U.S. Department of Transportation
Federal Highway Administration

Toward More Resilient Infrastructure

FHWA Territorial Meeting
August 22, 2018

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FHWA Office of Natural Environment

Introductions

hello

hafa dai

- What is your name?
- Where are you from?
- What role do you have in your agency?
- What do you hope to get out of today's session?

talofa

hola

Session Logistics and Outcomes

- Please ask questions and interrupt us
  - This session is for you
- Outcomes:
  - You will have outlined an approach to planning level vulnerability assessment for your community
  - You will be aware of FHWA tools
  - You will have learned from your peers

Agenda

I. Introductions
II. What is Resilience?
III. Vulnerability Assessments and Adaptation Options
IV. Project-Level Case Studies
V. Integrating Resilience into Decisionmaking

What resilience risks are you worried about?

What keeps you up at night?

What is Resilience?

What is resilience?

Resilience: the ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions

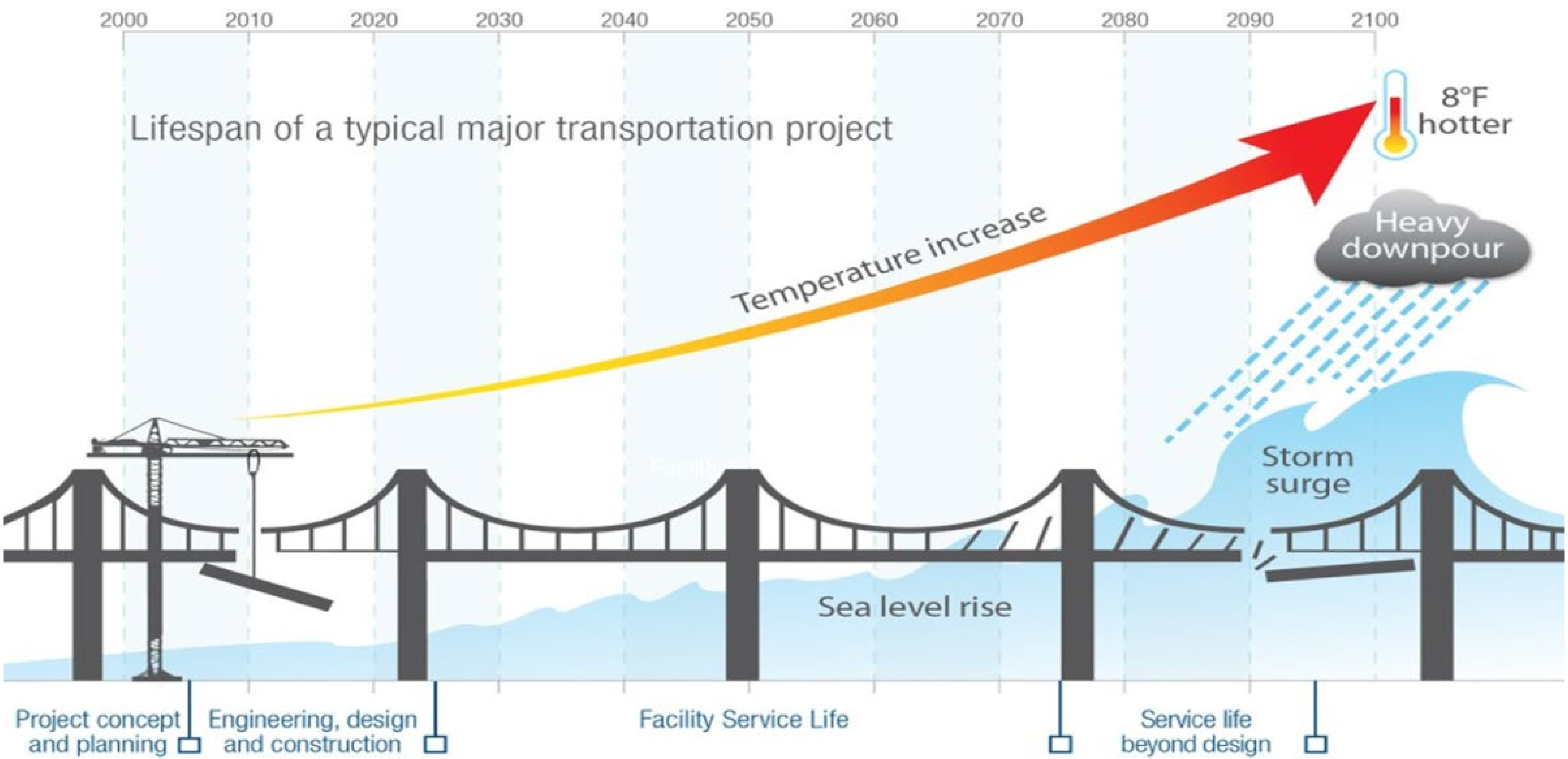
Adaptation: adjustment in natural or human systems in anticipation of or response to a changing environment in a way that effectively uses beneficial opportunities or reduces negative effects




Importance of Resilience

Story Created: Jul 4, 2008 at 5:07 PM PDT
Story Updated: Jul 4, 2008 at 5:25 PM PDT

Why Consider Changing Conditions?

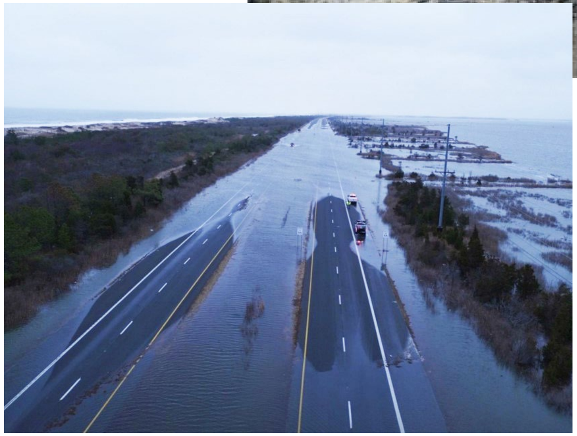


Impacts of a changing climate are being felt now, and will accelerate significantly in the future.

– National Academy of Sciences and National Climate Assessment

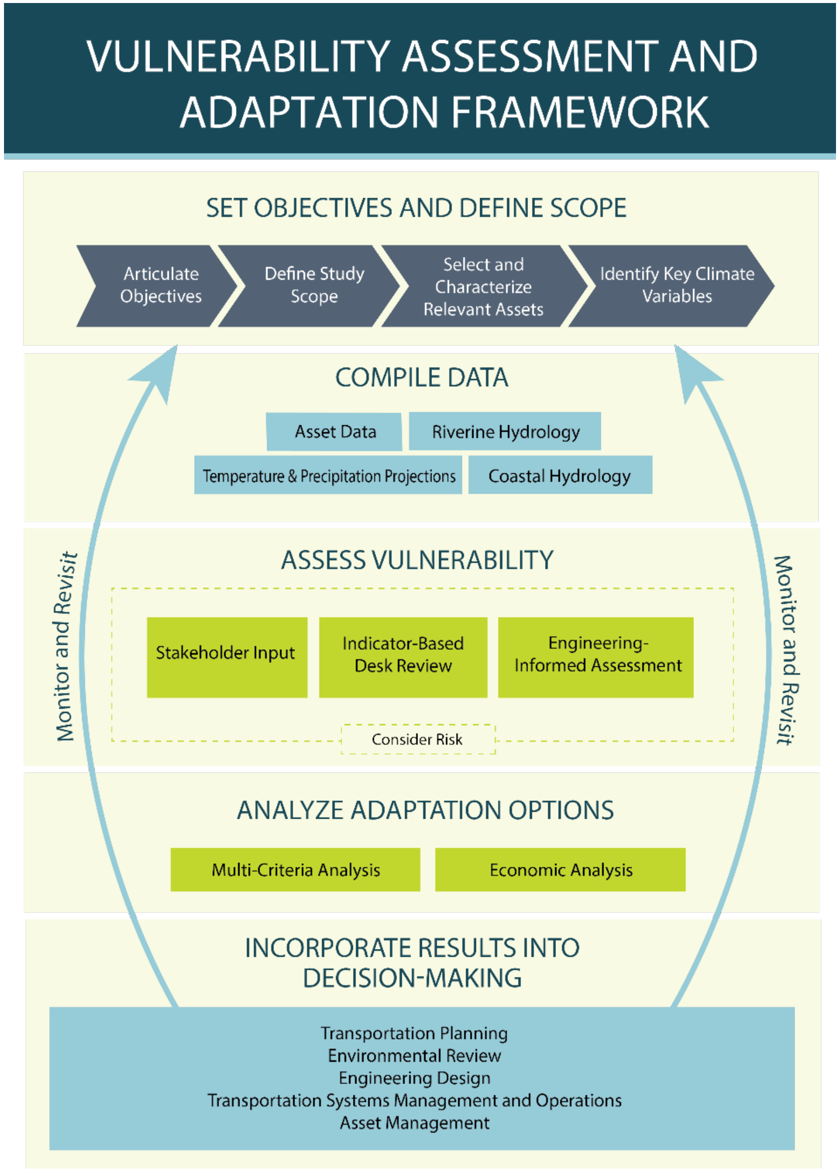
Climate Resilience Policy

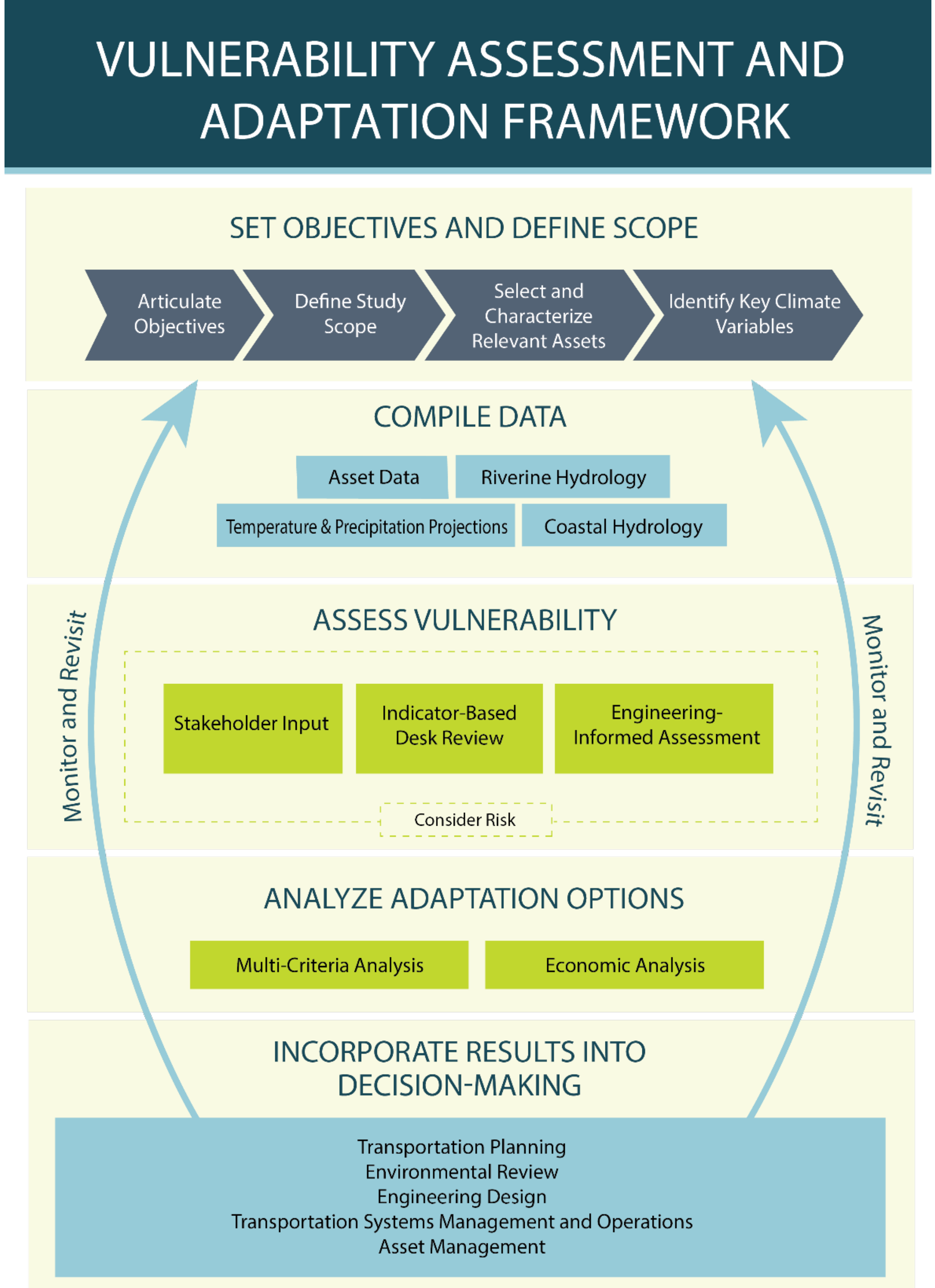
- USDOT FY 2018-22 Strategic Plan: "DOT will increase its effectiveness in ensuring that infrastructure is resilient enough to withstand extreme weather"
- FHWA Order 5520 commits FHWA to integrating climate risk consideration into programs
- Climate resilience eligible for FHWA funds
- Emergency relief program guidance encourages cost-effective resilience strategies



Vulnerability Assessment and Adaptation Framework, 3rd Edition

- Provides an in-depth and structured **process** for conducting a vulnerability assessment.
- Features **examples** from assessments conducted nationwide.
- Includes links and references to related **resources and tools**.




VULNERABILITY ASSESSMENT AND ADAPTATION FRAMEWORK
SET OBJECTIVES AND DEFINE SCOPE
Articulate Objectives
Define Study Scope
Select and Characterize Relevant Assets
Identify Key Climate Variables
COMPILE DATA
Asset Data
Riverine Hydrology
Temperature & Precipitation Projections
Coastal Hydrology
ASSESS VULNERABILITY
Stakeholder Input
Indicator-Based Desk Review
Engineering-Informed Assessment
Consider Risk
ANALYZE ADAPTATION OPTIONS
Multi-Criteria Analysis
Economic Analysis
INCORPORATE RESULTS INTO DECISION-MAKING
Transportation Planning
Environmental Review
Engineering Design
Transportation Systems Management and Operations
Asset Management
Monitor and Revisit
Monitor and Revisit

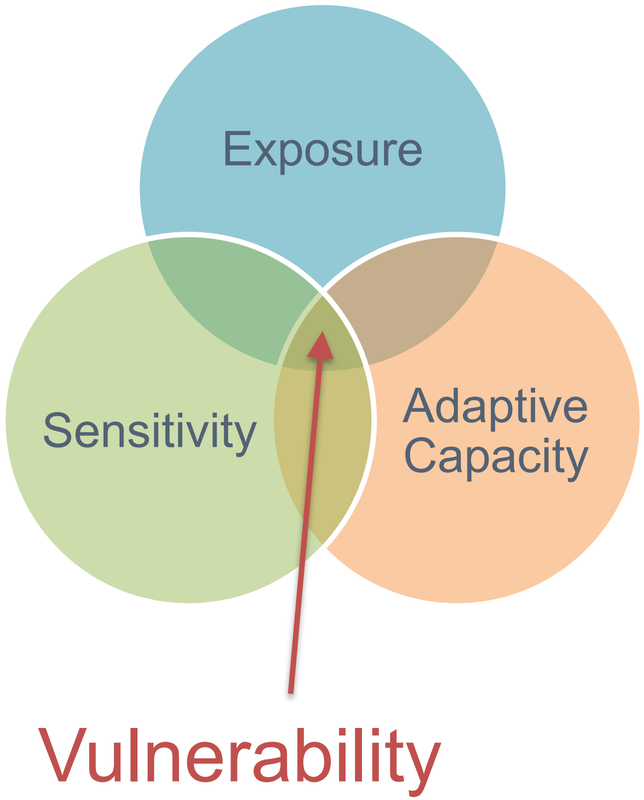
Vulnerability Assessments

Vulnerability Assessment

A starting point for identifying and assessing resilience concerns

- Where are your highest risk locations?
- How might future changes in climate impact your transportation system?

Vulnerability

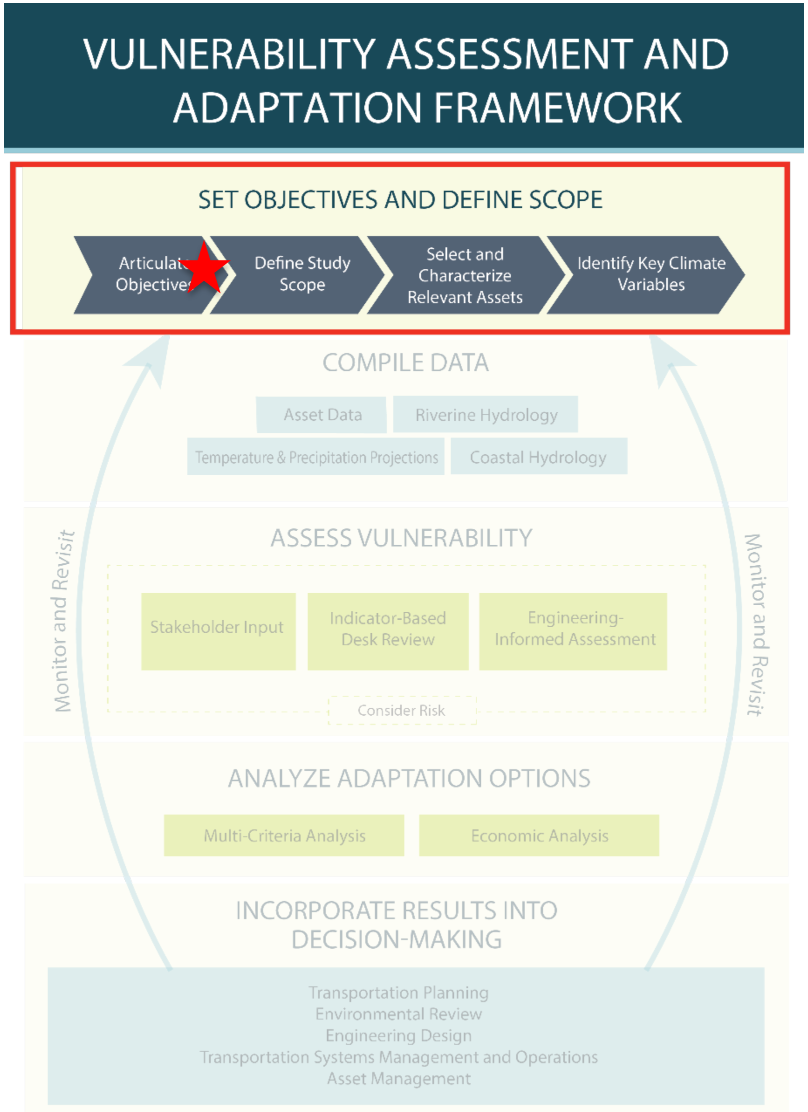


Vulnerability is a function of a transportation system's:

- **exposure** to extreme weather and climate effects
- **sensitivity** to climate effects, and
- **adaptive capacity**.

Risk considers the *probability* that an asset will experience a particular impact and the *severity or consequence* of the impact

Set Objectives and Define Scope



First, what do you want to find out?

- What type of agency decisions or actions should the assessment inform?
- What is motivating the need for the assessment?
- What level of detail (spatial, geographic, and temporal) is required?
- What results or products are needed and how will they be used?

Selecting & Characterizing Relevant Assets

Selection Factors :

- Jurisdictional
- Geographic
- Representative
- Repeatedly impacted
- Stage of life
- Most critical
- Existing and planned assets

Selecting & Characterizing Relevant Assets

Metropolitan Transportation Commission (MTC): Representative Assets

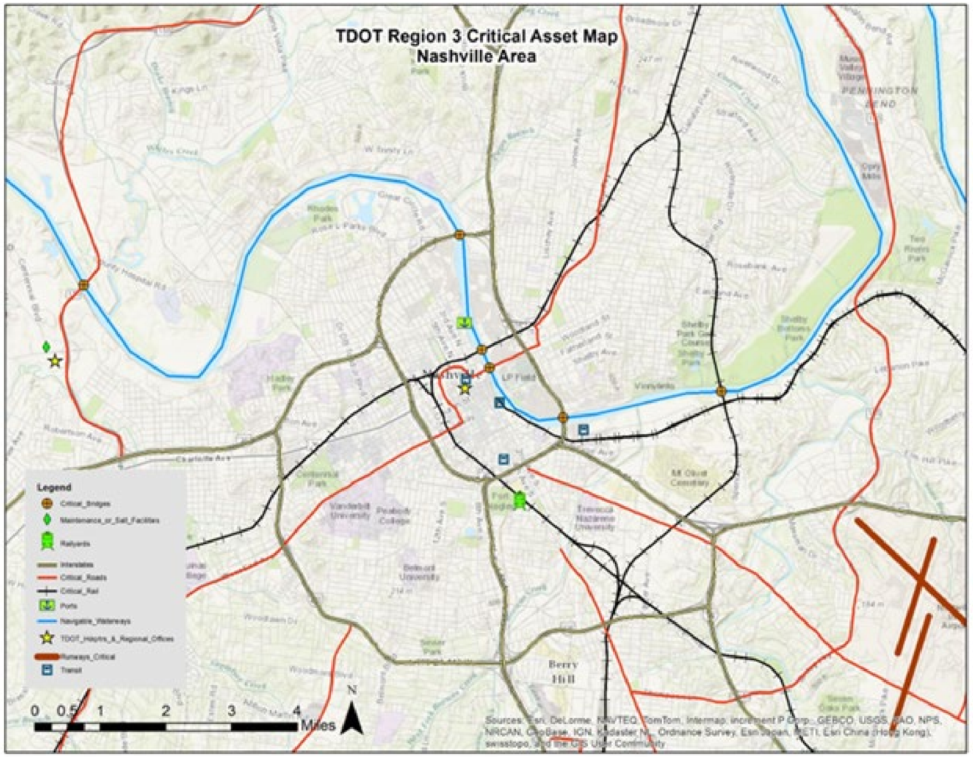
- **First study:** Selected three representative assets from each category:
  - Road network
  - Transit network
  - Bicycle and pedestrian network
  - Storage, operations and maintenance, and control facilities
- **Second study:** Chose three focus areas and developed adaptation strategies.

Source: MTC

Selecting & Characterizing Relevant Assets

Tennessee DOT: Critical Assets

- **Critical asset** defined as "any portion of the transportation system without which there would be an immediate, direct, and substantial disruption to the transportation system at the local, regional, or national level."
- Assigned degree of criticality:
  - Critical
  - Important
  - Other
- Verified with regional stakeholders



Identifying Key Climate Variables

What **climate variables** will you study?

- Examples: temperature, precipitation, sea level, storm surge and waves, streamflow, and drought.
- Also might consider other non-climate hazards such as earthquakes and tsunami waves

Sensitivity Matrix

- Spreadsheet tool. Matrix with info by asset and climate stressor: relationship, thresholds, indicators, key sources, notes and examples
- Assets covered: rail, ports & waterways, airports, pipelines, bridges, roads and highways
- Climate stressors: temperature, precipitation, sea level rise, storm surge, wind, drought, dust storms, wildfires, winter storms, freeze/thaw, permafrost

Return to Table of Contents | See References | Bridges | Rail | Airports and Heliports | Ports and Waterways | Oil and Gas Pipelines

Roads and Highways

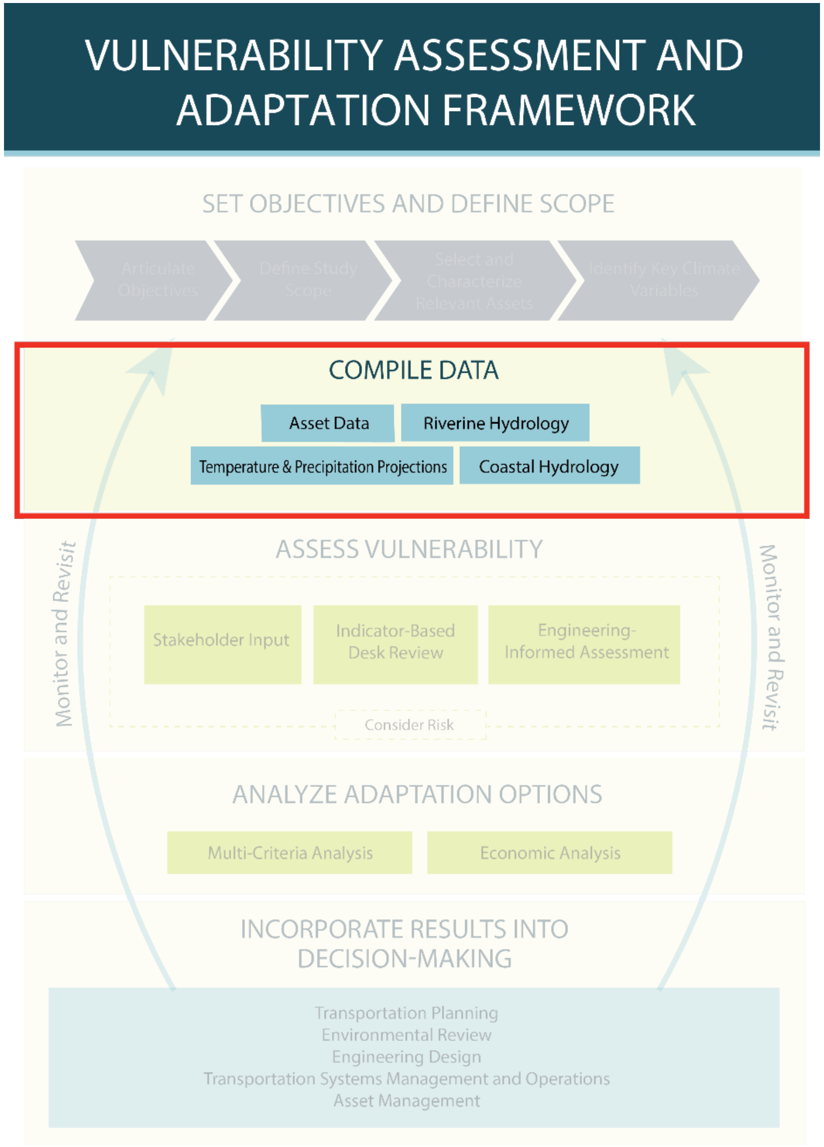
Climate Stressor	Information Type	Physical Infrastructure: Paved Roads (Surface and Subsurface)	Unpaved Roads	Stormwater Drainage (Culverts, Side Drains, etc.)	Signals and Signs	Service, Access, Maintenance, and Operations: Road Wor
Increased Temperatures and Extreme Heat	Relationship	Sustained high temperatures can cause asphalt concrete pavement to soften resulting in rutting and shoving. Concrete pavement can heave at the joints. When high heat is accompanied by drought conditions, asphalt concrete pavement can crack making it more vulnerable to water when it does rain. Asphalt binder is designed to withstand temperatures up to a certain threshold. Incremental temperature increases up until that point are not likely to cause much damage (Heitzman, 2010).	No documented relationship.	No documented relationship.	No documented relationship.	High temperat as engine and truck operatio vehicles (OFC increasing ext reaction time c increase was f accidents (Ko 1990).
	Threshold(s)	Thresholds vary depending on pavement design. Pavement binder may exhibit sensitivity beginning at 108°F, particularly if combined with truck traffic (Watson, 2010). In the Pg 64-22 grade, the number 64 stands for the average 7-day high pavement temperature (consecutive days) 20 mm below the surface. The relationship between that temperature and the ambient temperature is given by the following equation: T20mm = (Tair - 0.00618 lat2 + 0.2289 lat + 42.2) (0.9545) - 17.78 *Where* T is expressed in °C and the latitude is in degrees. Lat2 means latitude squared (Watson, 2010).	Not applicable.	Not applicable.	Not applicable.	heat stress be more critical a hours that roa 110°F, operatic Implications to (combined ten be at least 105 minimum is arc 2008).
	Indicator(s)	Although aggregate is not sensitive to temperature, it can influence the sensitivity of the overall hot mix asphalt paving. For example, more angular aggregate may help to prevent rutting, which can result from high temperatures (Heitzman, 2010; Anderson et al., 2009).	Not applicable.	Not applicable.	Not applicable.	Information lim
	Key Source(s)	Heitzman, 2010; Watson, 2010; Anderson et al., 2009	Not applicable.	Not applicable.	Not applicable.	Information lim
		Mobile County currently does not experience a lot of damage due to pavement softening. However, during extreme heat spells when the temperature can remain				

Overview | Report Generation | Results by Asset Type | Results by Stressor | Asset Type and Characteristics | Bridges | Roads | Rail | Airports and H ...

EXERCISE #1
SET OBJECTIVES AND DEFINE SCOPE

What do you want to find out?

Compile Data



Asset Data

Climate Data

Compiling Asset Data

Types of Data:

- Age of asset
- Design life and stage of life
- Geographic location
- Elevation information
- Current and historical performance and condition
- Level of use
- Replacement cost
- Maintenance schedule and costs
- Evacuation routes
- Emergency management/response costs
- Occurrence/location of maintenance events
- Structural design

Puerto Rico DTOP

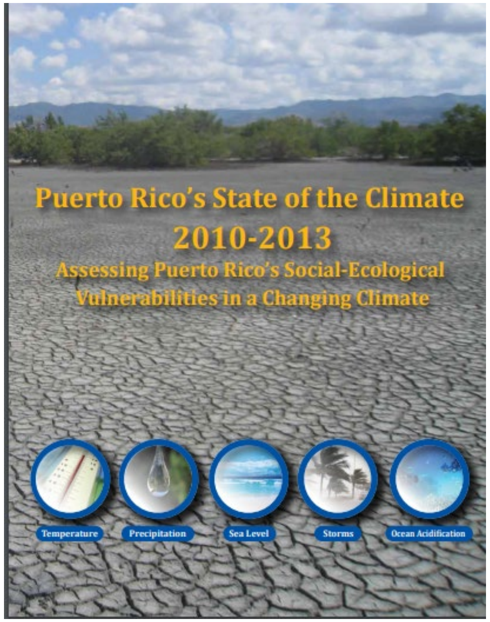
	Activo 1
Carretera identificada	
Municipio	Mayaguez
Ubicación	(PK, Coordenadas/sistema de coordenadas,
Longitud del segmento	153.3-153.5
¿Está ubicado en área costera (fren	No
Tipo de facilidad	Carretera Estatal
Otro tipo de facilidad	(Otro-> indicar)
Importancia de la facilidad	Alto tránsito
Otra importancia de la facilidad	Coneccion importante
Uso del suelo cercano a la facilidad	Residencial
Otro	(Otro-> indicar)
Tipo de evento de afectación	Inundación urbana
Otro tipo de evento de afectación	(Otro-> indicar)
Frecuencia de la afectación	Entre 2 a 4 veces al año
Magnitud de la afectación	Reducción de la capacidad sin cierre
Edad de la infraestructura	
Vida remanente	(En Años)
Elevación	(En metros)
Número de reparaciones por año	(Indicar en número)
Tipo de reparación común	Mantenimiento temporal
Costo aproximado reparaciones	10,000
Año de la última reparación	(xxxx)
¿Cuáles son las acciones de contingencia que comúnmente se realizan frente a un evento de afectación de esta	Se limpian las áreas aledañas en el moment
Comentarios adicionales	(Favor agregar si tiene comentarios adicionale activo)

Compiling Climate Data

- Climate data and projections:
  - Temperature & precipitation
  - Riverine hydrology
  - Coastal hydrology (sea level rise and storm surge)

Temperature and Precipitation Projections

[Puerto Rico Climate Change Council (PRCCC). 2013].



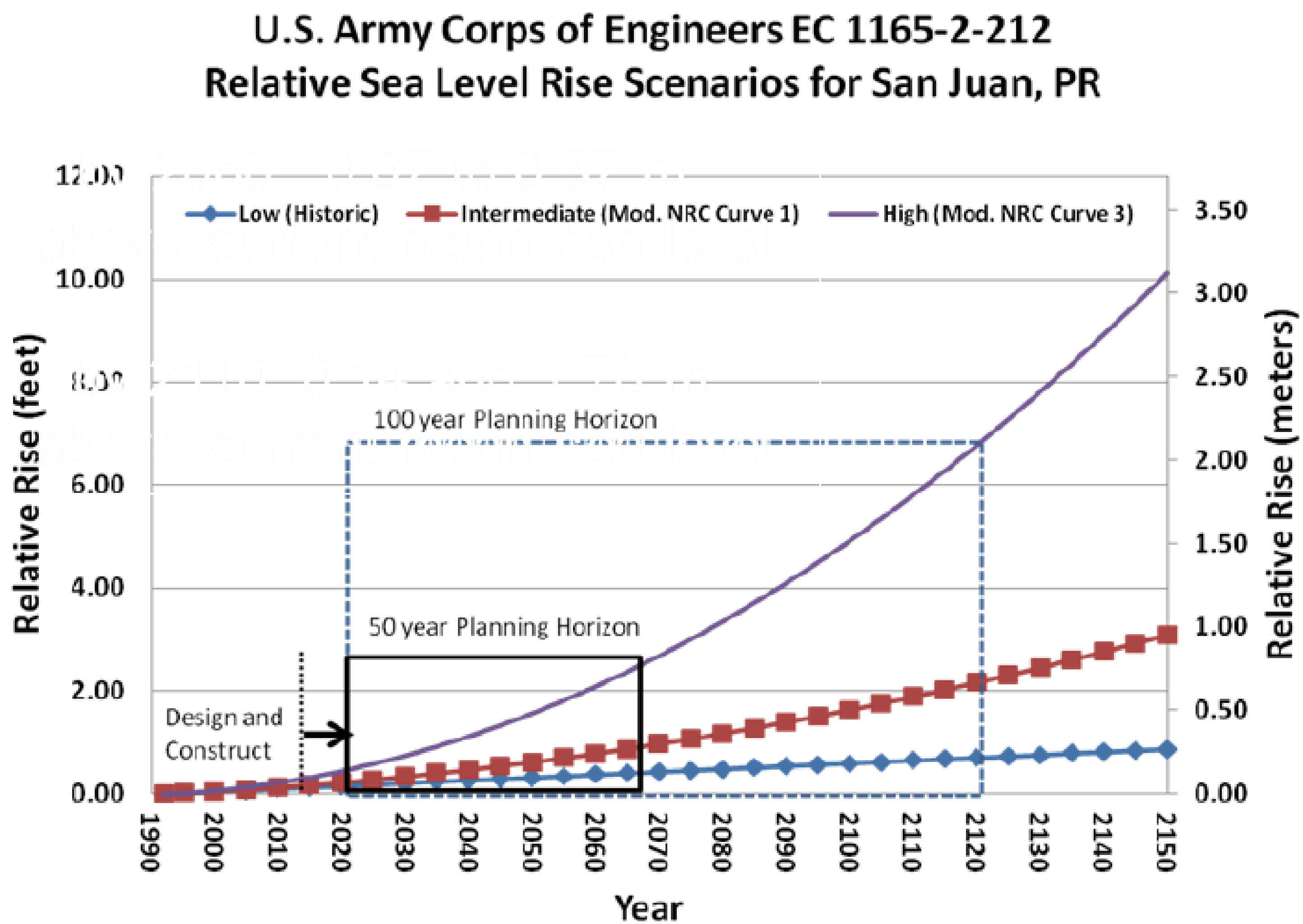
- Downscaled data not readily available for the territories

- Puerto Rico has developed its own climate report

Puerto Rico:

- 1.4 to 1.6 C since 1900
- 2 - 5C additional projected by 2100.
- 37% increase in very heavy precipitation, 1958 to 2007
- San Juan: 15% increase in # rainfall events greater than 78mm (3in) in 24 hrs. from 1955 to 2009.

Sea Level Rise Data for Puerto Rico



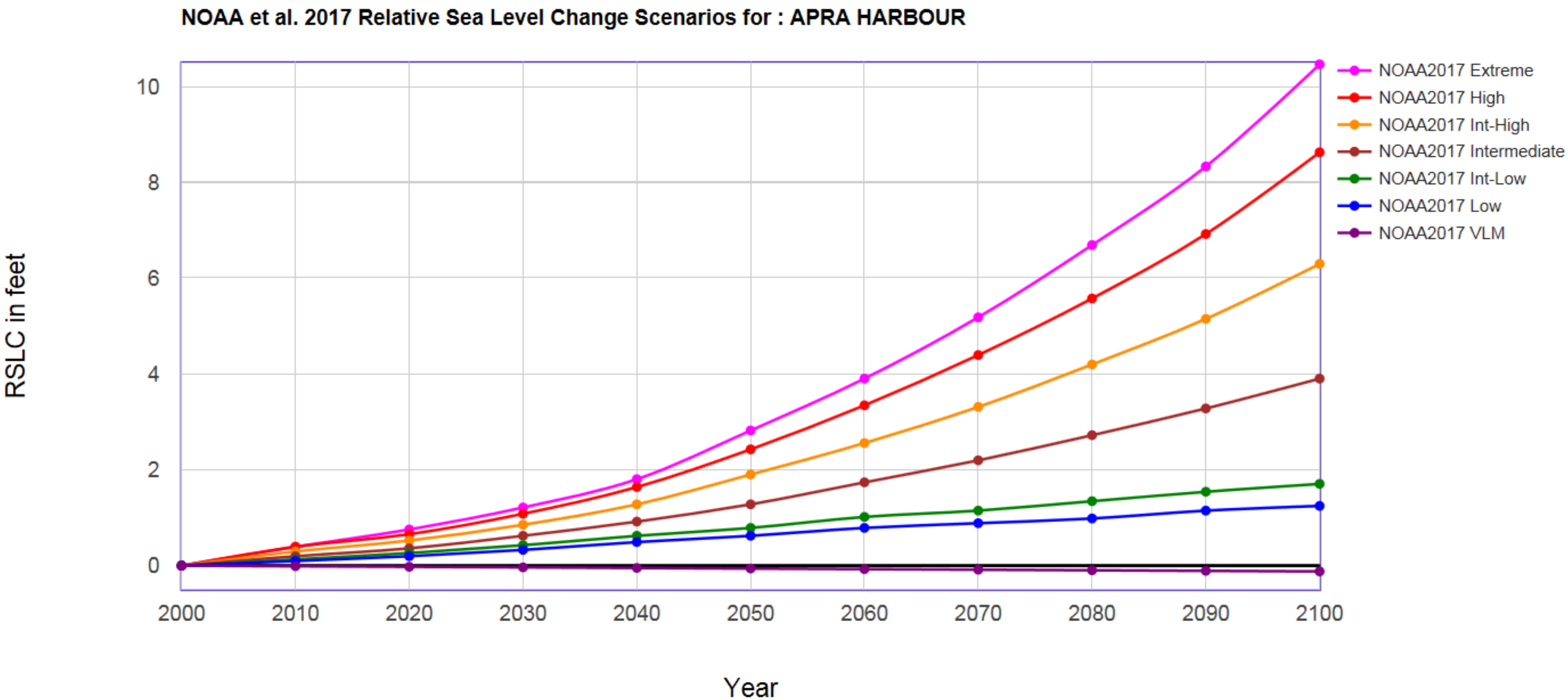
"Based on this information and future projections for sea level rise the PRCCC recommends planning for a rise of 0.5-1.0 meters by 2100."


San Juan
San Juan Antiguo
San Antonio
Aeropuerto de la Isla Grande
Santurce
Bahia de San Juan
Cataño
Hato Rey Norte
Hato Rey Central

PRCCC recommends planning for 0.5 to 1.0m sea level rise by 2100

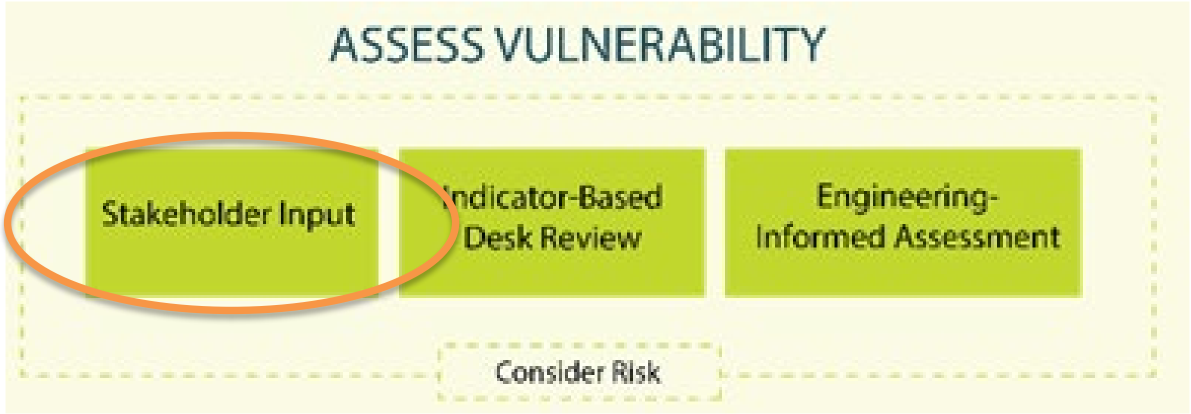
Map developed using Puerto Rico Climate Change Council Coastal Vulnerability Viewer
http://pr-ccc.org/prccc-coastal-vulnerability-viewer/

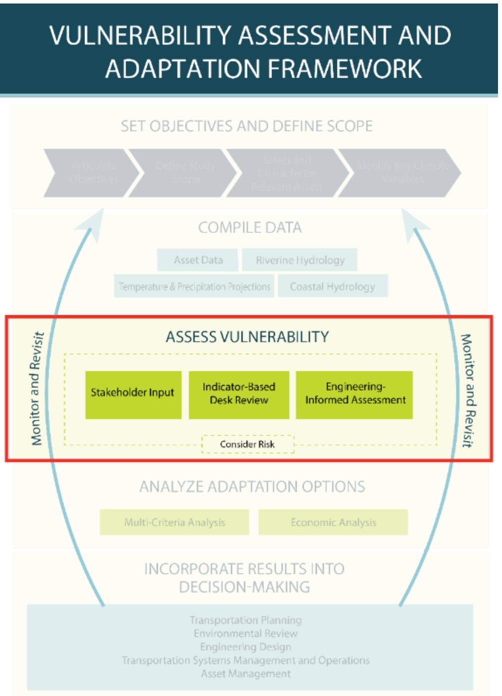
Sea Level Rise Scenarios for Guam



US Army Corps of Engineers Sea Level Rise Calculator:
http://corpsmapu.usace.army.mil/rccinfo/slc/slcc_calc.html

Assess Vulnerability





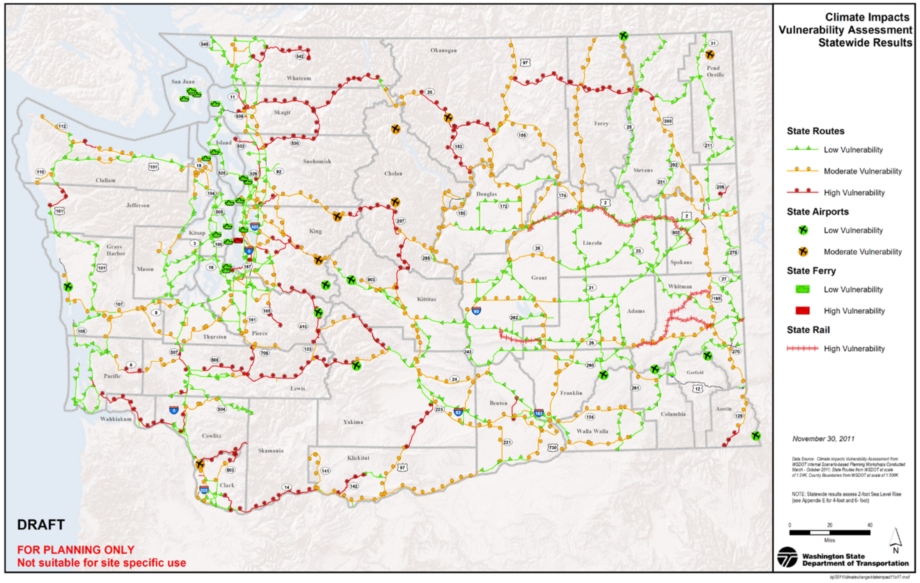
Framework describes three approaches:

1. **Stakeholder Input**
2. Indicator-Based Desk Review
3. Engineering-Informed Assessments

Stakeholder Input Approach

- Relies on **institutional knowledge** to identify and rate potential vulnerabilities
- Results are highly dependent upon:
  - the quality of facilitation,
  - composition of attendees, and
  - level of participation from experts
- Can help to create ownership and engagement among staff

Stakeholder Input Approach: WSDOT



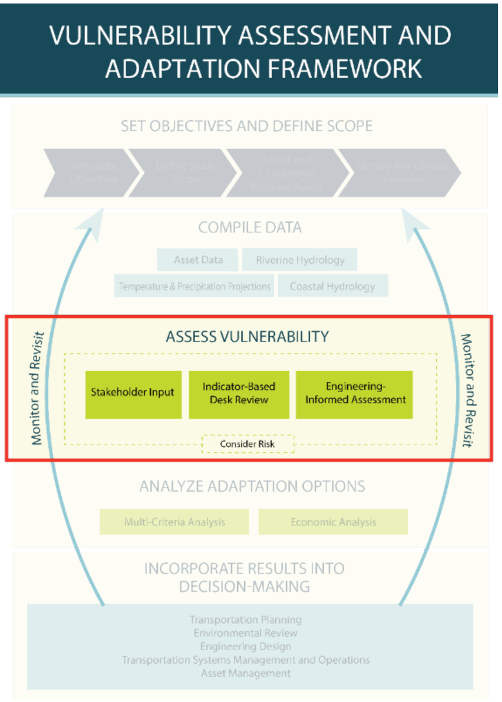
(Source: Washington State DOT)

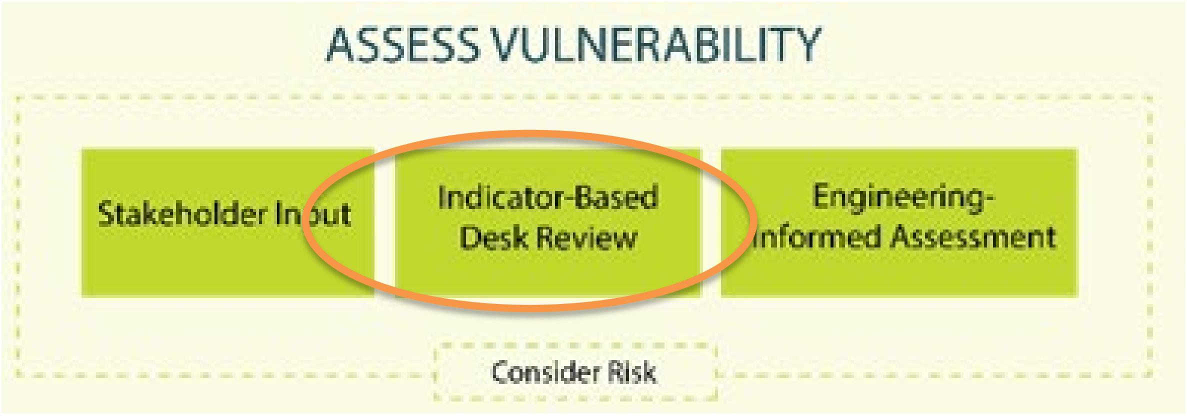
Stakeholder Input Approach: Oahu MPO

Asset	Overall Value	Impact to Society from:		
		Storm Surge	Sea Level Rise	Heavy Rain/Storm Events
Honolulu Harbor		Moderate	Low	Low
Honolulu International Airport				
TheBus (811 Middle Street)	High	Low	Low	Low
Oahu Baseyard (727 Kakoi Street)	Low	Low	High	Low
Honolulu International Airport and Access	High	High	Low	Low
Kalaeloa/Barbers Point				
Kalaeloa Airport	Low	Low	High	Low
Campbell Industrial Park	High	High	Low	Low
Kalaeloa Barbers Point Harbor	High	High	Low	Low
Three Waikiki Bridges	Moderate	High	High	Low
Farrington Highway on Waianae Coast	High	High	High	Low

- Held 2 day interagency workshop to select assets for further study
- Performed qualitative risk assessment on each asset
- Low budget
- Emergency management and interagency collaboration focus

Assess Vulnerability





Framework describes three approaches:

1. Stakeholder Input
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Indicator-Based Desk Review Approach

- Uses quantitative data to serve as **indicators.**
- Develop an overall **vulnerability score** for each asset by weighting and combining the **exposure, sensitivity, and adaptive capacity** scores.
- **VAST** is a spreadsheet tool to assist with the scoring process

Variable	Value for the Example Asset	Range of Values Across All Assets: Low	Range of Values Across All Assets: High	Scaled Value for the Ex Asset (0-100)	Variable Weight	Score
Sensitivity						
% change in design flow required for overtopping	-18%	-78%	2375%	98	60%	58.5
Channel condition rating	6	–	–	50	15%	7.5
Culvert condition rating	5	–	–	50	25%	12.5
			Sum of Sensitivity Variable Scores:			*78.5*
			Sensitivity Weight:			*33%*
			Final Sensitivity Score:			**25.9**
Exposure						
Stream velocity	7.01	0.74	37.53	17	20%	3.4
Previous flooding issues	1	0	1	100	35%	35
Belt width to span length ratio	3.68	0.32	209.24	2	10%	0.2
% forest land cover in drainage area	1.85%	0.00%	91.23%	2	10%	0.2
% of drainage area not lakes and wetlands	99.91%	97.71%	100.00%	96	10%	9.6
% drainage area urban land cover	4.00%	0.00%	53.52%	7	15%	1.1
			Sum of Exposure Variable Scores:			*49.5*
			Exposure Weight:			*33%*
			Final Exposure Score:			**16.3**
Adaptive Capacity						
Average Annual Daily Traffic (AADT)	5,700	90	49,200	11	35%	4
Heavy Commercial Average Daily Traffic (HCADT)	610	5	5,900	10	25%	2.6
Detour Length	0.6	-0.37	20	4	35%	1.3
Flow control regime	0	0	1	0	5%	0
			Sum of Adap. Cap. Variable Scores:			*7.8*
			Adaptive Capacity Weight:			*33%*
			Final Adaptive Capacity Score:			**2.6**
			OVERALL VULNERABILITY SCORE:			**45**

Indicator-Based Desk Review Approach: South Florida

Exposure indicators:

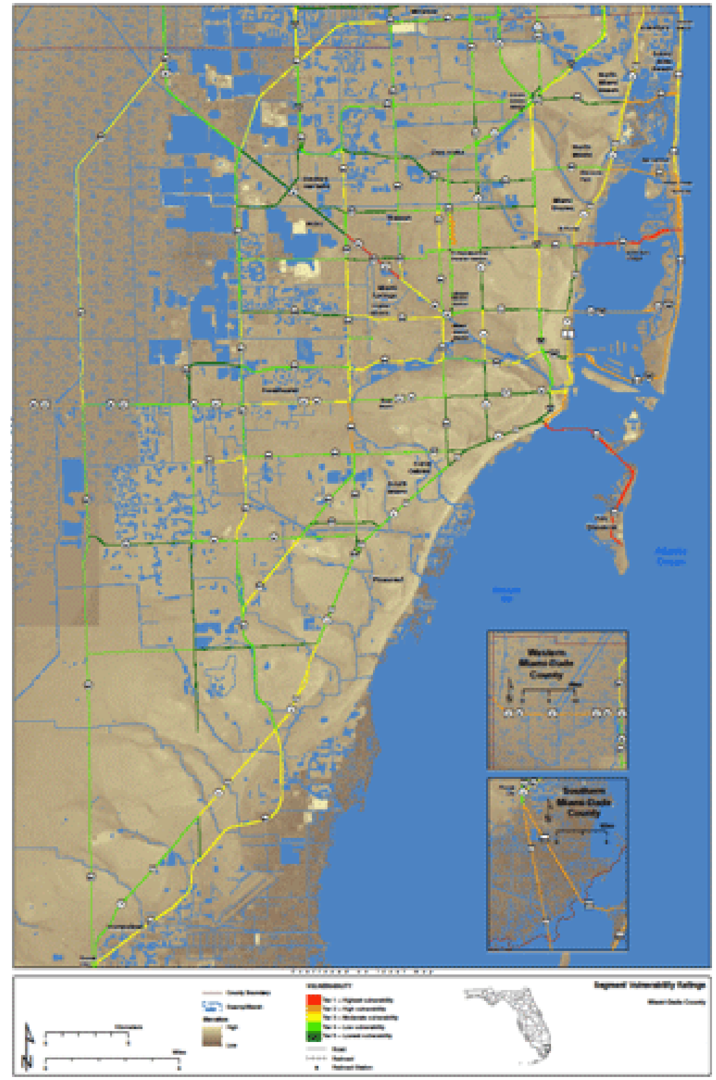
i. Percentage of the segment permanently inundated by 1, 2, or 3 feet of SLR by 2100
ii. Current “flood inundation exposure index”
iii. Future “flood inundation exposure index”

Sensitivity indicator:

i. Substructure condition rating

Adaptive capacity indicators:

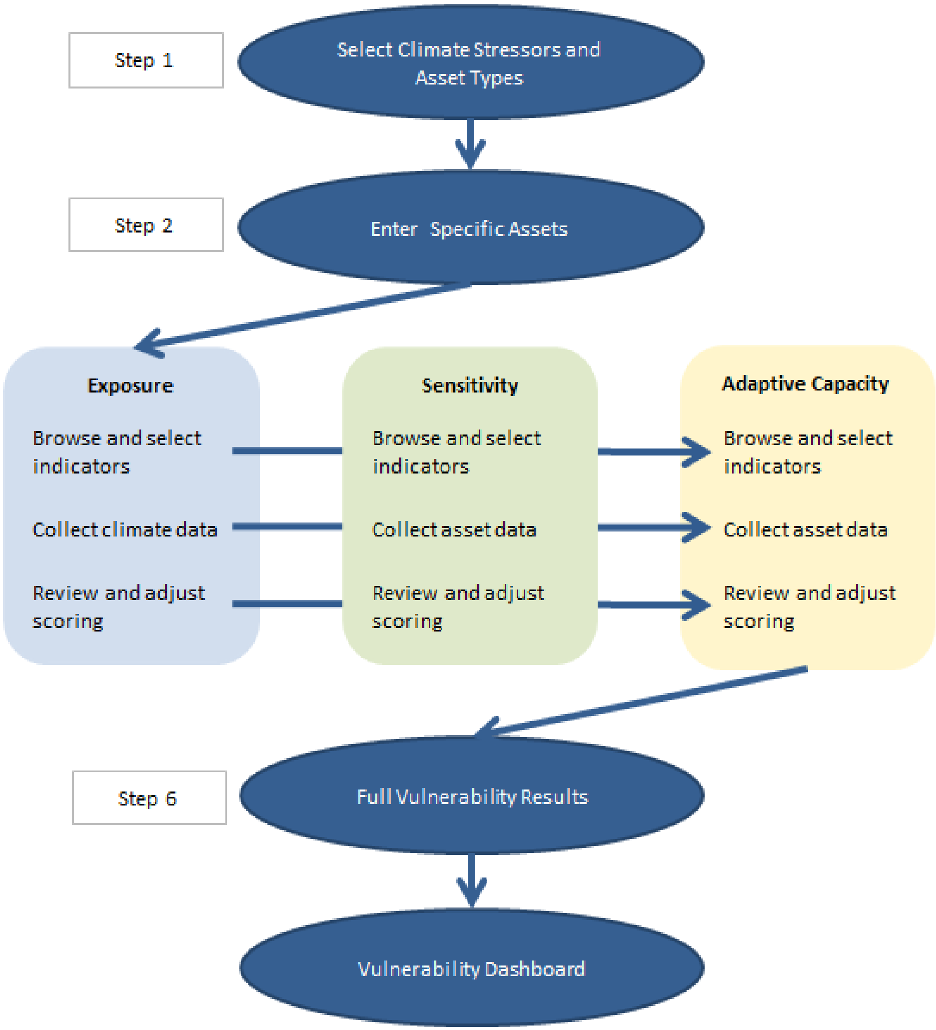
i. Average annual daily traffic
ii. Detour length
iii. Tri-Rail ridership



Vulnerability ratings for roads and rail track in Miami-Dade County (Source: Broward MPO).

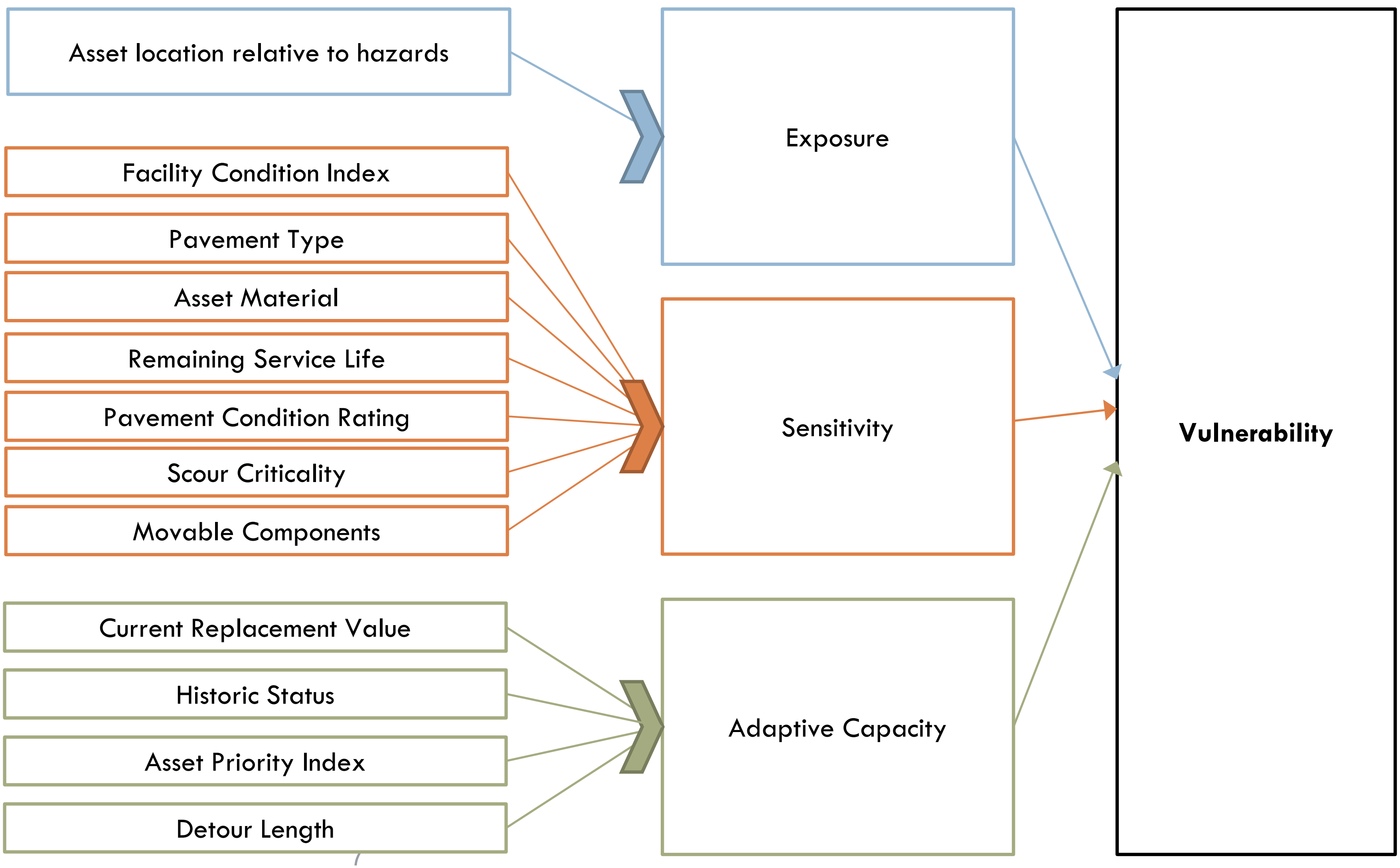
Indicator Approach: Vulnerability Assessment Scoring Tool (VAST)

- User makes decisions, enters information at each step
- Tool provides step-by-step guidance through the process
- Includes a database of proxy indicators

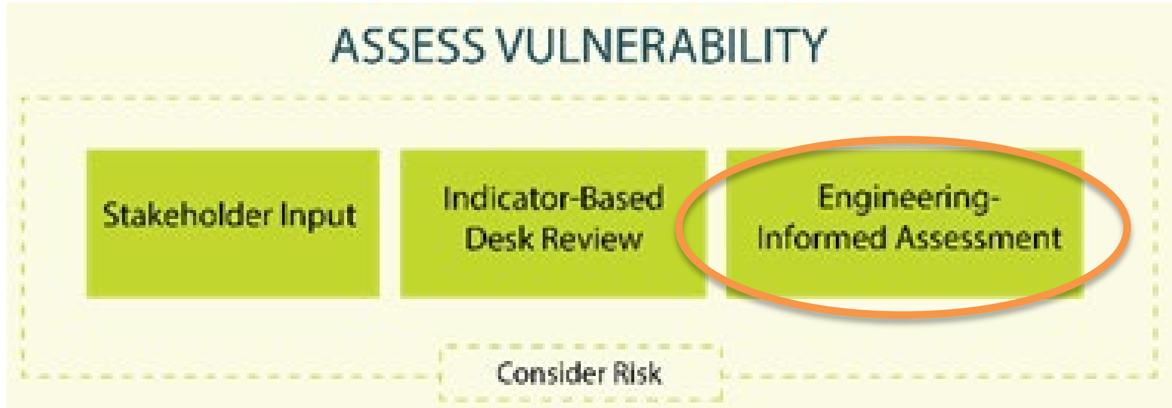


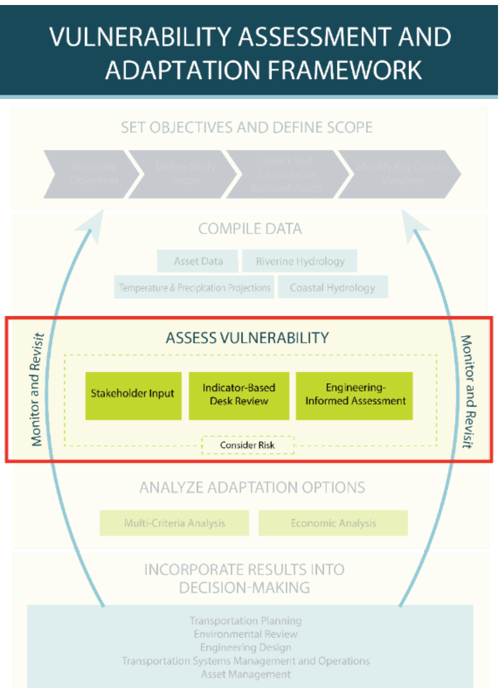
https://www.fhwa.dot.gov/environment/sustainability/resilience/tools/

Indicator Approach: Vulnerability Assessment Scoring Tool (VAST)



Assess Vulnerability





Framework describes three approaches:

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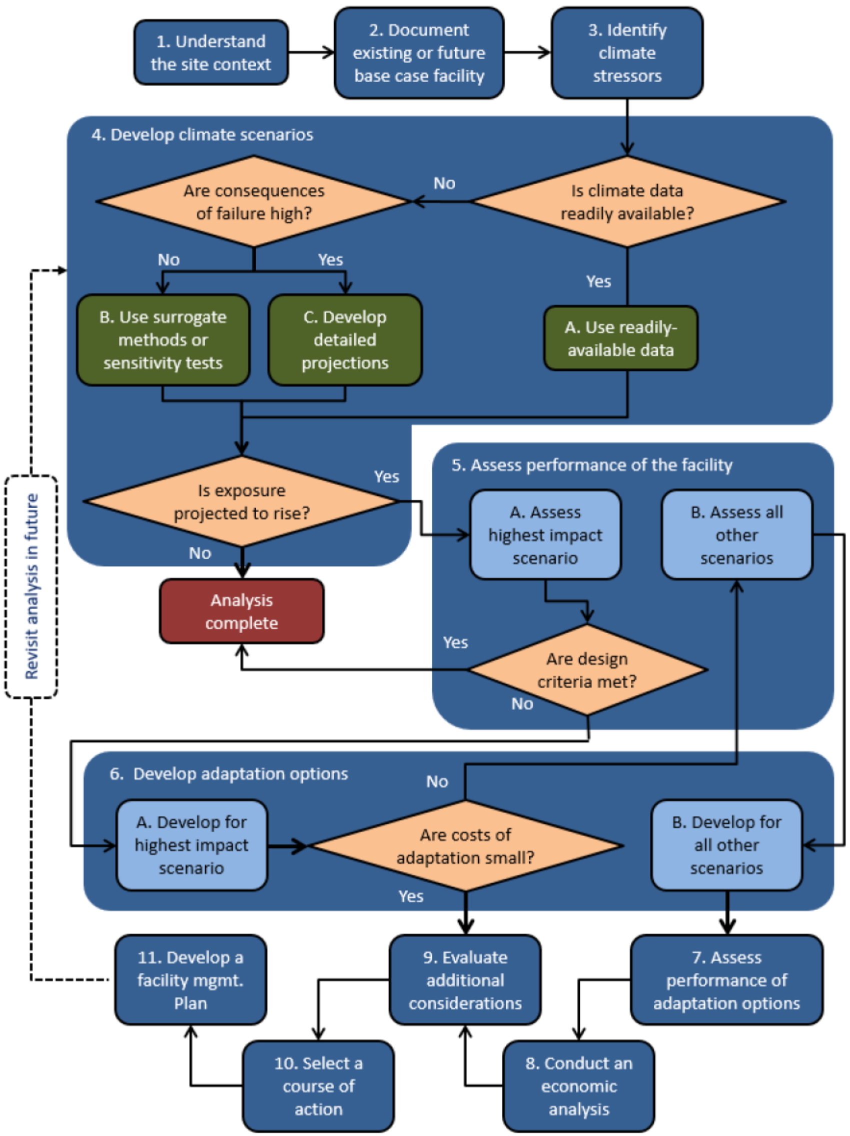
3. **Engineering-Informed Assessments**

Engineering Informed Assessment: ADAP



Adaptation Decision-making Assessment Process (ADAP)

1. Understand Site Context
2. Document Existing Facility
3. Identify climate stressors
4. Develop climate scenarios
5. Assess performance of facility
6. Develop adaptation options
7. Assess their performance
8. Conduct economic analysis
9. Evaluate additional considerations
10. Select course of action
11. Develop facility management plan

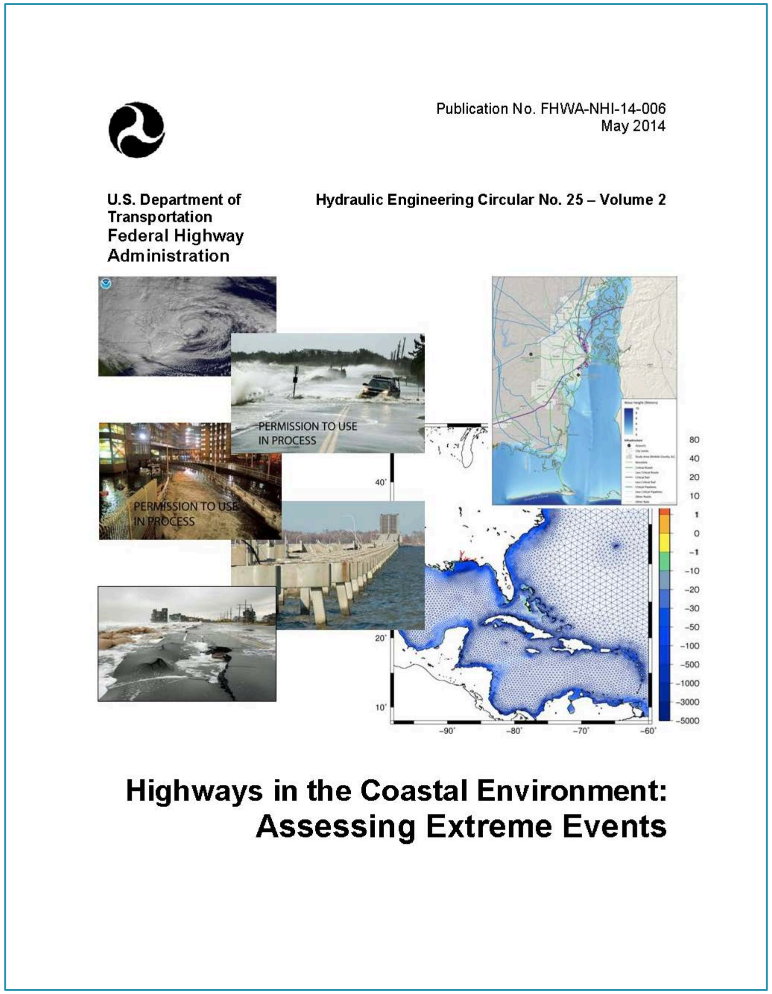
Engineering Informed Assessment: Coastal Hydraulics

Coastal Climate Change Adaptation Measures.
Source: SCE (left); FDOT (right)

Sensitivity to Climate Change

- Extreme water levels due to sea level rise and storm surge can damage coastal assets by:
  - Wave attack
  - Overwashing/overtopping
  - Shoreline erosion/recession
  - Wave runup
  - Waves on surge

HEC-25 - Coastal Guidance



HEC-25, Volume 2: Highways in the Coastal Environment: Assessing Extreme Events

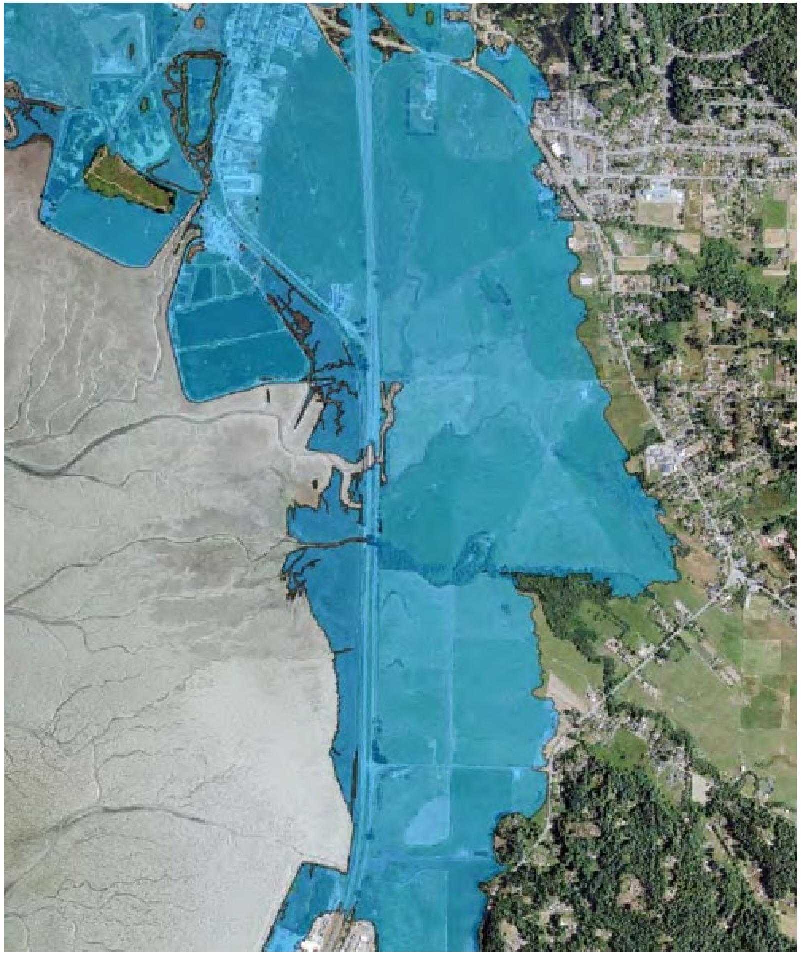
- How to incorporate extreme events and climate change into coastal highway design

- 3 analysis approaches (low, medium, high level of effort)
  1. Use existing data and resources
  2. Modeling of storm surge and waves
  3. Modeling in a probabilistic risk framework

Coastal Hydrology: Sea Level Rise

Caltrans:

- Used data from NOAA's Sea Level Rise Viewer web mapping tool
- Used daily high tide and annual high tide as approximations to identify sea level inundation areas

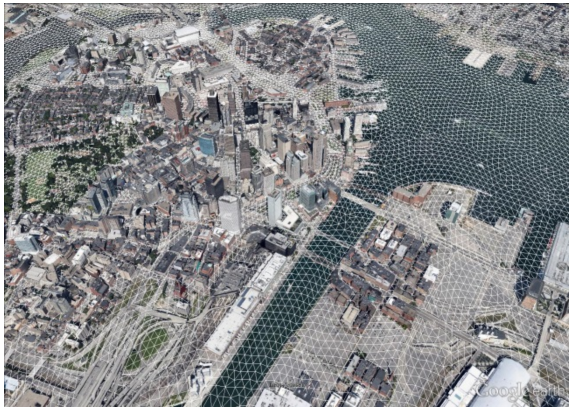


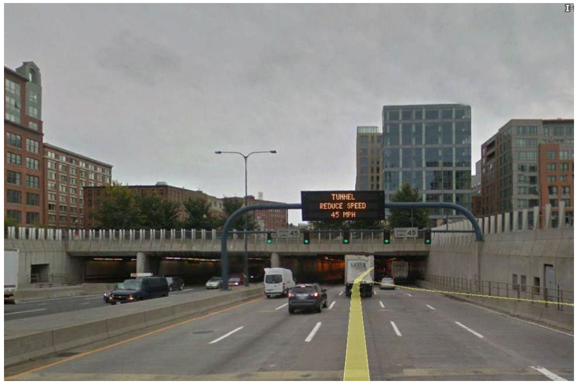
Modeled Flooding Conditions Caused by Sea Level Rise on California Highway 101. (Source: Caltrans)

Example of Coastal Hydrology Analysis: Massachusetts State DOT

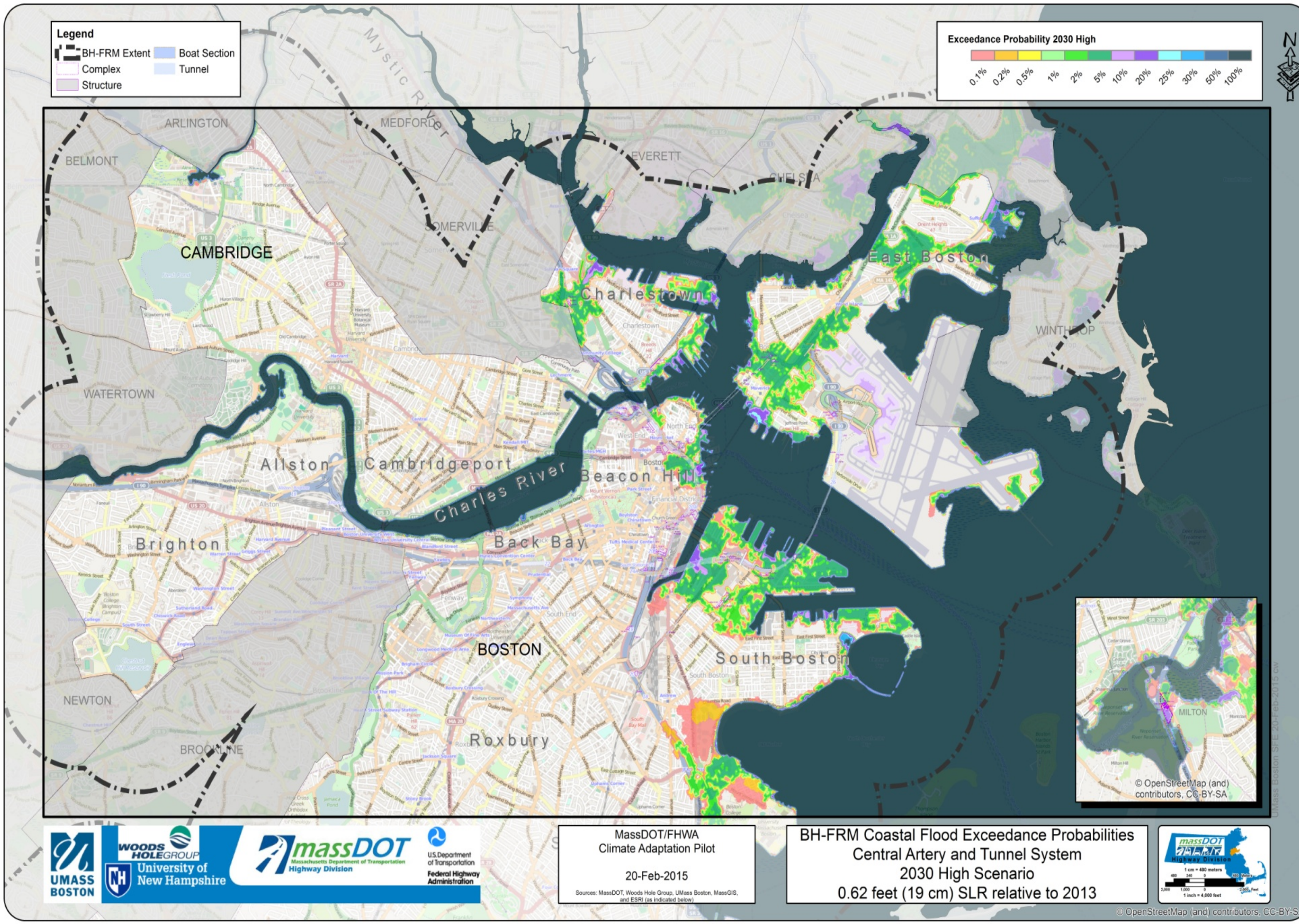
Boston Harbor Flood Risk Model

- Simulated thousands of storms to get probabilities of flooding around the Central Artery Tunnels today and in the future (Monte Carlo analysis)
- Included sea level rise scenarios for 2013, 2030, and 2100
- Simulated hurricanes, tropical storms, nor'easters (ADCIRC model)
- Modeled wave impacts (SWAN model)
- Included effects of tides, storm surge, wind, river discharge
- Included effects of wetlands and barrier islands
- Output flooding pathways and depths
- Maps for 1000 yr storm, 500 yr storm, 100 yr storm, 50, 20, 10, 5, 2, and 1 yr storms

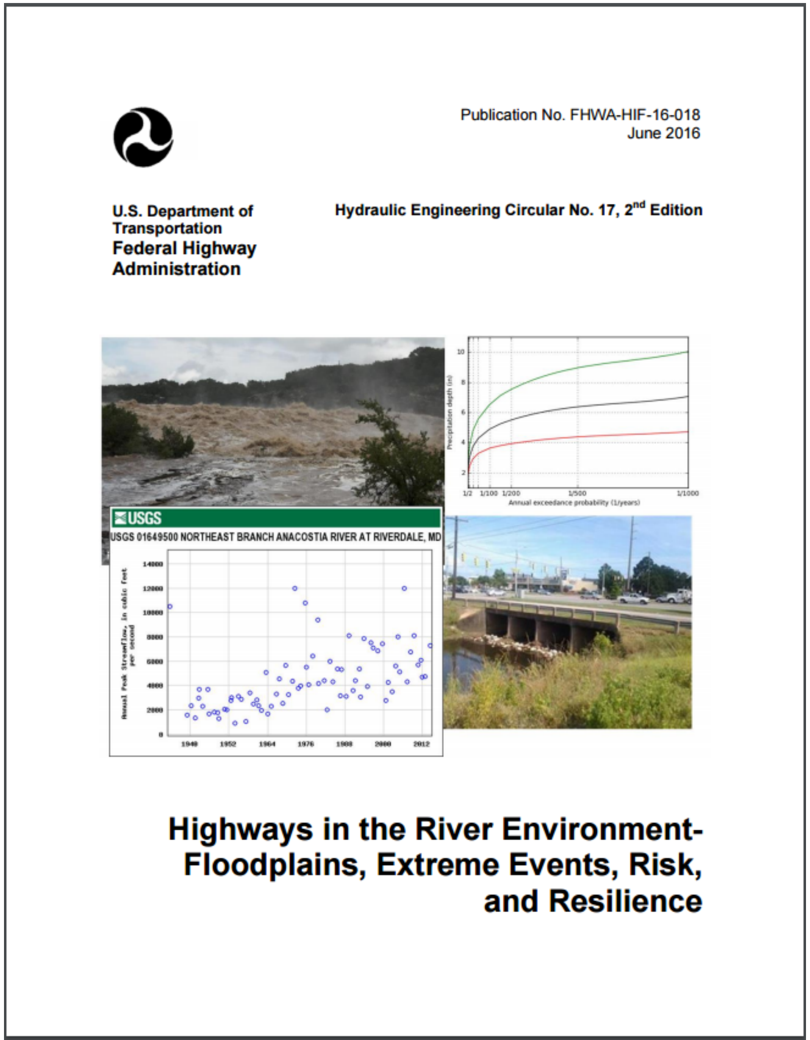




Example of Coastal Hydrology Analysis: Massachusetts State DOT



HEC-17 – Riverine Environment


Publication No. FHWA-HIF-16-018
June 2016

U.S. Department of Transportation
Federal Highway Administration

Hydraulic Engineering Circular No. 17, 2nd Edition

Highways in the River Environment- Floodplains, Extreme Events, Risk, and Resilience

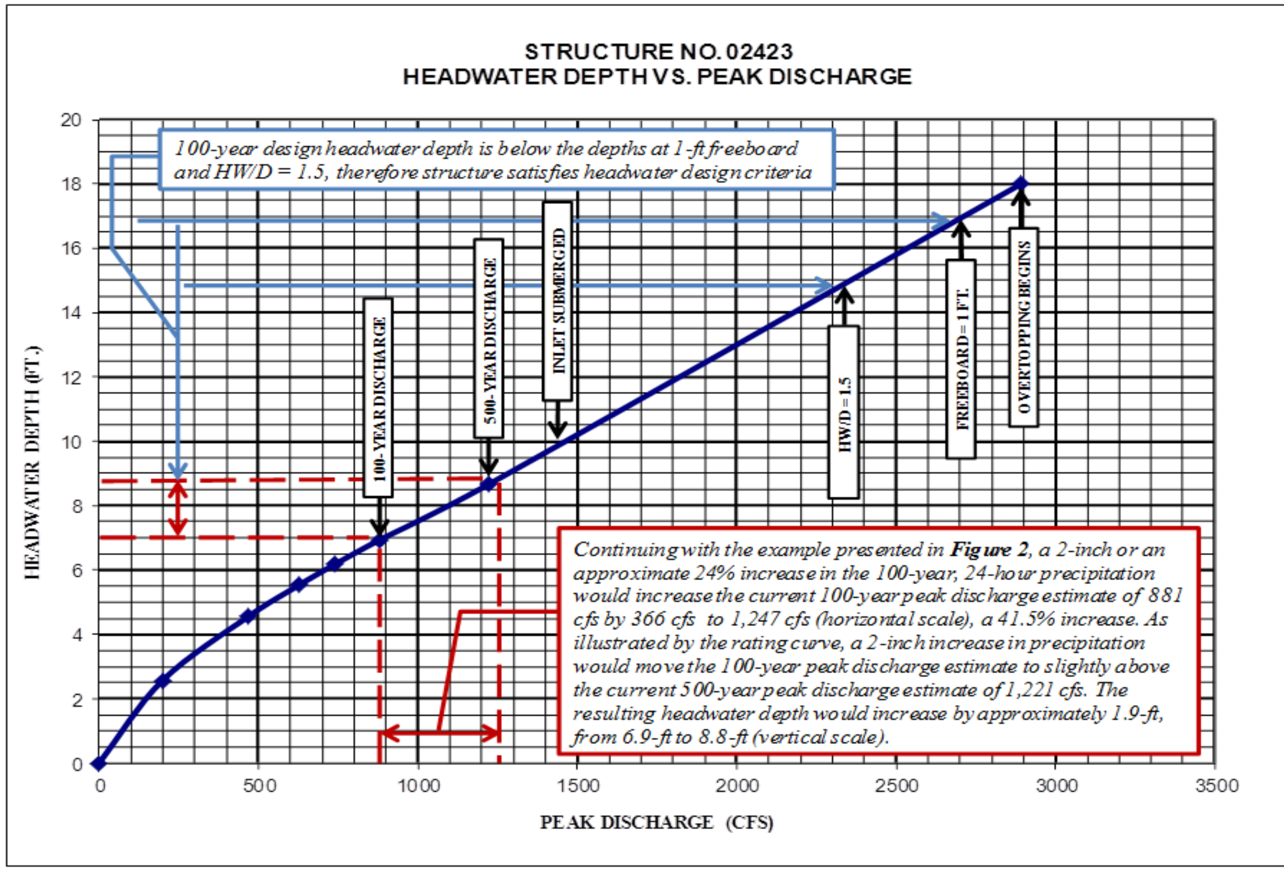
HEC-17, Highways in the River Environment: Floodplains, Extreme Events, Risk, and Resilience

- 5 levels of analysis
  1. Historical Discharges
  2. Historical Discharges + Confidence Limits
  3. Precipitation Projection Trend Test
  4. Projected Discharges using CMIP tool
  5. Customized Projected Discharges w/Climate Scientist
- RCP 6.0 and RCP 8.5 recommended

Riverine Hydrology

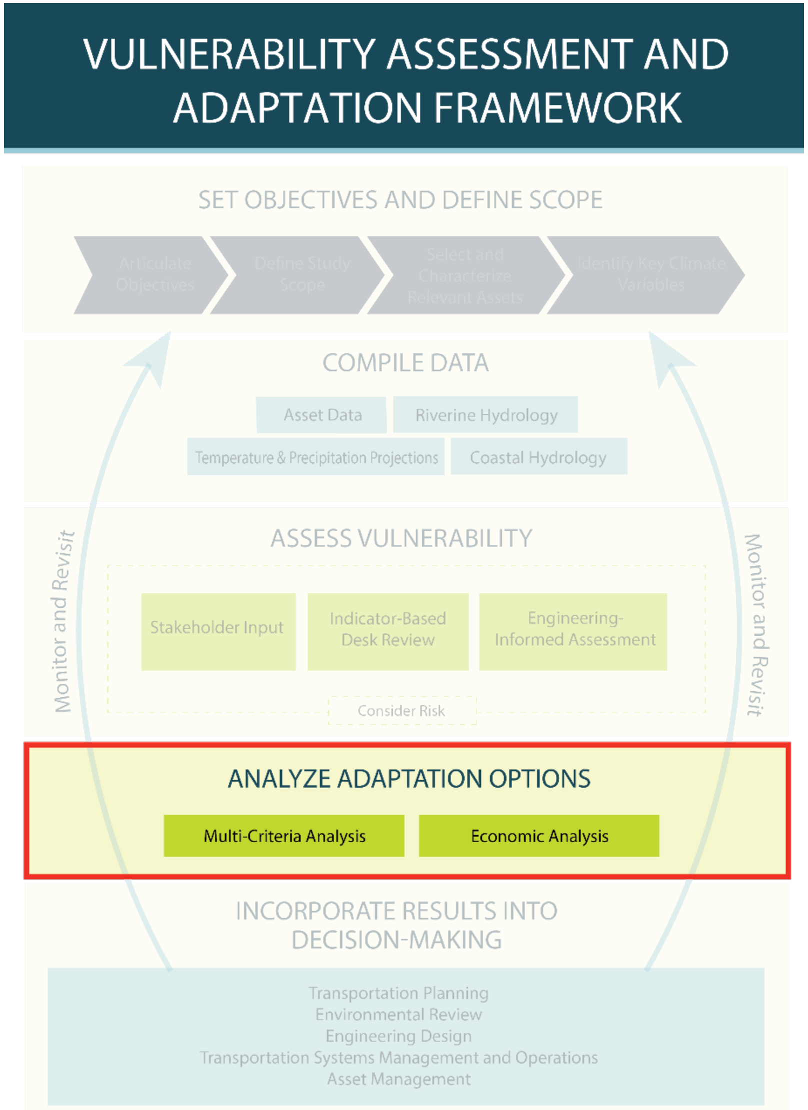
Connecticut DOT:

- Analyzed inland flooding associated with extreme rainfall events
- Evaluated the hydraulic adequacy of the structures and developed performance curves



Flood depth vs. peak discharge for a structure in Connecticut (Source: Connecticut DOT).

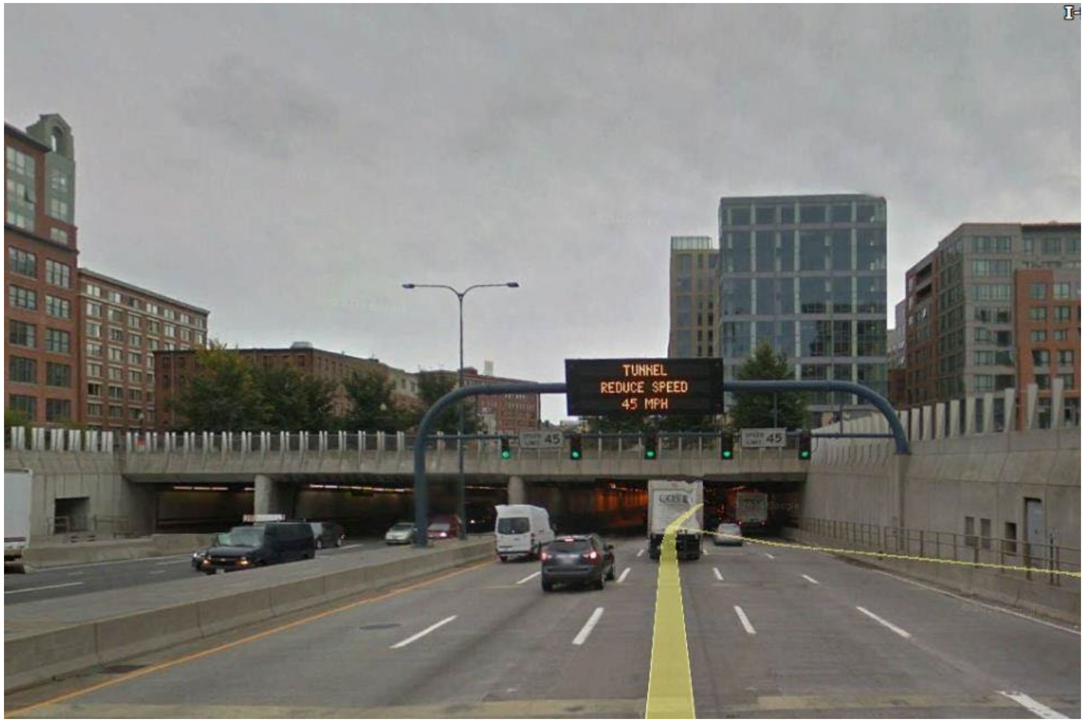
Analyze Adaptation Options



- Potential adaptation solutions:
  - Engineer new assets
  - Retrofit existing assets
  - Increase redundancy of the system
  - Relocate assets
  - Institute intensive maintenance schedules
  - Improve operations plans for weather emergencies

Example of Coastal Climate Change Analysis: Massachusetts State DOT

- Developing local and regional solutions
  - Temporary flood barriers
  - Watertight gates
  - Flood walls to block regional flood pathways



Street view of I-93 Northbound and Southbound Tip O'Neill Tunnel Portals at Zakim Bridge (from Google Earth) Source: MassDOT-FHWA Pilot Project Draft Report.

Adaptation Options: Nature-Based Solutions

Can protect highways from coastal flooding by using or mimicking natural processes.

Integrated Approach:

- **Structural** (e.g. armoring, raise road, widen culvert, pavement materials)
- **Natural features**: created through the action of physical, geological, biological, and chemical processes over time (e.g. wetlands, dunes)
- **Nature-based features**: created by human design, engineering, and construction to provide risk reduction in coastal areas by acting in concert with natural processes (e.g. wetland restoration, artificial reefs, beach nourishment)
- **Non-structural** (e.g. land use policies, infrastructure siting, insurance policies)

Credit: MTC

Photo Credit: Suzanne Kaspar, Mobjack Bay, VA

Adaptation Options: Nature-Based Solutions Considerations

Why talk about nature-based solutions (also called **green infrastructure**)?
May be cheaper; effective; more adaptable; and benefit habitat, fisheries, recreation

Advantages

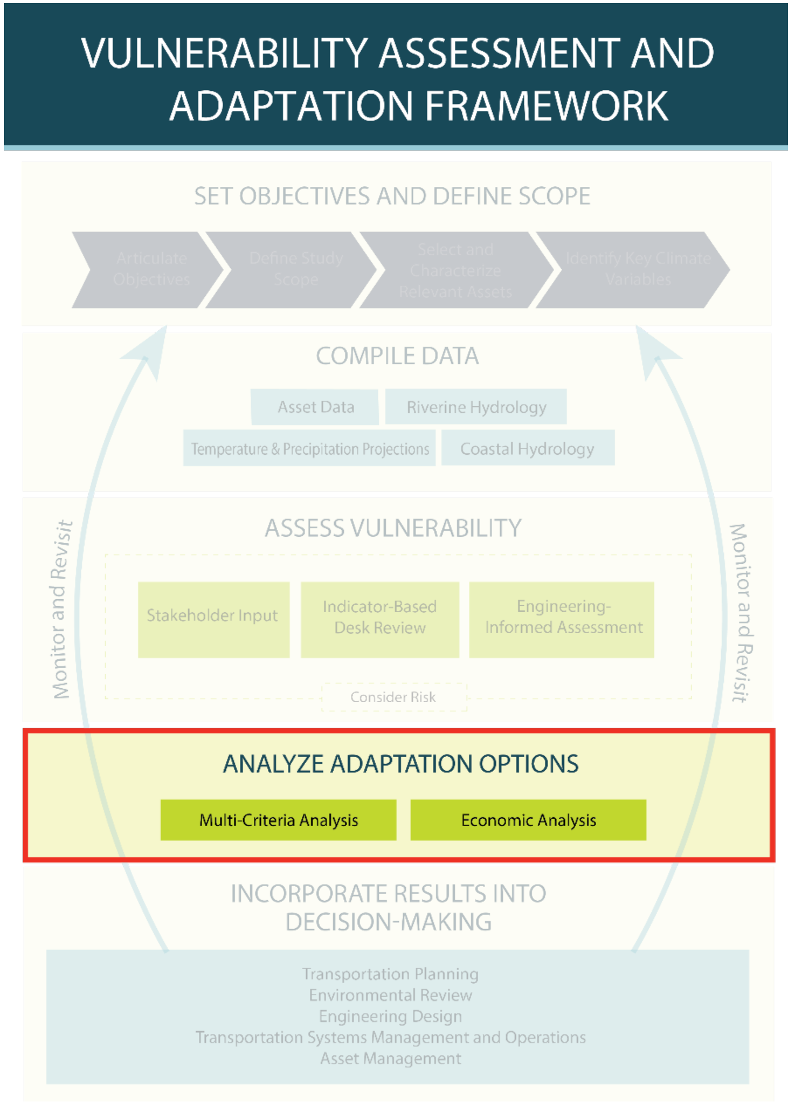
- Opportunity to meet multiple goals
  - Protect road
  - Protect surrounding community
  - Mitigation required under NEPA
  - Fits well with Eco-Logical approach
  - Habitat creation

Photo credits: Tina Hodges

Gaps

- Need data on costs and benefits of nature-based solutions compared to traditional projects
- Nature-based solutions may need more space than is in the ROW - need to partner with other landholders.
- Need information on maintenance

Adaptation Options: Evaluation and Selection



- Framework describes two methods to evaluate and prioritize adaptation options:
  - Multi-criteria analysis
  - Economic analysis

Adaptation Options: Multi-Criteria Analysis

Caltrans

Assessment Criteria	Value	Comments
Assumed Design Service Life	100 years	High end of the design life of an earthen structure. Assumed structure is properly maintained to protect integrity, and regular roadway overlays are implemented.
Assumed Total Capital Investment	$ 49,810,000	Assumed road is raised to above flood hazard elevation. Due to limited data on coastal flooding elevations, one cost was developed for 2050 and 2100
Usable Life	3: Surpasses	The usable life is beyond the 2100 scenario, thus, the option surpasses the climate horizon in its useful life
Level of Performance	3: Enhanced	This option provides enhanced performance relative to the existing condition.
Flexibility	1: Unlikely	With the costs and effort involved in constructing the new roadway on the raised fill prism, it would be difficult to add additional height in the future.
Environmental Considerations	-2: Some net impact	It is assumed that some wetlands would be impacted with a bigger fill footprint needed for an elevated road, and it would be more that raising the height of protective structures.
Social Considerations	3: Some net improvement	The use of the highway would be maintained, which provides a social benefit, however this option does not necessarily protect other social assets, such as telephone, gas, and water lines.

Highway 20/County Road 407 Example Scoring Sheet for Adaptation Option 1: Elevate the Infrastructure Above the Impact Zone, Lake County. California (Source: Caltrans)

Adaptation Options: Economic Analysis

- Framework describes three types of economic analysis:
  - **Economic Impact Analysis**: evaluate impacts of adaptation options on the local, regional, or national economy.
  - **Benefit Cost Analysis**: evaluate direct and indirect benefits and costs to travelers and businesses.
  - **Life-Cycle Cost Analysis**: focuses primarily on identifying the long-term costs to transportation agencies of different alternatives.

Adaptation Options: Benefit Cost Analysis

Costs of Adaptation Measures (Costs Incurred Relative to No-Adaptation Option)	Benefits of Adaptation (Costs Avoided Relative to No-Adaptation Option)
Costs to Agency: • Increased upfront engineering, land acquisition, and construction costs • Increased routine operation and general management costs • Increased reconstruction/rehabilitation costs **Costs to Users:** • Increased travel delay, safety, and vehicle operating costs during initial construction, maintenance activities, and reconstruction/rehabilitation	**Direct Benefits to Agency:** • Reduction in physical damages, repair costs • Reduction in operations and management **Direct Benefits to Primary Users:** • Reduction in travel time costs from detours • Reduction in vehicle operating costs from detours • Reduction in disruptions to freight movement • Minimized cost of potential injury **Indirect Benefits to Non-Primary Users:** • Impacts of lost access to businesses and government fees/taxes on revenues • Impacts to nearby properties (e.g., flooding caused by an undersized culvert)

Adaptation Options: MnDOT Example

Benefit-Cost Analysis

- Evaluated the performance of two large culverts under three climate scenarios
- Developed one adaptation option for each climate scenario
- Conducted a benefit-cost analysis to assess the physical damage and social costs of each adaptation option

Source: MnDOT

EXERCISE #2
VULNERABILITY ASSESSMENT APPROACH

What approach will you take? How might you come up with data?

Project-Level Case Studies

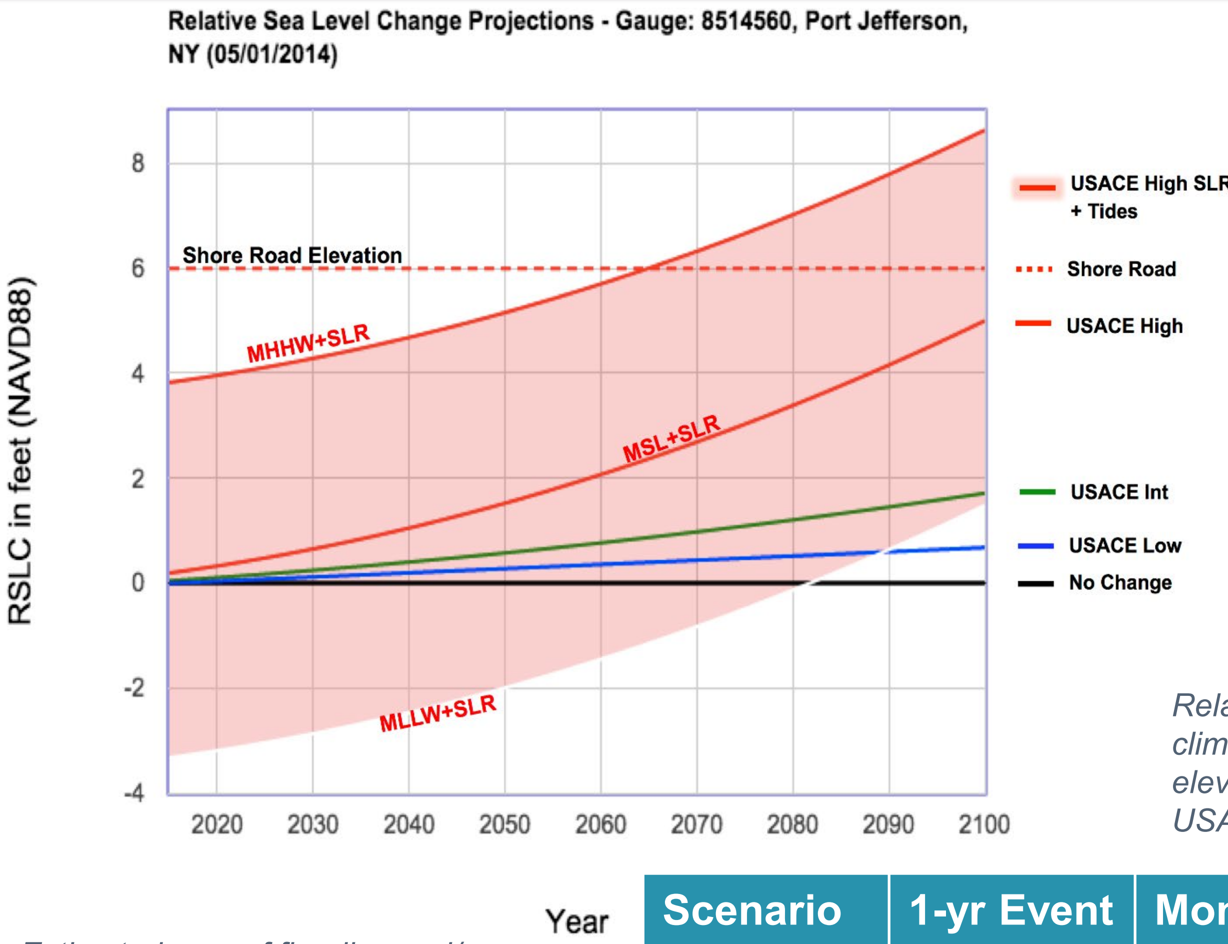
Living Shoreline along Coastal Roadways Exposed to Sea Level Rise

Brookhaven, NY
https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/teacr/ny_shore_road/

Map showing the location of Shore Road.
Source: Google Maps

Source: South Coast Engineers

Analytical Approach



Used sea level rise projections and local data to determine the year when the roadway would be inundated and the potential for wave damage.

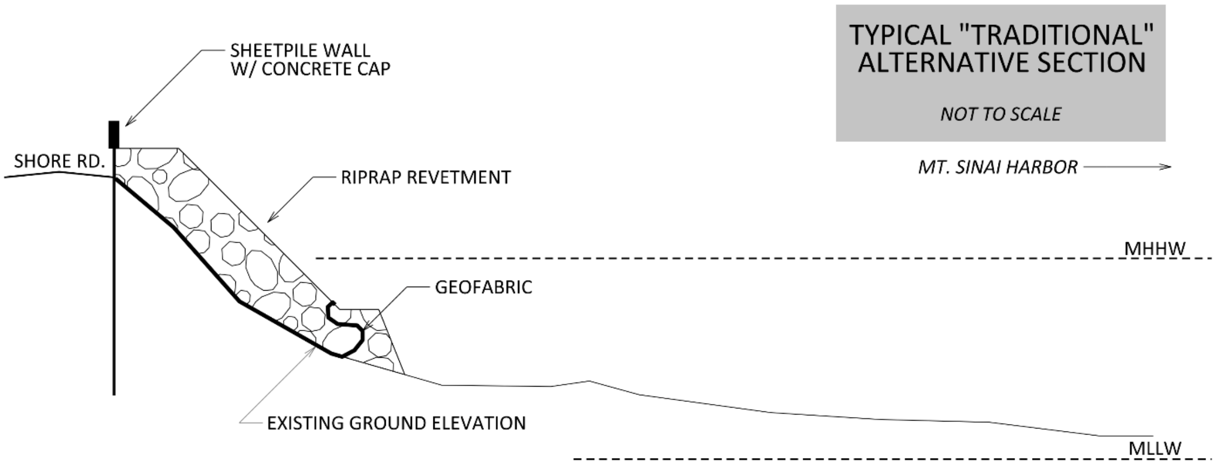
Relative sea level rise projections for three climate scenarios from 2015-2100 and elevation of pavement (dotted line). Source: USACE

Estimated year of flooding and/or damage.

Scenario	1-yr Event Flooding	Monthly Flooding	Daily Flooding	Wave Damage
USACE Low	2025	2270**	2300**	2080
USACE High	2015*	2060	2065	2025

**Indicates that asset currently floods.*
***Years beyond 2100 are reported for comparison only and these values should be interpreted as "not by 2100."*

Adaptation Options



Traditional Protection

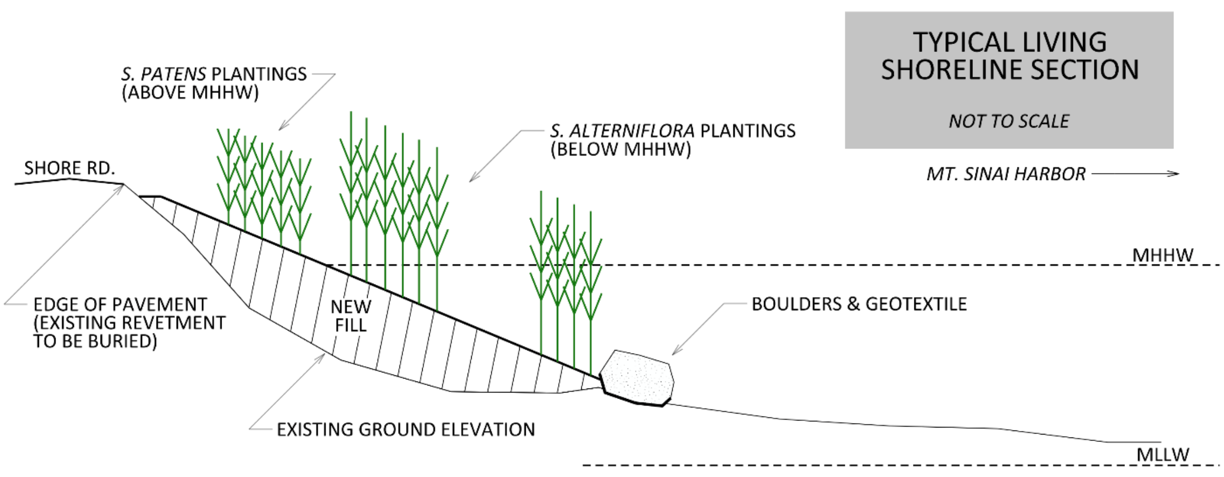
- Delay onset of daily nuisance flooding by 15 years
- $1.3 million

(Left) Diagram of traditional roadway embankment armoring and flood protection

Living Shoreline

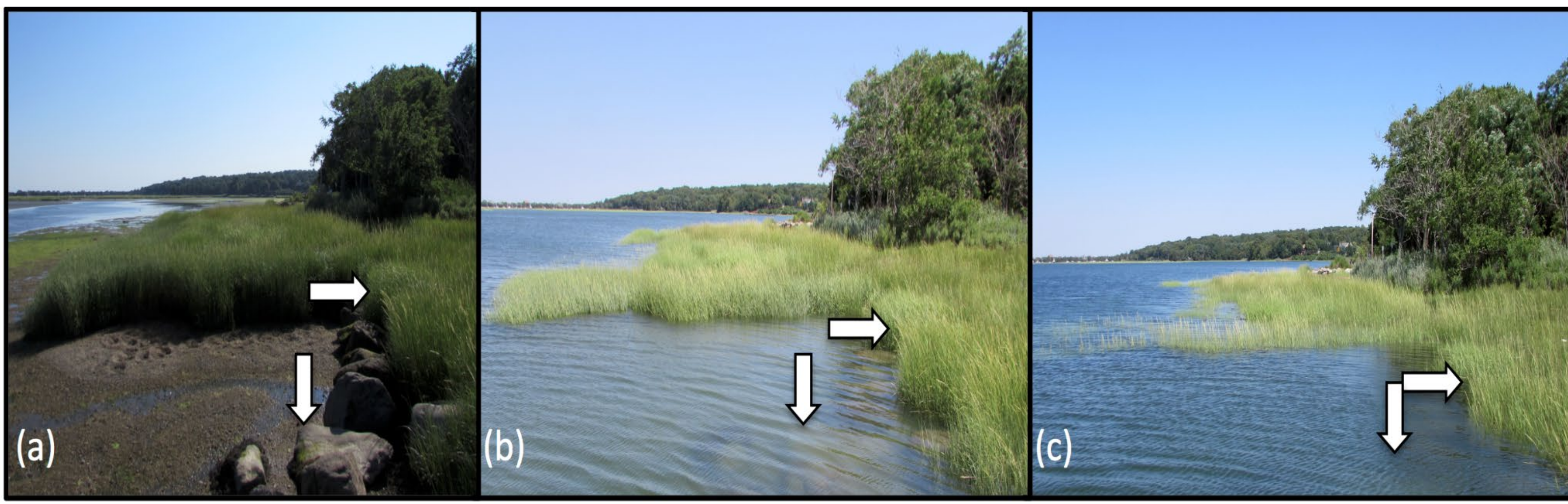
- Reduce wave damage
- $0.5 million

(Right) Diagram of constructed marsh profile.



Preferred Course of Action

- Living shoreline can protect road from erosion (from wave action at high tide), and also improve habitat and water quality – at lower cost than traditional protection.
- Can increase redundancy by burying the existing seawall/revetment.



Existing marsh site near Satterly Landing shown at (a) low tide, (b) near high tide, and (c) at high tide. Source: Bret Webb

Barrier Island Roadway Overwashing from Sea Level Rise and Storm Surge

Choctawhatchee Bay, Florida
https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/teacr/fl_us_98/

Map of the project area with the highway US 98 highway segment in blue. Source: South Coast Engineers and Ersi's World Imagery

Photograph of the north side of the US 98 eastbound travel lanes along Choctawhatchee Bay. Source: South Coast Engineers

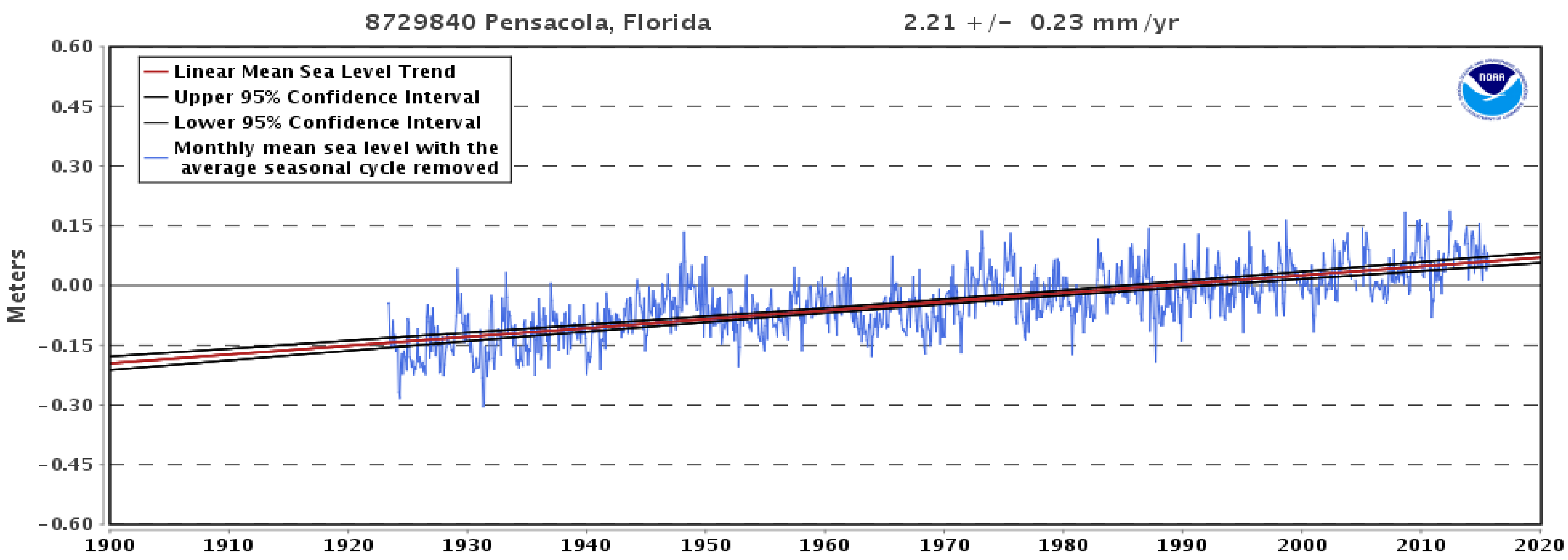
Climate Stressors and Scenarios

Storm Return Period	Estimated Storm Surge Elevation (NAVD)
5 – year	4.2 feet (1.3 m)
10 – year	5.9 feet (1.8 m)
15 – year	7.0 feet (2.1 m)
20 – year	7.7 feet (2.3 m)
25 – year	8.1 feet (2.5 m)

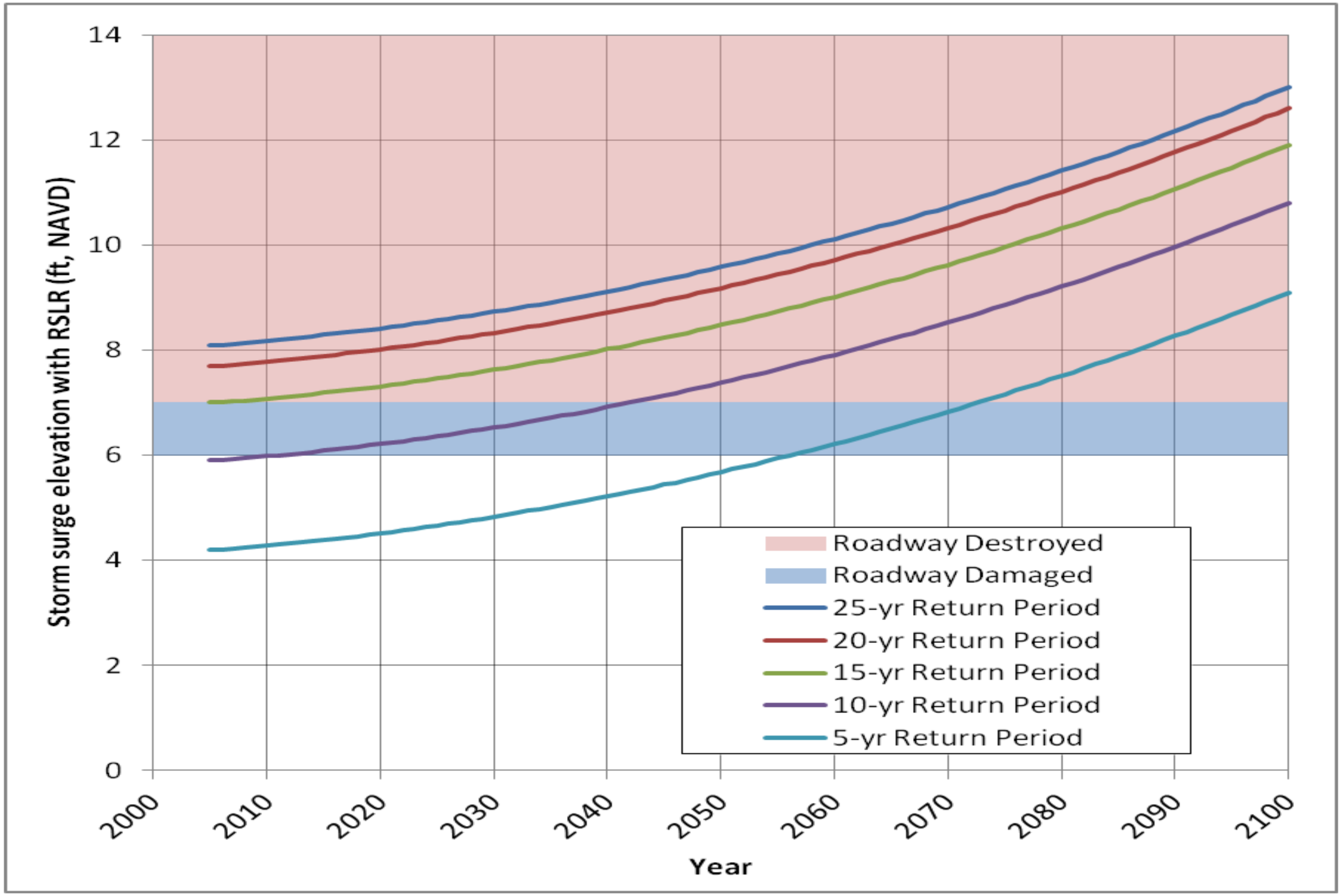
Considered climate change projections for:

- Storm Surge
- Sea Level Rise

(Left) Storm surge elevation estimates for US 98. Source: USACE Sea Level Change Curve Calculator
(Below) Historic relative sea level rise data for Pensacola, FL. Source: NOAA Tides & Currents



Analytical Approach

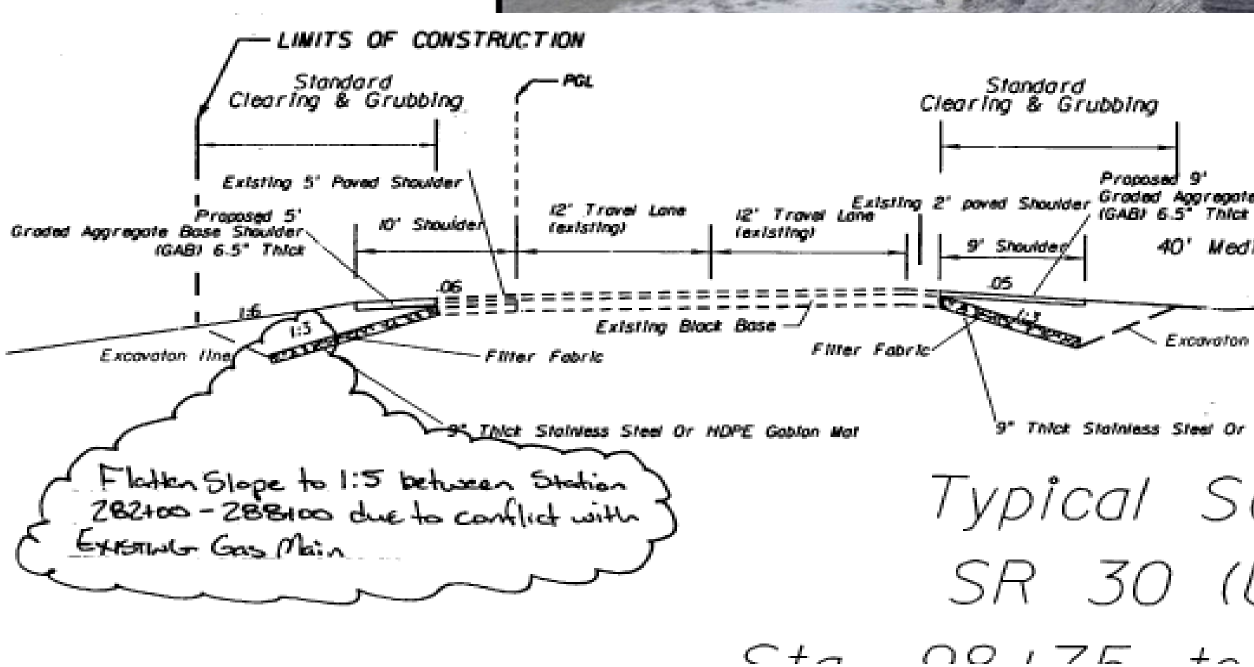


Storm surge elevations over time under a high (4.9 feet by 2100) relative sea level rise scenario.

Adaptation Options

Range of possible options:

- Buried gabion mats (stainless steal cages filled with rocks)
- Sheet-pile walls with toe scour protection

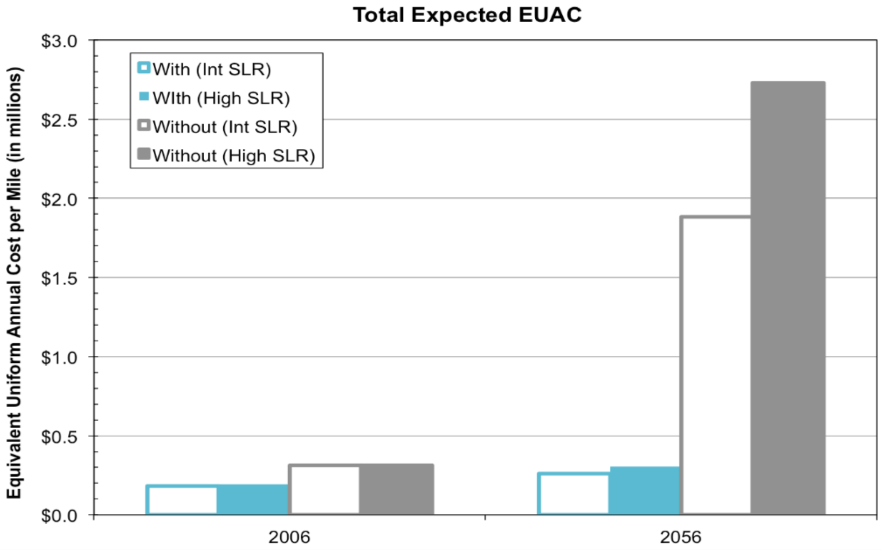


Economic Analysis

Equivalent Uniform Annual Costs (EUAC) approach

Methodology includes:

- Annual hazard probability considering future sea level rise
- Damage costs assuming the hazard occurs
- Cost of adaptation



Year	Adapt?	Damage if Event Occurs	Annual Hazard Probability	Expected Annual Damages	EUAC of First Cost	Total Expected EUAC
2006	Without	$3 M	X 0.1	= $0.3 M	+ $0	= $0.3 M
	With	$0.2 M	X 0.1	= $0.02 M	+ $0.2 M	= $0.2 M
2056	Without	$14 M	X 0.2	= $3 M	+ $0	= $3 M
	With	$0.7 M	X 0.2	= $0.1 M	+ $0.2 M	= $0.3 M

Lessons Learned

- These protections are economically justified today and the economic benefits of this adaptation will increase as sea levels rise.
- As sea levels rise, coast parallel roads can be exposed to and damaged by overwashing storm surges more frequently.
- Some adaptations to climate change will be similar to strategies required for improving infrastructure resilience to extreme events with today's sea levels.

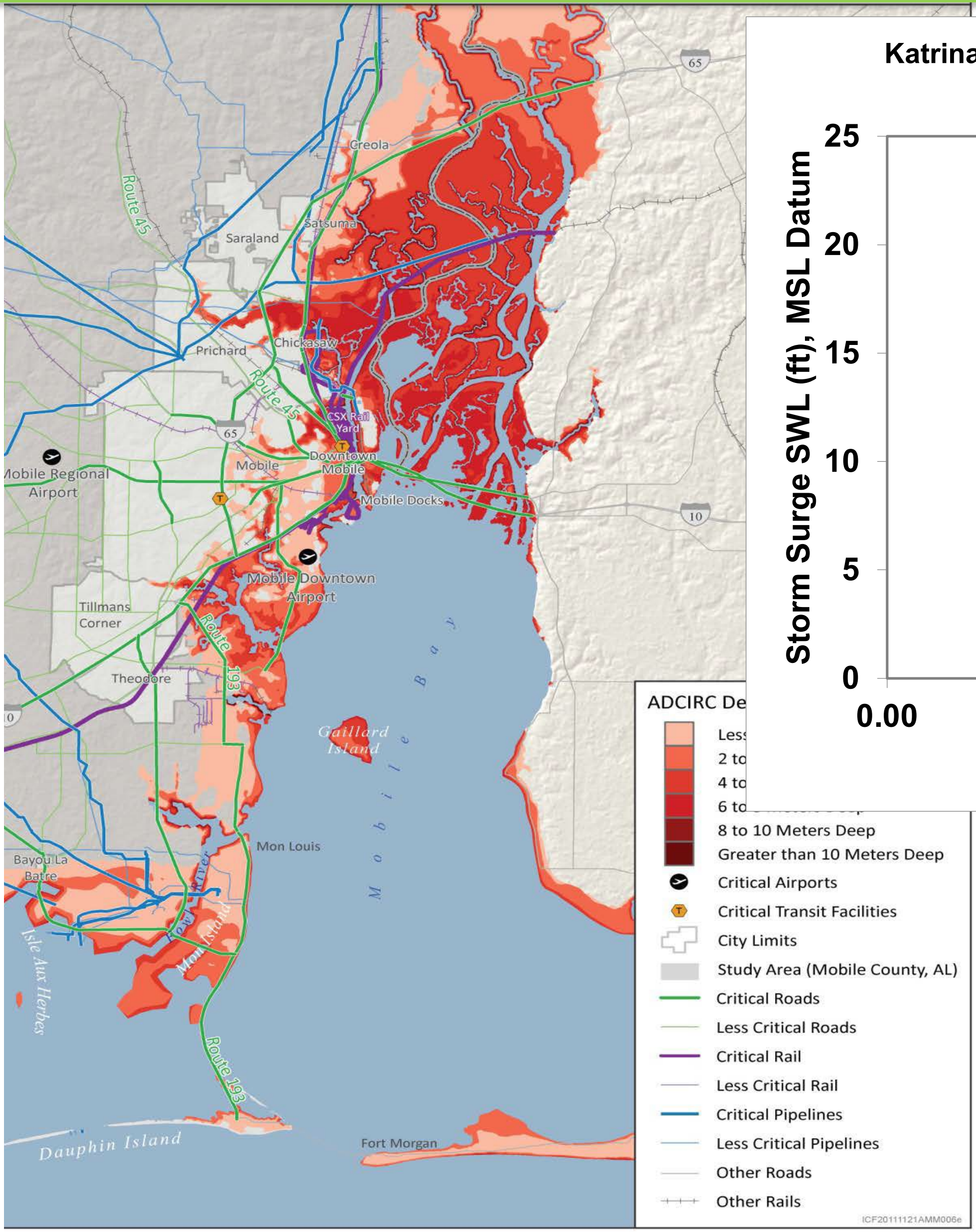
Sea Level Rise & Storm Surge on Coastal Bridge

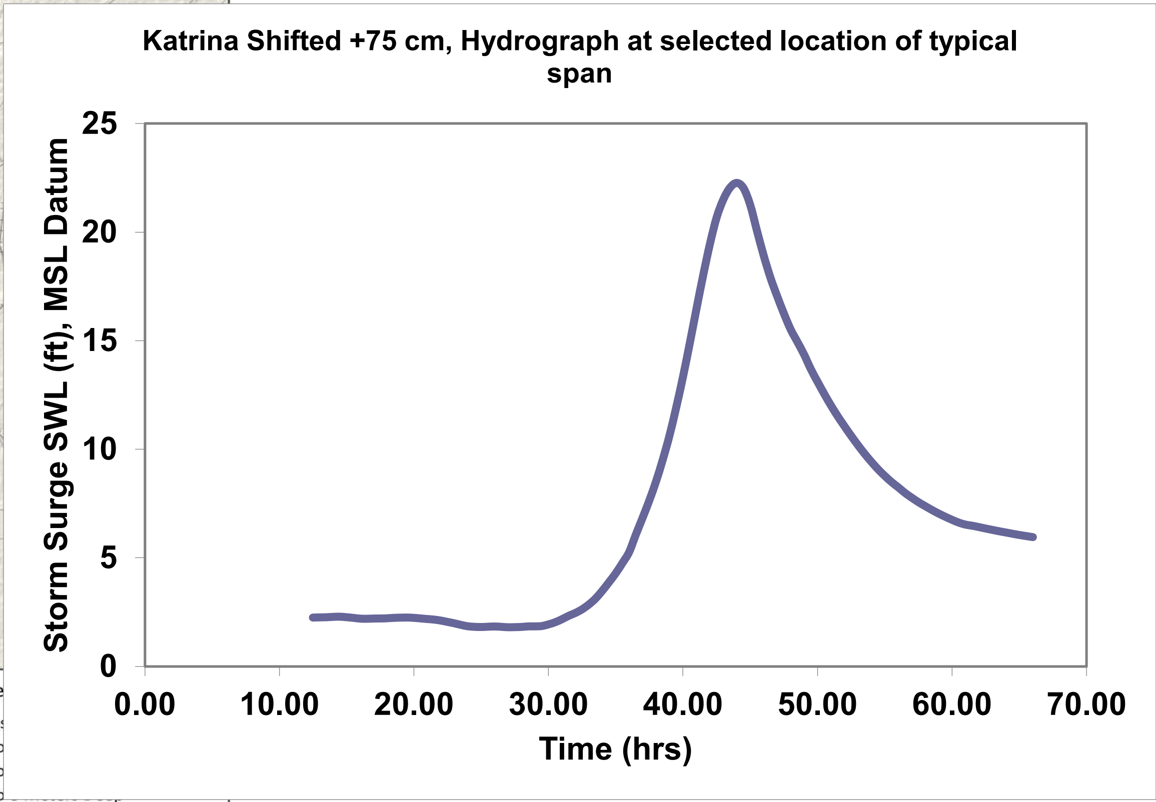
Mobile, AL

https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/teacr/al_i-10/

Outside edge of bridge showing concave configuration which traps an air pocket when a wave strikes it and potentially increases lateral loads. Source: South Coast Engineers

Climate Stressors and Scenarios





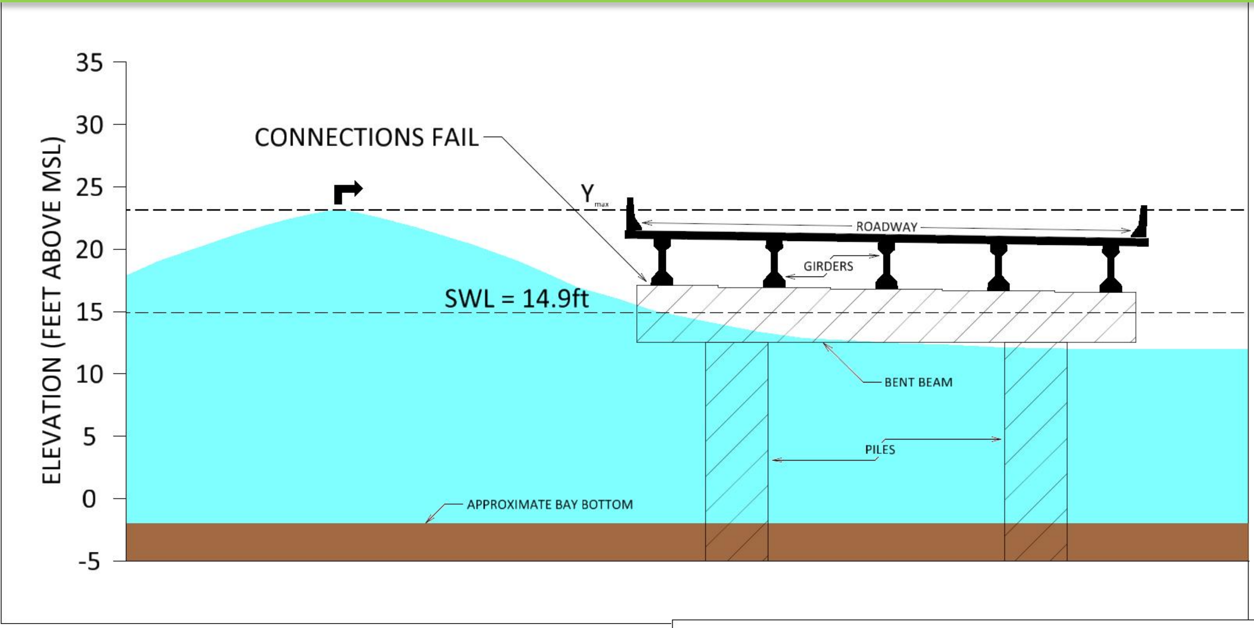
Climate Scenario: Katrina, shifted to make landfall farther east, with +75 cm of sea level rise

(Left) Surge inundation model results. Source: USDOT
(Above) Storm surge hydrograph at the selected span location. Source: USDOT

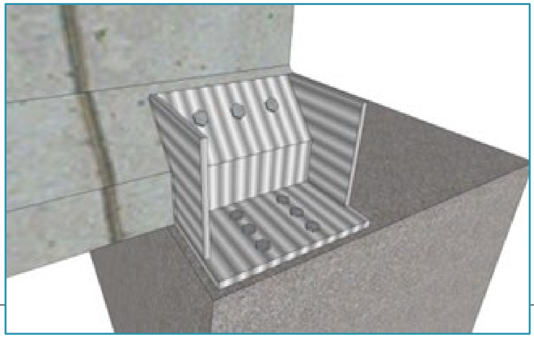
Adaptation Options

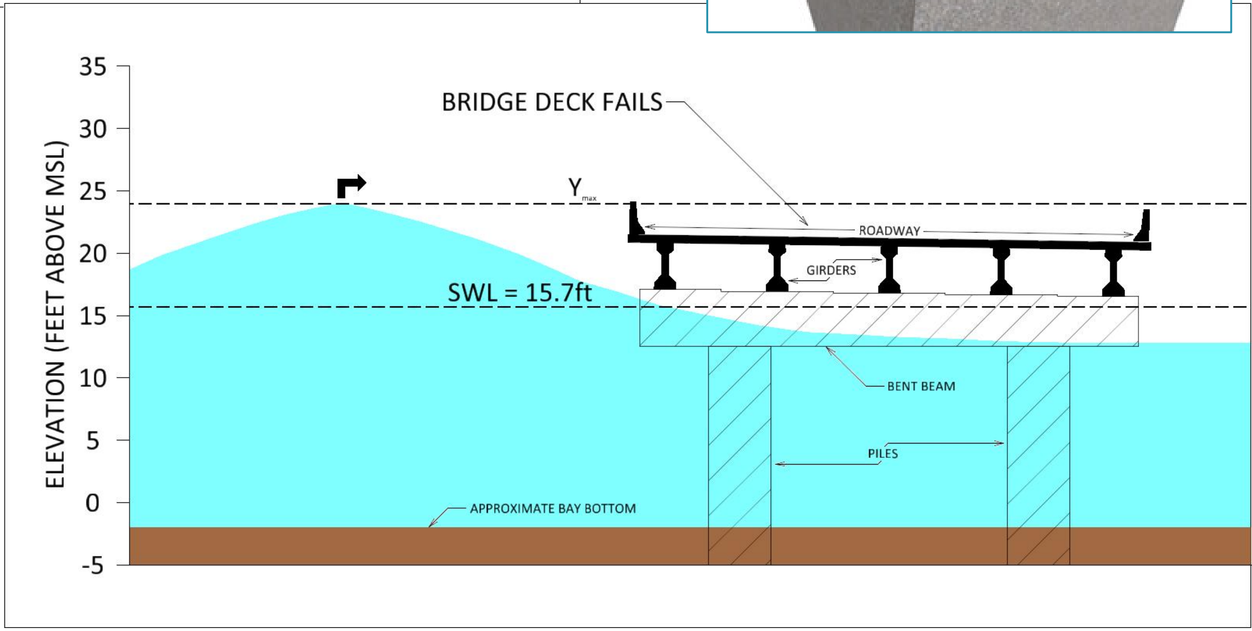
Adaptation Option	Description	Pros	Cons
Strengthened connections	Improve the connection of the girders to bent beams to resist wave-induced loads	Retrofit or new design option, provides a physical load path mechanism	Transfers loads to other elements of the bridge Limited guidance requires more research
Improved Span Continuity	Bridge decks are integrally connected to the adjacent decks	Increases the "effective" dead load of superstructure	Potential failures in the superstructure, foundation or substructure failure not addressed
Modified bridge shape	Modifications to the bridge cross-section	Potential to reduce lateral wave-induced loads	May not be an acceptable structural engineering option
Combination of increased elevation and other adaptations	Construction of bridges at a higher elevation but not so high as to always avoid wave-induced loads	Could reduce wave-induced loads on structure to a level within the design capacity	May be valuable as a new design adaptation strategy but more research would be required to develop guidance

Analytical Approach



In the current design, the **connections** would fail under the hurricane scenario.





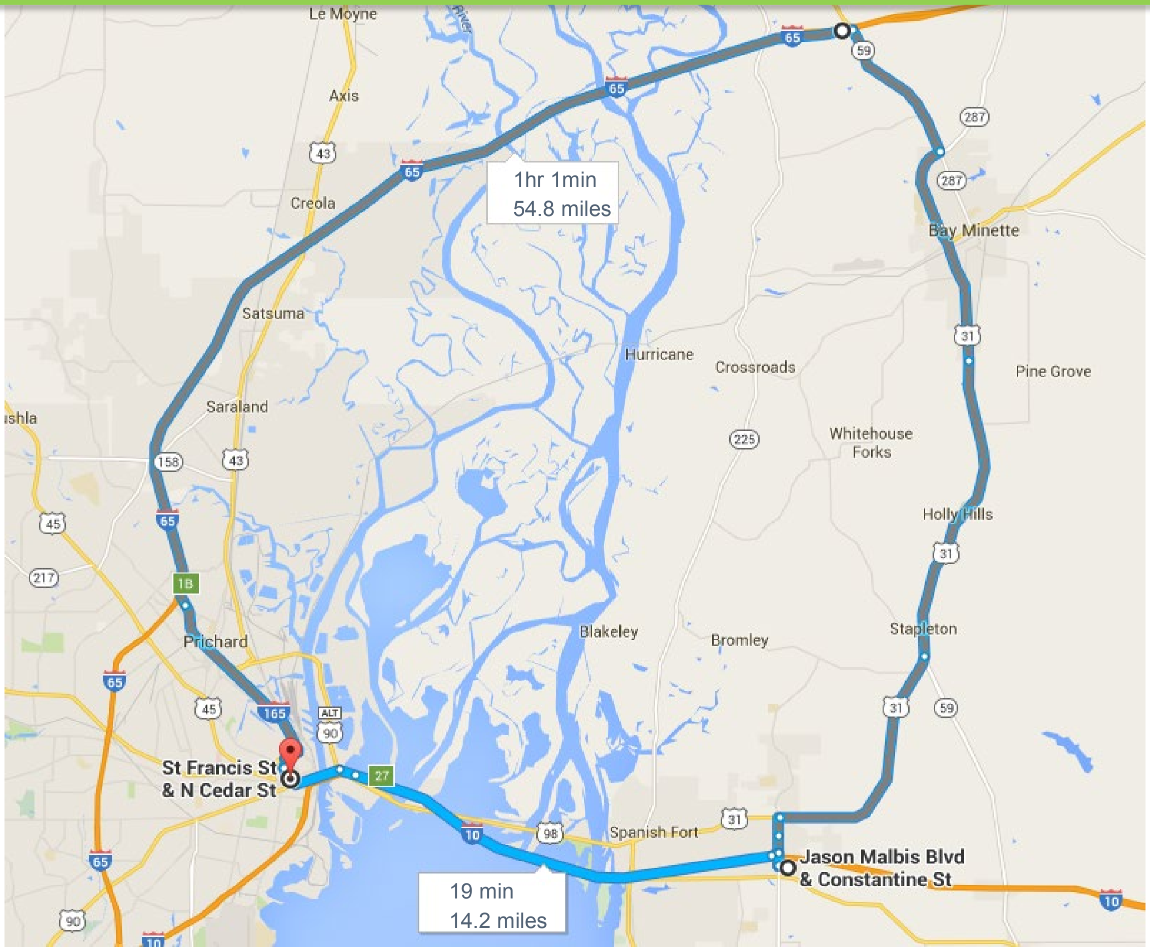
Strengthening the connections only "buys" one foot of surge protection before the **bridge deck** would fail.

Representations of study findings. Source: ALDOT

Economic Analysis

Economic analysis included:

- Direct impacts
- Indirect impacts
- Induced impacts



Impact Variable	Value
Additional Commuter Travel Time (ACTT), hours per day	11,506 hours
Additional Commuter Vehicle Miles Traveled (ACVMT), miles per day	629,710 miles
Additional Freight Travel Time (AFTT), hours per day	8,042 hours

Lessons Learned

- Sea level rise may have non-linear effects on peak storm surge levels.
- Original modeling of storm surge and waves is appropriate for major coastal projects.
- Following the load path implications through the entire structure is required to design of adaptations for coastal bridges exposed to wave-induced loads on storm surge.
- Only increasing the deck elevation would ensure the survival of this structure in this storm scenario.
- Wave induced loads have a “sweet spot”. The I-10 Bridge near Pensacola, FL, which was destroyed by Hurricane Ivan in 2004 may have been destroyed by the increase in wave-induced loads due to the sea level rise which occurred during the life of the structure.

Soils and Slopes

FHWA Guidance available at: https://www.fhwa.dot.gov/pavement/sustainability/hif15015.pdf

Source: Virginia DOT

Source: TEACR Pavement Shrink-Swell Study

Sensitivity to Climate Change

- Accelerated rock slope weathering and decreased slope stability from precipitation changes

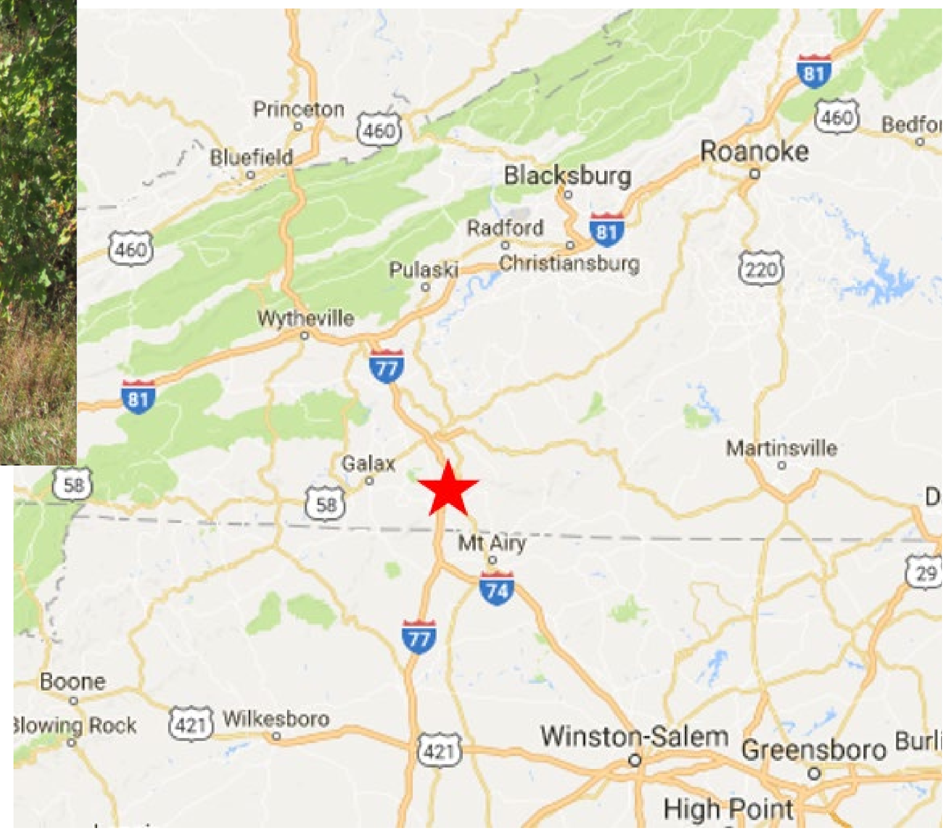
Existing FHWA Guidance

- TechBrief on Climate Change Adaptation for Pavements

Precipitation and Temperature Impacts on Rock and Soil Stability

Carroll County, Virginia
https://www.fhwa.dot.gov/environment/sustainability/resilience/ongoing_and_current_research/teacr/va_slopes/index.cfm

Soil slope slide along I-77. Source: VDOT



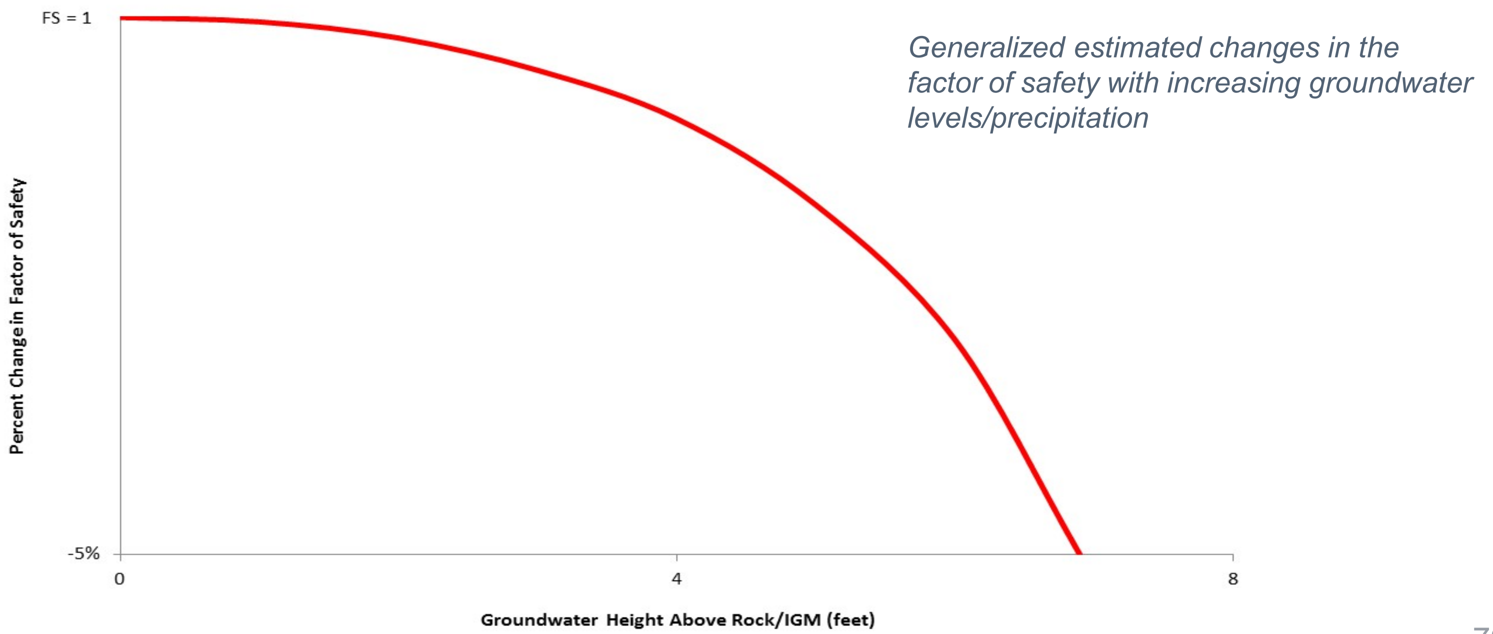
Map of site area (red star). Source: Google Maps

Analytical Approach

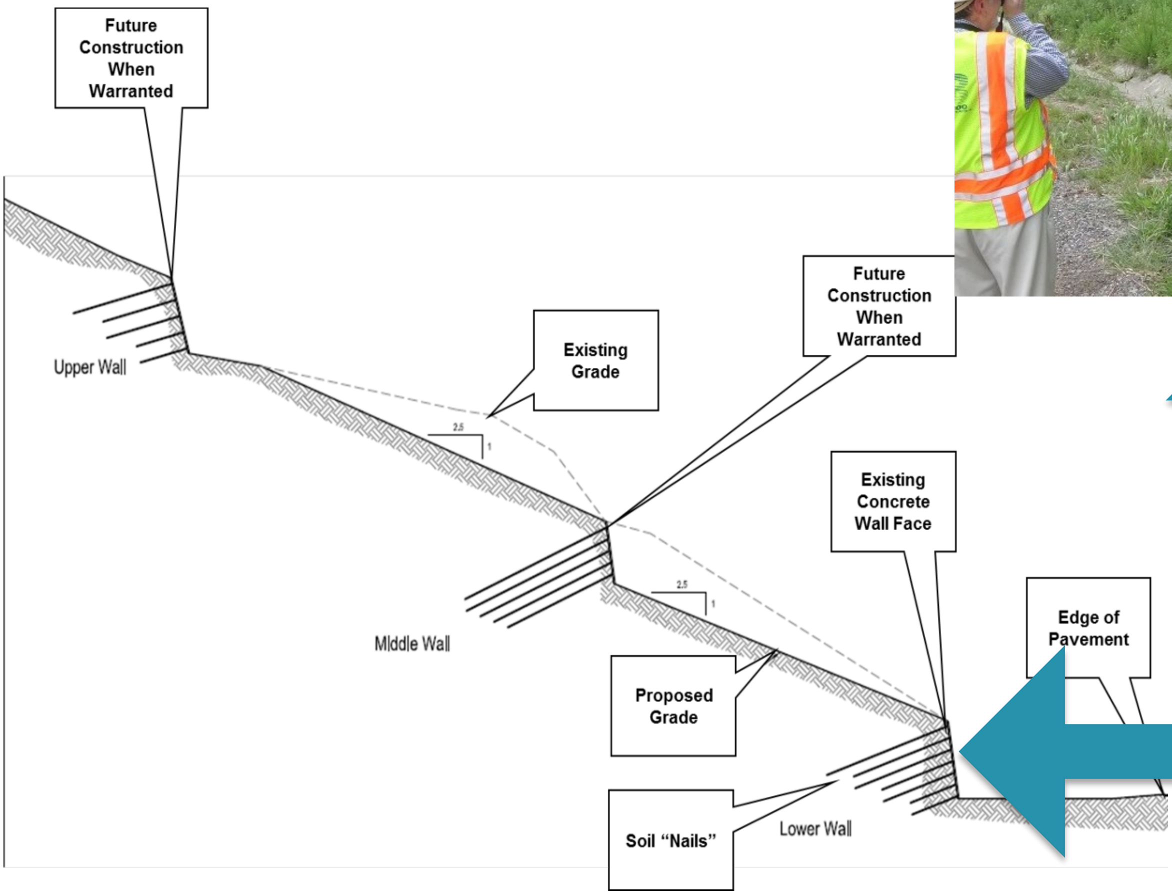
- Moderate increases in rainfall during10-, 50-, and 100-year storms projected
- Recommended preliminary steps to determine if climate change may impact soil slope stability:
  - Determine the steepness of the slope. Slopes steeper than 2 (horizontal) to 1 (vertical) should be initially suspect.
  - Perform a field inspection to detect physical clues such as soil bulges at the toe of the slope, deformed tree trunk growth, depressed elevation of the slope face.
  - Perform a parametric analysis (i.e., vary the groundwater elevation and soil unit weight) to see how the slope would respond under a wide range of conditions. Doing so could save considerable time and expense in instrumentation and data collection.

Parametric Analysis Results

- Variations in soil unit weight did not have an impact on the factor of safety.
- When the slope is already at a factor of safety close to one, increased precipitation on slopes in residual soils does not significantly affect the overall factor of safety.
- The impact of increased perched water table height shown below.



Adaptive Management



Completed Toe Wall at the Base of the Sliding Mass. Source: WSP

Lessons Learned

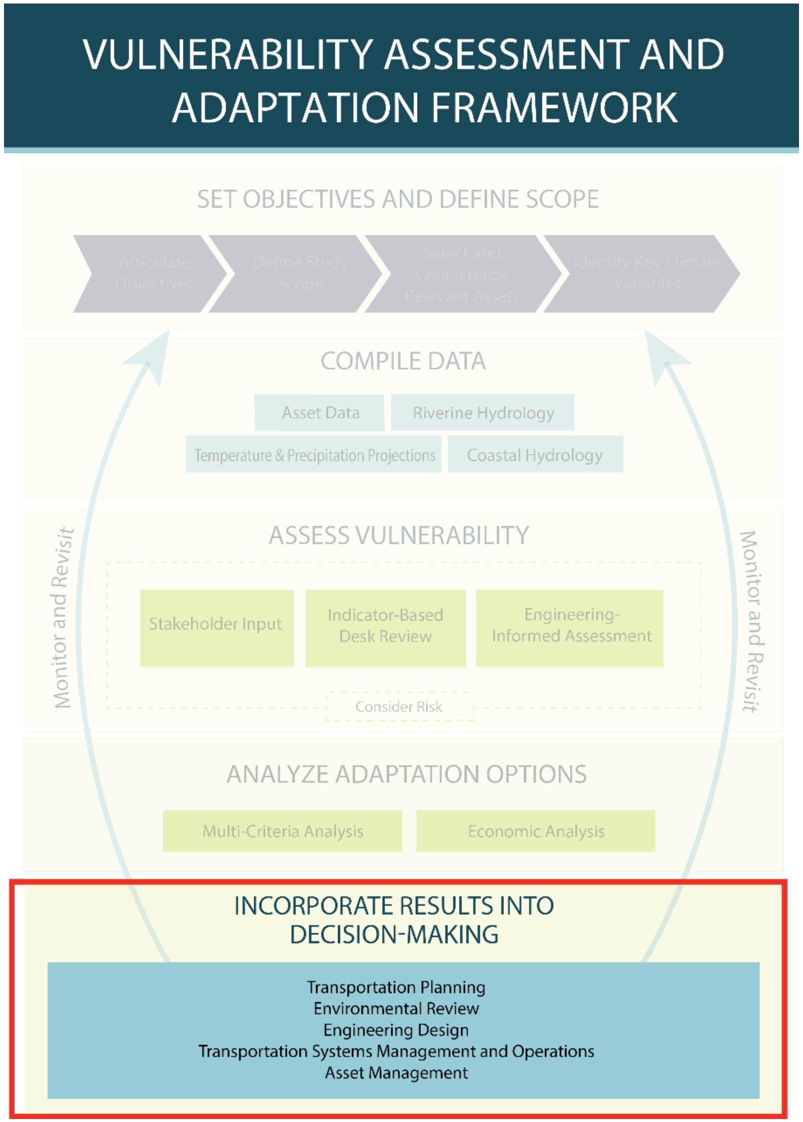
- It is not necessarily the case that increased precipitation would increase the likelihood of slope failure. A slope that is suspected of being vulnerable should be analyzed before drawing conclusions.
- Detailed climate data are not necessary for an initial, general assessment of climate change impacts on soil stability
- Rather than screening detailed climate change projections, the “worst case scenario” can be analyzed first without specific climate data.

Overall Lessons Learned

- The use of historic climate data in lieu of climate projections is sometimes appropriate, but historic data should always be as up to date as possible.
- Maintenance records from extreme weather events can help practitioners understand the likelihood of future infrastructure damage.
- Many climate adaptation measures will be amplified forms of countermeasures currently installed to manage risks associated with today’s environmental conditions.
- Given climate uncertainty, taking an incremental approach to adaptation may help reduce the risk of overspending while still increasing resilience.

Integrating Resilience into Decisionmaking

Incorporate Resilience into Decisionmaking



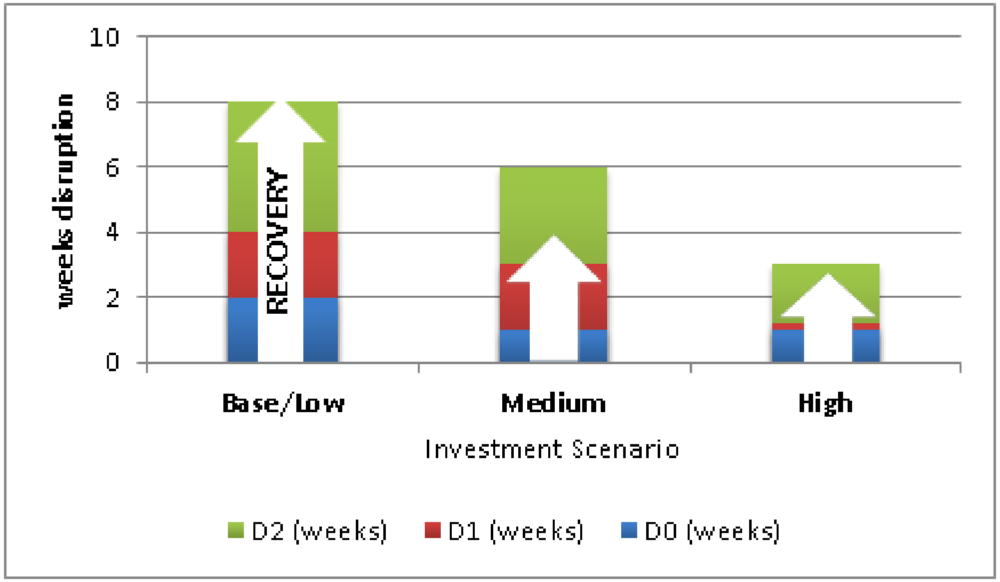
- Use study results in practice
- Cost-Effective
- Consider incorporating results into:
  - Transportation planning,
  - Project development & environmental review,
  - Project level design & engineering,
  - Operations and maintenance, and
  - Asset management.

Resilience in Transportation Planning

- Include resilience in transportation plan goals and objectives
- Identify, evaluate, and adopt strategies to address identified vulnerabilities
- Screen projects during planning to avoid making investments in particularly vulnerable areas
- Include resilience in the criteria for evaluating projects for funding
- Consider future environmental conditions in corridor planning studies

Example: Hillsborough MPO (Tampa, FL) 2040 Long Range Transportation Plan

- Objective: Increase the security & resiliency of the multimodal system
  - Performance measure: Recovery time and economic impact of a major storm
- Developed and evaluated three risk management investment scenarios
  - Evaluated disruption and economic loss from storms and flooding for different levels of investment in adaptation and mitigation



Source: Hillsborough MPO

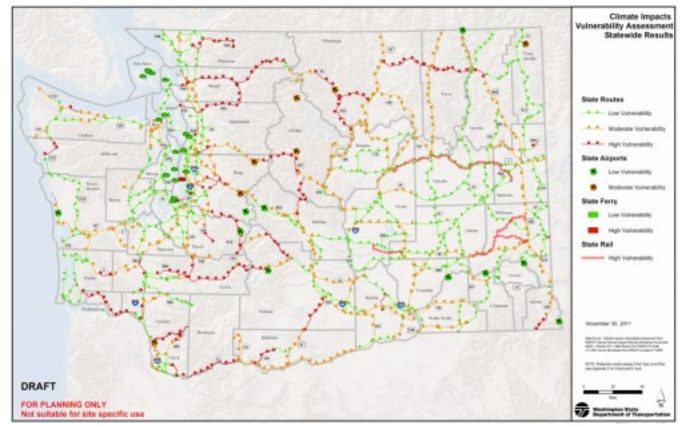
Resilience in Project Development and Environmental Review

- Use information developed in vulnerability assessments as a screen to identify facilities of concern.
- Use vulnerability information developed in regional and corridor planning studies in the environmental review process
- Include sea level rise projections in NEPA documents in the description of affected environment and in the analysis of alternatives.
- Develop and select project alternatives that minimize vulnerabilities
- Develop adaptation strategies as mitigation measures or for inclusion in the proposed action.

Resilience in Project Development and Environmental Review : WSDOT

- Incorporated vulnerability information into state environmental review guidance

Guidance for NEPA and SEPA Project-Level Climate Change Evaluations



Contact:

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WSDOT Environmental Services Office
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Washington State Department of Transportation

Environmental Services Office
January 2017 Update

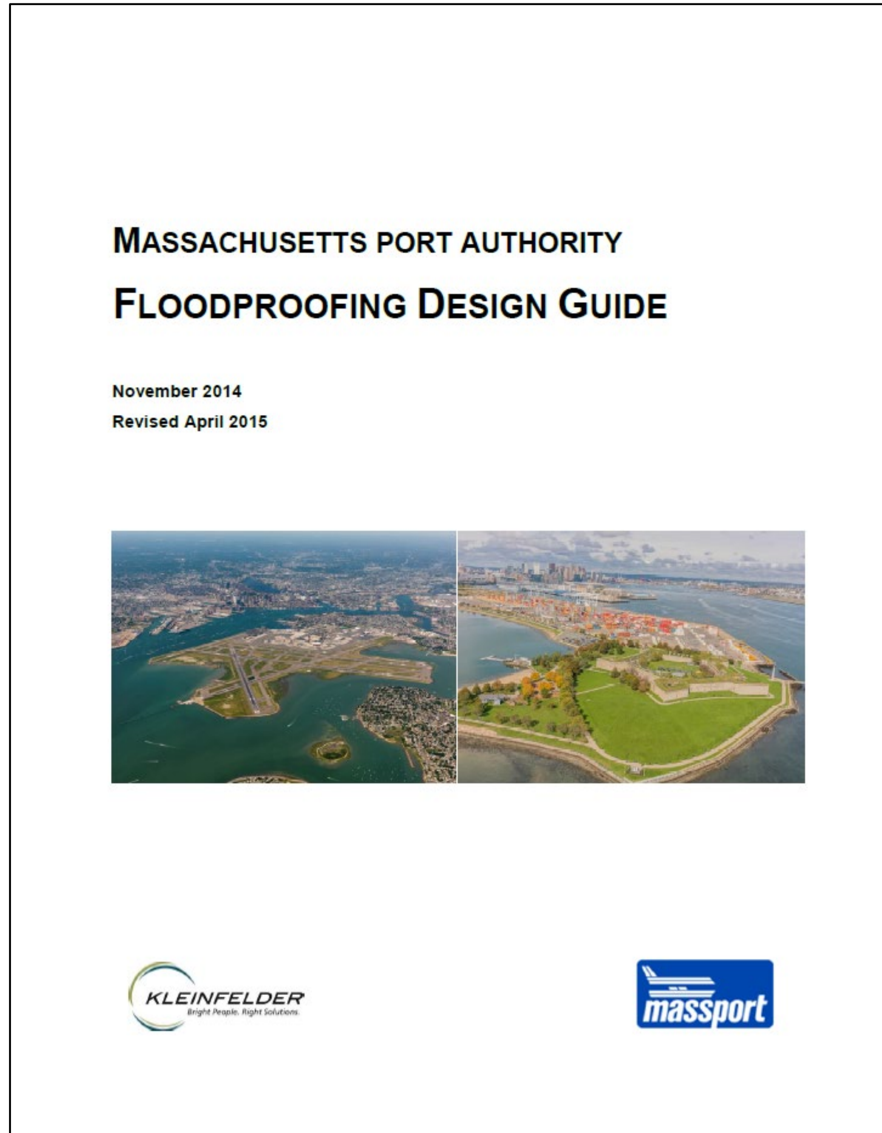
Resilience in Project Level Design and Engineering

- Vulnerability assessments conducted with more complex and detailed analysis can inform **engineering and design requirements** for **individual assets** in a way that accounts for future conditions.
- Addressing uncertainty:
  - Flexible adaptation pathways
  - Using information on the direction of change
  - Sensitivity analysis
  - Contracting

Resilience in Project Level Design and Engineering

Massachusetts Port Authority (MassPort):

- Developed Floodproofing Design Guide as result of Disaster and Infrastructure Resiliency Planning Study
- Design flood elevations, floodproofing strategies, performance standards



MASSACHUSETTS PORT AUTHORITY

FLOODPROOFING DESIGN GUIDE

November 2014

Revised April 2015

KLEINFELDER

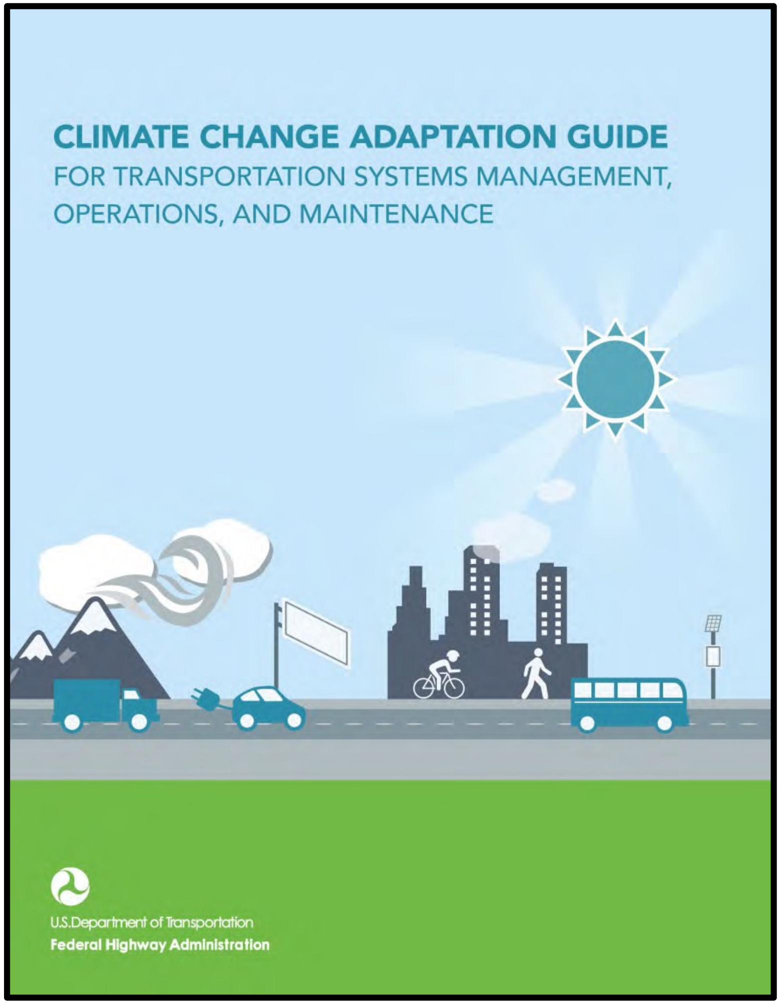
Bright People. Right Solutions.

massport

Resilience in Operations and Maintenance

Resilience in O&M decisions:

- Increasing regular maintenance activities
- Adding capacity for smaller infrastructure inspections
- Determining future maintenance needs and methods
- Maintaining mobility and safety
- Assessing future technology and system requirements
- Planning for new capital improvements and annual maintenance investments.



Resilience in Operations and Maintenance

- Establish interagency agreements to share equipment and other resources to aid in emergency response and recovery.
- Periodically review weather response strategies and plans to reflect increases in extreme weather severity or make them adaptable to accommodate anticipated weather extremes.
- Periodically review and update operator response quick-reference guidebooks and templates and make them adaptable to previously unexperienced extreme weather conditions.
- Keep electronic records of location and event information for facility closures, emergency repair, and maintenance activities. Use a platform that makes this information accessible to agency decision makers

Resilience in Operations and Maintenance

- Use weather responsive traffic management in conjunction with tools such as signal timing, variable speed limits, changeable lane assignment, and diversion routing.

- When assessing the technical viability of road weather management monitoring equipment as part of procurement
  - Consider the ability for the technology to withstand and function in extreme weather or mitigate traffic conditions during extreme weather.
  - Periodically review system engineering requirements for long-term changes in weather patterns.

In Asset Management

- Consider both current and future risks
- Perform statewide evaluations to determine if there are reasonable alternatives to roads, highways, and bridges that have required **repair and reconstruction activities** on two or more occasions due to emergency events.
- Include resilience in risk-based State Transportation Asset Management Plans.

In Asset Management

Los Angeles County Metropolitan Transportation Authority (Metro)

- Integrated climate risk into existing asset management system.
- Developed new data fields in the asset management system, and guidelines for assessing risk of the assets.

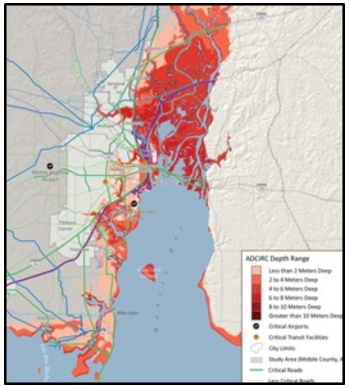
Source: Metro

EXERCISE #3
ELEVATOR SPEECH

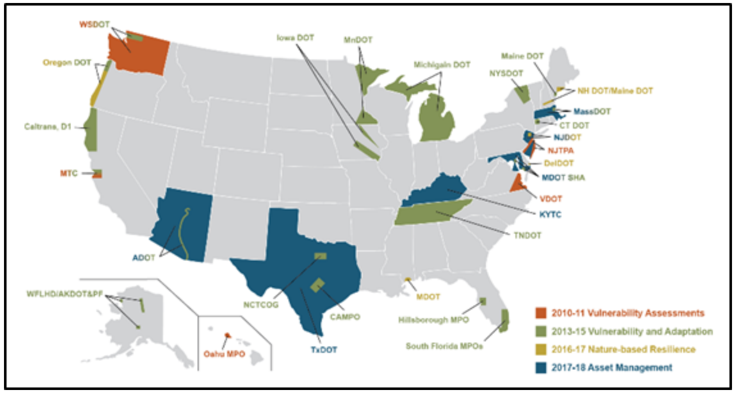
Pitch this to your leaders.

FHWA Resilience Resources

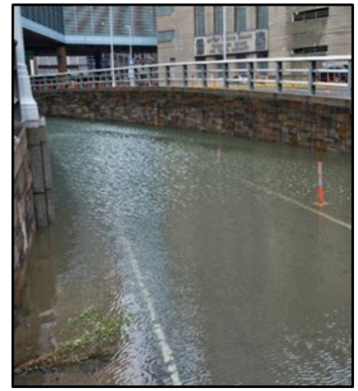
Gulf Coast 2 Study



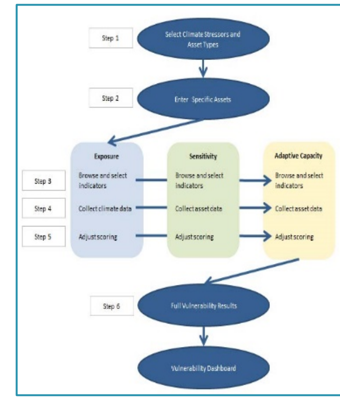
Resilience Pilots - State DOTs, MPOs, FLMAs



Hurricane Sandy Project



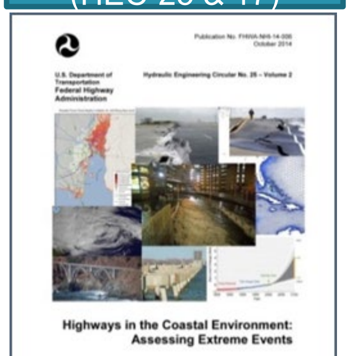
Tools



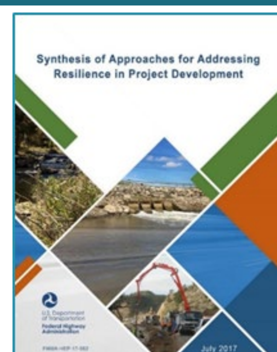
https://www.fhwa.dot.gov/environment/sustainability/resilience/

Vulnerability & Adaptation Framework

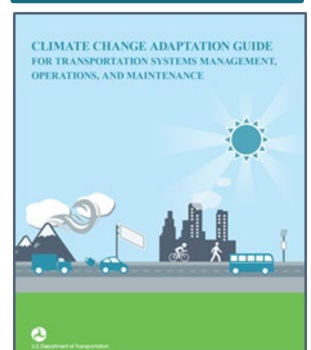
Engineering Guidance (HEC-25 & 17)



Project Development



Operations & Maintenance



Guidebooks under development on integrating resilience in:

- Asset Management
- Transportation Planning
- Nature-based solutions

Coastal Resilience Resources

COASTAL Resilience

ABOUT ⌄ NATURAL SOLUTIONS ⌄ COLLABORATIONS ⌄ PROJECTS ⌄ TOOLS ⌄ RESOURCES ⌄ MAPPING PORTAL

Habitats

Mangrove	Coral Reefs	Oyster Reefs	Saltmarshes	Seagrass

Coastal mangrove forest in the area of the Sandy Island Oyster Bay Marine Protected Area (SIOBMPA) at Carriacou, Grenada. Sandy Island Oyster Bay Marine Protected Area, designed with the support of the Conservancy, was officially launched by Grenada in July 2010. The new reserve is one of three new marine protected areas the country will launch to help improve the management of the country's marine resources and protect coastlines from errosion . Grenada and St. Vincent and the Grenadines are located at the Southern end of the Lesser Antilles. Photo Credit: Mario Aho

Mangroves grow in the up
predominantly in the warr
some warm temperate reg
forests. Mangroves are hig
in areas where freshwater
growth. They provide critic
storms, habitat or nursery
support the lives and liveli
through the provision of fo

While large areas of mang
development and the expa
have shown that mangrov

The following reports are a
around the globe, mangro

- The Nature Conservancy website has coastal resilience information relevant to the territories
  - Tropical island case studies
  - Nature-based solutions