Climate Change and Transportation-related Adaptation Planning

Michael D. Meyer, Ph.D., P.E., F.ASCE
Transport Studio, LLC

J.P. O'Har
Georgia Tech

What is the Difference between Mitigation & Adaptation?

Transportation Activity

Driving, shipping, transit, rail, operations, maintenance, etc.

↓

GHG Emissions

CO2, CH4, N2O, +……..

↓

Changes to Climate

sea level, temperature, precipitation, storms

↓

Impacts on Transport

infrastructure, operations, users, suppliers, services, travel demand

→ **GHG Mitigation Strategies**

To slow down rate of change and reduce impacts

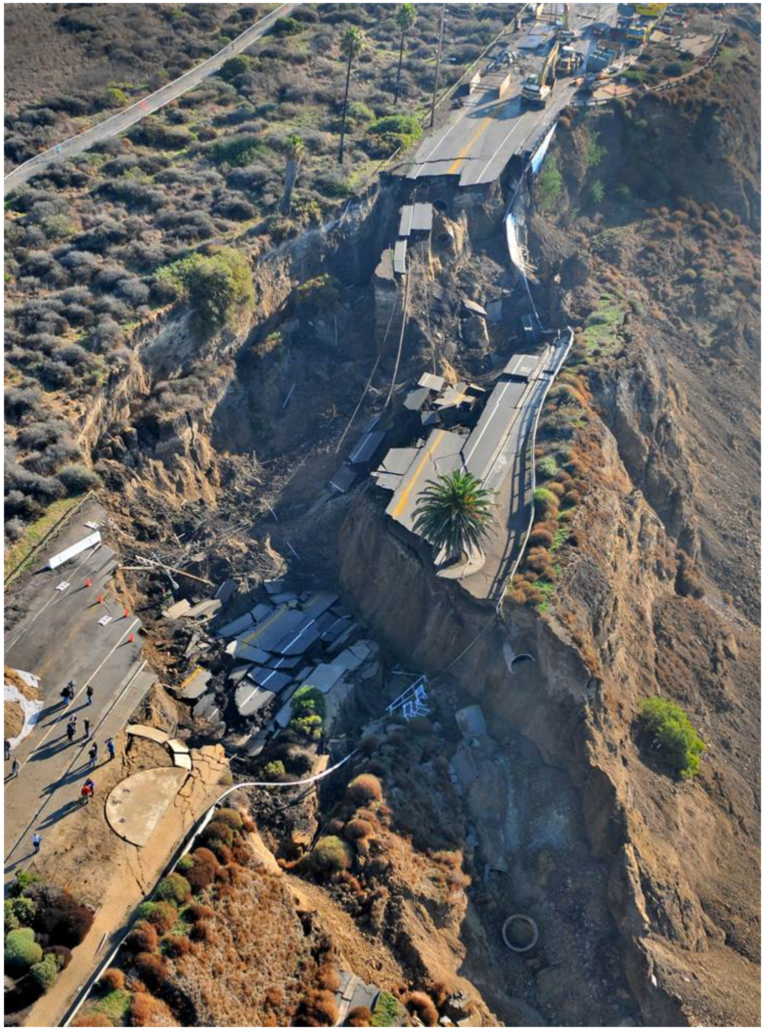
→ **Climate Change Preparation and Adaptation**

To plan for and deal with expected impacts

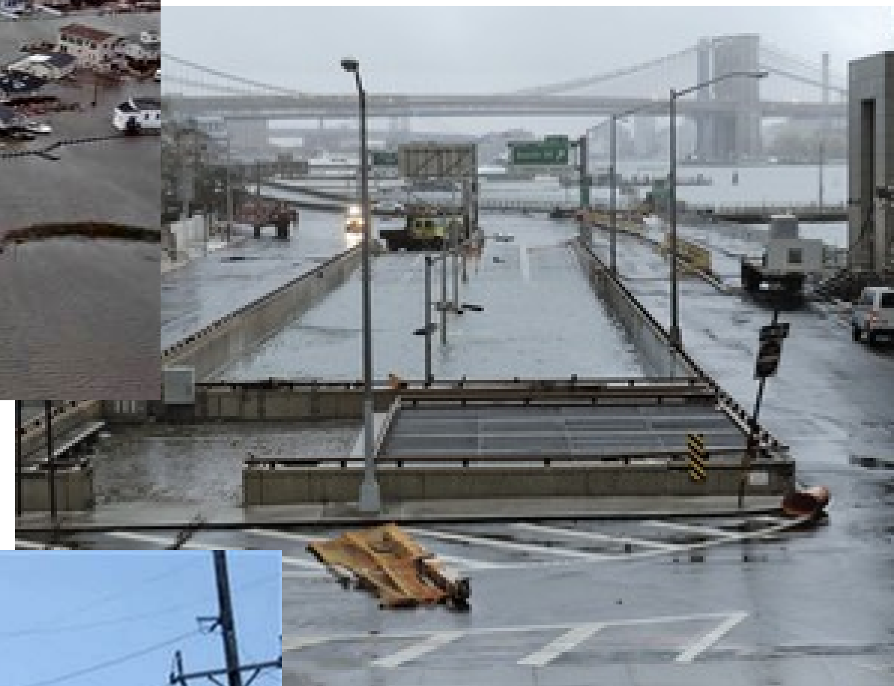
Extreme Events

Katrina

Irene

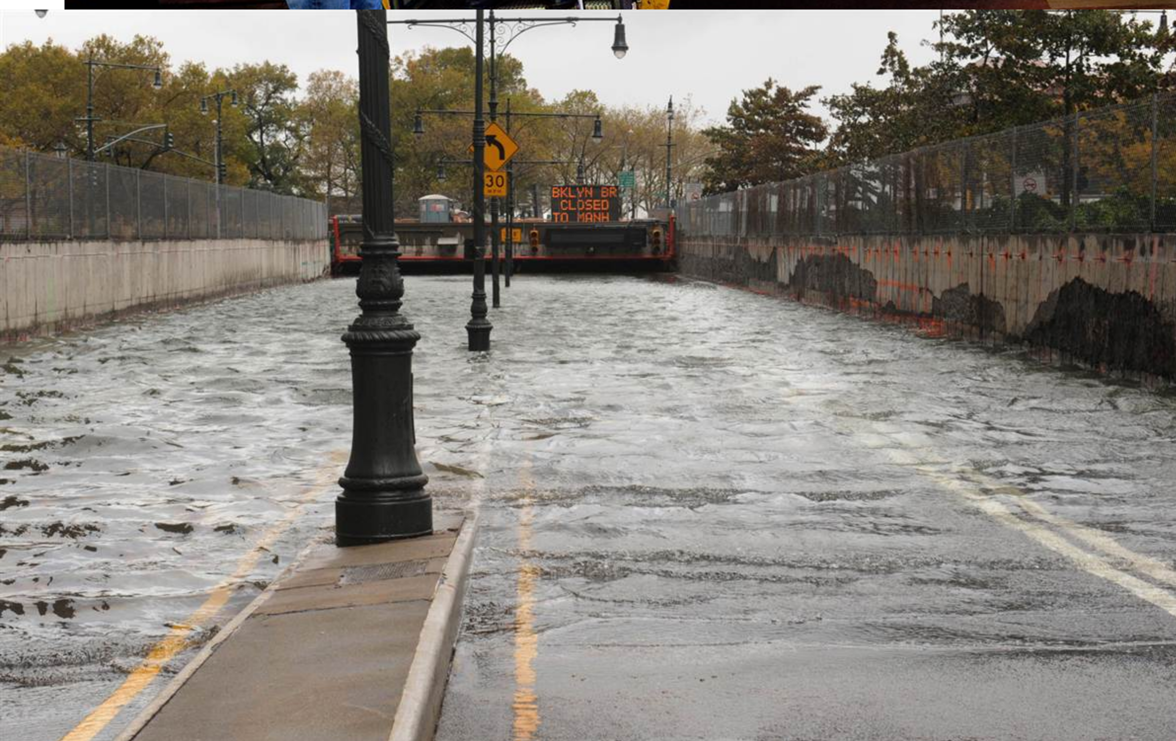


Sandy



STOP
629
US DOT 1853267
11-08 30TH
LONG ISLAND CITY


30
BKLYN BR
CLOSED
TO MANH

2012--- A Record Year

Hottest March on record in the contiguous United States, and July was the hottest single month ever recorded in the lower 48 states

Worst drought in 50 years across the Midwest and South, with over 1,300 US counties across 29 states declared drought disaster areas.

Wildfires burned over 9.2 million acres, with the average size of the fires setting an all-time record of 165 acres per fire.

Hurricane Sandy's storm surge height (13.88 feet) broke the all-time record in New York Harbor

2012--- A Record Year

Georgia: Total of 37 broken heat records, 14 broken precipitation records, and 9 large wildfires

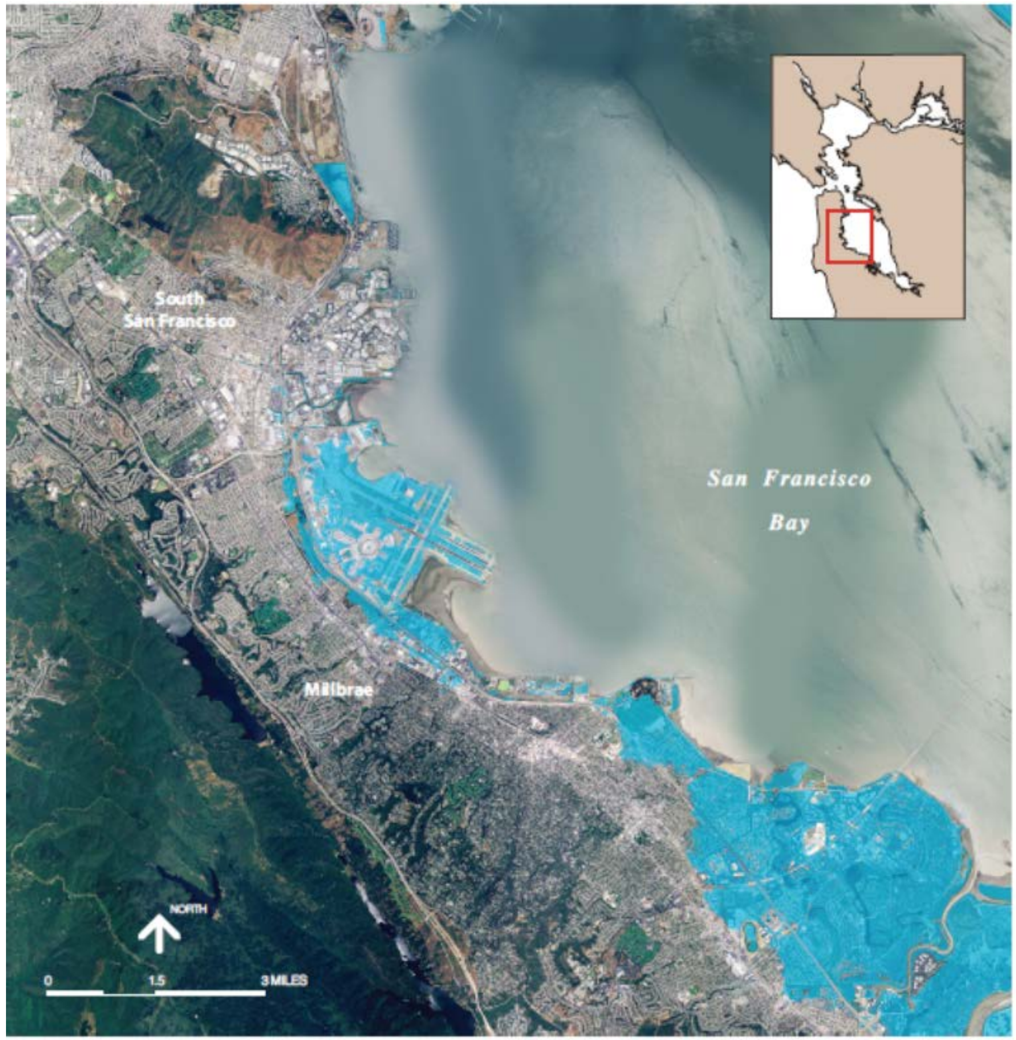
Kansas: Total of 64 broken heat records, 42 broken precipitation records, and 30 large wildfires

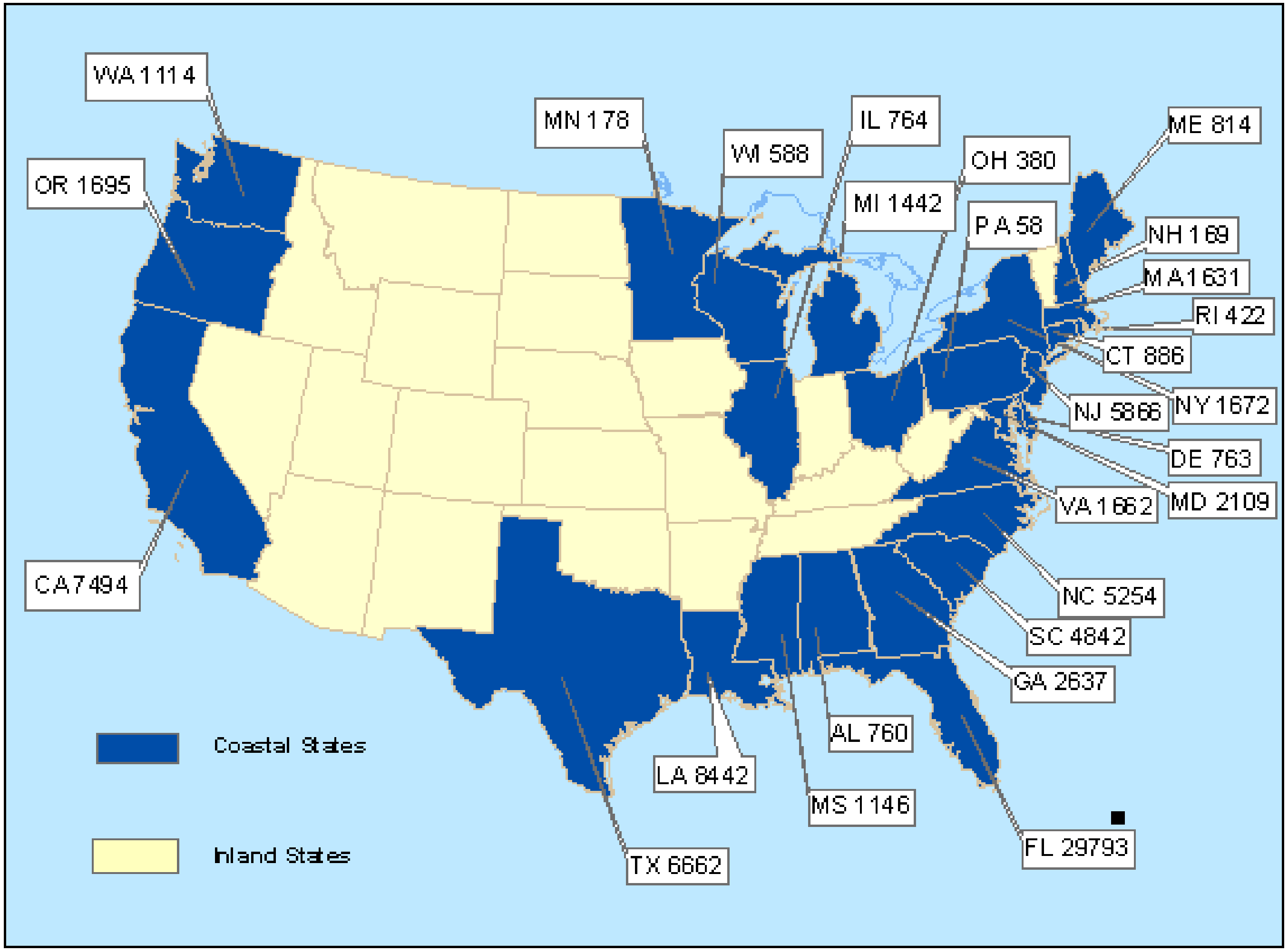
Montana: Total of 59 broken heat records, 16 broken snow records, 17 broken precipitation records, and 128 large wildfires

Texas: Total of 144 broken heat records, 8 broken snow records, 115 broken precipitation records, and 34 large wildfires

Long-term Environmental Changes

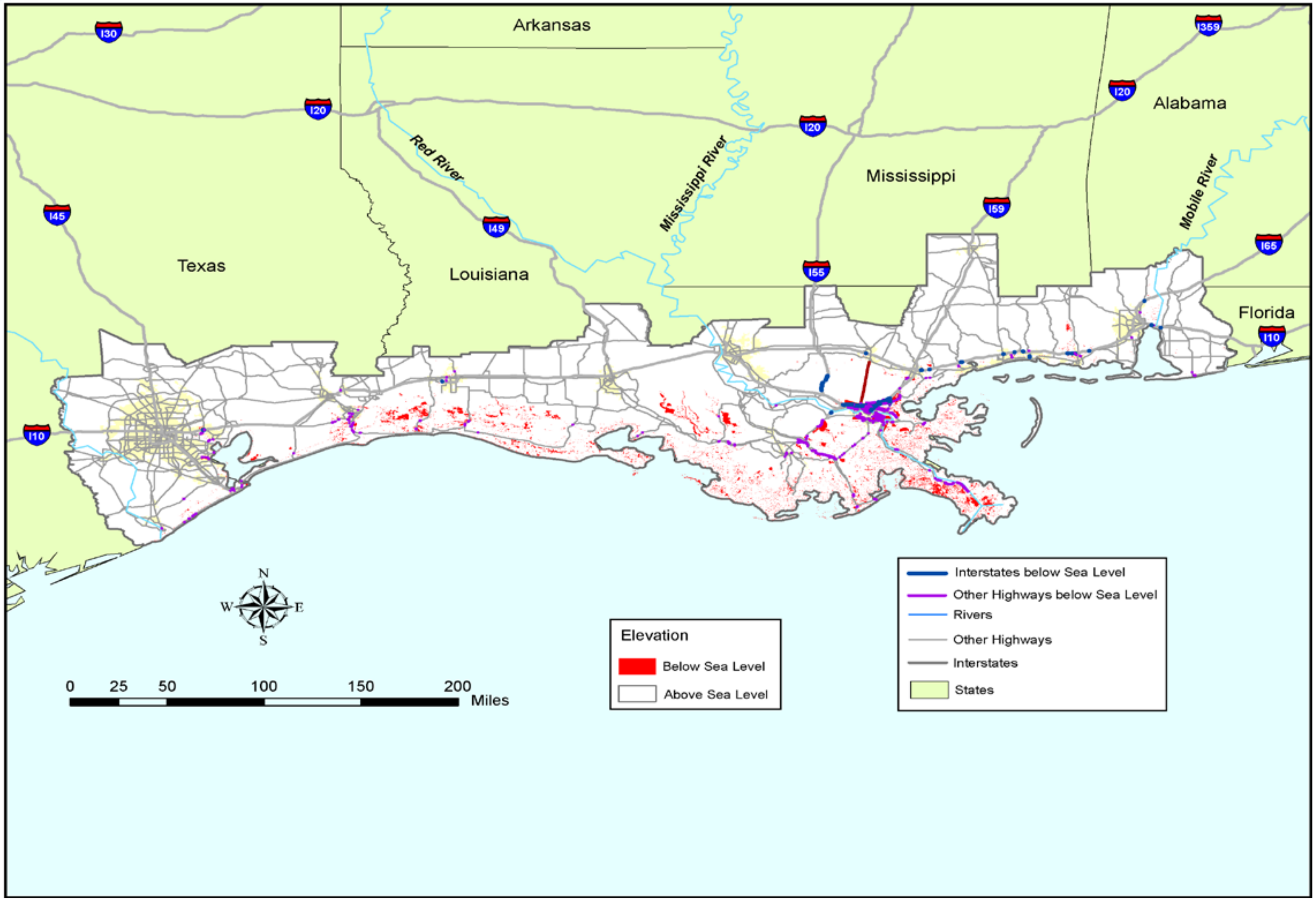
San Francisco International Airport – 16 inches of SLR



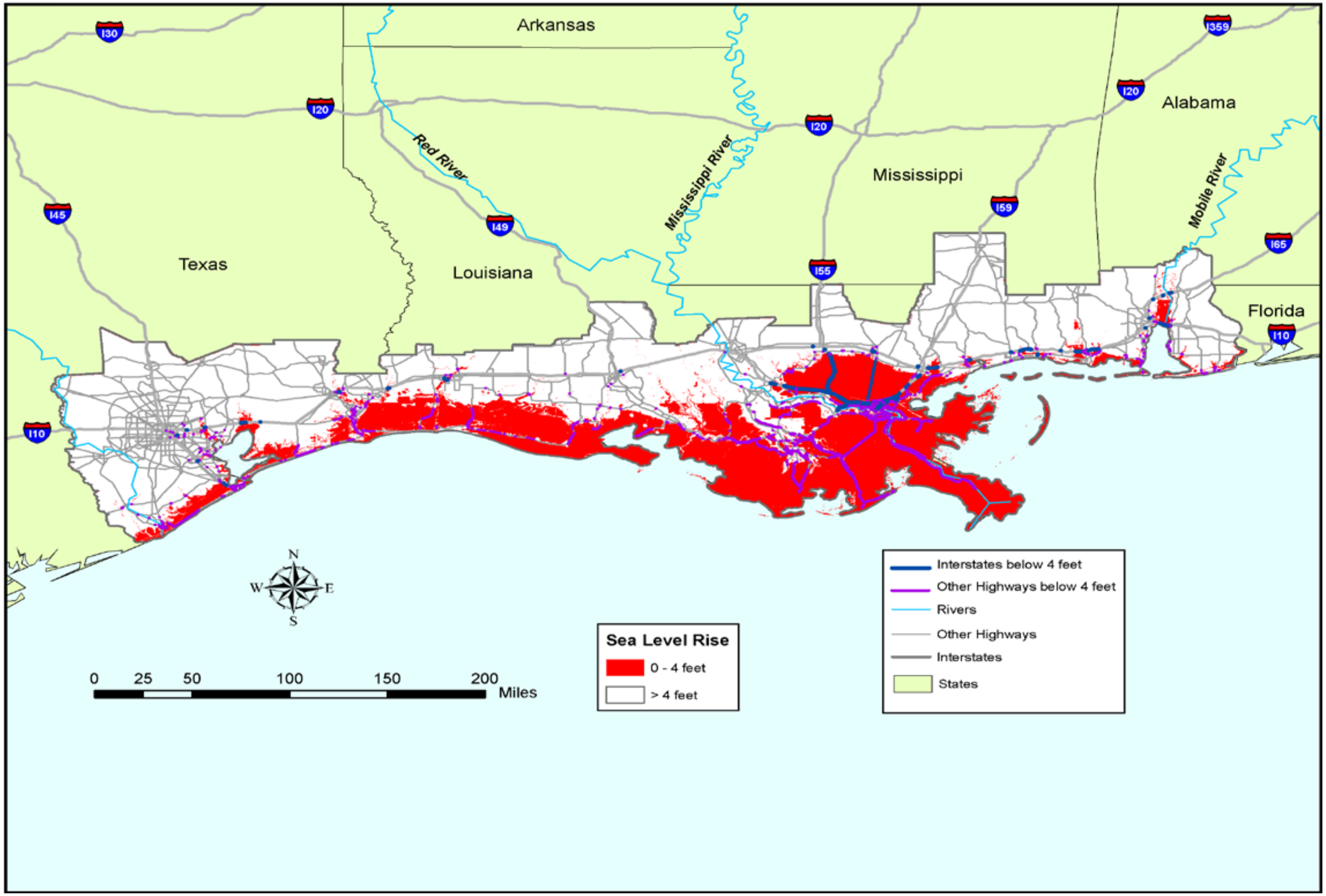


60,000 miles in FEMA coastal flood zone; 36,000 bridges within 15 nautical miles of coasts

Current Sea Level



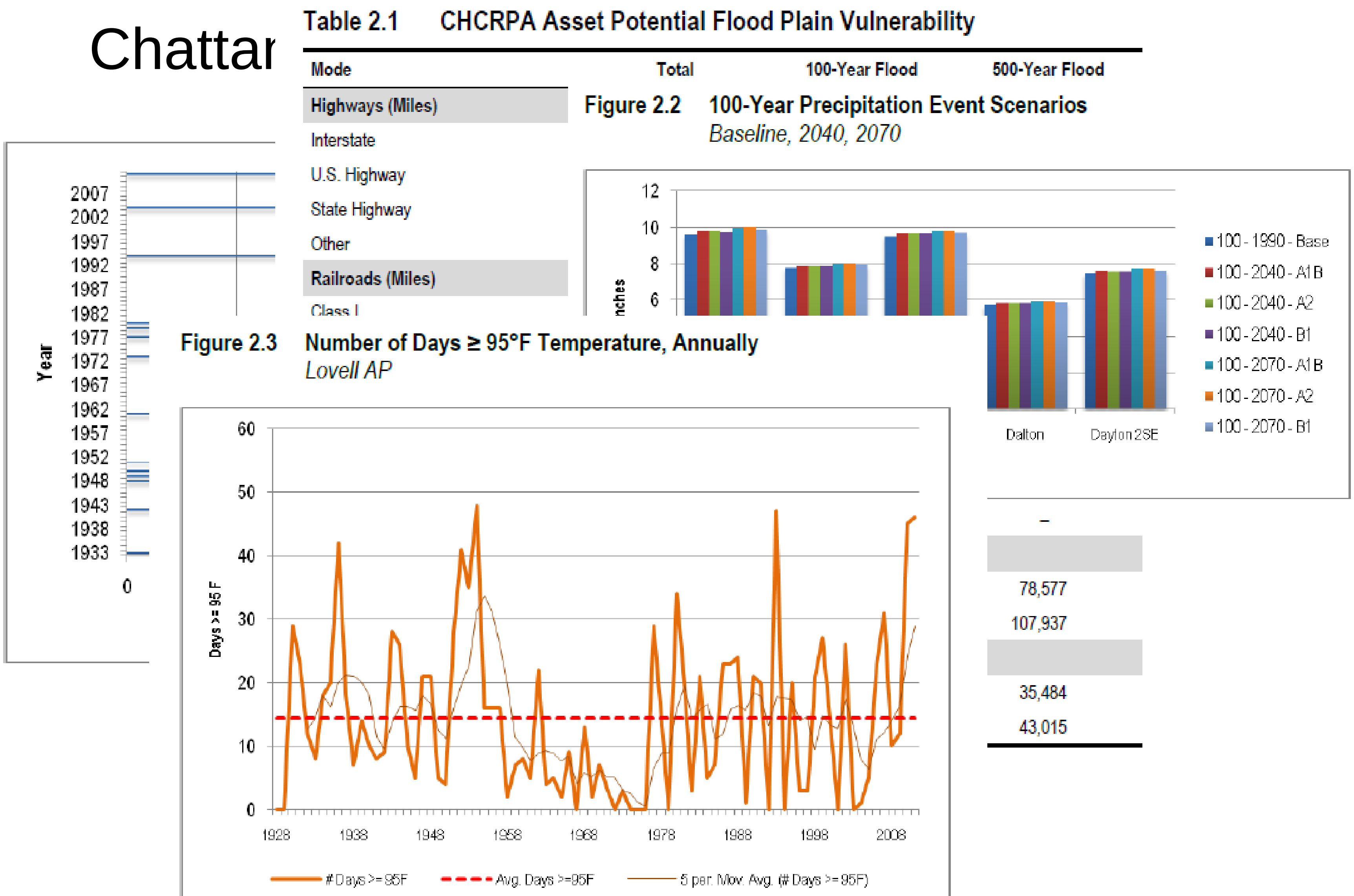
4-Foot Sea-Level Rise



Transportation infrastructure that is vulnerable to 18 feet of storm surge includes:

- 51% of interstate miles, 56% of arterial miles, and most transit authorities
- 98% of port facilities vulnerable to surge and 100% to wind
- 33% of rail miles operated, 43% of freight facilities,
- 22 airports in the study area at or below 18 feet MSL
- Potentially significant damage to offshore facilities

Some Other Examples



Criticality

What does transportation do? What role does it play in the community?

For example, need access to and from:

- Jobs/economic opportunities;
- Services/healthcare;
- Families/social opportunities;
- Parks/recreational opportunities;

Figure 3.2 Example of Critical Assets Exercise

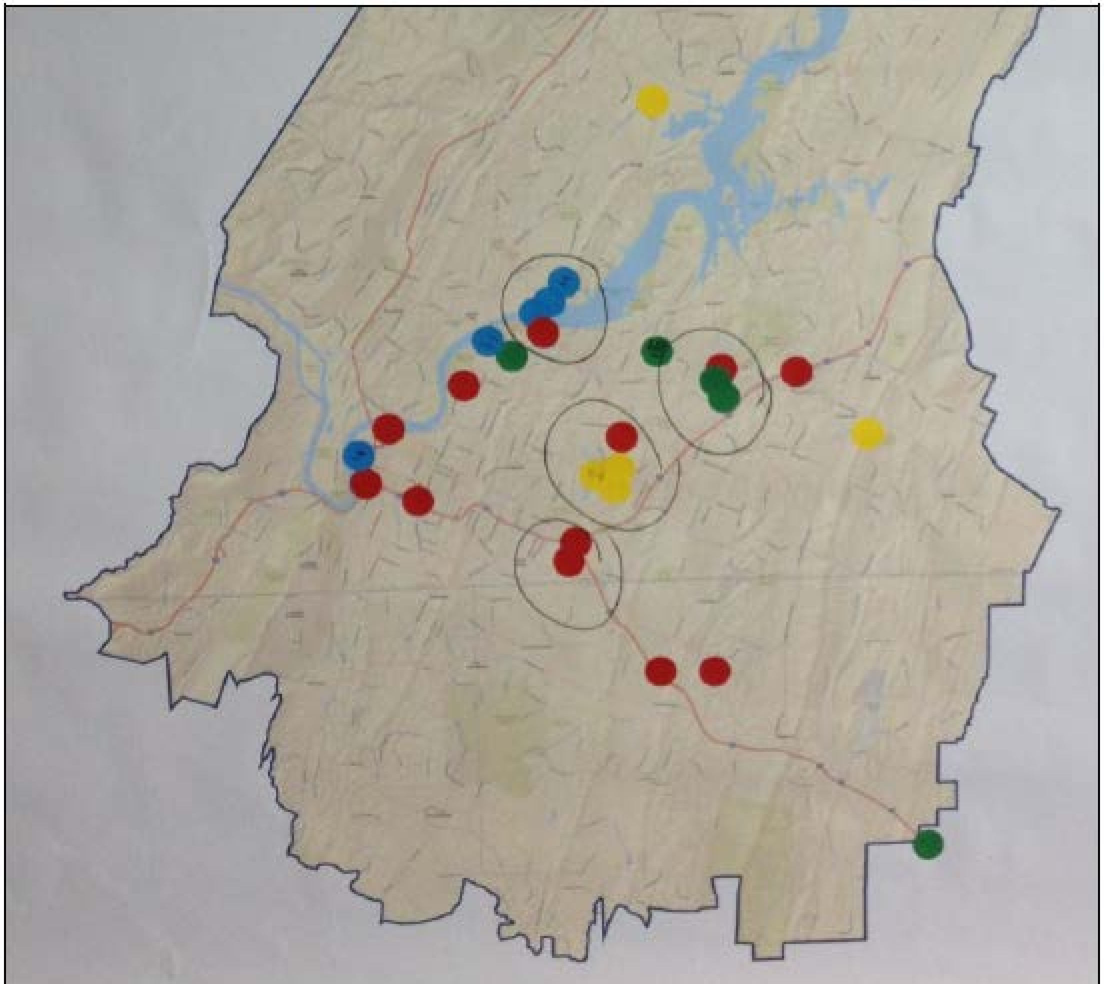


Table 3.2 Critical Assets (Shortlist)

Asset	Description	Why Critical?
Chickamauga Lock and Dam*	River lock Flood control/power Major roadway bridge Associated park	Movement of freight and people Movement of river cargo Mitigation of flooding Quality of life
Chattanooga Metropolitan Airport, Access Roads (SR 153), and Rail*	Intermodal complex, including the airport, access roads, and adjacent rail infrastructure	Economy – freight movement, jobs, and interregional commerce Tourist/travel opportunities (connection to national air network) Potential intermodal hub
Interchange of I-75 and I-24*	Interchange of I-75 (to Knoxville/Atlanta) and I-24 (Nashville) Structurally connected with Brainerd Levee	Highly congested major regional/interregional connector
Tennessee River Bridges	Three vehicle and one pedestrian bridges crossing the Tennessee River in the vicinity of downtown Chattanooga	Multimodal (vehicle, bicycle, walking) access between destinations on either side of the river Associated river travel and destinations
Volkswagen/ Enterprise South Area	A multi-destination, multimodal complex, anchored by Volkswagen	Economy – major source of jobs Services (healthcare) Recreational opportunities

Figure 3.4 Critical Transportation Assets in the Chattanooga Region (Detail)

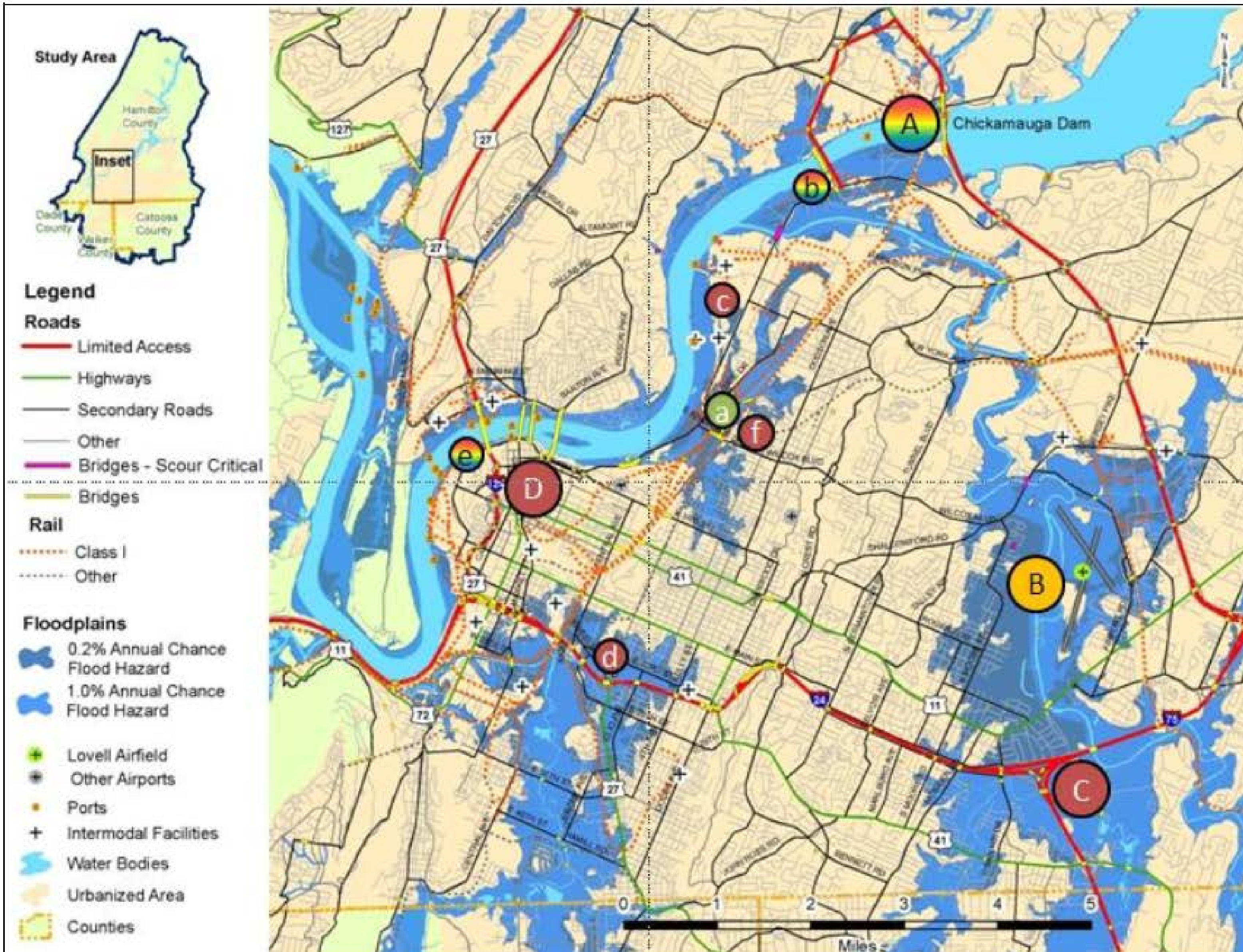


Table 4.1 Risk Assessment and Adaptation Matrix for Lock and Dam

Stressor	Potential Impacts	Consequence	Frequency	Adaptation Strategies
Extreme Precipitation	Flooding that overstresses dam structure	Up to catastrophic damage	Unknown, but increasing	Conduct a probabilistic risk assessment
	Flooding that impacts recreational activity	Disruption	Unknown, but increasing	Swift closure policies to protect life and safety
Extreme Temperature	Concrete blow ups of Dam structure	Deterioration, progressive damage	Unknown, but increasing	Continuous maintenance and monitoring
	Limiting activity at recreational area, increased heat island effect	Reduced use of facility	Unknown, but increasing	Expand the tree canopy and reduce/curb expansion of heat sinks

Source: CHCRPA RTP Climate Adaptation Workshop, September 17, 2012.

Table 4.2 Risk Assessment and Adaptation Matrix for Airport and SR153

Stressor	Potential Impacts	Consequence	Frequency	Adaptation Strategies
Extreme Precipitation	Flooding of access roads (including SR 153)	Disruption Deterioration	Currently once every 5-10 years, but increasing	Reconstruct vulnerable intersections, upgrade drainage Green infrastructure (bioswales, removing impervious surfaces)
	Flooding of Navigational Aids (NAVAIDS)	Disruption (moderate)	Currently once every 25 years, but increasing	Elevate NAVAIDS Create auto shut-off feature corresponding to inundation
Extreme Temperature	Asphalt rutting	Damage (minor) Deterioration	Unknown, but increasing	Concrete pavement (instead of asphalt)
	Loss of aircraft lift	Operational constraints	Unknown, but increasing	Conduct analysis Address through aircraft technology (monitor)

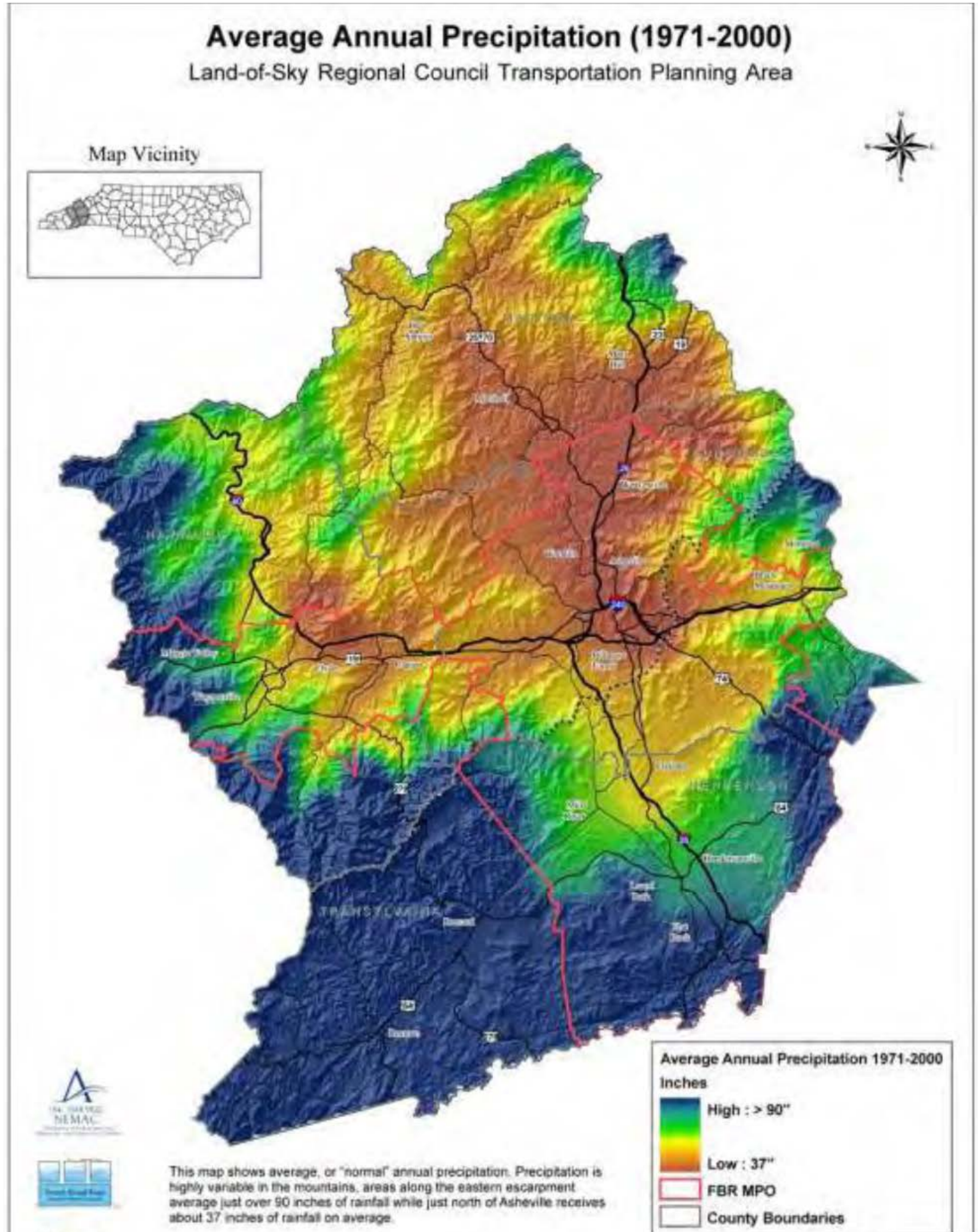
Source: CHCRPA RTP Climate Adaptation Workshop, September 17, 2012.

Table 4.3 Risk Assessment and Adaptation Matrix for I-75/I-24 Interchange

Stressor	Potential Impacts	Consequence	Frequency	Adaptation Strategies
Extreme Precipitation	Flooding	Damage to levee Damage to I-75 Disruption to I-24	Currently once every 100 years, but increasing	Raise levee Comprehensive redesign
Extreme Temperature	Significant expansion	Major damage Disruption	Unknown, but increasing	Alternative route planning
	Slight pavement expansion	Major deterioration	Unknown, but increasing	Pavement improvements

Source: CHCRPA RTP Climate Adaptation Workshop, September 17, 2012.

Asheville, NC



“Climate change models indicate that our future planning will need to be able to accommodate a greater frequency for the hazards of wildfire, flooding, landslides and dam breach in our region.”

“Therefore, roads in the valleys will need to be designed to withstand greater periods of extreme heat, while the roads in the higher elevations will need to be designed to withstand colder temperatures and icing events.”

Implement strategies to reduce risk of flooding (and other risks), including reviewing roads and bridges in flood-prone areas to ensure they are designed to handle the risk.

Redesign railroads to make them more resilient to climate change impacts

Factor in budgetary impacts caused by preparation for responding to temperature extremes.

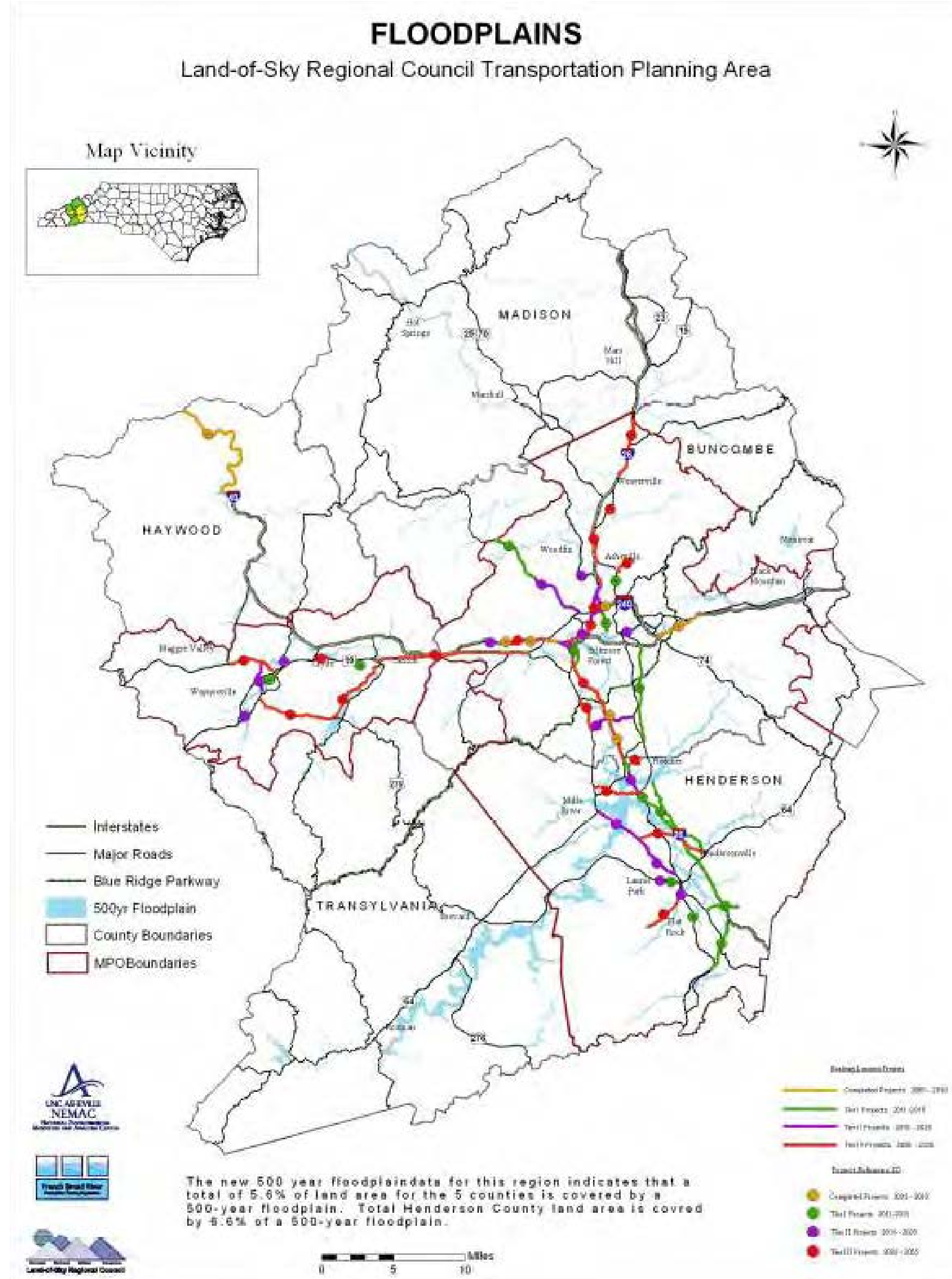
Coordinate with the region’s local governments and planning partners to link transportation with land use.

Use future scenarios in transportation and land use planning to design systems that are robust and resilient compared to just being optimized for current conditions and economics.

Pinch points on maps to show vulnerable “hotspots” that lack options. More drought, fires and intense rainfall amounts will produce more landslides that can be a major disruption to our main transportation corridors.

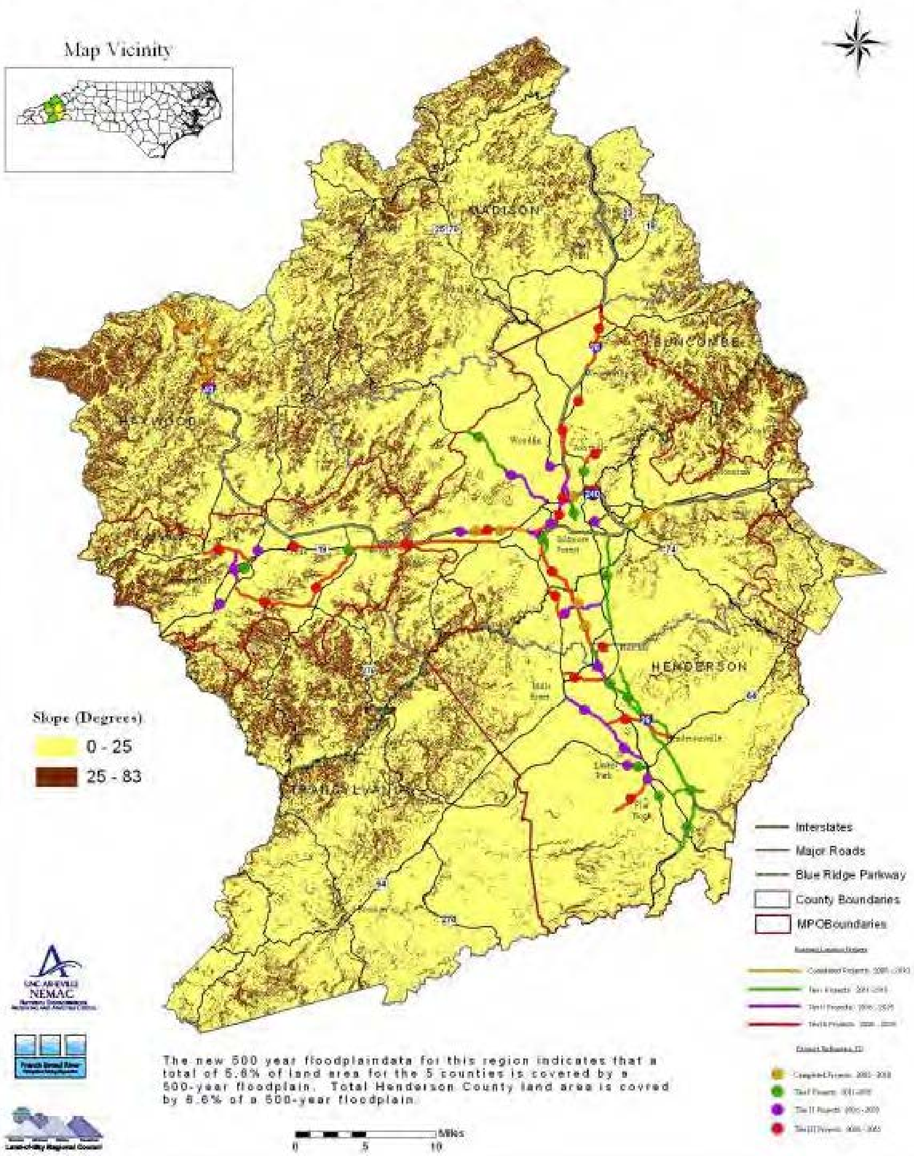
MPO staff analyzed the potential for proposed LRTP projects to be impacted by climate change concerns.

Proposed LRTP projects were overlaid on maps of the region's 500 year floodplain, wildfire risk, and steep slopes (prone to landslides).



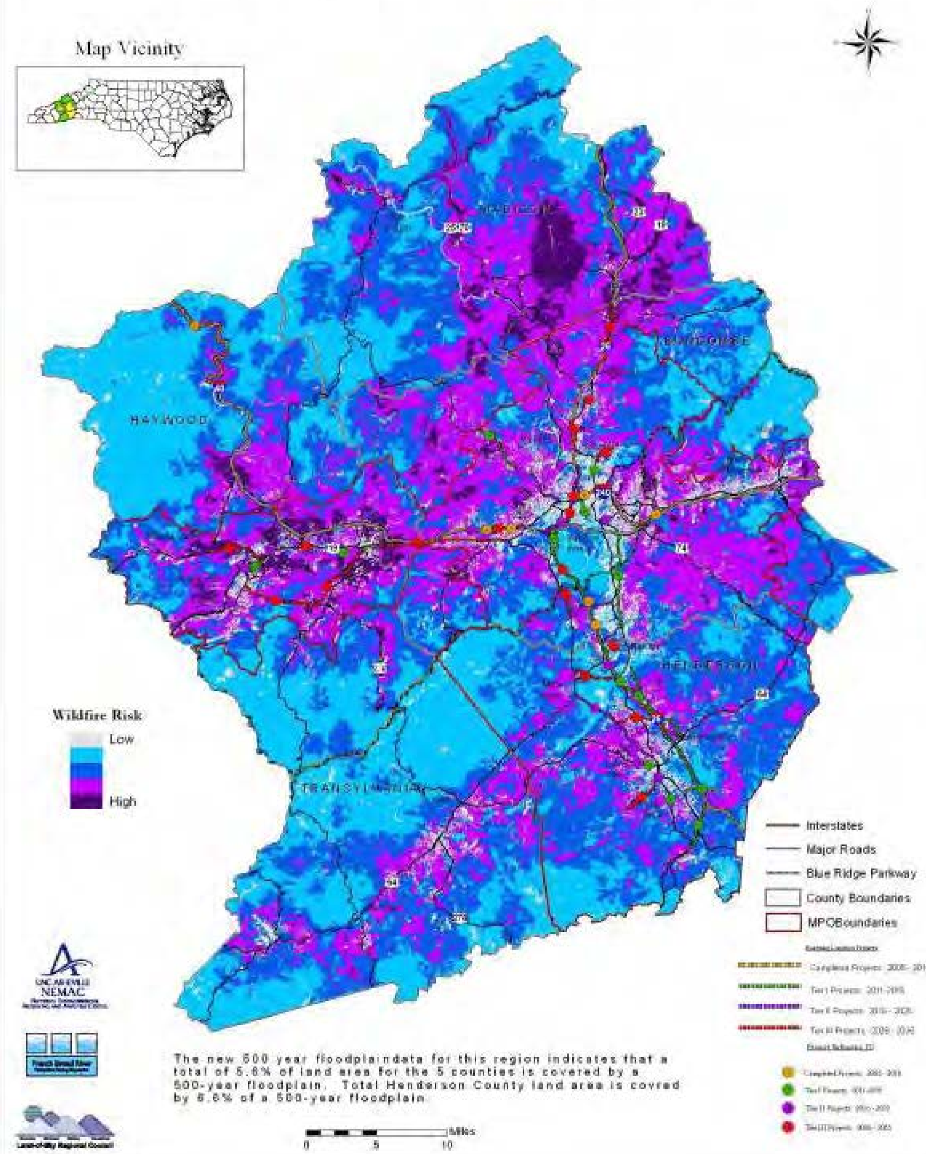
Slope (Above and Below 25 Degrees)

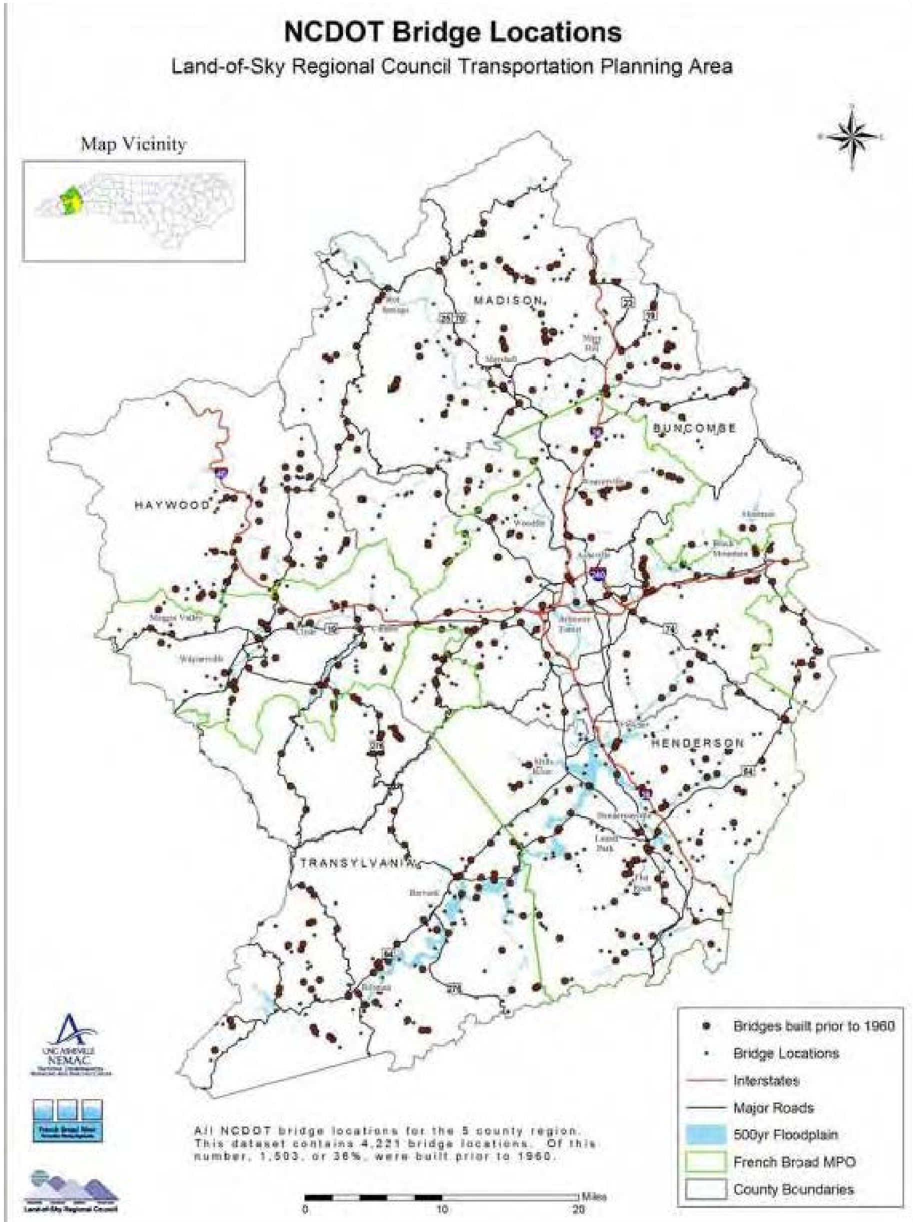
Land-of-Sky Regional Council Transportation Planning Area



Risk of Wildfire

Land-of-Sky Regional Council Transportation Planning Area




NCDOT Bridge Locations
Land-of-Sky Regional Council Transportation Planning Area
Map Vicinity
MADISON
BUNCOMBE
HAYWOOD
HENDERSON
TRANSYLVANIA
Bridges built prior to 1960
Bridge Locations
Interstates
Major Roads
500yr Floodplain
French Broad MPO
County Boundaries
All NCDOT bridge locations for the 5 county region. This dataset contains 4,221 bridge locations. Of this number, 1,503, or 36%, were built prior to 1960.
Miles
0
10
20
Land-of-Sky Regional Council

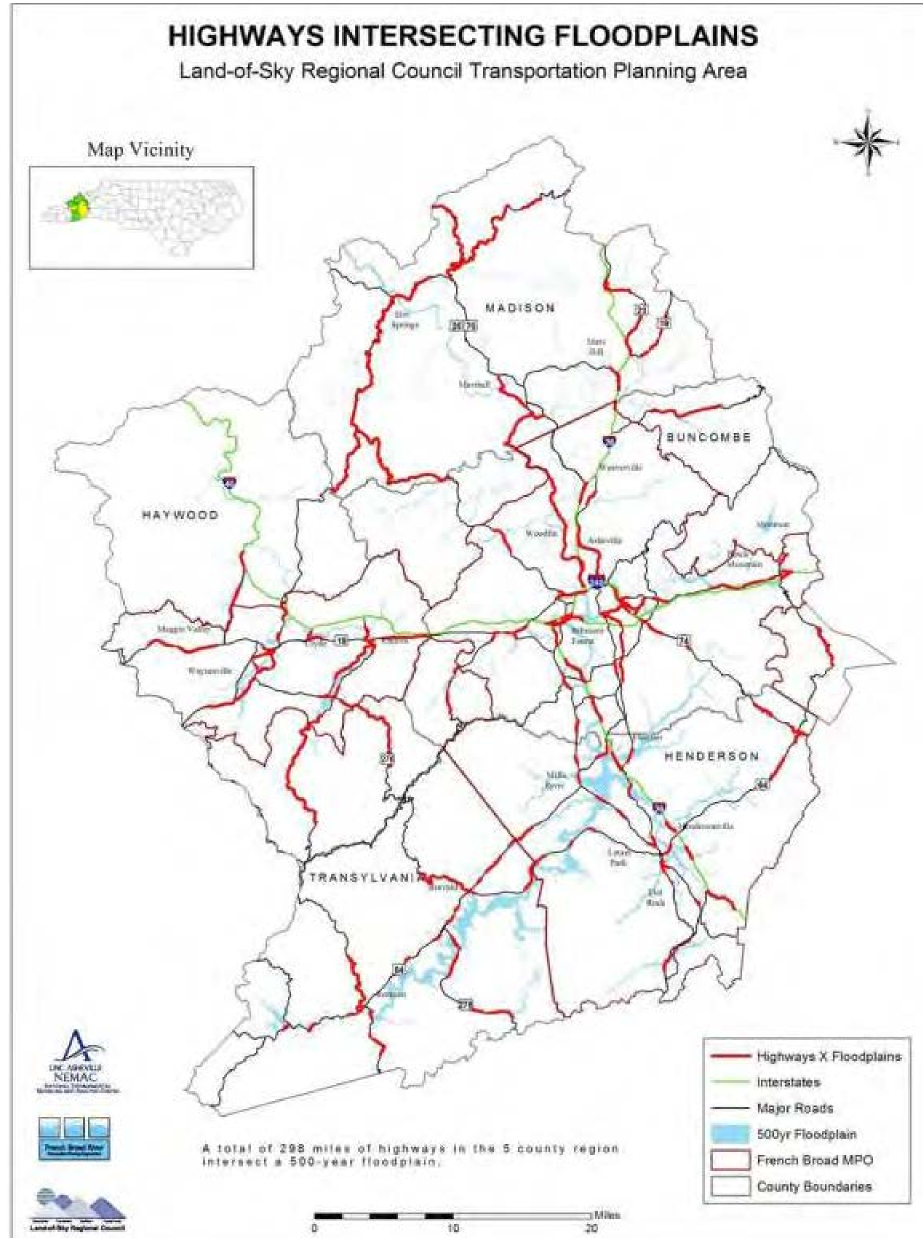

HIGHWAYS INTERSECTING FLOODPLAINS
Land-of-Sky Regional Council Transportation Planning Area
Map Vicinity
MADISON
BUNCOMBE
HAYWOOD
HENDERSON
TRANSYLVANIA
Highways X Floodplains
Interstates
Major Roads
500yr Floodplain
French Broad MPO
County Boundaries
A total of 298 miles of highways in the 5 county region intersect a 500-year floodplain.
Miles
0
10
20
Land-of-Sky Regional Council

Table 13.1 Impact Matrix - Climate Change						
Completed/ In progress Projects: 2005-2010						
Project Number	**Map Number**	**Facility**	**Project Description/Extents**	**Floodplains**	**Wildfire Risk**	**Slope > 25 Degrees**
I-4400	A1	I-26	NC 255 (US 25 Connector) to NC 280. Widen to six lanes	x		
I-4700	A2	I-26	NC 280 to I-40 at Asheville. Add additional lanes	x	x	
I-4752	A3	I-26, I-49 and I-240	Installation of guide signs to Biltmore Estate	x	x	
I-4920	A4	I-26	North of NC 146 (milepost 37) to North of Henderson County Line (Milepost 40), Pavement Rehabilitation	x		
I-4401	A5	I-40	I-20 to west of US 19-23, add additional lanes	x		
I-4417	A6	I-40	Old Fort Mountain. Installation of fog detection system to detect low visibility conditions to provide advance warning to motorists	x		
4726	A7	I-40	US 74A (Milepost 53) to west of SR 2750 (Milepost 55). Patch reinforced concrete pavement (CRCP). West of SR 750 (Milepost 55) to east of SR 2750 (Milepost 59)	x	x	x

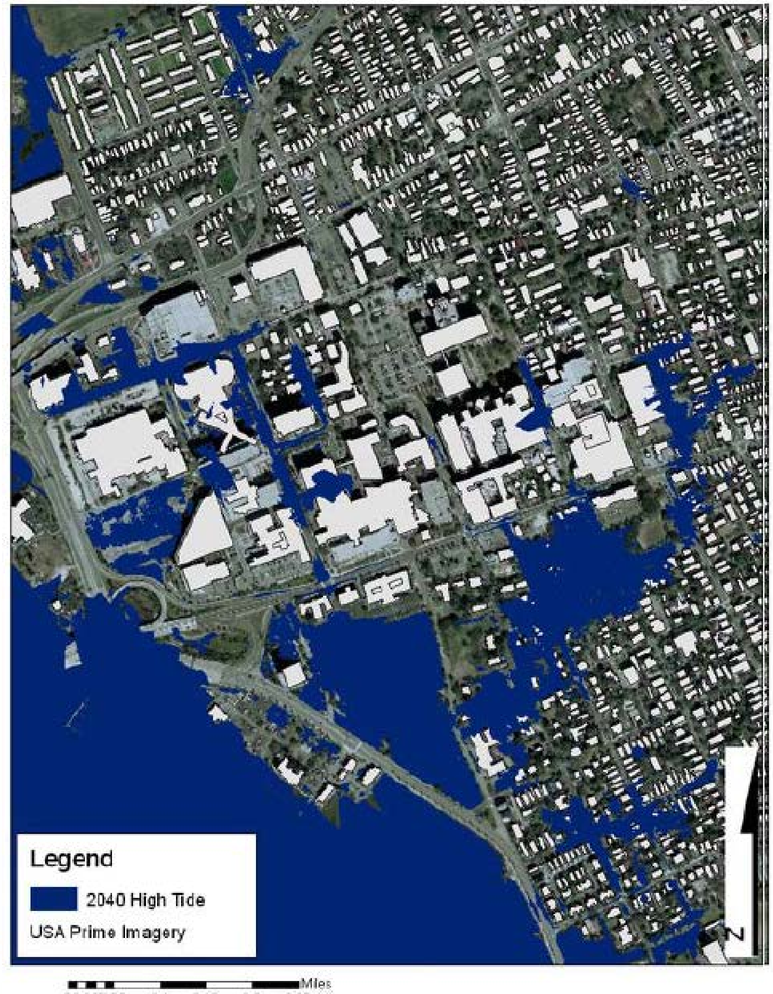
Charleston 0.5 m SLR

Critical Infrastructure:

VA Hospital

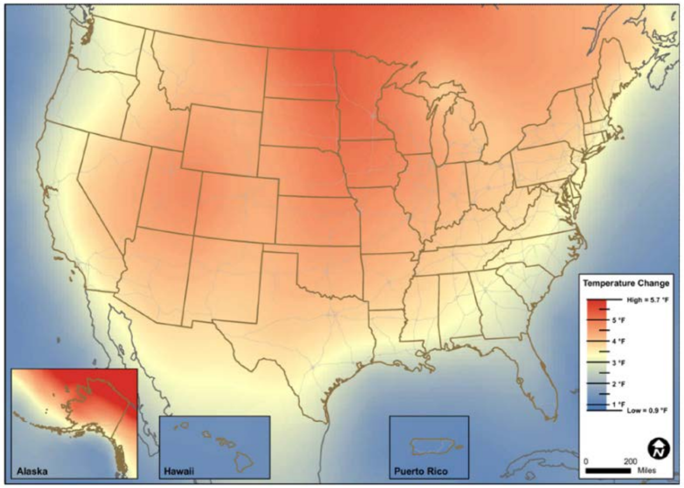
Medical University of SC

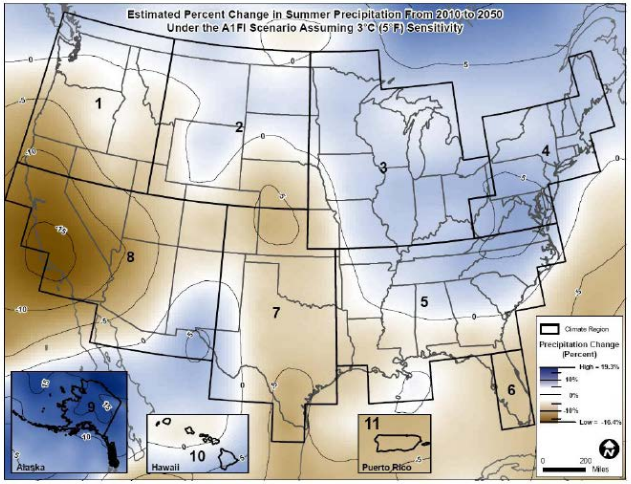
Roper Hospital



NCHRP 20-83(5)

Climate Change and the Highway System: Impacts and Adaptation Approaches





SPECIAL
REPORT
299

A Transportation Research Program for Mitigating and Adapting to Climate Change and Conserving Energy

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

Transportation Research Board
Special Report 290

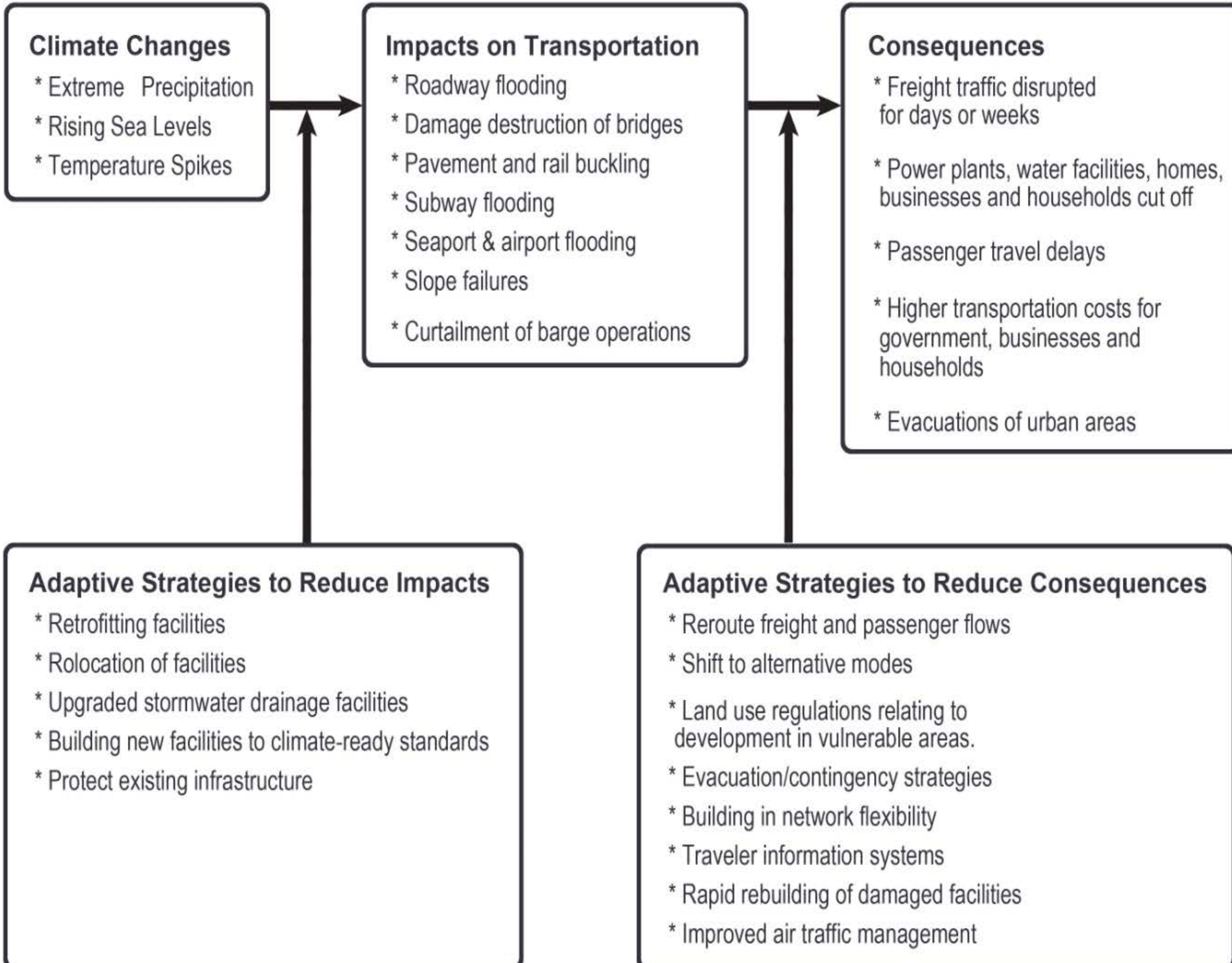
Potential Impacts of Climate Change on U.S. Transportation

Prepublication Copy • Uncorrected Proofs

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

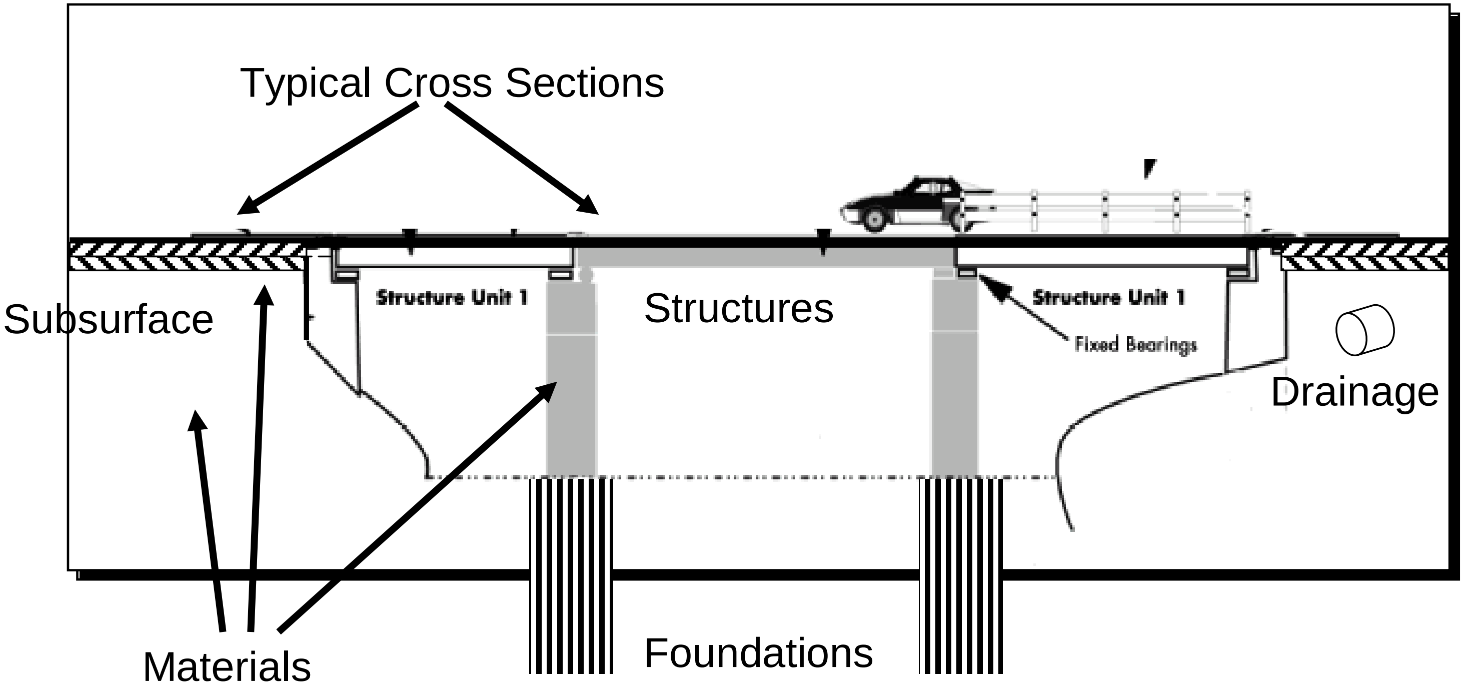
Adaptation per the Pew Center on Global Climate Change (as modified)

"Actions by individuals or systems to avoid, withstand, or take advantage of current and projected climate changes and impacts. Adaptation decreases a system's vulnerability, reduces risk and/or increases its resilience to impacts."



Climate Changes
* Extreme Precipitation
* Rising Sea Levels
* Temperature Spikes
Impacts on Transportation
* Roadway flooding
* Damage destruction of bridges
* Pavement and rail buckling
* Subway flooding
* Seaport & airport flooding
* Slope failures
* Curtailment of barge operations
Consequences
* Freight traffic disrupted for days or weeks
* Power plants, water facilities, homes, businesses and households cut off
* Passenger travel delays
* Higher transportation costs for government, businesses and households
* Evacuations of urban areas
Adaptive Strategies to Reduce Impacts
* Retrofitting facilities
* Rolocation of facilities
* Upgraded stormwater drainage facilities
* Building new facilities to climate-ready standards
* Protect existing infrastructure
Adaptive Strategies to Reduce Consequences
* Reroute freight and passenger flows
* Shift to alternative modes
* Land use regulations relating to development in vulnerable areas.
* Evacuation/contingency strategies
* Building in network flexibility
* Traveler information systems
* Rapid rebuilding of damaged facilities
* Improved air traffic management

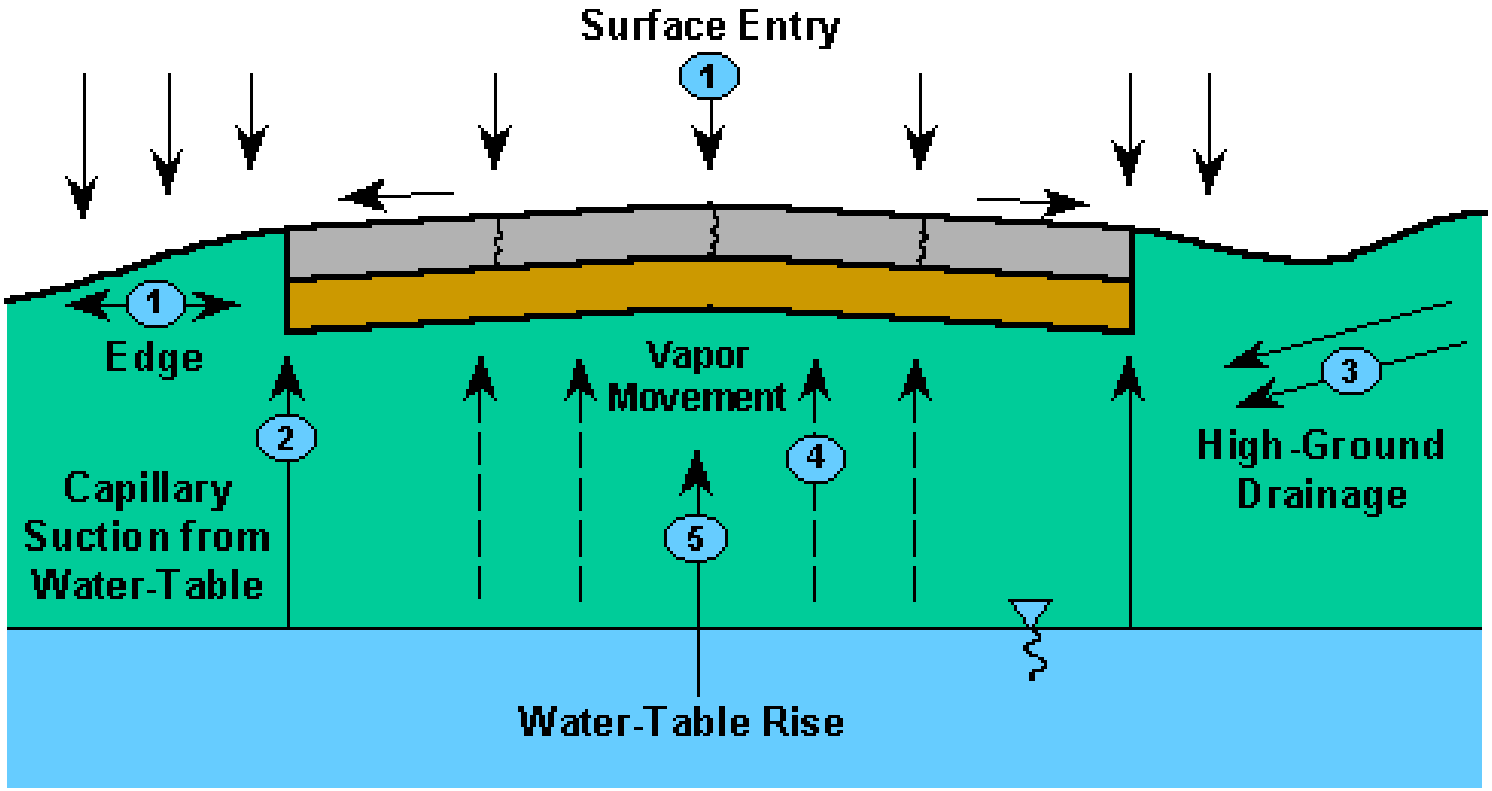
A Typical Road Segment

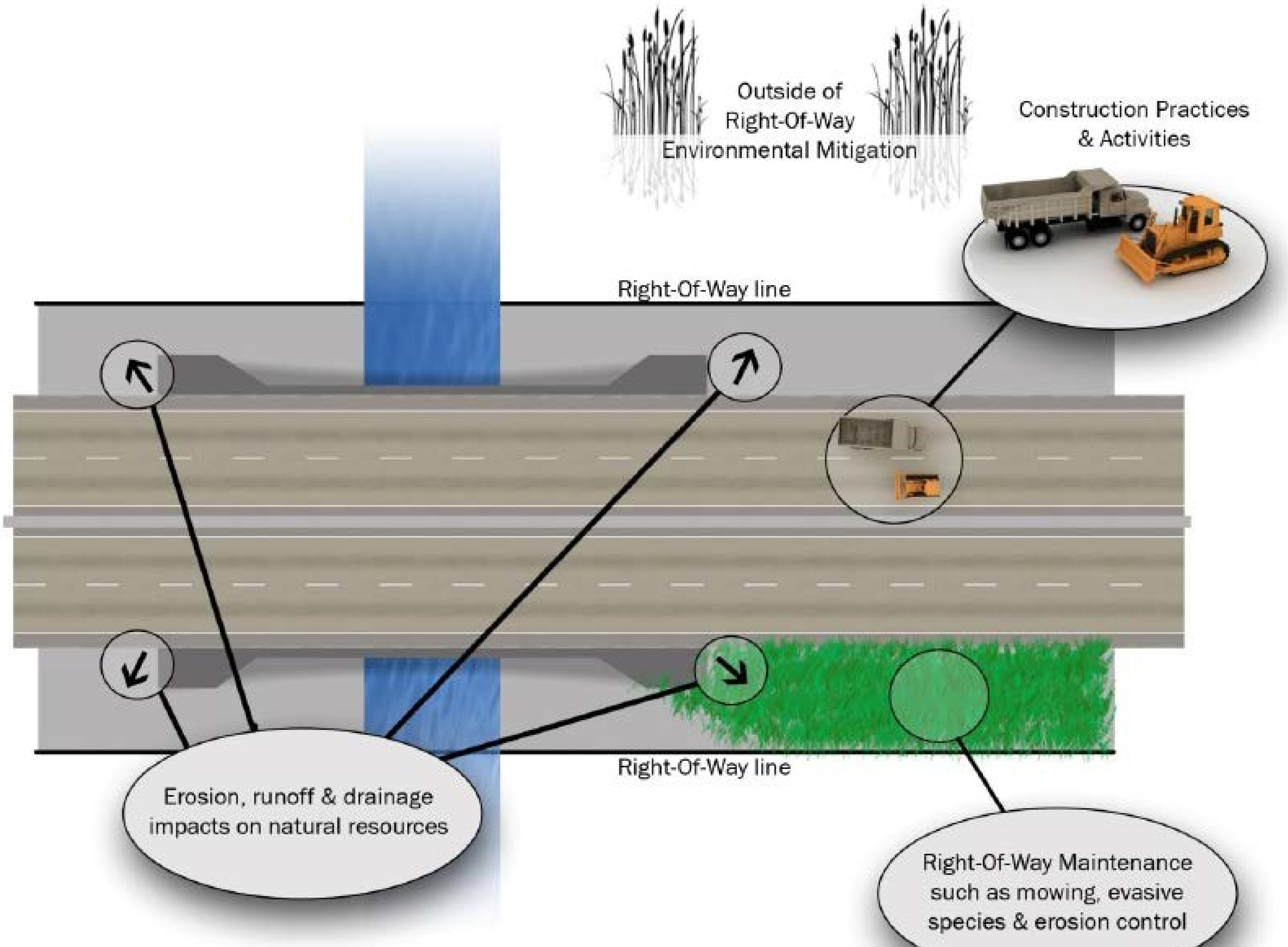


Critical Components of Infrastructure Design

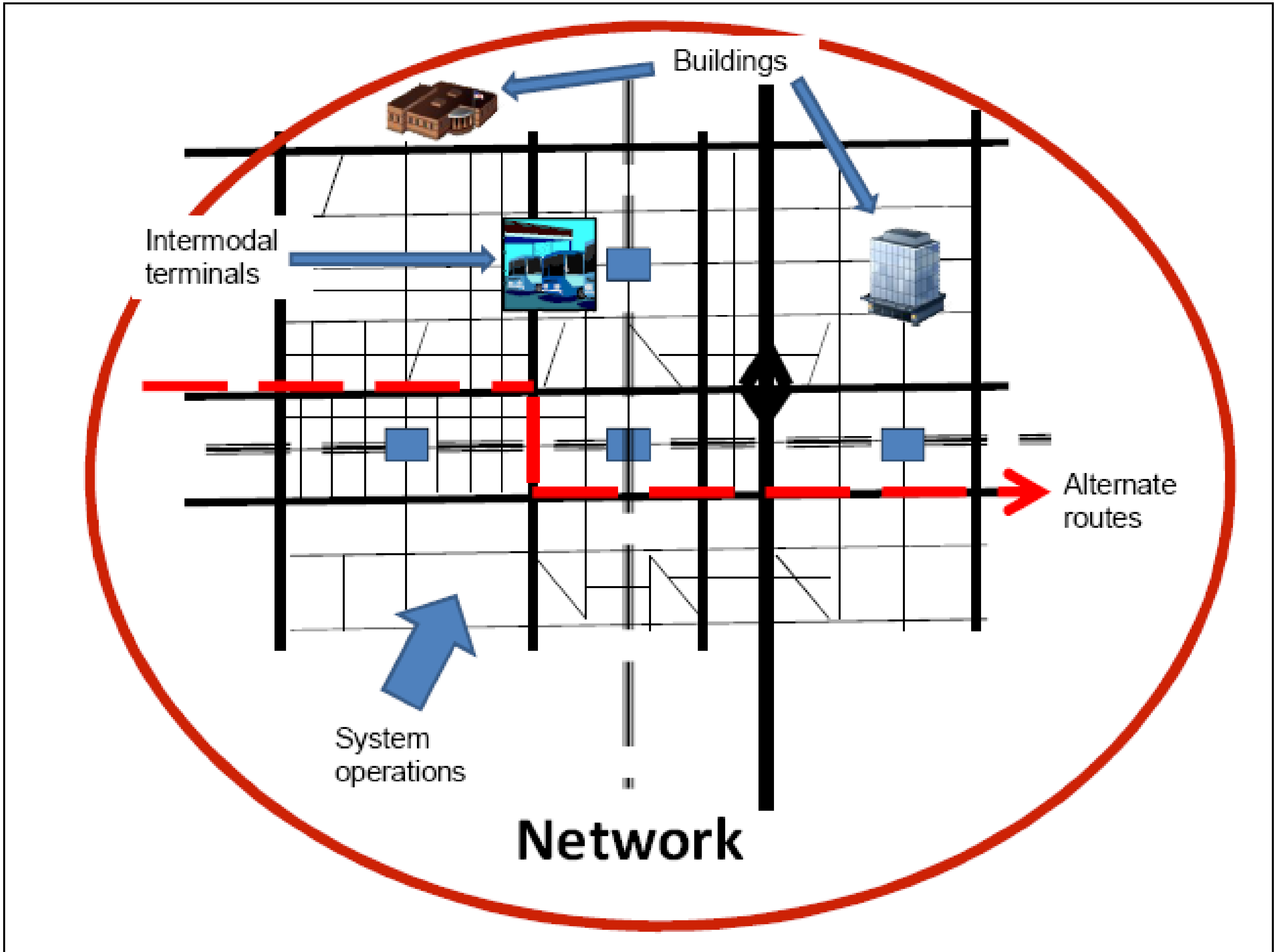
1. Subsurface conditions
2. Materials specifications
3. Cross sections/standard dimensions
4. Drainage and erosion
5. Structures
6. Location engineering

Water, for example, ……..





Corridor Impacts


Buildings
Intermodal terminals
Alternate routes
System operations
Network

Adaptation in response to what?

Figure 4-1: Estimated Increases in Temperature (°F) in 2050 Relative to 2010 Using A1F1 Scenario, 3°C Sensitivity

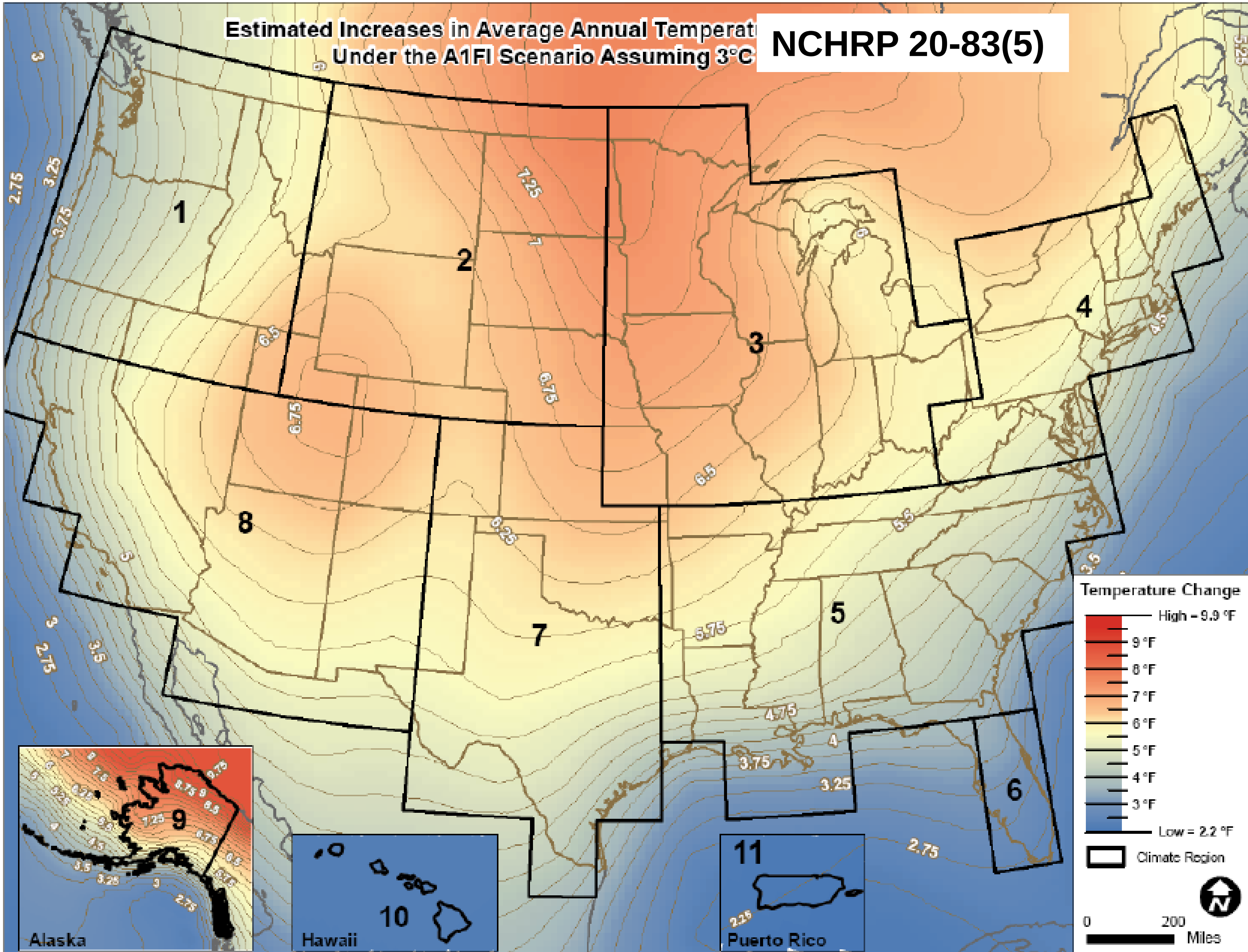
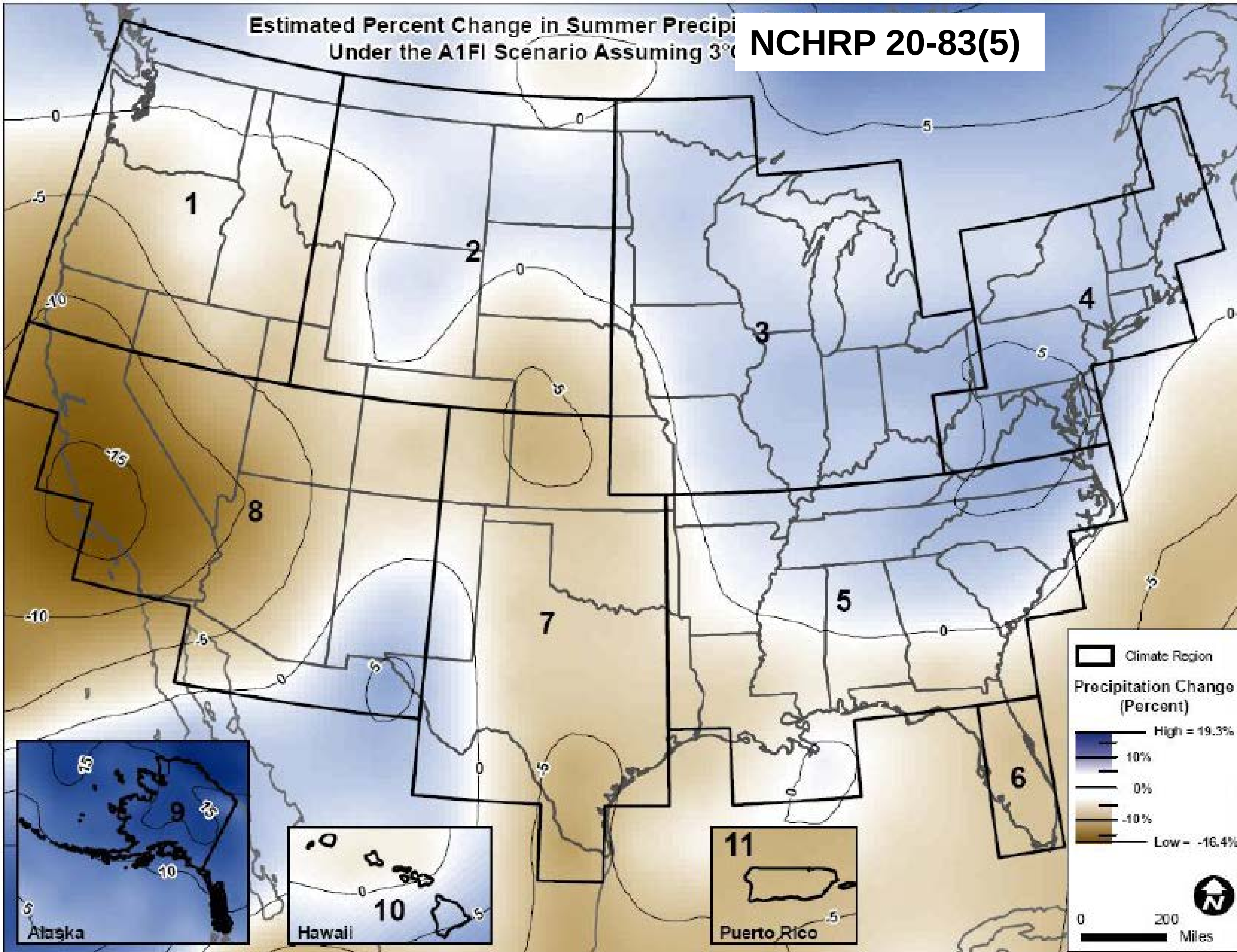
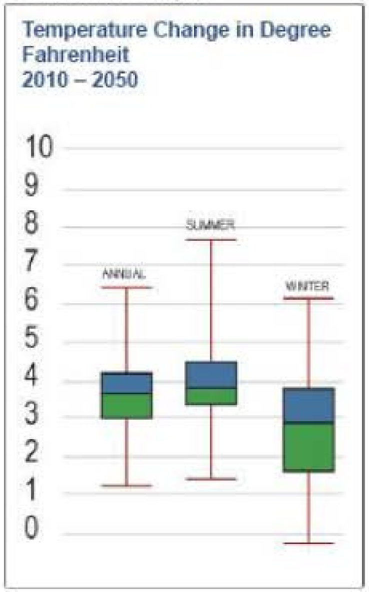
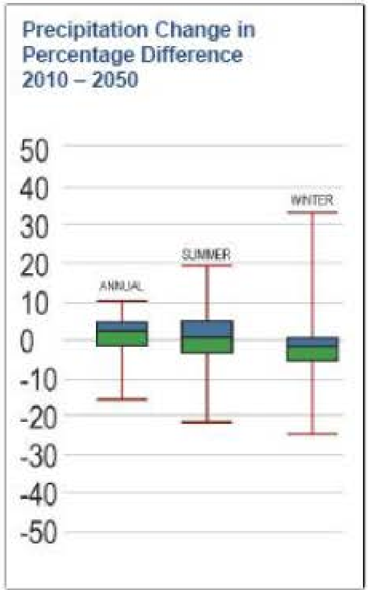


Figure 44-2: Percentage Change in Annual Precipitation in 2050 Relative to 2010 Using A1F1 Scenario, 3°C Sensitivity

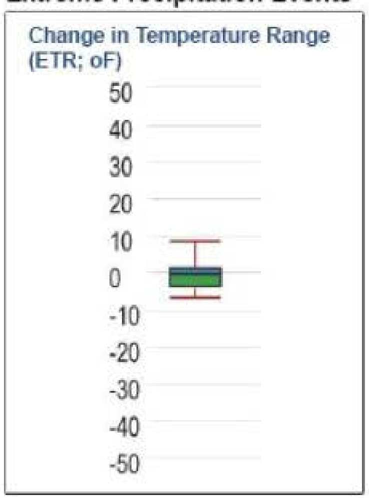


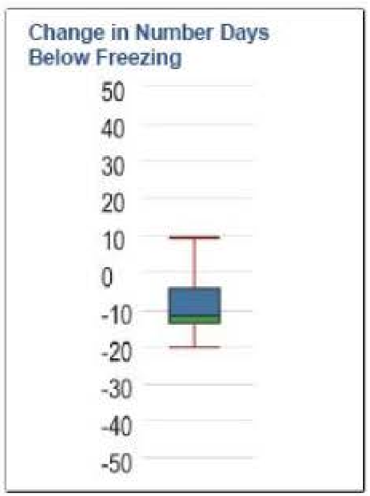
Season Averages

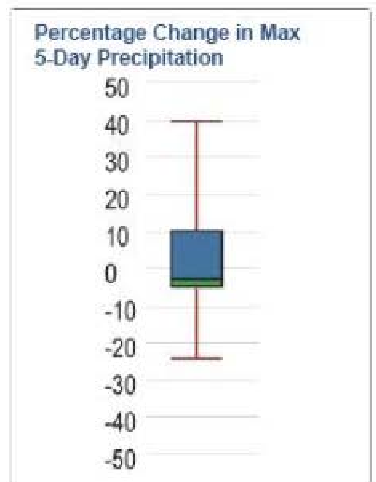




Extreme Precipitation Events







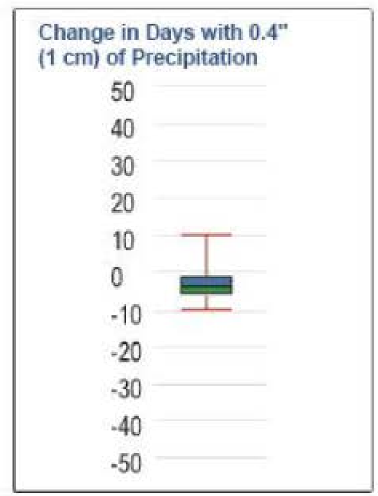
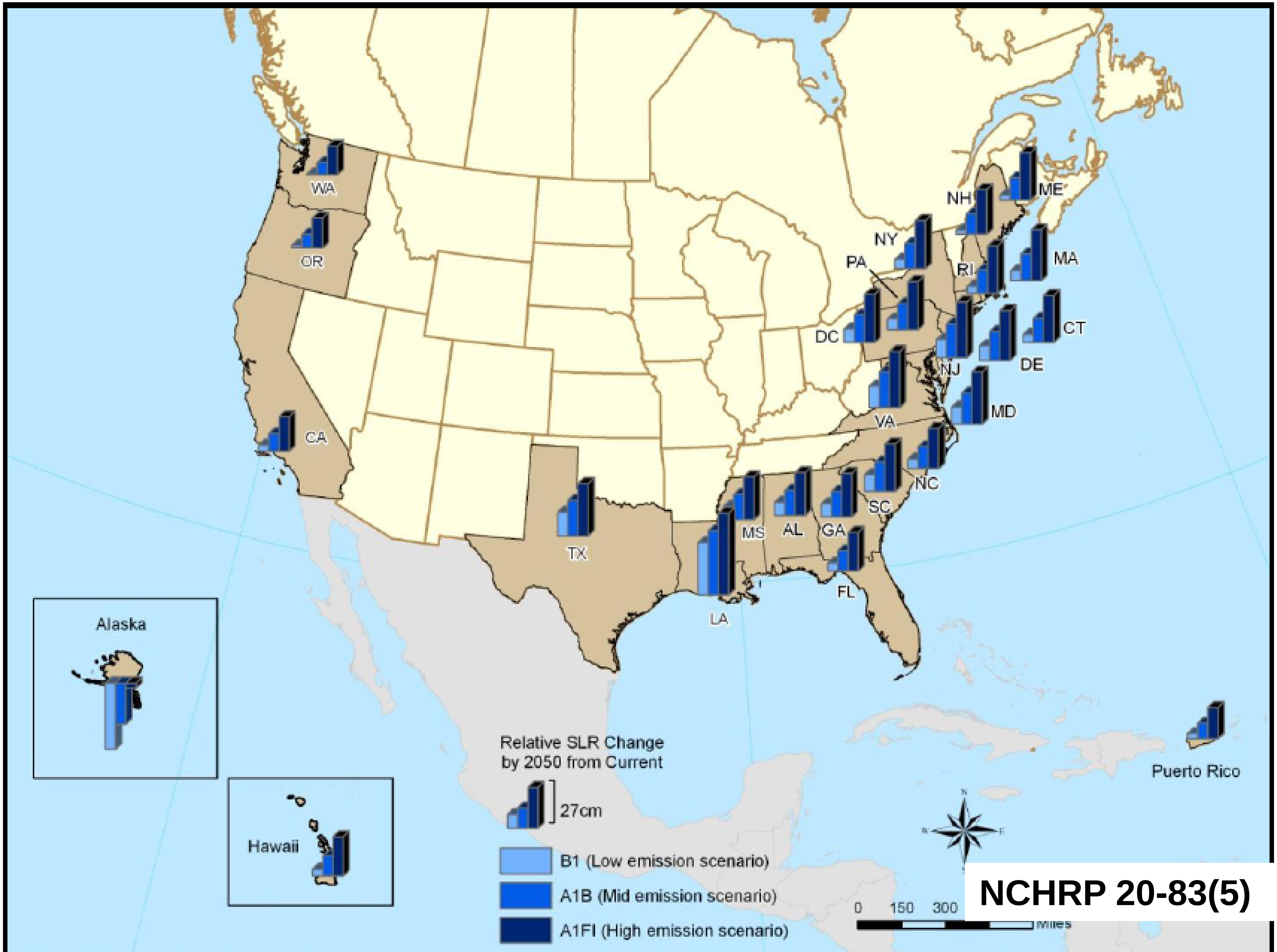
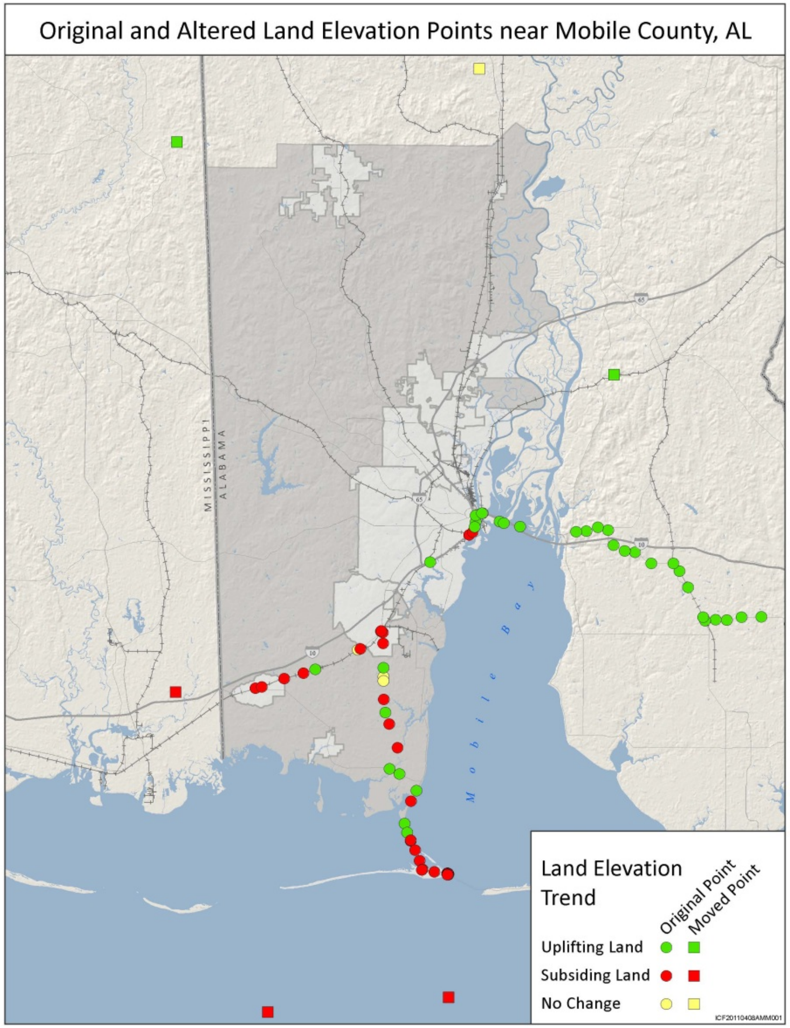


Figure 6-2: Projected Sea Level Rise, 2050 Relative to 2010

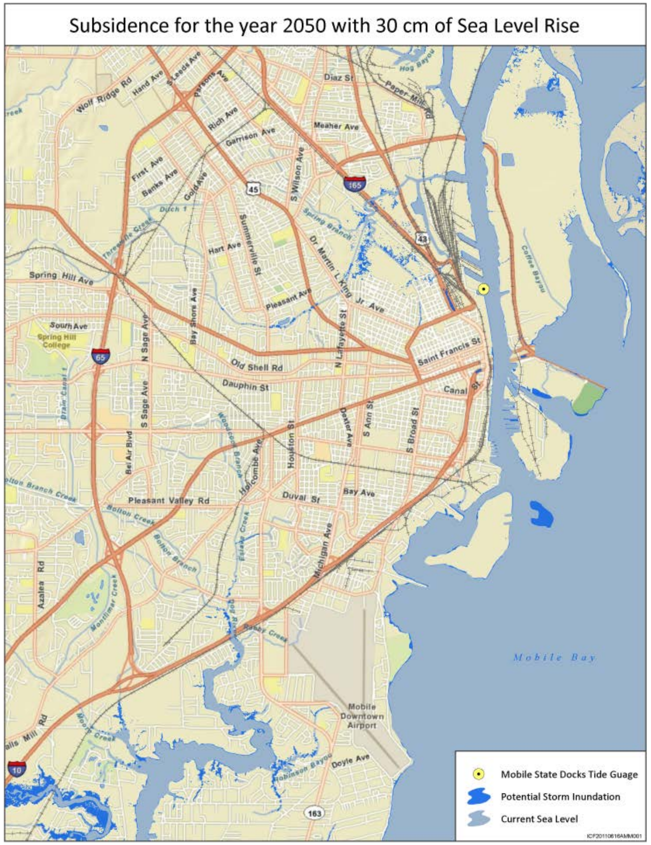


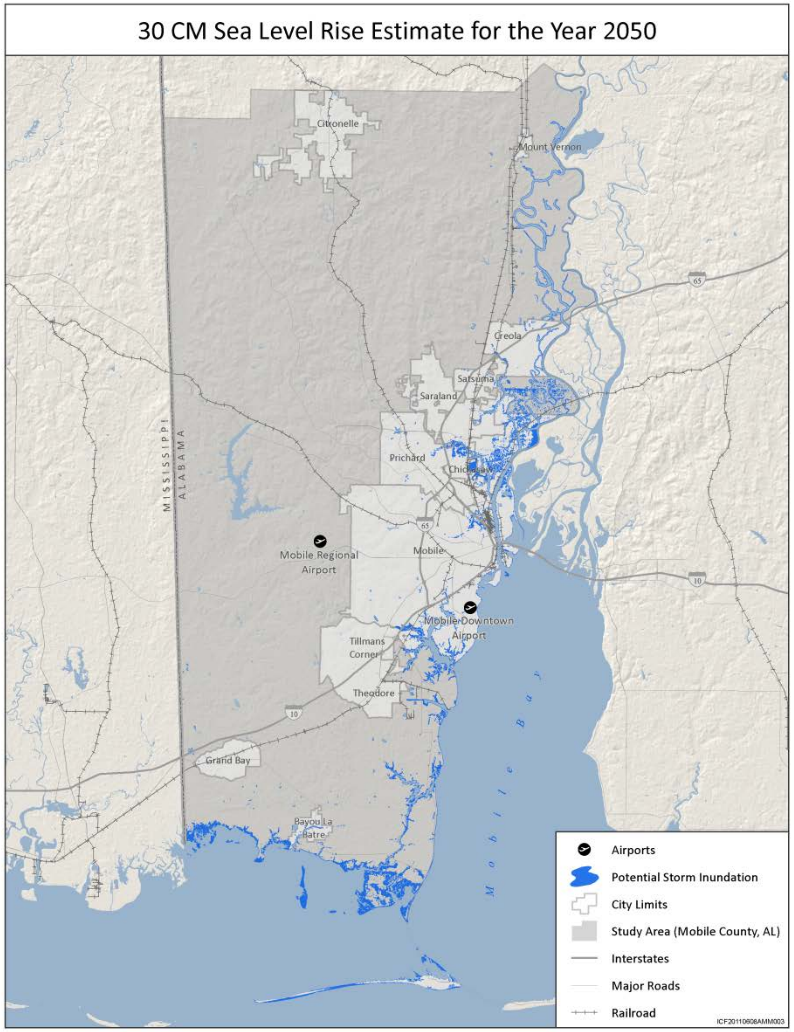
NCHRP 20-83(5)

Sea Level Rise Modeling, Gulf Coast 2



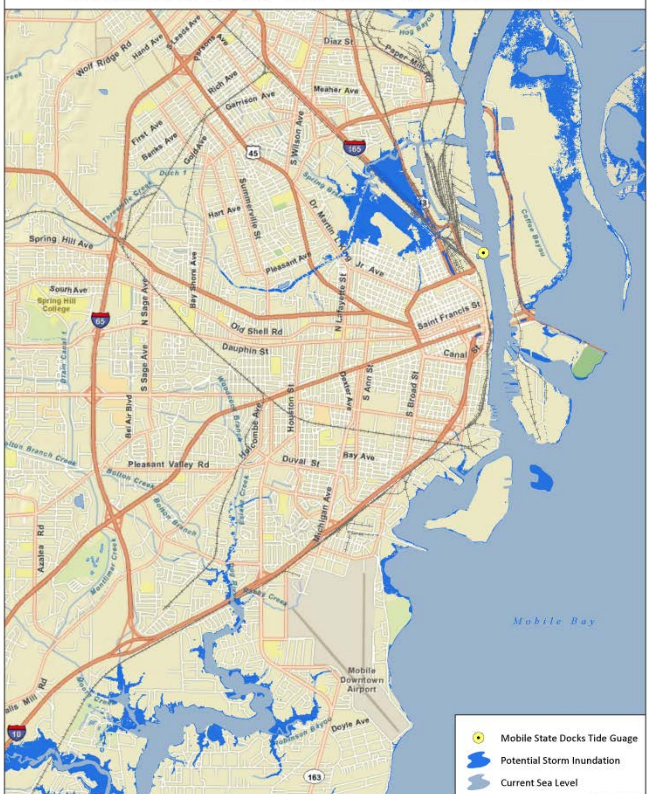
Sea Level Rise Modeling, Gulf Coast 2



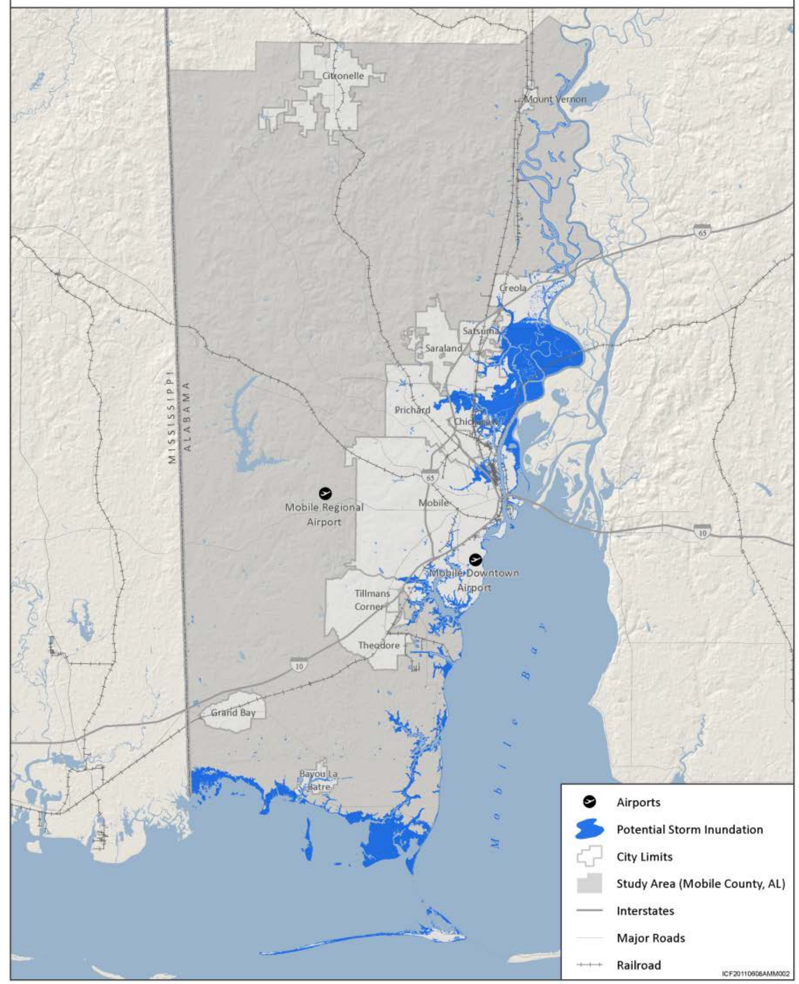


Sea Level Rise Modeling, Gulf Coast 2

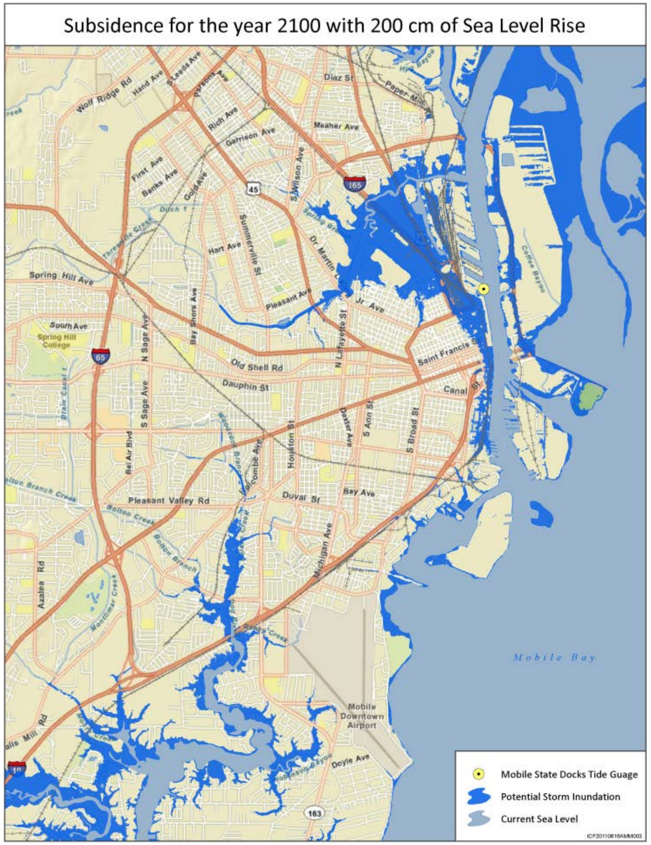
Subsidence for the year 2100 with 75 cm of Sea Level Rise

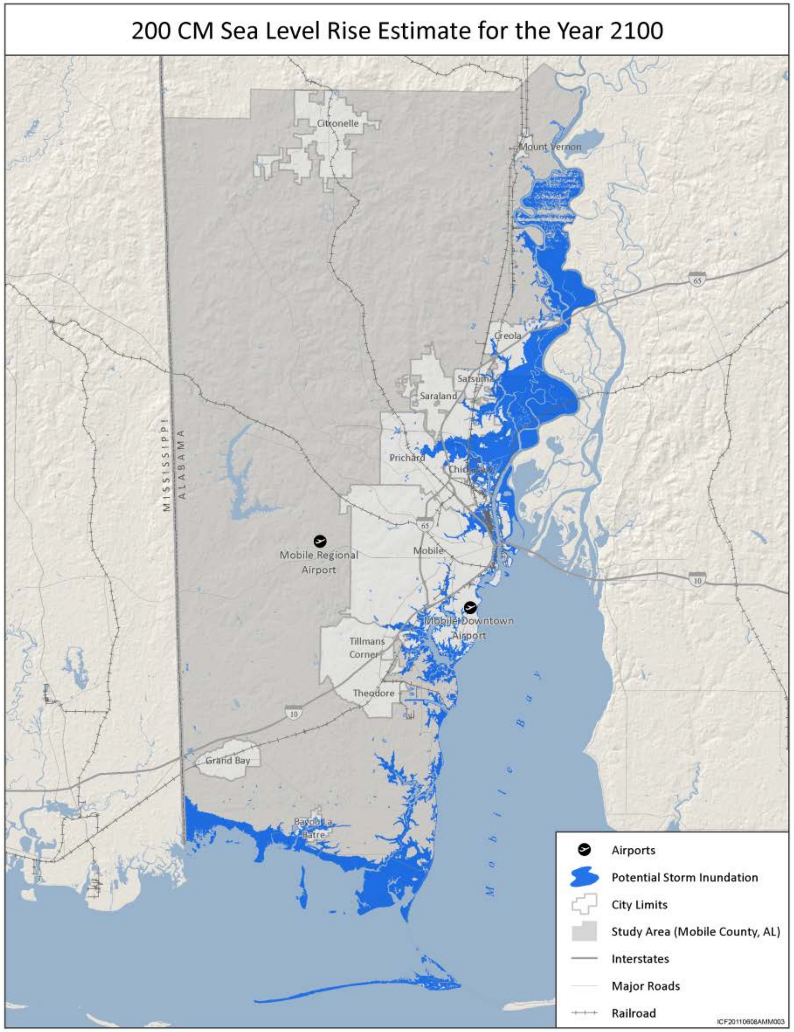


75 CM Sea Level Rise Estimate for the Year 2100



Sea Level Rise Modeling, Gulf Coast 2





Storm Surge Modeling, Gulf Coast 2

Storm Scenarios

Hurricane Georges

Natural Path, No Sea Level Rise

Natural Path, 30 CM Sea Level Rise

Natural Path, 75 CM Sea Level Rise

Natural Path, 200 CM Sea Level Rise

Hurricane Katrina

Natural Path, No Sea Level Rise

Natural Path, 75 CM Sea Level Rise

Shifted, No Sea Level Rise

Shifted, 75 CM Sea Level Rise

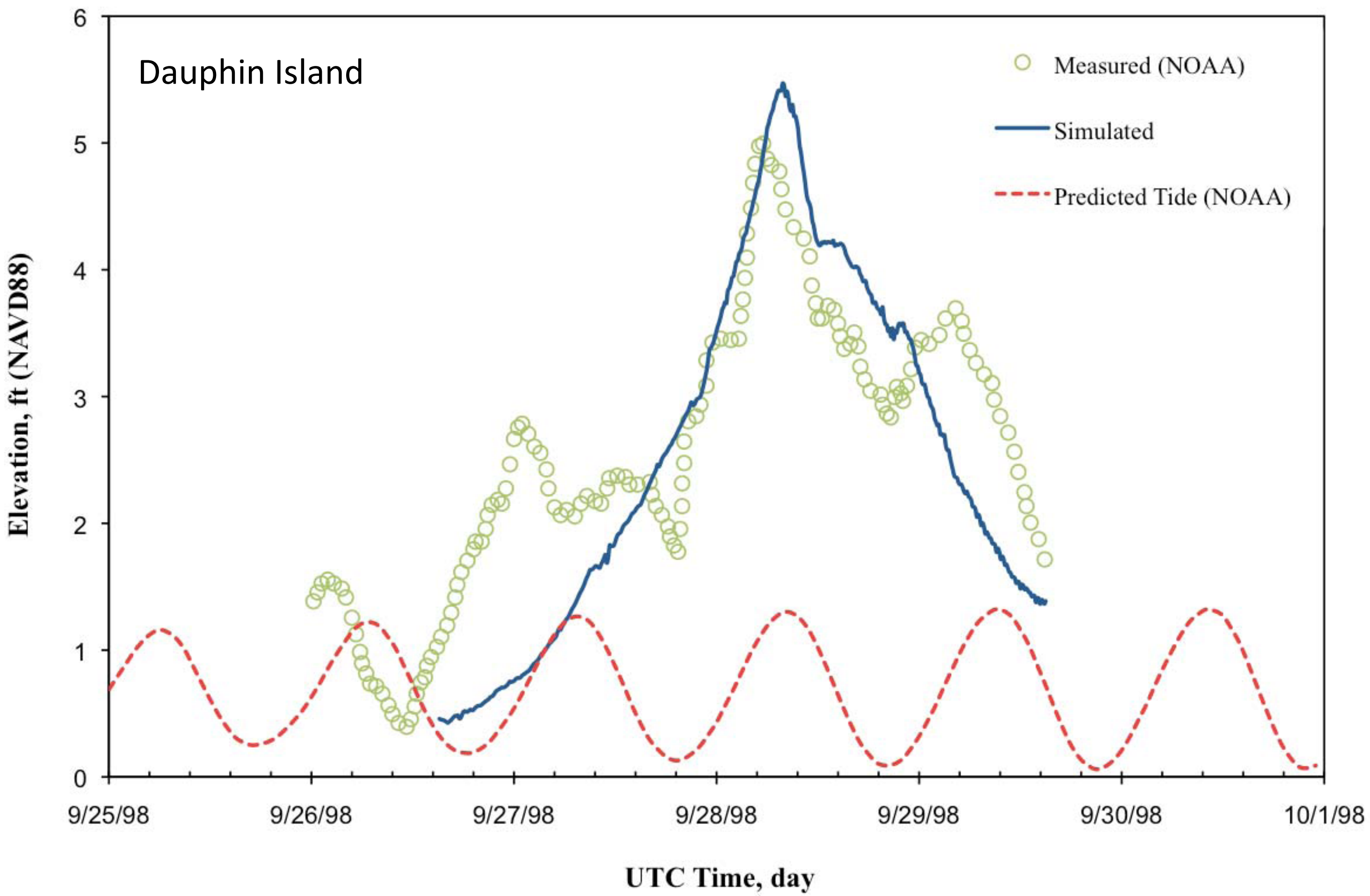
Shifted, Intensified, No Sea Level Rise

Shifted, Intensified, 75 CM Sea Level Rise

Shifted, Intensified, Pressure Reduced, 75 CM Sea Level Rise

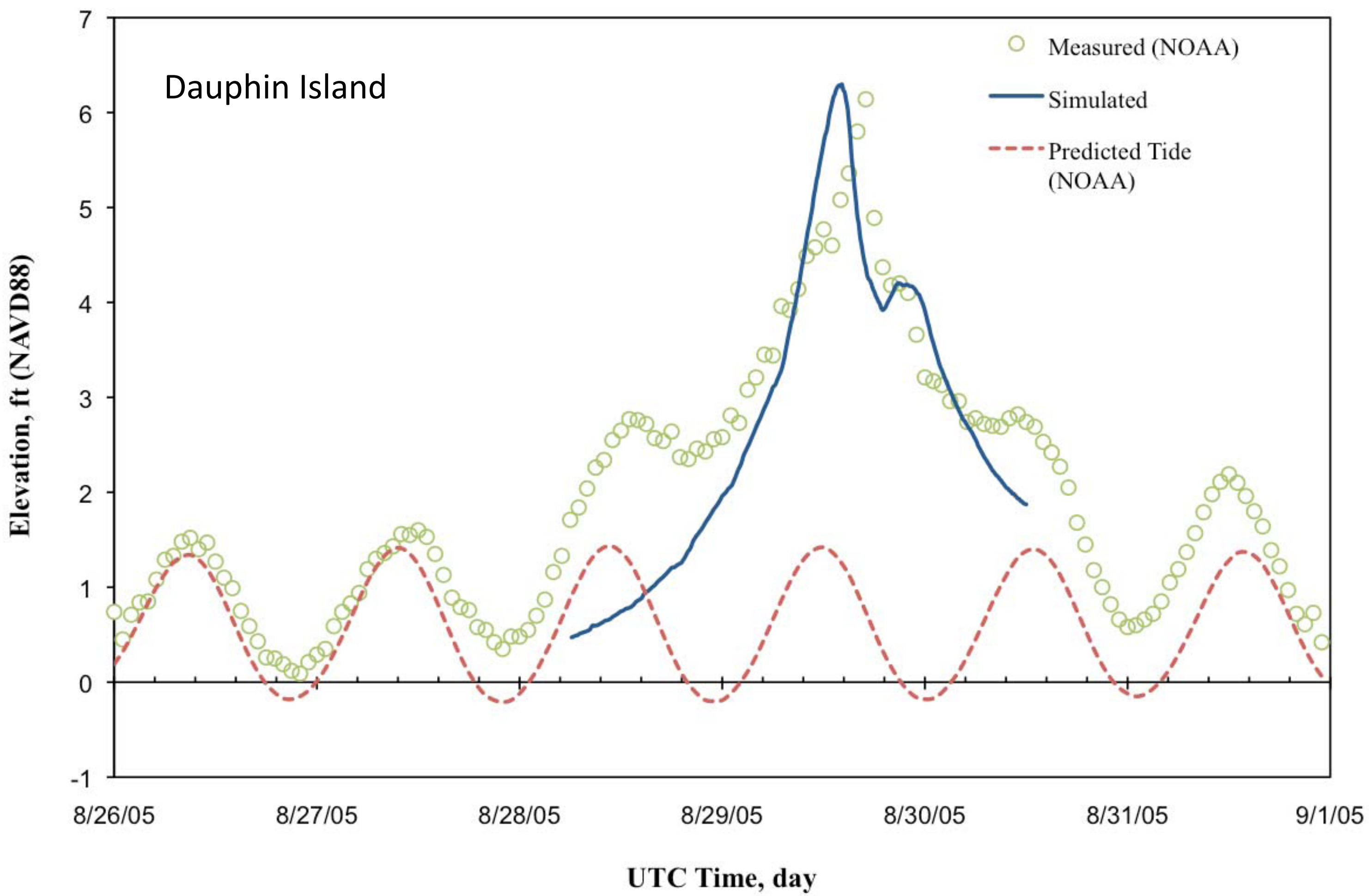
Storm Surge Modeling, Gulf Coast 2

Georges: Simulation vs. Observation

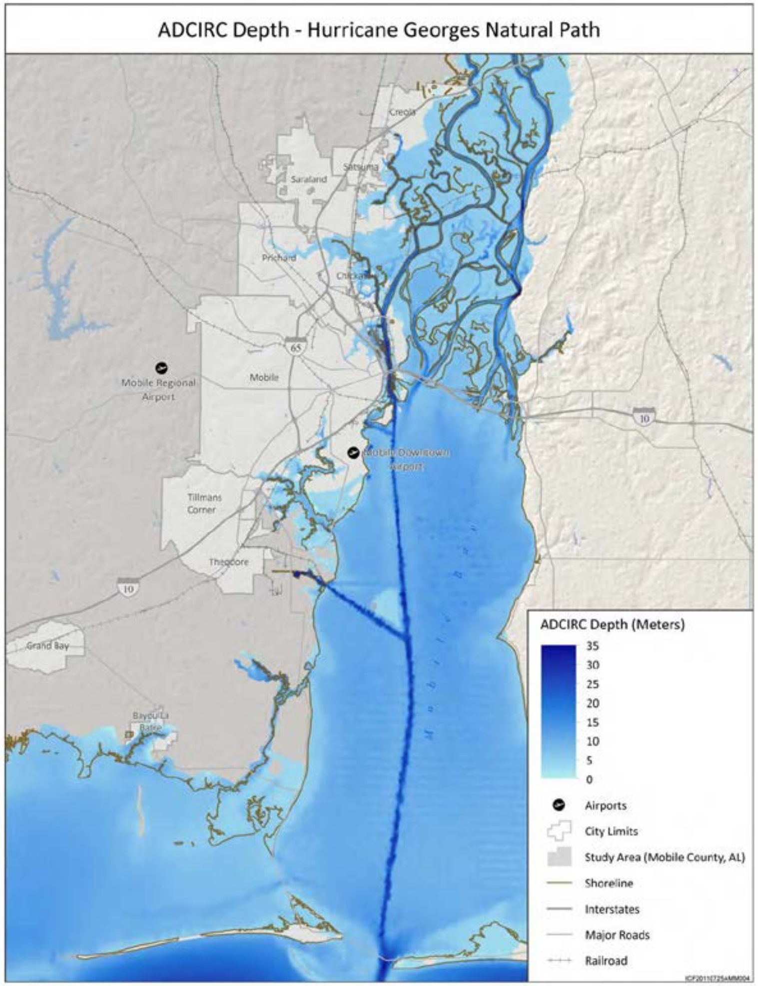


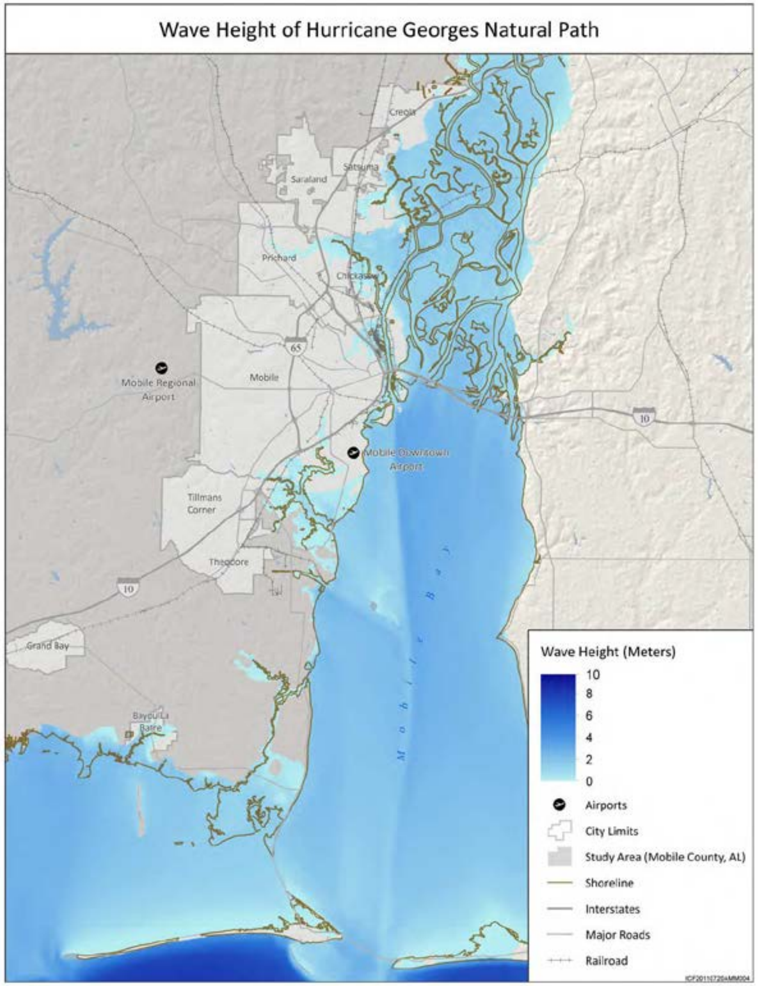
Storm Surge Modeling, Gulf Coast 2

Katrina: Simulation vs. Observation

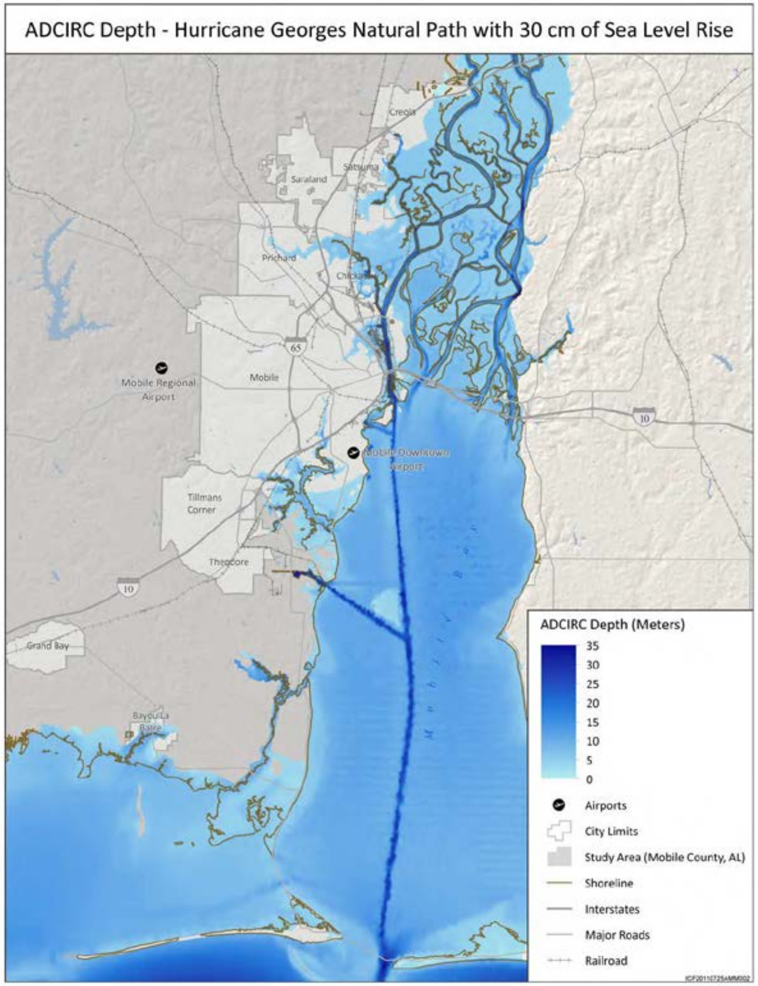


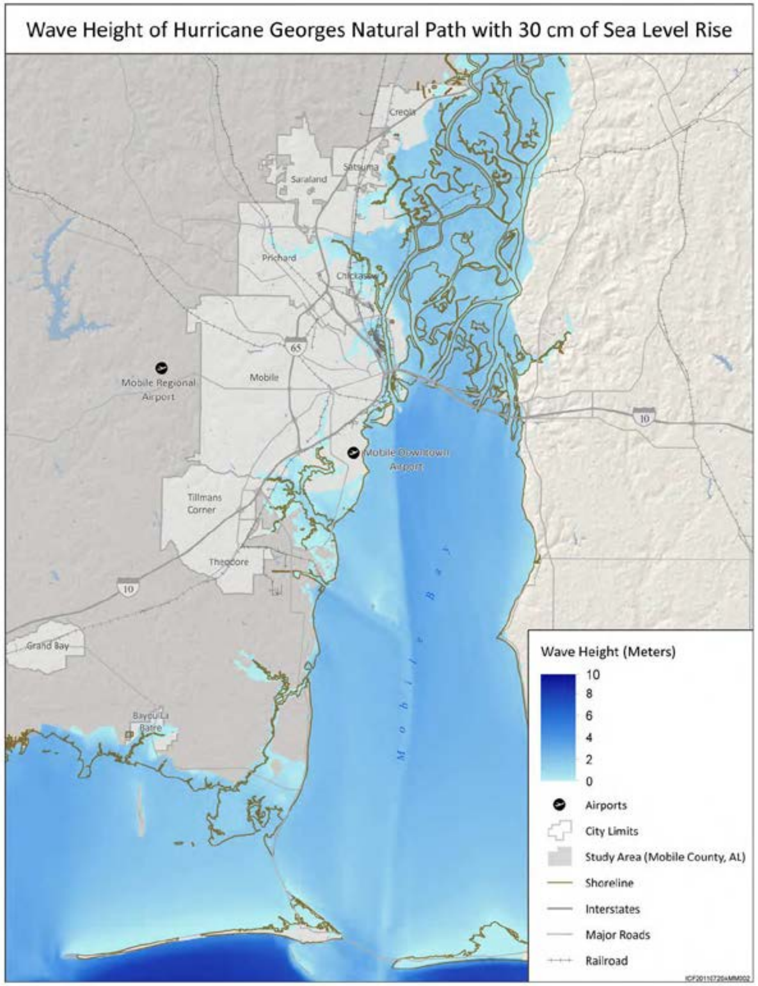
Georges Natural Path, No Sea Level Rise



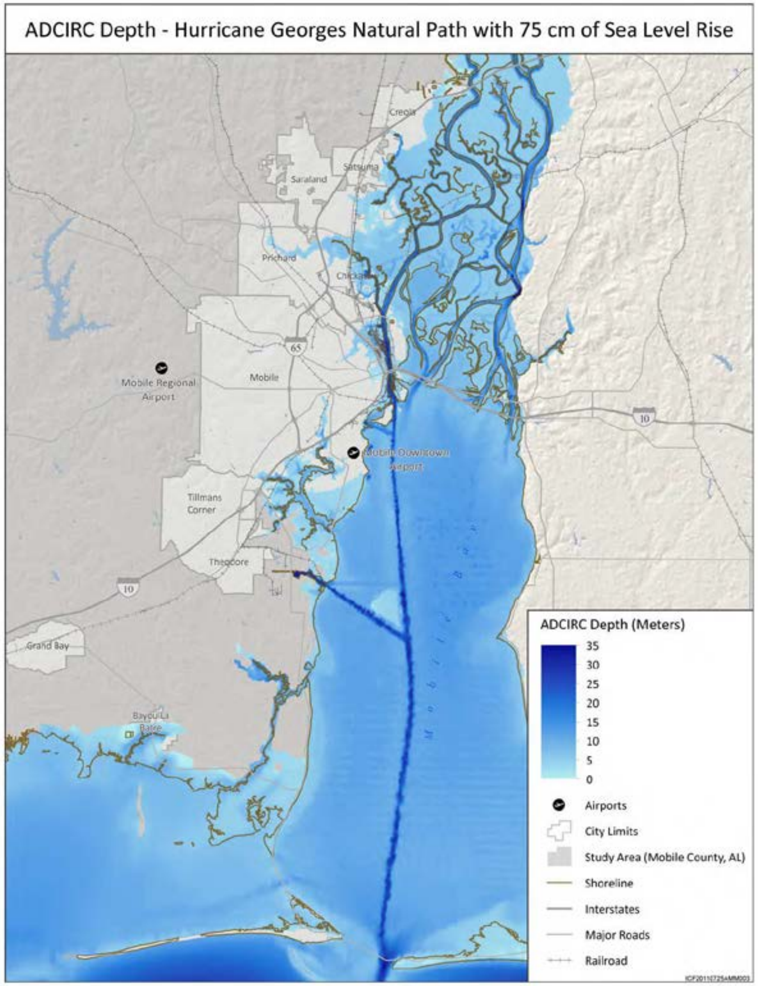


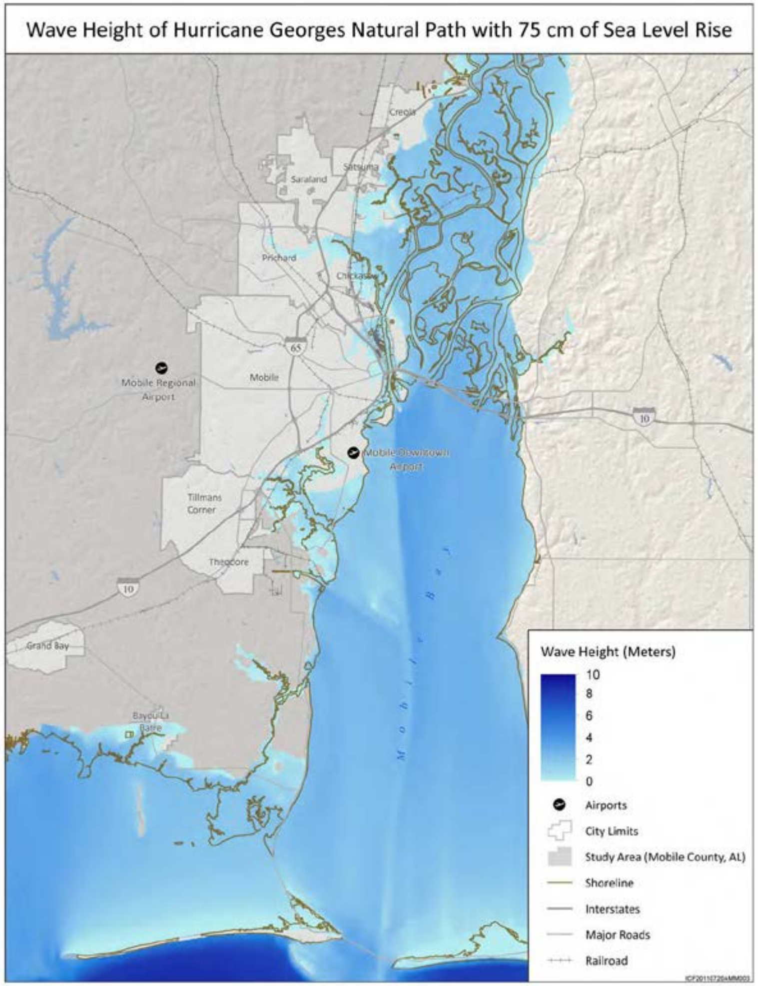
Georges Natural Path, 30 CM Sea Level Rise





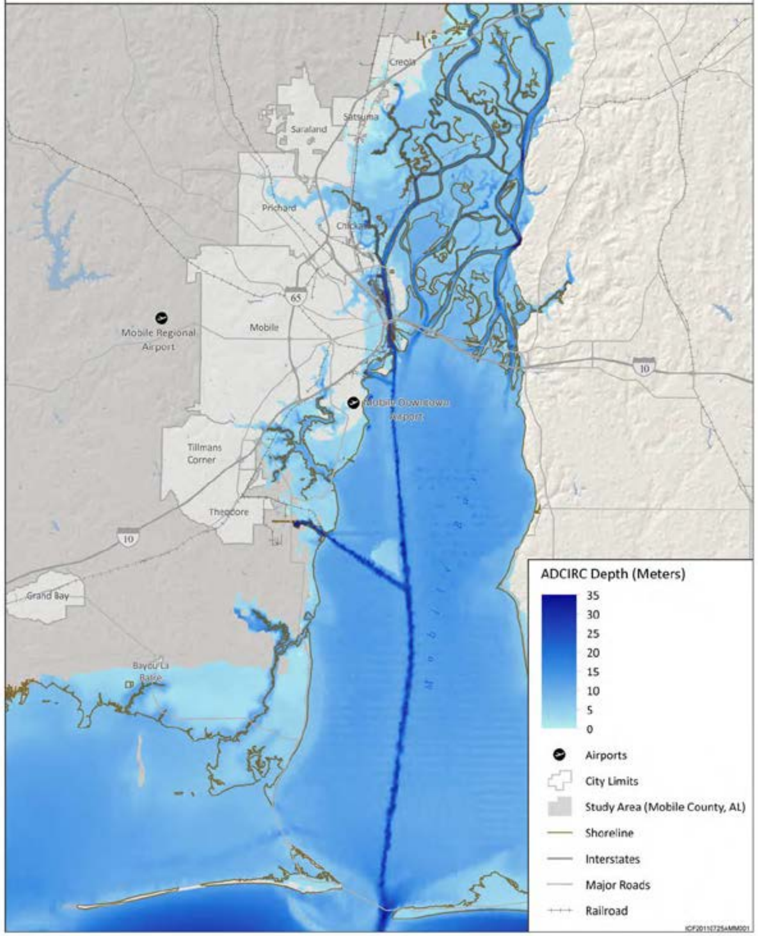
Georges Natural Path, 75 CM Sea Level Rise



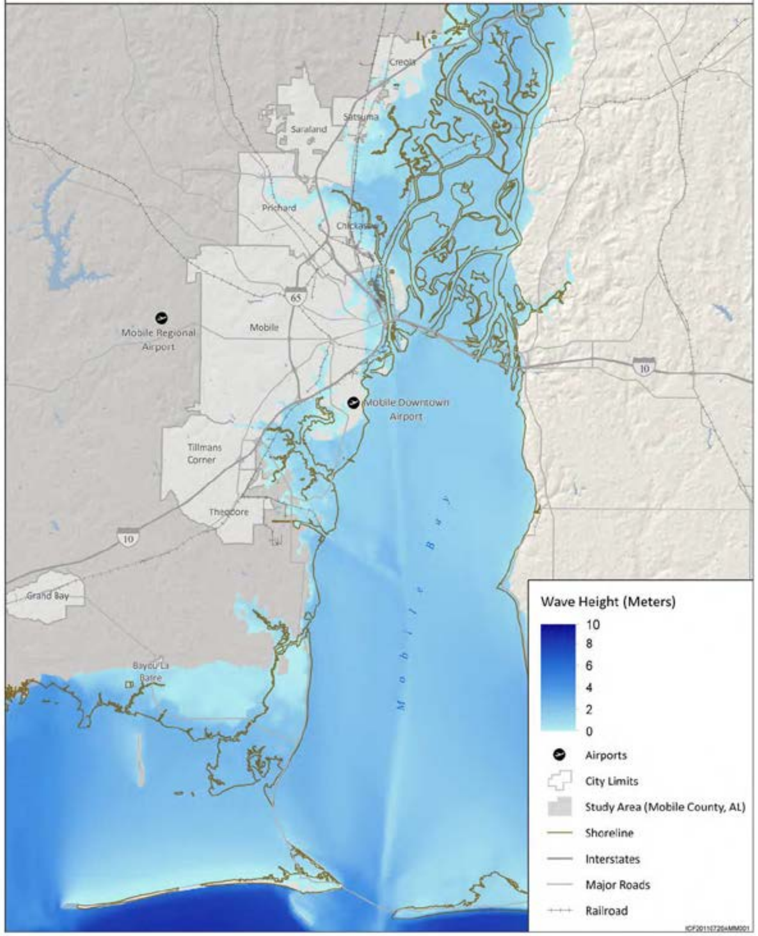


Georges Natural Path, 200 CM Sea Level Rise

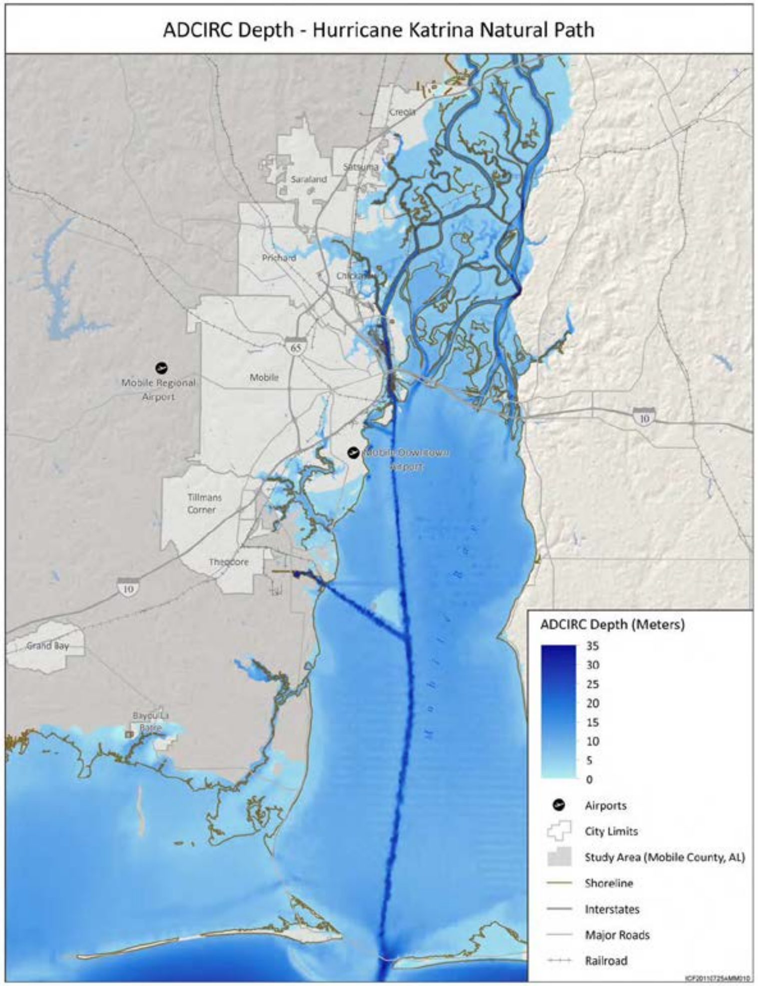
ADCIRC Depth - Hurricane Georges Natural Path with 200 cm of Sea Level Rise

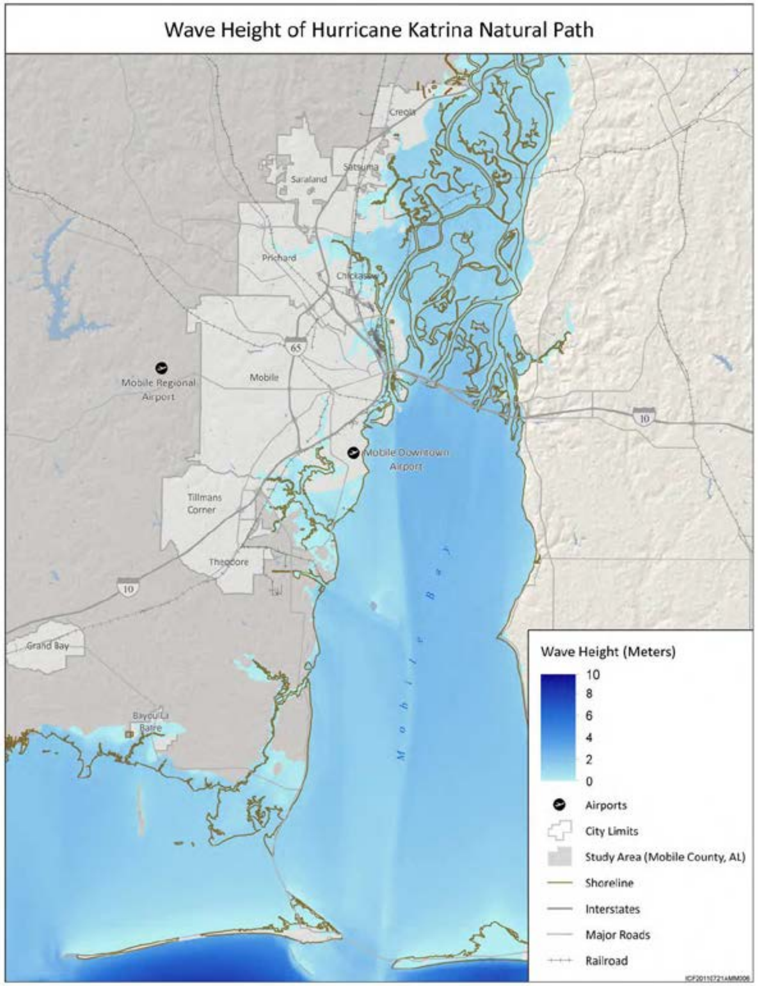


Wave Height of Hurricane Georges Natural Path with 200 cm of Sea Level Rise

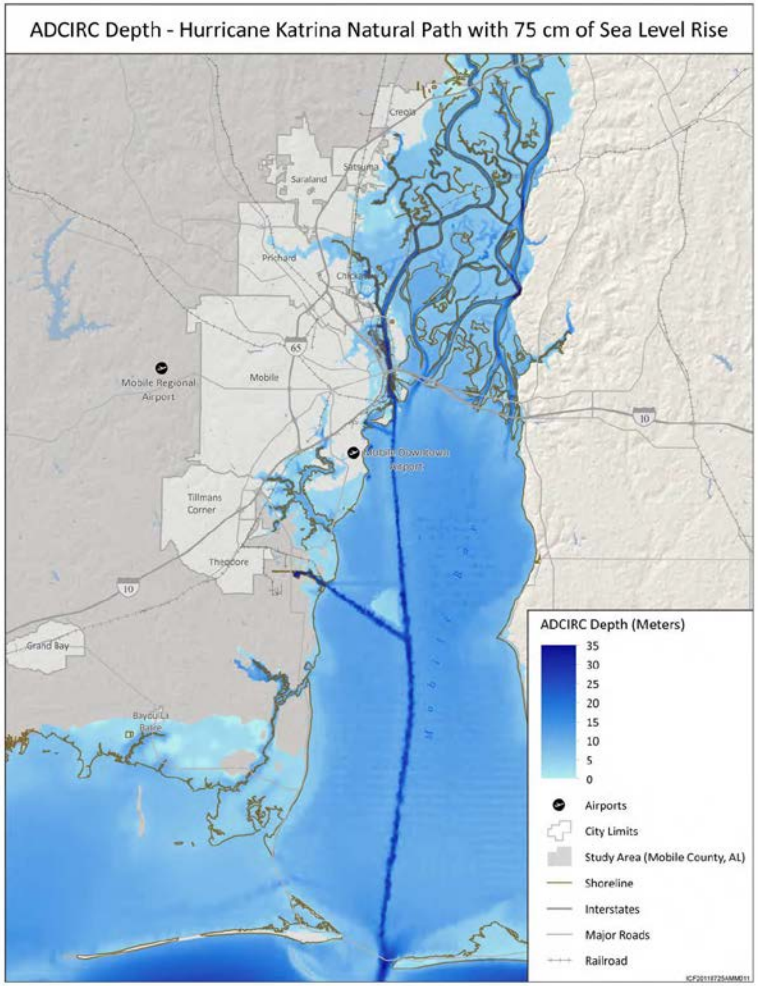


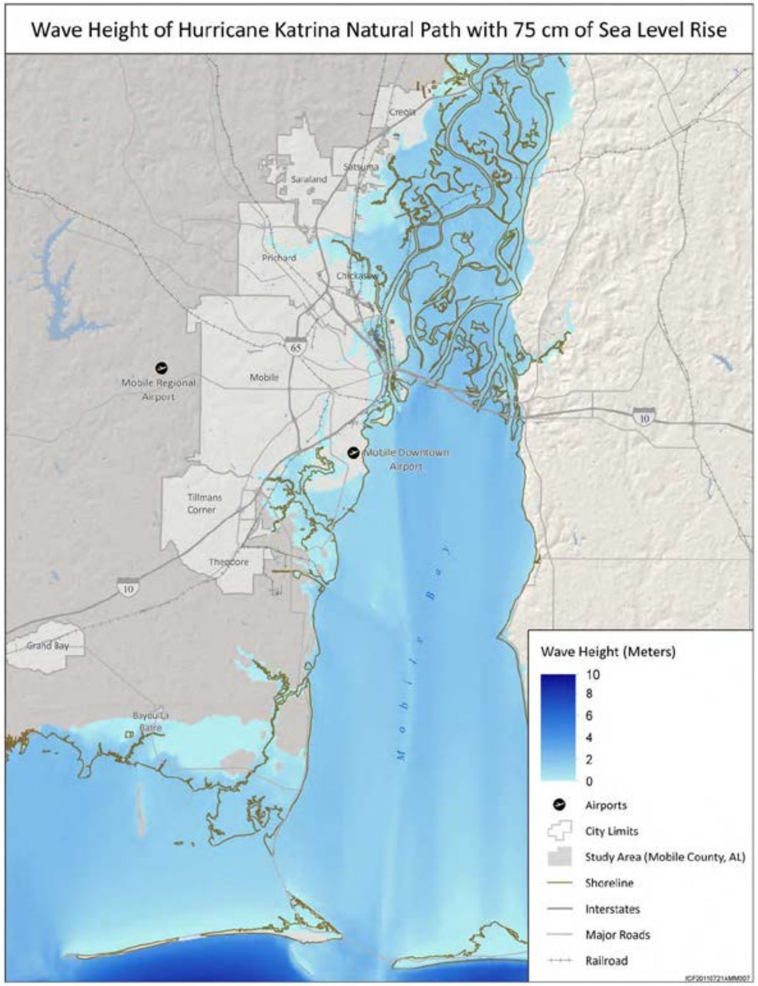
Katrina Natural Path, No Sea Level Rise



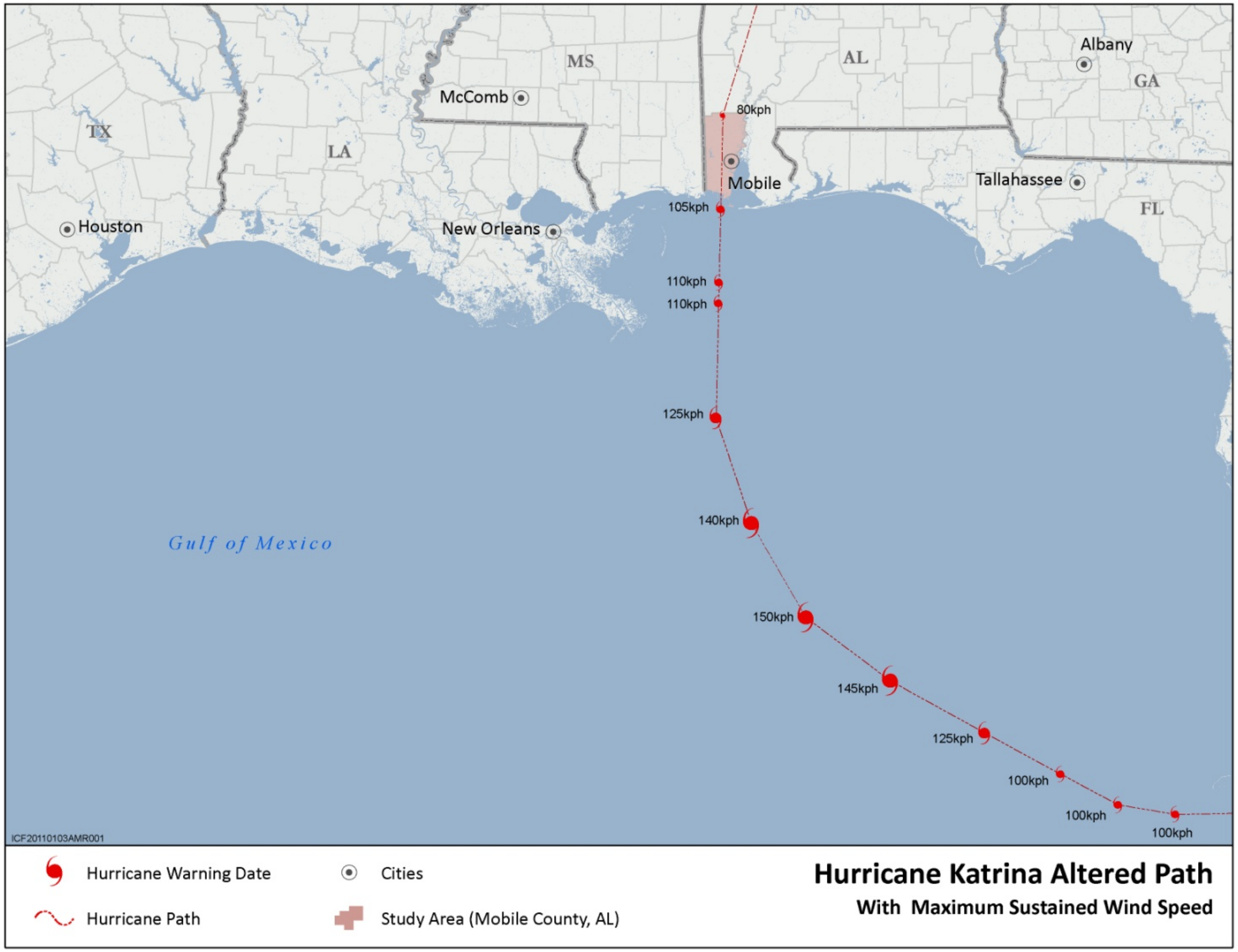


Katrina Natural Path, 75 CM Sea Level Rise

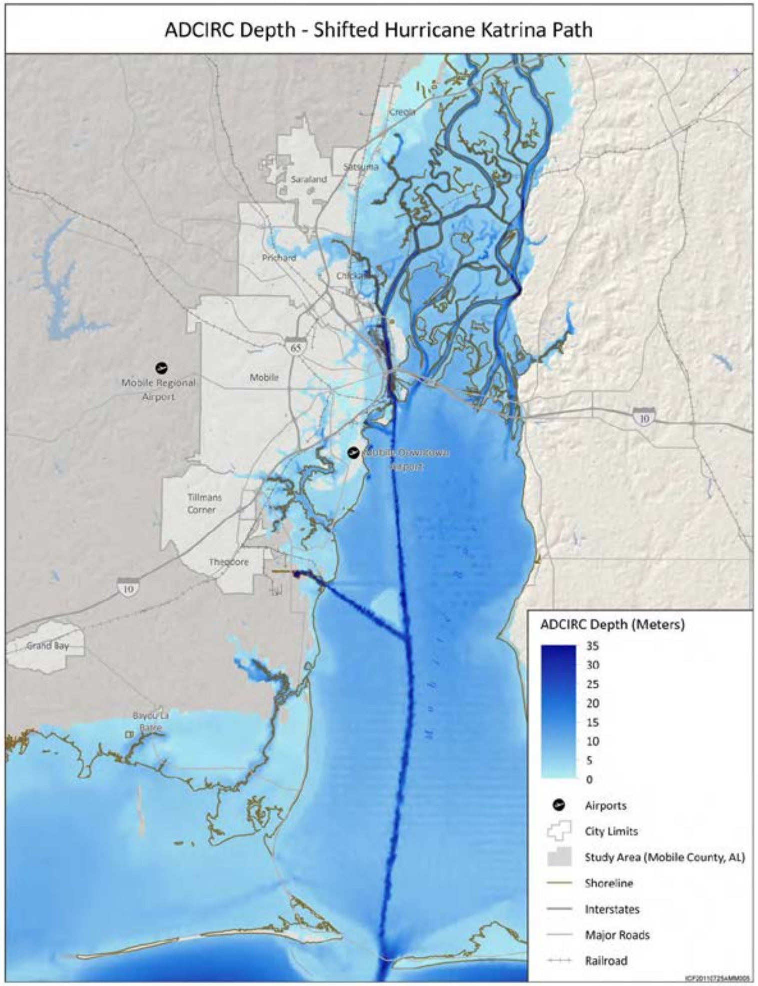


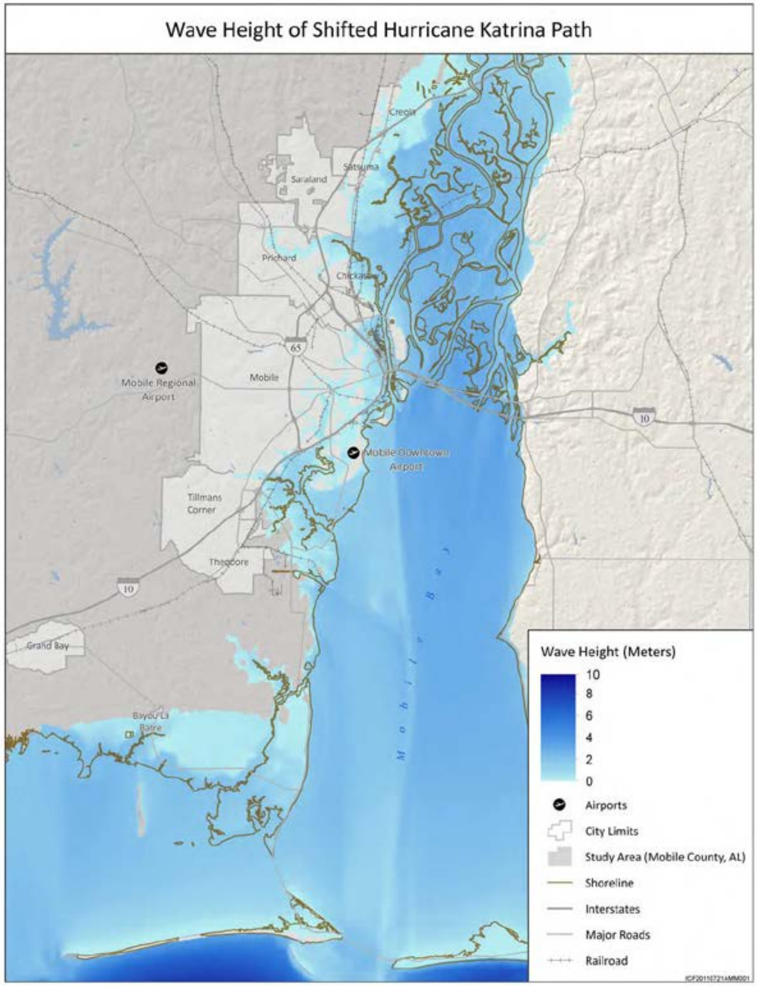


Shifting the Hurricane Katrina Path

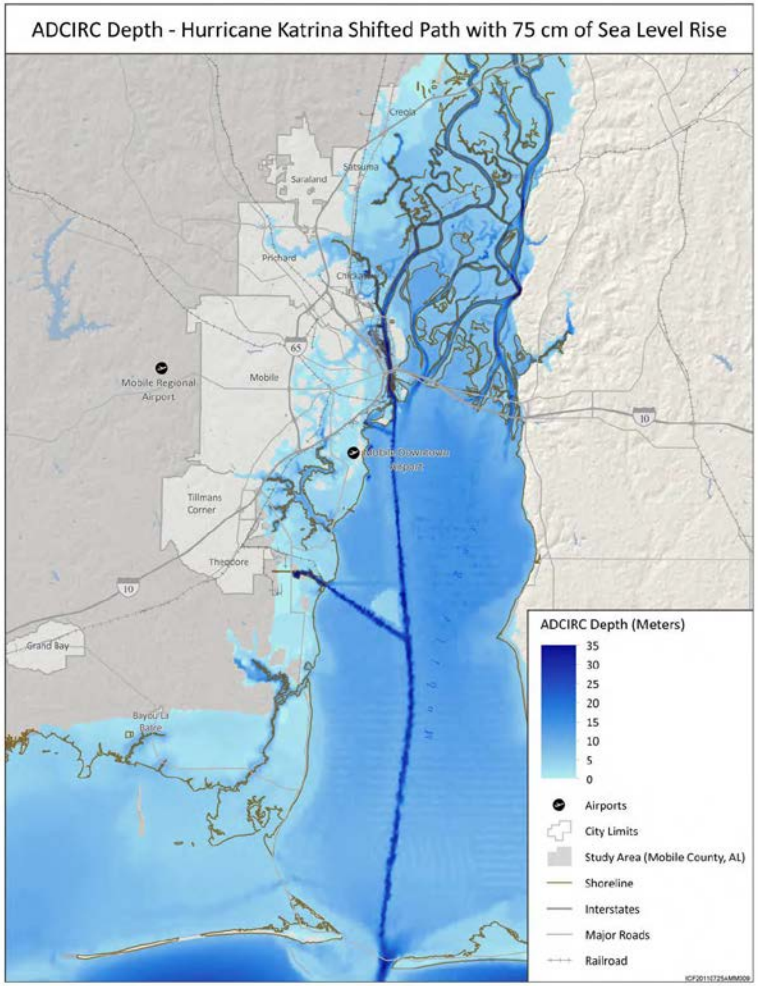


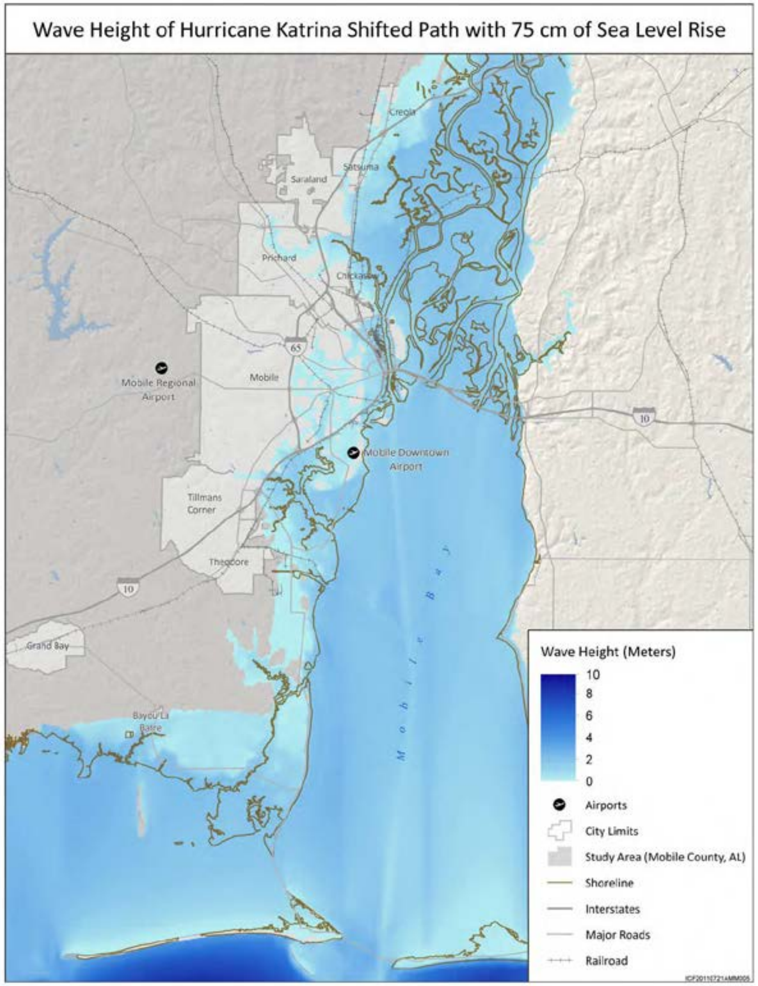
Katrina Shifted, No Sea Level Rise



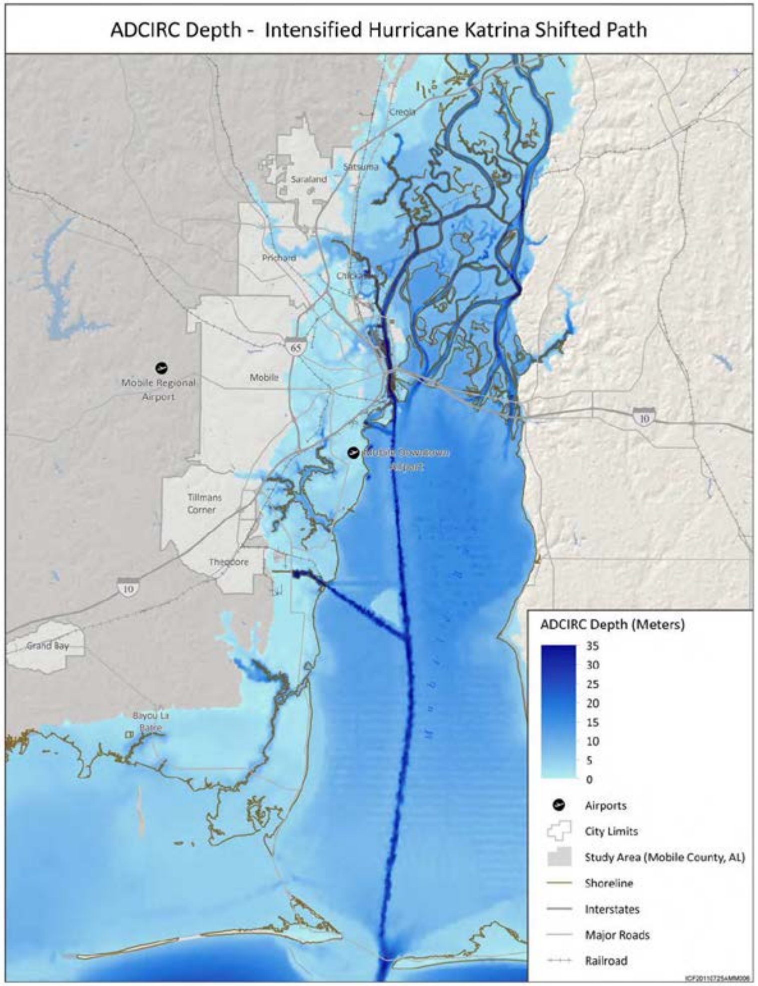


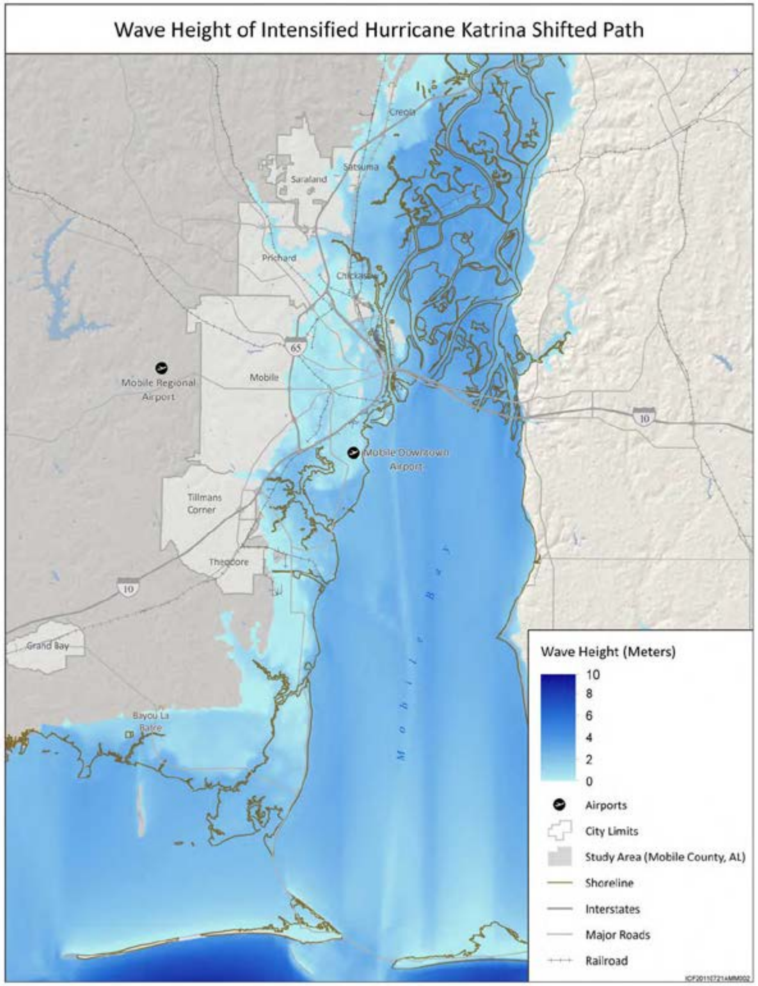
Katrina Shifted, 75 CM Sea Level Rise



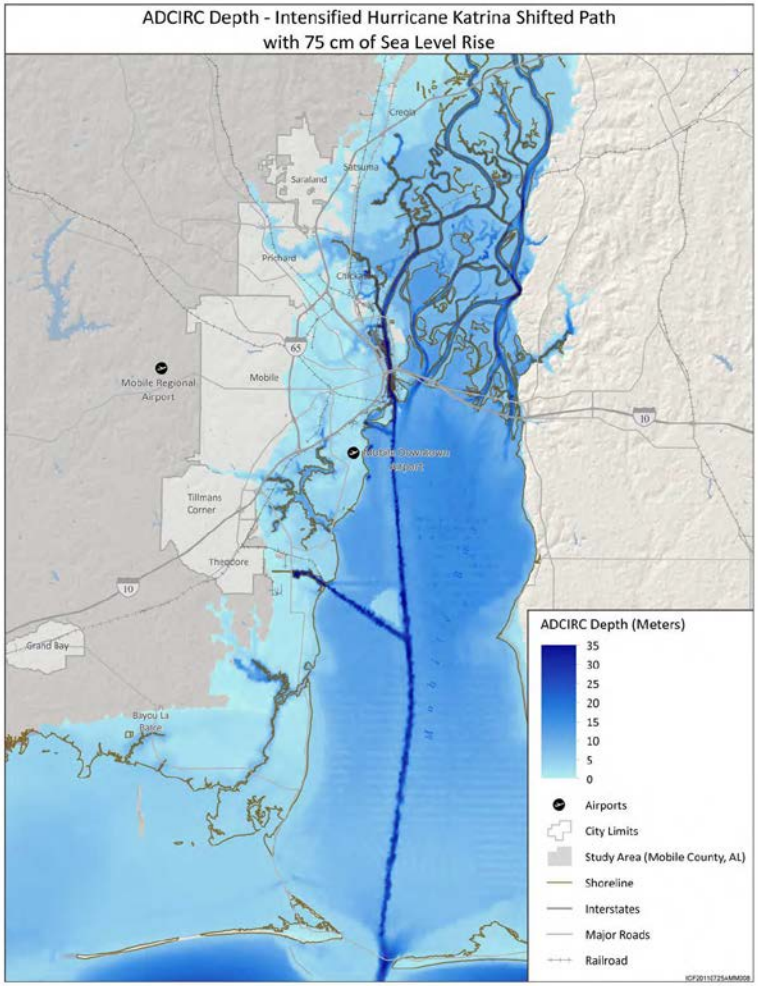


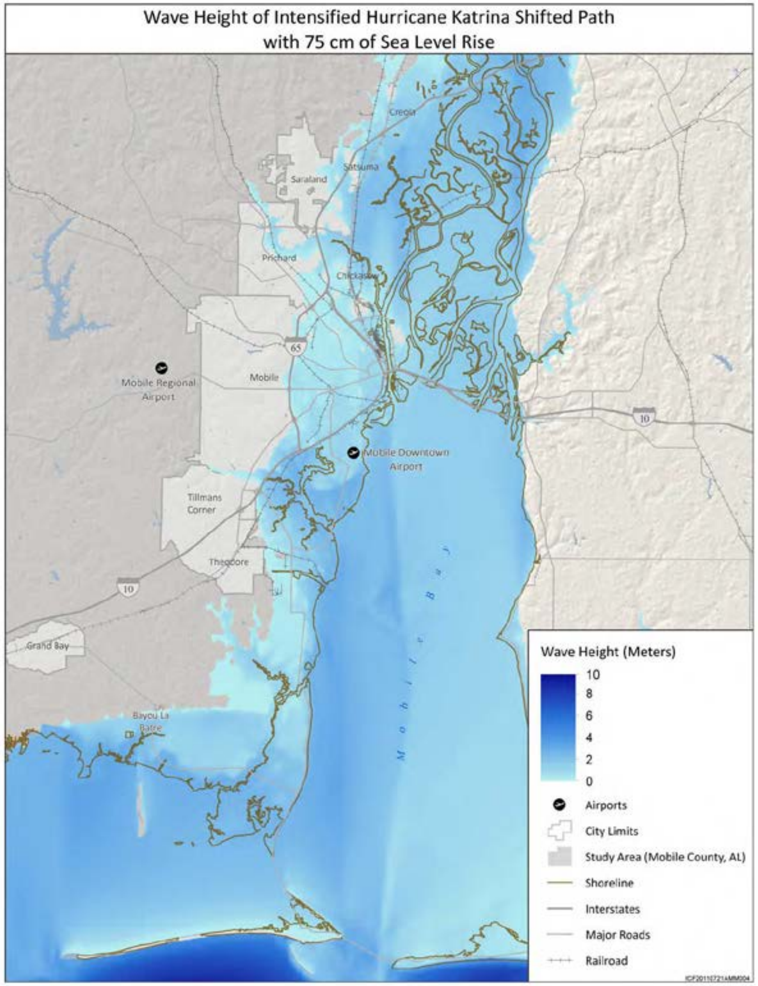
Katrina Shifted, Intensified, No Sea Level Rise



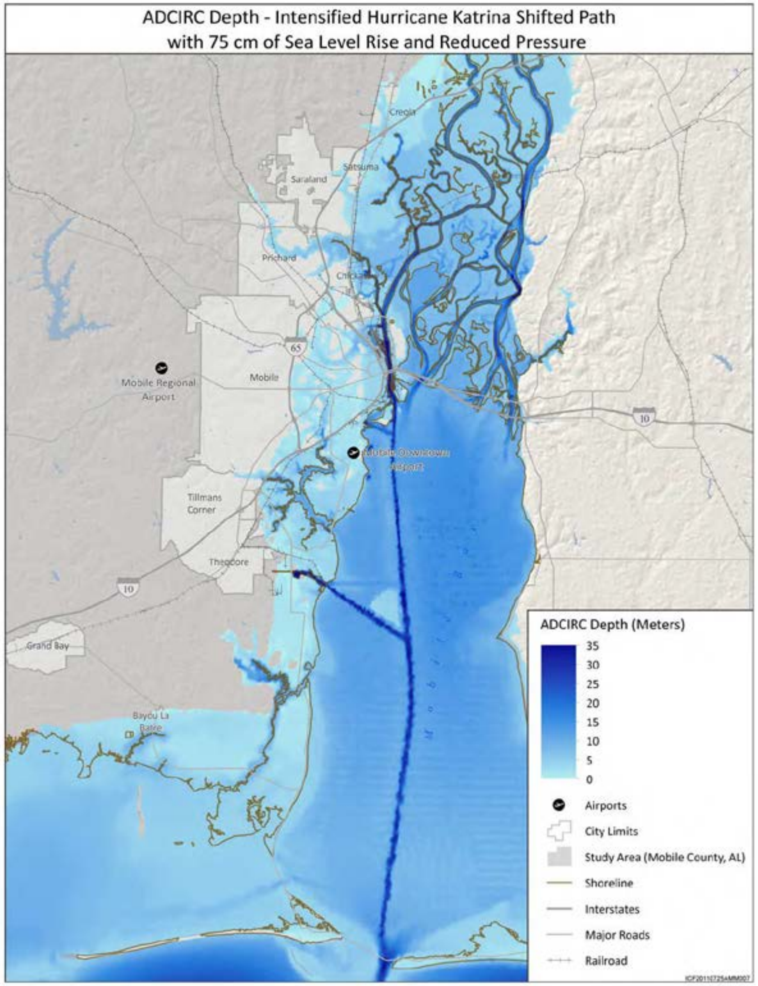


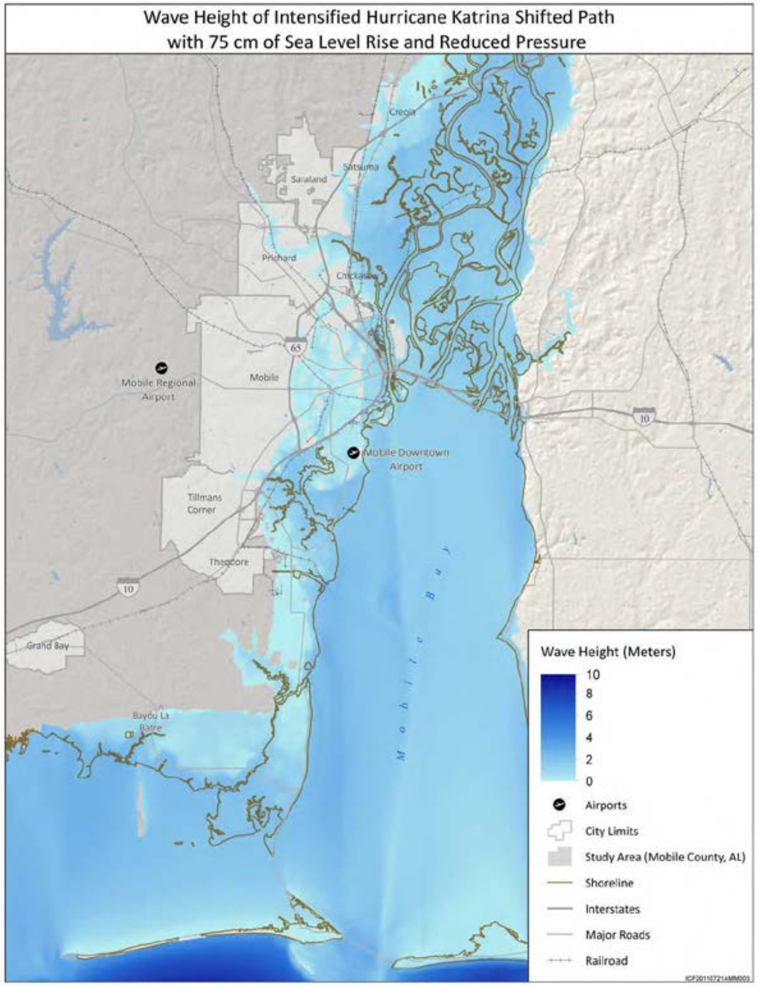
Katrina Shifted, Intensified, 75 CM Sea Level Rise





Katrina Shifted, Intensified, Pressure Reduced, 75 CM Sea Level Rise





Observations at Mobile State Docks Tidal Station

- Nearby ADCIRC Node: 347,463
- Original Elevation, 2.538 Meters Above Sea Level

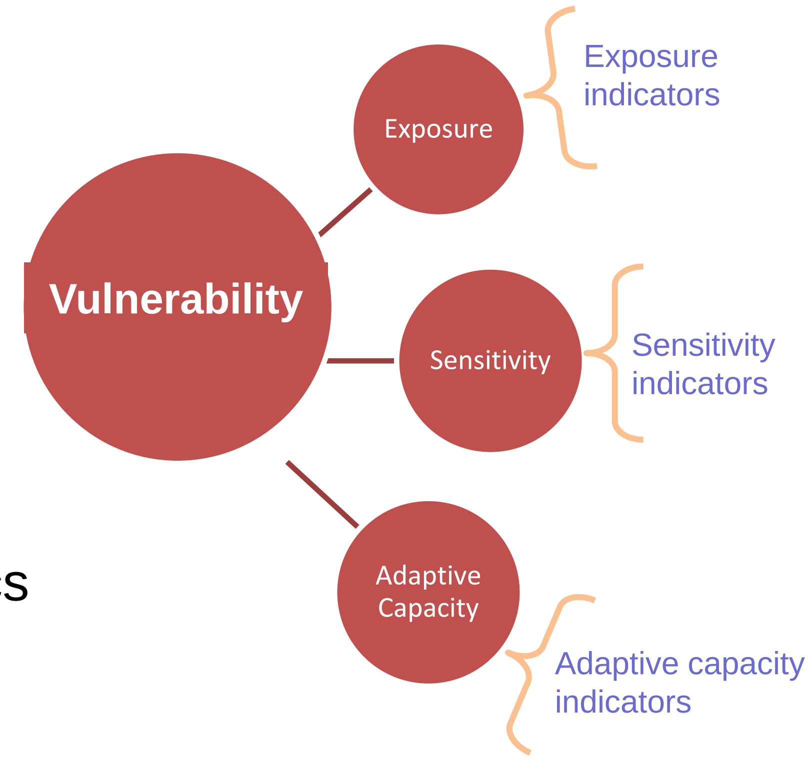
ADCIRC Model	Maximum Elevation in Meters
Hurricane Georges Natural Path	3.4301
Hurricane Katrina Natural Path	3.7556
Georges Natural Path with 75 cm Sea Level Rise	4.1192
Katrina Natural Path with 75 cm Sea Level Rise	4.5897
Shifted Hurricane Katrina Path	5.8795
Hurricane Katrina Shifted Path with 75 cm Sea Level Rise	6.8915
Shifted Intensified Katrina	8.3831
Shifted Intensified Katrina with 75 cm Sea Level Rise	9.4044

Mobile Study: Vulnerability Screen

- **Objective:**
  - Identify the assets **most likely to be vulnerable** to sea level rise, storm surge, extreme heat, precipitation, and wind
- **Method:**
  - Assets scored by “indicators” of vulnerability to each climate impact
  - Assets receive multiple vulnerability scores – for each variable, time period, and climate narrative
- **Outcomes:**
  - A prioritized list of potentially vulnerable assets to facilitate selection of assets for the engineering assessment
  - Better understanding of system-level vulnerabilities for specific modes, geographies, and climate variables

Using Indicators to Score Vulnerability

- Exposure, sensitivity, and adaptive capacity are abstract concepts
  - No formulas tell us how individual assets are specifically damaged by certain weather conditions
- We chose indicators to represent these concepts
  - Indicators help evaluate characteristics that could indicate an asset may or may not be vulnerable
- Averages (potentially weighted) of indicators drive scoring



Example Indicators

Exposure

- **Temp**-Days above 95°F
- 24-hour **precipitation**
- **Storm surge** height
- **Wind** speed exceeds threshold above which impacts may occur (yes/no)
- Inundated by **sea level rise** (yes/no)

Sensitivity

- **Temp** - Pavement binder, traffic (roads)
- **Precip** - FEMA flood zones, ponding, surface permeability (all modes)
- **Storm surge** – Height & condition (bridges), electric signaling & soil type (rail), access (transit)
- **Wind** - Building height, materials, roof type; road sign or signal density (road and rail)
- **Sea level rise** – Drainage (air), protection (transit, roads)

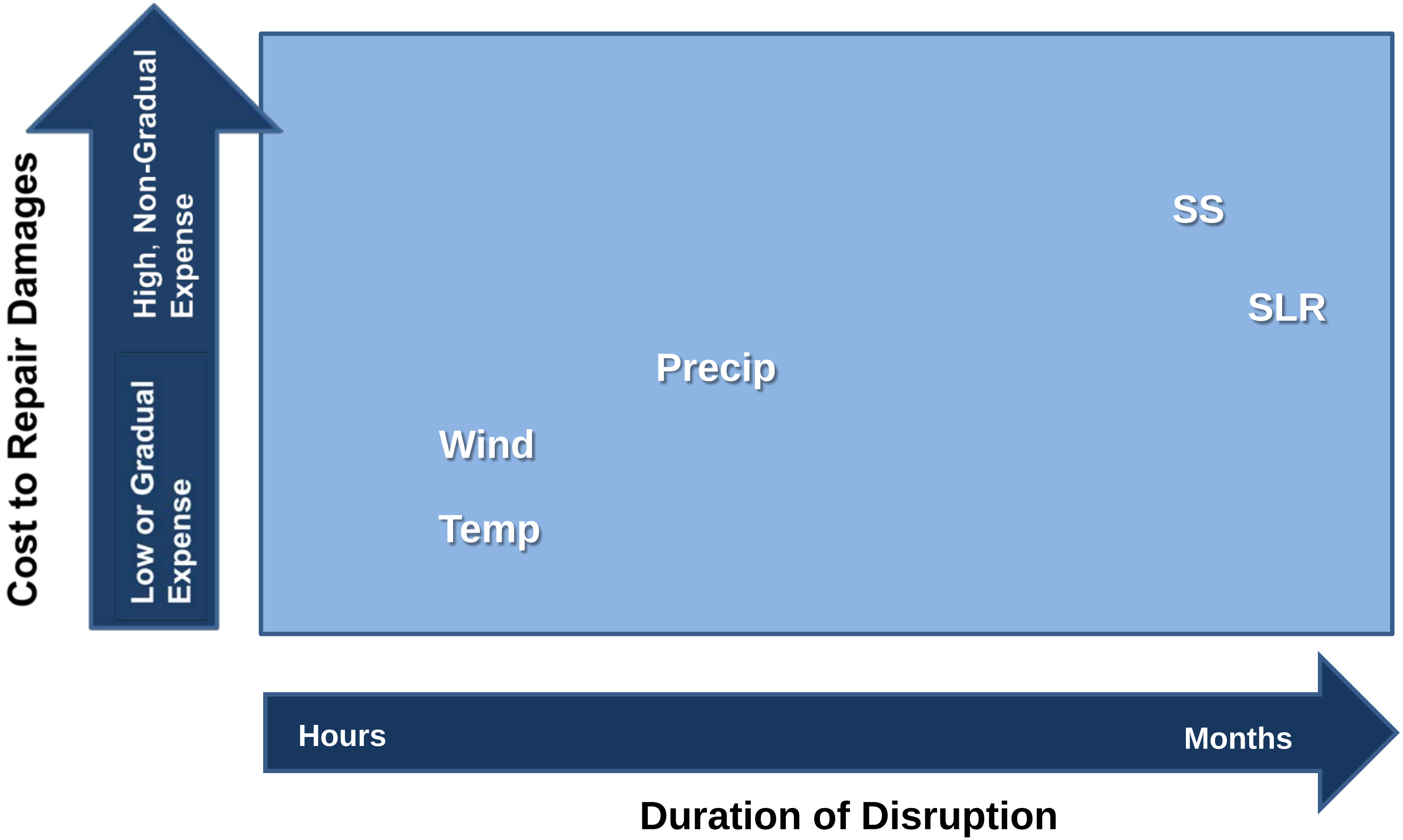
Adaptive Capacity

- **Speed to recover asset** – cost of improvement (bridges), identified as a priority in emergency planning (rail, air, transit)
- **Redundancy** - detour length (bridges, air), number of terminals/ runways (air), ability to reroute (transit and rail), rail yard interchange utility (rail)
- **System disruption duration** (climate variable-specific)

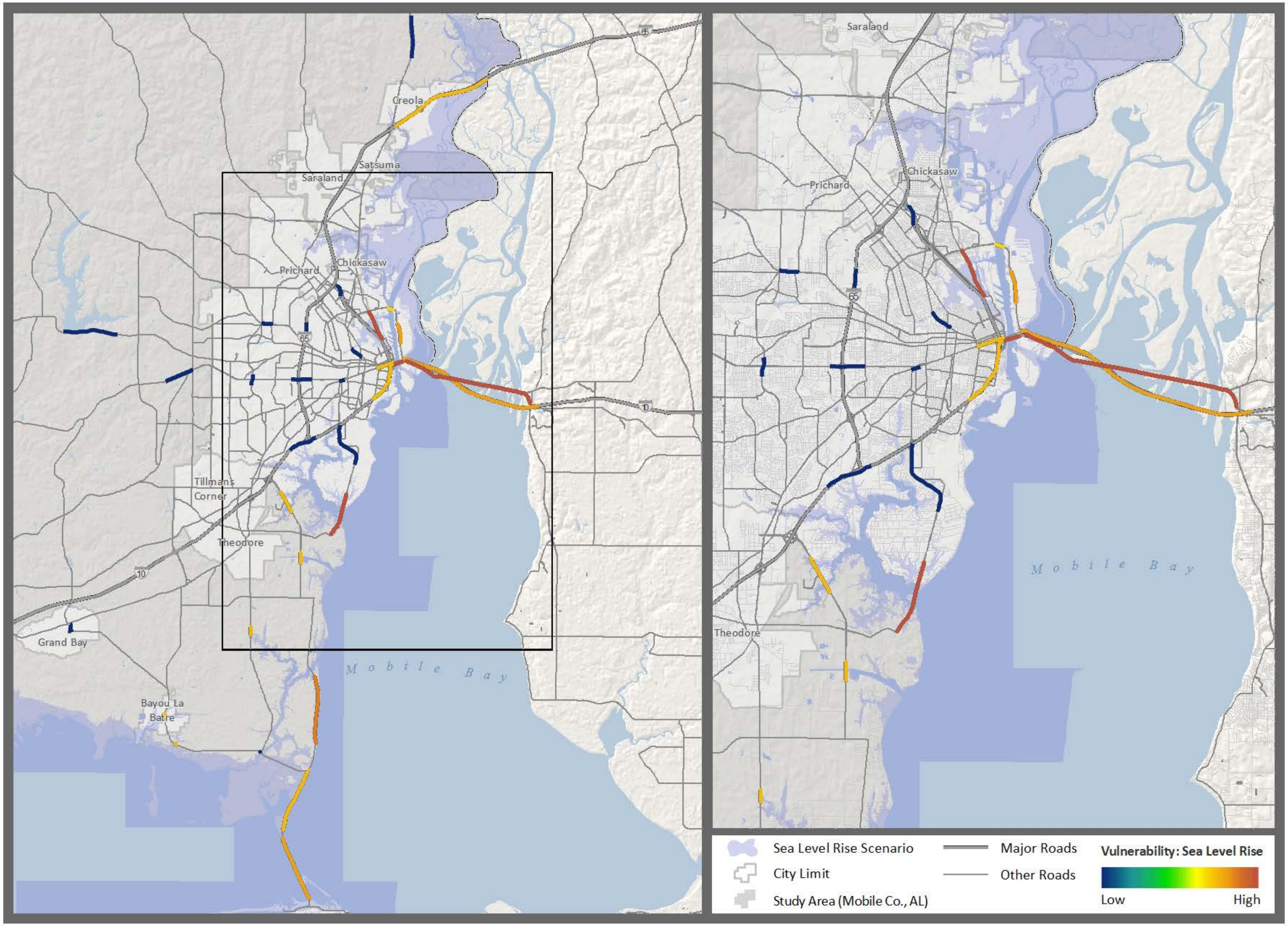
A Few Notes on Results

- Each asset assigned a score for each climate variable
  - 0 = not exposed/not vulnerable
  - 1.0-1.9 = low vulnerability
  - 2.0-2.9 = moderate vulnerability
  - 3.0-4.0 = high vulnerability
- Data availability score highlights availability of indicators contributing to each vulnerability score

Relative Damages of Climate Stressors



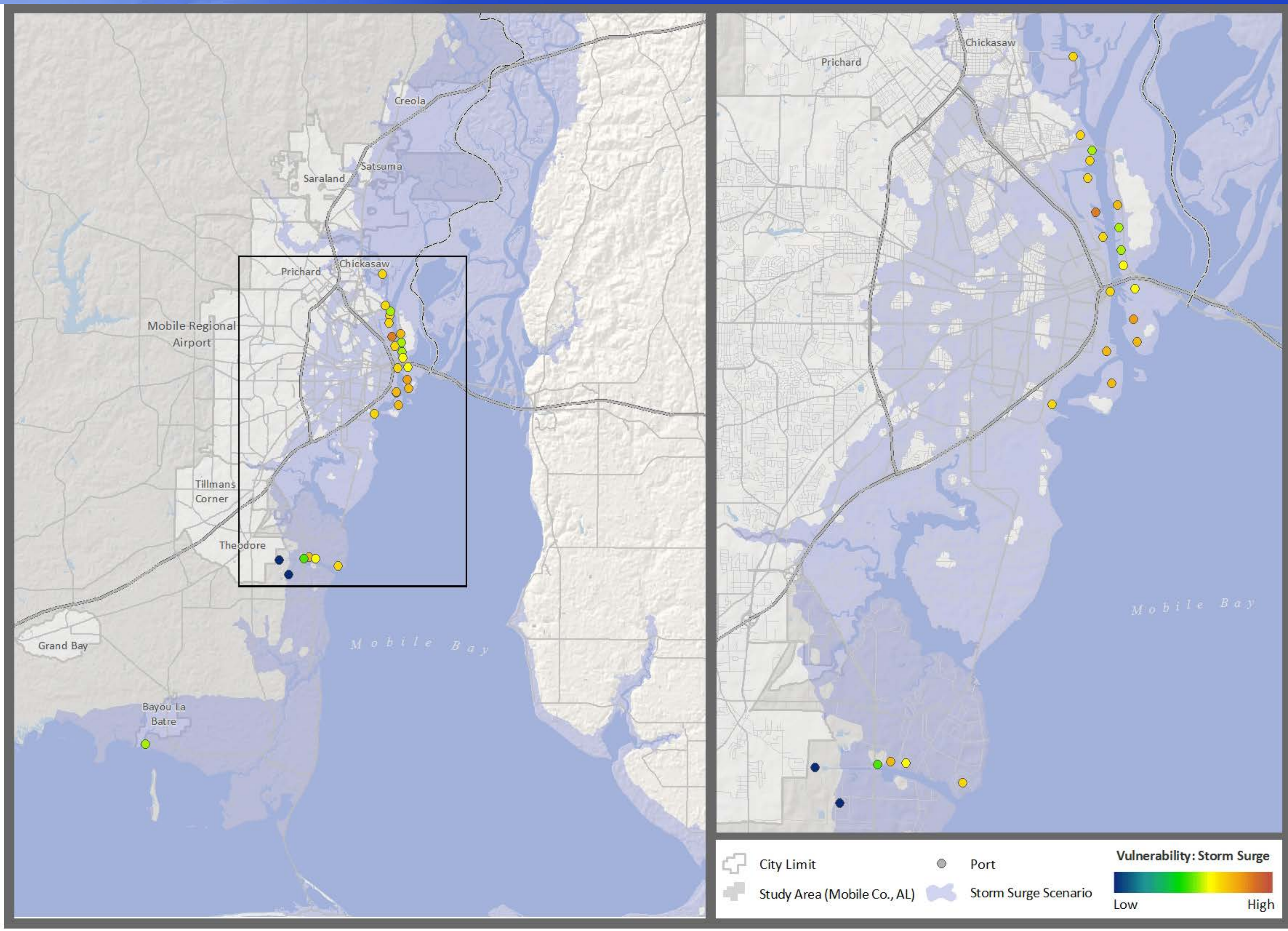
Vulnerability of Roads to Sea Level Rise: 200cm



Sea Level Rise: Most Vulnerable Roads

Sub-Segment	Name	30cm	200cm	Data Availability
R1	I-10 Tunnel (Wallace Tunnel)	4.0	4.0	67%
R10	The Causeway (Battleship Parkway)	4.0	4.0	82%
R14	SR-163 (Dauphin Island Parkway) from Island Road to Terrel Road	4.0	4.0	71%
R22	SR-193 (Dauphin Island Parkway) from Old Cedar Point Road to Day Springs Road	3.5	3.5	78%
R26	Dauphin Island Bridge	3.3	3.3	100%
R27	I-10 Bridge Across Mobile Bay	3.3	3.3	77%
R3	I-10 from Tunnel to S Broad Street	3.1	3.1	73%
R5	I-65 from US-43 and County boundary	3.1	3.1	79%
R9	US-90 (SR-16), Section East of Broad Street	3.1	3.1	67%
R15	SR-193 (Dauphin Island Parkway) from Dauphin Island Bridge to CR-188	3.1	3.1	75%
R16	SR-193 (Range Line Road): segment runs about 0.5 mile on either side of Theodore Industrial Canal	3.1	3.1	75%
R17	SR-193 (Range Line Road) between Rabbit Creek Drive and Tufts Road	3.1	3.1	80%
R20	SR-188, where it crosses the river just North of Bayou la Batre	3.1	3.1	67%
R23	SR 188, river crossing near Coden	3.1	3.1	75%

Vulnerability of Ports to Storm Surge: Katrina, Shifted, Pressure Reduced, 75cm SLR

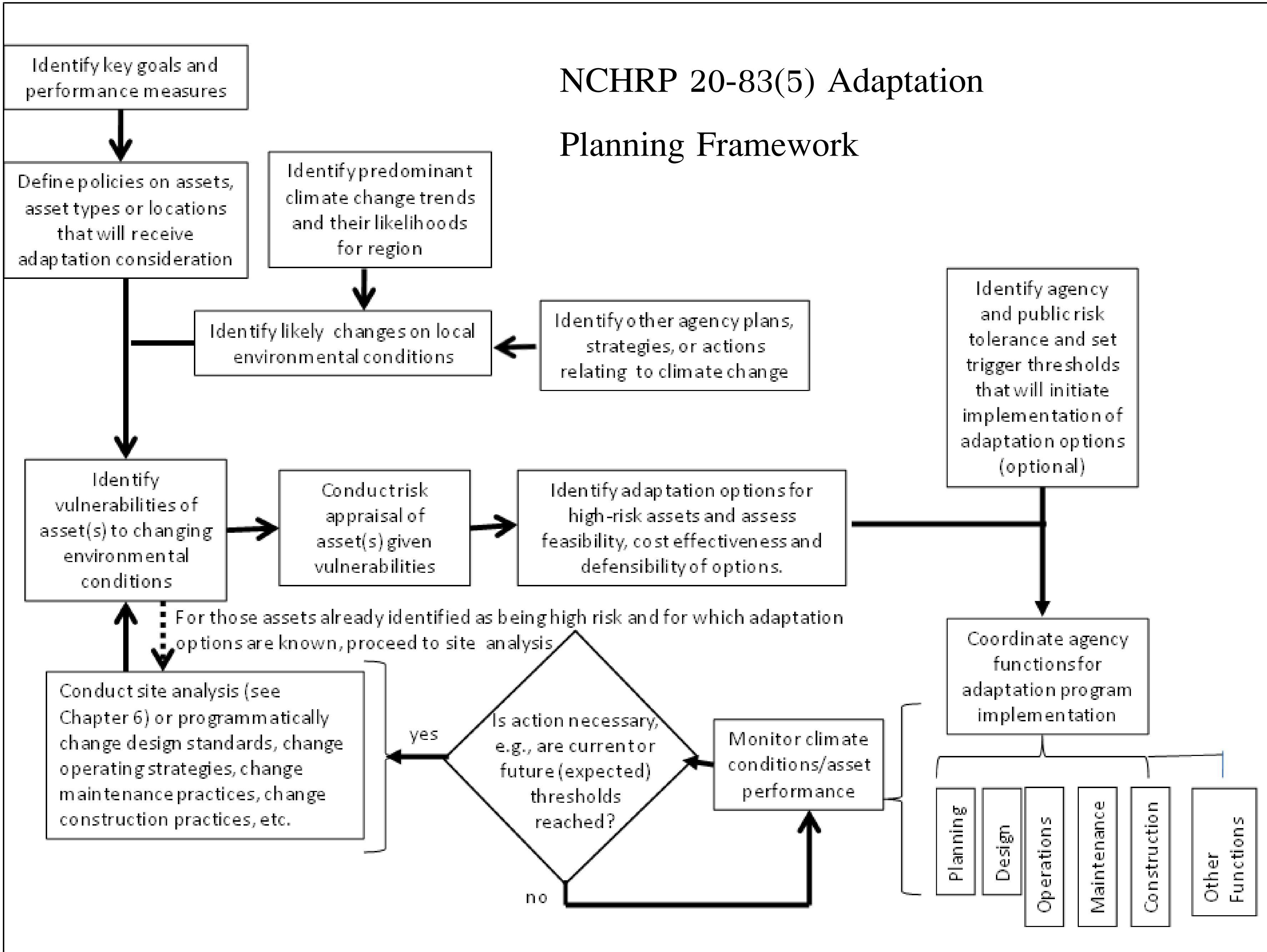


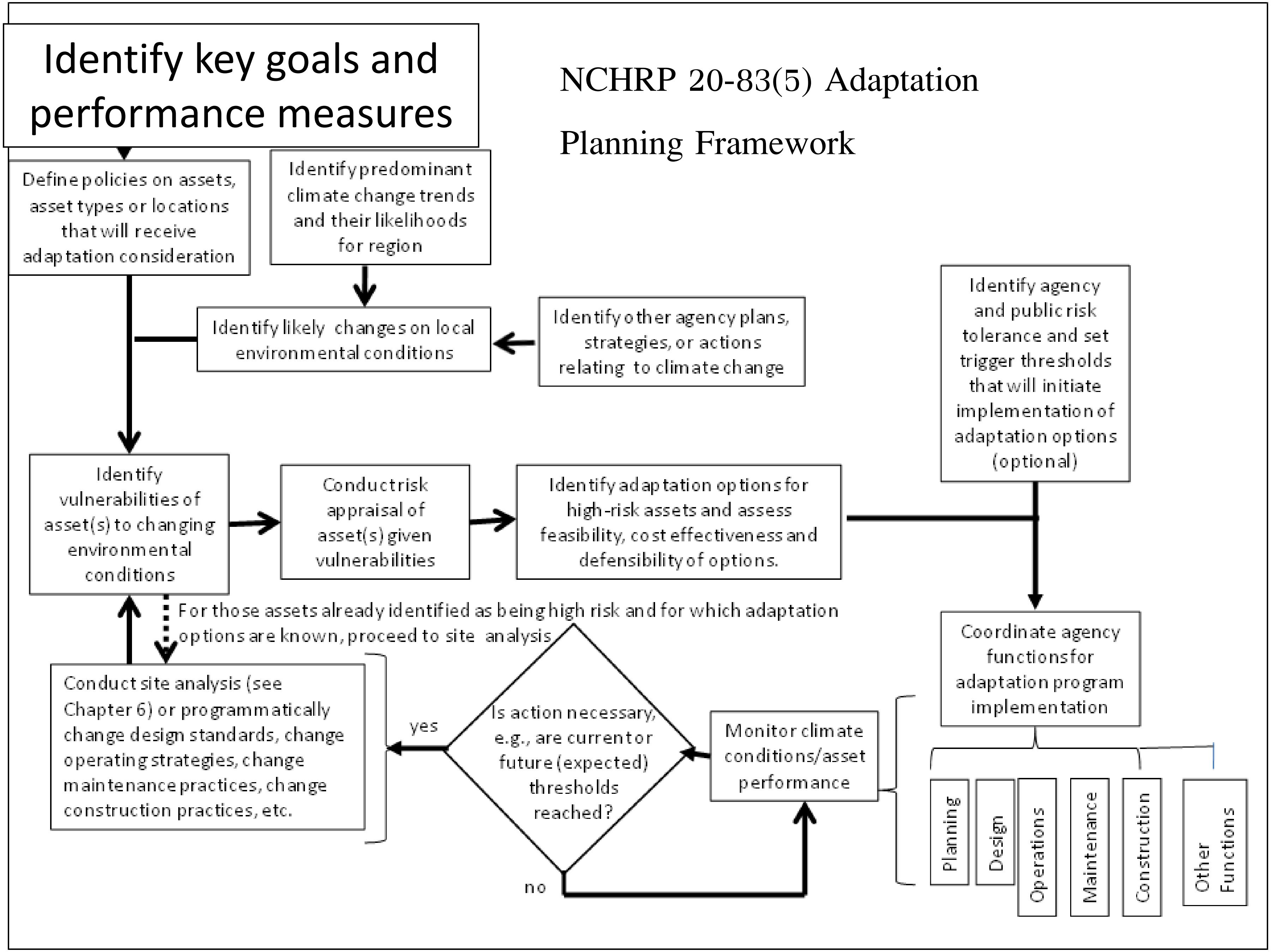
Storm Surge: Most Vulnerable Ports

Port Code	Name	Katrina Base	Katrina Shifted + Pressure Reduced + 75 cm SLR	Data Availability Score
P-2	Alabama State Port Authority (ASPA) - Alabama State Docks Main Complex	3.4	3.4	100%
P-11	Environmental Treatment Team Wharf	3.2	3.2	53%
P-3	Alabama State Port Authority (ASPA) - McDuffie Terminal	3.0	3.0	96%
P-6	Atlantic Marine (BAE Systems Southeast Shipyards)	3.0	3.3	96%
P-20	Oil Recovery Co. of Alabama, Mobile Terminal Pier	2.8	3.2	53%
P-16	Kimberly-Clark Corporation	2.8	2.8	53%
P-26	U.S. Coast Guard Pier	2.8	2.8	53%
P-18	Mobile Container Terminal	2.8	3.1	100%
P-1	Alabama Bulk Terminal Co. (Hunt Refining Company)	2.8	2.8	100%
P-5	Alabama State Port Authority (ASPA) - Pinto Island	2.8	3.1	87%
P-23	Shell Chemical Co.	2.7	3.0	100%
P-7	Austal	2.7	2.7	96%
P-10	Crescent Towing & Salvage Co., River A Wharf	2.7	3.0	61%

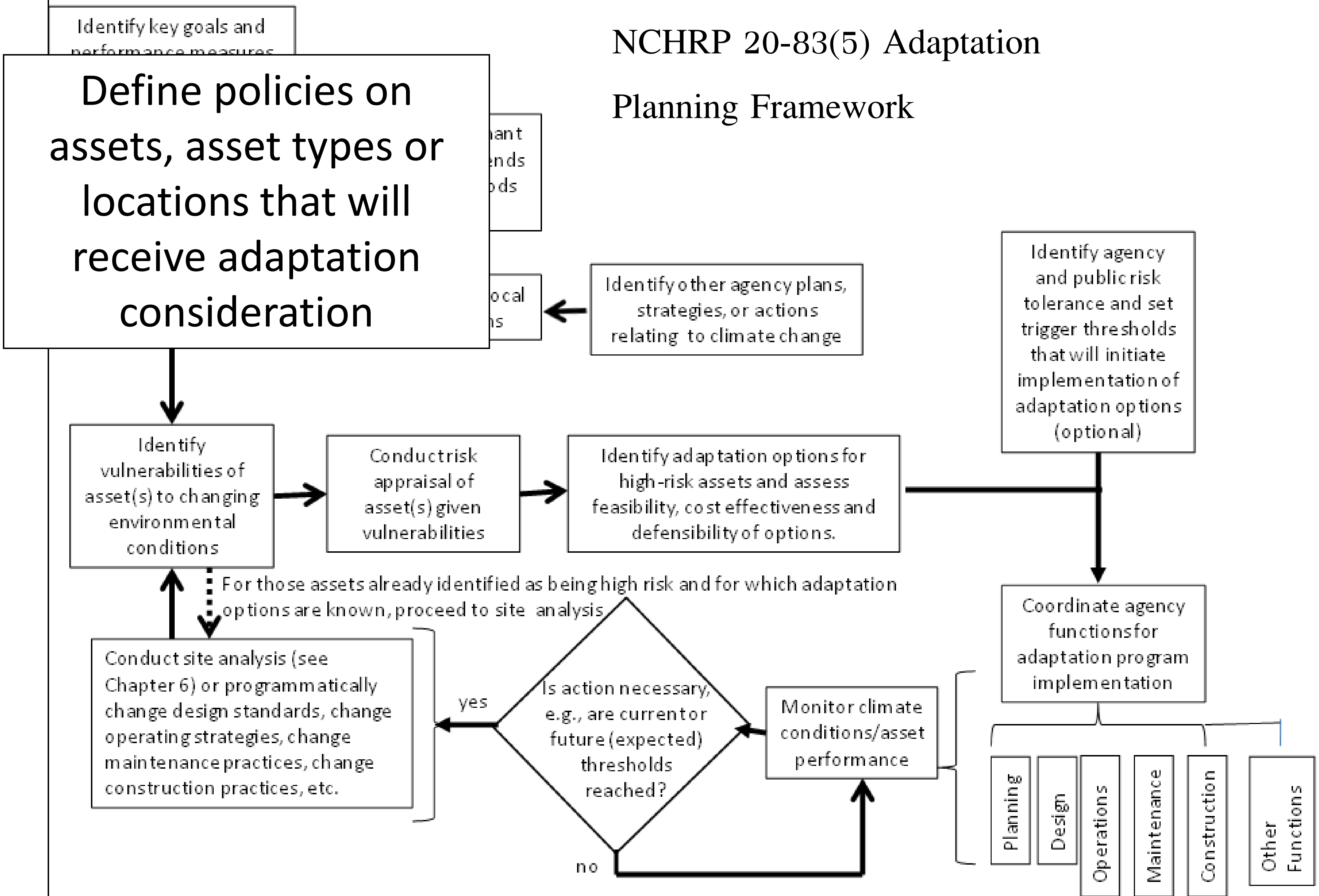
Environmental Factor	Facility	Possible Effect	Cause	Formula #
Rainfall intensity /frequency increase	Roadway foundation	Foundation weakening	Saturation	300, 301
			Erosion	
			Groundwater elevation increase	
		Foundation and roadway loss	Flooded culvert or bridge failure	
	Roadway pavement	Surface deterioration	Base and sub-base saturation	403, 404, 405, 406
		Surface loss	Flooded culvert failure	100-106
	Roadside slopes	Slope failure	Erosion	302
			Soil saturation	302
	Roadside planting	Species growth	Hydration	
	Bridge- water crossing	Structural damage	Scour	100-106
			Water load	202
			Soils pressure change	

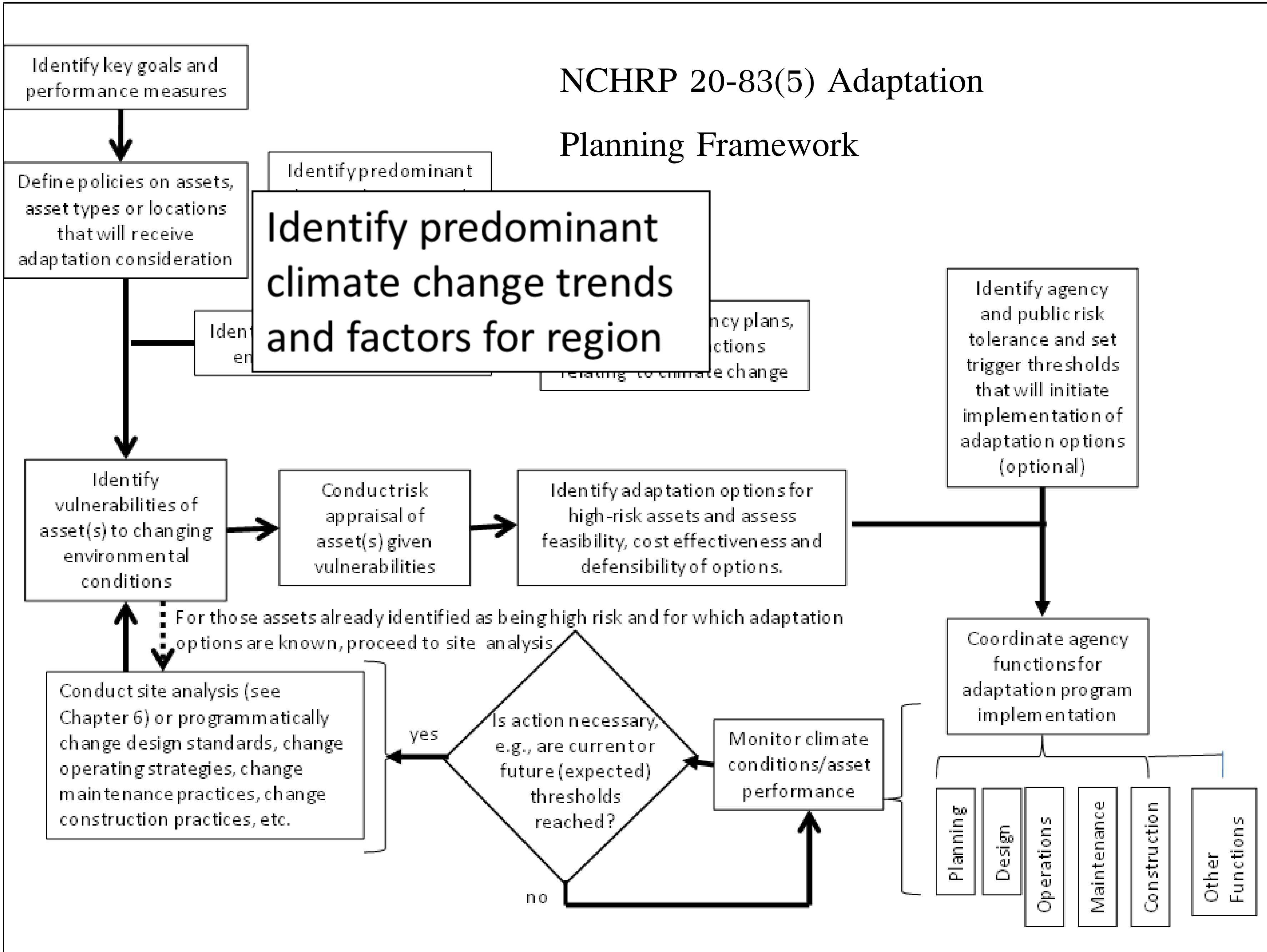
Keller, Jake A.; Armstrong, Amit; Flood, Michael; Meyer, Michael D., AN APPROACH TO ADDRESSING THE IMPACTS OF CLIMATE VARIABILITY ON ROADWAY AND BRIDGE DESIGN, Paper presented at the Annual Meeting of the Transportation Research Board, Jan. 2011.

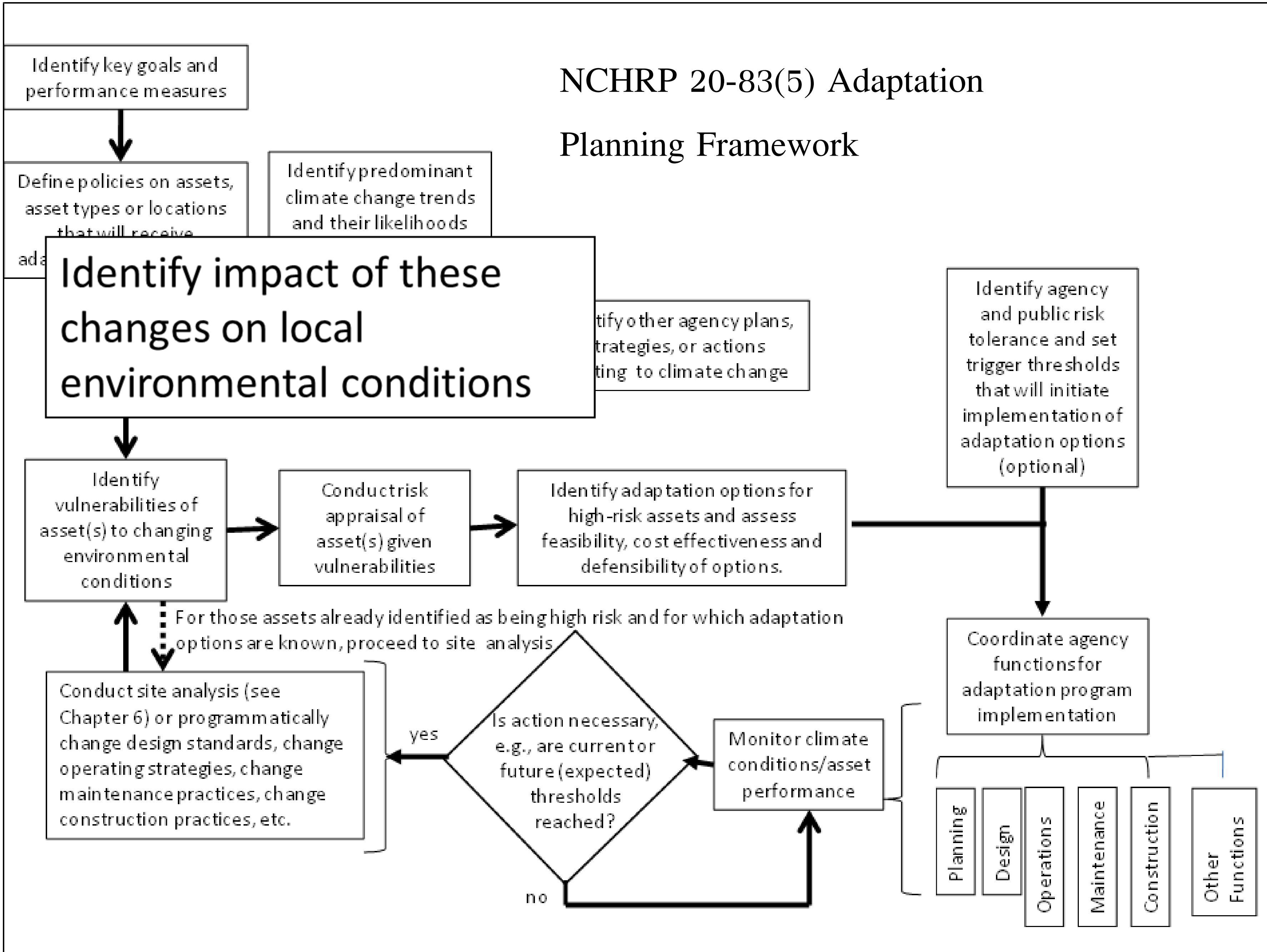

NCHRP 20-83(5) Adaptation Planning Framework
Identify key goals and performance measures
Define policies on assets, asset types or locations that will receive adaptation consideration
Identify predominant climate change trends and their likelihoods for region
Identify likely changes on local environmental conditions
Identify other agency plans, strategies, or actions relating to climate change
Identify agency and public risk tolerance and set trigger thresholds that will initiate implementation of adaptation options (optional)
Identify vulnerabilities of asset(s) to changing environmental conditions
Conduct risk appraisal of asset(s) given vulnerabilities
Identify adaptation options for high-risk assets and assess feasibility, cost effectiveness and defensibility of options.
For those assets already identified as being high risk and for which adaptation options are known, proceed to site analysis
Coordinate agency functions for adaptation program implementation
Conduct site analysis (see Chapter 6) or programmatically change design standards, change operating strategies, change maintenance practices, change construction practices, etc.
yes
Is action necessary, e.g., are current or future (expected) thresholds reached?
no
Monitor climate conditions/asset performance
Planning
Design
Operations
Maintenance
Construction
Other Functions

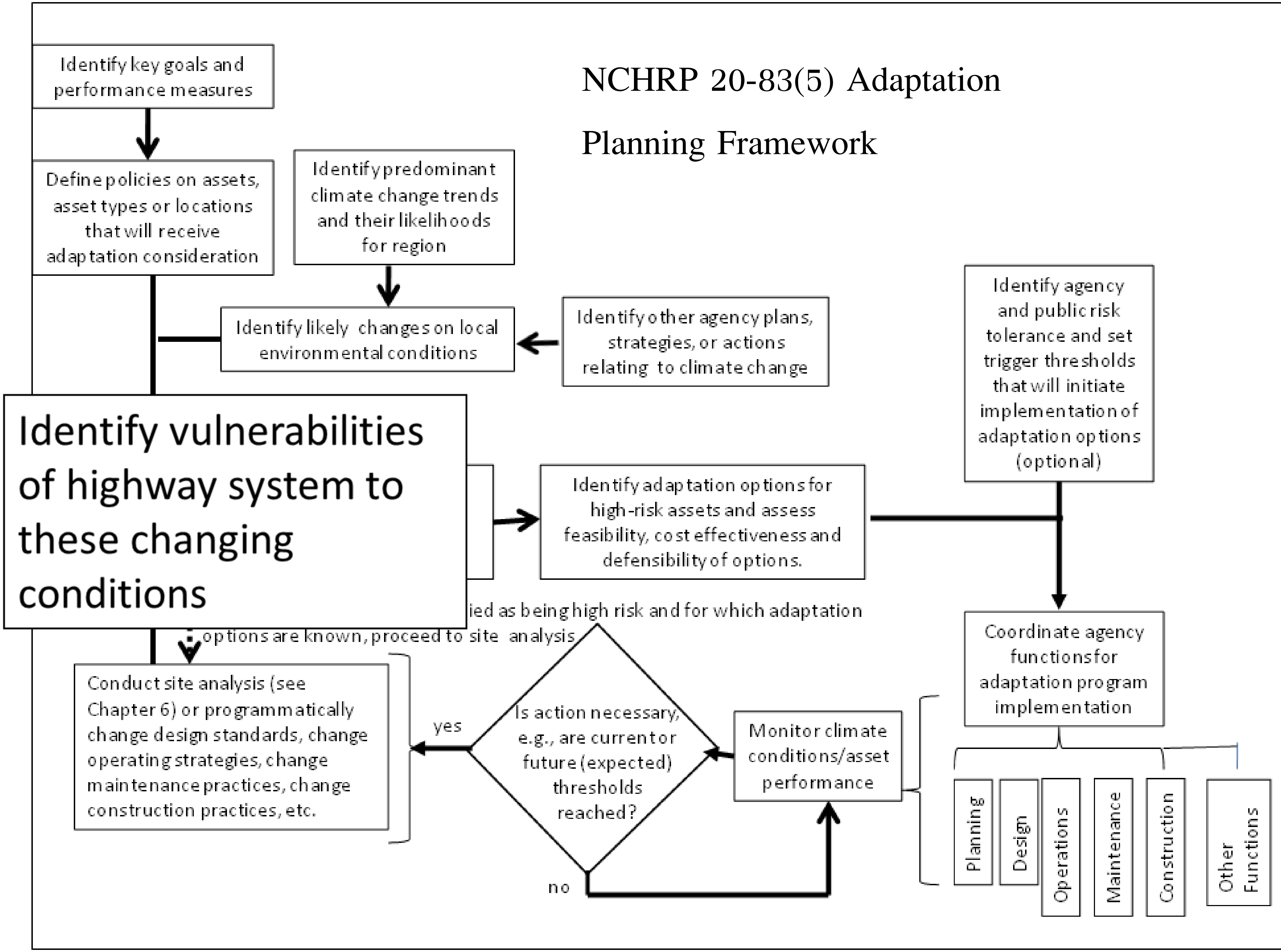

Identify key goals and performance measures
NCHRP 20-83(5) Adaptation Planning Framework
Define policies on assets, asset types or locations that will receive adaptation consideration
Identify predominant climate change trends and their likelihoods for region
Identify likely changes on local environmental conditions
Identify other agency plans, strategies, or actions relating to climate change
Identify agency and public risk tolerance and set trigger thresholds that will initiate implementation of adaptation options (optional)
Identify vulnerabilities of asset(s) to changing environmental conditions
Conduct risk appraisal of asset(s) given vulnerabilities
Identify adaptation options for high-risk assets and assess feasibility, cost effectiveness and defensibility of options.
For those assets already identified as being high risk and for which adaptation options are known, proceed to site analysis
Coordinate agency functions for adaptation program implementation
Conduct site analysis (see Chapter 6) or programmatically change design standards, change operating strategies, change maintenance practices, change construction practices, etc.
yes
Is action necessary, e.g., are current or future (expected) thresholds reached?
no
Monitor climate conditions/asset performance
Planning
Design
Operations
Maintenance
Construction
Other Functions

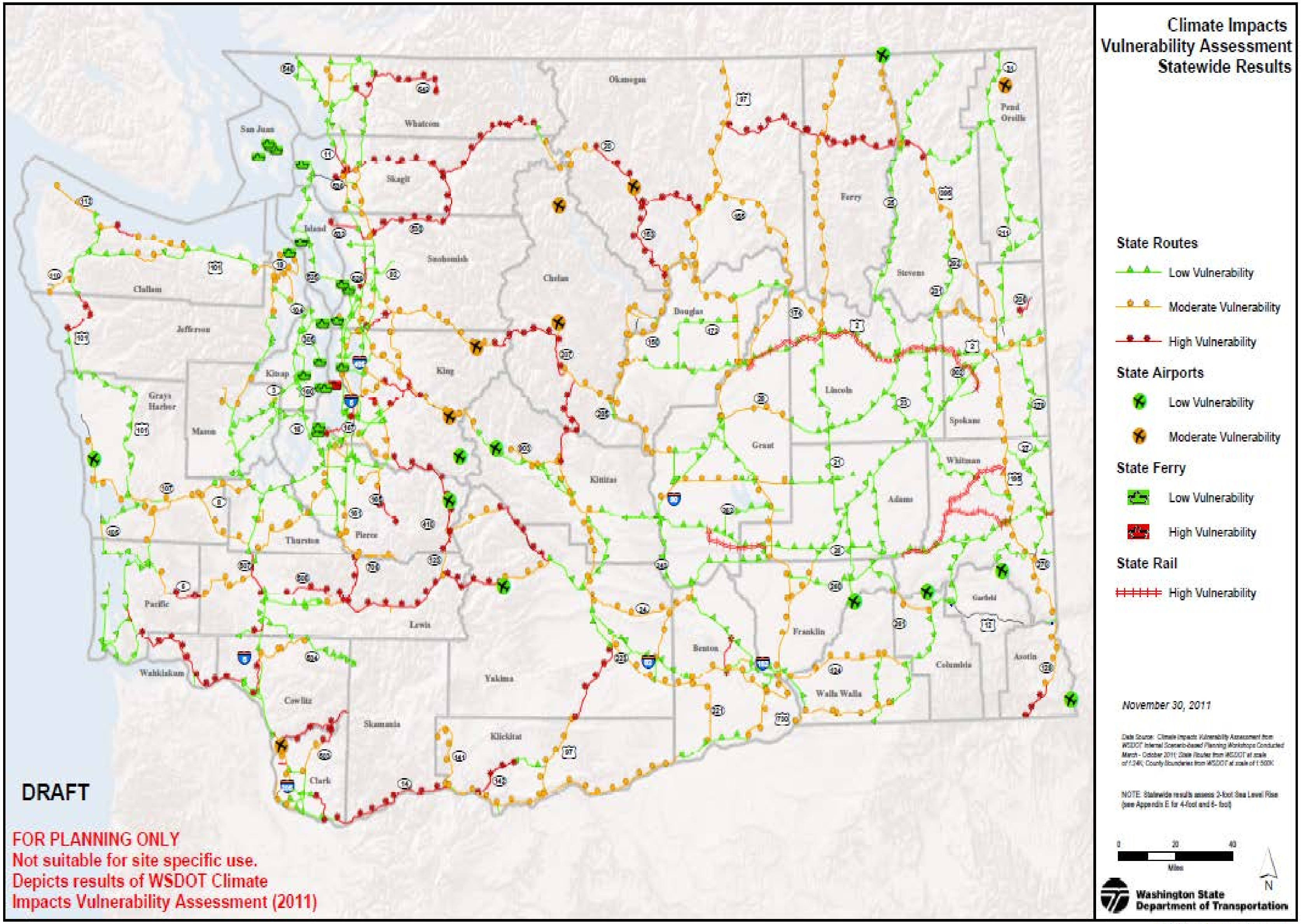
NCHRP 20-83(5) Adaptation Planning Framework

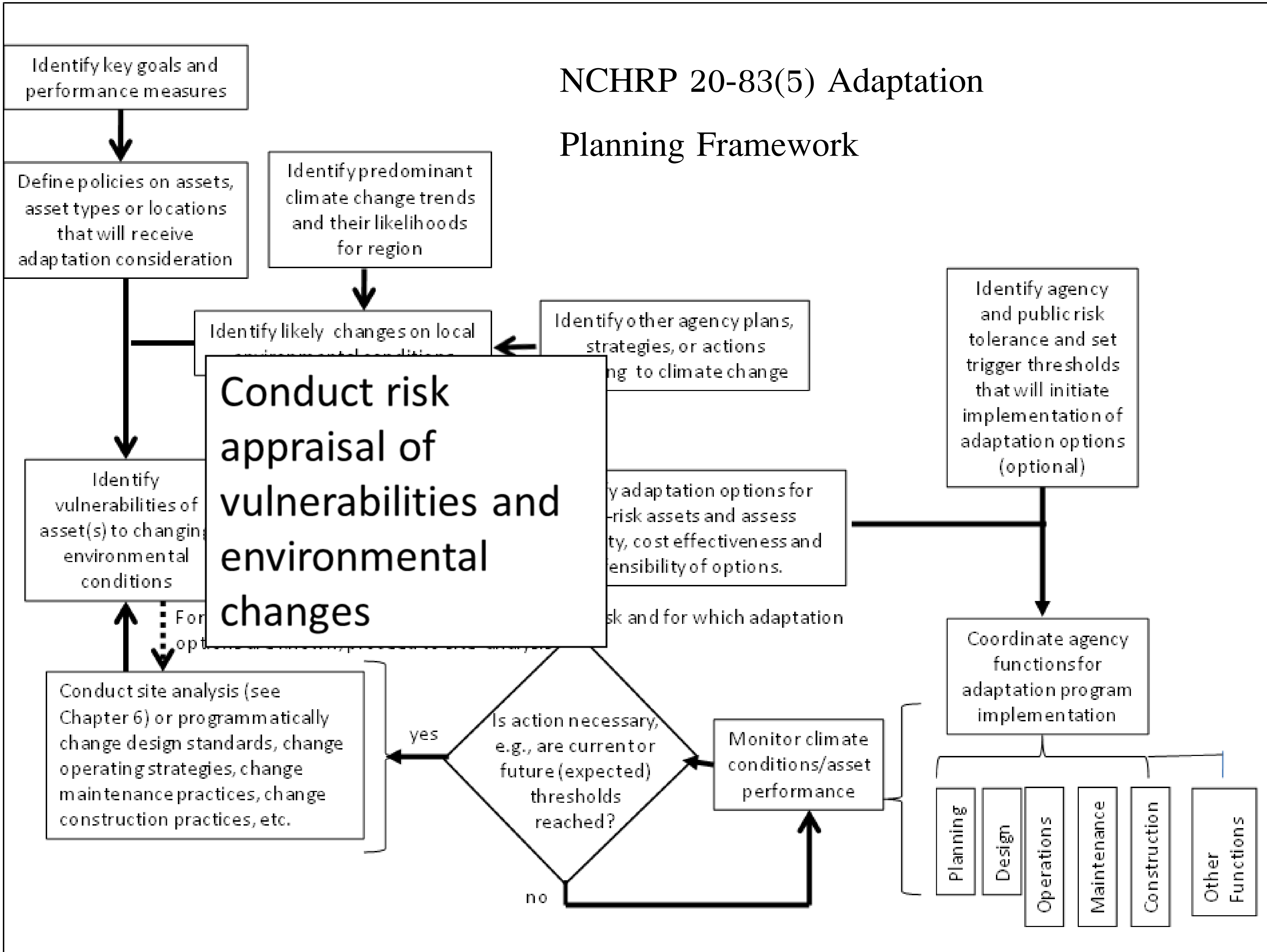



NCHRP 20-83(5) Adaptation
Planning Framework
Identify key goals and performance measures
Define policies on assets, asset types or locations that will receive adaptation consideration
Identify predominant
Identify predominant climate change trends and factors for region
ncy plans,
ctions
to climate change
Identify agency and public risk tolerance and set trigger thresholds that will initiate implementation of adaptation options (optional)
Identify vulnerabilities of asset(s) to changing environmental conditions
Conduct risk appraisal of asset(s) given vulnerabilities
Identify adaptation options for high-risk assets and assess feasibility, cost effectiveness and defensibility of options.
For those assets already identified as being high risk and for which adaptation options are known, proceed to site analysis
Coordinate agency functions for adaptation program implementation
Conduct site analysis (see Chapter 6) or programmatically change design standards, change operating strategies, change maintenance practices, change construction practices, etc.
yes
Is action necessary, e.g., are current or future (expected) thresholds reached?
no
Monitor climate conditions/asset performance
Planning
Design
Operations
Maintenance
Construction
Other Functions


NCHRP 20-83(5) Adaptation
Planning Framework
Identify key goals and performance measures
Define policies on assets, asset types or locations
Identify predominant climate change trends and their likelihoods
Identify impact of these changes on local environmental conditions
tify other agency plans, trategies, or actions ting to climate change
Identify agency and public risk tolerance and set trigger thresholds that will initiate implementation of adaptation options (optional)
Identify vulnerabilities of asset(s) to changing environmental conditions
Conduct risk appraisal of asset(s) given vulnerabilities
Identify adaptation options for high-risk assets and assess feasibility, cost effectiveness and defensibility of options.
For those assets already identified as being high risk and for which adaptation options are known, proceed to site analysis
Coordinate agency functions for adaptation program implementation
Conduct site analysis (see Chapter 6) or programmatically change design standards, change operating strategies, change maintenance practices, change construction practices, etc.
yes
Is action necessary, e.g., are current or future (expected) thresholds reached?
no
Monitor climate conditions/asset performance
Planning
Design
Operations
Maintenance
Construction
Other Functions


NCHRP 20-83(5) Adaptation Planning Framework
Identify key goals and performance measures
Define policies on assets, asset types or locations that will receive adaptation consideration
Identify predominant climate change trends and their likelihoods for region
Identify likely changes on local environmental conditions
Identify other agency plans, strategies, or actions relating to climate change
Identify vulnerabilities of highway system to these changing conditions
Identify adaptation options for high-risk assets and assess feasibility, cost effectiveness and defensibility of options.
Identify agency and public risk tolerance and set trigger thresholds that will initiate implementation of adaptation options (optional)
ied as being high risk and for which adaptation options are known, proceed to site analysis
Conduct site analysis (see Chapter 6) or programmatically change design standards, change operating strategies, change maintenance practices, change construction practices, etc.
yes
Is action necessary, e.g., are current or future (expected) thresholds reached?
no
Monitor climate conditions/asset performance
Coordinate agency functions for adaptation program implementation
Planning
Design
Operations
Maintenance
Construction
Other Functions


Climate Impacts
Vulnerability Assessment
Statewide Results
State Routes
Low Vulnerability
Moderate Vulnerability
High Vulnerability
State Airports
Low Vulnerability
Moderate Vulnerability
State Ferry
Low Vulnerability
High Vulnerability
State Rail
High Vulnerability
November 30, 2011
NOTE: Statewide results assess 2-foot Sea Level Rise (see Appendix E for 4-foot and 6- foot)
Miles
N
Washington State Department of Transportation
DRAFT
FOR PLANNING ONLY
Not suitable for site specific use.
Depicts results of WSDOT Climate Impacts Vulnerability Assessment (2011)
San Juan
Whatcom
Okanogan
Ferry
Stevens
Pend Oreille
Skagit
Island
Snohomish
Chelan
Douglas
Lincoln
Spokane
Clallam
Jefferson
Kitsap
King
Grays Harbor
Mason
Grant
Kittitas
Adams
Whitman
Thurston
Pierce
Pacific
Lewis
Franklin
Garfield
Columbia
Asotin
Walla Walla
Benton
Yakima
Wahkiakum
Cowlitz
Skamania
Klickitat
Clark

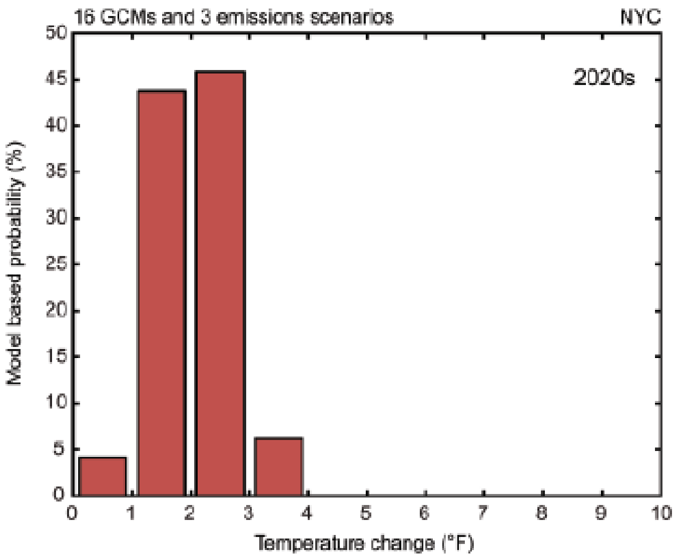

NCHRP 20-83(5) Adaptation
Planning Framework
Identify key goals and performance measures
Define policies on assets, asset types or locations that will receive adaptation consideration
Identify predominant climate change trends and their likelihoods for region
Identify likely changes on local
Identify other agency plans, strategies, or actions
ng to climate change
Conduct risk appraisal of vulnerabilities and environmental changes
Identify agency and public risk tolerance and set trigger thresholds that will initiate implementation of adaptation options (optional)
Identify vulnerabilities of asset(s) to changin environmental conditions
y adaptation options for
-risk assets and assess
ty, cost effectiveness and
ensibility of options.
For
sk and for which adaptation
op
Coordinate agency functions for adaptation program implementation
Conduct site analysis (see Chapter 6) or programmatically change design standards, change operating strategies, change maintenance practices, change construction practices, etc.
yes
Is action necessary, e.g., are current or future (expected) thresholds reached?
no
Monitor climate conditions/asset performance
Planning
Design
Operations
Maintenance
Construction
Other Functions

Frequency Distributions

FIGURE 10.

Model-Based Frequency Distribution of Temperature Changes

Frequency distribution of model-based temperature changes (°F) in NYC, relative to the 1971-2000 base period, for 16 models and three emissions scenarios



New York City Panel on Climate Change

Virtually certain	> 99% probability of occurrence
Extremely likely	> 95% probability of occurrence
Very likely	> 90% probability of occurrence
Likely	> 66% probability of occurrence
More likely than not	> 50% probability of occurrence
About as likely as not	33-66% probability of occurrence

Level	Likelihood
A	Remote
B	Unlikely
C	Likely
D	Highly Likely
E	Near Certainty

ASSESSMENT GUIDE

Likelihood	a	b	c	d	e
E	M	M	H	H	H
D	L	M	M	H	H
C	L	L	M	M	H
B	L	L	L	M	M
A	L	L	L	L	M

Consequence

Level	Schedule	and/or	Cost
a	Minimal or no impact		Minimal or no impact
b	Additional resources required; able to meet		<5%
c	Minor slip in key milestones; not able to meet need date		5-7%
d	Major slip in key milestone or critical path impacted		7-10%
e	Can't achieve key team or major program milestone		>10%

RISK ASSESSMENT

High (Red)

Unacceptable. Major disruption likely. Different approach required. Priority management attention required

Moderate (Yellow)

Some disruption. Different approach may be required. Additional management attention may be needed

Low (Green)

Minimum impact. Minimum oversight needed to ensure risk remains low

Risk Rating: Victoria

Table 9: Risk Rating Matrix

Likelihood	Consequences				
	Insignificant 1	Minor 2	Moderate 3	Major 4	Catastrophic 5
A (almost certain)	L	M	H	E	E
B (likely)	L	M	M	H	E
C (moderate)	L	L	M	H	E
D (unlikely)	L	L	M	M	H
E (very unlikely)	L	L	L	M	M

E - Extreme risk, requiring immediate action.
H - High risk issue requiring detailed research and planning at senior management level.
M - Moderate risk issue requiring change to design standards and maintenance of assets.
L - Low risk issue requiring action through routine maintenance of assets.

Holper, Paul, Sean Lucy, Michael Nolan, Claudio Senese, and Kevin Hennessy (eds.), 2006: *Infrastructure and Climate Change Risk Assessment for Victoria*. Victoria Government. (http://www.greenhouse.vic.gov.au/CA256F310024B628/0/2021C307264A6473CA2572DD00055CBB/$File/Climate+change+and+Infrastructure+Final.pdf)

Example Risk Assessment from the Bay Area

		Consequence				
Likelihood		**1**	**2**	**3**	**4**	**5**
	1	2	3	4	5	6
	2	3	4	5	6	7
	3	4	5	6	7	8
	4	5	6	7	8	9
	5	6	7	8	9	10
Risk	Low		Moderate		High	

Unacceptable, major disruption likely; priority management attention required.

Moderate Risk (Orange)

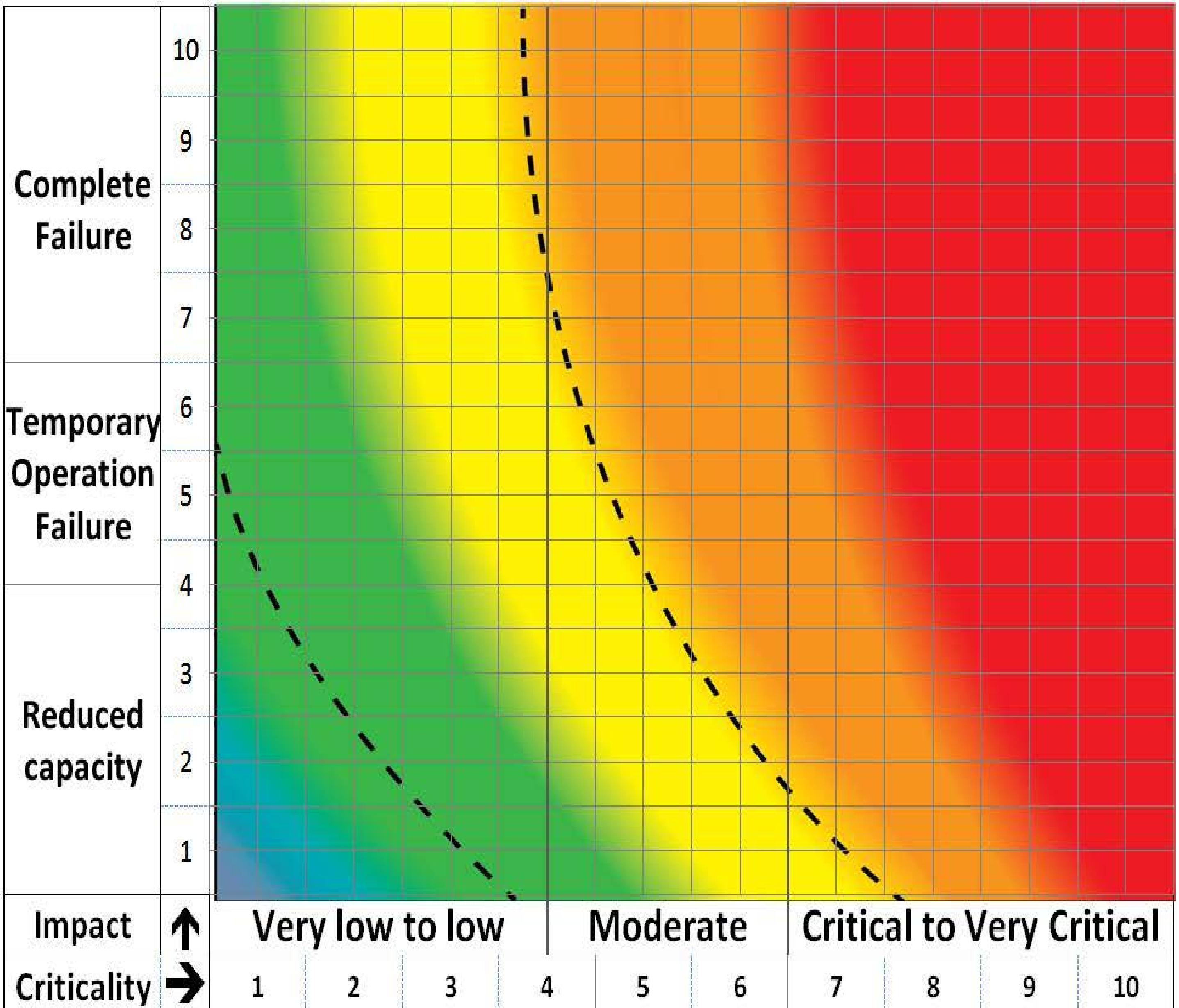
Some disruption; additional management attention may be needed.

Low Risk (Green)

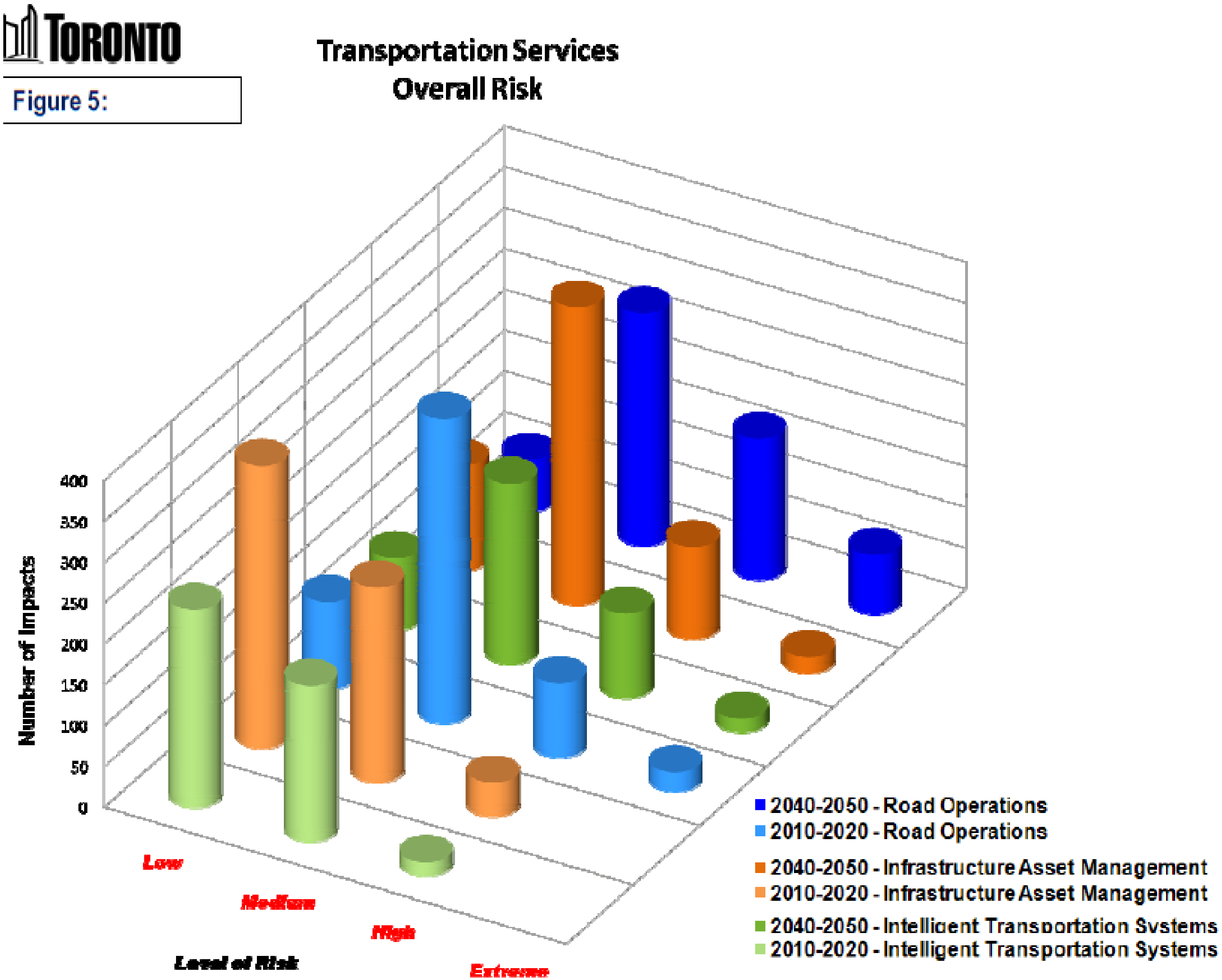
Minimum impact; minimum oversight needed to ensure risk remains low.

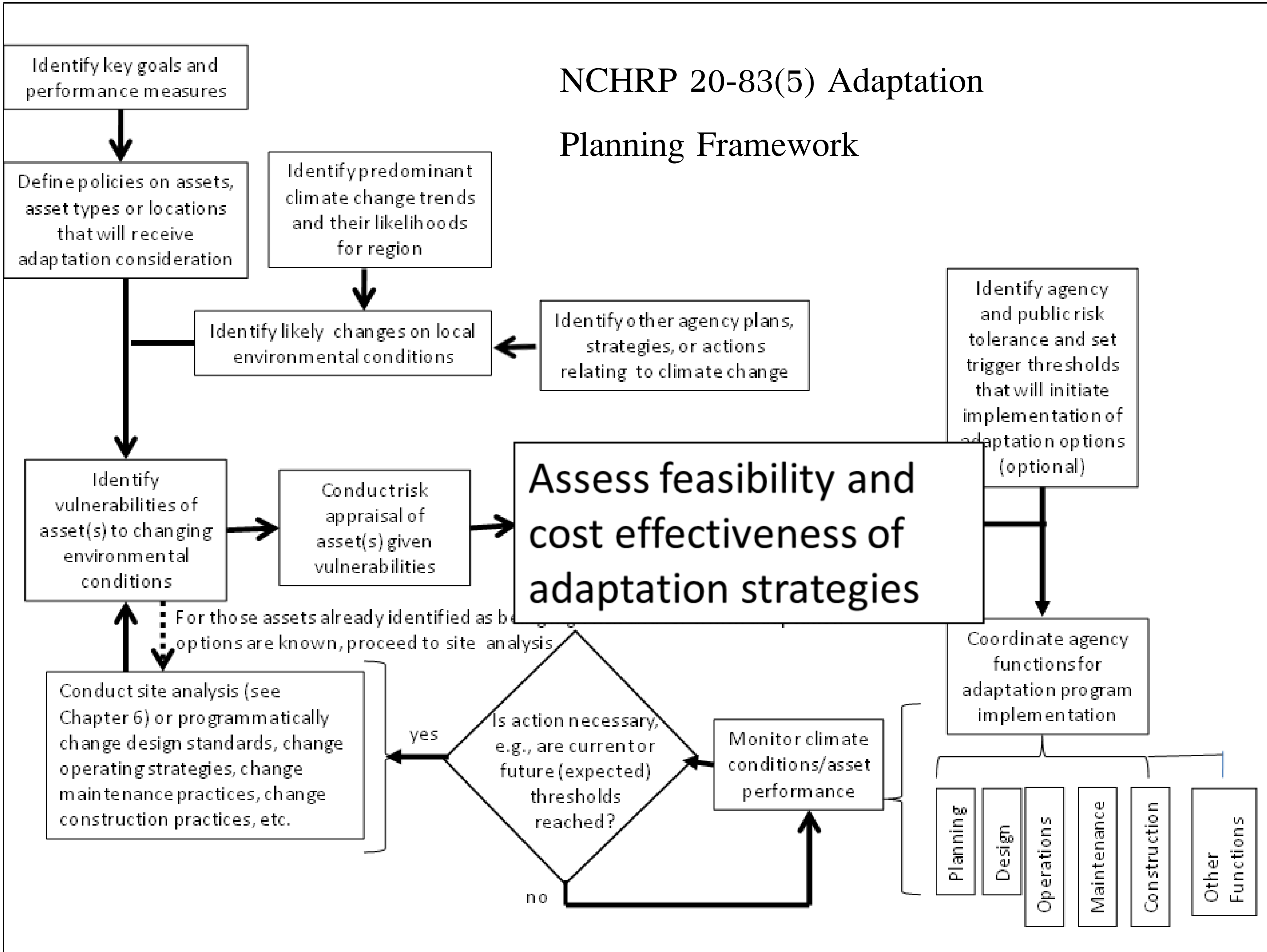
Metropolitan Transportation Commission, Caltrans, Bay Conservation and Development Commission

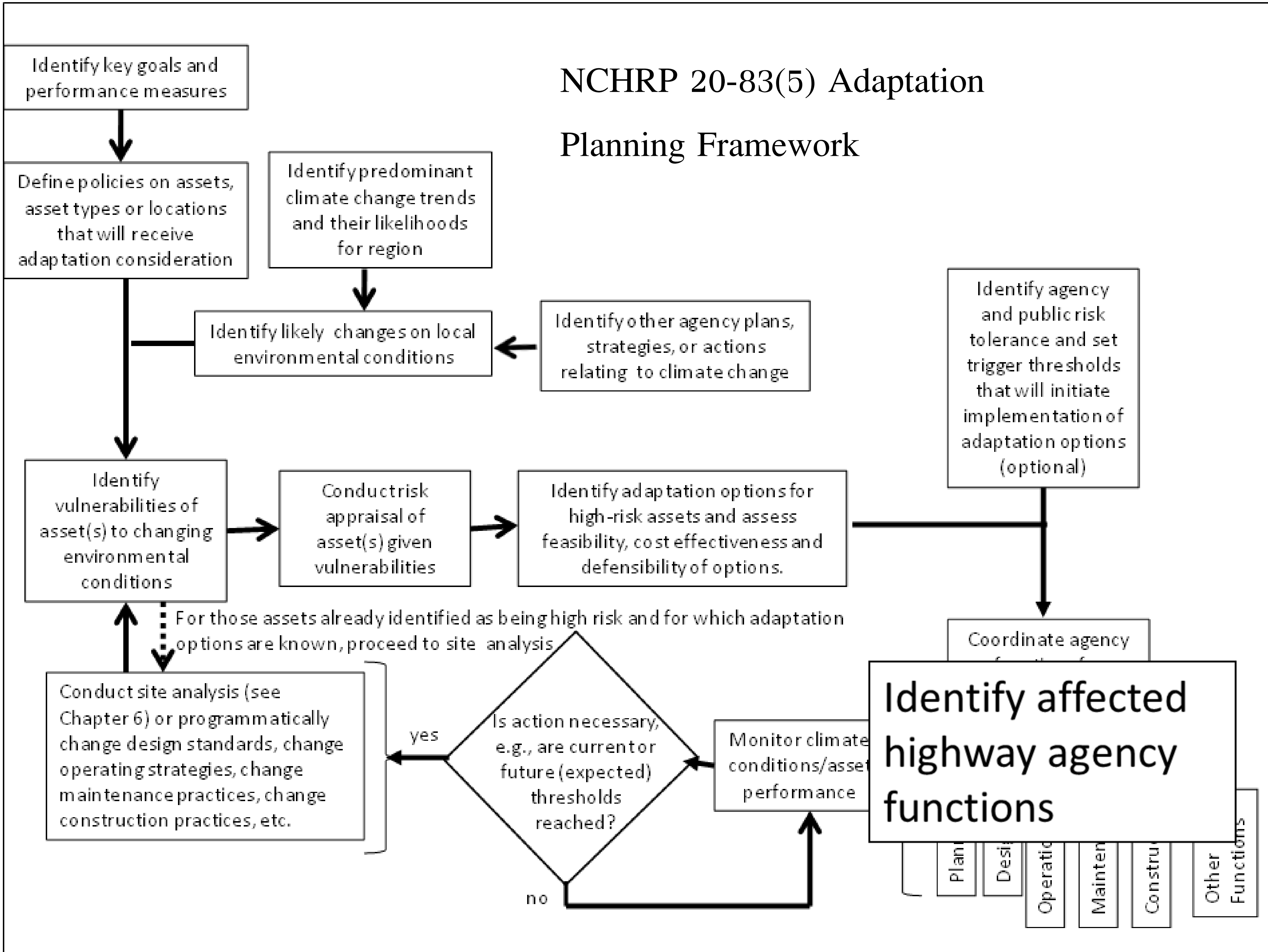
Washington State DOT's Assessment Approach for Identifying Assets at Risk



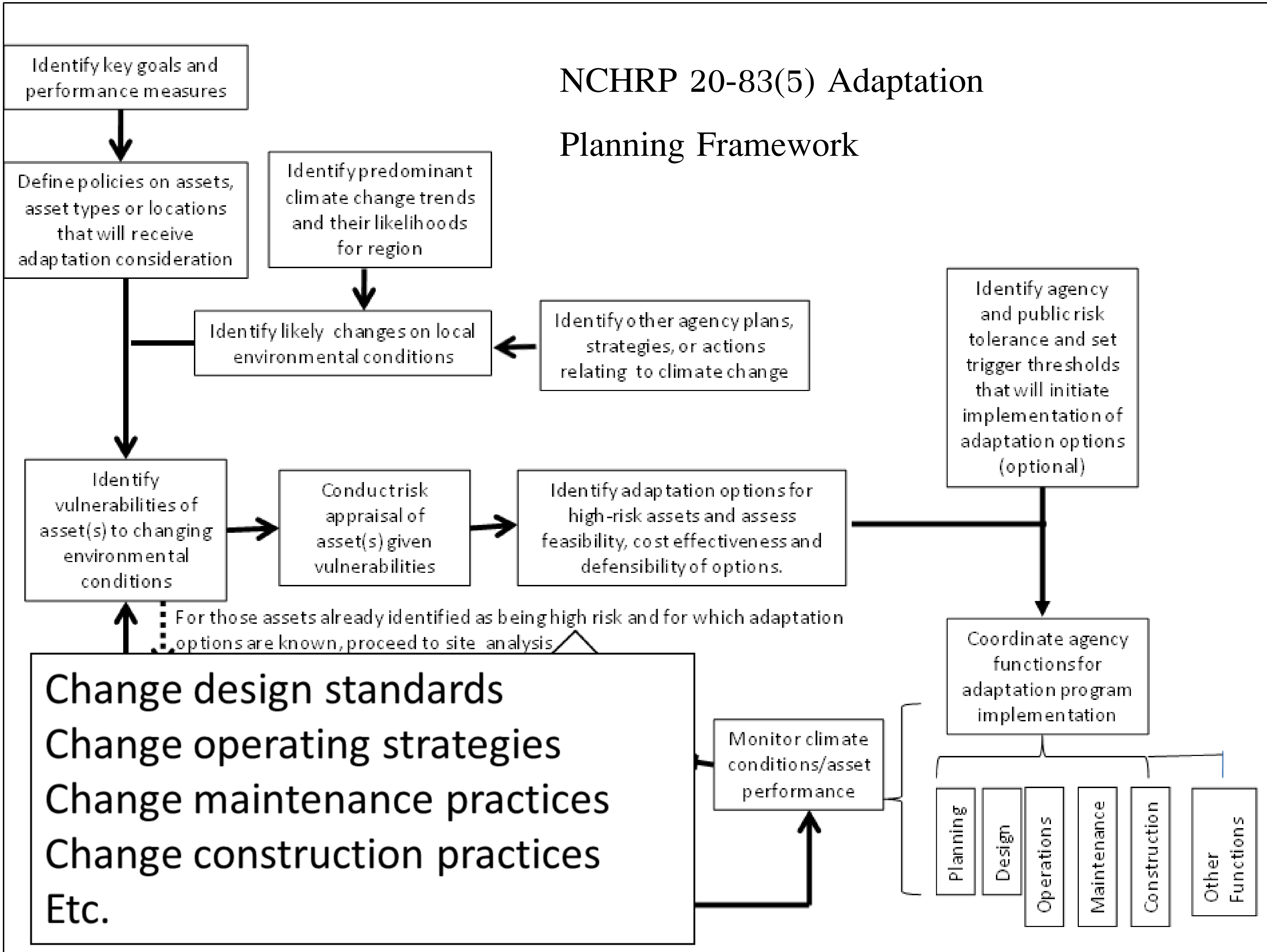
Overall Transportation System Risk Assessment to Climate Change, Toronto

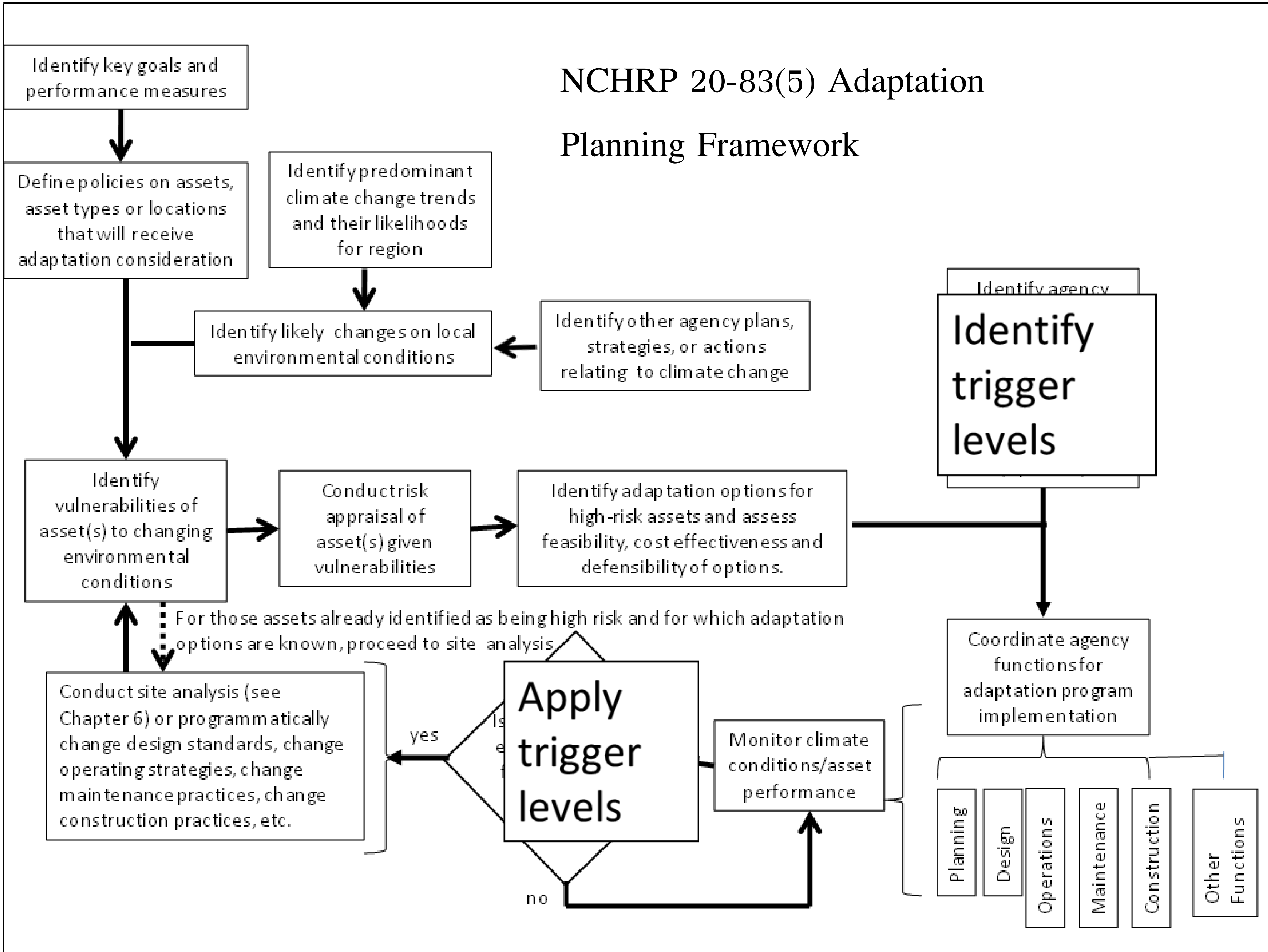



NCHRP 20-83(5) Adaptation Planning Framework
Identify key goals and performance measures
Define policies on assets, asset types or locations that will receive adaptation consideration
Identify predominant climate change trends and their likelihoods for region
Identify likely changes on local environmental conditions
Identify other agency plans, strategies, or actions relating to climate change
Identify agency and public risk tolerance and set trigger thresholds that will initiate implementation of adaptation options (optional)
Identify vulnerabilities of asset(s) to changing environmental conditions
Conduct risk appraisal of asset(s) given vulnerabilities
Assess feasibility and cost effectiveness of adaptation strategies
For those assets already identified as be
options are known, proceed to site analysis
Conduct site analysis (see Chapter 6) or programmatically change design standards, change operating strategies, change maintenance practices, change construction practices, etc.
yes
Is action necessary, e.g., are current or future (expected) thresholds reached?
no
Monitor climate conditions/asset performance
Coordinate agency functions for adaptation program implementation
Planning
Design
Operations
Maintenance
Construction
Other Functions



NCHRP 20-83(5) Adaptation Planning Framework
Identify key goals and performance measures
Define policies on assets, asset types or locations that will receive adaptation consideration
Identify predominant climate change trends and their likelihoods for region
Identify likely changes on local environmental conditions
Identify other agency plans, strategies, or actions relating to climate change
Identify agency and public risk tolerance and set trigger thresholds that will initiate implementation of adaptation options (optional)
Identify vulnerabilities of asset(s) to changing environmental conditions
Conduct risk appraisal of asset(s) given vulnerabilities
Identify adaptation options for high-risk assets and assess feasibility, cost effectiveness and defensibility of options.
For those assets already identified as being high risk and for which adaptation options are known, proceed to site analysis
Coordinate agency
Conduct site analysis (see Chapter 6) or programmatically change design standards, change operating strategies, change maintenance practices, change construction practices, etc.
yes
Is action necessary, e.g., are current or future (expected) thresholds reached?
no
Monitor climate conditions/asset performance
Identify affected highway agency functions
Other Functions


NCHRP 20-83(5) Adaptation Planning Framework
Identify key goals and performance measures
Define policies on assets, asset types or locations that will receive adaptation consideration
Identify predominant climate change trends and their likelihoods for region
Identify likely changes on local environmental conditions
Identify other agency plans, strategies, or actions relating to climate change
Identify agency and public risk tolerance and set trigger thresholds that will initiate implementation of adaptation options (optional)
Identify vulnerabilities of asset(s) to changing environmental conditions
Conduct risk appraisal of asset(s) given vulnerabilities
Identify adaptation options for high-risk assets and assess feasibility, cost effectiveness and defensibility of options.
For those assets already identified as being high risk and for which adaptation options are known, proceed to site analysis
Coordinate agency functions for adaptation program implementation
Change design standards
Change operating strategies
Change maintenance practices
Change construction practices
Etc.
Monitor climate conditions/asset performance
Planning
Design
Operations
Maintenance
Construction
Other Functions


NCHRP 20-83(5) Adaptation
Planning Framework
Identify key goals and performance measures
Define policies on assets, asset types or locations that will receive adaptation consideration
Identify predominant climate change trends and their likelihoods for region
Identify likely changes on local environmental conditions
Identify other agency plans, strategies, or actions relating to climate change
Identify trigger levels
Identify vulnerabilities of asset(s) to changing environmental conditions
Conduct risk appraisal of asset(s) given vulnerabilities
Identify adaptation options for high-risk assets and assess feasibility, cost effectiveness and defensibility of options.
For those assets already identified as being high risk and for which adaptation options are known, proceed to site analysis
Coordinate agency functions for adaptation program implementation
Conduct site analysis (see Chapter 6) or programmatically change design standards, change operating strategies, change maintenance practices, change construction practices, etc.
yes
Apply trigger levels
Monitor climate conditions/asset performance
no
Planning
Design
Operations
Maintenance
Construction
Other Functions

Importantly, climate adaptation is not just design oriented….it also includes operations, maintenance, construction, location engineering, land use and public policy (just to name a few).

Operations and Maintenance???

Meyer's Top Ten O&M "Things To Do"

1. *Culverts:* Keeping culverts debris free and maintained to handle above average flows.

2. *Bridge Scour:* In high risk river/stream basins, protecting bridge columns and piers from higher than average flows during extreme precipitation events to reduce probability of bridge scour.

3. *Evacuation Routes*: In coastal and flood prone areas, developing and operating effective evacuation routes.

4. *Traveler Information:* Developing effective public and traveler information systems/services that can be used during weather emergencies to inform travelers of travel options.

5. *Workforce Protection:* Protecting O&M workers from extreme temperatures during day-to-day activities.

Meyer's Top Ten O&M "Things To Do"

6. *<u>Pre-Positioning Materials and Equipment:</u>* Developing strategies for responding to transportation system and facility disruptions due to weather-related events, including pre-positioning replacement materials in vulnerable areas
7. *<u>Mudslide and Landslide Strategies</u>:* Identifying facility locations vulnerable to mudslides or landslides, and developing appropriate strategies to minimize such risk.
8. *<u>Back-Up Power</u>:* Putting in place power back up for electrical devices in areas prone to extreme weather events, especially for traffic signals.
9. *<u>Early Warning Indicators</u>:* Incorporating "early warning indicators" for potential extreme weather-related risks into asset and maintenance management systems.
10. *<u>Landscaping and Vegetation</u>:* Where appropriate, using drought-proof landscaping and vegetation, and multi-culture families of vegetation

Options for the treatment of risks:

- Future-proofing of designs
- Retro-fit solutions
- Developing contingency plans
- Updating operating procedures
- Monitoring
- Research

Michigan DOT

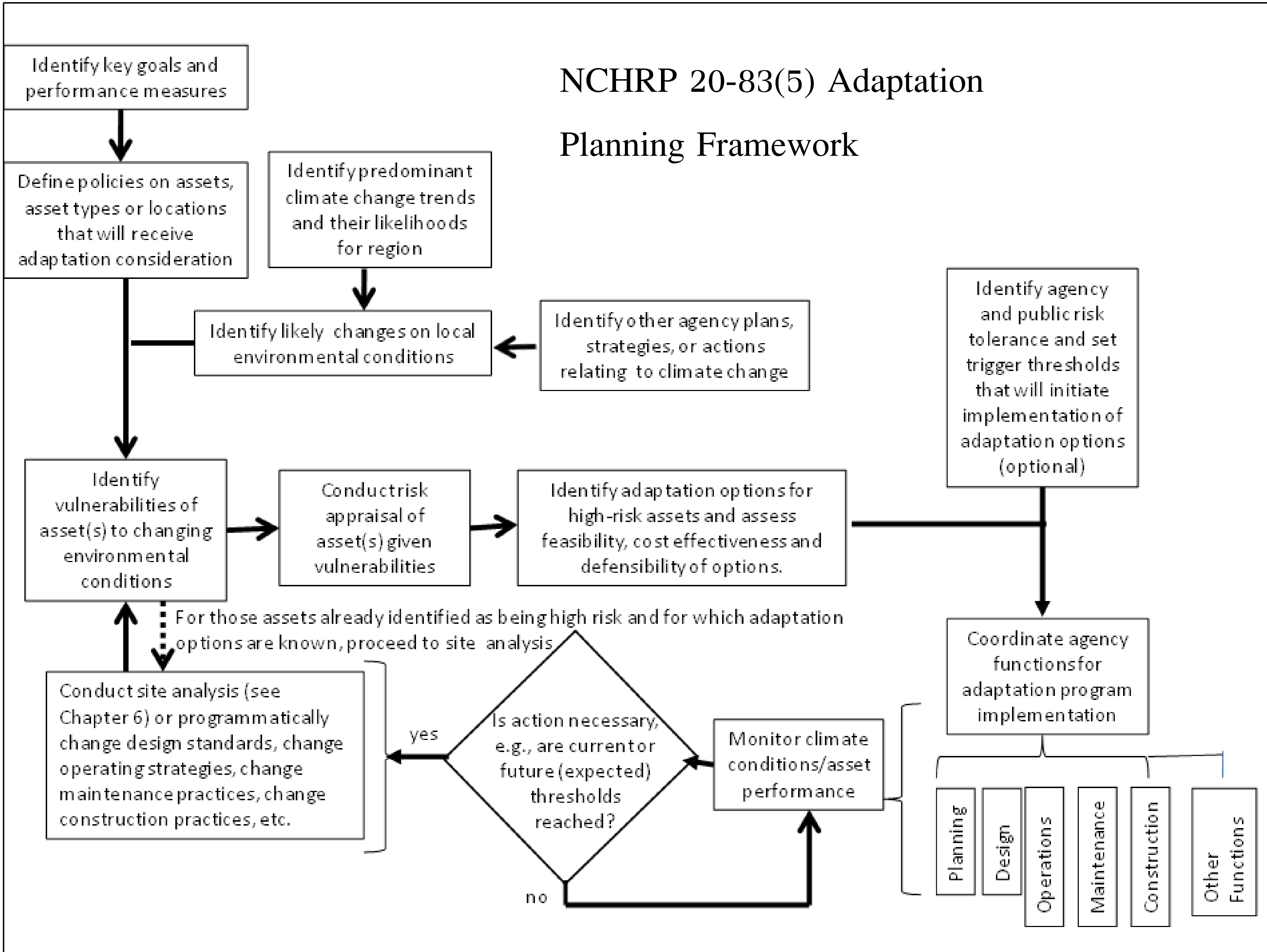
More Intense Storms – Strategy: Design assets that are less impacted by affects of Climate Change

- Larger hydraulic openings for bridges over waterways
- Heavier and lengthier armoring of river and stream banks and ditches to prevent erosion
- Investigate greater pavement crowns to move runoff off of pavement quicker

- Design of additional in-system detention to meter runoff outflow
- Eliminate bridge design elements that could make a bridge scour critical
  - i.e. piers in the river, spread footings, use more sheet piling left in place
- Design terraced vegetated slopes using a variety of plant species

- Eliminate monoculture roadside vegetation designs that may not survive extended drought periods or invasive species attack

- Incorporate materials whose performances are less variable in weather extremes
- Larger capacity pumps/pump stations for below grade freeways to prevent flooding
- Stronger specifications for protection of work under construction
- Monitor and clean, as needed, bike lanes, shoulders, and non motorized trails in vertical curve sag areas.



NCHRP 20-83(5) Adaptation Planning Framework
Identify key goals and performance measures
Define policies on assets, asset types or locations that will receive adaptation consideration
Identify predominant climate change trends and their likelihoods for region
Identify likely changes on local environmental conditions
Identify other agency plans, strategies, or actions relating to climate change
Identify agency and public risk tolerance and set trigger thresholds that will initiate implementation of adaptation options (optional)
Identify vulnerabilities of asset(s) to changing environmental conditions
Conduct risk appraisal of asset(s) given vulnerabilities
Identify adaptation options for high-risk assets and assess feasibility, cost effectiveness and defensibility of options.
For those assets already identified as being high risk and for which adaptation options are known, proceed to site analysis
Coordinate agency functions for adaptation program implementation
Conduct site analysis (see Chapter 6) or programmatically change design standards, change operating strategies, change maintenance practices, change construction practices, etc.
yes
Is action necessary, e.g., are current or future (expected) thresholds reached?
no
Monitor climate conditions/asset performance
Planning
Design
Operations
Maintenance
Construction
Other Functions