Key Findings for Transit Agencies from FHWA Climate Vulnerability Pilots

The Federal Highway Administration (FHWA) funded state departments of transportation (DOTs) and metropolitan planning organizations (MPOs) to pilot a conceptual model to use in conducting vulnerability and risk assessments of transportation infrastructure to the projected impacts of global climate change. The purpose of the pilots was twofold: 1) to assist state DOTs and MPOs more quickly advance existing adaptation assessment activities; and 2) to assist FHWA in "test-driving" the model. The model has three main steps: 1) develop inventory of assets; 2) gather climate information; and 3) assess the risk to assets and the transportation system as a whole from projected climate change.

The pilot projects included analysis of public transportation assets. They also utilized methodologies that are in many cases directly applicable to public transportation agencies. The purpose of this memo is to highlight some of the key findings relevant to public transportation agencies.

For more details, please refer to the final reports for each of the pilots, which were completed in December 2011 and are available at the website links in the references section of this document. The conceptual model used for the pilots can be found at http://www.fhwa.dot.gov/hep/climate/pilots.htm. This memo also includes key findings to date related to transit from the U.S. DOT Gulf Coast Study Phase II, which is underway. More information on the Gulf Coast Study can be found at: http://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/index.cfm. This memo is for informational purposes only. Any errors are the responsibility of the author.

Key Findings for Transit

Project	Transit Analysis	Methodologies of Interest
1. San Francisco	Risk profiles of Bay Area Rapid Transit District (BART) assets	• Method of taking shoreline assets (wetlands, levees, etc) into account when determining vulnerability of coastal transportation assets • Risk profile template
2. New Jersey	Analysis of New Jersey Transit track and bus routes vulnerable to coastal flooding from sea level rise, storm surge, and rainfall related inland flooding.	• Method for estimating future increase in floodplain area due to heavier rainfall from climate change
3. Washington State	Analysis of impact of climate change on Washington State Ferries (ferries are considered transit and receive FTA funding)	• Workshop format for conducting vulnerability assessment with local maintenance staff and subject matter experts • Introductory video created for workshops
4. Oahu	Flooding risks to transit facility	• Broad stakeholder input followed by high level analysis
5. Gulf Coast Study Phase II	1 of 2 bus maintenance facilities owned by Waves Transit of Mobile, AL is highly vulnerable to sea level rise and storm surge, as are several bus routes	• Very detailed climate analysis and storm surge modeling

1. San Francisco

The San Francisco Bay Area pilot focused on sea level rise and storm surge impacts on a study area consisting of the Alameda County shoreline. The study area contains the terminus for BART's transbay tunnel, two bay bridge touchdowns, Oakland International Airport, and other key transportation infrastructure. The pilot studied two sea level rise scenarios - 16 inches at mid-century and 55 inches at the end of the century. Each of the sea level rise scenarios was analyzed under three conditions:

- high tide
- 100-year extreme water level from storms
- 100-year extreme water level coupled with wind waves

The San Francisco Bay Area pilot took shoreline assets (wetlands, levees, etc) into account when determining the vulnerability of coastal transportation assets. This provides more actionable information than simpler studies that only identify areas lying below a certain elevation. The pilot categorized stretches of shoreline in a GIS mapping exercise into the following five categories:

- Engineered flood protection structures (levees, flood walls)
- Engineered shoreline protection structures (bulkheads, revetments)
- Non-engineered berms
- Wetlands (natural, managed, tidal flats)
- Natural shorelines (non-wetland)

These five categories are ordered above from those that provide the most potential protection from inundation to the transportation infrastructure behind them to those that provide the least potential for inhibiting inland inundation. The project team grouped the individual shoreline assets into larger systems of protection that protected a certain area. For the different sea level and storm scenarios, the team then analyzed the depth of water overtopping the asset and what percent of the length of the shoreline asset system is overtopped.

The project team developed a very helpful, concise, two-page risk profile for transportation assets. The profile provides information on the sensitivity, exposure, and adaptive capacity of the transportation asset, which is then combined into a vulnerability rating. Sensitivity is determined by level of use, age of facility, maintenance cost, seismic retrofit status, and liquefaction susceptibility. (In a sea level rise scenario, rising groundwater levels could lead to an increased likelihood of liquefaction and lateral spreading, magnifying the impact of an earthquake.) Adaptive capacity is measured as the availability of alternate routes. Exposure is rated as follows:

- High exposure: asset inundated by sea level rise at midcentury
- Medium exposure: asset inundated at mid-century under 100-yr storm surge without wind-induced waves, or asset inundated at end of century under either high tide or 100-yr storm surge.
- Low exposure: asset inundated only under a mid or end century scenario that includes wind induced waves on top of the 100-yr storm surge and the sea level rise.

The profile then provides information on consequence, which is used to develop a risk rating that combines likelihood and consequence. Since the study only considered two sea level rise scenarios, one for mid-century and one for end of century, the likelihood rating is the same for each transportation asset. If a range of sea level rise scenarios for a given timeframe had been considered, then a range of likelihoods could have been identified.

The transit findings are summarized in the table below:

Asset	Segment	Risk Rating
BART Line 2a – Subgrade: Transbay Tube	Entire facility	High
BART Line 3a – Elevated: between Transbay Tube and Oakland Wye	Elevated structure between I-880 overcrossing and I-880 undercrossing	Medium
West Oakland BART Station	Entire facility	Medium
Coliseum/Airport BART Station	Entire facility	Medium
Oakland Jack London Square Amtrak Station	Entire facility	Low
Rail line Segment 1	Emeryville Segment (I-580 to 14)	Medium
Rail line Segment 2	Oakland Segment (17-23)	Medium
Jack London Square Ferry Terminal	Entire facility	Low
Alameda Gateway Terminal Ferry (including Park&Ride, bike, ADA access)	Entire facility	Low

The risk profile template and the risk profile for the BART Transbay Tube is found in figures 1 and 2 at the end of this document. The other risk profiles can be found in the pilot report.

2. New Jersey

The New Jersey Transportation Planning Authority (NJTPA) led an interagency partnership to pilot the FHWA model in two study areas in the state - a coastal area and a central area – encompasing large population centers and high value transportation infrastructure.

In the coastal study area, 658 NJ Transit bus route miles[1] and 2.9 miles of NJ Transit track are vulnerable to a medium 2100 sea level rise scenario of 39 inches (1 meter) (see figure 3). The inland study area also has some level of vulnerability to sea level rise because of tidal rivers. For the inland study area, 260 NJ Transit bus route miles and 1.4 miles of NJ Transit track are potentially vulnerable to 39 inches of sea level rise (see pp. 64-65 of NJ pilot).

Storm surge levels were estimated by adding sea level rise to outputs of modeling a Category 1 huricane at high tide with the SLOSH[2] model. This expanded the set of vulnerable transportation assets (see NJ pilot report).

For inland flooding from heavy rain, the New Jersey pilot analyzed the impact of climate change on the 1-in-100 year floodplains.[3] To do this, the project team used a national regression equation that was

[1]The pilot report explains this metric further: "Because multiple bus routes may travel over the same roadway segment, bus "route miles" impacted are often significantly greater than "centerline miles" impacted."
[2] SLOSH is the Sea, Lake, and Overland Surges from Hurricanes model from the National Oceanic and Atmospheric Association (NOAA)
[3] The 1-in-100 year floodplain, also called 100 year flood or 1% flood, is the land area flooded during a heavy rain event that has a 1% chance of occurring in any given year, or in other words, on average, once every one hundred years.

developed through a Federal Emergency Management Agency (FEMA) study.[4] The inputs to the equation are total number of frost days annually (days below freezing), maximum number of consecutive dry days anually, and maximum five-day rainfall during a given year (mm).[5] The project team generated these inputs specific to the study area through analysis of climate models.

Using the statistical methods described above, the estimated future floodplains in the study areas were an average 8%, 40%, and 59% wider in 2050 than the current 1-in-100-year flood plain under the low, medium, and high emissions scenarios[6], respectively, and an average 17%, 80% and 178% wider than current floodplains in 2100. 81 miles of roadways, 1120 transit bus route miles, and 26 NJ Transit track miles lie in the projected 1-in-100 year floodplain for 2100 under the medium emissions scenario (see figure 4).

The project team notes that the statistically adjusted floodplain top-width approach used in the study is a good one for high-level assessments of large study areas. Although not as sensitive as hydrological approaches would be, the statistical approach only requires a small fraction of the resources. The New Jersey pilot project spent around $15,000 to develop expanded 1-in-100 year floodplains for three scenarios and two time periods for a study area of over 500 square miles.

To provide persepctive on the scale of the 1-in-100 year rainfall event and its relationship to engineering design standards, which are typically in units of inches of rain per hour, the current 1-in-in 100 year rainfall event delivers 10 inches of rain in New Brunswick, NJ. The 1-in-100 year rainfall event of 2100 delivers an estimated 10.5, 11.5, and 14 inches under the low, medium, and high emissions scenarios. For comparison, rainfall in New Brunswick from Tropical Storm Irene in August 2011 was 8 inches. 24 hour rainfalls exceeding 4 inches have historically occurred every 5.5 years in New Brunswick. These events are projected to occur on average every 5, 4, and 2 years under the low, medium, and high emissions scenarios, respectively.

Heat impacts assessed by the pilot include rail kinks (rail in New Jersey is set at 95°F, meaning it is suceptible to warping at temperatures above that), catenary sagging (catenary is set at 60°F, though tension lines and pulleys prevent sagging until higher temperatures, which have been experienced in recent years), brownout disruption of electrical supply, increased air conditioning loads on vehicles, and expansion of bridge joints.

3. Washington State

The Washington State Department of Transportation (WSDOT) held a series of workshops throughout the state in order to take advantage of the knowledge of WSDOT experts in materials, hydrology and geology, and maintenance staff who are intimately familiar with current weather impacts on transportation assets.

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[4] Thomas et al., "Effects of Climate Change on the National Flood Insurance Program in the United States – Riverine Flooding

[5] These are the variables found in the FEMA study to be most highly correlated with the 1% annual chance flood discharge, in cubic feet per second.

[6] The emissions scenarios are those developed by the United Nations Intergovernmental Panel on Climate Change (IPCC). The low scenario refers to the IPCC B1 scenario, the medium to A1B, and the high to A2.

The workshops began by showing a video explaining how the climate assessment fits into WSDOT's overall asset management. The video included explanation of anticipated climate impacts and featured WSDOT maintenance staff pointing to impacts being experienced on bridges and roads. Workshop participants then qualitatively rated the criticality of transportation assets in their region on a scale of 1 to 10, considering average daily traffic, availability of alternative routes, and functional classification. Then workshop participants qualitatively rated the consequence of impacts on a scale of 1 to 10 ranging from reduced capacity, to temporary operation failure, to complete failure. The assessment did not include probabilities, as it is not generally possible to say which emissions scenario is more probable than another. As such, the two dimensional WSDOT climate risk map is of criticality on one axis and consequence on the other, rather than the more typical risk map of likelihood on one axis and consequence on the other. The project team used climate scenarios developed for the state by the University of Washington. WSDOT has made the video, workshop agendas, rating tools, and risk maps available to other transportation agencies.

The WSDOT pilot summarized climate impacts on state ferries as follows:

"Ferry terminals are all generally resistant to sea level rise impacts, or they can accommodate rising sea levels in future terminal or loading ramp designs. Current closures due to low tides may not occur with higher sea levels. When terminals close now due to severe weather, vessels and users are rerouted to other terminals. The Eagle Harbor ferry maintenance facility is located near sea level. If this facility is inundated permanently, other options would need to be explored."

"If rivers bring more debris into Puget Sound, operational expenses would need to be increased to clean out debris that could damage ferries or docks. Large waves that come over decks can move cars; and ferry elevators do not work if the vessel is rocked by large waves. With larger waves and more extreme storms, this risk may increase. With 4-foot and 6-foot sea levels, power lines to docks may be inundated." See figure 5 for a map of the impacts to WSDOT-owned ferry facilities.

4. Oahu

The climate vulnerability pilot for the island of Oahu in Hawaii, home to the state capital of Honolulu, included an assessment of the transit facility at 811 Middle Street, near the Honolulu Airport. The relevant text from the report is reproduced below.

Criticality Assessment

"The 811 Middle Street facility houses 1800 employees, 531 buses, and 166 vehicles for TheHandi-Van. TheBus has a weekday ridership of 236,000 people and serves 100 different bus routes including express routes, community circulator routes, and urban feeder routes. TheHandi-Van's daily weekday ridership is 2,800 customers. When looking at this asset for the combined TheBus and TheHandi-Van Baseyard and Intermodal Transit Center, the team determined that the climate change variables of storm surge, sea level rise, and heavy rain/storm events would have a socioeconomic valuation of the asset of high. This is because the vehicles may be needed for evacuations, and the social value of providing mobility to the community makes this asset important."

"These facilities have some redundancy, and the vehicles and equipment have some mobility. The Pearl City/Manana Baseyard can provide some redundancy for TheBus and TheHandi-Van operations in the event of a storm. The buses and TheHandi-Van vehicles are normally not at the facility because they are used for islandwide evacuation in the event of an emergency. TheBus keeps approximately two days of diesel fuel for backup at 811 Middle Street with another two days of backup at the Pearl City/Manana Baseyard. Possibly their largest issue, like on Kauai after Hurricane Iniki, would be getting drivers and other employees to report back to work following an emergency event."

Sea Level Rise
"While the 811 Middle Street facility is currently in a flood zone, its existing ground elevation gives it a low vulnerability and impact rating from sea level rise in 2050. Because this facility is adjacent to Kalihi Stream, situated at a bend in the stream channel, it may suffer more flooding by 2100 due to the combined effects of sea level rise and increased runoff intensity. This is because the bend in Kalihi Stream forms a sharp 90 degree deflection as circled in Figure 6, which may experience increased stream bank scour and become a collection point for mud and debris from upstream. The collection of debris and mud, coupled with high tide would make this asset more prone to flooding than already occurs."

Storm Surge
"At the 811 Middle Street facility, if the modeled hurricane occurred during high tide, portions of the facility may flood with nearly 10 feet of water, according to the storm surge modeling map. This is because the dredged channels could amplify the effect of storm surge, and the streams could channel the surging water further inland. Sea level rise in 2050 and 2100 will only amplify this effect. The team also noted that debris and mud clogging Kalihi Stream could make this asset more prone to flooding during a storm surge. Currently, the mud has formed "islands" in the middle of the stream, which have vegetation growing on them."

Wind
"TheBus 811 Middle Street hosts communication equipment on its rooftop, which may be susceptible to wind damage in a storm, hurricane, or wind gust event. This impact from wind damage is seen as growing with wind velocities predicted to increase by 25% by 2100."

High Intensity Rainfall
"Kalihi Stream appears to be susceptible to a decrease in discharge capacity as a result of sediment and debris accumulation, especially near the channel bend adjacent to the 811 Middle Street facility. The debris has deposited and formed islands in the middle of the stream, which will cause the stream to backup when large debris from upstream accumulate."

Vulnerability Assessment for Honolulu Middle Street Transit Facility

Asset	Period	Sea Level Rise		Storm Surge		High Intensity Rainfall	
		Vulnerability	Impact	Vulnerability	Impact	Vulnerability	Impact
TheBus (811 Middle Street)	2050	low	low	moderate	moderate	low	low
	2100	low-moderate	low-moderate	high	high	moderate	high

5. Gulf Coast Study

Phase I of the US DOT Gulf Coast Study, published in 2008, conducted a high level assessment of the impact of climate change on the central Gulf Coast region. Phase II focuses on the case study area of Mobile, AL and aims to produce detailed analysis of the climate impacts on Mobile-area transportation infrastructure and develop risk assessment tools applicable to communities across the country. While the study will not be complete until 2013, data from the first two deliverables is available.

Phase II uses a very detailed and robust downscaling of climate models, assessment of runoff and evapotranspoiration, sea level rise, and storm surge and wave analysis. This provides a good model for transit agencies seeking an in-depth (and therefore more expensive) analysis. Readers are referred to the interim deliverable reports for details.

The primary transit system for Mobile, Wave Transit, administers demand-response service as well as fixed-route service consisting of 11 local bus routes, a downtown circulator bus, and a regional connection bus service. The transit agency has two facilities. The Gulf, Mobile and Ohio (GM&O) Terminal houses the agency's administrative functions and serves as the central transfer hub, with 9 of the 11 routes terminating there. The GM&O Terminal is located downtown, close to Mobile Bay. The Beltline facility houses administrative, oeprations, and maintenance functions. A summary of key transit results developed so far appears below. See figure 8 for an example of the maps developed for the project.

Transit Exposure to Sea Level Rise

Transit	1 ft Sea Level Rise, 2050	2 ½ ft Sea Level Rise, 2100	6 ½ ft Sea Level Rise, 2100
Facilities	0of 2 (0%)	0 of 2 (0%)	1 of 2 (50%)
SDE Facilities	O of 193 (0%)	0 of 193 (0%)	10 of 193 (5%)
Bus Stops	0 of 907 (0%)	0 of 907 (0%)	10 of 907 (1%)
Bus Routes (km)	0 of 204 (0%)	0 of 204 (0%)	9 of 204 (4%)
MODA Stops	0 of 22 (0%)	0 of 22 (0%)	0 of 22 (0%)
Bike Routes (km)	1 of 212 (0%)	3 of 212 (2%)	20 of 212 (9%)

Transit Exposure to Storm Scenarios

Storm Scenario	Facilities	SDE facilities	Bus Stops	Bus Routes (km)	Downtown Circulator Stops	Bike Routes (km)
Georges, Natural Path	1 of 2	29 of 193 (15%)	64 of 907 (7%)	16 of 203 (8%)	2 of 22 (9%)	24 of 212 (11%)
Katrina, Natural Path	1 of 2	32 of 193 (17%)	81 of 907 (9%)	17 of 203 (8%)	7 of 22 (23%)	25 of 212 (12%)
Georges, Natural Path, Plus 1 ft Sea Level Rise	1 of 2	32 of 193 (17%)	70 of 907 (8%)	17 of 203 (8%)	5 of 22 (23%)	25 of 212 (12%)
Georges, Natural Path, Plus 2.5 ft Sea Level Rise	1 of 2	56 of 193 (29%)	147 of 907 (16%)	25 of 203 (12%)	22 of 22 (100%)	32 of 212 (15%)
Georges, Natural Path, Plus 6.5 ft Sea Level Rise	1 of 2	73 of 193 (38%)	211 of 907 (23%)	37 of 203 (18%)	22 of 22 (100%)	50 of 212 (24%)
Katrina, Natural Path, Plus 2.5 ft Sea Level Rise	1 of 2	66 of 193 (34%)	171 of 907 (19%)	28 of 203 (32%)	22 of 22 (100%)	38 of 212 (18%)
Katrina, Path Shifted for Direct Hit, Increased Winds	1 of 2	105 of 193 (54%)	375 of 907 (41%)	74 of 203 (36%)	22 of 22 (100%)	85 of 212 (40%)
Katrina, Path Shifted for Direct Hit, Increased Winds, Plus 2.5 ft Sea Level Rise	1 of 2	140 of 193 (73%)	654 of 907 (72%)	133 of 203 (65%)	22 of 22 (100%)	112 of 212 (53%)
Katrina, Path Shifted for Direct Hit, Reduced Pressure	1 of 2	115 of 193 (60%)	483 of 907 (53%)	96 of 203 (47%)	22 of 22 (100%)	95 of 212 (45%)

Figure 1: Risk Profile Template Developmed by San Francisco Pilot – Page 1

Asset Location/Jurisdiction Location of the asset in the region/agency responsible for the asset	
Summary Summarizes the technical information on the risk profile in a couple of sentences	
Characteristics This section lists the functionality of the asset selecting from: • Lifeline route • Mass evacuation plan route • Goods movement • Transit routes • Bike route • Commuter route • Regional importance • Socioeconomic importance: supports transit-dependent populations	
Sensitivity: Low /Medium/High – provides the overall sensitivity rating allocated for the asset	
Year Built	Year
Level of Use	
Peak Hour AADT (Annual Average Daily Traffic AADTT (Annual Average Daily Truck Traffic)	Number
Seismic Retrofit	Yes / No
Annual Operations & Maintenance	Cost $
Liquefaction Suceptibility	VH = very high H = high M = moderate L = low
Exposure: Low /Medium/High – provides the overall exposure rating allocated for the asset	
Maximum Inundation Depths	
16" + MHHW 16" + 100-yr SWEL 16" + 100-yr SWEL + wind waves	ft ft Yes/No
55" + MHHW 55" + 100-yr SWEL 55" + 100-yr SWEL + wind waves	ft ft Yes/No
Inadequate Adaptive Capacity (16" SLR): Rating Notes on alternative routes available if asset is inundation	
Vulnerability Rating (midcentury): Low /Medium Low / Medium/ Medium High / High	

Images shown on each risk profile

- Context map showing where the asset is in the subregion
- Photograph(s) of the asset
- Map thumbnail showing projected inundation with 16-inch SLR + 100-yr SWEL
- Map thumbnail showing projected inundation with 55-inch SLR + 100-yr SWEL
- Map thumbnail showing projected overtopping with 16-inch SLR + 100-yr SWEL (light blue)
- Map thumbnail showing projected overtopping with 55-inch SLR + 100-yr SWEL

*Note that there may be symbols in the thumbnail images that are not explained – for the full legend please see the inundation and overtopping maps in Chapter 6.

- MHHW = Mean Higher High Water = high tide
- 100-yr SWEL = 100-yr stillwater elevation = 100-year extreme water level from storms
- 100-yr SWEL + wind waves = above plus the wave heights generated from the wind

Figure 1 (Continued): Risk Profile Template Developmed by San Francisco Pilot – Page 2

Consequence Rating (out of 5): Number between 0 and 5 Ranges of consequence or impact - major (5), moderate (3) and minor (1) were developed for each of the impacts below.	
Capital improvement cost	Cost to restore to same design standard/ infrastructure type.
Time to rebuild	To original condition, based on 84-, 60-, and 24-month estimates
Public safety	Lifeline or evacuation route
Economic impact - goods movement	Based on average annual daily truck traffic (AADTT) data
Economic impact - commuter route	Daily ridership figures (also all freeways, bridges, tubes assigned major impact)
Socioeconomic impact	Based on MTC communities of concern, MTC data on household car ownership and whether providing a transit route
Risk Rating: High / Medium / Low (from combination of "likelihood" and "consequence") rating	

Shoreline Asset "Overtopping" Analysis ***(see Section 4.3.2 for more detail)***	
Proximity of transportation asset to overtopped shoreline asset (distance)	***16" + 100-yr SWEL*** ft Transportation assets that are closer to the shoreline could have a higher likelihood of future inundation
	55" + 100-yr SWEL ft
Length overtopped (% of System)	***16" + 100-yr SWEL*** ft (%) The greater the percentage, potentially the more at risk the asset is
	55" + 100-yr SWEL ft (%)
Average depth of overtopping	The average depth of inundation along the overtopped portion of the shoreline assets within a particular system. Portions of the shoreline system that are not overtopped (overtopping depth = 0) are not included in the average overtopping depth calculation. As sea level rises from the 16" to 55" SLR scenarios, additional lengths of shoreline are inundated within each system; therefore, the average overtopping depth increase between the two scenarios is less than the 39" increase in sea level.
	16" + 100-yr SWEL ft The deeper the overtopping, potentially the more at risk the asset is
	55" + 100-yr SWEL ft
System responsible for inundating transportation asset **(See overview map)**	Number of System: The study area is divided into 28 shoreline "systems" – contiguous reaches of shoreline that act together to prevent inundation of inland areas, ranging in length from approximately 1 to 18 miles. Section 6.5

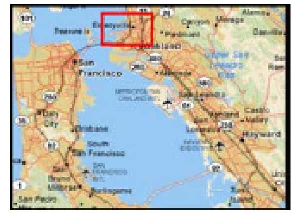
Future Projects
Description of any future projects anticipated for the asset.

Figure 2: BART Transbay Tube Risk Profile

Asset Location / Jurisdiction Oakland / BART	
Summary The Transbay Tube is a core component of the BART system, connecting Alameda and other East Bay counties with the City and County of San Francisco and San Mateo County on the Peninsula. Due to lack of data, this asset was not rated with respect to sensitivity. Exposure is medium due to inundation under the 55" + 100-yr SWEL SLR scenario. Because BART trains cannot be rerouted, the Transbay Tube has inadequate adaptive capacity, resulting in an overall vulnerability rating of medium-high. High capital improvement costs, rebuilding time, public safety consequence and commuter use result in a consequence rating of 4.00, making this a high-risk asset.	
Characteristics: • Subgrade • Transit routes [4 BART lines] • Commuter route • Regional importance	

Sensitivity	
Information unavailable in project timeframe.	
Liquefaction Susceptibility	Very High
Exposure: Medium	
Maximum Inundation Depths	
16" + MHHW	0 ft
16" + 100-yr SWEL	0 ft
16" + 100-yr SWEL + wind waves	YES
55" + MHHW	0 ft
55" + 100-yr SWEL	18 ft*
55" + 100-yr SWEL + wind waves	YES
Inadequate Adaptive Capacity (16" SLR): High No possible rerouting	
Vulnerability Rating (mid century): Medium-High	

*High inundation depth is due to below-grade alignment



Projected Inundation with 16 inch SLR + 100-yr SWEL

Projected Inundation with 55 inch SLR + 100-yr SWEL

Figure 2 (Continued): Bart Transbay Tube Risk Profile

Consequence Rating (out of 5): 4.00	
Capital improvement cost	One of the most expensive components of the BART system (5)
Time to rebuild	Construction originally took 9 years (5)
Public safety	Regional significance, alternative to Bay Bridge (5)
Economic impact - goods movement	Not applicable (1)
Economic impact - commuter route	175,546 daily transit riders (5)
Socio-economic impact	Pass-though transit (multiple lines) (3)
Risk Rating: High	

Shoreline Asset "Overtopping" Analysis	
Proximity to Overtopping (distance)	*16" + 100-yr SWEL*
	2,970 ft
	55" + 100-yr SWEL
	2,660 ft
Length Overtopped (% of System)	*16" + 100-yr SWEL*
	5,800 ft (12%)
	55" + 100-yr SWEL
	20,780 ft (41%)
Average Depth of Overtopping	*16" + 100-yr SWEL*
	1.4 ft
	55" + 100-yr SWEL
	2.6 ft
System Responsible (See overview map)	3

Future Projects
None

Projected Overtopping Depth at 16 inch SLR + 100-yr SWEL

Projected Overtopping Depth at 55 inch SLR + 100- yr SWEL

Figure 3: Vulnerability of Rail Transportation to 1 meter Sea Level Rise, Coastal Area of New Jersey

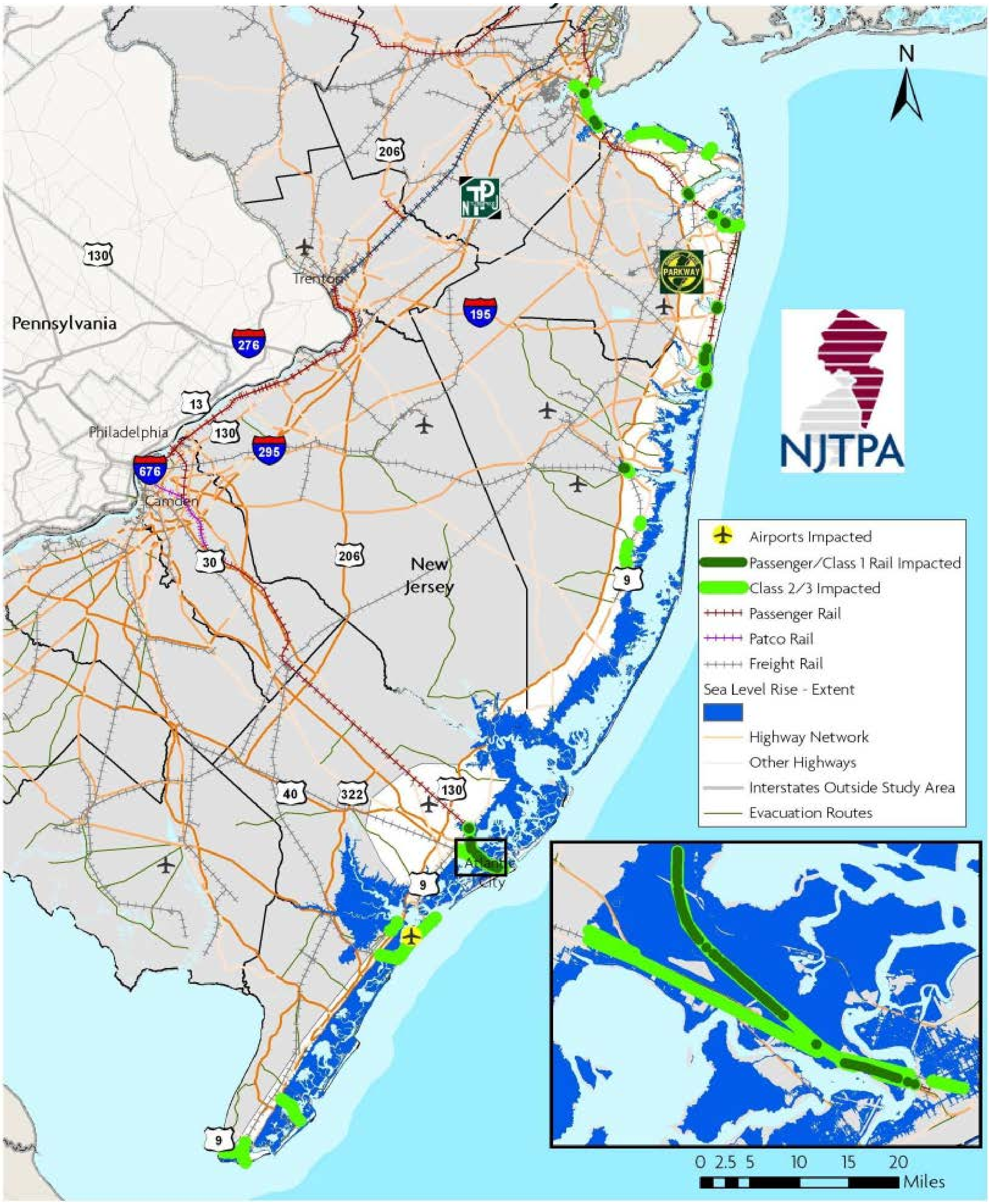


Figure 4: Vulnerability of Rail Transportation to 1-in-100 year Flood from Heavy Rainfall in 2100 in New Jersey Central Study Area, Medium emissions scenario (A1B)

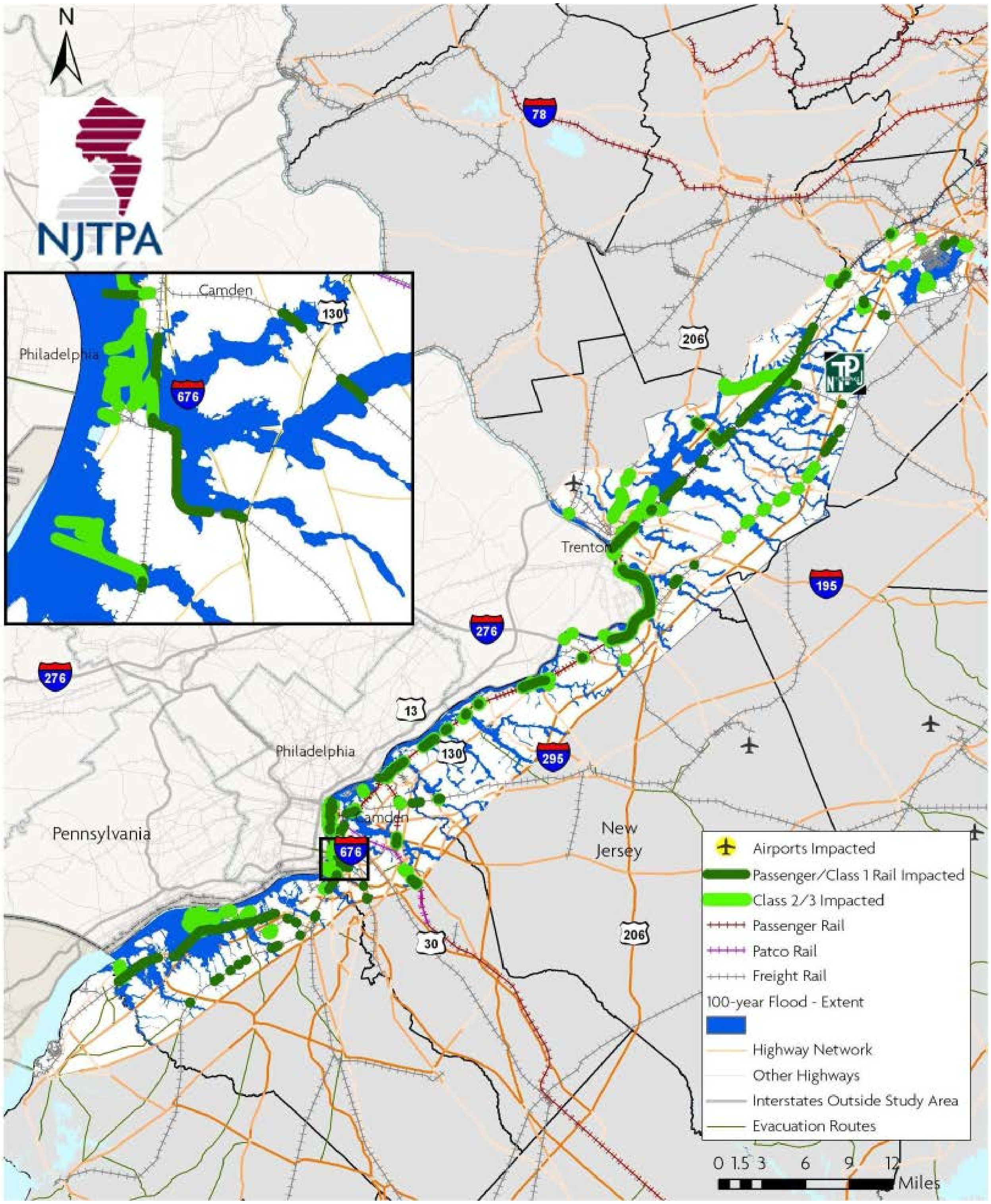


Figure 5: Washington State Ferry Vulnerability to 2 feet Sea Level Rise (main map) as well as 4 and 6 feet (reduced size maps)

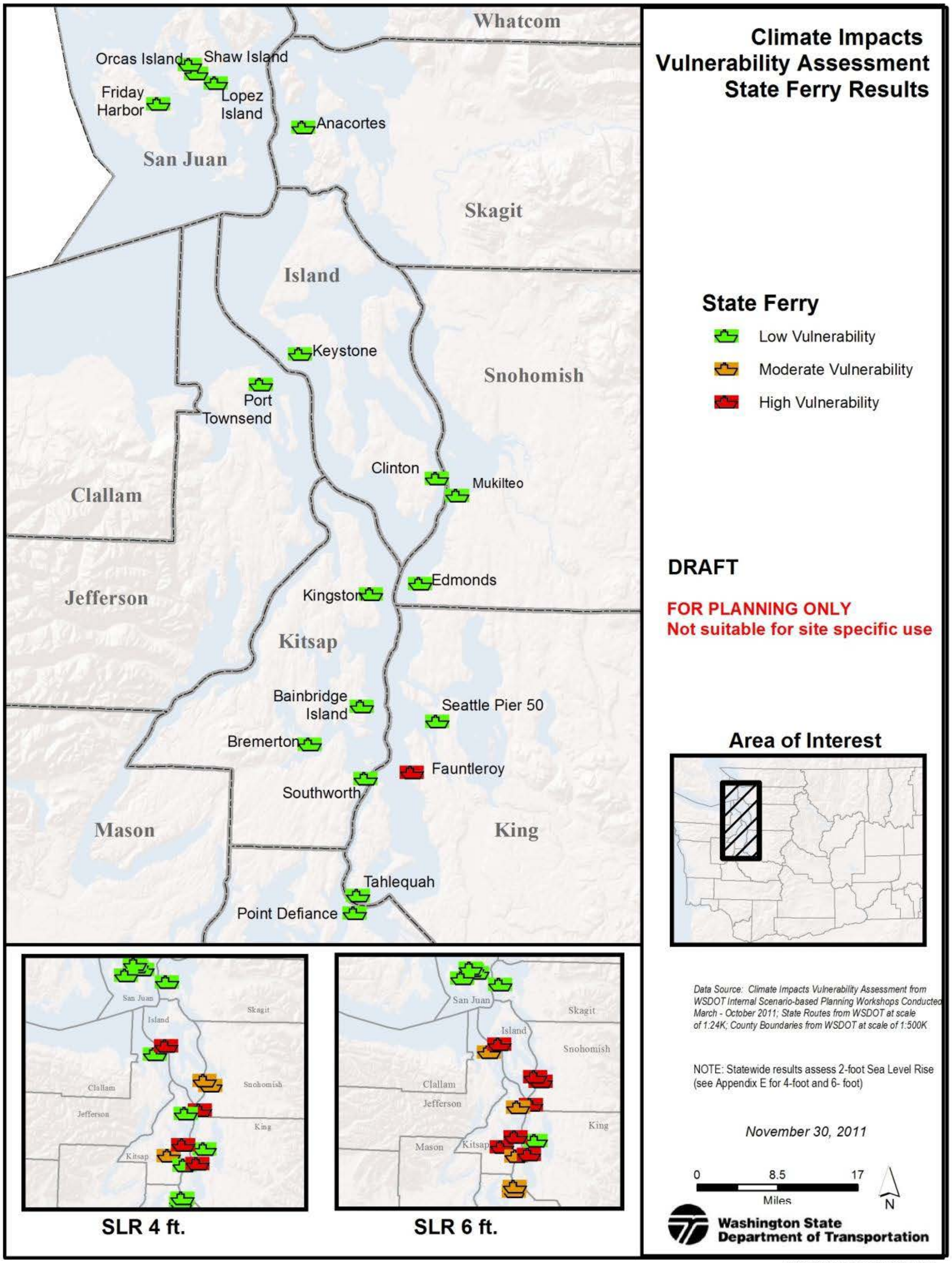


Figure 6: Aerial Photo of Kalihi Stream at 811 Middle Street Transit Facility

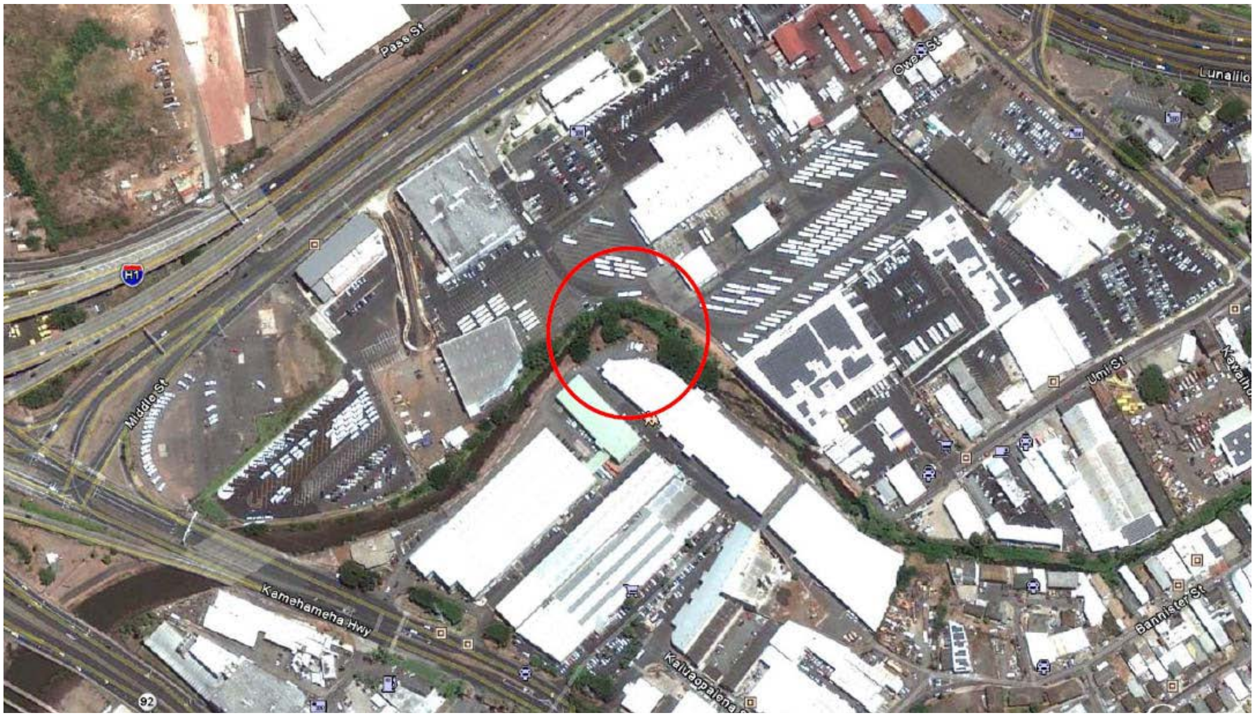


Figure 7: Storm Surge Modeling for Honolulu Airport Area and Transit Facility, Category 4 Hurricane

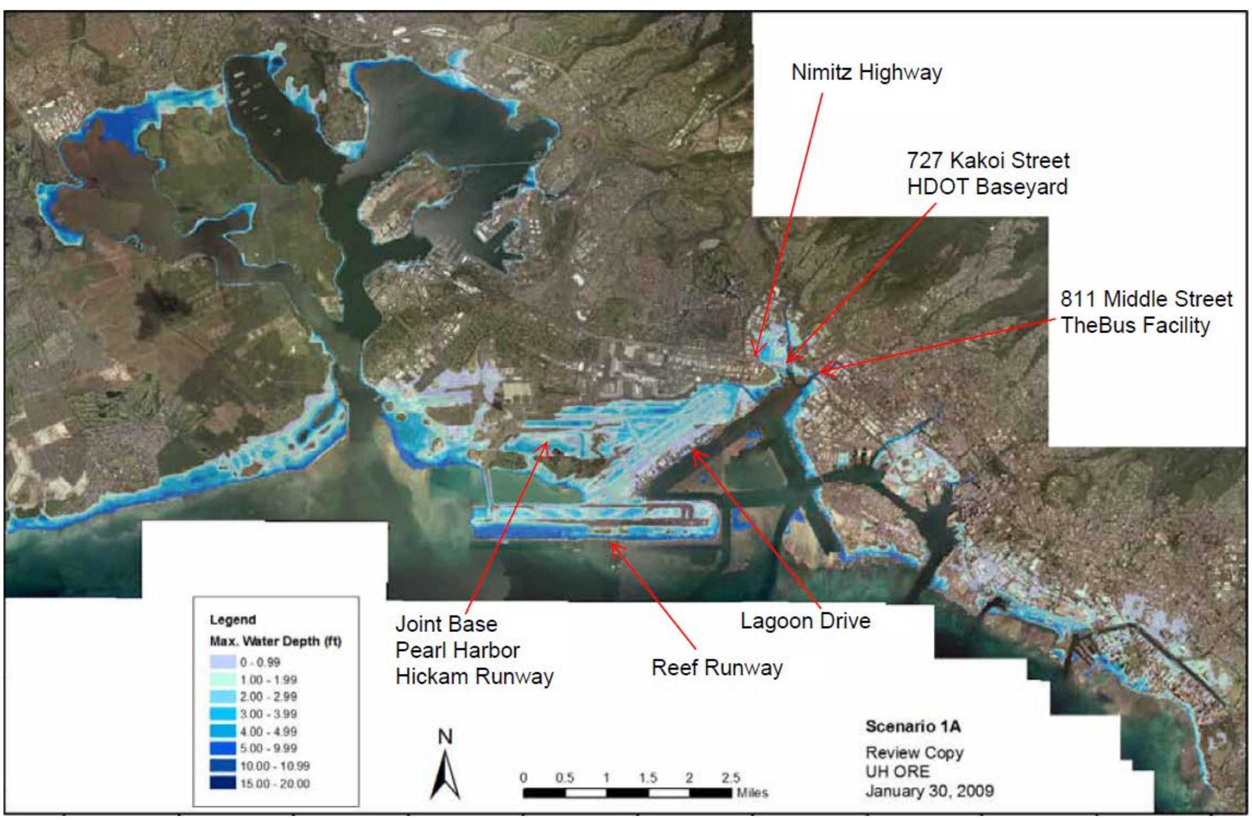
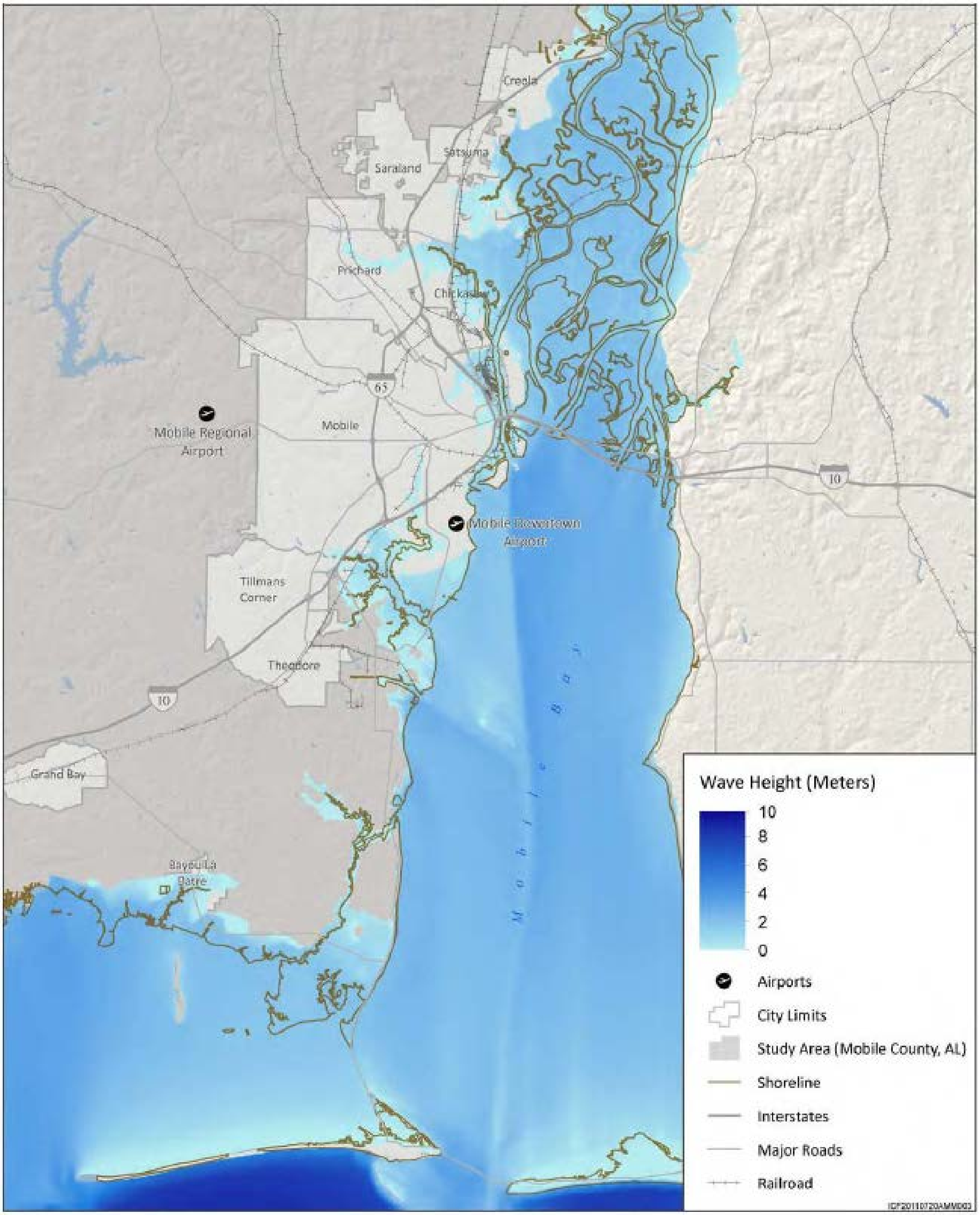


Figure 8: Wave Height of Hurricane Georges Natural Path Scenario with 2 ½ ft Sea Level Rise



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