaten the system (both its critical assets and its functionality)
- **Sensitivity**
  - The potential of a system to be affected (either positively or negatively) by the changes caused by a hazard (aka **fragility**)
- **Adaptive Capacity**
  - Describes a system's **ability to evolve**, either naturally or through engineered maintenance activities, in such a way as to preserve or enhance the system's functionality

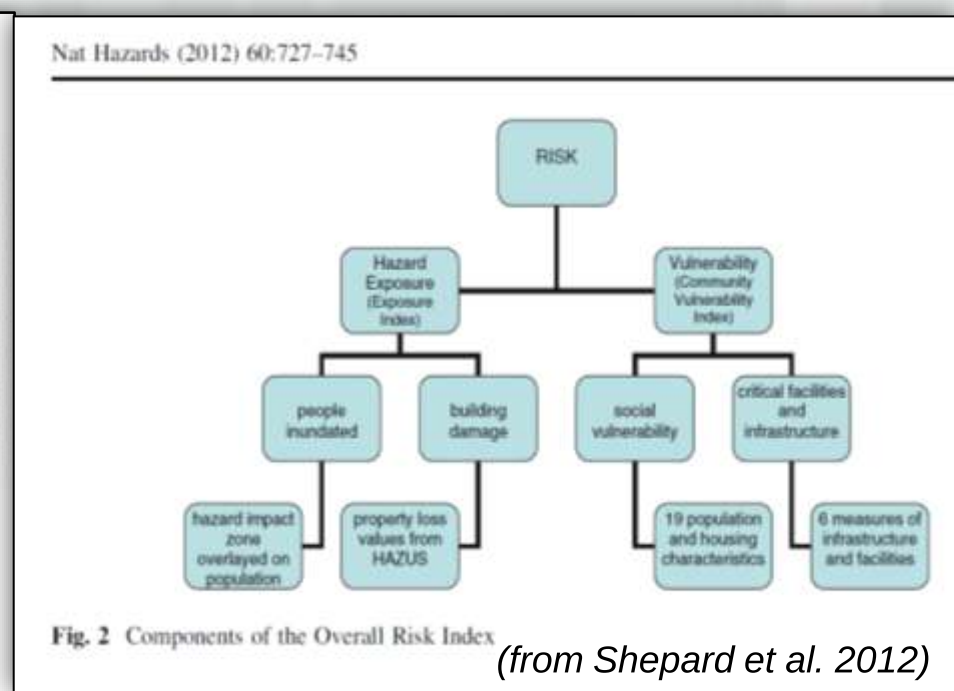


Vulnerability & Risk Assessment 101: Basic Lexicon

- **Vulnerability**
  - The degree to which a system is susceptible to, and unable to cope with, the adverse effects of hazard over a period of time (**exposure + sensitivity + adaptive capacity**)
- **Risk**
  - The combination of the magnitude of the potential consequence(s) of climate change impact(s) and the likelihood that the consequence(s) will occur. Risk is an overarching concept that includes the components of **hazard, performance, exposure, vulnerability, and subsequent consequences**.
- **Resilience**
  - The ability of a system to **prepare for**, **resist**, **recover**, and **adapt** to achieve functional performance under the stress of natural hazards and human-based disturbances through time. (ERDC NNBF Report, 2014 in press)



(from Baker 2003)



(from Shepard et al. 2012)

Vulnerability & Risk Assessment 101: Basic Steps

1. **Establish a team**
2. **Set the goals & objectives**
3. **Define the problem context**
   a) Study area
   b) Define an actionable scale (temporal & spatial)
   c) Mine for data
4. **Define the threat (aka scenarios)**
   a) SLR scenarios
   b) Coastal storm intervals
5. **Characterize exposure**
6. **Decompose infrastructure network**
   a) Determine sensitivity (i.e., fragility)
   b) Determine adaptive capacity
   c) Focus on systems approach (assets, capabilities, services, mission)
7. **Characterize Vulnerability & Risk**
   1. Establish heuristics to determine sustainability
   2. Combination of exposure, sensitivity, adaptive capacity and consequences
8. **Proactively manage adaptation**
   1. Establish triggers or response thresholds and monitor
   2. Consider life cycles & costs **with the intent of managing regrets!**

Quantifying Coastal Storm and Sea Level Rise Risks to Naval Station Norfolk, VA

Funded by the Strategic Environmental Research and Development Program (SERDP)

Problem Statement

- Devise and demonstrate a rigorous yet flexible **systems-scale** approach
- **Quantitatively evaluate** natural hazard risks to critical military assets (i.e., infrastructure) and mission capabilities
- **Address a range** of SLR, tidal fluctuation, and storm stage-frequencies

Technical Goals

- **Characterize** impacts
- **Decompose** mission & infrastructure systems
- **Pinpoint** vulnerabilities
- **Quantify** performance sustainability risks
- **Identify** adaptive capacity tipping points
- **Communicate** results to field

Study details available on: *https://ClimateChange.erdc.dren.mil*

Report available online at:

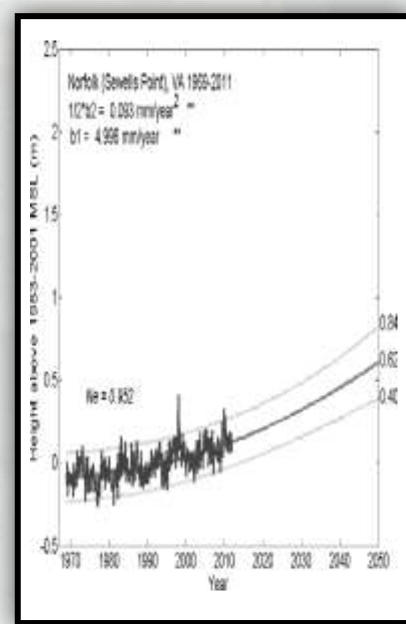
https://serdp-estcp.org/content/download/30139/291303/file/RC_1701_Final%20Report.pdf

Technical Approach

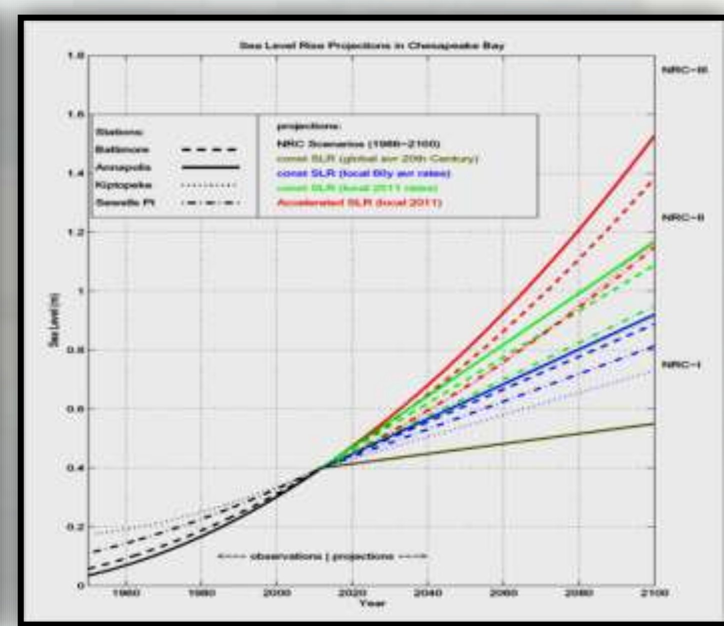
- **This is a Demonstration Project –**
  - Select missions, capabilities, assets, hazards, and forcings are modeled
  - Coastal storm parameters are not altered due to potential climate change effects
- **Datums**
  - Horizontal datum = North American Datum of 1983 (NAD83)
  - Vertical datum = North American Vertical Datum of 1988 (NAVD 88)
- **Period of Analysis**
  - Start Date = 2000
  - End Date = 2100 (100 yr period of analysis)
- **Sea Level Rise**

  (local MSL between 2000-2100)
  - 0.5m
  - 1.0m
  - 1.5m
  - 2.0m
- **Storm Return Intervals**

Recurrence interval	Probability of occurrence in any given year	Percent chance of occurrence in any given year
100-yr	1 in 100	1%
50-yr	1 in 50	2%
10-yr	1 in 10	10%
1-yr	1 in 1	100%

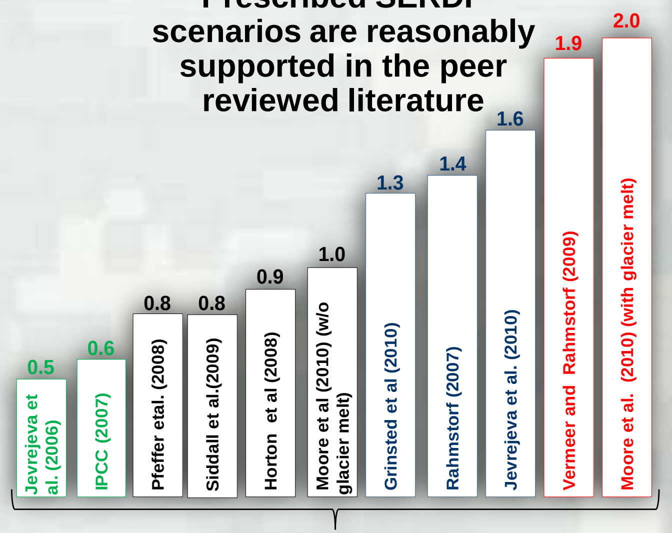


Boon (2012)

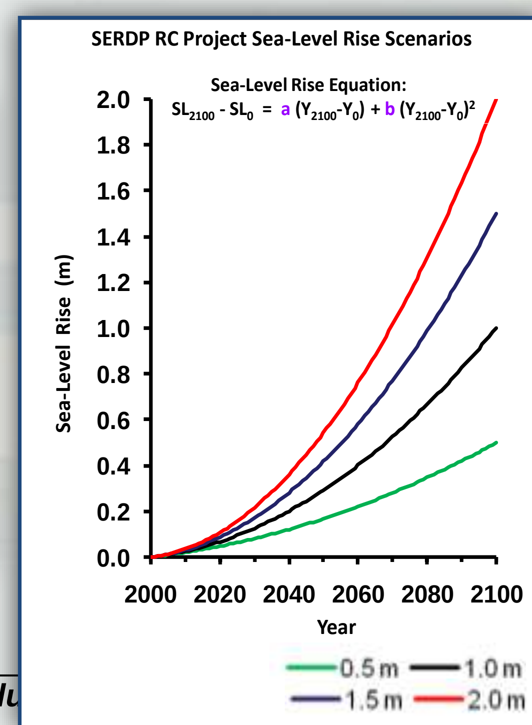


Ezer and Corlett (2012)

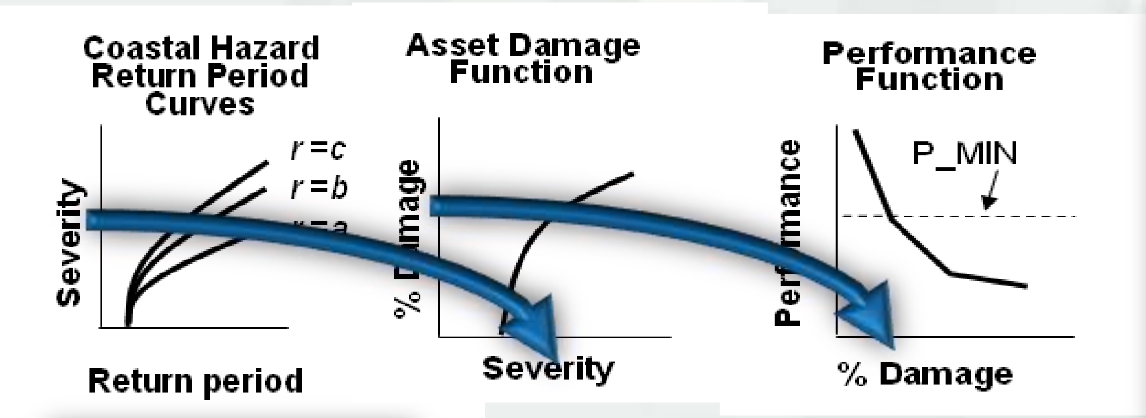
Prescribed SERDP scenarios are reasonably supported in the peer reviewed literature

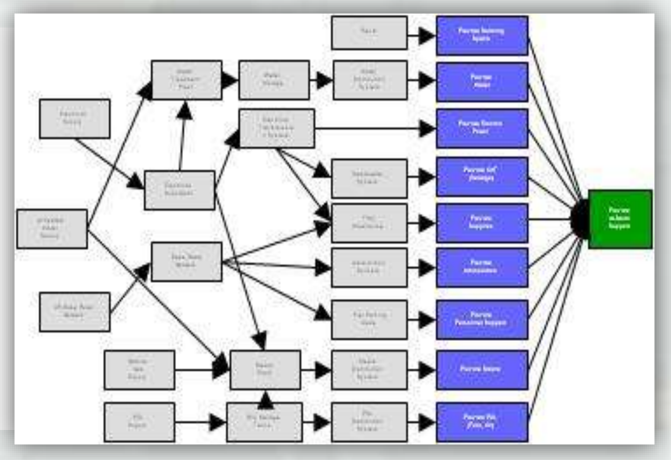


Recent Published Model Estimates of Year 2100 Sea-Level Rise (m)



Technical Approach

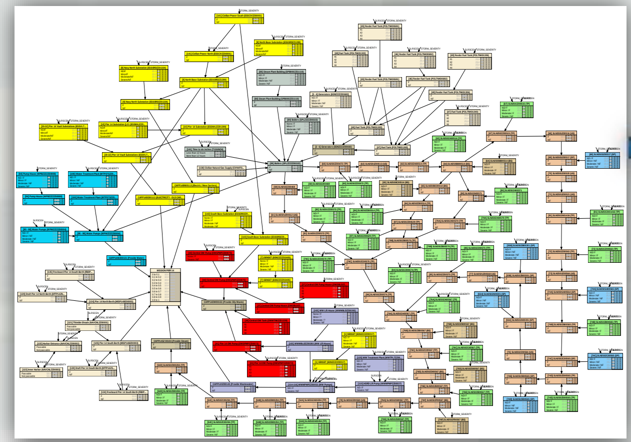




Coastal Hazard Simulation Modeling

Vulnerability Assessment

Asset Decomposition



Risk Analysis

Visualization

Project Team

- **Principal Investigators**
  - **Dr. Kelly Burks-Copes**
  - Dr. Edmond Russo
- **Geomorphologic Modeling**
  - Dr. Andrew Morang
- **Environmental Modeling**
  - Dr. Craig Fischenich
  - Mr. Kyle McKay
- **Groundwater Surveying**
  - Dr. Janet Simms
  - Mr. Eric Smith
- **Hydrodynamic Modeling**
  - Dr. Jane Smith
  - Dr. Jay Ratcliff
  - Dr. Honghai Li
  - Dr. Lihwa Lin
  - Dr. Cary Talbot
  - Mr. Mike Follum
  - Mr. Ryan Pickett
  - Mr. Kevin Winters
- **Installation Modeling**
  - Dr. Michael Case
  - Mr. Steve Pranger
- **Asset Damage Modeling**
  - Dr. Paul Mlakar
  - Mr. Jose Rullan-Rodriguez
- **Database Development and Spatial Analyses**
  - Mr. Scott Bourne
  - Mr. Austin Davis
- **Risk Assessment Modeling**
  - Dr. Martin Schultz

I'd rather be managing a large coastal hazard risk-assessment research project.

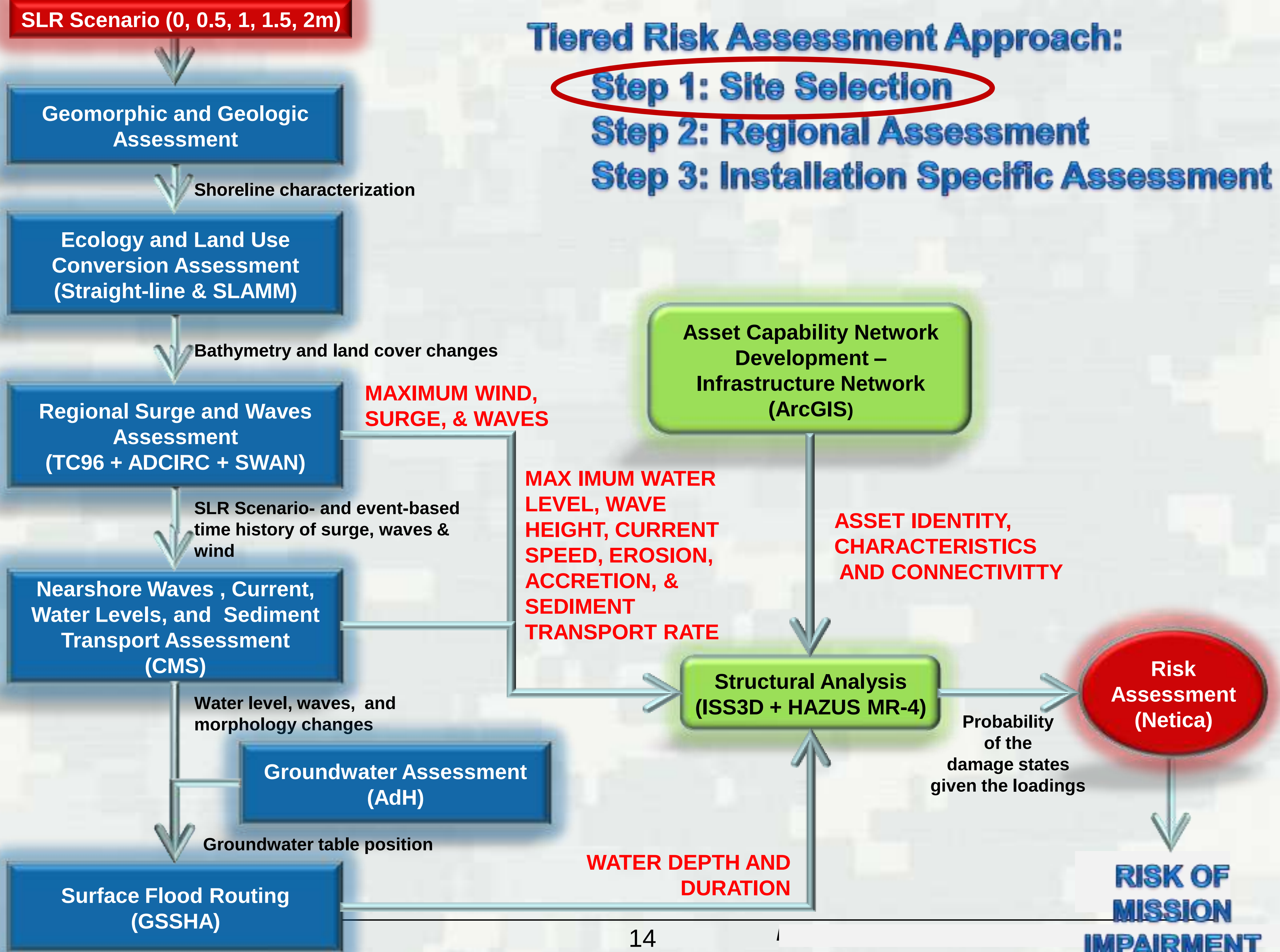
The daydreams of cat herders

"Move the food."

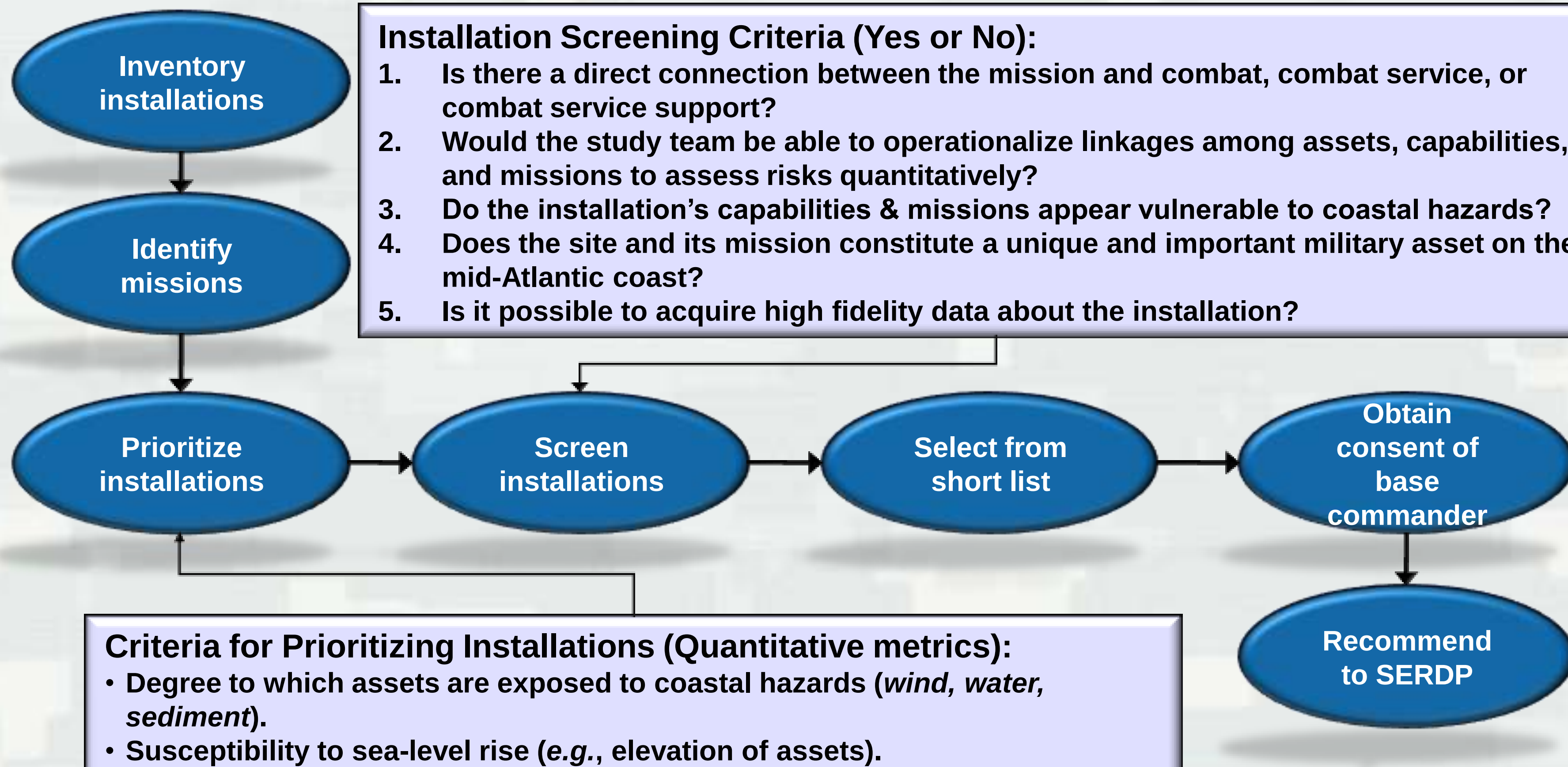
John Hall, SERDP PM

ERDC

Innovative solutions for a safer, better world


Tiered Risk Assessment Approach:
Step 1: Site Selection
Step 2: Regional Assessment
Step 3: Installation Specific Assessment
SLR Scenario (0, 0.5, 1, 1.5, 2m)
Geomorphic and Geologic Assessment
Shoreline characterization
Ecology and Land Use Conversion Assessment (Straight-line & SLAMM)
Bathymetry and land cover changes
Regional Surge and Waves Assessment (TC96 + ADCIRC + SWAN)
MAXIMUM WIND, SURGE, & WAVES
SLR Scenario- and event-based time history of surge, waves & wind
Nearshore Waves , Current, Water Levels, and Sediment Transport Assessment (CMS)
MAX IMUM WATER LEVEL, WAVE HEIGHT, CURRENT SPEED, EROSION, ACCRETION, & SEDIMENT TRANSPORT RATE
Water level, waves, and morphology changes
Groundwater Assessment (AdH)
Groundwater table position
Surface Flood Routing (GSSHA)
WATER DEPTH AND DURATION
Asset Capability Network Development – Infrastructure Network (ArcGIS)
ASSET IDENTITY, CHARACTERISTICS AND CONNECTIVITTY
Structural Analysis (ISS3D + HAZUS MR-4)
Probability of the damage states given the loadings
Risk Assessment (Netica)
RISK OF MISSION IMPAIRMENT

Installation Site Selection Process



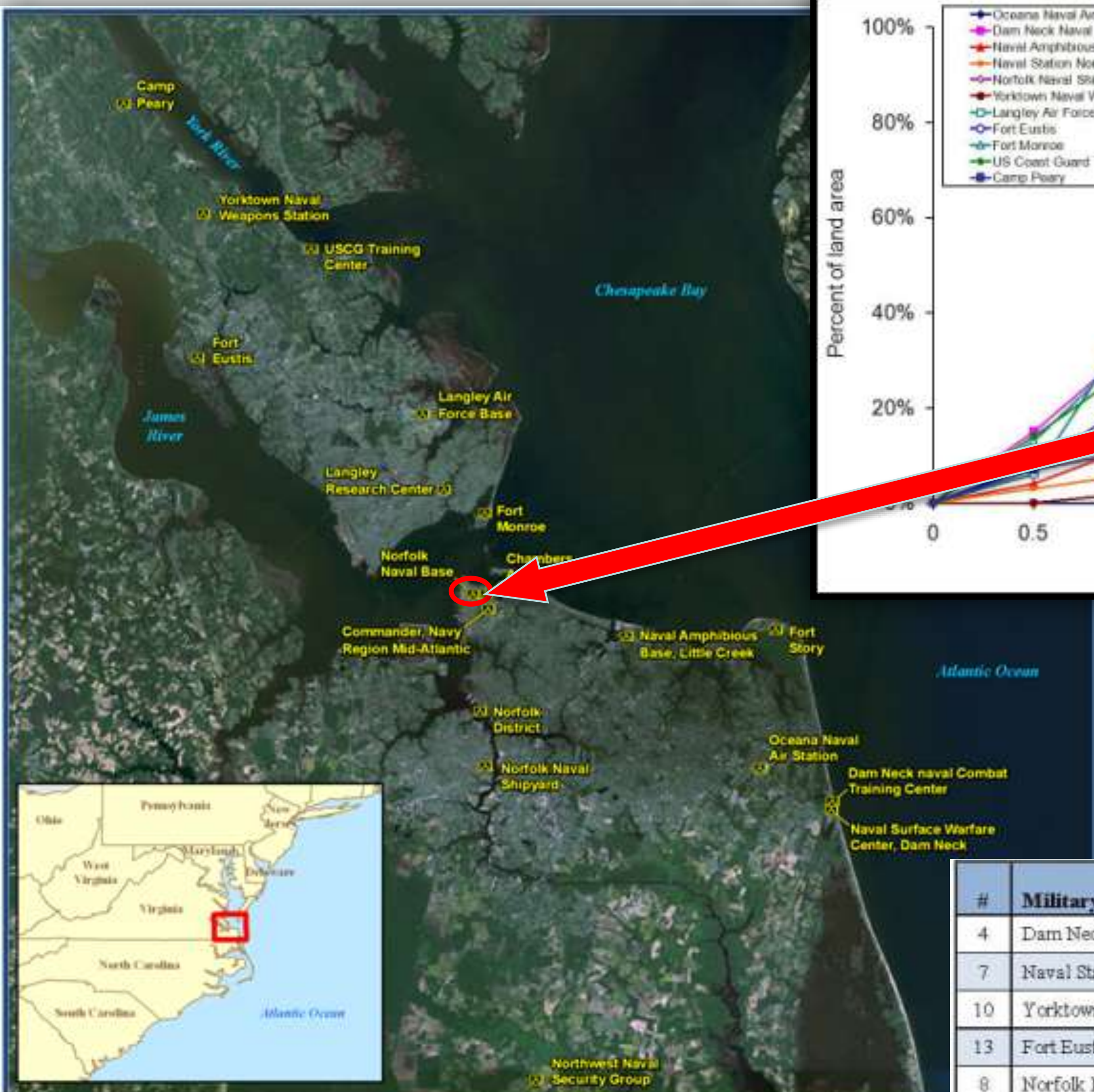
Installation Screening Criteria (Yes or No):

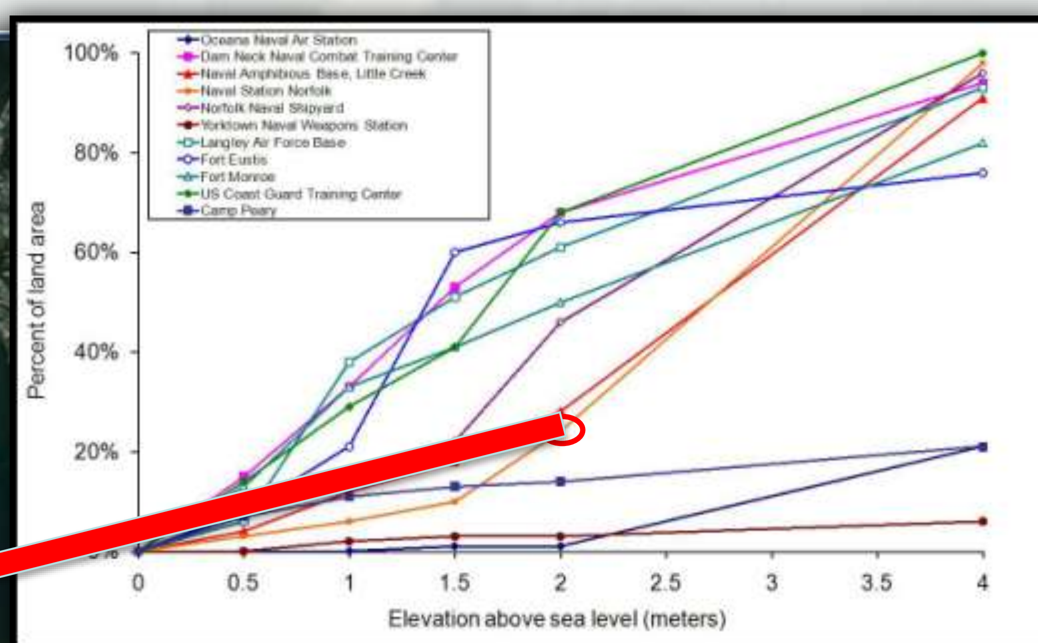
1. Is there a direct connection between the mission and combat, combat service, or combat service support?
2. Would the study team be able to operationalize linkages among assets, capabilities, and missions to assess risks quantitatively?
3. Do the installation’s capabilities & missions appear vulnerable to coastal hazards?
4. Does the site and its mission constitute a unique and important military asset on the mid-Atlantic coast?
5. Is it possible to acquire high fidelity data about the installation?

Criteria for Prioritizing Installations (Quantitative metrics):

- Degree to which assets are exposed to coastal hazards (*wind, water, sediment*).
- Susceptibility to sea-level rise (*e.g.*, elevation of assets).
- Presence of unique, significant, and scarce assets and capabilities.
- Potential for coastal shoreline change increasing hazard exposure.
- Potential for contaminant releases from installations.
- Presence of unique, significant, and scarce coastal habitats at the installation.

Site Selected: Naval Station Norfolk



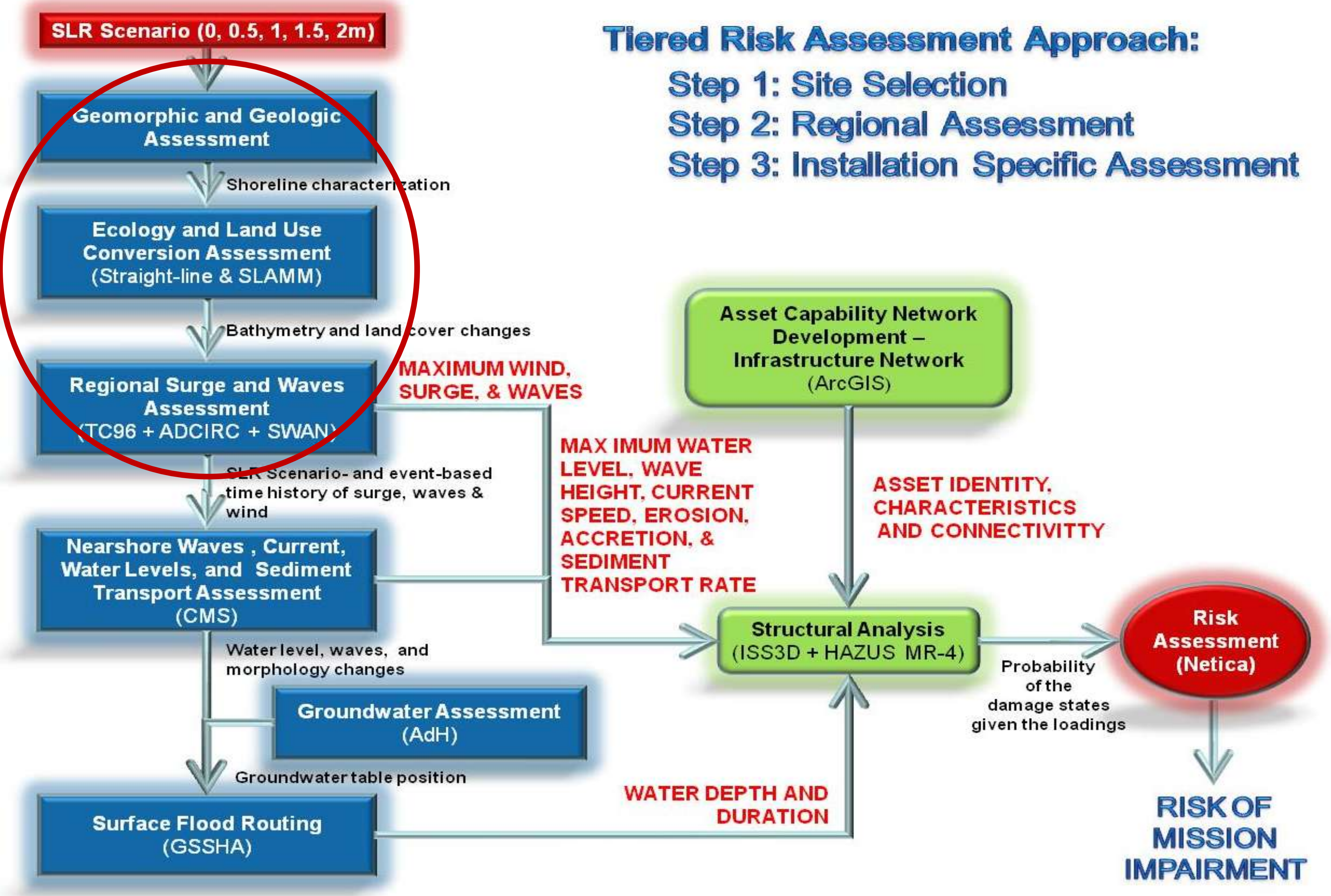


Result: A high-level, transparent vulnerability assessment that can be easily "ported" to other regions

#	Military Installation	Location	Prioritization Score
4	Dam Neck Naval Combat Training Center	Dam Neck, VA	14
7	Naval Station Norfolk	Norfolk, VA	12
10	Yorktown Naval Weapons Station	Yorktown, VA	11
13	Fort Eustis	Newport News, VA	11
8	Norfolk Naval Shipyard	Portsmouth, VA	8

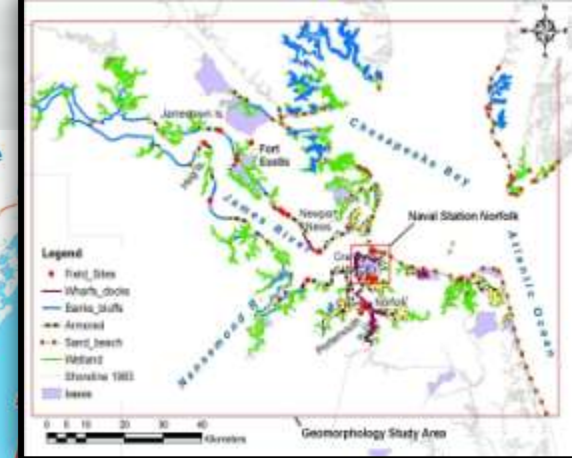
Tiered Risk Assessment Approach:

Step 1: Site Selection
Step 2: Regional Assessment
Step 3: Installation Specific Assessment

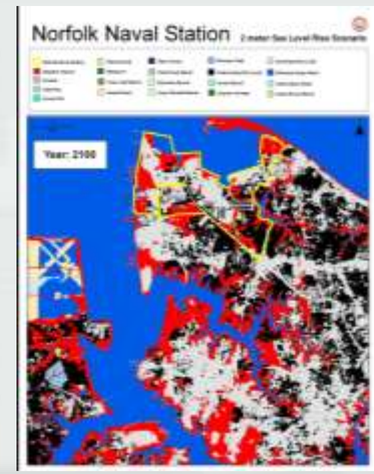


Regional Assessments

- **Geomorphological Assessment**
  - Modeled geomorphic evolution as sea levels rise
  - Inventory natural and engineered coastal features
  - Assess stability of features as sea levels rise
  - Provided inputs on base conditions in the bay for sediment transport modeling
- **Ecological Assessment**
  - Sea Level Affecting Marsh Model (SLAMM)
  - Biome Shifts
  - Open Water Surface Increases
- **Coastal Storm Simulations**
  - Used Joint Probability Method with Optimal Sampling (JPM-OS) for storm parameterization
    - Nor'easters included (3 total)
    - Parameters:
      - C_p (central pressure)
      - R_{max} (radius of maximum winds)
      - Tracks / heading
      - V_f (forward speed)
      - Holland B (landfall decay)
    - Wind Forcings using TC96 Model
    - Envelope of maximum wind speed
    - Inputs to circulation and wave models at both region and nearshore scales
    - Storm parameters not modified to reflect climate change
    - Same wind fields used for modeling in all SLR scenarios



Hurricane tracks impacting the project region.

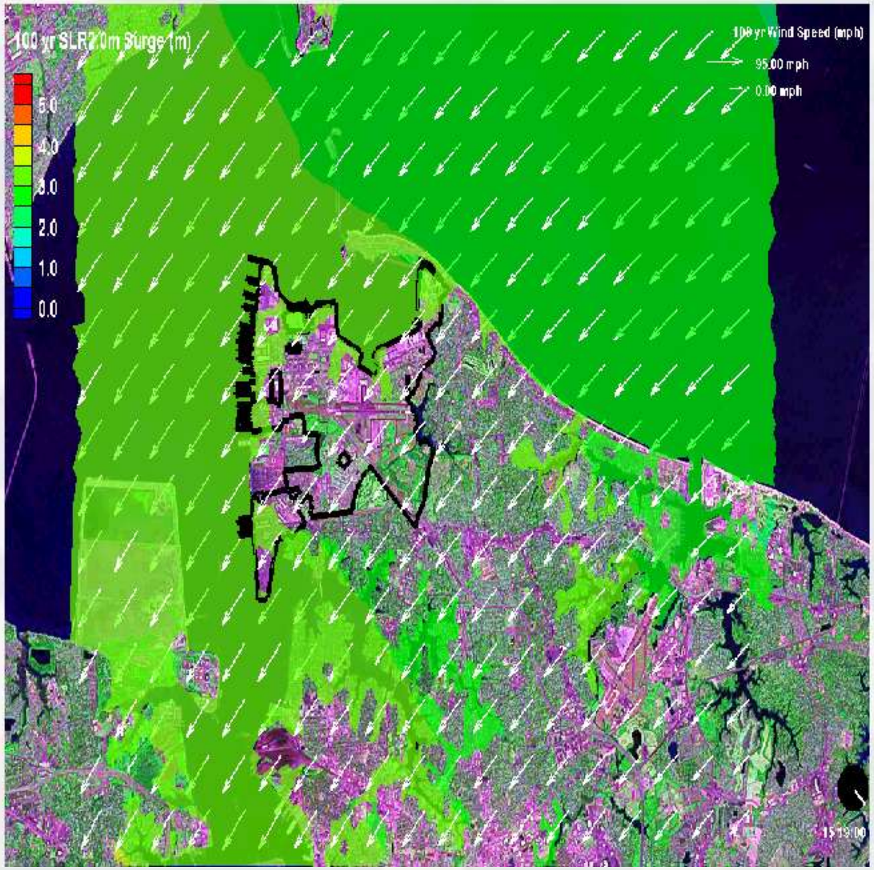


Maximum wind speed in miles per hour for Hurricane 449

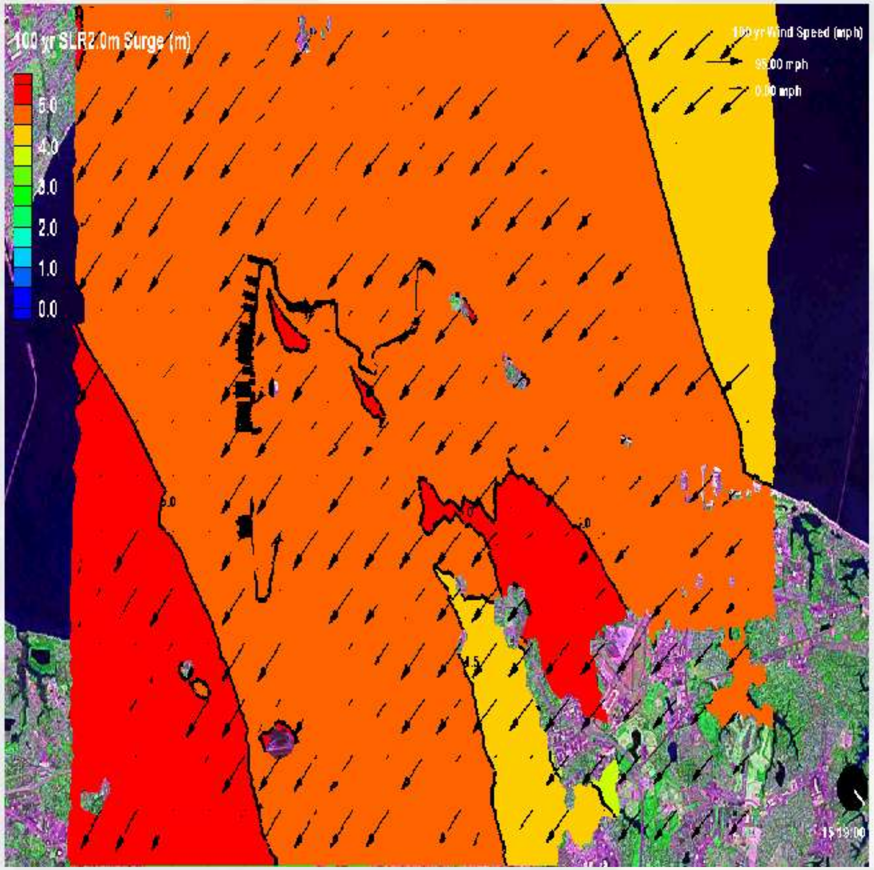
Regional Storm Results

- Regional surge/wave water levels were generated for each of the storms with Advanced Circulation (ADCIRC) and Simulating Waves Nearshore (SWAN) models
- Models driven using wind fields, considering topo/bathy contours and friction coefficients derived from land cover and interpolated onto the model mesh
- 100 ADCIRC, SWAN & TC96 Runs Made (17 hurricanes & 3 nor'easters x 5 SLR Scenarios)

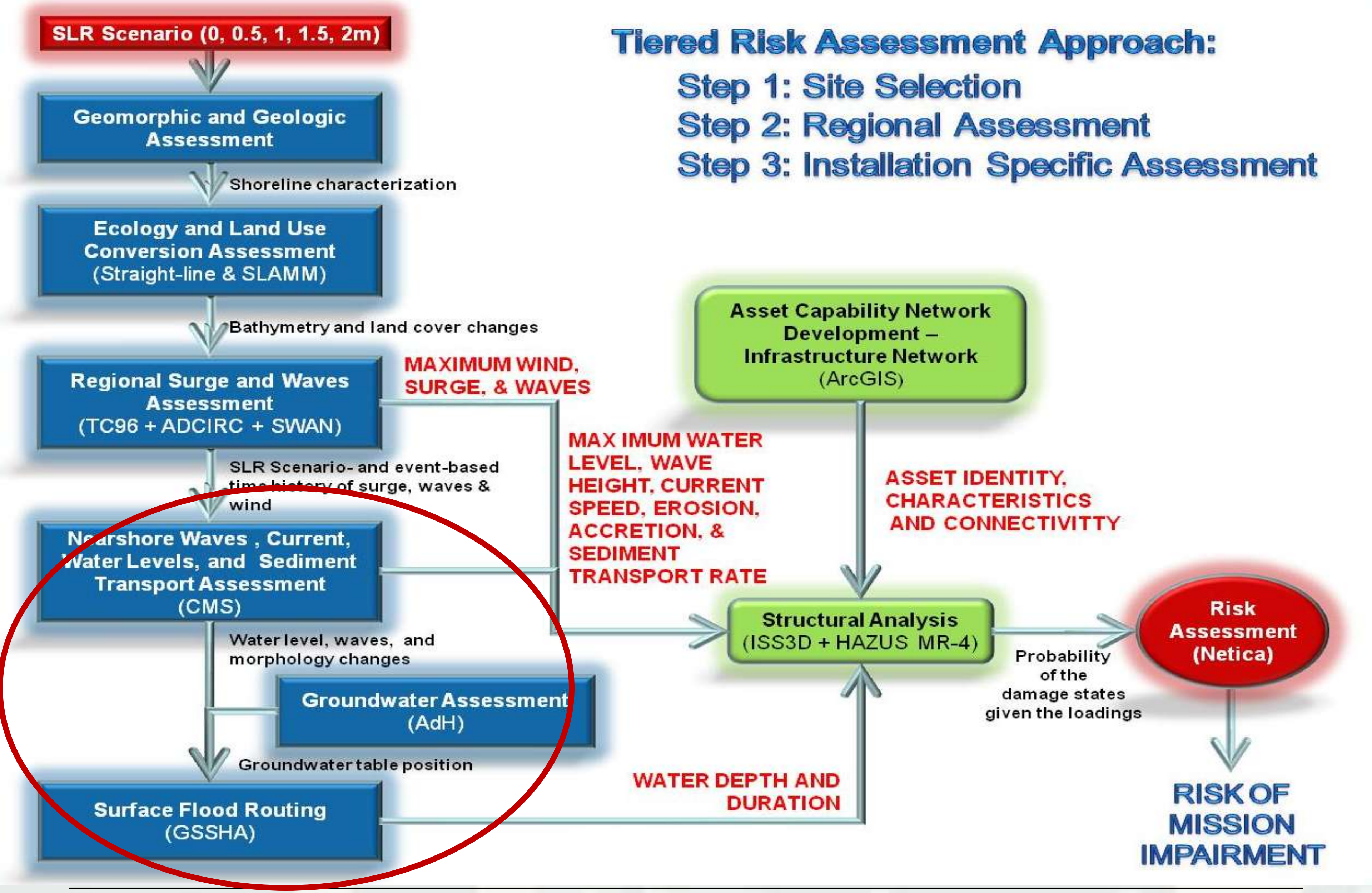
Storm 449 0m SLR (max surge = 3.0 m)



Storm 449 2m SLR (max surge = 5.8 m)

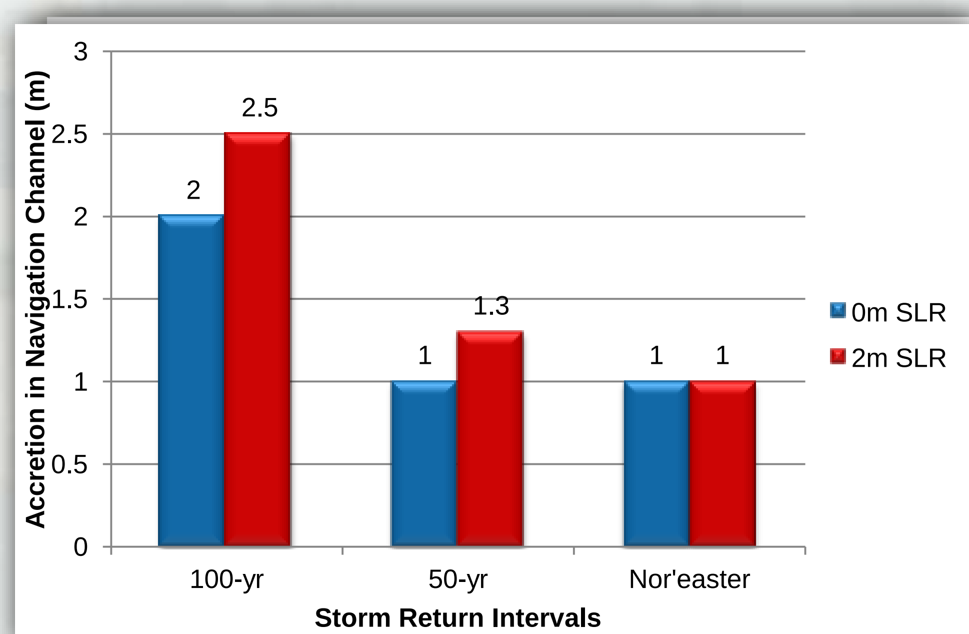


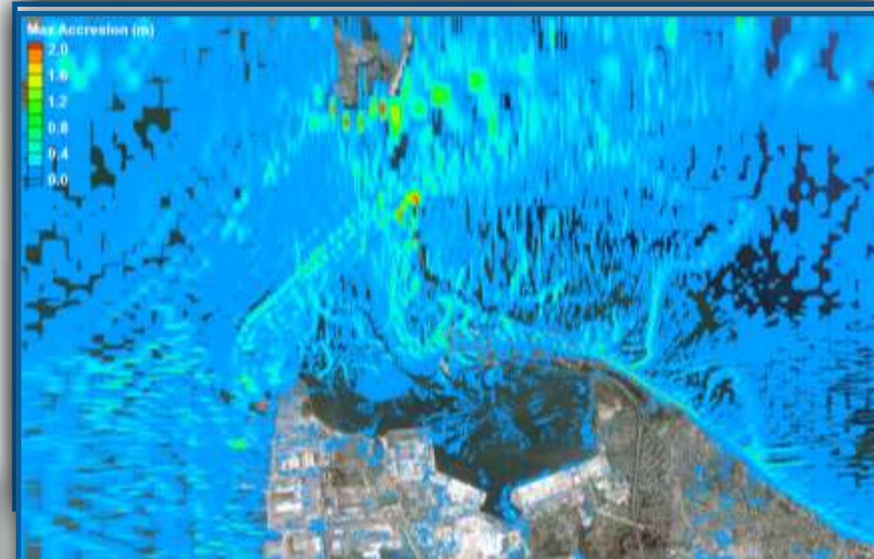
Installation-Level Storm Modeling

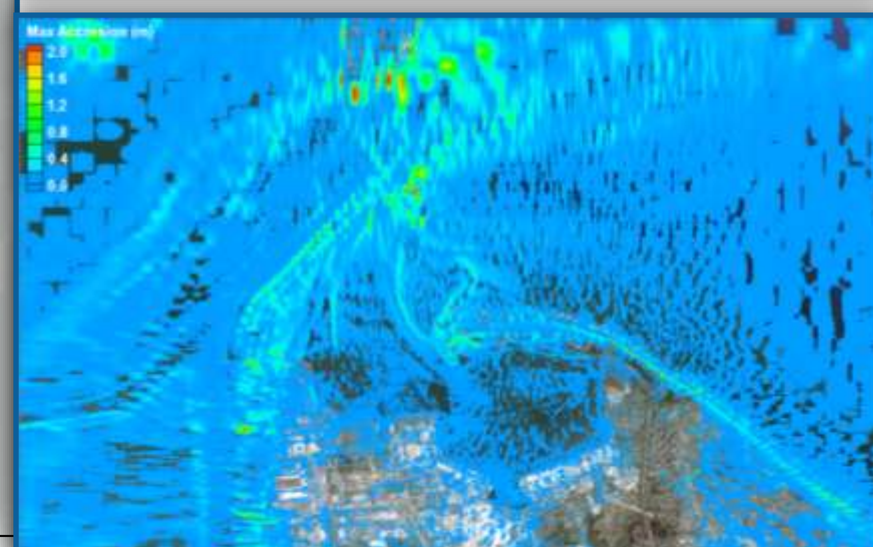


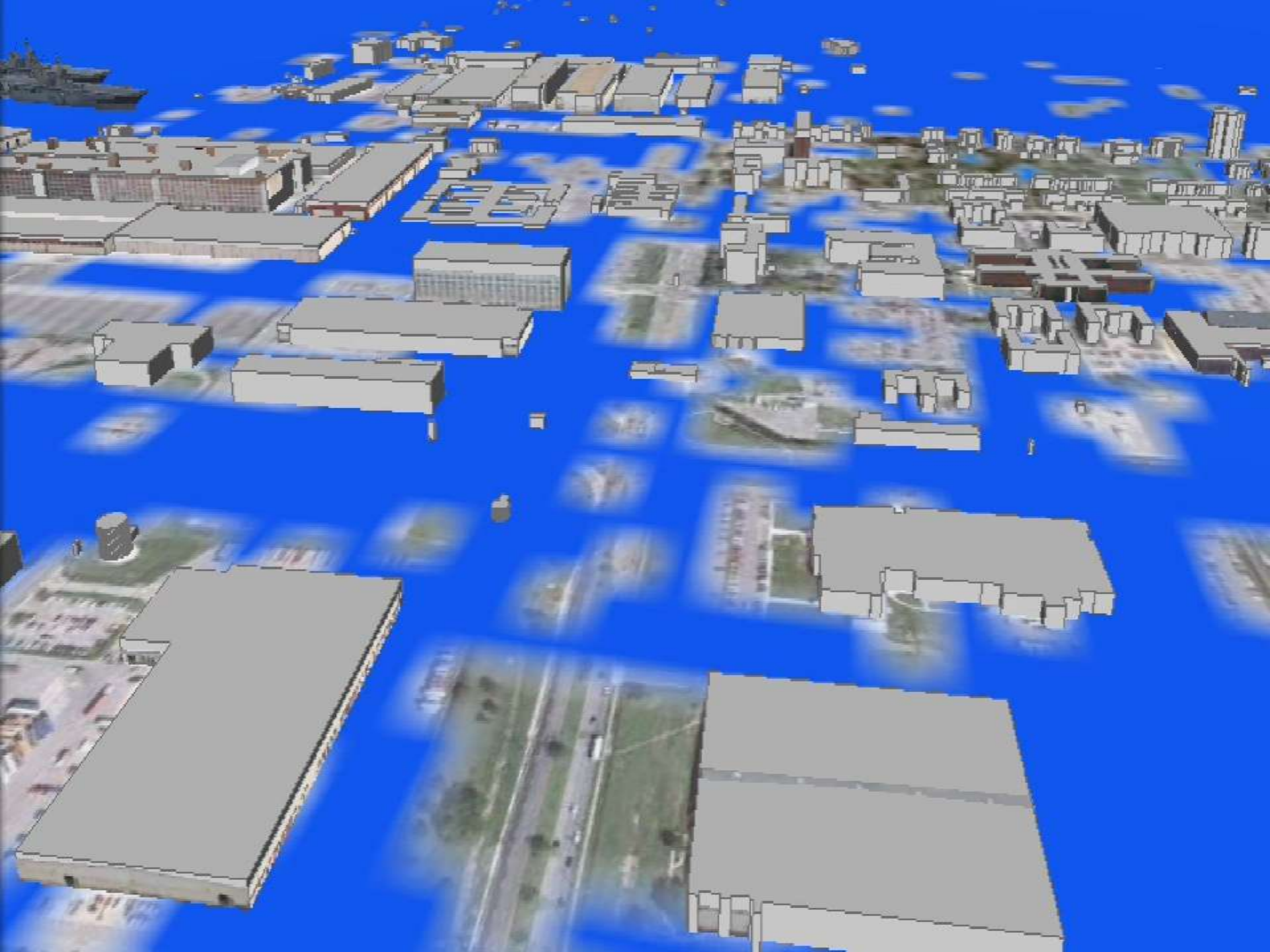
Nearshore Modeling –
<u>C</u>oastal <u>M</u>odeling <u>S</u>ystem (CMS)

- Water surface elevation
- Nearshore waves
- Currents
- Sediment transport
- Morphology change for coastal and inlet applications
- Water bottom and surface erosion and accretion areas in extreme storms



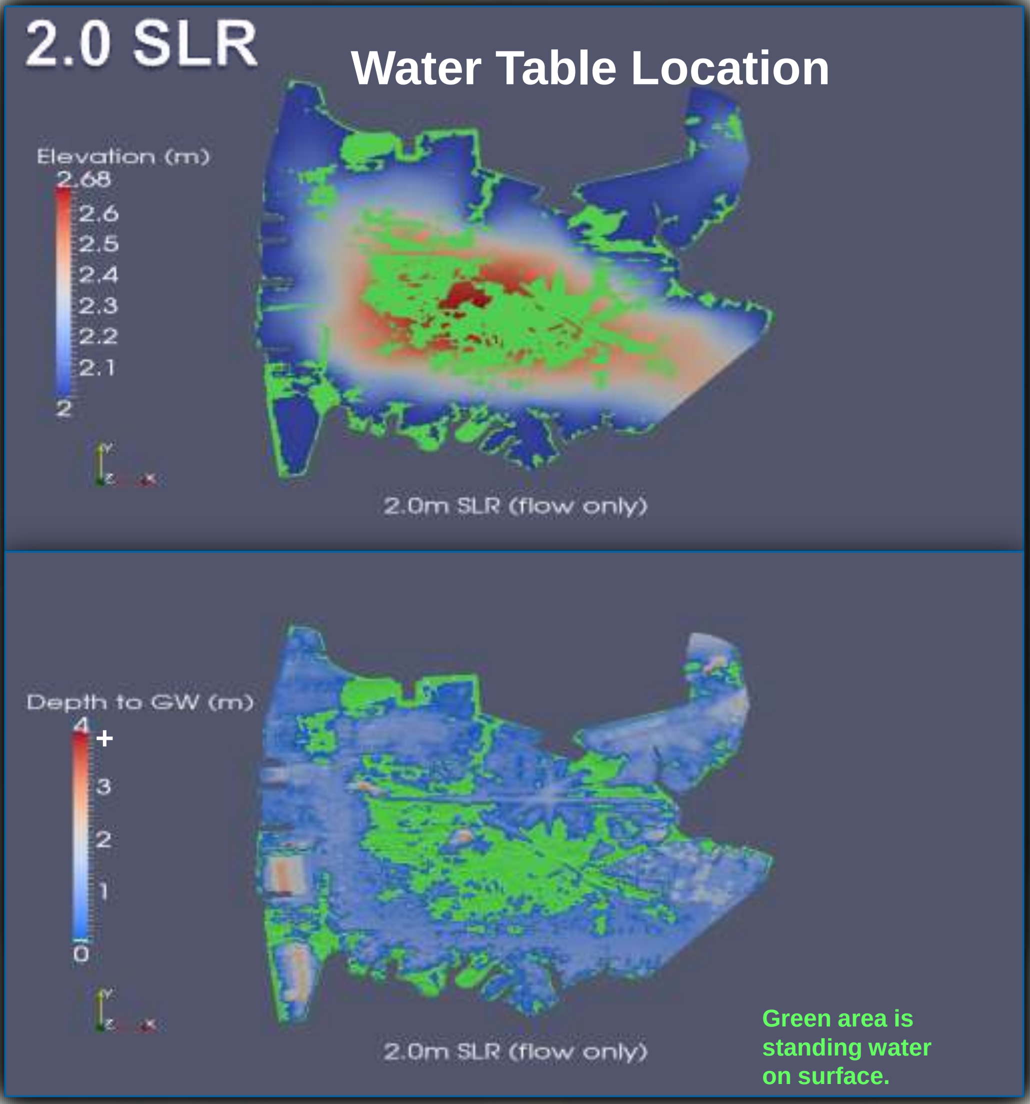






Groundwater Modeling –
Advanced Hydraulic Model (AdH)

- Characterizing movements of:
  - Isohaline boundary and accompanying changes in water table
  - Groundwater flux
- Parameterization of surface flood routing model



Surface Flood Routing –

Gridded Surface-Subsurface Hydraulic Assessment (GSSHA)

1-yr Storm

0.0 m SLR

0.5 m SLR

1.0 m SLR

1.5 m SLR

2.0 m SLR

Surface Flood Routing –

Gridded Surface-Subsurface Hydraulic Assessment (GSSHA)

10-yr Storm

0.0 m SLR

0.5 m SLR

1.0 m SLR

1.5 m SLR

2.0 m SLR

Surface Flood Routing –
Gridded Surface-Subsurface Hydraulic Assessment (GSSHA)

50-yr Storm

0.0 m SLR

0.5 m SLR

1.0 m SLR

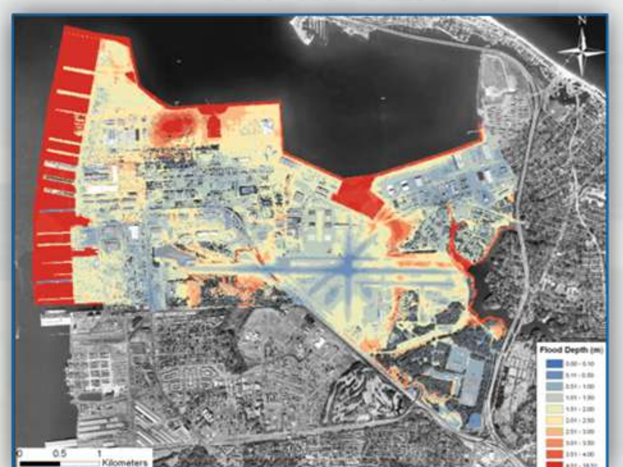
1.5 m SLR

2.0 m SLR

Surface Flood Routing –
Gridded Surface-Subsurface Hydraulic Assessment (GSSHA)

100-yr Storm

0.0 m SLR



0.5 m SLR

1.0 m SLR

1.5 m SLR

2.0 m SLR

Surface Flood Routing –
Gridded Surface-Subsurface Hydraulic Assessment (GSSHA)

Nor'easter

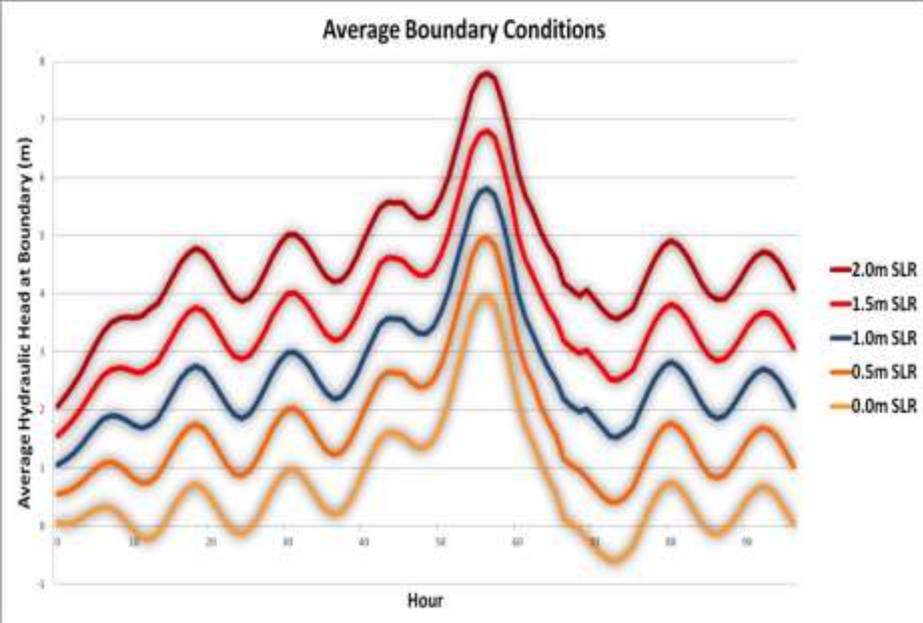
0.0 m SLR

0.5 m SLR

1.0 m SLR

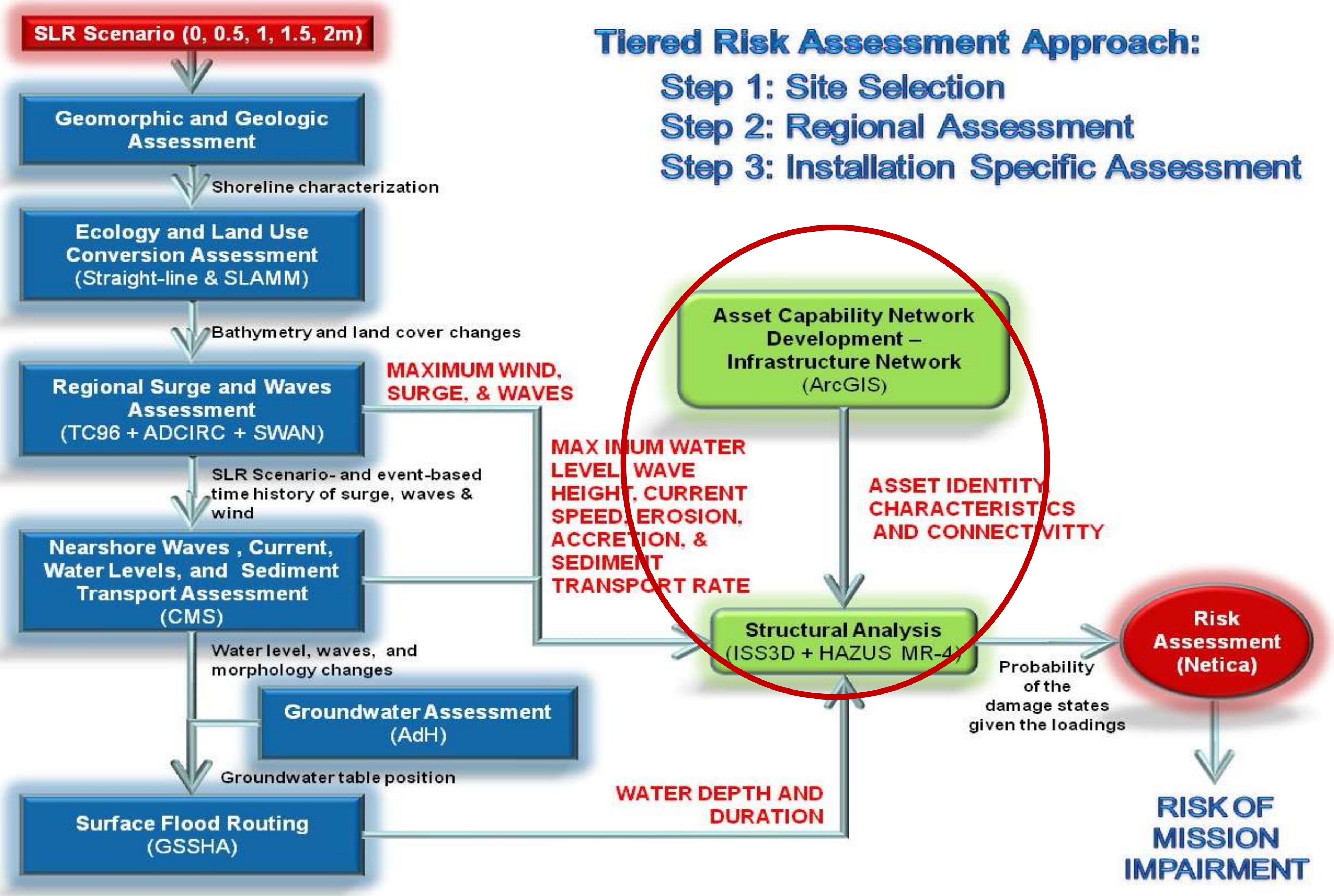
1.5 m SLR

2.0 m SLR

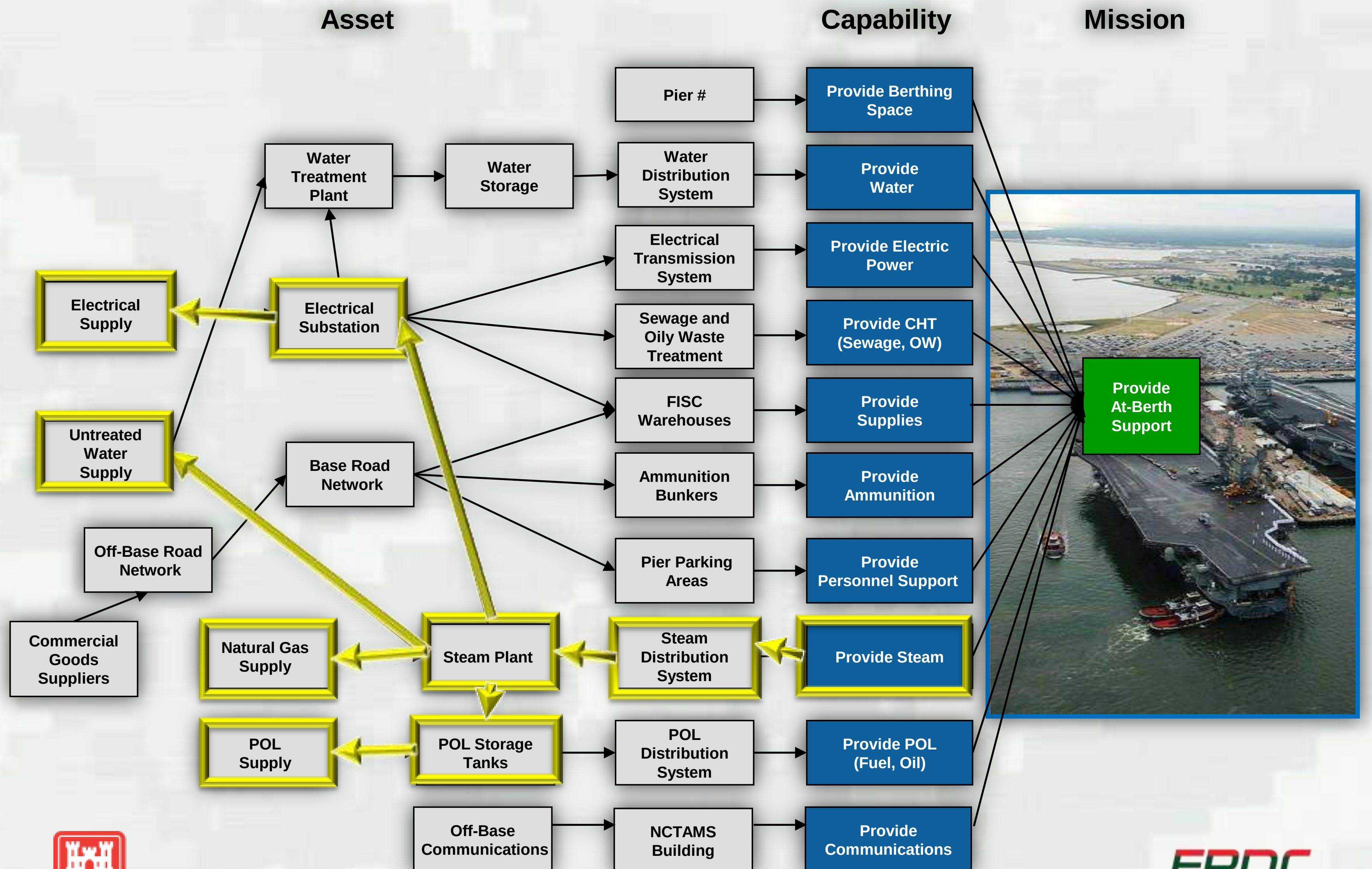

Average Boundary Conditions
Average Hydraulic Head at Boundary (m)
Hour
2.0m SLR
1.5m SLR
1.0m SLR
0.5m SLR
0.0m SLR


Willoughby Bay
Naval Station Norfolk
Google earth

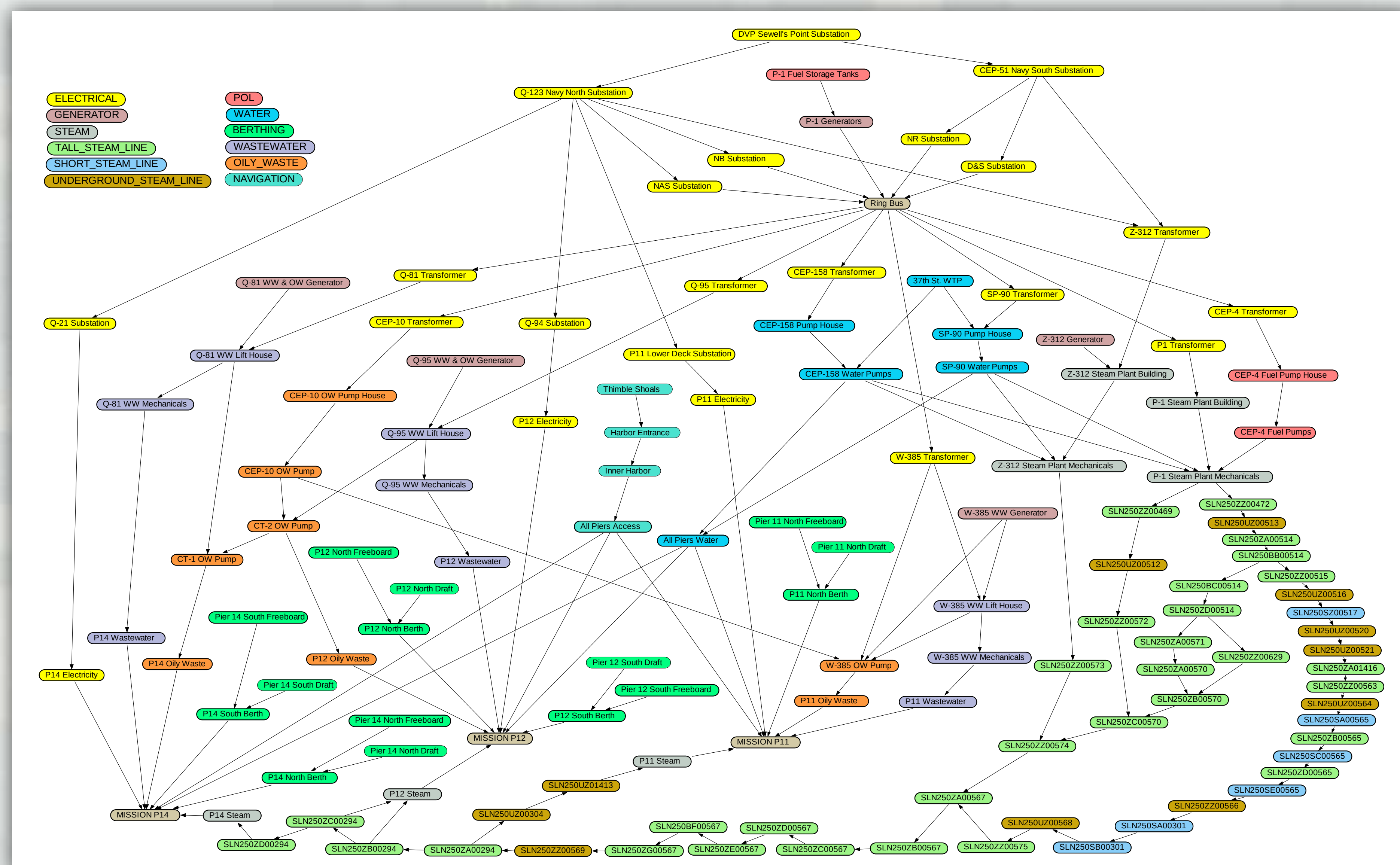
Infrastructure Vulnerability Assessment



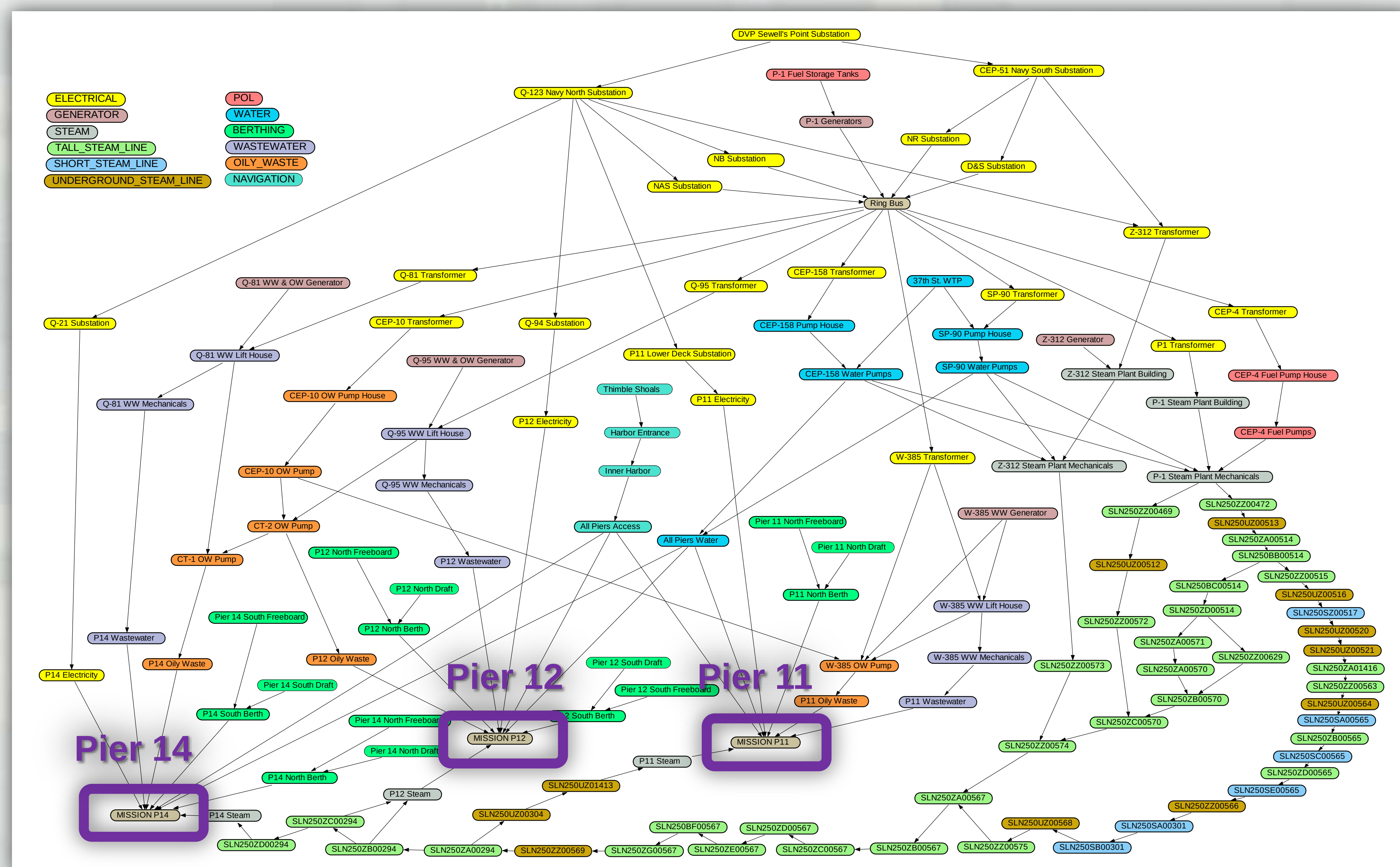
Asset Network Diagramming



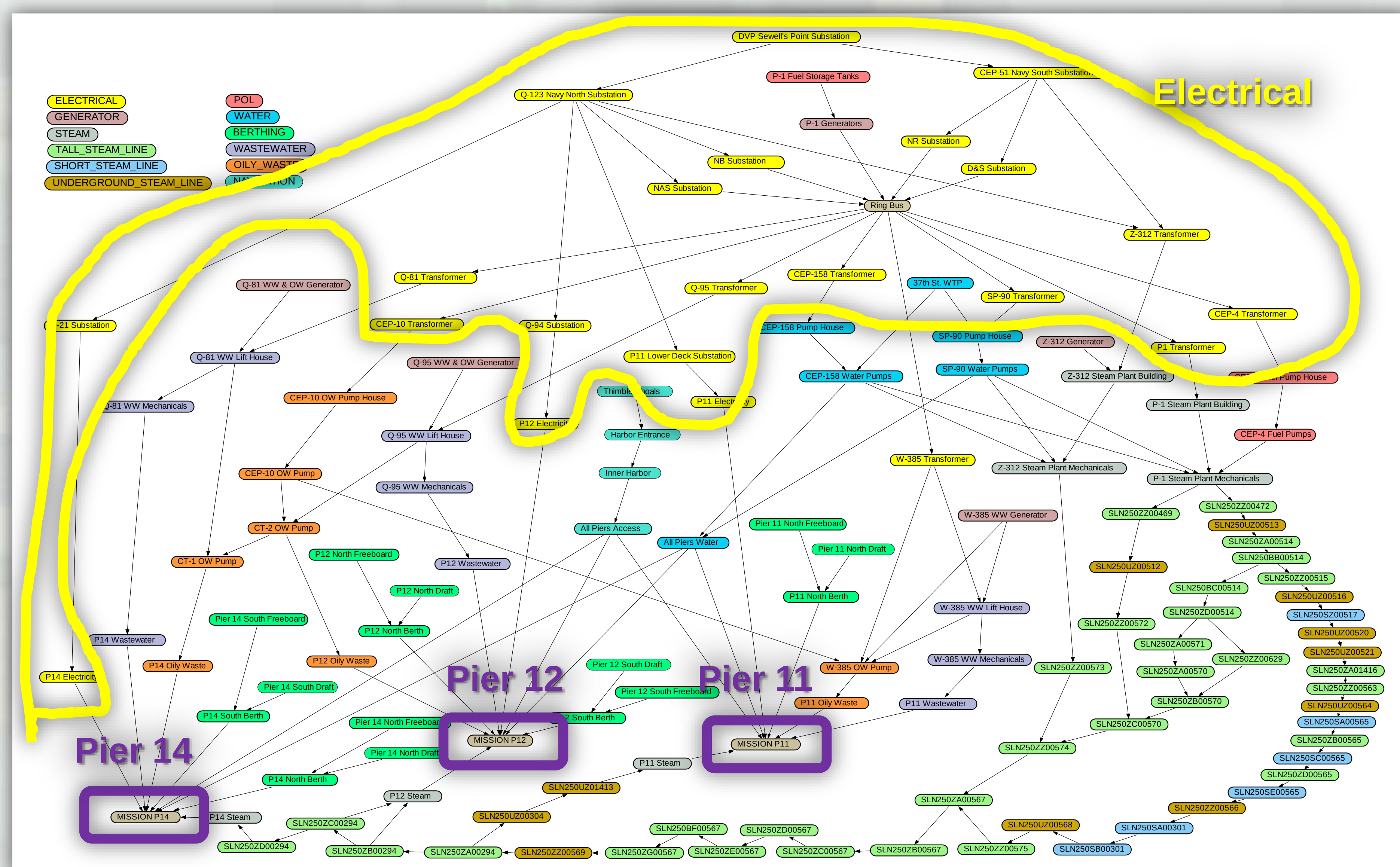
Asset Connectivity



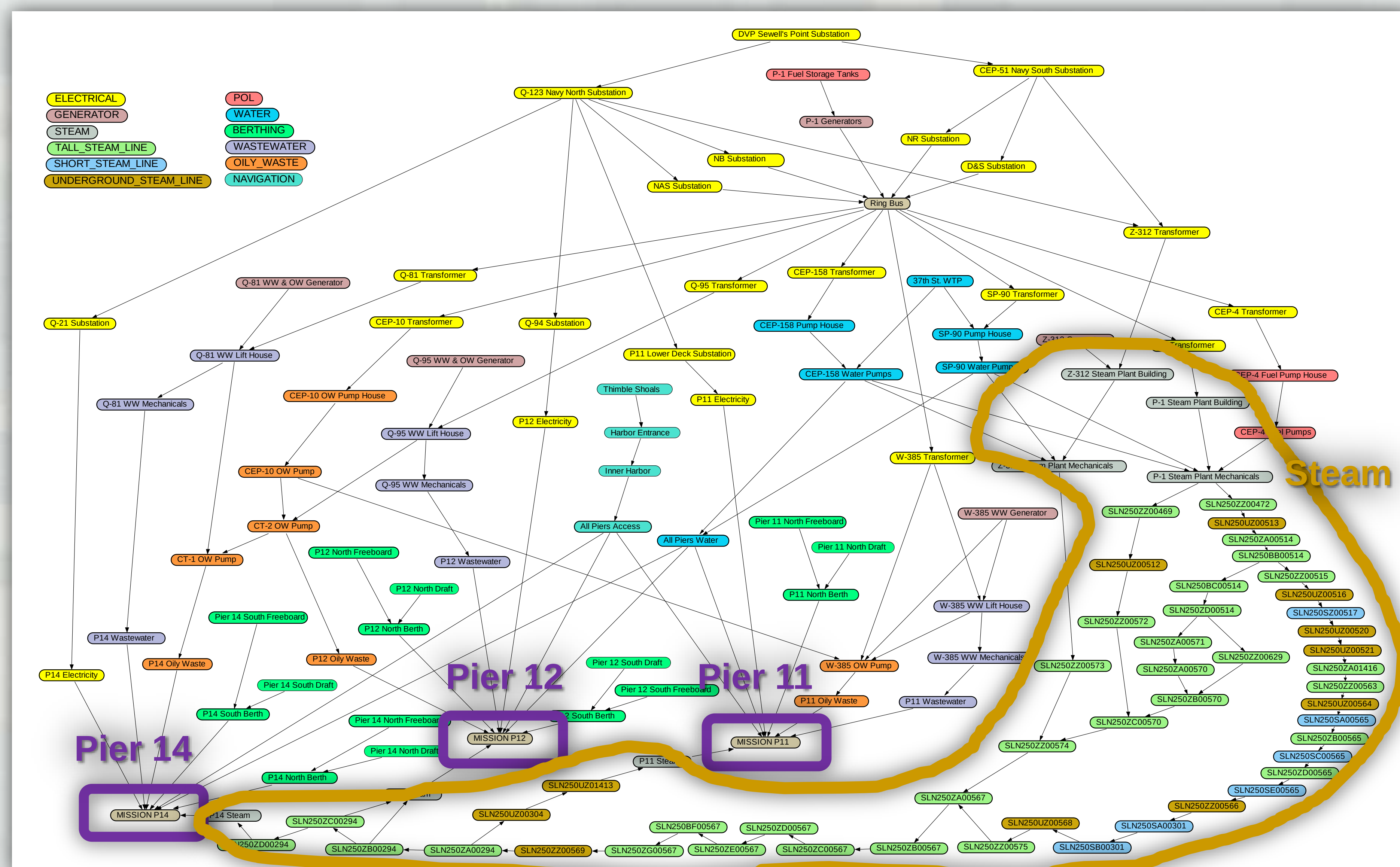
Asset Connectivity



Asset Connectivity



Asset Connectivity



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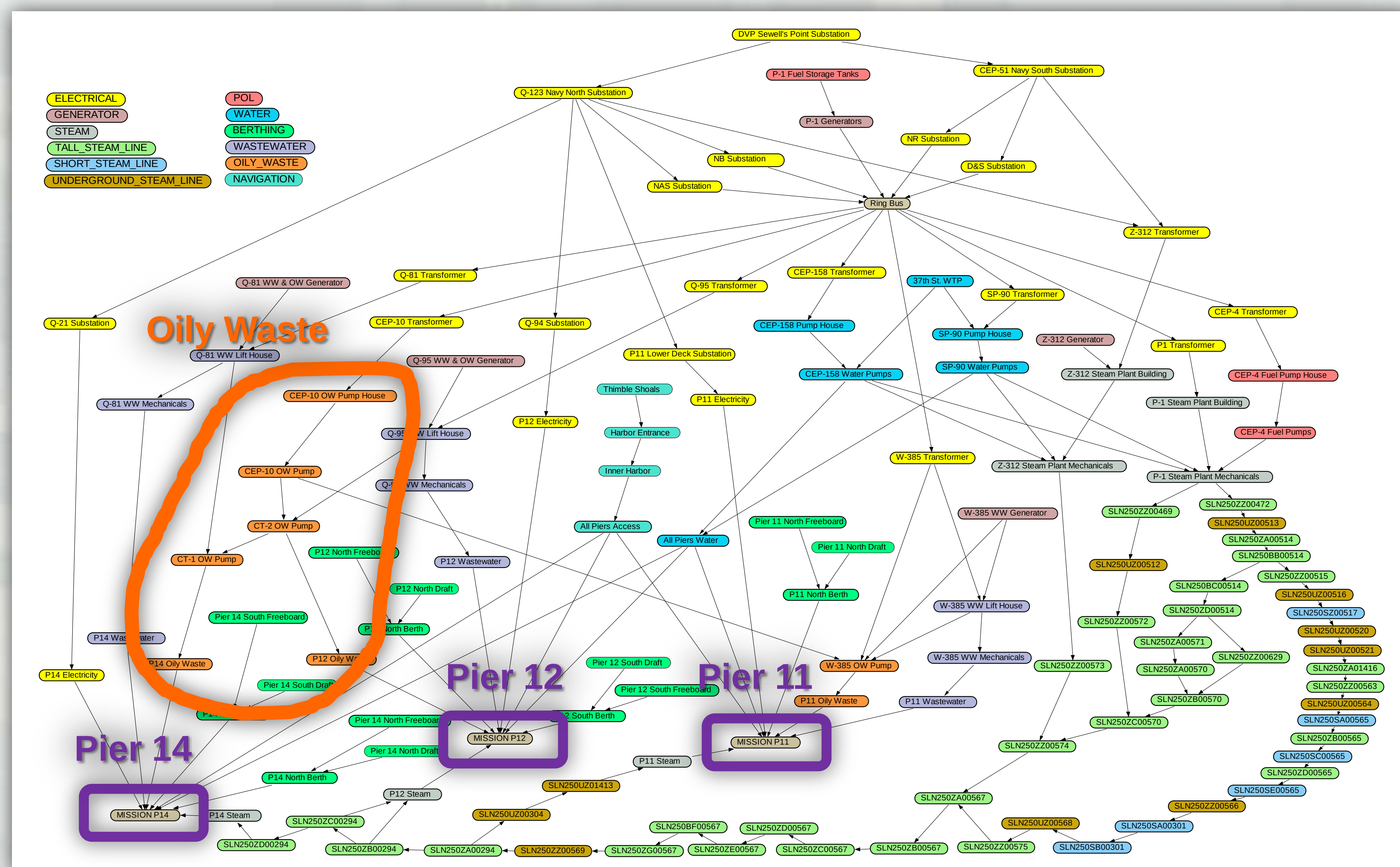

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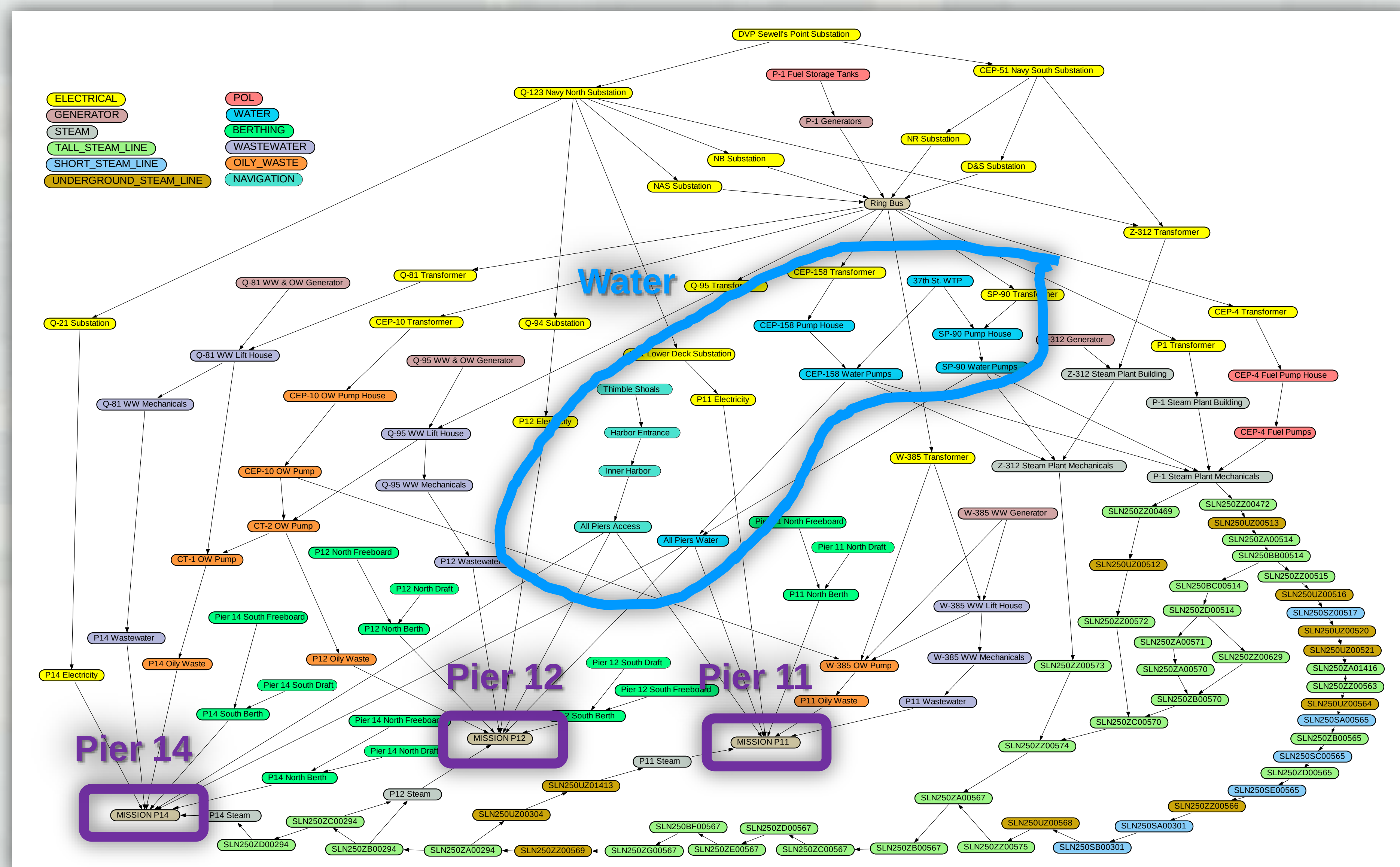
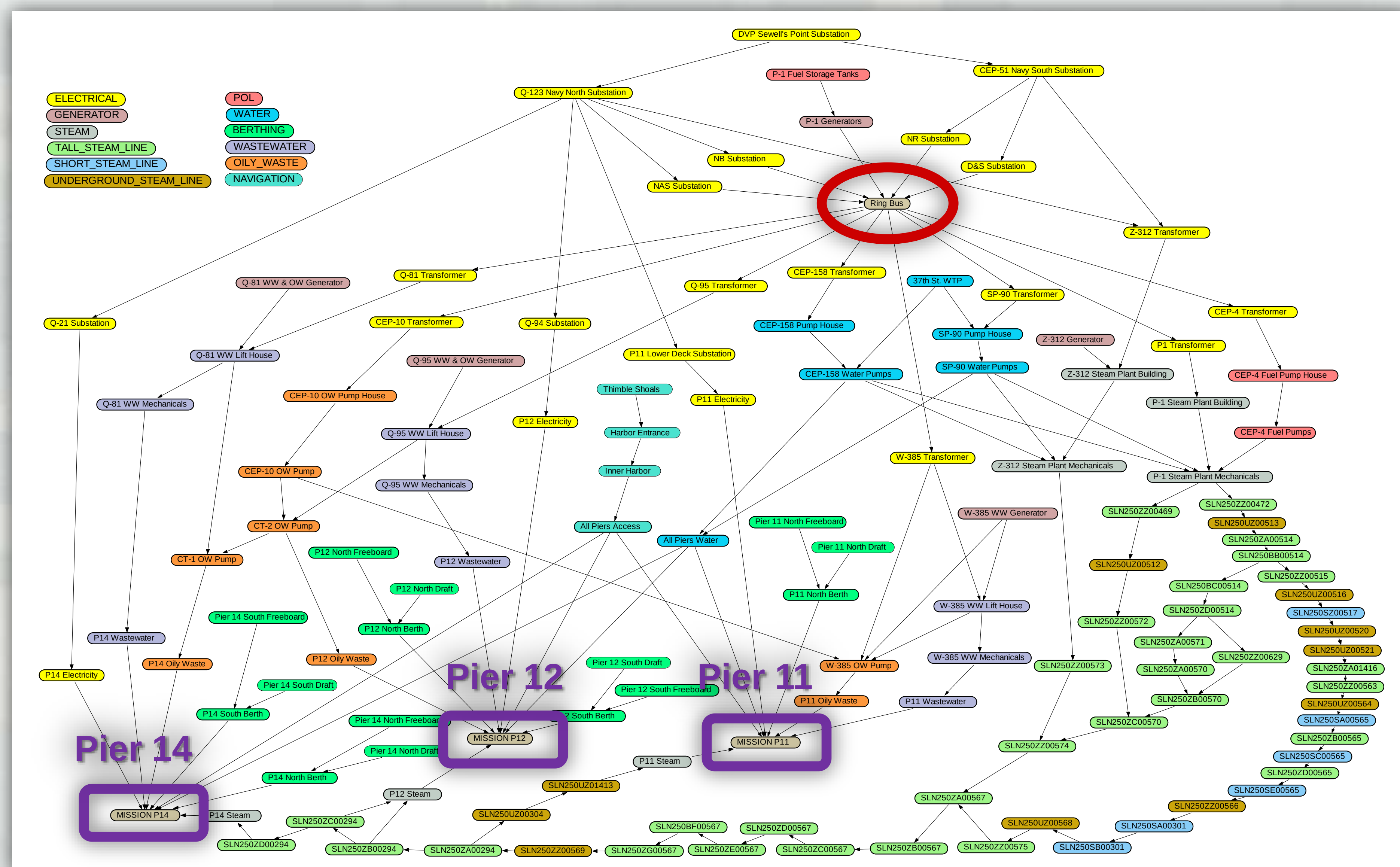


Asset Connectivity



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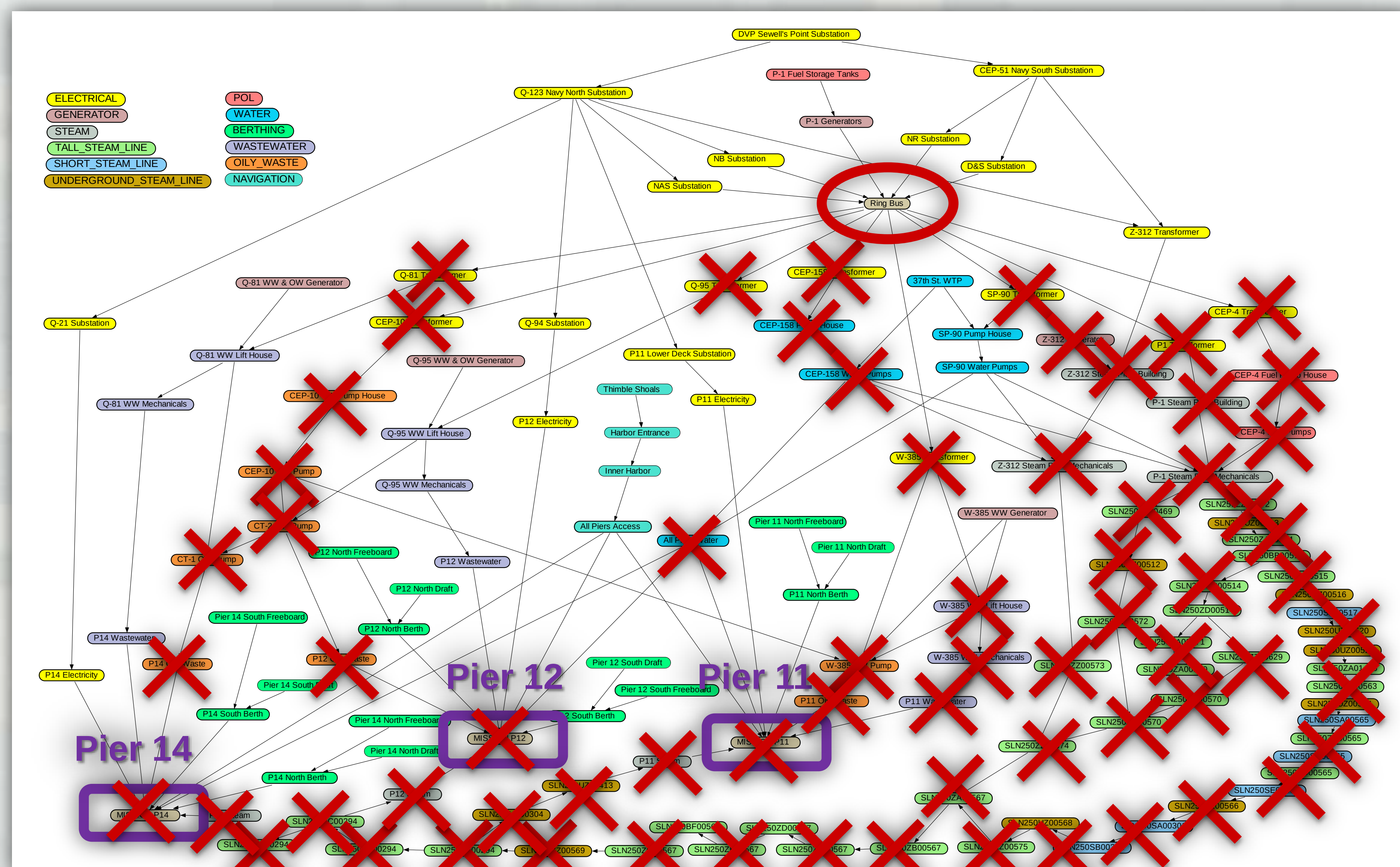

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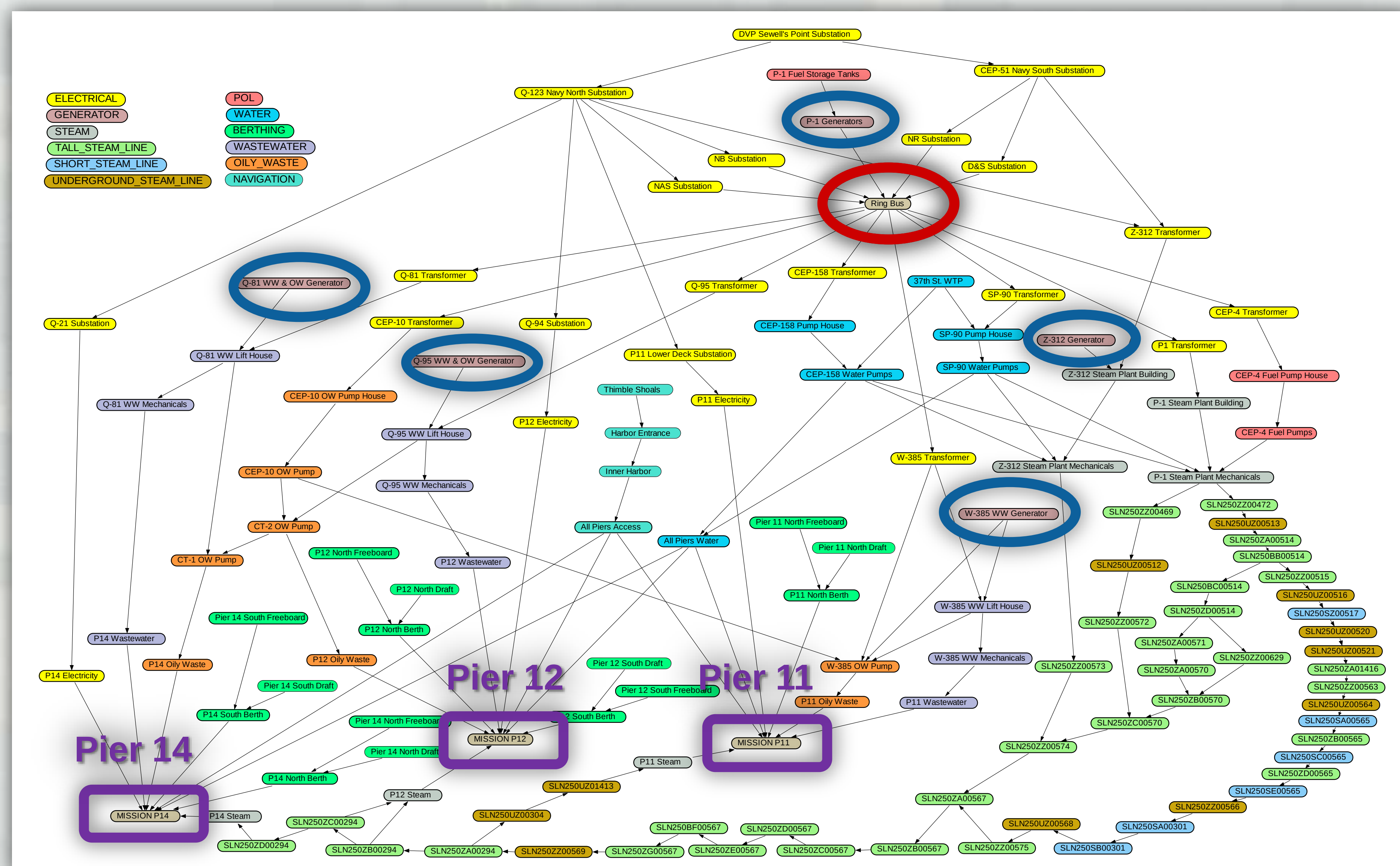

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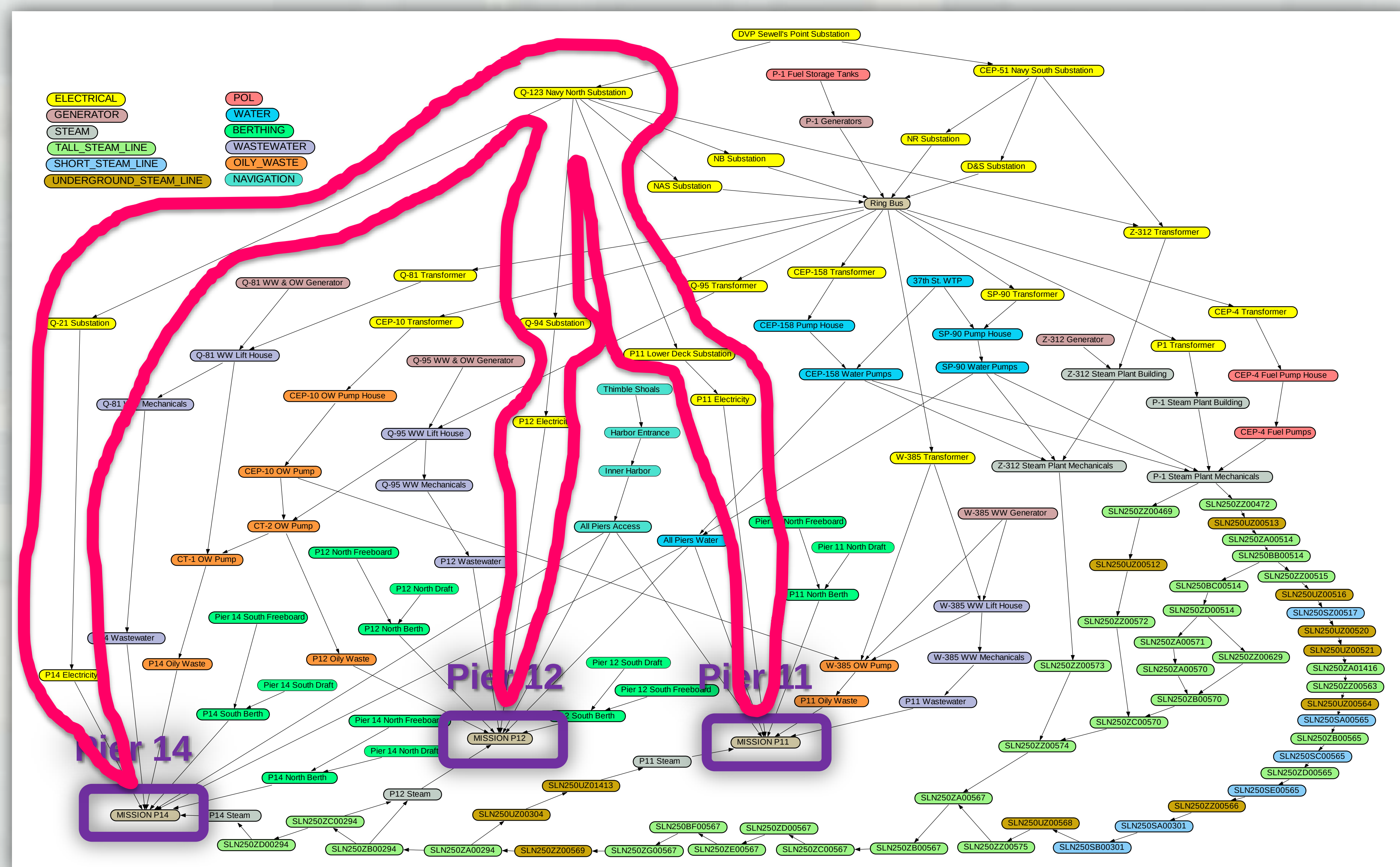
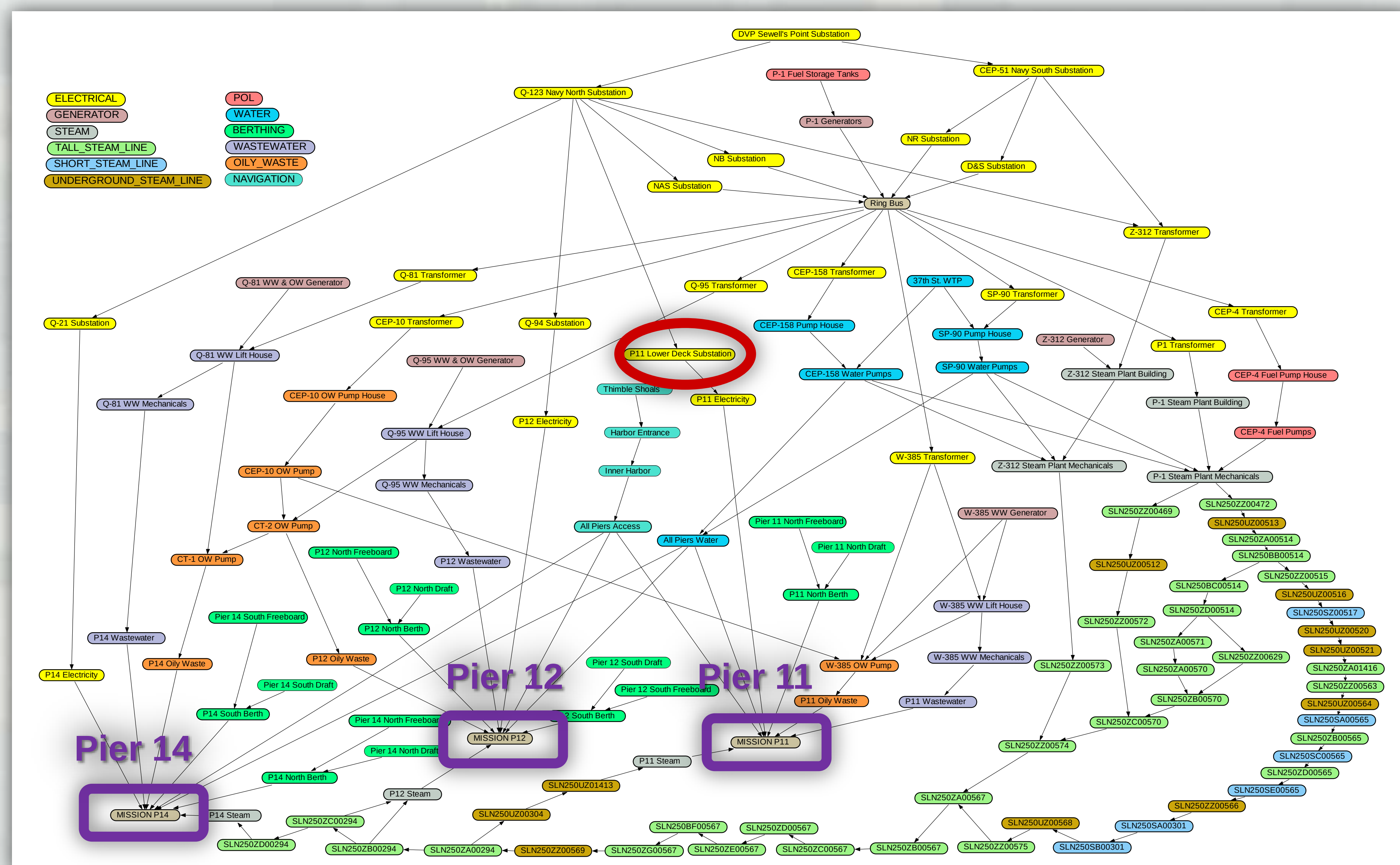


Asset Connectivity



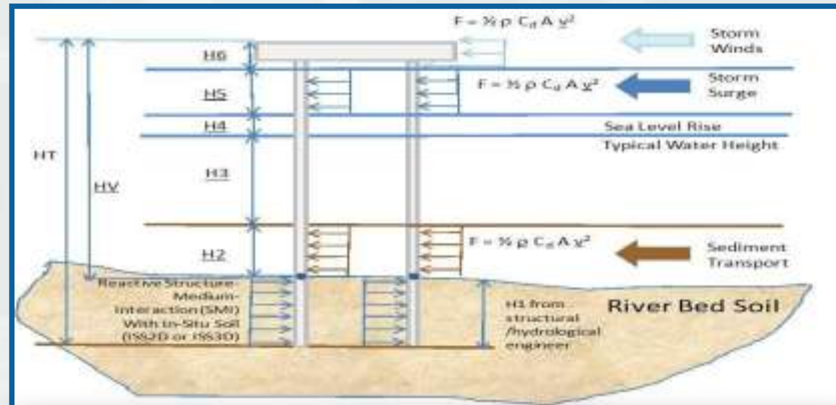
Structural Assessment

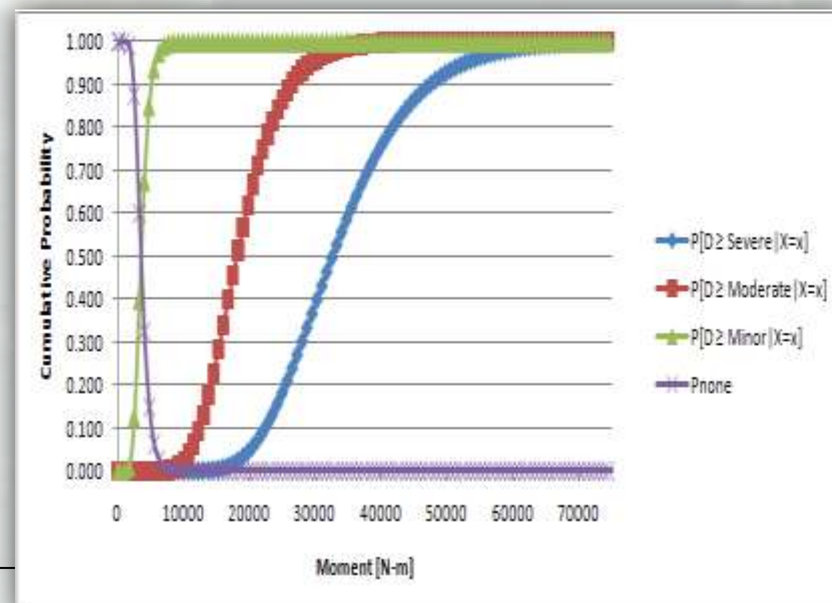
1. Potential damage states were defined

State	Description	Functional?
None	No damage.	Yes
Minor	Cracks in pylon. No visible damage to steam line.	Yes
Moderate	Pylon replacement required. No visible damage to steam line.	Yes
Severe	Pylon concrete crushed. Steam line has visible cracks.	No

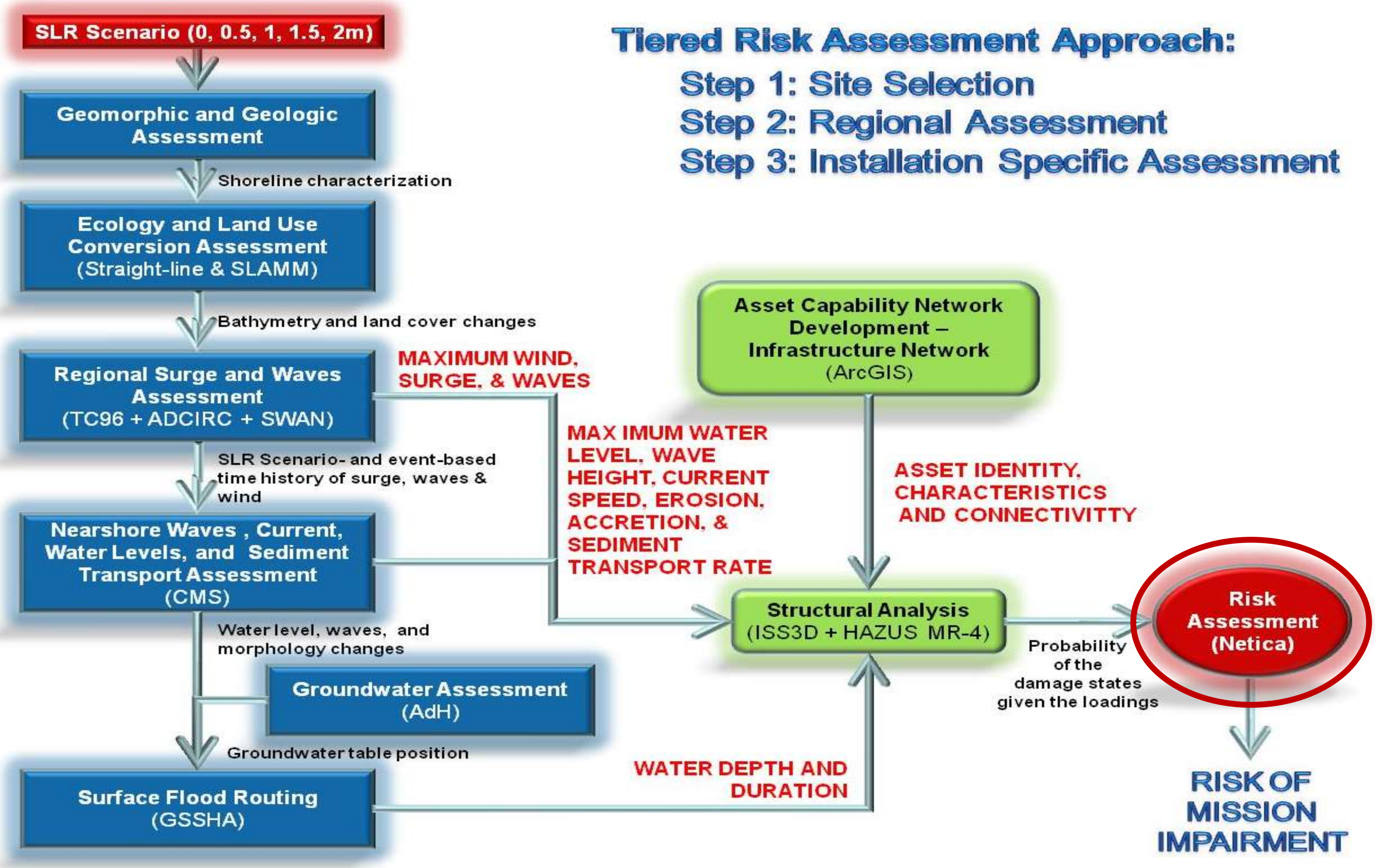
2. **Damage functions predicted the response of the SUA to wind, waves, surge, inundation, and sediment loads.**

3. **Fragility curves estimated the probability of each damage state as a function of the moment given the wind, water, and sediment loads acting on the asset.**





Risk Assessment



Utilization of the ERDC Approach:

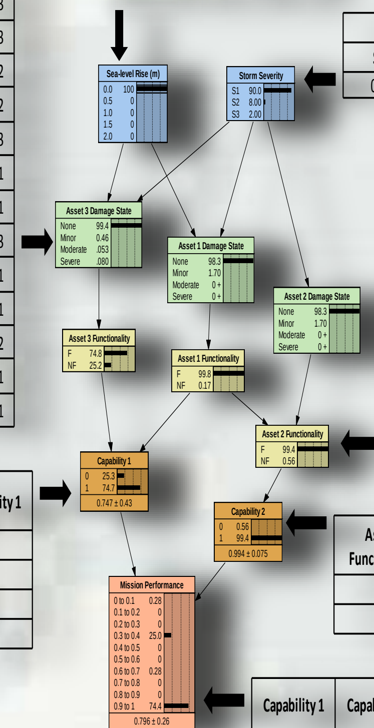
The model is used for inference about the infrastructure system and management.

1. Probability of asset **damage states** and functionality.
2. Probability of a loss in capability (**service interruption**).
3. Probability **potential losses in mission** performance.
4. How would **alternative system design** or retrofits affect mission performance?
5. Where should **better information** on structural reliability be obtained?

SLR	SEV	Asset 3 Damage State			
		None	Minor	Moderate	Severe
0.0	S1	9.98E-01	9.27E-04	2.13E-04	6.60E-04
0.0	S2	9.71E-01	2.46E-02	2.53E-03	1.82E-03
0.0	S3	9.01E-01	8.89E-02	6.99E-03	3.22E-03
0.5	S1	9.75E-01	2.09E-02	2.24E-03	1.71E-03
0.5	S2	7.76E-02	7.55E-01	1.39E-01	2.79E-02
0.5	S3	2.77E-04	4.80E-01	4.24E-01	9.62E-02
1.0	S1	9.04E-01	8.63E-02	6.81E-03	3.17E-03
1.0	S2	9.46E-05	4.25E-01	4.64E-01	1.11E-01
1.0	S3	7.15E-12	4.46E-02	5.79E-01	3.77E-01
1.5	S1	6.75E-01	2.96E-01	2.19E-02	6.66E-03
1.5	S2	1.02E-11	4.71E-02	5.82E-01	3.71E-01
1.5	S3	0.00E+00	6.70E-05	1.69E-01	8.31E-01
2.0	S1	2.09E-01	6.89E-01	8.38E-02	1.80E-02
2.0	S2	0.00E+00	5.11E-05	1.59E-01	8.41E-01
2.0	S3	0.00E+00	1.49E-12	2.16E-03	9.98E-01

SLR: Sea-level Rise (m)				
0.0	0.5	1.0	1.5	2.0
0.20	0.20	0.20	0.20	0.20

SEV: Storm Severity Index		
S1	S2	S3
0.9	0.08	0.02



ASSET 1 Functionality	ASSET 2 Damage State	Asset 2 Functionality	
		F	NF
F	None	1.00	0.00
F	Minor	0.75	0.25
F	Moderate	0.25	0.75
F	Severe	0.00	1.00
NF	None	0.00	1.00
NF	Minor	0.00	1.00
NF	Moderate	0.00	1.00
NF	Severe	0.00	1.00

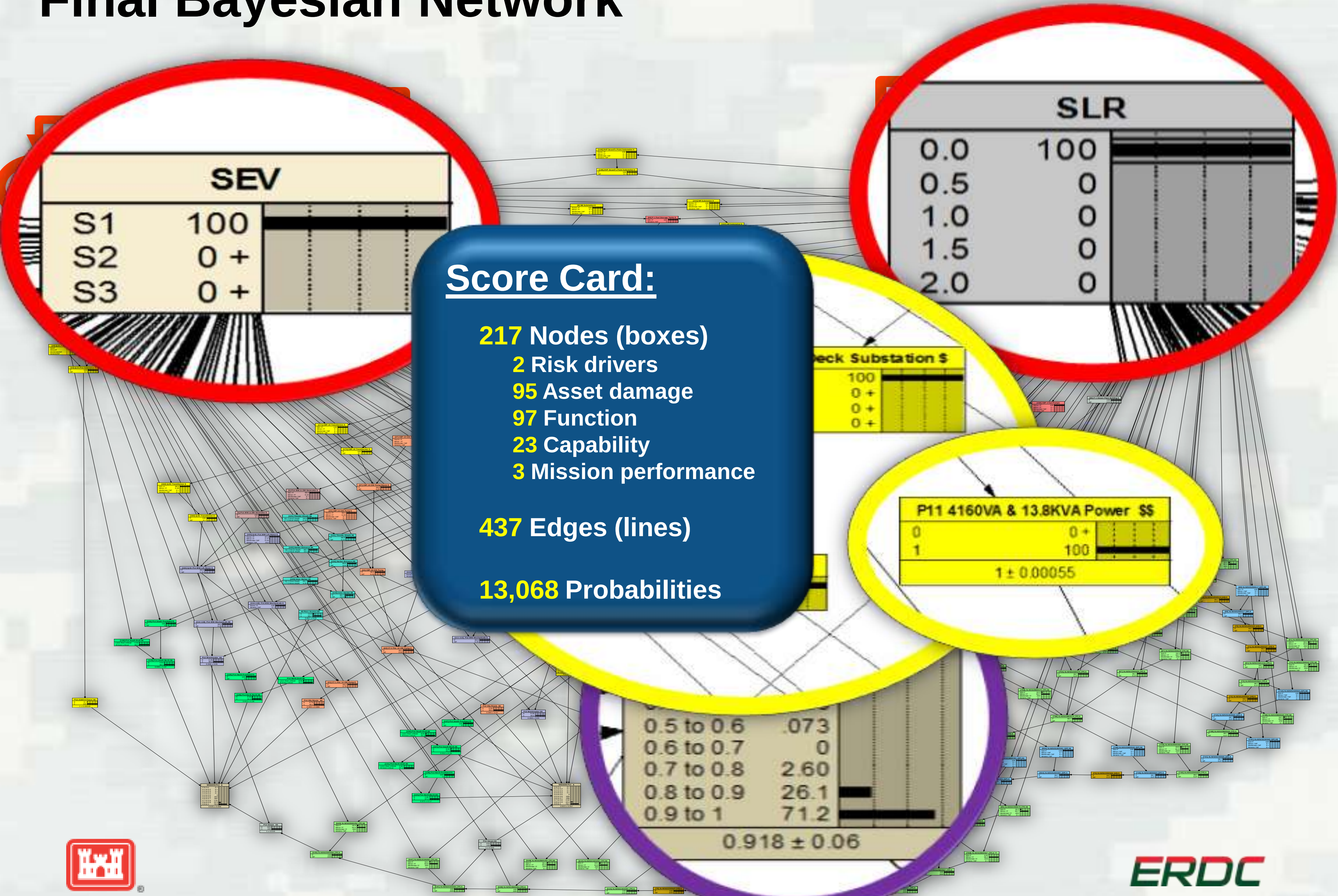
Asset 3 Functionality	Asset 2 Functionality	Capability 1
F	F	1
F	NF	0
NF	F	0
NF	NF	0

Asset 2 Functionality	Capability 2
F	1
NF	0

Capability 1	Capability 2	Mission Performance
0	0	0
0	1	0.35
1	0	0.65
1	1	1

ERDC

Final Bayesian Network



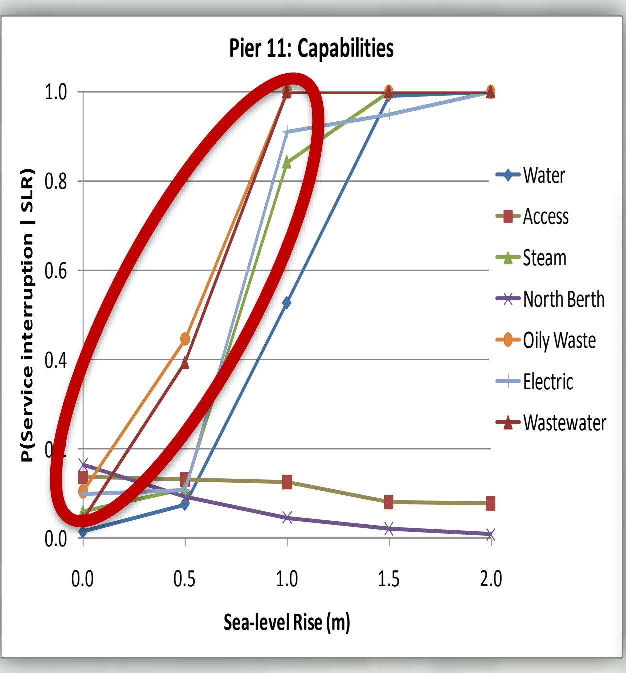
Score Card:

- **217** Nodes (boxes)
  - **2** Risk drivers
  - **95** Asset damage
  - **97** Function
  - **23** Capability
  - **3** Mission performance
- **437** Edges (lines)
- **13,068** Probabilities

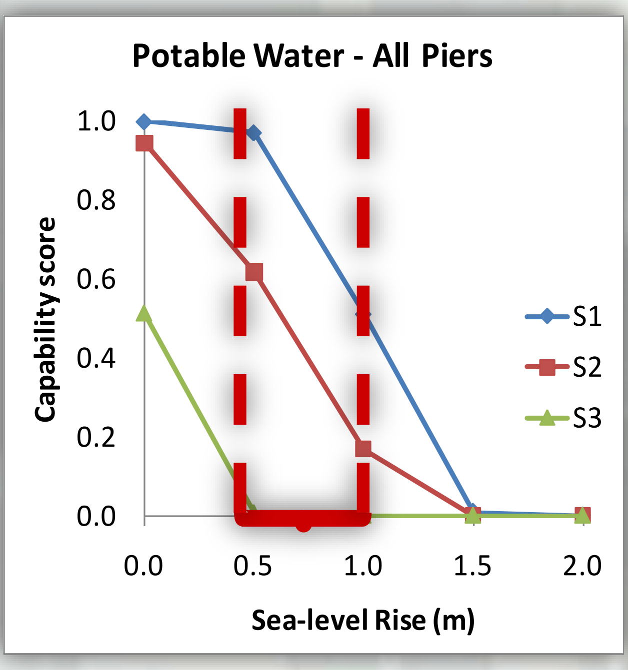
Final Risk Assessment Results

Burks-Copes et. al. (2014)

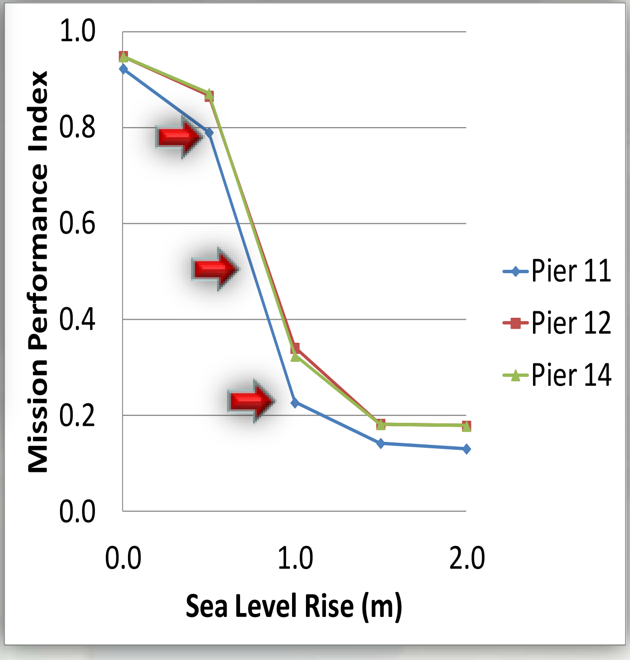
Service Interruption



Loss in Capability



Loss in Mission Performance

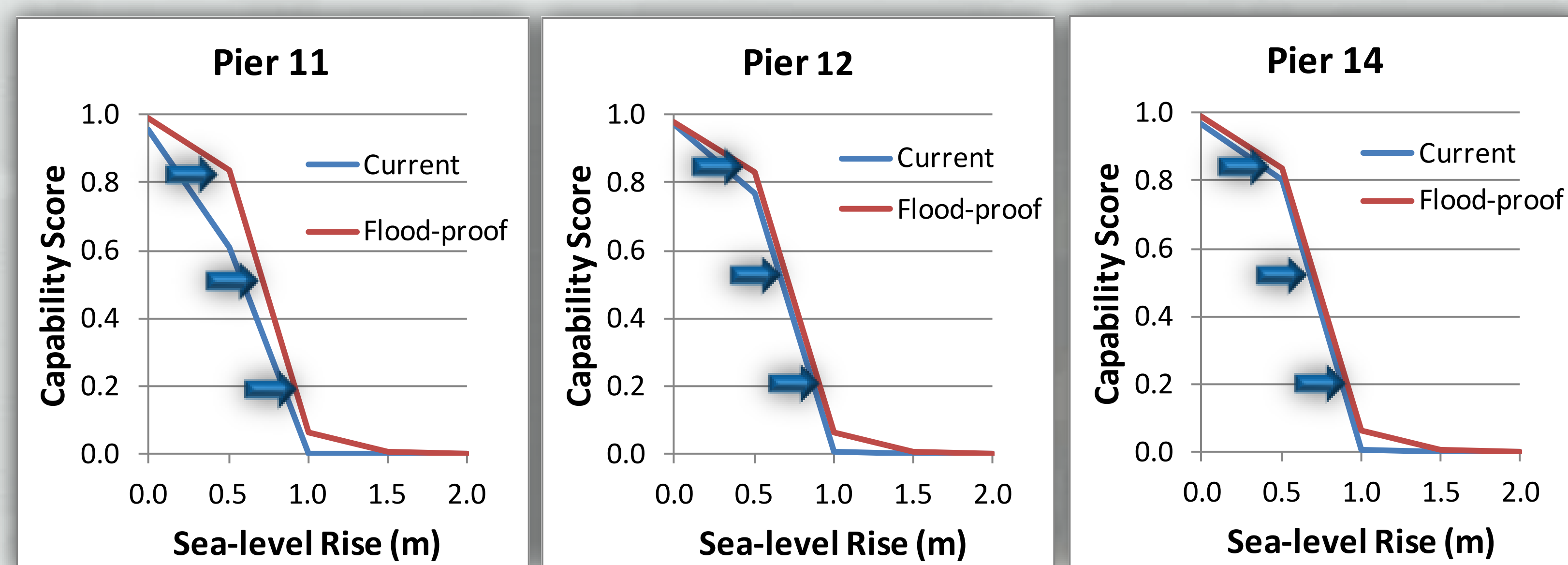


Tipping point is between 0.5 and 1.0 m SLR

Tipping point => where changes in SLR resulted in significant increases in probabilities of damage and mission impairment

Adaptive Management and Regret Management

- **Flood proof pumps and controls, transformers, generators, and electrical connections.**
- **Difference is the change in capability score relative to existing asset design.**
- **Flood-proofing greatly increases capability score at Pier 11 when SLR = 0.5 m.**
- **Effects diminish as sea-level rises.**



Capability score is for Provide Wastewater

Burks-Copes et. al. (2014)

ERDC

Future Directions

- **Portable, Scalable Approach**
  - Demo Project - NSN Master Planning, Adaptive Management (Retrofits), Contingency Planning
  - Assist with Informing Policy and Planning
  - Portfolio Risk Management
  - **Navy's Task Force Climate Change Worldwide Installation Vulnerability Assessment**
- **Dependencies Outside the Fence Line**
  - Stakeholders Forum(s)
  - Hampton Roads Installations 
  - VA Recurrent Flooding Study

Point of Contact

Dr. Kelly A. Burks-Copes

SERDP RC-1701 Project Team Leader

Environmental Laboratory

US Army Engineer Research & Development Center (ERDC)

3909 Halls Ferry Rd., Vicksburg, MS 39180

Office: 601-634-2290, Mobile: 601-618-5565

Email: Kelly.A.Burks-Copes@usace.army.mil

- *Study details available on:* *https://ClimateChange.erdc.dren.mil*

- *Final Report Citation:*

  Burks-Copes, K. A., et al. 2014. Risk Quantification for Sustaining Coastal Military Installation Assets and Mission Capabilities, Final Technical Report. Prepared by the U.S. Army Engineer Research and Development Center (ERDC), Environmental Laboratory (EL), Vicksburg, MS for the Strategic Environmental Research and Development Program (SERDP) under project #RC-1701.

- *Final Report available online at:* *https://serdp-estcp.org/content/download/30139/291303/file/RC_1701_Final%20Report.pdf*

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