Adapting to Rising Tides

Transportation Vulnerability and Risk Assessment Pilot Project

Briefing Book • November 2011

Acknowledgments

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TRANSPORTATION SUBCOMMITTEE: Representatives from Caltrans, MTC, Bay Area Rapid Transit, BCDC, Capitol Corridor Joint Powers Authority, Alameda County Transportation Commission, AC Transit, Port of Oakland, City of Oakland, City of Hayward, City of Union City, Water Emergency Transportation Authority, and the Association of Bay Area Governments

SHORELINE ASSET SUBCOMMITTEE: Representatives from the Alameda County Flood Control and Water Conservation District, Alameda County Public Works Agency, BCDC, California Department of Fish and Game, California State Coastal Conservancy, San Francisco Estuary Institute, U.S. Geological Survey, and U.S. Army Corps of Engineers

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Jack London Square at the end of Broadway during King Tide

"The San Francisco Bay Area is one of the most economically and ecologically vibrant regions in the world. But it is also critically vulnerable to the impacts of climate change. As a region, it is imperative that we adapt to the impacts of climate change by fostering resilient and sustainable development. This challenge brings us an exciting opportunity to embrace a spirit of stewardship that advances both economic and environmental prosperity." *—Will Travis, Executive Director, BCDC*

1.0

INTRODUCTION

1.0 INTRODUCTION

1.1 BACKGROUND

1.1.1 ADAPTING TO RISING TIDES PROJECT AND FEDERAL HIGHWAY ADMINISTRATION PILOT PROJECT

The San Francisco Bay Conservation and Development Commission (BCDC) has partnered with the National Oceanic and Atmospheric Administration Coastal Services Center to work with San Francisco Bay Area shoreline communities on planning for sea level rise (SLR) and other climate change–related impacts. The overall goal of the project, called Adapting to Rising Tides (ART), is to increase the preparedness and resilience of Bay Area communities to SLR and other climate change–related impacts while protecting ecosystem and community services. It involves evaluating potential shoreline impacts, vulnerabilities, and risks; identifying effective adaptation strategies; and developing and refining adaptation planning tools and resources that will be useful to communities throughout the Bay Area.

As part of the project, the Metropolitan Transportation Commission (MTC), California Department of Transportation (Caltrans) District 4, and BCDC collaborated on a subregional planning pilot project to test the conceptual Risk Assessment model developed by the Federal Highway Administration (FHWA) to assess the climate change–related SLR risks to transportation infrastructure in a select portion of the San Francisco Bay Area.

The purpose of the pilot project is to enable the region's transportation planners, including those at the MTC, Caltrans, congestion management agencies, and local governments, to improve vulnerability and risk assessment practices and to help craft effective adaptation strategies. If both existing and planned transportation infrastructure is assessed, vital infrastructure can be protected, and future investments can be guided by the best available information about future climate and SLR conditions.

The map opposite shows the pilot project area overlaid with the anticipated sea level rise for the mid and the end of the century.

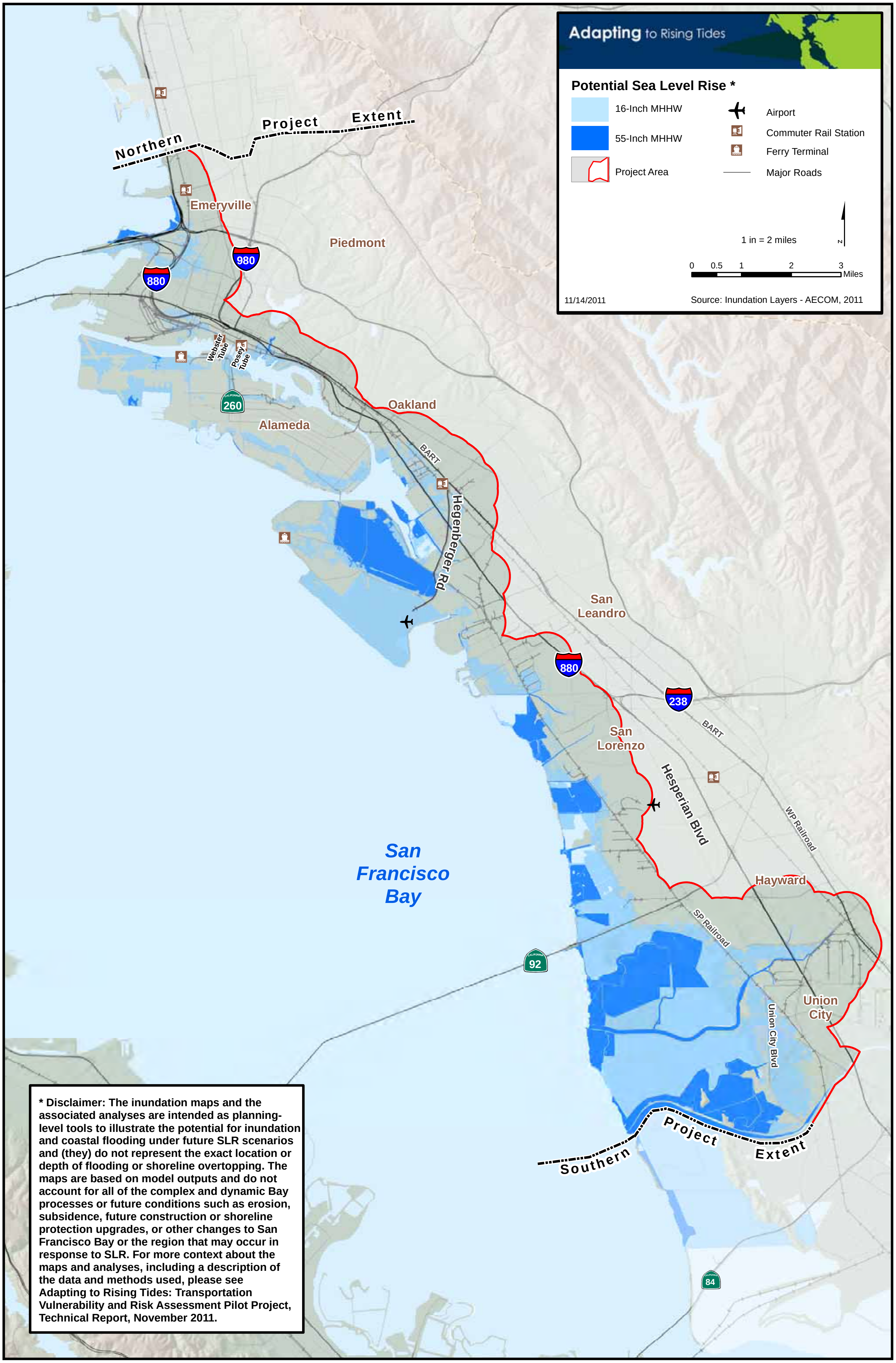


FIGURE 1.1 Map Showing Pilot Project Area and Projected Inundation Extent for Mid and End of Century Scenarios

1.1.2 PILOT PROJECT AREA

The nine-county San Francisco Bay Area, home to approximately 7 million people, is the nation's fifth most populated metropolitan or urbanized area. Its economy, culture, and landscape—supporting prosperous businesses, vibrant neighborhoods, and productive ecosystems—are linked with a vital system of public infrastructure, including freeways, seaports, railroads, and airports, local roads, mass transit, and bicycle and pedestrian facilities that connects the shoreline communities to each other and to the rest of the region, the state, the nation, and the world.

According to current projections, climate change will cause the Bay to rise 16 inches by midcentury and 55 inches by the end of the century (CO-CAT 2010). (These are the two SLR scenarios that were selected for analysis as part of the pilot project, see Chapter 4 for more detail.) This means that today's floods will be the future's high tides and areas that currently flood every 10–20 years will flood much more frequently. Neighborhoods, businesses, and entire industries that currently exist on the shoreline will be subject to this flooding and the many other direct impacts that will result from it. These areas are home to more than 250,000 residents who will be directly affected and many others, including workers, who will be indirectly affected by reduced access to important services, such as transit and commercial centers, health-care facilities, and schools.

After a competitive process, the Alameda County shoreline (stretching from Emeryville in the north to Union City in the south) was selected as the subregion of the Bay Area to be assessed for the FHWA pilot project. The shoreline of the subregion is diverse and includes airports, seaports, industrial, residential, parks, and natural systems. The subregion also contains a large amount of regionally significant transportation infrastructure including rail, highways, two bridge touchdowns, the Oakland International Airport and port, and Bay Area Rapid Transit (BART). This selection process ensured the pilot project had committed and interested stakeholders from the beginning.

1.2 PARTIES INVOLVED

1.2.1 PROJECT TEAM—ROLES AND RESPONSIBILITIES

PROJECT MANAGEMENT TEAM

The Project Management Team (PMT) consisted of representatives from MTC, Caltrans, and BCDC. The PMT provided review of and guidance for the pilot project and supported the Consultant Team (CT) (described in the following section) by obtaining data from their own departments and from local stakeholders. MTC and Caltrans led the identification and assessment of transportation assets, and BCDC led the effort of assembling the information on shoreline assets, climate science, and SLR. BCDC is also leading the ART project and thus provided additional input and guidance on methodology and project process to the team.

CONSULTANT TEAM

The Consultant Team (CT) was composed of transportation planners and engineers, environmental planners, and coastal engineering specialists from AECOM Technical Services and its subconsultants for this project: ARCADIS, Geografika, and 3-D Vision. Note that references to the "project team" include both the PMT and CT.

1.2.2 STAKEHOLDERS

TRANSPORTATION AND SHORELINE ASSET SUBCOMMITTEES

The ART project stakeholder group was a valuable resource and sounding board for the FHWA pilot project. For the purposes of the pilot project, the group was organized into Transportation and Shoreline Asset Subcommittees.

The Transportation Asset Subcommittee included representatives from Caltrans, MTC, BART, BCDC, Capitol Corridor Joint Powers Authority, Association of Bay Area Governments, Alameda County Transportation Commission, AC Transit, Port of Oakland, City of Oakland, City of Hayward, City of Union City, and Water Emergency Transportation Authority.

The Shoreline Asset Subcommittee included representatives from the Alameda County Flood Control and Water Conservation District, Alameda County Public Works Agency, BCDC, California Department of Fish and Game, California State Coastal Conservancy, San Francisco Estuary Institute, U.S. Geological Survey, and U.S. Army Corps of Engineers.

ART SUBREGION WORKING GROUP

The ART project holds regular Subregion Working Group meetings to allow for public input. At these meetings (three were held during the duration of the FHWA pilot project), progress on the FHWA pilot project was reported, and feedback was sought where appropriate. For example, shoreline and transportation assets were discussed as critical categories for analysis as part of the larger ART effort.

1.3 OVERVIEW OF FHWA PILOT PROCESS

The goal of the FHWA conceptual Risk Assessment model is to help transportation decision makers (particularly transportation planners, asset managers, and system operators) identify which of their assets are most exposed to the threats from climate change and/or are associated with the most serious potential consequences of those threats.

The purpose of the pilot projects is twofold: (1) to assist state DOTs and MPOs in more quickly advancing existing adaptation assessment activities and (2) to assist FHWA in "test-driving" the model. Based on the feedback received through the pilots, FHWA will revise and finalize the model for national application. The conceptual model consists of three primary components:

1. Develop inventory of assets.
2. Gather climate information.
3. Assess the risk to assets and the transportation system as a whole from projected climate change.

During the FHWA pilot project, the CT revised and updated this process because the methodology suitable for the Alameda County subregion context evolved over the lifetime of the project. The updated process for the pilot project is outlined in Figure 1.2.

1.4 STRUCTURE OF THE BRIEFING BOOK

This briefing book (executive summary) distills the key elements of the project for a more general reader. It accompanies a Technical Report with appendices that document the full project process. The briefing book is structured as follows, with lessons learned and recommendations for the FHWA on the pilot model integrated into relevant chapters:

- Chapter 2, "Asset Inventory Development and Asset Selection," describes the process of developing an asset inventory and collecting relevant data on transportation and shoreline assets, as well as the process of selecting assets for future analysis.
- Chapter 3, "Seismic Vulnerability Assessment," describes the seismic vulnerabilities and risk for transportation facilities in the project area from ground shaking and liquefaction of unconsolidated soils and the effect that SLR will have on this seismic risk.
- Chapter 4, "Climate Science and Climate Impacts," describes the climate science and climate impacts for the subregion, as well as the detailed inundation mapping and overtopping analysis carried out for the shoreline assets.
- Chapter 5, "Vulnerability and Risk Assessment," describes the vulnerability assessment and risk assessment of the assets identified in Chapter 2. This chapter also includes example risk profiles of the selected assets, summarizing the vulnerability and risk-related information gathered.
- Chapter 6, "Sea Level Rise Maps," contains examples of the detailed inundation and overtopping maps created especially for the project.
- Chapter 7, "Potential Adaptation Approach," describes a suggested methodology on how to use the information from the risk profiles to determine what type of adaptation measures can be used to address the vulnerability of transportation assets. It includes, as an example, descriptions of the methodology used to assess impacts, potential adaptation measures, and nonphysical aspects of climate adaptation for one selected transportation asset.

The appendices to the Technical Report contains more detailed technical information, including the results of the data inventory, lists of transportation assets, and a description of the mapping methodology.

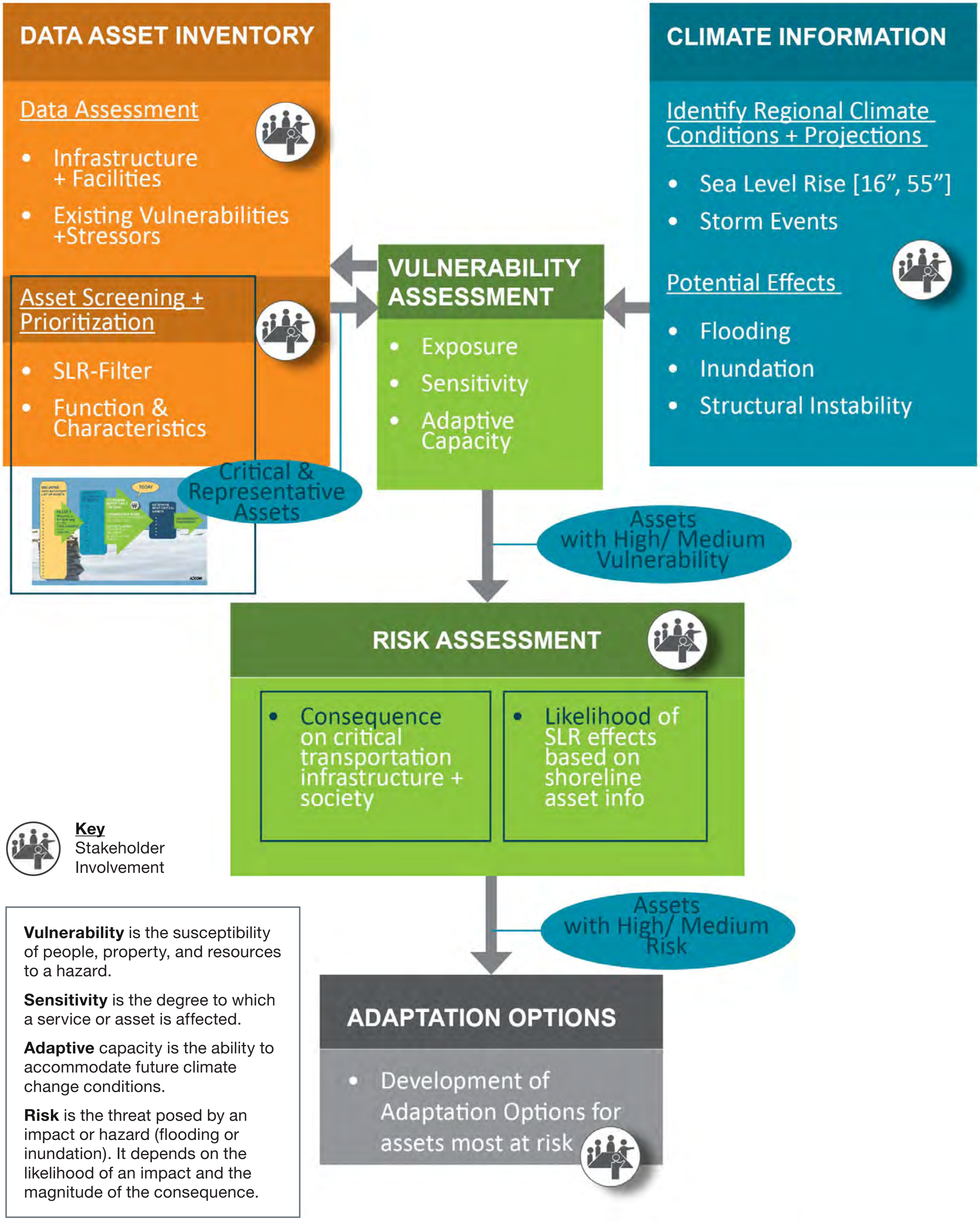


FIGURE 1.2 Adapting to Rising Tides: Transportation Vulnerability and Risk Assessment Pilot Process (this process is adapted from FHWA conceptual risk assessment model which was tested through this pilot process)

2.0

ASSET INVENTORY DEVELOPMENT AND ASSET SELECTION

2.0 ASSET INVENTORY DEVELOPMENT AND ASSET SELECTION

2.1 INTRODUCTION

The first step outlined in the Federal Highway Administration (FHWA) conceptual model is to compile an inventory of all transportation assets that are to be evaluated. Example asset categories are provided to assist in this task, with a suggested focus on the categories that correspond with the region's planning priorities. While the inventory is being compiled, information is also collected to help evaluate how resilient the asset is to climate stressors and how costly damage to the asset could be. Existing agency inventories of assets are suggested as the primary source of this information.

The second step of the FHWA model process is to "screen" the asset inventory based on the relative importance of each asset. Using existing priorities and metrics (such as volume of use, movement of goods, number of commuters, use as emergency route), the most important assets are identified for the region.

During this initial data collection and inventory development process, it became clear that due to a lack of readily available data in an accessible format and the extensive number of transportation assets in the selected region, an alternative approach would be required. This led to the iterative data collection and asset selection process described in this chapter rather than a sequential process of data collection followed by asset selection as described by the FHWA model. The data collection process in particular evolved to occur in phases, as follows:

1. Initial data collection for the larger subregion consisting mostly of geographic information system (GIS) and spatial data with some metadata,
2. Data regarding functionality and other characteristics collected to assist with selecting representative assets, and
3. Detailed stressor information collected following the selection of assets.

The approach for the shoreline assets was different from that used for the transportation assets since it was never the intention to conduct a full vulnerability assessment of the shoreline. The approach evolved to focus on the categorization of the shoreline assets and to use the elevation of these shoreline assets, coupled with the inundation maps (see Chapter 4) to assess which shoreline assets contributed to the inundation of the transportation assets over time.

2.2 ASSET INVENTORY DEVELOPMENT

2.2.1 IDENTIFICATION OF ASSET CATEGORIES AND ASSET TYPES

After the initial data collection effort, with input from the Transportation Asset Subcommittee, the project team identified four major asset categories with associated types, as outlined in Table 2.1:

Asset Category	Asset Type
A. Road Network	
	- Interstates/Freeways and State Routes
	- Arterial, Collector, and Local Streets
	- Connectors to Isolated Neighborhoods
	- Tunnels and Tubes
	- Toll, Interstate, and State Bridges
	- Local Bridges
B. Transit Network	
	- Bus Routes
	- BART Lines
	- BART Stations
	- Railroads
	- Rail Stations
	- Ferry Terminals
C. Transportation Facilities	
	- Traffic/Transportation Management Centers
	- Caltrans Maintenance Facilities
	- Bus Service Facilities
	- BART System Assets
	- Rail Yards and Depots
	- Ferry Maintenance Facilities
D. Bicycle and Pedestrian Networks	
	- Trails/Class I Bike Facilities
	- Class II Bike Facilities

Table 2.1 Transportation Asset Categories and Types

2.3 TRANSPORTATION ASSET SELECTION METHODOLOGY

The FHWA conceptual model suggests selecting assets based on their importance to the region (e.g., traffic flow, emergency management, movement of goods), using detailed information from the data inventory. However, after drafting and reviewing a preliminary framework to assess importance as per the FHWA model, the project team decided to change course due to the following factors:

- Most assets in the subregion are arguably important, and the subregion is relatively small (county size), so the team considered the number of assets per asset type to be compared to one another to be too small.
- The amount of data necessary to do a robust importance rating of each asset was beyond the budget and schedule of the project because detailed information was not readily available on individual assets in a readily usable format; also insufficient background information precluded making quantitative assessments/decisions on importance.
- The team did not want to pass over assets that may not meet the importance criteria but that may have intrinsic value for the region (e.g., the Bay Trail).

Thus, the project team amended the process to select representative assets for each asset type and refine the number of assets for which additional data would be requested. Considerations developed for the initial framework, including environmental, economic, and equity considerations that are also used in the larger Adapting to Rising Tides project, were included to develop characteristics and functionalities for the assets. This aided in the selection of representative assets in the project area. A series of steps (which were repeated to narrow the list down to a manageable number for data collection) enabled the high number of assets to be narrowed down:

1. Only assets touched by SLR, as identified from preliminary inundation mapping, using USGS data (Knowles 2009)
2. Including assets with greater functionality or representing a broader range of characteristics:
    a. **Physical Characteristics**, focusing on whether an asset is built at-grade, below grade or elevated on embankments or structures;
    b. **Functional Characteristics**, including lifeline routes, evacuation routes, goods movement routes, transit routes, and bike routes;
    c. **Jurisdiction**, referring to the agency, city, or other entity with ownership and/or management responsibility for the asset; and
    d. **Social/Economic Considerations**, such as connecting to jobs, regional importance, and support of transit-dependent populations.
3. Input from the Transportation Asset Subcommittee and PMT to help identify focus areas for the "Arterial, Collector, and Local Streets" category.

The short list of assets was sent to the following relevant agencies—Metropolitan Transportation Commission (MTC), BART, Water Emergency Transportation Authority, California Department of Transportation (Caltrans), Bay Trail, City of Alameda, AC Transit, and Capitol Corridor—to collect the final detailed stressor information outlined below that would contribute toward assessing the sensitivity of the asset to inundation by SLR. It should be noted that all assets that are within the SLR exposure zone but were not further assessed as part of the project should be evaluated for vulnerability using the process described in this report by the appropriate agency in the future.

DETAILED STRESSOR OR "SENSITIVITY" TRANSPORTATION DATA COLLECTION

The stressor criteria provide information on the potential sensitivity of the asset to inundation to SLR. As a result, seven criteria were developed and data was requested from the responsible agencies for selected assets to support the vulnerability assessment:

- **Age of Facility**, in terms of year built or number of years in service;
- **Level of Use**, measured by traffic volumes for road assets and ridership for transit assets;
- **Seismic Retrofitting**, indicating whether structures have been strengthened to improve resistance to seismic activity, ground motion or soil failure due to earthquakes;
- **Operations and Maintenance (O&M) Costs**, recorded as annual or lifetime O&M costs;
- **Condition/Remaining Service Life**
- **Liquefaction Susceptibility**, as mapped by the Association of Bay Area Governments (ABAG); and
- **Foundation Condition**, including the type, age, extent of last maintenance, and any existing issues with foundations or subgrades.

Within the schedule required for the project, information was generally available only for the road network. Data exist for the transit facilities but were not easily accessible in the timeframe required. There were considerable challenges in collecting the information needed for the vulnerability assessment, see section 2.4. The information collected is summarized on the risk profiles of the most vulnerable assets, see Section 5.4, Chapter 5 of the technical report.

2.4 SHORELINE ASSET CATEGORIZATION

The shoreline assets were categorized using a method different from that used for transportation assets. The shoreline categorization focused on identifying the main line of shoreline defense (and protection assets) along the subregional coastline because the primary focus of the FHWA conceptual model is to understand the risk and vulnerability of transportation assets. However, the vulnerability of shoreline assets clearly plays an important role in the vulnerability of transportation assets. For this project, the primary drivers affecting transportation asset vulnerability and risk related to the shoreline assets were as follows:

- Shoreline asset type (or suite of types creating a flood protection system that protects a transportation asset) and elevation;
- Inundation level at the shoreline asset (e.g., the depth of inundation directly over a flood protection levee, not inland of the levee), both under daily tidal inundation (mean higher high water [MHHW] plus SLR) and under 100-year storm events (stillwater levels and stillwater levels plus wave effects); and
- Wave climate (wave height, period, and velocity) outboard of the shoreline asset(s).

Example of a Revetment in the Pilot Project Area

To conduct this analysis, stretches of shoreline were categorized in a GIS mapping exercise. This allowed the project team to analyze the shoreline near a transportation asset to better understand inundation behind the shoreline asset. The five agreed upon shoreline categories for this project are as follows:

- Engineered Flood Protection Structures (Levee, Flood Walls)
- Engineered Shoreline Protection Structures (Bulkheads, Revetments)
- Nonengineered Berms
- Wetlands (Natural, Managed, Tidal flats)
- Natural Shorelines (Nonwetland)

These shoreline asset categories attempt to collapse a highly varied and diverse shoreline into distinct classes that will support the vulnerability and risk assessment. The categories were defined based on their primary function and are presented in order from those assets that provide the most potential protection from inundation to those assets that have the least potential for inhibiting inland inundation.

The engineered flood protection structures protect inland areas from flooding and inundation; engineered shoreline protection structures harden the shoreline to reduce erosion and prevent land loss; nonengineered berms protect marshes and ponds from wave erosion and provide flood protection to inland developments and, in some cases, serve to maintain hydraulic separation between the bay and the protected/managed areas; wetlands dissipate wave energy and provide ecological habitat value; and other natural or managed nonwetland shorelines, such as natural or artificially maintained beaches, can provide some wave energy dissipation.

The Technical Report contains definitions and images of each of the shoreline protection categories outlined above.

2.4.1 SHORELINE CATEGORIZATION MAPS

This project specifically developed shoreline categorization maps (Figure 2.1 and Figure 2.2), using the shoreline categories defined above, because existing data did not meet project needs. See Appendix A of the Technical Report for full details of the methodology used to create the maps.

2.5 RECOMMENDED REFINEMENTS TO THE FHWA CONCEPTUAL MODEL

Highlighted recommendations for the data inventory and asset selection component of the FHWA conceptual model include the following:

- There were considerable challenges in creating the data inventory for both the shoreline and the transportation assets due to:
    - Inconsistent availability of data (i.e., often the information is not routinely collected and updated, is not available in GIS, nor in a database that is easily accessible);
    - A need to compile data when limited data was readily available;
    - High level of effort needed to collect data; and
    - A limited project budget and tight schedule for the pilot project.
- Creating the data inventory was a helpful first step to understanding the benefits and limitations of the data available. However, a project with numerous assets and a limited budget or timeline will likely require the collection of more detailed data for a refined list of assets during the vulnerability assessment phase. Thus, we recommend splitting up the data collection effort into overall and focused exercises.
- Determining the criticality of one asset over another was not politically acceptable given that the assessment would have been largely based on professional judgment and limited data.
- The most important asset selection filter was exposure to flooding and inundation (location of an asset in the projected inundation zone); characteristics and functionality were only marginally involved in reducing the list of assets. (This is consistent with the Guidance on SLR by Caltrans, May 16, 2011.)
- Agencies should be advised of the data required to carry out vulnerability to SLR and should start to collate the data going forward in order to facilitate future assessments.

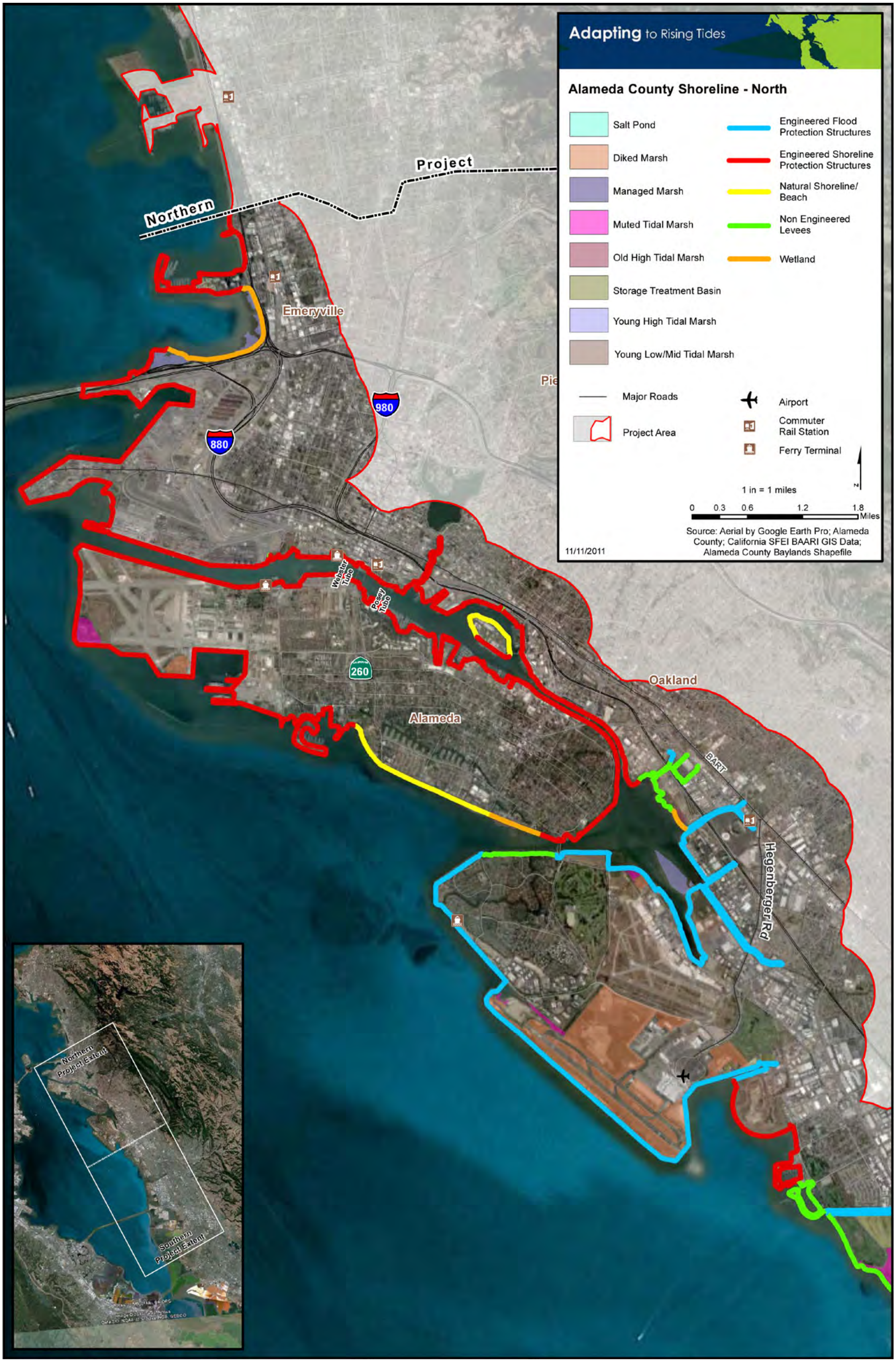


FIGURE 2.1 Shoreline Categorization Map—Northern Extent

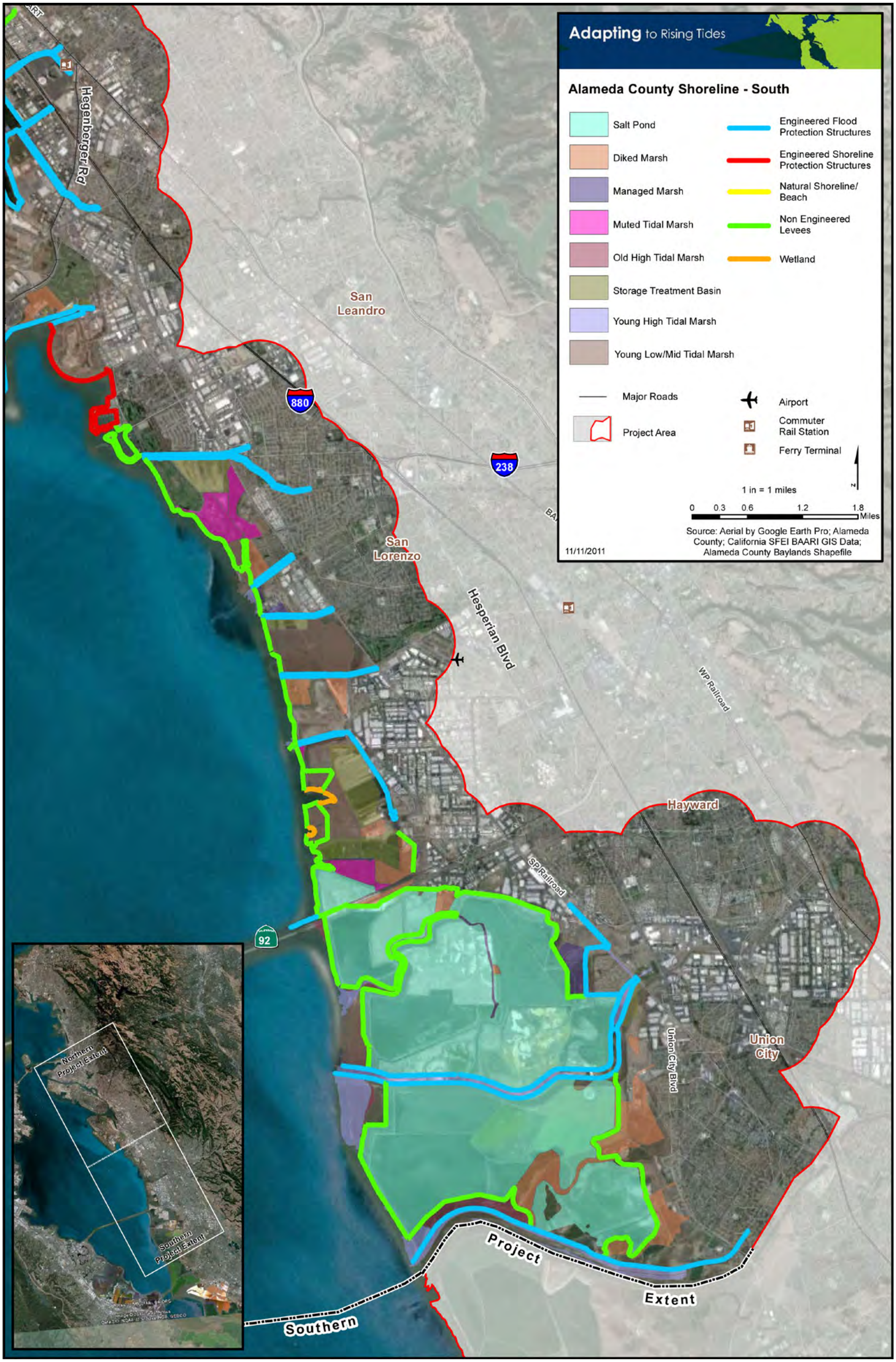


FIGURE 2.2 Shoreline Categorization Map—Southern Extent

3.0

SEISMIC VULNERABILITY ASSESSMENT

3.0 SEISMIC VULNERABILITY ASSESSMENT

3.1 INTRODUCTION

The project area is in an area of high seismic vulnerability, so all of the transportation assets are at risk from ground shaking and liquefaction of unconsolidated soils. In a sea level rise (SLR) scenario, rising groundwater levels could lead to an increased likelihood of liquefaction and lateral spreading, magnifying the impact of an earthquake. Through a review of the available geographic information system (GIS) information from the California Department of Conservation, U.S. Geological Survey (USGS), and Association of Bay Area Governments (ABAG), a review was carried out of the impact of high seismic vulnerability and how this, coupled with rising seas, might affect the resilience of existing shoreline protection systems and selected transportation assets.

3.2 CURRENT GEOTECHNICAL/SEISMIC HAZARD CONDITIONS

This section qualitatively evaluates the seismic vulnerability of the identified transportation and shoreline assets relative to potential SLR. In order to address seismic vulnerability and assess potential risk to the transportation and shoreline assets, the current primary geotechnical and seismic hazard conditions in the project area are summarized below.

3.2.1 SOFT/WEAK SOILS/FILL

The historical baylands (Figure 3.1) and modern baylands maps, along with other documented San Francisco Bay fill maps, show that a majority of the project area has zones of bay fill that was placed at various times over the past century and a half. Importantly, a majority of this bay filling occurred prior to the 1960s, before much stricter controls and engineering criteria were imposed on subsequent bay filling.

Since the mid-1800s, hundreds of millions of cubic yards of fill materials have been placed into San Francisco Bay to reclaim marshland, tidal land, and submerged land. In general, what underlies bay fills is predominantly relatively weak clay materials that increase in strength with depth and degree of consolidation. The majority of bay fills, being placed prior to the 1960s, had little engineering and controls. In many instances, the limited, more recently engineered fills with improved construction standards overlie the older, less controlled fill. Therefore, with the exception of specific improved sites or locations with only recent filling, prevalent unconsolidated, poorly controlled fills overlying soft native soil materials create generally weak soil conditions in the bay fringe areas of the project area.

3.2.2 GROUND SHAKING POTENTIAL

The shaking severity levels map (Figure 3.2) shows that a majority of the SLR area is identified with a violent shaking severity rating. The only exceptions are a few small locations at the most inland portion of Union City in southern Alameda County, which are out of the bay fill area. These areas are mapped with a strong shaking severity rating. Locations generally expected to experience the greatest severity of earthquake shaking are those with thick soil deposits and fill (including, in particular, weak bay mud materials), which can amplify ground shaking to the surface. Structures less

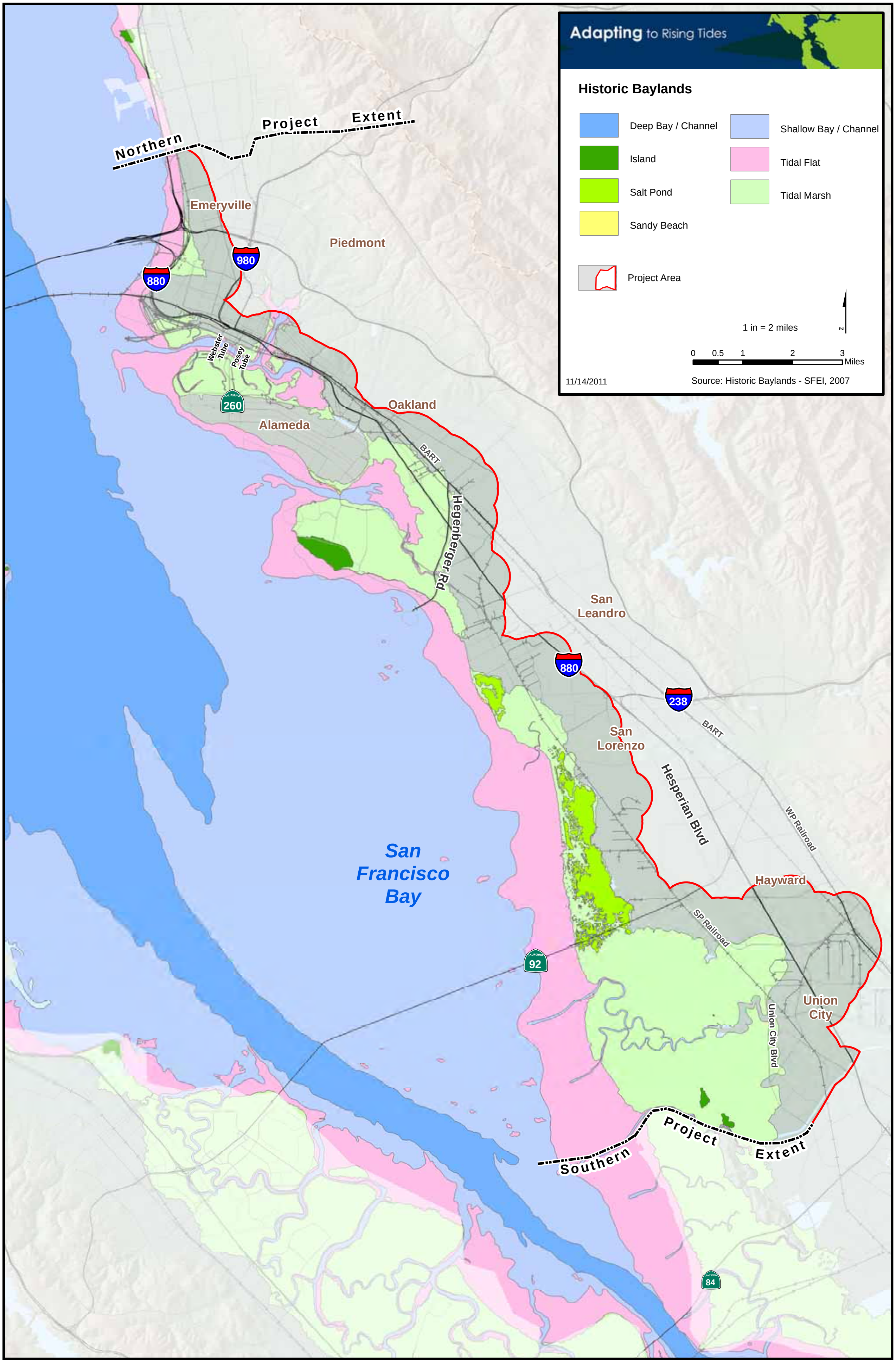


FIGURE 3.1 Historical Baylands

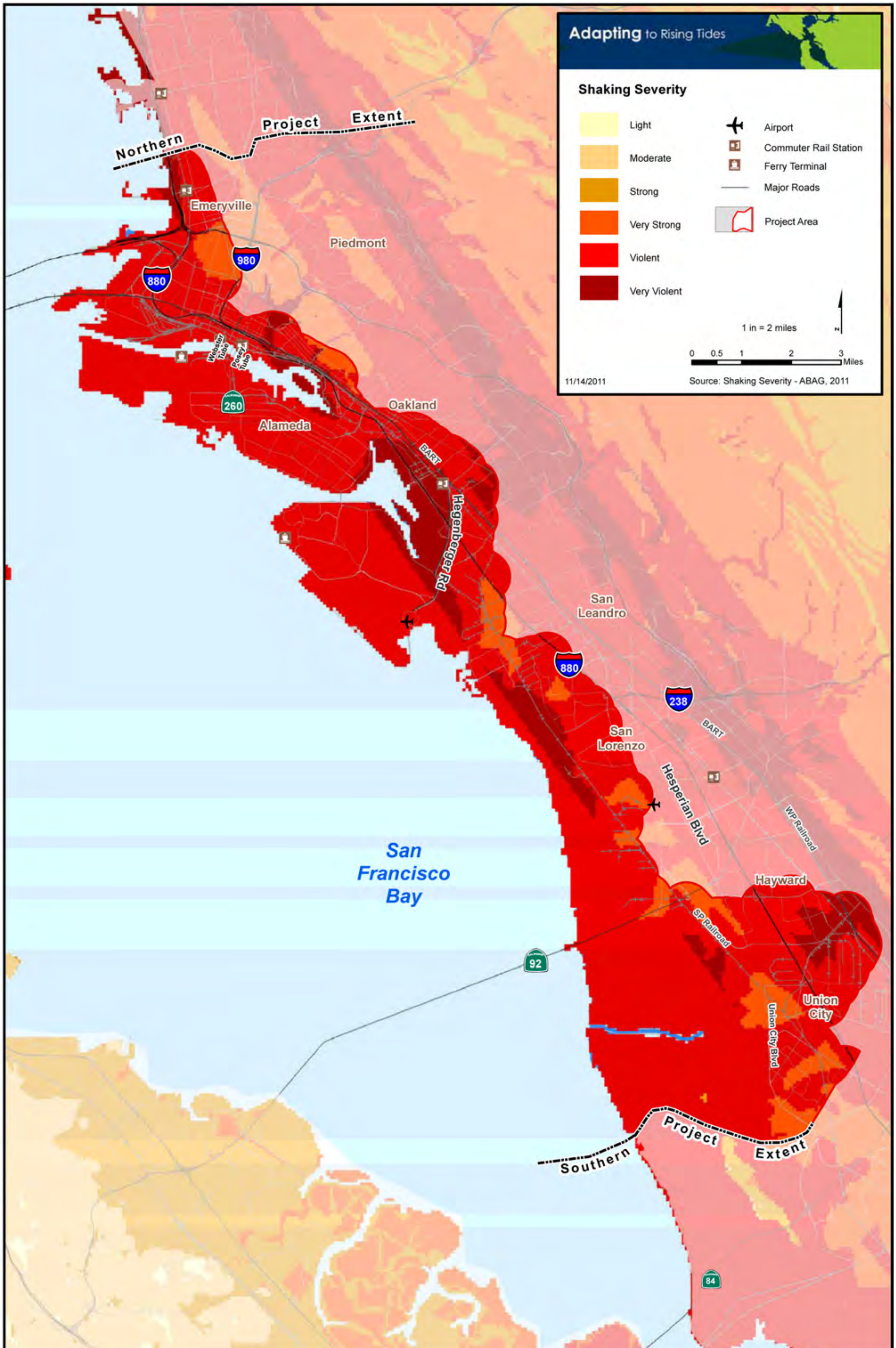


FIGURE 3.2 Shaking Severity

compatible with these ground motions require compensation in their engineering and construction.

However, of primary importance to this study is any amplification of seismic vulnerability caused by SLR. This may occur in the form of increased local ground motion at locations that see an increase in liquefaction potential due to rising ground water as a result of SLR.

3.2.3 LIQUEFACTION POTENTIAL

The liquefaction susceptibility map (Figure 3.3.) shows that the northern portion of the project area is identified with a very high liquefaction susceptibility rating. In particular, the Emeryville, Oakland, and Alameda waterfront and Oakland International Airport fill areas are believed to have sandy fills with greater susceptibility to liquefaction. To the south, most of the project area in San Leandro, Hayward, and Union City is identified with a moderate liquefaction susceptibility rating.

Soil liquefaction usually has the greatest potential in clean, loose, saturated, uniformly graded silt and fine sand deposits. Liquefaction susceptibility increases as a function of less fine material content in sand/gravel materials, lower density, and greater degree of saturation. The liquefaction phenomenon occurs when the susceptible soils lose their strength with seismic shaking and increased pore water pressure during an earthquake. Coarser, gravelly soils and finer, more cohesive soils, particularly silts and silty clays, can also be vulnerable to liquefaction.

3.2.4 GROUNDWATER

Groundwater and soil saturation play a significant role in seismic vulnerability due to their role in establishing conditions that lead to liquefaction caused by earthquake shaking. Relatively high groundwater levels exist in the relatively flat terrain along the bay margins and within the SLR area. This condition in itself presents special circumstances that must be compensated for in the engineering and construction of certain structures. A recent USGS study of the hydrogeology of aquifers beneath the San Leandro and San Lorenzo areas in the central portion of the project area shows groundwater essentially at sea level close to the bay and rising inland, toward the east (Izbicki et al. 2003). For the scenario of end of century SLR considered by the pilot project, it would seem that already high groundwater levels near the bay would rise over the long term essentially in line with the magnitude of the SLR expected.

3.3 SEISMIC VULNERABILITY FROM SLR DIRECT INUNDATION AND INDIRECT GROUNDWATER RISE

For the transportation assets being evaluated, the obvious direct effect of rising sea level is inundation. The primary indirect effect on seismic vulnerability of the transportation assets is considered to be the groundwater-level rise associated with the direct effect from increased tidal levels with SLR.

In general, bridges in California built after 1972, following the 1971 Sylmar (Los Angeles area) earthquake, were designed to a more modern code, which better addressed the actual seismic demands and detailing requirements. Incremental advancements in seismic design and detailing, especially following the 1987 Whittier Narrows, 1989 Loma Prieta, and 1994 Northridge earthquakes, have continued to this day. Beginning in the early 1990s, Caltrans began a more aggressive (Phase 2) seismic retrofit program to strengthen vulnerable bridges. Cities, counties, and other agencies also began retrofitting their bridges. The intent of these retrofits is to increase the seismic performance of bridges to meet “no collapse” criteria (major damage is acceptable provided the bridge will not collapse). A majority of the road assets in this study were built before the modern codes.

However, of primary importance to this study is any amplification of seismic vulnerability caused by SLR, which is assumed to be most prevalent in regards to liquefaction and associated lateral spreading (tendency of soil layers above liquefiable layers to “flow” downhill). This is particularly pertinent in zones where soils underlying a transportation facility that are in the classification of liquefiable soils but are currently above the water table, become saturated due to the rising ground water associated with SLR.

Although it was standard practice to evaluate the potential for liquefaction during the Phase 2 seismic retrofit program, lateral spreading was typically not accounted for. Caltrans now requires that new transportation structures consider the potential for this effect. Therefore, this study area contains many structures that are currently vulnerable and SLR will result in additional structures becoming vulnerable.

Liquefaction-induced lateral spreading is usually considered to occur just following a seismic event. Once the ground shaking from the earthquake has caused the underlying layer to liquefy, the overlying “crust” loses its resistance to moving down slope. This moving soil can result in tremendous pressure on bridge foundations, causing them to fail or displacing them to the point that the bridge deck could collapse.

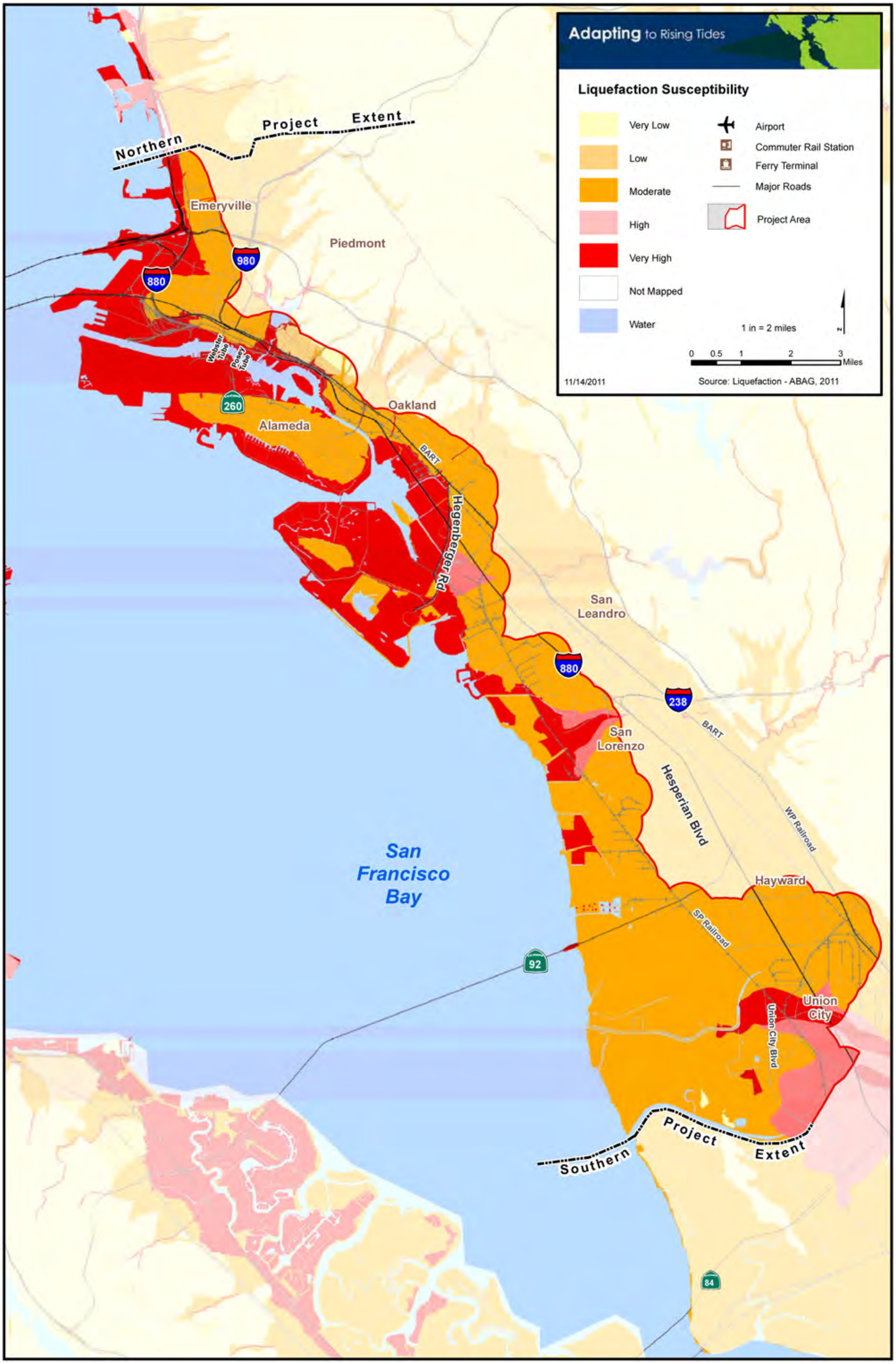


FIGURE 3.3 Liquefaction Susceptibility

In the event of SLR, it is obvious that shoreline protection systems, either existing or new, would be required to mitigate the effects of inundation. The inundation maps show that the shoreline assets would protect the transportation assets to a certain level under the midcentury and end-of-century SLR scenarios. However, regardless of the existing type and location of shoreline protection, the inundation mapping for the maximum 55 inches scenario with the most severe flood and wave conditions considered, indicates that nearly all the shoreline assets would be inundated or submerged.

It is assumed that any new shoreline protection installed to protect against SLR and inundation would be engineered and constructed to current standards and minimum regulatory requirements and thus would likely adequately protect against failure and resulting inundation as a result of a seismic event. However, any new loading or adverse conditions imposed, such as from SLR, would at a minimum reduce the level of protection or safety factor against failure, up to creating a failure condition.

3.4 RECOMMENDED REFINEMENTS TO THE FHWA CONCEPTUAL MODEL

Highlighted lessons learned and recommendations for the seismic review component of the project include the following:

- Compared to the detailed work establishing the transportation and shoreline assets and mapping the various SLR and other conditions, the scope of the seismic vulnerability assessment was very limited and qualitative in nature. The scope did not include identifying the seismic vulnerability of various specific categories and types of transportation and shoreline assets. The assessment was quite broad and generalized, which seemed somewhat inconsistent with the level of detail for the rest of the assessment work.
- For a more focused and effective evaluation, it would be a more streamlined process to assess the seismic vulnerability once the initial asset identification and mapping had been completed.

Revetment, Shoreline Park, Alameda


Jack London Square · Oakland

4.0

CLIMATE SCIENCE AND CLIMATE IMPACTS

4.0 CLIMATE SCIENCE AND CLIMATE IMPACTS

4.1 INTRODUCTION

A summary of local- and regional-level climate information has been compiled that provides historical, current, and projected conditions of climate change. This chapter provides an overview of the climate change–related information and a justification for the selection of the two sea level rise (SLR) scenarios evaluated for the project: specifically, 16 inches by midcentury and 55 inches by the end of the century.

The chapter also describes the preparation of new inundation maps for these two scenarios. The new inundation maps were used to assess the depth of inundation along the affected transportation assets to inform the vulnerability rating of these assets and to evaluate the potential for overtopping along the Alameda County shoreline to inform potential adaptation strategies. This chapter also provides a list of the major caveats and uncertainties associated with the inundation maps. The analysis performed to develop the inundation maps is appropriate for a high-level planning effort and is not intended to represent, or take the place of, detailed engineering analyses.

4.2 CLIMATE INFORMATION SUMMARY

The climate change information reviewed and the SLR scenarios selected are critical input to assess the vulnerability of transportation infrastructure in the subregion. Sea level rise will have a large impact on California and on the low lying parts of San Francisco Bay Area in particular. Over the last century sea level has already risen by as much as 7 inches along the California coast, increasing flood risk and erosion and adding pressure to the state's infrastructure, water supplies, and natural resources (California Natural Resources Agency 2009). During this period, and despite annual variations in weather patterns, California has also seen a trend of increased average temperatures, more extreme hot days, fewer cold nights, longer growing seasons, less winter snow, and earlier snowmelt and rainwater runoff (California Natural Resources Agency 2009).

In order to better understand the climate change effects on the Bay Area, conceptual model guidance, sources presenting historical, current, and projected data were reviewed to summarize local- and regional-level climate information for use in assessing the vulnerability of transportation infrastructure to climate change effects (FHWA 2010) The sources reviewed included, amongst others, reports from Intergovernmental Panel on Climate Change (IPCC), National Aeronautics and Space Administration (NASA), National Academy of Sciences (NAS), the National Oceanographic and Atmospheric Administration (NOAA), California Natural Resources Agency, California Energy Commission and California Climate Change Center.

An increase in the rate of SLR is one of the primary effects of global warming and climate change (Knowles 2009). SLR has the potential to cause major damage to residential, commercial, and industrial structures in low-lying areas near the shoreline, as well as to important habitats and wildlife resources. For this reason, planning for SLR has become a higher priority in California. Through the use of innovative efforts to identify vulnerable areas, like this study, California will be better prepared to protect communities and the environment from the potentially devastating impacts of SLR.

The two SLR scenarios selected for the pilot project represent a high-end estimate for midcentury (16 inches of SLR) and a midrange estimate for the high IPCC emission scenario for the end of the century (55 inches of SLR). This selection is consistent with the State of California Sea-Level Rise Interim Guidance Document (CO-CAT 2010). And the two SLR scenarios are also compatible with previous SLR planning efforts in San Francisco Bay led by the San Francisco Bay Conservation and Development Commission (BCDC) and the U.S. Geological Survey (USGS). These 2 scenarios form the foundation for this effort. It is important to note that in addition to SLR, scientists also predict that global warming will increase the frequency of major storms. With increasing storm intensity, the potential exists for storm-generated waves to increase in height, resulting in an overall change in the San Francisco Bay wave climate. When large storm events coincide with high tides or extreme coastal water levels, there is a greater potential that existing shoreline protection infrastructure would be overtopped, resulting in a potentially larger inundation area.

4.3 INUNDATION MAPPING

This chapter presents the methodology for developing the new SLR inundation maps produced for the pilot project. Two modeling efforts were leveraged for this study, and this chapter, along with the detailed methodology presented in Appendix B of the Technical Report, documents how the model output from these efforts was used to develop the inundation maps. In addition, the major caveats and assumptions associated with the inundation maps are described.

4.3.1 INUNDATION MAPS

Six inundation scenarios were evaluated as part of the project. Each SLR scenario—16 inches by midcentury and 55 inches by the end of the century—is evaluated under three storm/tide conditions: inundation associated with high tides, also known as mean higher high water (MHHW); inundation associated with 100-year extreme water levels, also known as stillwater elevations (100-yr SWEL); and inundation associated with 100-year extreme water levels coupled with wind waves. The three storm/tide conditions were selected as they represent a reasonable range of potential inundation conditions. The inundated area associated with high tides under each SLR scenario is representative of the area that would be subjected to frequent or permanent tidal inundation. This level of inundation could correspond to slow and regular degradation of infrastructure, including shoreline protection. Although storm conditions represent a lower frequency event, they come with a larger potential flooded area, with deeper flooded depths, higher velocities, and a greater likelihood of wind-driven waves that could overtop existing shore protection infrastructure.

New inundation maps were created to show these conditions, and are presented in Chapter 6 of the Technical Report, including overall maps for the project area and five focus area maps that provide a more detailed look at the inundated depth and extent overlain with the selected transportation assets. Examples of the overview maps are shown in Chapter 6.

4.3.2 SHORELINE OVERTOPPING POTENTIAL

Information on the depth of inundation was extracted along the shoreline assets described in Chapter 2 to provide a high-level assessment of the potential for shoreline overtopping. "Overtopping potential" refers to the condition where the water surface elevation associated with a particular SLR scenario exceeds the elevation of the shoreline asset. This assessment is considered a planning-level tool only, as it does not account for the physics of wave runup and overtopping. It also does not account for potential vulnerabilities along the shoreline protection infrastructure that could result in complete failure of the flood protection infrastructure through scour, undermining, or breach after the initial overtopping occurs. The detailed methodology used for the shoreline overtopping potential analysis is presented in Appendix B of the Technical Report.

The shoreline delineation was also subdivided into "systems" that act together to prevent or influence inland inundation. This approach was taken to develop meaningful metrics for assessing the vulnerability of the transportation assets and identifying potential adaptation strategies. A system could be defined as a reach of levee along the shoreline between two adjacent tributaries. Alternatively, a system could be defined as the combination of several asset types (e.g., levees, nonengineered berms, roadway embankments) that act together to influence the inundation of an inland area with similar topographic elevation. The following primary metrics were used to evaluate shoreline overtopping potential:

- Potential overtopped length of each system.
- Percent of shoreline overtopped for each system.
- Average depth of inundation along a segment.
- Distance of each transportation asset from the nearest overtopped segment along the shoreline assets.

4.3.3 TRANSPORTATION ASSET INUNDATION POTENTIAL

In a manner similar to that described in Section 4.3.2, the depth of inundation information was extracted along the transportation assets described in Chapter 2 to inform the vulnerability of the transportation assets under the two SLR scenarios and the three storm/tide conditions. The results of this assessment are described in more detail in Chapter 5.

4.3.4 UNDERLYING ASSUMPTIONS AND CAVEATS

The inundation maps are intended only as a screening-level tool for performing the vulnerability and risk assessment. Although the inundation maps do account for additional processes and they rely on new data, they are still associated with a series of assumptions and caveats that are outlined in section 6.2.

4.4 RECOMMENDED REFINEMENTS TO THE FHWA CONCEPTUAL MODEL

Recommendations for the climate science and climate impacts component of the FHWA conceptual model include the following:

- Depending on the geographic area where the risk assessment is being carried out, it may be sufficient to use existing climate science information. However, this study shows how further mapping of the likely climate impacts is an integrated piece of understanding transportation asset vulnerability (the model could highlight that there may need to be considerable effort spent on categorizing shoreline assets, and undertaking new inundation mapping (and overtopping analysis) for projects addressing sea level rise). This mapping work was important to help assess the vulnerability of the transportation assets.
- An indication of the time consuming nature of additional mapping should be provided in the model.
- It should be noted that climate science is continually evolving so vulnerability and risk assessments will also need regular updating as new modeling becomes available.

5.0

VULNERABILITY AND RISK ASSESSMENT

5.0 VULNERABILITY AND RISK ASSESSMENT

5.1 INTRODUCTION

Understanding the level of vulnerability of an asset to climate impacts is a valuable part of decision making and policy development for future adaptation, as it provides a basis for establishing priorities. For this project, the vulnerability assessment identifies the degree to which the assets would be affected by sea level rise (SLR).

Risk is the potential for an unwanted outcome resulting from an event. It is determined by the product of (a) the likelihood of the impact and (b) the consequence of the impact. During the risk assessment, (1) the vulnerability of the selected assets to SLR was reviewed in order to screen out assets that were less vulnerable to projected climate effects; (2) the likelihood of inundation occurring from SLR was assessed; (3) the consequence of the impact was reviewed, not just in terms of what the impact would do to a particular asset, but in terms of how it would affect the surrounding community and beyond; and (4) the risk rating of the consequence and likelihood of inundation occurring was determined.

5.2 VULNERABILITY ASSESSMENT

5.2.1 INTRODUCTION

The vulnerability of an asset is related to its potential for, or its susceptibility to, damage. Vulnerability to climate change is often assessed in terms of exposure, sensitivity, and adaptive capacity. This analysis used definitions from the Intergovernmental Panel on Climate Change (IPCC 2007) for the following terms:

- **Vulnerability** *"is the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes."*
- **Exposure** *"is the nature and degree to which a system is exposed to significant climatic variations."* (For this project, this is SLR and will be measured by depth of inundation at midcentury and at the end of the century.)
- **Sensitivity** *"is the degree to which a system is affected, either adversely or beneficially, by climate-related stimuli."* (For this project, this is the physical condition of the asset. The worse the condition of the asset, the larger the magnitude of an adverse reaction to SLR is assumed.)

- **Adaptive capacity** *"is the ability of a system to adjust to climate change to moderate potential damages, to take advantage of opportunities or cope with the consequences"* (IPCC 2001, also referenced in the 2009 California Climate Adaptation Strategy [California Natural Resources Agency 2009). (For this project, for the vulnerability assessment this has been defined as the ability to divert traffic onto alternative routes.)

5.2.2 EXPOSURE TO SLR

The maps described in Chapter 4 for the 16-inch (midcentury) and 55-inch (end-of-century) SLR were used to assess whether or not the asset was inundated by SLR under the different scenarios. If the maps showed a selected asset inundated at midcentury, it automatically received a high exposure rating. This midcentury exposure rating guided the overall exposure rating. If an asset would be inundated at midcentury under the 100-year stillwater elevation (SWEL) scenario, then a medium exposure rating was assigned, as it is a less likely scenario that would affect an asset on a more temporary basis. If an asset would be inundated at the end of the century under either the mean higher high water (MHHW) or 100-year SWEL scenario, it received a medium exposure rating. Note that the elevation of an asset above inundation level was not considered important for this rating, as any inundation could potentially weaken the foundations or supports of an elevated structure, therefore still placing it at risk. An asset that is inundated only under either of the wind wave scenarios received a low exposure rating.

5.2.3 SENSITIVITY

Sensitivity of an asset to inundation by SLR relates to both the condition and the function of an asset. This study used physical condition to evaluate sensitivity, while data related to function (goods movement, socioeconomic impact, etc.) were used to evaluate consequence. The following physical characteristics were determined to best describe the sensitivity of an asset to SLR:

- Level of use (e.g., average daily traffic [ADT] volume [cars/trucks])
- Age of facility
- Seismic retrofit status
- Maintenance (ongoing operations and maintenance [O&M]) cost
- Liquefaction susceptibility

Information was also collected on the following other physical characteristics but ultimately not used to evaluate the sensitivity of assets, because:

- Condition/remaining service life—It was determined that data on remaining service life does not provide a conclusive indication of sensitivity. For instance, an asset with a short remaining service life could be characterized as sensitive, because it soon must be replaced – however, once this replacement occurs, it would then count among the assets with the greatest remaining service life, and therefore least sensitive. Since the timing of the impacts of sea level rise and of future replacement or improvements is not known, it was decided not to include "remaining service life" or age as inputs to the sensitivity rating; however, where provided this information is presented in the risk profiles.
- Foundation condition—Data was requested for foundation condition, but very little information was actually collected.

The sensitivity criteria were not appropriate for all asset types and therefore, the information for those asset types was neither available nor relevant.

This data was requested for the short list of assets described in Chapter 2, however, due to the final quality and quantity of data received on the assets, not all of the sensitivity data were used in the development of sensitivity ratings. Therefore, sensitivity ratings were developed based on the data collected and were compared within asset types. For example, the sensitivity of a roadway asset was compared with other roadway assets, not with other asset types, such as rail facilities. Overall sensitivities were therefore compared only within particular asset types and not between asset types. The approach for each asset type is described in full in the Technical report.

5.2.4 ADAPTIVE CAPACITY

For the purposes of this project for the vulnerability assessment, the adaptive capacity of an asset was determined solely by the availability of (a) comparable asset(s) that could provide an alternative route or provide a similar level of functionality should the asset be closed. This included considering transit as an alternative route should a roadway or bridge be closed. (It should be noted when developing potential adaptation strategies, the adaptive capacity of assets can be more broadly defined as the ability to improve resilience to sea level rise through protection measures.)

When evaluating adaptive capacity, the project team measured the inability to adapt for consistency with the high, medium, and low ratings given when assessing exposure and sensitivity. (It is more standard practice to define adaptive capacity as the ability to adapt, which would lead to an asset that has a high adaptive capacity, having a high rating.) The rating approach was based on the identification of nearby or parallel assets that provide alternative routes or replacement functionality for each asset at midcentury. If no alternative route existed, the asset got a high rating; if an alternative route was available but it was not fully comparable it got medium rating and if multiple alternative routes were available it got a low rating. The vulnerability assessment incorporated only the ratings assigned for midcentury, although the ratings assigned for the end of the century were noted. The project team assumed that the transportation network may change considerably by the end of the century (due to adaptation strategies), so the ratings were not used to alter the vulnerability rating. Despite this uncertainty, the vulnerability ratings were not changed as a result of the rating assigned for the end of the century scenario.

5.2.5 OVERALL VULNERABILITY ASSESSMENT

As a result of the assessment exercise, each asset received a rating of high, medium, or low for each factor of exposure, sensitivity, and adaptive capacity (inability to adapt). Some assets were not evaluated for sensitivity, in which case vulnerability was only based on exposure and the ability to re-route.

Table C5.6 in Appendix C of the Technical Report shows the list of assets and their respective vulnerability ratings (as well as which of those assets were selected to undergo the risk assessment process, and for which a risk profile was developed).

5.3 RISK ASSESSMENT

5.3.1 INTRODUCTION

The vulnerability assessment identified the vulnerability of the selected assets based on the information available. The next step in the process was to undertake a risk assessment of the most vulnerable assets to identify the level of risk from SLR facing the selected assets. A risk assessment typically looks at the likelihood that an asset would experience a particular impact (in this case, SLR) and the consequence of that impact on the surrounding community or region.

Generally, assets that have a low likelihood of being affected by future climate change (SLR) and a low consequence if that impact occurs are identified as having low risk, and those that have a high likelihood of being affected by future climate change and that would have a high consequence if that impact occurs are identified as having high risk. Therefore, as a result of this analysis, agencies will have a risk profile associated with each of their representative assets to inform future adaptation strategies. High-risk assets will need to be prioritized for adaptation strategies, and low-risk assets will need to be monitored and revisited periodically to ensure that their risk status has not changed.

5.3.2 SELECTION OF ASSETS FOR RISK ASSESSMENT

As a result of the vulnerability assessment, the PMT selected the most vulnerable assets for the development of risk profiles, in order to develop two to three risk profiles per asset type. As part of this process, it was decided to combine assets in the same geographic location into one risk profile.

A number of assets require special mention due to their unique circumstances, although they were not in the end selected to have a risk profile developed. The Lake Merritt BART station received a low vulnerability rating as it would not be inundated at midcentury or at the end of the century; however, it has current groundwater flooding issues that may be worsened through SLR. Future research is required to understand how this may affect its vulnerability. The Bay Trail is an asset that is highly vulnerable due to its location at the shoreline. However, it is not a typical transportation asset, so when compared to the other transportation assets, the impact of its inundation from a transportation perspective is low. The trail is nevertheless of great value to the region from a recreational perspective and provides a valuable commuting route for local populations.

5.3.3 LIKELIHOOD

Likelihood is determined by estimating the probability that a certain climate change impact will occur. For this project, the climate change impact is limited to a certain set of SLR scenarios. Since this study considered only two climate change scenarios and the project area is relatively small, the likelihood rating is the same for each transportation asset for each scenario. If a range of SLR scenarios had been considered (for example, different depths of inundation expected by midcentury), then a range of likelihoods could have been identified.

5.3.4 CONSEQUENCE

“Consequence” refers to the impact on the wider region of the inundation due to SLR. The Federal FHWA pilot model guidance suggests criteria to consider consequence, including the level of use of an asset, the degree of redundancy in the system, and the value of an asset to the surrounding community (e.g., goods movement, socioeconomic impacts, and/or decreased public safety). The criteria most relevant for the Alameda County context was identified, agreed upon by the PMT, and ranges of consequence or impact (major, moderate, and minor) were developed for direct and indirect impacts by the project team, as follows:

- Capital improvement cost (original cost in 2011 $) Cost to restore to same design standard/ infrastructure type
- Time to rebuild when damaged beyond further use (if rebuilding is possible)
- Public safety: lifeline/evacuation route impact
- Economic Impact (goods movement)
- Economic Impact (commuter route) Ridership/train load for transit, and/or freeway
- Socioeconomic impact (transit-dependent population/ MTC communities of concern)

The consequence of an asset rendered unavailable to the community and region due to inundation was reviewed by applying this set of criteria to assess each vulnerable asset. Since consequence is considered on the basis of overall impacts on the community and region, ratings were assigned by comparing all asset types using the same rating scale. Where data did not exist, professional judgment was used to assign a rating to an asset across the consequence criteria.

The project team averaged the six consequence criteria ratings for each asset to provide a final numerical rating. Table 5.1 gives an example of the rating assigned for the Webster Tube.

Asset R-11: Webster Tube (SR 61) including approach ramps	Major Consequence 5	Moderate Consequence 3	Minor Consequence 1
Capital Improvement Cost (Original cost in 2011 $)	Replacement cost: $180,000,000		
Time to rebuild when damaged beyond further use	Seismic retrofit took about 8 years; rebuild would take at least as long		
Public safety: Lifeline/Mass evacuation route impact		Alameda evacuation route	
Economic Impact (Goods movement)		535 AADTT	
Economic Impact (Commuter route)	18,333 daily riders		
Socioeconomic impact		MTC communities of concern and pass-through transit (multiple lines)	
Total Average		4.0	

TABLE 5.1 Example Consequence Rating

OVERALL RISK RATING

The project team used a matrix provided by the FHWA conceptual model that evaluates both likelihood and consequence (Figure 5.1) to allocate an overall risk profile for each asset. In this project, due to the unique definition of "likelihood," each asset received a score of 3 for likelihood and a score of from 1 to 5 for consequence, which, when added together, yields an overall score that is categorized as high, moderate, or low risk. The following examples provide more detail on the approach used:

- An asset with a likelihood rating of 3, with an overall consequence impact rating of 1 would result in an overall risk assessment of 4 (low).
- An asset with a likelihood rating of 3, with an overall consequence impact rating of 3 would result in an overall risk assessment of 6 (moderate).
- An asset with a likelihood rating of 3, with an overall consequence impact rating of 5 would result in an overall risk assessment of 8 (high).

Consequence						
		1	2	3	4	5
Likelihood	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	

FIGURE 5.1 Risk Rating Matrix

5.4 RISK PROFILES

5.4.1 INTRODUCTION

A risk profile summarizes the vulnerability and risk characteristics identified for each of the selected assets. Its purpose is to act as an information source and tool for the development and prioritization of adaptation strategies for the agencies responsible for each asset. In addition to the vulnerability and risk characteristics, each of the risk profiles contains data relating to the overtopping potential described in Chapter 4. Table 5.2 details the final list of risk profiles developed. Some example risk profiles have been included in the briefing book—these are highlighted in bold in the table below. The full set of risk profiles can be found in Appendix C of the technical report.

Code	Asset Category & Asset Types	Segments Chosen and Associated Future Projects	Final Risk Rating
Road Network (R)			
R-01	**I-80 (includes part of I-580)**	**Powell Street to Bay Bridge Toll Plaza**	**High**
R-02a	I-880	Oak St to 23rd Ave	High
R-02b	I-880	High St to 98th Ave	High
R-03	**SR 92**	**Clawiter Rd to San Mateo Bridge Toll Plaza**	**Medium**
R-04	West Grand Ave	I-80 to Adeline St	Medium
R-05	Hegenberger Rd	San Leandro Street to Doolittle Dr	Medium
	Airport Dr	Entire facility	Medium
	Future BART Line—Oakland International Airport Connector	Route serving/crossing SLR exposure area	Medium
R-06	**Powell St (City of Emeryville)**	**West of I-80**	**Low**
R-07	Mandela Pkwy	West Grand Ave to I-580	Low
R-08	**Ron Cowan Pkwy**	**Entire facility**	**Medium**
R-09	Burma Rd	Entire facility	Low
R-10	Cabot Blvd	Entire facility	Medium
R-11	**Posey Tube (SR 260) Webster St Tube (SR 61)**	**All, including approach ramps**	**High High**
R-12	**Bay Bridge (I-80)**	**From Toll Plaza until Alameda County boundary**	**High**
R-13	San Mateo Bridge (SR 92)	From Toll Plaza until Alameda County boundary	Medium
R-14	Bay Farm Island Bridge	Entire facility, including adjacent bicycle bridge	Medium
Transit (T)			
T -01	**BART Line 2a—Subgrade: Transbay Tube**	**Entire facility**	**High**
T -02	BART Line 3a—Elevated: between Transbay Tube and Oakland Wye	Elevated structure between I-880 overcrossing and I-880 undercrossing	Medium
T-03	West Oakland BART Station	Entire facility	Medium
T-04	**Coliseum/Airport BART Station**	**Entire facility**	**Medium**
T-05	Oakland Jack London Square Amtrak Station	Entire facility	Low
T-06	Rail line Segment 1	Emeryville Segment (I-580 to 14)	Medium
T-07	**Rail line Segment 2**	**Oakland Segment (17-23)**	**Medium**
T-08	Jack London Square Ferry Terminal	Entire facility	Low
T-09	**Alameda Gateway Terminal Ferry (including Park & Ride, bike, ADA access)**	**Entire facility**	**Low**
Facilities (F)			
F-01	**AC Transit Maintenance (1100 Seminary)**	**Not Applicable**	**Medium**
F-02	Burlington Northern Santa Fe International Gateway Intermodal Yard	Not Applicable	Medium
F-03	Capitol Corridor Norcal O&M Yard	Not Applicable	Medium
F-04	7th Street Highway and Railroad Pumps	Not Applicable	Medium

TABLE 5.2 Final List of Risk Profiles, by Asset Category and Asset Type, Showing Final Risk Rating

5.4.2 RISK PROFILES

Risk Profile Glossary

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.

Risk Profile Glossary

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 5.2 Risk Profile Glossary: Asset Name (Asset Code)

Asset Risk Profile

Interstate 80 (R-01)

Asset Location / Jurisdiction

Oakland, Emeryville / FHWA, Caltrans

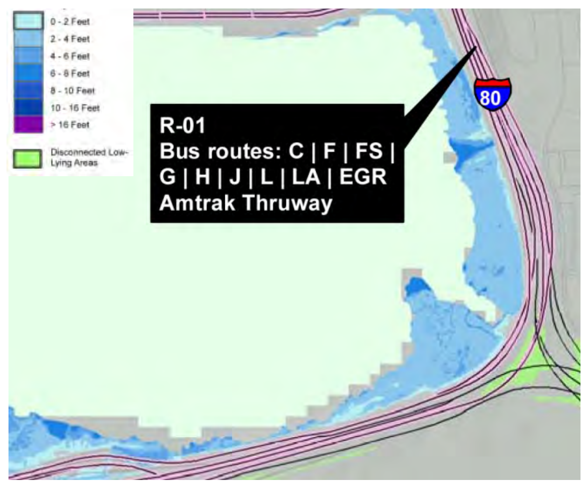
Summary

Interstate 80 (I-80) is a freeway that connects Alameda County to the greater region. This profile considers the segment of I-80 between the Bay Bridge Toll Plaza in Oakland and Powell Street in Emeryville. Sensitivity is high (due primarily to the high level of use and very high liquefaction potential), while exposure is medium (due to inundation under the 16" + 100-yr SWEL and 55" + MHHW SLR scenarios). When combined with the lack of adequate alternate routes, this results in a high vulnerability rating. All considerations under consequence rate high, with the exception of socioeconomic impact (which is moderate because transit lines only pass through on this asset). The overall consequence is 4.67, making this a high-risk asset.

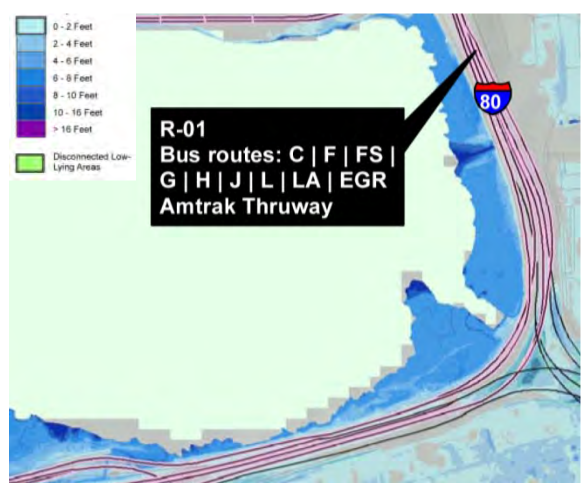
Characteristics:

- At grade or on elevated structures
- Caltrans Lifeline route
- Goods movement
- Transit routes [AC Transit: C, F, FS, G, H, J, L, LA; Emery Go-Round, Amtrak Thruway]
- Commuter route
- Regional importance

Sensitivity: High	
Year Built	Prior to 1964
Level of Use	
Peak Hour	16,300
AADT	251,000
AADTT	6,300
Seismic Retrofit	Temescal Creek Crossing; Bay Bridge HOV Separation; WB HOV - Toll Plaza Overcrossing
Annual O&M	$673,000
Liquefaction Susceptibility	Very High
Exposure: Medium	
Maximum Inundation Depths	
16” + MHHW 16” + 100-yr SWEL 16” + 100-yr SWEL + wind waves	0 ft 2 ft YES
55” + MHHW 55” + 100-yr SWEL 55” + 100-yr SWEL + wind waves	3 ft 5 ft YES
Inadequate Adaptive Capacity (16” SLR): High No adequate alternative	
Vulnerability Rating (**mid century**)**: High**	



Projected Inundation with 16 inch SLR + 100-yr SWEL



Projected Inundation with 55 inch SLR + 100-yr SWEL

Consequence Rating (out of 5): 4.67	
Capital improvement cost	$45,087,000 (5)
Time to rebuild	84 months (bridge/elevated portions) (5)
Public safety	Caltrans Lifeline Highway, Emeryville Evacuation Route (5)
Economic impact - goods movement	6,300 AADTT (5)
Economic impact - commuter route	Freeway (and 7,826 daily transit riders) (5)
Socio-economic impact	Transit-Dependent area and pass-through transit (multiple lines) (3)
Risk Rating: High	

Shoreline Asset “Overtopping” Analysis	
Proximity to Overtopping (distance)	***16” + 100-yr SWEL***
	30 ft
	55” + 100-yr SWEL
	30 ft
Length Overtopped (% of System)	***16” + 100-yr SWEL***
	10,510 ft (45%)
	55” + 100-yr SWEL
	16,900 ft (72%)
Average Depth of Overtopping	***16” + 100-yr SWEL***
	1.7 ft
	55” + 100-yr SWEL
	3.9 ft
System Responsible (See overview map)	2

Future Projects
• Install Traffic Operations System • Install bicycle pedestrian path from Bay Bridge to West Grand Avenue • Reconstruct the Bay Bridge Maintenance Complex - South Yard • Construct Tow Services Building and Fueling Station at the Bay Bridge Toll Plaza area • Install median strip landscape planting at the Bay Bridge Toll Plaza area • Rehabilitate pavement between the Port of Oakland overcrossing and the Toll Plaza

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

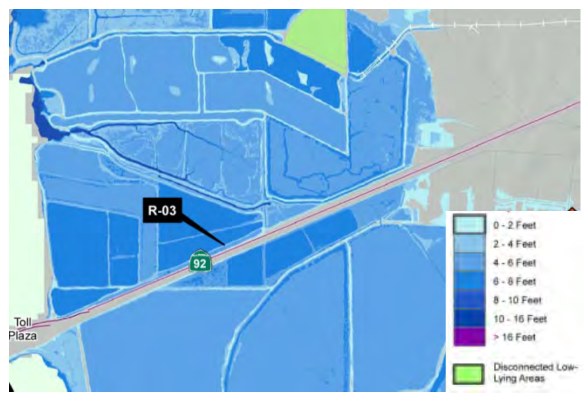
Projected Overtopping Depth at 55 inch SLR + 100-yr SWEL

Asset Risk Profile

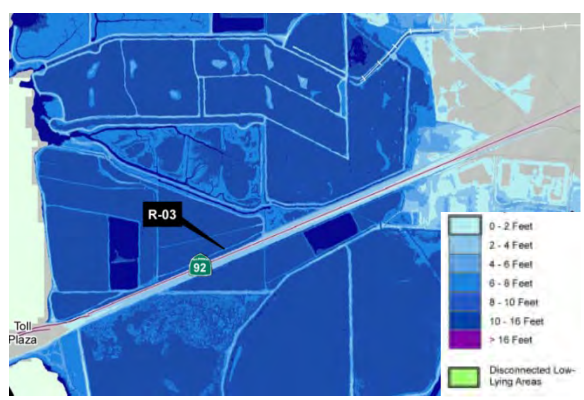
State Route (SR) 92 (R-03)

Asset Location / Jurisdiction Hayward / Caltrans
Summary State Route (SR) 92 is a freeway that connects Alameda County to the greater region. The segment of SR 92 between the San Mateo Bridge toll plaza and Clawiter Road in Hayward is considered in this profile. Sensitivity is low due to moderate level of use and operations and maintenance costs and medium liquefaction potential, while exposure is medium (due to inundation under the 55" + 100-yr SWEL SLR scenario). When combined with the lack of adequate alternate routes, this results in a medium vulnerability rating. Considerations under consequence rate medium to low, with the exception of economic impact – commuter route (rated high because SR 92 is a freeway), resulting in an overall consequence of 2.67, making this a medium-risk asset.
Characteristics: • Goods movement • Transit routes [AC Transit: M] • Commuter route • Regional importance

Sensitivity: Low	
Year Built	Significant changes in 1967
Level of Use	
Peak Hour	7,800
AADT	86,000
AADTT	1,806
Seismic Retrofit	At grade, not applicable
Annual O&M	$436,000
Liquefaction Susceptibility	Medium
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	3 ft
55” + 100-yr SWEL + wind waves	YES
Inadequate Adaptive Capacity (16” SLR): High No adequate alternative	
Vulnerability Rating (**mid century**)**: Medium**	



Projected Inundation with 16 inch SLR + 100-yr SWEL



Projected Inundation with 55 inch SLR + 100-yr SWEL

Consequence Rating (out of 5): 2.67	
Capital improvement cost	$13.2 million (1)
Time to rebuild	60 months (3)
Public safety	Freeway (3)
Economic impact - goods movement	1,806 AADTT (3)
Economic impact - commuter route	Freeway (and 491 daily transit riders) (5)
Socio-economic impact	Pass-through transit (1)
Risk Rating: Medium	

Shoreline Asset "Overtopping" Analysis	
Proximity to Overtopping (distance)	***16" + 100-yr SWEL***
	70 ft
	55" + 100-yr SWEL
	0 ft
Length Overtopped (% of System)	***16" + 100-yr SWEL***
	34,790 ft (26%)
	55" + 100-yr SWEL
	125,270 ft (93%)
Average Depth of Overtopping	***16" + 100-yr SWEL***
	1.6 ft
	55" + 100-yr SWEL
	3.2 ft
System Responsible (See overview map)	23, 24

Future Projects

- SR 92/Clawiter Road/Whitesell Street interchange improvements and local intersection improvements
- Non-capacity increasing freeway/expressway interchange modifications
- Install ramp metering
- Install Fiber Optic Communication

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

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

Asset Risk Profile

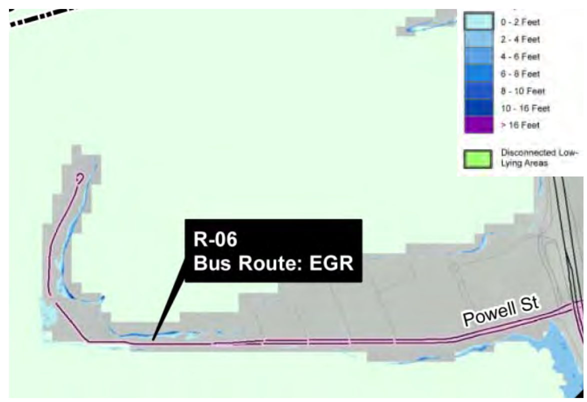
Powell Street (R-06)

Asset Location / Jurisdiction
Emeryville / City of Emeryville

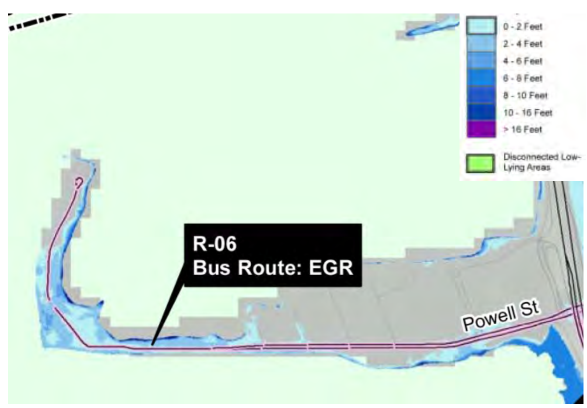
Summary
Powell Street connects between San Pablo Avenue and Marina Park in Emeryville, and has an interchange with I-80/I-580. This profile considers the segment of Powell Street west of I-80/I-580. Sensitivity is high (due to its relatively high level of use and very high liquefaction potential), while exposure is medium (due to inundation under the 55" + MHHW SLR scenario). When combined with the lack of adequate alternate routes, this results in a high vulnerability rating. Consequence rates low for all but Powell Street's role as a commuter route, which is moderate, given its relatively low level of transit ridership. The overall consequence rating is 1.33, making this a low-risk asset.

Characteristics:
- Transit routes [Emery Go-Round]
- Bike route

Sensitivity: High	
Year Built	1973
Level of Use	
Peak Hour	2,652
ADT	26,520
Seismic Retrofit	Not applicable
Annual O&M	$40,000
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	1 ft
55" + 100-yr SWEL	3 ft
55" + 100-yr SWEL + wind waves	YES
Inadequate Adaptive Capacity (16" SLR): High No adequate alternative	
Vulnerability Rating (mid century): High	



Projected Inundation with 16 inch SLR + 100-yr SWEL



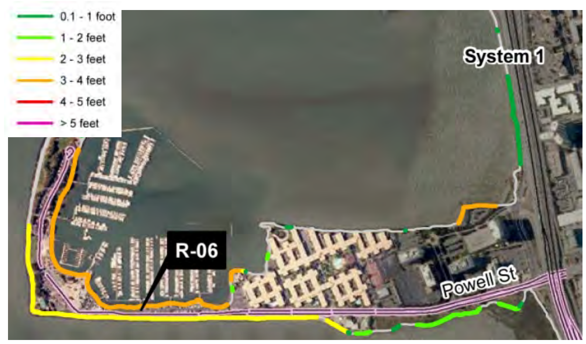
Projected Inundation with 55 inch SLR + 100-yr SWEL

Consequence Rating (out of 5): 1.33	
Capital improvement cost	$15 million (paving, storm drain, lights, underground power lines) (1)
Time to rebuild	2 years (1)
Public safety	Local street; however, provides fire station access (1)
Economic impact - goods movement	Local street (1)
Economic impact - commuter route	3,500 daily transit riders (3)
Socio-economic impact	Local transit access only (1)
Risk Rating: Low	

Shoreline Asset “Overtopping” Analysis		
Proximity to Overtopping (distance)	***16” + 100-yr SWEL***	50 ft
	55” + 100-yr SWEL	30 ft
Length Overtopped (% of System)	***16” + 100-yr SWEL***	1,910 ft (9%)
	55” + 100-yr SWEL	11,360 ft (52%)
Average Depth of Overtopping	***16” + 100-yr SWEL***	1.5 ft
	55” + 100-yr SWEL	2.8 ft
System Responsible (See overview map)	1	

Future Projects
None

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



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

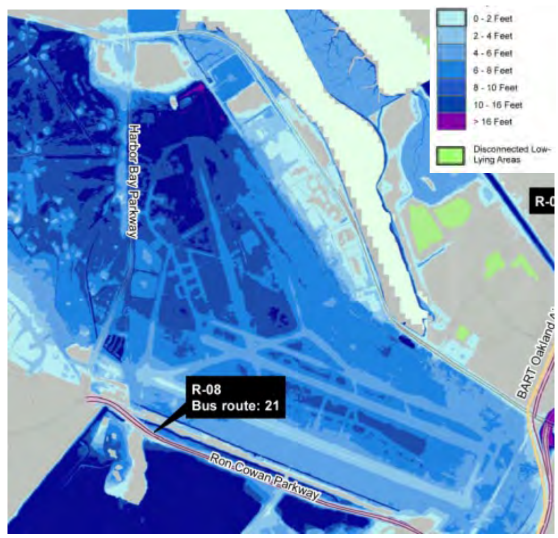
Asset Risk Profile

Ron Cowan Parkway (R-08)

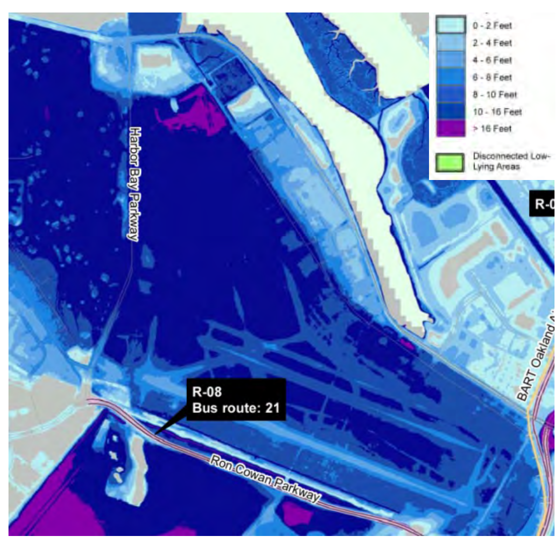
Asset Location / Jurisdiction Oakland / Port of Oakland
Summary Ron Cowan Parkway is a collector street that connects Bay Farm Island in Alameda with the Oakland International Airport. Sensitivity is high (due to very high liquefaction potential), as is exposure (due to inundation under the 16" + MHHW SLR scenario). Harbor Bay Parkway/Doolittle Drive provides an alternate route, but would likely be similarly affected by inundation, resulting in a high vulnerability rating. Consequence rates moderate for nearly all considerations except goods movement, which is high (given that the street is connected to the airport), and public safety, which is low. The overall consequence rating is 3.00, making this a medium-risk asset.
Characteristics: • Transit routes [AC Transit: 21] • Bike route

Sensitivity: High	
Data unavailable in project timeframe.	
Liquefaction Susceptibility	Very high
Exposure: High	
Maximum Inundation Depths	
16” + MHHW	15 ft*
16” + 100-yr SWEL	19 ft*
16” + 100-yr SWEL + wind waves	YES
55” + MHHW	19 ft*
55” + 100-yr SWEL	22 ft*
55” + 100-yr SWEL + wind waves	YES
Inadequate Adaptive Capacity (16” SLR): High Harbor Bay Parkway/Doolittle Drive provide an alternate route, but would likely be similarly affected by inundation.	
Vulnerability Rating (**mid century**)**: High**	

* High inundation depth is due to below-grade road segment



Projected Inundation with 16 inch SLR + 100-yr SWEL

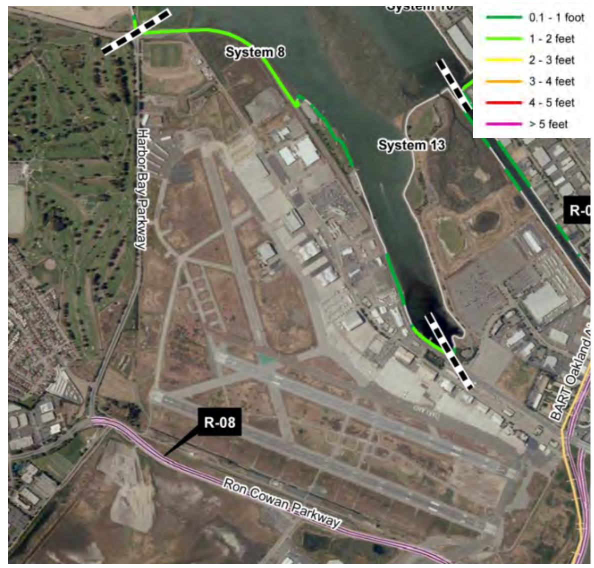


Projected Inundation with 55 inch SLR + 100-yr SWEL

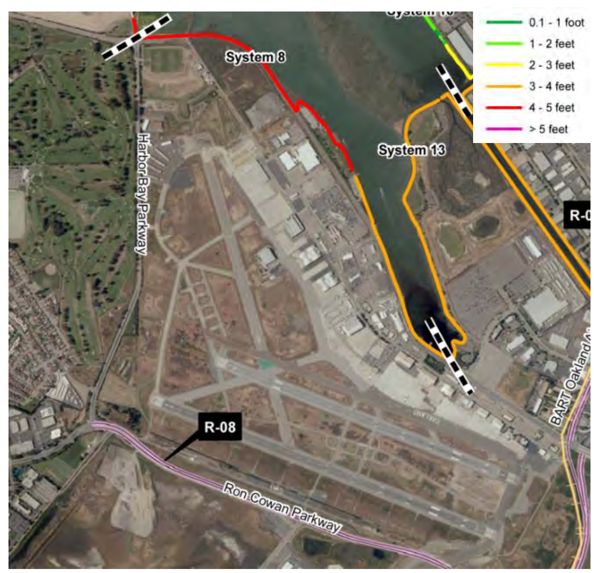
Consequence Rating (out of 5): 3.00	
Capital improvement cost	Data unavailable; professional judgment (includes an underpass) (3)
Time to rebuild	Data unavailable; professional judgment (includes an underpass) (3)
Public safety	Not applicable (1)
Economic impact - goods movement	Connects Port of Oakland (air freight) to freeway network (5)
Economic impact - commuter route	2,064 daily transit riders (3)
Socio-economic impact	Transit Dependent area; local transit access (3)
Risk Rating: Medium	

Shoreline Asset "Overtopping" Analysis	
Proximity to Overtopping (distance)	***16" + 100-yr SWEL***
	3,290 ft
	55" + 100-yr SWEL
	1,880 ft
Length Overtopped (% of System)	***16" + 100-yr SWEL***
	6,460 ft (19%)
	55" + 100-yr SWEL
	21,630 ft (63%)
Average Depth of Overtopping	***16" + 100-yr SWEL***
	1.2 ft
	55" + 100-yr SWEL
	2.7 ft
System Responsible (See overview map)	8, 11 System 8 responsible for inundation at 16" SLR. Systems 8 & 11 responsible for inundation at 55" SLR.

Future Projects
None



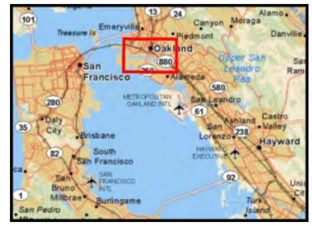
Projected Overtopping Depth at 16 inch SLR + 100-yr SWEL



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

Asset Risk Profile

Webster and Posey Tubes (R-11)



Asset Location / Jurisdiction

Oakland – Alameda / Caltrans

Summary

The Webster and Posey Tubes are underwater tunnels that connect Alameda and Oakland and compose State Route 260, though they are signed as State Route 61. Both assets rank medium for sensitivity. Exposure for Webster Tube is medium (due to inundation under both the 16" + 100-yr SWEL and 55" + MHHW SLR scenarios) and high for Posey Tube (due to inundation under the 16" + MHHW SLR scenario). Bridges connecting Alameda with Oakland provide alternate routes, giving both medium vulnerability ratings. Consequence rates high for capital improvement cost and time to rebuild, as well as the tubes' role as commuter routes. Ratings for public safety, goods movement, and socioeconomic impacts are all moderate, since the tubes provide evacuation routes and serve multiple transit routes. The overall consequence rating is 4.00 for both the Webster and Posey Tubes, making them high-risk assets.

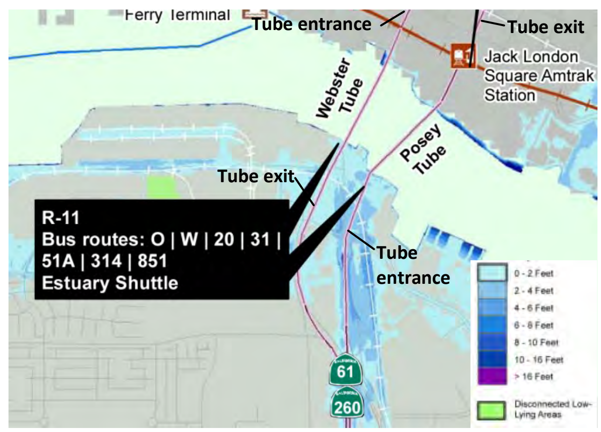
Characteristics:

- Commuter Route
- Goods movement
- Transit Routes [AC Transit: O, W, 20, 31, 51A, 314, 851; Estuary Shuttle]

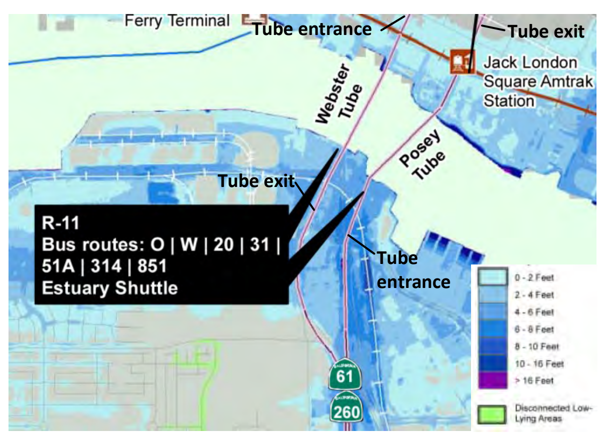
	Posey Tube	**Webster Tube**
Sensitivity:	**Medium**	**Medium**
Year Built	1927	1963
Level of Use		
Peak Hour	1,850	1,850
AADT	22,300	22,300
AADTT	535	535
Seismic Retrofit	Yes (2004; liquefaction potential was accounted for)	Yes (2005; liquefaction potential was accounted for)
Annual O&M	$83,300	$72,800
Liquefaction Suceptibility	Very High	Very High
Exposure:	**High**	**Medium**
Maximum Inundation Depths*		
16" + MHHW	4 ft	0 ft
16" + 100-yr SWEL	22 ft	22 ft
16" + 100-yr SWEL + wind waves	YES	YES
55" + MHHW	23 ft	23 ft
55" + 100-yr SWEL	25 ft	25 ft
55" + 100-yr SWEL + wind waves	YES	YES
Inadequate Adaptive Capacity (16" SLR): Park Street, Fruitvale and High Street Bridges provide alternate routes		
Vulnerability Rating (mid century): High		

*Depths due to tunnels filling with water entering at the portals

Webster Tube



Projected Inundation with 16 inch SLR + 100-yr SWEL



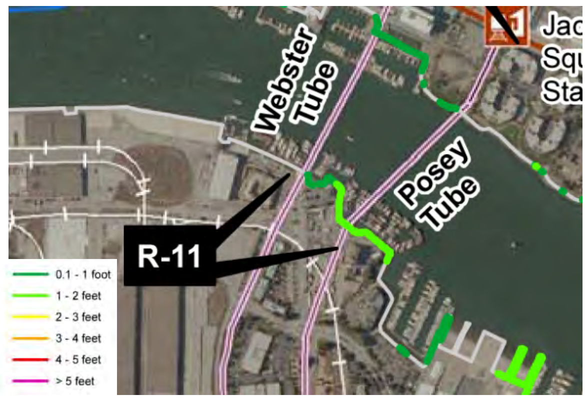
Projected Inundation with 55 inch SLR + 100-yr SWEL

Consequence Rating (out of 5): 4.0	
Capital improvement cost	Replacement cost: $360,000,000 (for both tubes) (5)
Time to rebuild	Seismic retrofit took about 8 years; rebuild would take at least as long (5)
Public safety	Alameda evacuation route (3)
Economic impact - goods movement	535 AADTT (3)
Economic impact - commuter route	18,333 daily transit riders (5)
Socio-economic impact	MTC Communities of Concern and pass-through transit (multiple lines) (3)
Risk Rating: High	

Shoreline Asset “Overtopping” Analysis		
	Posey Tube	**Webster Tube**
Proximity to Overtopping (distance)	***16” + 100-yr SWEL***	
	650 ft	950 ft
	55” + 100-yr SWEL	
	530 ft	940 ft
Length Overtopped (% of System)	***16” + 100-yr SWEL***	
	3,640 ft (23%)	
	55” + 100-yr SWEL	
	13,300 ft (83%)	
Average Depth of Overtopping	***16” + 100-yr SWEL***	
	1.1 ft	
	55” + 100-yr SWEL	
	2.8 ft	
System Responsible (See overview map)	16 (System 3 also a consideration, but does not produce significant inundation.)	

Future Projects
Replacement of the handrail and portions of the sidewalk along both Posey and Webster Street tubes. Restoration of the exterior surface of the portal buildings of Posey tube.

Posey Tube

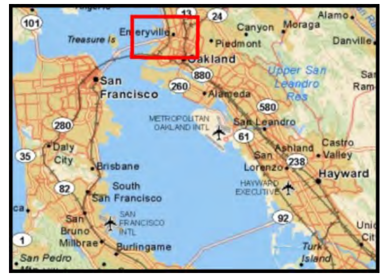


Projected Overtopping Depth at 16 inch SLR + 100-yr SWEL

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

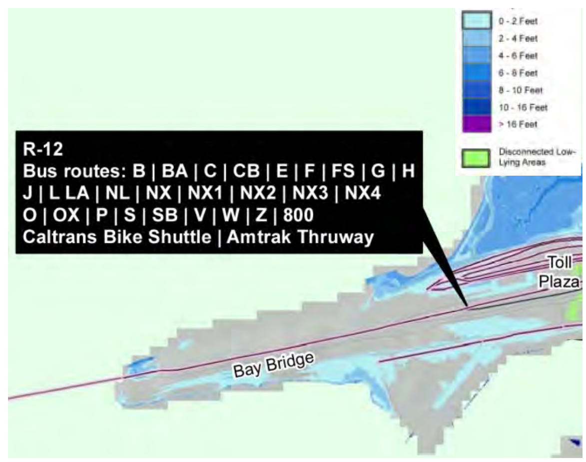
Asset Risk Profile

San Francisco – Oakland Bay Bridge Approach (R-12)

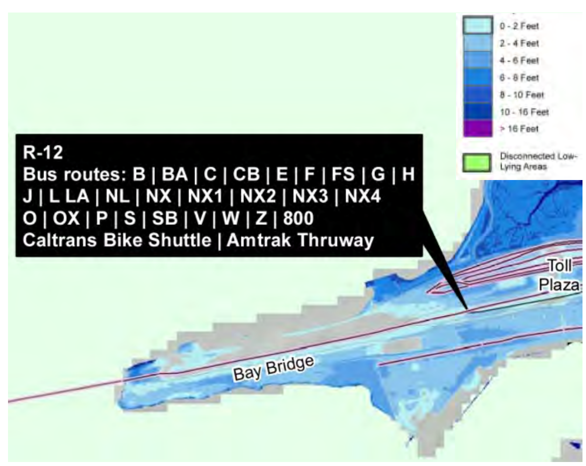


Asset Location / Jurisdiction
Oakland / FHWA, Caltrans
Summary The San Francisco – Oakland Bay Bridge connects Alameda County with the City and County of San Francisco. This profile considers the approach to the bridge. Sensitivity is high (due to relatively high level of use and very high liquefaction potential), while exposure is medium (due to inundation under the 16" + 100-yr SWEL and 55" + MHHW SLR scenarios). When combined with the lack of adequate alternate routes, this results in a high vulnerability rating. All considerations under consequence rate high, with the exception of socioeconomic impact (which is moderate because transit lines only pass through on this asset). The overall consequence is 4.67, making this a high-risk asset.
Characteristics: • Caltrans Lifeline route • Goods movement • Transit routes [AC Transit: B, BA, C, CB, E, F, FS, G, H, J, L, LA, NL, NX, NX1, NX2, NX3, NX4, O, OX, P, S, SB, V, W, Z, 800; Caltrans Bike Shuttle, Amtrak Thruway] • Commuter route • Regional importance

Sensitivity: High	
Year Built	1936; widened 1962 New span under construction
Level of Use	
Peak Hour AADT AADTT	16,300 251,000 6,476
Seismic Retrofit	New span under construction
Annual O&M	$721,000
Liquefaction Susceptibility	Very High
Exposure: Medium	
Maximum Inundation Depths	
16" + MHHW 16" + 100-yr SWEL 16" + 100-yr SWEL + wind waves	0 ft 2 ft YES
55" + MHHW 55" + 100-yr SWEL 55" + 100-yr SWEL + wind waves	2 ft 5 ft YES
Inadequate Adaptive Capacity (16" SLR): Medium BART and ferries provide alternate routes	
Vulnerability Rating (**mid century**)**: High**	



Projected Inundation with 16 inch SLR + 100-yr SWEL



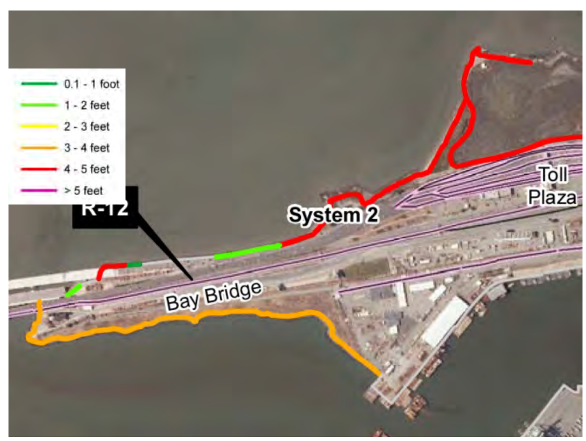
Projected Inundation with 55 inch SLR + 100-yr SWEL

Consequence Rating (out of 5): 4.67	
Capital improvement cost	$5.5 billion (new span) (5)
Time to rebuild	More than 84 months (5)
Public safety	Caltrans Lifeline Highway (5)
Economic impact - goods movement	6,476 AADTT (5)
Economic impact - commuter route	Freeway (and 13,834 daily transit riders) (5)
Socio-economic impact	Pass-through transit (multiple lines) (3)
Risk Rating: High	

Shoreline Asset "Overtopping" Analysis	
Proximity to Overtopping (distance)	***16" + 100-yr SWEL***
	30 ft
	55" + 100-yr SWEL
	30 ft
Length Overtopped (% of System)	***16" + 100-yr SWEL***
	10,510 ft (45%)
	55" + 100-yr SWEL
	16,900 ft (72%)
Average Depth of Overtopping	***16" + 100-yr SWEL***
	1.7 ft
	55" + 100-yr SWEL
	3.9 ft
System Responsible (See overview map)	2

Future Projects
• Rehabilitate Pavement • Install Traffic Operations System

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



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

Asset Risk Profile

BART Transbay Tube (T-01)

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

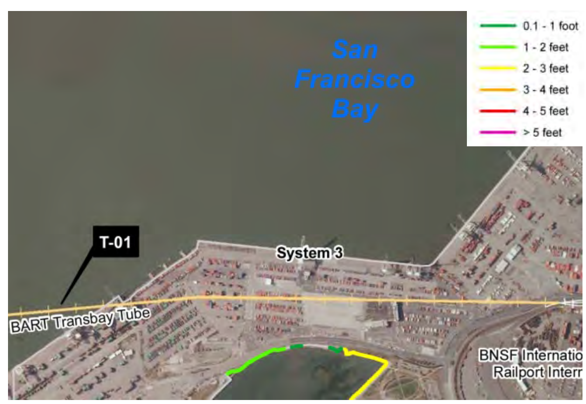
Projected Inundation with 55 inch SLR + 100-yr SWEL

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

Asset Risk Profile

Coliseum / Oakland Airport BART Station (T-04)

Asset Location / Jurisdiction
Oakland / BART

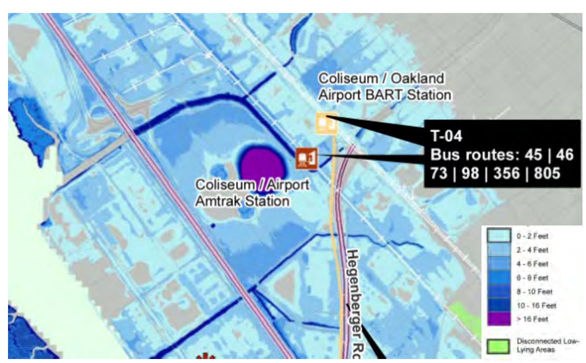
Summary
The Coliseum / Oakland Airport BART Station is a transit facility serving East Oakland neighborhoods and includes bus transfer and parking facilities. Pedestrian connections are available to Oakland Coliseum Amtrak Station, and frequent and direct bus service is provided from the BART station to Oakland International Airport. The future Oakland Airport BART Connector, currently under construction, will provide an automated guideway transit connection between the station and the airport. Due to lack of data, this asset was not rated with respect to sensitivity. Exposure is rated low, due to inundation under only 100-year SWEL + wind waves for both the 16" and 55" SLR scenarios. No adequate alternative station exists for the Coliseum / Oakland Airport BART Station, resulting in a medium vulnerability rating. Consequence is rated high for capital improvement costs, commuter use, and socioeconomic impact; moderate for time to rebuild; and low for public safety and goods movement, which does not apply. The overall consequence rating is 3.33, making this a medium-risk asset.

Characteristics:
- Elevated
- Commuter route
- Transit routes [3 BART Lines; AC Transit: 45, 46, 73, 98, 356, 805]

Sensitivity	
Data unavailable in project timeframe.	
Liquefaction Susceptibility	Medium
Exposure: Low	
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	0 ft*
55" + 100-yr SWEL + wind waves	YES
Inadequate Adaptive Capacity (16" SLR): High No adequate alternative station	
Vulnerability Rating (mid century): Medium	

*The asset is inundated to 0.3 ft at 55" + 100-yr SWEL SLR scenario, which was rounded down to 0 ft due to resolution limitations of the mapping

Projected Inundation with 16 inch SLR + 100-yr SWEL



Projected Inundation with 55 inch SLR + 100-yr SWEL

Consequence Rating (out of 5): 3.33	
Capital improvement cost	West / Dublin Pleasanton Station cost $106 million (5)
Time to rebuild	West Dublin / Pleasanton Station construction planned at 3 years (3)
Public safety	Minor consequence (1)
Economic impact - goods movement	Not applicable (1)
Economic impact - commuter route	12,132 daily BART riders (5)
Socio-economic impact	Community of Concern + Transit-Dependent area; local transit access (multiple lines) (5)
Risk Rating: Medium	

Shoreline Asset “Overtopping” Analysis	
Proximity to Overtopping (distance)	***16” + 100-yr SWEL***
	1,270 ft
	55” + 100-yr SWEL
	710 ft
Length Overtopped (% of System)	***16” + 100-yr SWEL***
	3,640 ft (18%)
	55” + 100-yr SWEL
	18,790 ft (95%)
Average Depth of Overtopping	***16” + 100-yr SWEL***
	0.9 ft
	55” + 100-yr SWEL
	3.1 ft
System Responsible (See overview map)	10

Future Projects
Oakland Airport BART Connector under construction

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

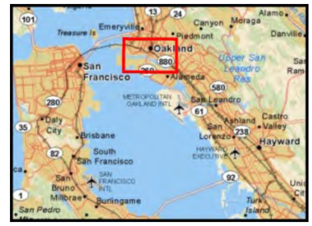
Projected Overtopping Depth at 55 inch SLR + 100-yr SWEL

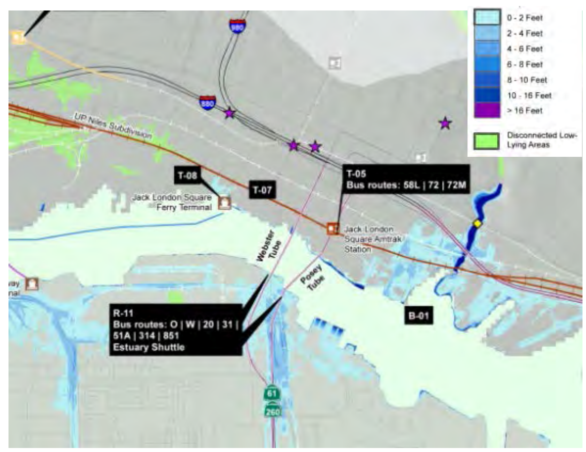
Asset Risk Profile

UP Niles Subdivision (T-07)

Asset Location / Jurisdiction
Oakland / Union Pacific Railroad
Summary The Niles Subdivision is owned by Union Pacific Railroad and serves passenger and freight operations. This profile considers the segment between the Magnolia Crossover and East Oakland Yard in Oakland. Due to lack of data, this asset was not rated with respect to sensitivity. Exposure is rated medium, due to inundation under both the 16” + 100-yr SWEL and 55" + MHHW SLR scenarios. No adequate alternative exists for this asset, resulting in a medium-high vulnerability rating. Consequence is rated high for capital improvement costs and goods movement, moderate for time to rebuild and commuter use, and low for public safety and socioeconomic impact. The overall consequence rating is 3.00, making this a medium-risk asset.
Characteristics: • At grade • Passenger and freight operations

Sensitivity	
Data unavailable in project timeframe.	
Liquefaction Susceptibility	Very High
Exposure: Medium	
Maximum Inundation Depths	
16” + MHHW	0 ft
16” + 100-yr SWEL	1 ft
16” + 100-yr SWEL + wind waves	YES
55” + MHHW	2 ft
55” + 100-yr SWEL	4 ft
55” + 100-yr SWEL + wind waves	YES
Inadequate Adaptive Capacity (16” SLR): High No adequate alternative	
Vulnerability Rating (mid century): Medium-High	





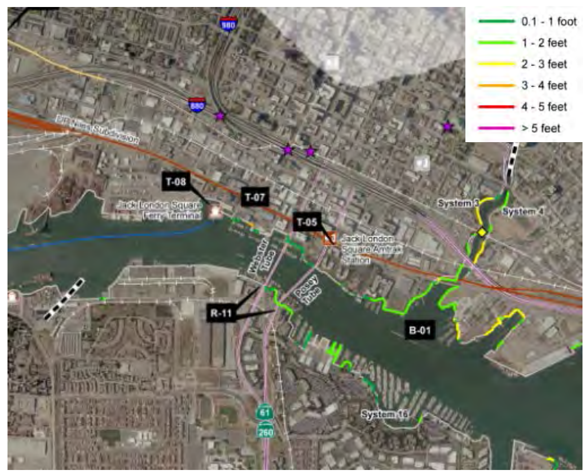
Projected Inundation with 16 inch SLR + 100-yr SWEL

Projected Inundation with 55 inch SLR + 100-yr SWEL

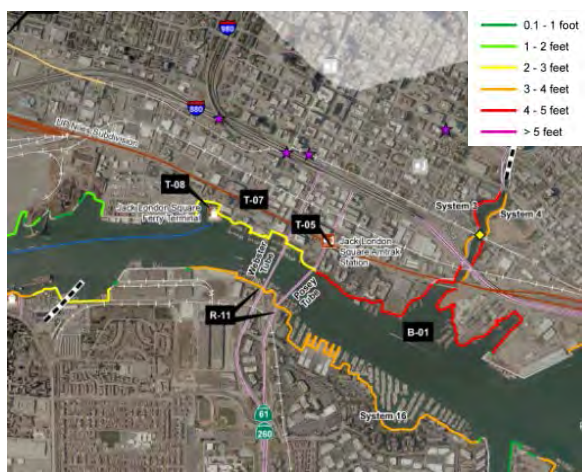
Consequence Rating (out of 5): 3.00	
Capital improvement cost	At-grade railroad plus bridge over Lake Merritt inlet to cost at least $50 million (5)
Time to rebuild	At-grade, plus bridge over Lake Merritt inlet, likely within 5 years (3)
Public safety	Minor consequence (1)
Economic impact - goods movement	Connects Port of Oakland to regional/national rail network (5)
Economic impact - commuter route	4,330 daily riders for entire Capitol Corridor (3)
Socio-economic impact	Community of Concern; pass-through “Premium” transit (1)
Risk Rating: Medium	

Shoreline Asset “Overtopping” Analysis	
Proximity to Overtopping (distance)	***16” + 100-yr SWEL***
	< 10 ft
	55” + 100-yr SWEL
	< 10 ft
Length Overtopped (% of System)	***16” + 100-yr SWEL***
	10,470 ft (17%)
	55” + 100-yr SWEL
	29,870 ft (48%)
Average Depth of Overtopping	***16” + 100-yr SWEL***
	1.5 ft
	55” + 100-yr SWEL
	3.0 ft
System Responsible (See overview map)	3, 4

Future Projects
None



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



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

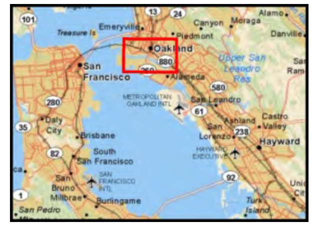
Asset Risk Profile

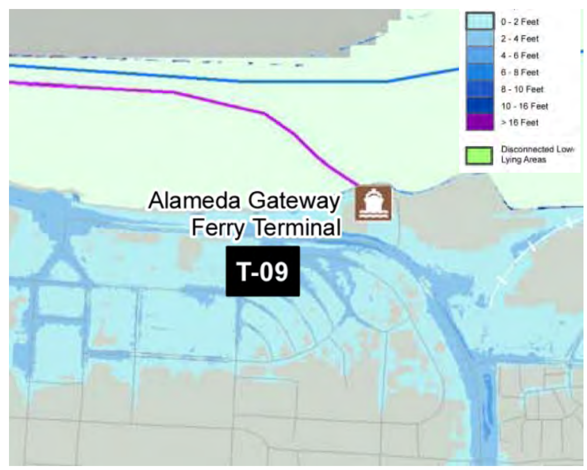
Alameda Gateway Ferry Terminal (T-09)

Asset Location / Jurisdiction Oakland / WETA	
Summary The Alameda Gateway Ferry Terminal facilitates ferry service between Alameda and the City and County of San Francisco, and includes parking, bicycle and ADA access. Sensitivity is medium (due to 'fair' condition), as is exposure (due to inundation under the 55" + 100-yr SWEL SLR scenario). No adequate alternative exists for this asset, resulting in a high vulnerability rating. Consequence is moderate for commuter use and public safety, given the role of ferries in disaster response and recovery, and low for all other considerations. The overall consequence rating is 1.67, making this a low-risk asset.	
Characteristics: • Transit routes: [1 ferry route]	

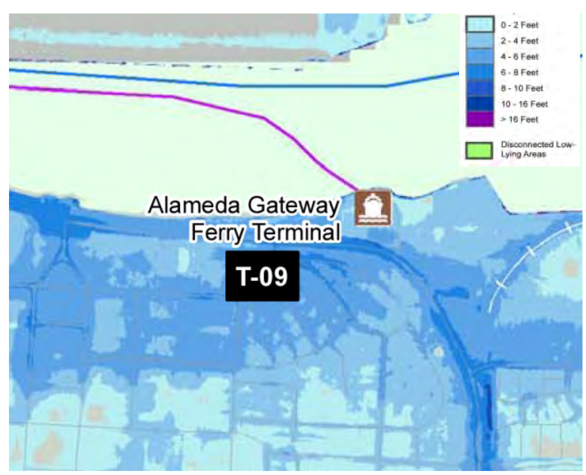
Sensitivity: Medium	
Built	ca. 1991
Level of Use	13 ferries/day 239,000 trips/year
Seismic Retrofit	No
Annual O&M	$5,000-$10,000
Liquefaction Susceptibility	Very High
Exposure: Medium	
Maximum Inundation Depths	
16" + MHHW 16" + 100-yr SWEL 16" + 100-yr SWEL + wind waves	0 ft 0 ft* YES
55" + MHHW 55" + 100-yr SWEL 55" + 100-yr SWEL + wind waves	0 ft 2 ft YES
Inadequate Adaptive Capacity (16" SLR): High No adequate alternative	
Vulnerability Rating (**mid century**)**: High**	

*The asset is inundated to 0.05 ft at the 16" + 100-yr SWEL scenario, which was rounded down due to resolution limitations of the mapping





Projected Inundation with 16 inch SLR + 100-yr SWEL

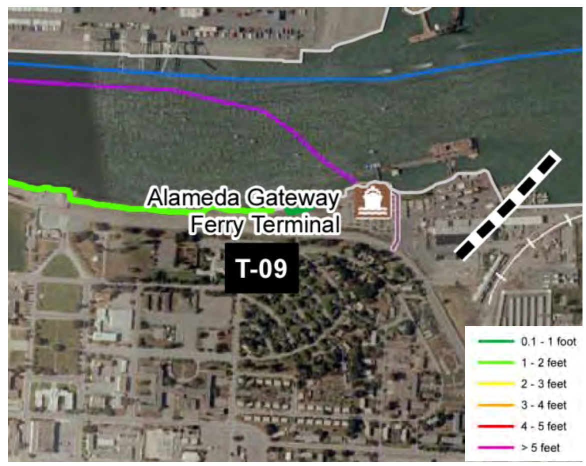


Projected Inundation with 55 inch SLR + 100-yr SWEL

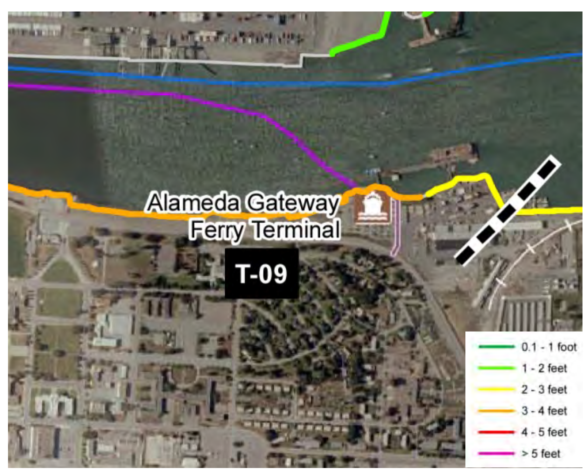
Consequence Rating (out of 5): 1.67	
Capital improvement cost	$15-20 million for total replacement (1)
Time to rebuild	18-24 months from start of construction (1)
Public safety	Critical to immediate disaster response and recovery (3)
Economic impact - goods movement	Not applicable (1)
Economic impact - commuter route	655 daily ferry riders (3)
Socio-economic impact	Community of Concern; local “Premium” transit (1)
Risk Rating: Low	

Shoreline Asset “Overtopping” Analysis	
Proximity to Overtopping (distance)	***16” + 100-yr SWEL***
	560 ft
	55” + 100-yr SWEL
	50 ft
Length Overtopped (% of System)	***16” + 100-yr SWEL***
	14,970 ft (49%)
	55” + 100-yr SWEL
	25,840 ft (85%)
Average Depth of Overtopping	***16” + 100-yr SWEL***
	1.1 ft
	55” + 100-yr SWEL
	3.6 ft
System Responsible (See overview map)	12

Future Projects
None



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



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

Asset Risk Profile

AC Transit Maintenance Facility (1100 Seminary Avenue) (F-01)

Asset Location / Jurisdiction
Oakland / AC Transit

Summary
AC Transit operates a bus maintenance and storage facility at 1100 Seminary Avenue in Oakland. Due to lack of data, this asset was not rated with respect to sensitivity. Exposure is rated medium, due to inundation under the 55" + 100-yr SWEL SLR scenario. AC Transit operates other maintenance facilities, but they are likely insufficient to fully compensate for loss of this facility, resulting in a medium vulnerability rating for this asset. Consequence is rated high for capital improvement costs, time to rebuild, and commuter use; moderate for time to rebuild and socioeconomic impact; and low for public safety and goods movement, which does not apply. The overall consequence rating is 3.00, making this a medium-risk asset.

Characteristics:
- At grade
- Maintenance facility

Sensitivity	
Data unavailable in project timeframe.	
Liquefaction Susceptibility	Medium
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	2 ft
55" + 100-yr SWEL + wind waves	YES
Inadequate Adaptive Capacity (16" SLR): Medium AC Transit maintains other maintenance facilities, but they are likely insufficient to fully compensate for loss of this facility	
Vulnerability Rating (mid century): Medium	

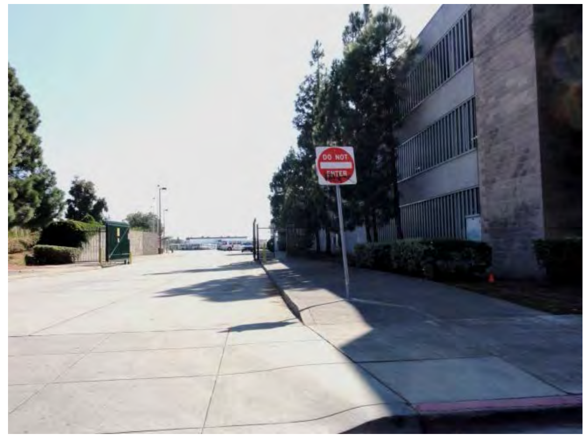
Projected Inundation with 16 inch SLR + 100-yr SWEL

Projected Inundation with 55 inch SLR + 100-yr SWEL

Consequence Rating (out of 5): 3.00	
Capital improvement cost	$87 million (estimate from new bus maintenance facility in Nevada) (5)
Time to rebuild	Likely within 5 years (3)
Public safety	Minor consequence (1)
Economic impact - goods movement	Not applicable (1)
Economic impact - commuter route	Critical to providing AC Transit service (5)
Socio-economic impact	Community of Concern + Transit-Dependent area; supporting local transit (multiple lines) (5)
Risk Rating: Medium	

Shoreline Asset "Overtopping" Analysis	
Proximity to Overtopping (distance)	***16" + 100-yr SWEL***
	1,540 ft
	55" + 100-yr SWEL
	1,360 ft
Length Overtopped (% of System)	***16" + 100-yr SWEL***
	7,840 ft (47%)
	55" + 100-yr SWEL
	16,170 ft (98%)
Average Depth of Overtopping	***16" + 100-yr SWEL***
	1.5 ft
	55" + 100-yr SWEL
	3.8 ft
System Responsible (See overview map)	6

Future Projects
None



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

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

5.5 RECOMMENDED REFINEMENTS TO THE FHWA CONCEPTUAL MODEL

Recommendations for the vulnerability and risk component of the FHWA conceptual model include the following:

- Provide fuller definitions or guidance on what exposure, sensitivity, and adaptive capacity mean and how to use them for different project types.
- Obtain early input from stakeholders on definitions of the consequence impact criteria as this insight is valuable to ensuring that criteria are tailored to the local context.
- Provide guidance and examples on how to rate the sensitivity of an asset when the availability of data is inconsistent between assets.
- Provide guidance on when it is appropriate to assess assets across asset types and when it is appropriate to assess assets within asset types.
- Provide guidance on the range of asset types that should be included in a project scope so that like-with-like comparisons can be made.
- Agencies should put in place data inventory development processes to consolidate data about transportation assets to facilitate future risk assessment exercises.
- Include guidance or suggestions on what type of more detailed inundation mapping can be helpful for prioritizing vulnerable assets and understanding how the protection that a shoreline asset is offering changes with SLR.
- Provide guidance about whether or not agencies may wish to add a weighting to certain impacts in the instance that multiple impacts are being rated and averaged to provide an overall consequence rating which may mask the highest (and most concerning) consequence rating.
- Organizational impacts to the agencies themselves are not included as consequence criteria and should be considered in the future. Decisions made by agencies today that increase the vulnerability by not taking climate change into account may led to liability issues in the future.

NOTE ABOUT THE BAY TRAIL

There was much discussion regarding how to assess the Bay Trail and other pedestrian or bicycle infrastructure in terms of impact or consequence of inundation from SLR. Although the Bay Trail is of great importance as a recreational and social asset for the local community and is a valuable commuting route for some, when compared to other transportation infrastructure, such as freeways or the Bay Tube, it cannot compete in terms of regional significance. For the risk assessment exercise for this project, it was decided that all assets should be compared using a common scale to be able to use the assessment as a prioritization tool. The Bay Trail was carried through the vulnerability assessment stage as an important representative asset for the region and was determined to be highly vulnerable. However, when assessed with the consequence criteria, it was determined to have low impact or consequence (because it would be comparatively inexpensive to rebuild and does not carry significant commuter or goods traffic). Given the trail's importance to the region (even though not from a regional transportation perspective), the project team decided that it was not appropriate to label it of low consequence if it were inundated. (It should be noted that for other projects, if prioritization or comparison is not being made across asset types, then metrics can be developed to enable assets to be compared within their asset types.)

Bay Trail

BAY TRAIL AND CONNECTING TRAILS

Lake Merritt Connector Trail

The Bay Trail provides easily accessible recreational opportunities for outdoor enthusiasts, including hikers, joggers, bicyclists and skaters. It also offers a setting for wildlife viewing and environmental education, and it increases public respect and appreciation for the Bay. It also has important transportation benefits, providing a commute alternative for cyclists, and connects to numerous public transportation facilities (including ferry terminals, light-rail lines, bus stops and Caltrain, Amtrak, and BART stations); also, the Bay Trail will eventually cross all the major toll bridges in the Bay Area. Within the subregion, the Bay Trail consists of off-street paved or gravel paths; on-street bike lanes and sidewalks; off-street unimproved paths (of varying width and surfaces). Other paved or gravel paths connect to the Bay Trail.

This project evaluated two off-street trail segments along the Alameda County shoreline: the trail around Lake Merritt connecting to the Bay Trail (the “Lake Merritt Connector Trail”) and the segment of the Bay Trail along the Hayward Regional Shoreline (the “Hayward Regional Shoreline Trail”). Due to lack of data, these assets were not rated with respect to sensitivity. Exposure for both trail segments is high (due to significant inundation under both the 16" and 55" SLR scenarios). While the Lake Merritt Connector Trail has a parallel trail, it is likely to be similarly affected by inundation; no parallel trail is available for the Hayward Regional Shoreline Trail, making the vulnerability of both trail segments high. For both trail segments, all consequence criteria have a low rating, making them low-risk assets.

Bay Trail

6.0

EXAMPLE SEA LEVEL RISE MAPS

6.0 EXAMPLE SEA LEVEL RISE MAPS

6.1 INTRODUCTION

This chapter contains a few examples of the maps generated for the FHWA pilot project. There are two main types of maps—those that show expected inundation, and those that show the overtopping potential of the shoreline assets. The inundation maps present the depth and extent of inundation associated with the six inundation scenarios evaluated as part of this effort. Each SLR scenario—16 inches (40 cm) by mid-century and 55 inches (140 cm) by end of century—is evaluated under three storm/tide conditions: inundation associated with high tides also known as mean higher high water (MHHW)), inundation associated with 100-year extreme water levels also known as still water elevations (100-yr SWEL), and inundation associated with 100-year extreme water levels coupled with wind waves (100-yr SWEL + wind waves). The depth of inundation information associated with the six inundation scenarios was extracted along the shoreline assets to provide a high-level assessment of the potential for shoreline overtopping. The shoreline overtopping potential maps present the results of this exercise.

The full set of maps can be found in chapter 6 of the Technical Report. Before reviewing the maps, please read section 6.2 to understand the caveats associated with the maps due to data availability and methodology limitations.

Examples shown in this chapter:

- 16-Inch MHHW Sea Level Rise Extent and Depth Overview Map
- 55-Inch MHHW Sea Level Rise Extent and Depth Overview Map
- Zoom-in Map 1: 16-Inch Sea Level Rise plus 100-year Stillwater Levels Extent and Depth
- Zoom-in Map 5: 16-Inch Sea Level Rise plus 100-year Stillwater Levels Extent and Depth
- Zoom-in Map 1: 16-Inch Sea Level Rise plus 100-year Stillwater Levels Overtopping Depth Along Shoreline Feature
- Zoom-in Map 5: 16-Inch Sea Level Rise plus 100-year Stillwater Levels Overtopping Depth Along Shoreline Feature

6.2 CAVEATS ASSOCIATED WITH THE MAPS

The inundation maps and shoreline overtopping potential maps are intended as planning-level tools to illustrate the potential for inundation and coastal flooding under future SLR scenarios and the maps do not represent the exact location or depth of flooding or shoreline overtopping. The maps are based on model outputs and do not account for all of the complex and dynamic Bay processes or future conditions such as erosion, subsidence, future construction or shoreline protection upgrades, or other changes to San Francisco Bay or the region that may occur in response to SLR. For more context about the maps and analyses, including a description of the data and methods used, please refer to Chapter 4 and the associated Appendix. Users agree to hold harmless and blameless the State of California and its representatives and its agents for any liability associated with the use of the maps. The maps and data shall not be used to assess actual coastal hazards, insurance requirements, or property values or be used in lieu of Flood Insurance Rate Maps issued by the Federal Emergency Management Agency (FEMA).

The inundation maps created for the pilot study region represent advancement over previous inundation maps that characterized the extent of inland inundation due to sea level rise. Most notably, the new maps include:

- The depth and extent of inundation.
- The maps rely on topographic information from the 2010 USGS LIDAR. The flood protection levees and other features that could impede flood conveyance are captured in this latest set.
- Wave dynamics along the Alameda County shoreline are considered. Wave heights along the shoreline can exceed 4 feet in height therefore wave dynamics are important processes to consider when evaluating the potential for shoreline overtopping and inundation in nearshore coastal areas.
- The new mapping effort also benefited from an assessment of hydraulic connectivity, using inundation mapping methodologies developed by the NOAA Coastal Services Center to exclude low-lying areas that are below the inundated water surface elevation, but are not hydraulically-connected to the inundated areas.

Photo used under Creative Commons. Provided by Flickr user 'Nina Stawski'.

The inundation maps are intended only as a screening-level tool for performing the vulnerability and risk assessment. Although the inundation maps do account for additional processes and they rely on new data, they are still associated with the following series of assumptions and caveats:

- The bathymetry of San Francisco Bay and the topography of the landward areas, including levees and other flood and shore protection features, would not change in response to SLR and increased inundation (e.g., the morphology of the region is constant over time).
- The maps do not account for the accumulation of organic matter in wetlands or potential sediment deposition and/or resuspension that could alter San Francisco Bay hydrodynamics and/or bathymetry.
- The maps do not account for erosion, subsidence, future construction, or levee upgrades.
- The maps do not account for the existing condition or age of the shore protection assets. No degradation or levee failure modes have been analyzed as part of the inundation mapping effort.
- The levee heights and the heights of roadways and/or other topographic features that may impact flood water conveyance are derived from the USGS 2010 Light Detection and Ranging (LIDAR) at a two meter horizontal grid resolution. Although this data set represents the best available topographic data, and the data has undergone a rigorous QA/QC by a third party, the data has not been extensively ground-truthed. Levee crests and other topographic features may be over or under-represented by the LIDAR data.
- The inundation depth and extent shown on the MHHW maps are associated with the highest high tides, in an attempt to approximate the maximum extent of future daily tidal inundation. This level of inundation can also be referred to as "permanent inundation," as it represents the area that would be inundated regularly. Tides in San Francisco Bay exhibit two highs and two lows in any given day, and the daily high tide on any given day may be less than the calculated MHHW tidal elevation.
- The inundation depth and extent shown on the 100-yr SWEL maps is associated with a 100-year extreme water level condition—in other words, an extreme tide level with a 1-percent chance of occurring in any given year. This inundation is considered "episodic inundation" because the newly inundated areas (the areas not inundated under the MHHW scenario) would be inundated only during extreme high tides. It should be noted that extreme tide levels with greater return intervals (i.e., 500-yr SWEL with a 0.2-percent chance of occurring in a given year) can also occur and would result in greater inundation depths and a larger inundated area.
- The depth of inundation is not shown for the extreme coastal storm event conditions (i.e., 100-yr SWEL + waves) because the physics associated with overland wave propagation and wave dissipation are not included in this study. These processes would have a significant effect on the ultimate depth of inundation associated with the large coastal wave events, resulting in a potential reduction in the depth of inundation in most areas. Alternatively, the wave heights used in this analysis are associated with existing 10-year wave heights, and as sea level rises and bay water depths increase, the potential for larger waves to develop in the nearshore environment increases. This dynamic could result in increases in the depth of inundation, particularly directly adjacent to the shoreline assets.
- The inundation maps focus on the potential for coastal flooding associated with sea level rise and coastal storm events. The inundation maps do not account for localized inundation associated with rainfall-runoff events, or the potential for riverine overbank flooding in the local tributaries associated with large rainfall events.
- The maps do not account for inundation associated with changing rainfall patterns, frequency, or intensity as a result of climate change.

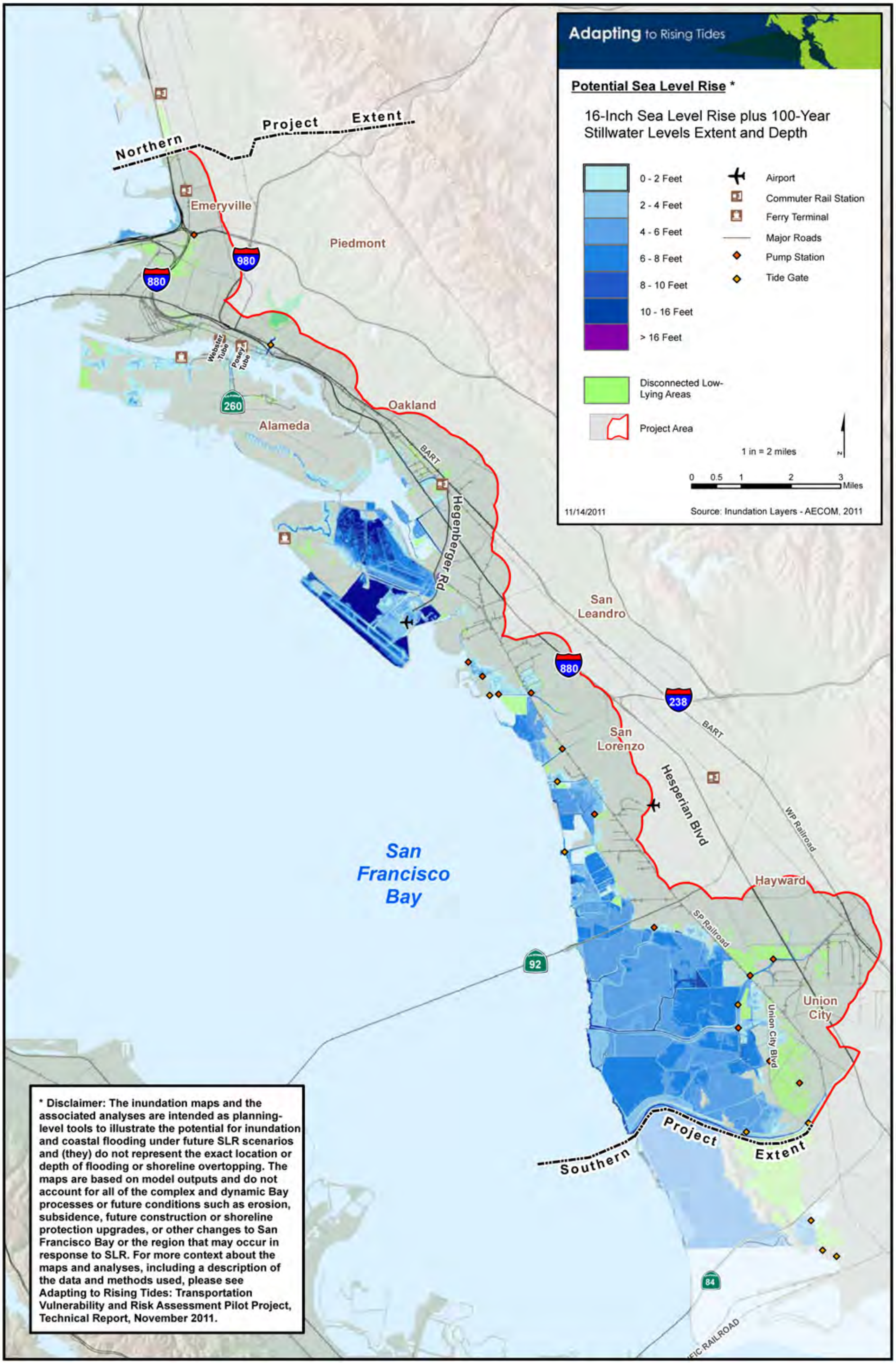


FIGURE 6.1 16-Inch Sea Level Rise plus 100-Year Stillwater Levels Extent and Depth

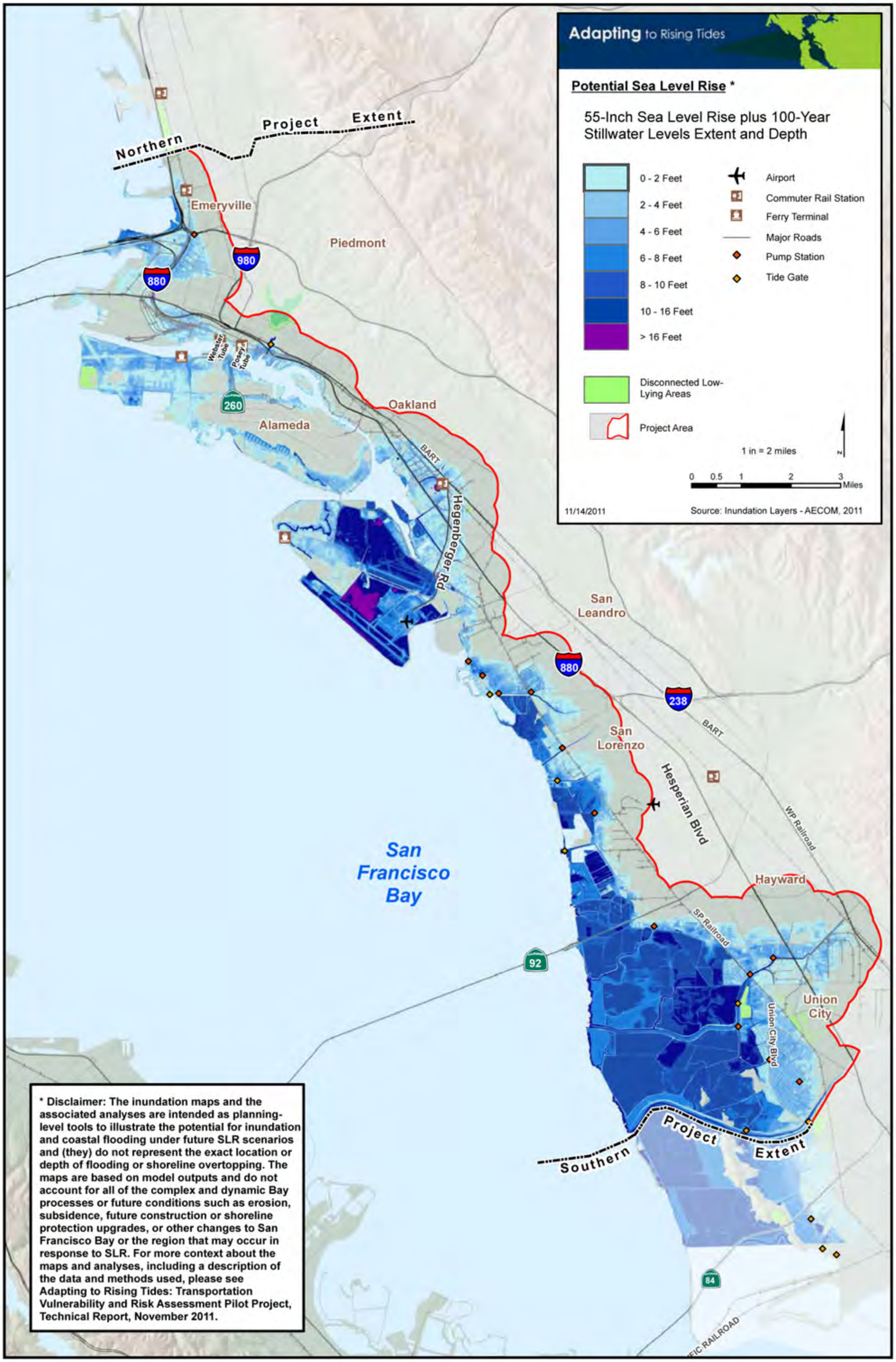


FIGURE 6.2 **55-Inch Sea Level Rise plus 100-Year Stillwater Levels Extent and Depth**

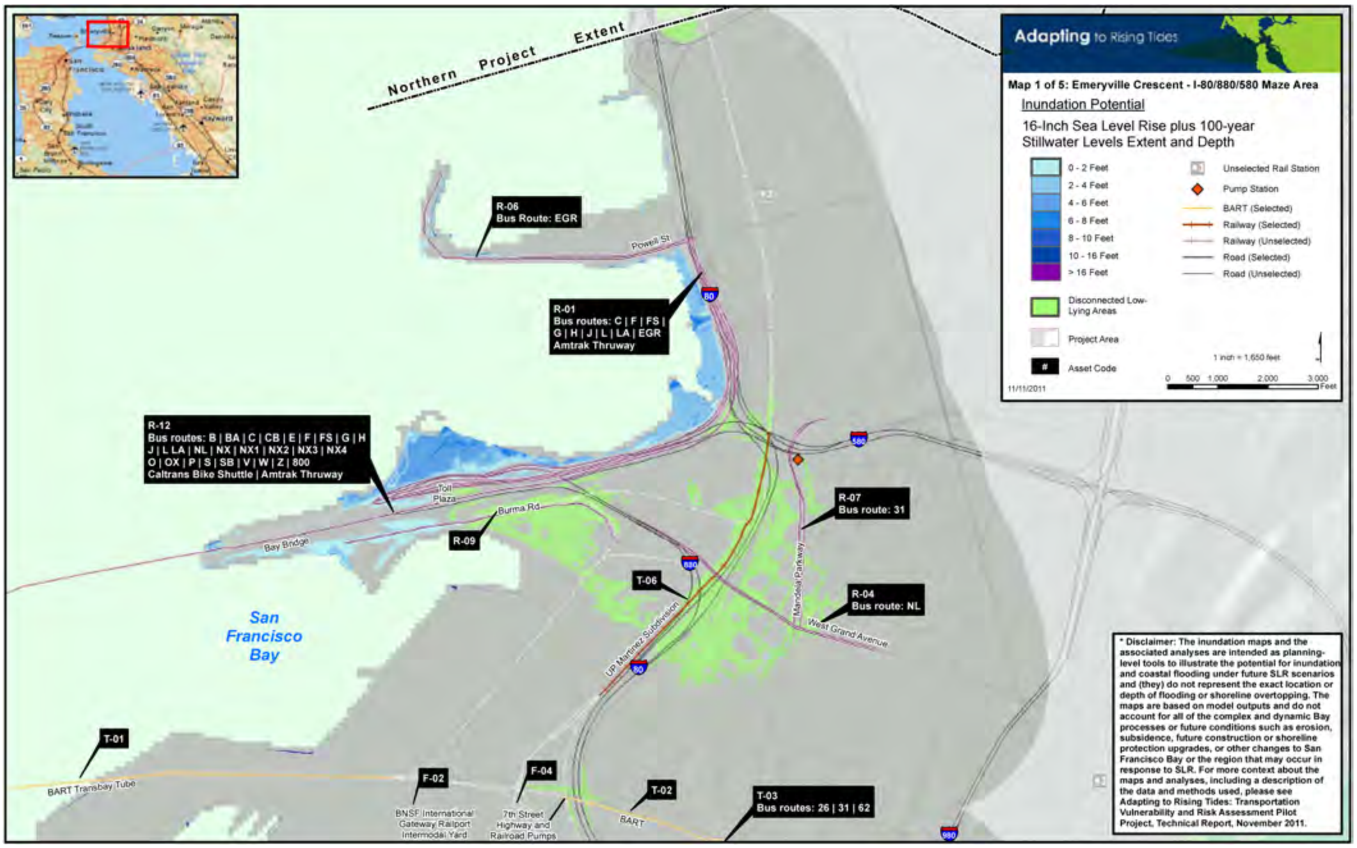


FIGURE 6.3 **Zoom in Map 1: 16-Inch Sea Level Rise plus 100-year Stillwater Levels Extent and Depth**

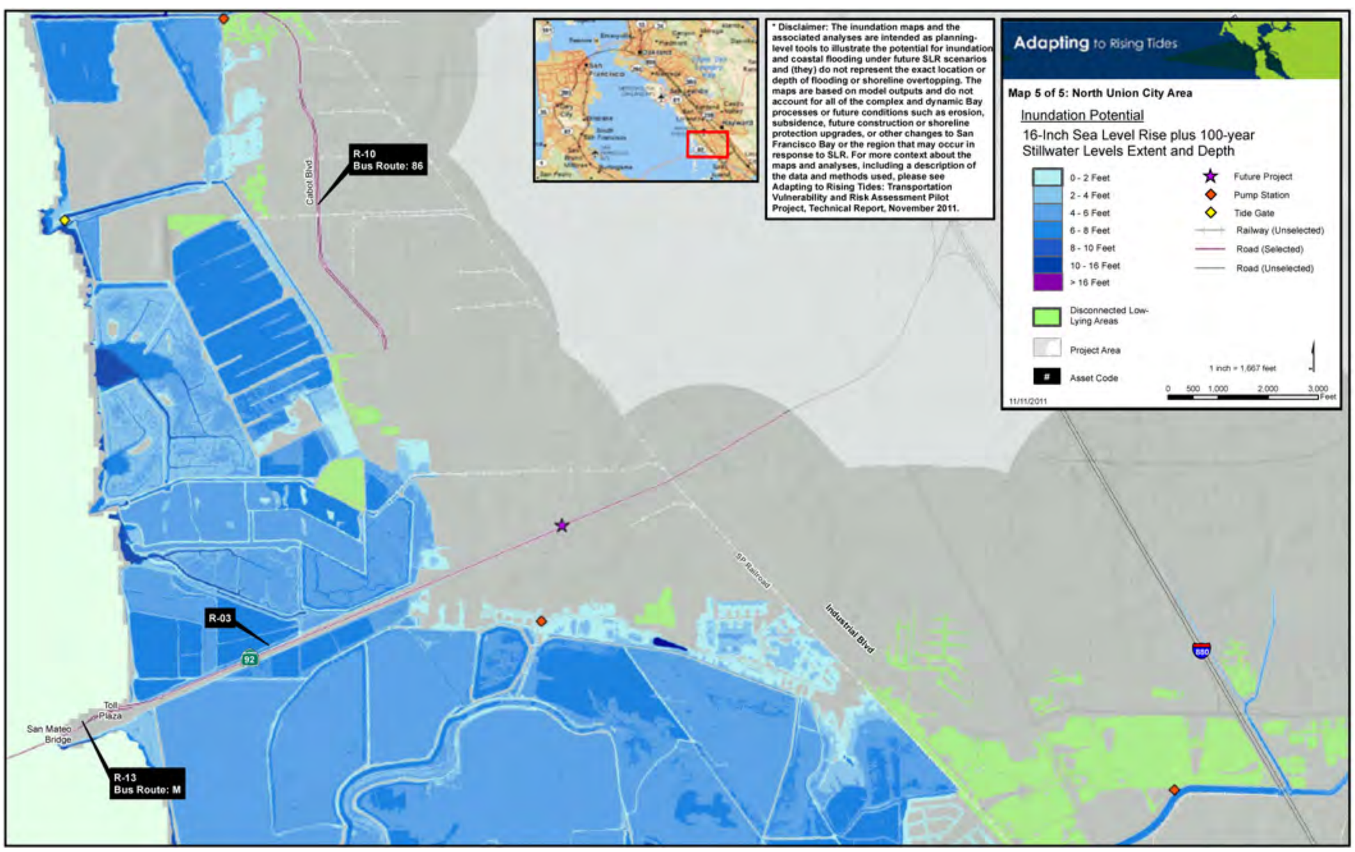


FIGURE 6.4 **Zoom in Map 5: 16-Inch Sea Level Rise plus 100-year Stillwater Levels Extent and Depth**

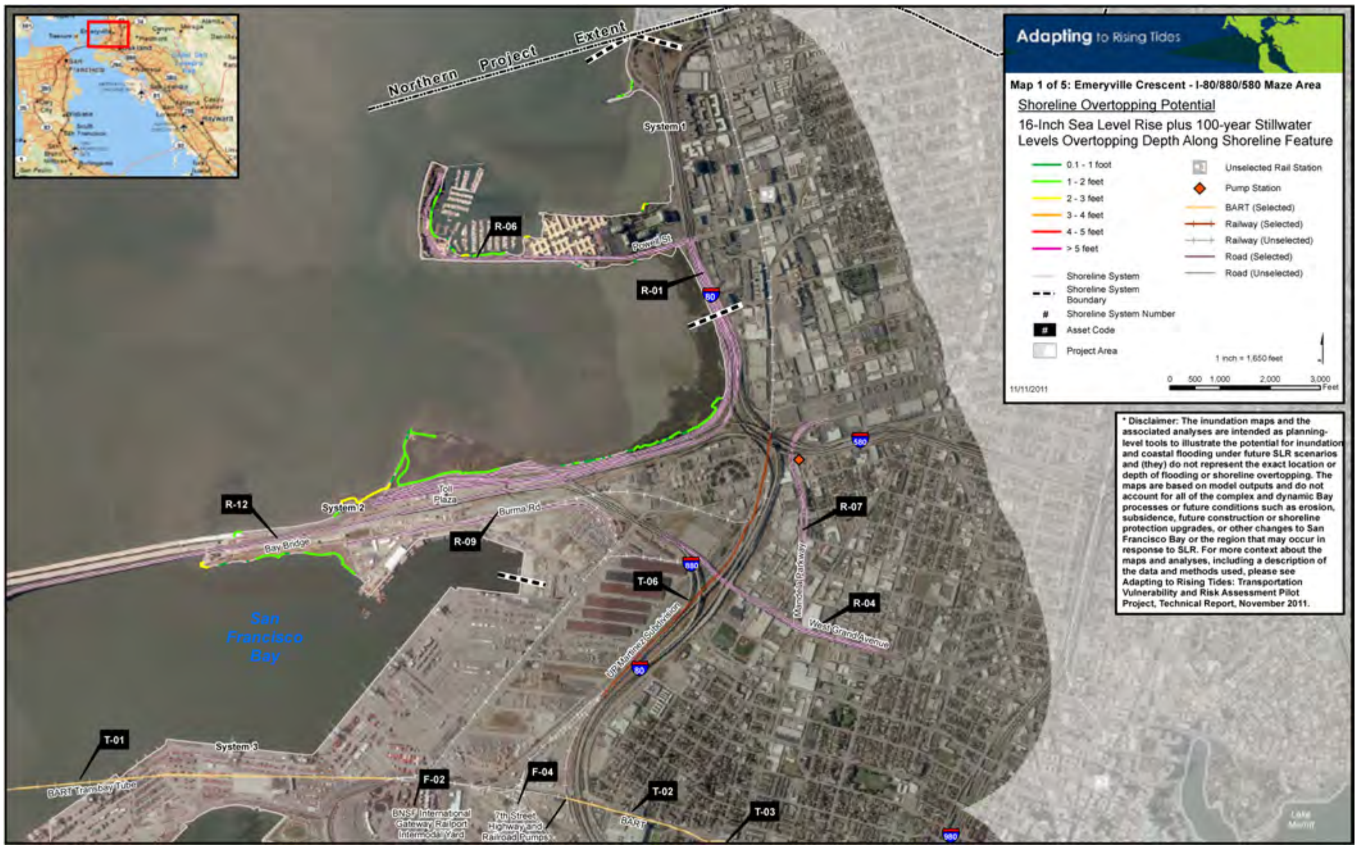


FIGURE 6.5 **Zoom in Map 1: 16-Inch Sea Level Rise plus 100-year Stillwater Levels Overtopping Depth Along Shoreline Feature**

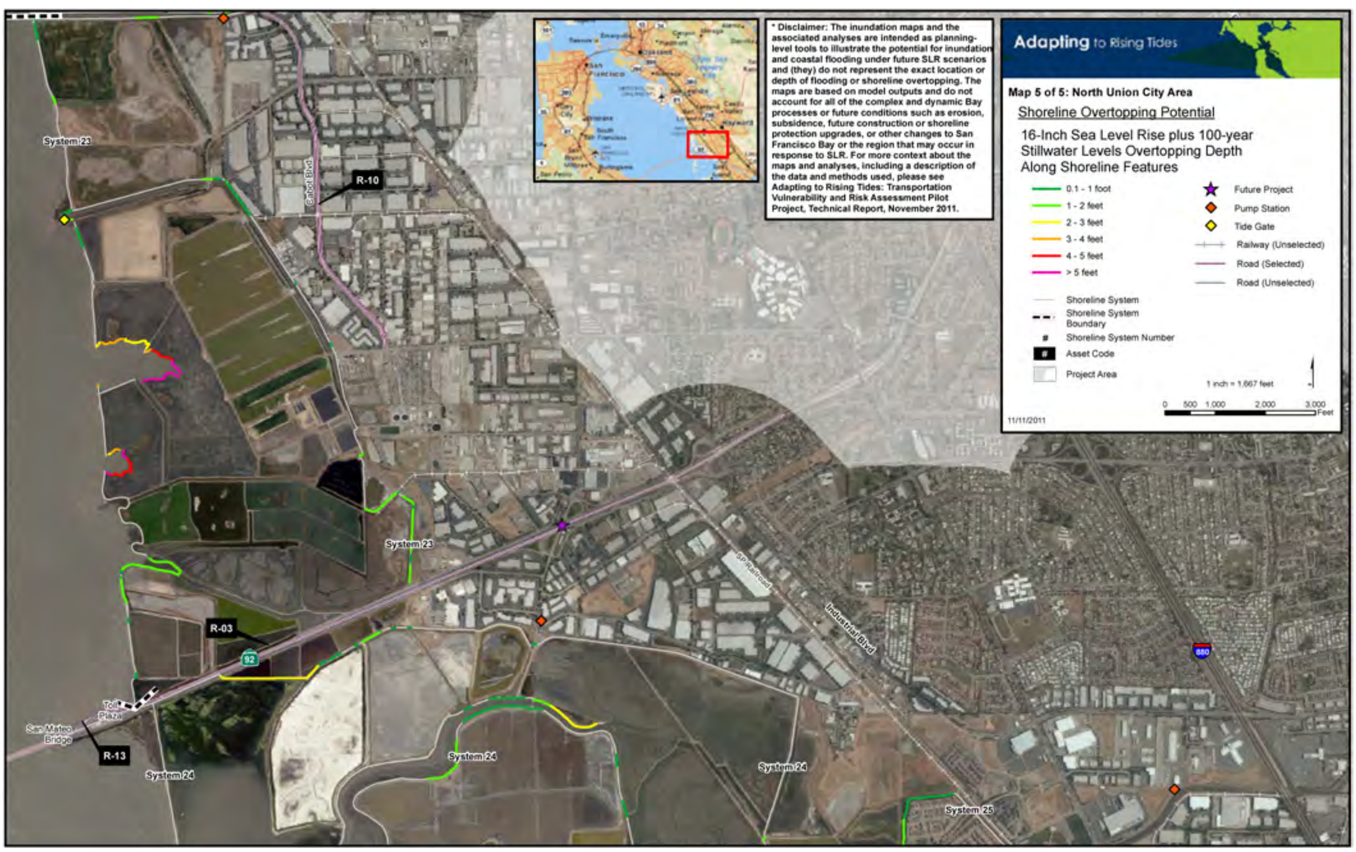


FIGURE 6.6 **Zoom in Map 5: 16-Inch Sea Level Rise plus 100-year Stillwater Levels Overtopping Depth Along Shoreline Feature**

7.0

ADAPTATION PLANNING

7.0 ADAPTATION PLANNING

7.1 INTRODUCTION

Chapter 6 identifies the vulnerability and risk level of the selected representative transportation assets that are exposed to inundation under different sea level rise (SLR) scenarios. The subsequent task is to consider what can be done to mitigate these risks. This chapter explores preliminary ideas and possibilities for adapting to SLR in the pilot project area. Adaptation planning is not part of the Federal Highway Administration conceptual model; however, it is the essential next step in the process.

Section 7.2 reviews a list of potential adaptation measures, some of which were identified through previous planning efforts, including preparation of *San Francisco Bay: Preparing for the Next Level* (BCDC 2009). Section 7.3 provides suggestions on how to use information collected on the risk profiles and additional evaluation criteria to help select adaptation measures. Based on this information, Section 7.4 presents a potential range of near-term and longer term adaptation options for one example asset—the San Francisco—Oakland Bay Bridge (which in this review focuses on the bridge touchdown and toll plaza, R-12). Chapter 7 of the Technical Report presents a second example asset, the Oakland Jack London Square Amtrak Station (T-05). This chapter concludes by recommending next steps for developing an approach to adapting transportation infrastructure to SLR. Consultation with the organizations involved in the Shoreline Asset and Transportation Asset subcommittees would be an essential part of the process.

Note that the adaptation measures discussed in this chapter provide a range of possible solutions based only on the information available to the project team. The outcomes of this chapter are not intended to represent specific adaptation measures but rather, to identify a range of potential adaptation measures to be further investigated as part of the adaptation planning phase of the ART project.

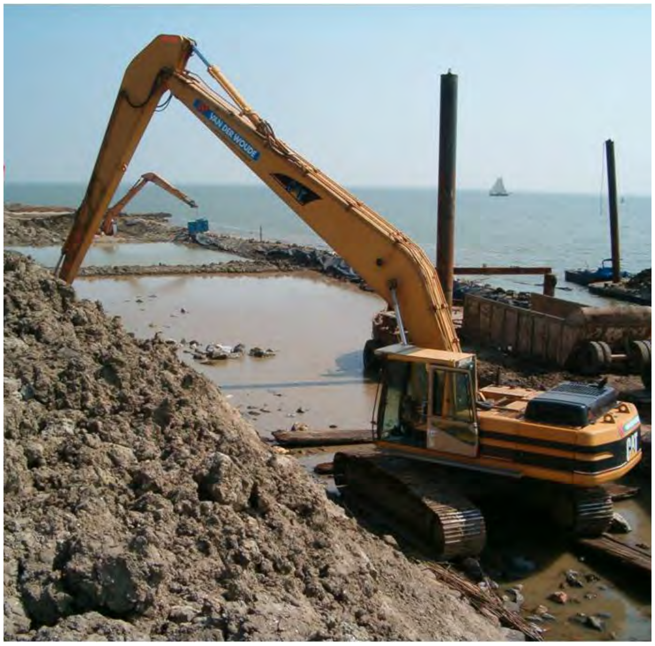
7.2 CLIMATE CHANGE ADAPTATION MEASURES

The risk assessment exercise described in Chapter 6 shows that adapting transportation infrastructure to rising sea levels will be required to maintain the level of service expected within the Alameda County subregion. San Francisco Bay sea levels have already risen by 7 inches (California Natural Resources Agency 2009) in the past century and will continue to rise, and rising tides are already affecting the Bay Area's transportation network. Not adapting to these changing circumstances will likely result in large economic and social impacts to the region. By taking a proactive approach, various agencies around the bay will allow the region to remain safe and competitive.

Key questions to answer at the outset of adaptation planning are: "What is an acceptable impact to the region, and what adaptation measures are needed to achieve this?" In relation to transportation, these questions lead to establishing the minimum level of service that must be provided by the road and rail networks. Under present-day conditions, agencies are likely to require at least the same or a better level of service and the current (or better) level of flood protection. These questions were not addressed for the two example assets reviewed for the project, but it would be a key question in the development of an adaptation strategy.

For this project, adaptation measures have been organized into several categories to structure the discussion on how to select the most appropriate adaptation measures for any given asset—structural and nonstructural measures, and asset-specific and regional (or non asset-specific) measures. These categories can be defined as follows:

- **Structural Adaptation Measures**—are physical measures, such as constructing levees, flood walls, and wetlands or relocating an asset, that mitigate the flooding impacts of SLR.
- **Nonstructural Adaptation Measures**—are non physical measures that can include changing policies and regulations (e.g., new building codes, zoning requirements like setbacks or buffer zones), updating design guidance, or providing education and community outreach to increase awareness and make communities more resilient. Nonstructural measures could also include rerouting traffic or temporarily closing infrastructure.
- **Asset-Specific Adaptation Measures**—are measures that are directly related to adapting the transportation asset to SLR impacts.
- **Regional Adaptation Measures**—are measures that may protect more than one transportation asset and assets in other sectors (e.g., residential, commerce, recreation) in the same area.



Levee Construction

Both structural and nonstructural measures are essential for adaptation planning and in many instances, the two complement one another, as the nonstructural measure enables implementation of the structural measure.

In addition, the timing of implementation of adaptation measures can be used as an organizing principle to identify the most appropriate point of intervention in an asset's life cycle for implementation of adaptation measures. Opportunistic adaptation measures are those that can be made during regularly scheduled maintenance or end-of-life-cycle replacement. Proactive adaptation measures are those that are implemented in anticipation of a climate change stressor—in this case, SLR—independent of other activities (e.g., elevating a road before the end of its life cycle to better protect it from rising tides). Consideration of the various categories of adaptation measures and their points of interventions shaped the discussion on conducting an initial screening of appropriate adaptation measures. It should be noted that adaptation measures typically fall into multiple categories, meaning that an asset-specific measure can be, for example, structural in nature as well as opportunistic.

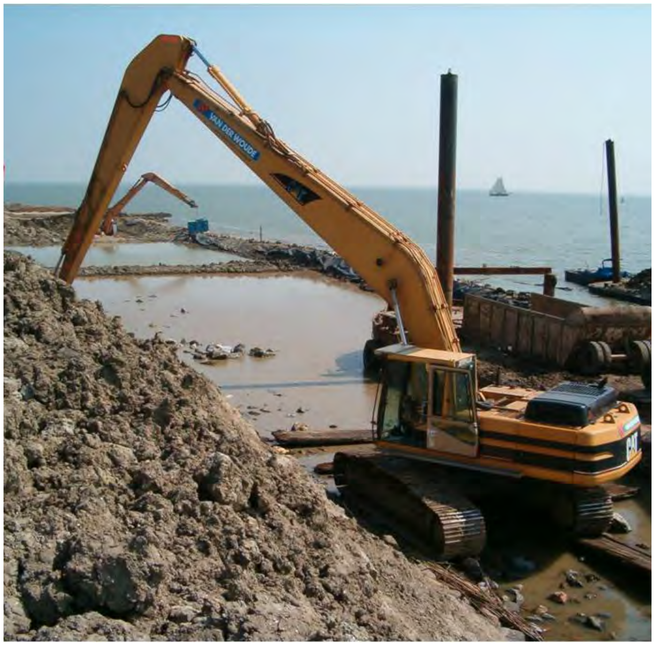
Table 7.1 in Chapter 7 of the Technical Report provides an overview of adaptation measures that were found to be potentially applicable for the Alameda County subregion. These measures represent a matrix of structural and nonstructural, and asset-specific and regional adaptation measures. Most of the measures could be implemented as either opportunistic or proactive measures.

7.3 METHODOLOGY TO ANALYZE AND USE RISK PROFILES FOR ADAPTATION PLANNING

7.3.1 EVALUATION OF RISK PROFILES

The information presented in the risk profiles (Appendix C) provides valuable information to help understand the most appropriate adaptation measure for a particular transportation asset. Transportation assets with the highest risk ratings should be addressed first, as the impacts of SLR are likely to occur sooner, and the consequences are high relative to other assets. The information in the risk profile can be assessed in six steps:

1. **Exposure**—How would the transportation asset be affected by inundation at midcentury, and what would the impacts be at the end of the century (for this example, we have used the 16-inch and 55-inch 100-year stillwater elevation [SWEL] scenarios)? For example:
   - If the inundation would be less than 1 foot and would occur only during an extreme weather event, then improved drainage, reinforced foundations, temporary closure, or a demountable flood wall may be appropriate.
   - If the inundation would be permanent and more than 1 foot, then raising the asset, building a flood protection structure, or abandonment of the asset may be appropriate.
2. **Sensitivity**—What characteristics of the asset can be used to understand its sensitivity to climate change stressors? For example:
   - If the asset is in poor condition, not yet seismically upgraded, or near the end of its service life, opportunistic measures should be taken to raise or reroute the asset, upgrade it with new materials, or waterproof it.
   - If the sensitivity of an asset can be reduced, the likelihood of occurrence of a climate change impact to this asset can also be reduced. Often, reducing sensitivity in this sense can offer a low cost and fast (interim) adaptation solution.
3. **Adaptive capacity**—How does adaptive capacity affect the vulnerability of the asset, and can this be used as part of an adaptation strategy? For example:
   - If use of the asset can be wholly or partially rerouted, then structural measures could potentially be avoided; temporary closure could be acceptable in the short term.



Levee Construction

4. **Consequence rating**—What are the consequences if this asset is temporarily or permanently out of use? What is its importance to the subregion or Bay Area or beyond? Assets with high consequence ratings should be prioritized for adaptation planning.
   - If the asset has a high consequence rating, then temporary or partial closure is unlikely to be acceptable; an asset with a low consequence rating, however, could likely be temporarily or partially closed.
5. **Overtopping potential**—Which stretches of shoreline would be overtopped and therefore, would be responsible for inundation of the asset? (An explanation of overtopping is presented in Chapter 4.) For example:
   - If a short length of shoreline is overtopped, this segment alone could be raised.
   - If a long length of shoreline is overtopped, a major rebuild, raise, or strengthening of the entire shoreline may be required.
6. **Shoreline systems**—Are there other assets protected by the same shoreline system, and what type of shoreline category does the system consist of? (Descriptions and location of the different shoreline assets are presented in Chapter 2.) For example:
   - If more than one system or asset is involved, more jurisdictions may need to be involved, and more complex solutions and planning may be required.

Table D1 in Appendix D provides additional examples of how to interpret the information in the risk profiles to inform decisions about potential adaptation measures.

7.3.2 USE OF EVALUATION CRITERIA

After going through these six steps, decision makers can evaluate the adaptation measures that may be suitable to reduce the risk of inundation from SLR and the level of service that the adaptation measures will facilitate. In addition to the categories of adaptation measures, a range of criteria and considerations should be used to evaluate the different adaptation measures. These criteria have been grouped according to the lenses of economy, ecology, equity, and governance, as defined in the larger Adapting to Rising Tides project (and the Technical Report).

Different weightings or rankings of importance can be applied to the criteria presented in Table 7.1. For example, more emphasis could be placed on the level of service an asset provides and its implementation cost (in the face of SLR). Whether to assign weightings to the criteria (or rankings of importance) is a determination to be made by transportation agencies. (Note that weightings were not assigned to the criteria for the example assets discussed in this chapter, but should be considered a potential approach by agencies when reviewing adaptation options for specific assets in the subregion.)

(Also note that the likelihood of climate change impacts occurring needs to be reviewed regularly, along with updates to regional climate modeling data, in case predictions regarding the depth and timing of SLR change (from the 16 inches predicted for midcentury and the 55 inches predicted for the end of century).

7.4 EXAMPLE ASSETS

The two example assets selected to test the methodology are the San Francisco-Oakland Bay Bridge, focusing on the bridge touchdown and toll plaza (R-12), and the Oakland Jack London Square Amtrak Station (T-05). These two assets were selected because they represent two different categories of transportation assets and are close to the shoreline. Assets close to the shoreline were selected to avoid overlapping with other sectors (e.g., communities, land) being addressed in the larger Adapting to Rising Tides project. Only the San Francisco-Oakland Bay Bridge is included in the Briefing Book—please see Chapter 7 of the Technical Report for the Oakland Jack London Square Amtrak Station example.

Economy	Ecology
- **Protection of functionality**—Although the continued use of the asset may be limited, the function of the system as a whole can be protected if other facilities (e.g., Bay Area Rapid Transit [BART] or ferries, alternative routes) can provide the same or similar functionality. - **Protection of asset**—When the asset is protected, the asset could still be used. - **Economic benefit**—Does the improved flood protection/ climate resiliency spur new investment or growth? - **Cost and time to build**—What are the time and costs associated with implementing the adaptation measures? - **Operation and maintenance cost**—What are the operation and maintenance costs? - **Spatial requirements**—How much land is required to implement the adaptation measure? - **Adaptability**—Can an adaptation measure be designed to adapt to future climatic changes as likelihood increases or new technologies become available? - **Applicability in time**—Which measures are appropriate for the midterm and which for the longer term, given different SLR scenarios?	- **Ecological value**—Does the adaptation measure provide benefits to the natural environment through species or habitat protection? - **Ecological function**—Does the adaptation measure improve ecological function (e.g., wetland vs. flood wall)? - **Sustainability (longevity)**—Do the different adaptation measures provide long-term sustainable solutions (e.g., next 50, 100, or 200 years)? - **Sustainability (materials)**—Are the materials used for the adaptation measure environmentally sustainable? - **Environmental impacts**—What are the environmental impacts of implementing the adaptation measure, can they be mitigated, and do they reduce green house gas emissions?
Equity	**Governance**
- **Safety**—Does the adaptation measure enhance public safety and security? - **Environmental justice**—Does the adaptation measure benefit underserved populations? - **Regional benefit**—Is there a regional benefit to the local community selecting a specific adaptation measure (e.g., systems approach to protect the region vs. asset-specific protection)? - **Awareness**—Does the measure enhance public awareness and technical knowledge about SLR? - **Public access and aesthetic importance**—Can the adaptation measure be integrated into the natural or urban landscape so that it becomes an amenity and (for example) provides public access to the shoreline? - **Unintentional consequences**—Are there beneficial or negative consequences to the surrounding community or other assets by implementing this measure?	- **Institutional (organizational) arrangements, including jurisdiction**—Are governmental bodies and current policies and regulations equipped to ensure or facilitate long-term planning and timely implementation of the adaptation measure? - **Funding**—Which organization is providing the funding for the adaptation measure, and are there funds available? - **Public or private land**—Which entity or individual owns the land, and how does this affect implementation of the adaptation measure? - **Policies**—Does the adaptation measure build on existing policies, and do new policies allow for modifications as new climate change data/insights become available? - **Development**—Does the adaptation measure facilitate (undesired) development in low lying areas (through improving the flood protection level)?

TABLE 7.1 Criteria for Helping Selection of Adaptation Measures

A range of adaptation measures can be considered from the options presented in Section 7.2 and the information provided by the risk profiles, as discussed in Section 7.3. The Project Management Team and the Consultant Team held a joint work session to select potentially applicable measures looking at midterm (16 inches + 100-year SWEL) and end-of-century (55 inches + 100-year SWEL) SLR scenarios for the two example assets. This was an initial, qualitative assessment that will need further investigation to determine the real cost-effectiveness, applicability, and viability of proposed adaptation measures. Due to time constraints, nonstructural adaptation measures were not discussed during the meeting, but a narrative with some suggested measures is provided in Section 7.4.3. Note that the adaptation measures described cannot be seen in isolation of one another—ultimately, a system consisting of a combination of different types of adaptation measures, both structural and nonstructural, will have to be developed to protect against inundation from SLR.

7.4.1 SAN FRANCISCO—OAKLAND BAY BRIDGE

The San Francisco–Oakland Bay Bridge connects Alameda County with the City and County of San Francisco. For this assessment, the bridge touchdown on the Oakland side and toll plaza are considered. Also note that the Bay Bridge does not function in isolation and should be considered in relation to the freeways it connects with.

A review of the risk profile identifies that:

1. The **exposure** is rated medium because the bridge would be inundated only under the 16 inches + 100-year SWEL and 55 inches + 100-year SWEL SLR scenarios. However, under both scenarios, significant inundation could occur (2 and 5 feet) that could be exacerbated by wind wave effects.

2. The **sensitivity** of the asset is high because of the high level of use and very high liquefaction potential (although the new span under construction is being built to current seismic standards). Given its high operations and maintenance (O&M) costs, opportunistic measures could be considered as part of scheduled maintenance and upgrades to the facility.

3. Some **adaptive capacity** is provided by the alternative routes of BART and ferries, but this is likely inadequate for the volume of commuters and for goods movement. Given its limited adaptive capacity, structural adaptation of either the asset or the region will be critical.

4. The **consequence** rating for this asset is high due to its high level of use and importance to the region, limiting options for temporary or partial closure during inundation under the midcentury scenario.

5. The bridge touchdown and toll plaza are protected by Shoreline System 2, which is a combination of engineered shoreline protection and natural shoreline (wetlands). The overtopping potential at midcentury and at the end of the century is quite high: 10,510 feet of shoreline would be overtopped by midcentury at an average depth of 1.7 feet, and at the end of the century, more than 16,900 feet would be overtopped at an average depth of 3.9 feet for the 16 inches + 100-year SWEL and 55 inches + 100-year SWEL SLR scenarios, respectively. Asset-specific adaptation could, therefore, still have significant impacts on the region surrounding the asset.

Other transportation assets that are affected by overtopping of Shoreline System 2 include other parts of Interstate 80 (I-80), West Grand Avenue, Mandela Parkway, Burma Road, 7th Street Highway and Railroad Pumps (55 inches), and Union Pacific Martinez subdivision.

Table 7.2 provides an overview of potential adaptation measures for the San Francisco-Oakland Bay Bridge. These measures are described in more detail in the paragraphs below.

ASSET-SPECIFIC ADAPTATION

Near-term and midterm asset-specific adaptation for the Bay Bridge touchdown and toll plaza seems to be a viable option, as limited inundation will occur under the midcentury scenario. Minor modifications to the asset can be made in an opportunistic manner during scheduled maintenance to mitigate for future inundation to improve resilience to flooding. The following adaptation measures are considered for this location:

- **Improve drainage**—The drainage system around the freeway and the toll plaza could be improved so that when inundation occurs, there might be only partial closure of the roadway and, after a storm/high tide event, water would drain off the road surface quickly enough to minimize disruption. This measure can be considered “low regret” adaptation.

	Midcentury	End-of-Century
Asset-specific adaptation	- Improve drainage - Retrofit—make waterproof - Raise touchdown and toll plaza area - Partial closure	- Raise road surface - Build causeway
Regional adaptation (along Shoreline System 2)	- Create berm - Wetland restoration/ creation - Construct floodwall	- Build levee - Build floodwall - Wetland restoration/ creation
Nonstructural adaptation	- Develop new building and design codes - Revise transportation planning guidance and policy - Form multi-jurisdictional partnerships	- Continue implementation and revision of nonstructural adaptation measures as needed

TABLE 7.2 Criteria for Helping Selection of Adaptation Measures

- **Retrofit**—To minimize the consequences of temporary inundation for the physical infrastructure of the asset, retrofitting can be considered. For the toll plaza, this would require that water-sensitive elements (such as wiring and electronics) be placed above a certain flood elevation. Entrances to buildings, buildings themselves, and toll booths can be made flood resilient through water proofing so that they can withstand temporary inundation. This measure would assume periodic partial or temporary closure of the freeway. (The level of service required would determine whether this adaptation response is considered adequate.)
- **Raise road surface**—As part of regularly scheduled maintenance for the midcentury planning horizon, raising the road in areas identified as vulnerable to inundation could be considered.
- **Conduct partial or temporary closure**—A nonstructural/management option during extreme events could be to close part or all parts of the freeway. (The level of service required would determine whether this adaptation response is considered adequate.) It is unlikely that recurring closure would be acceptable.

For the end-of-century scenario, minor modifications to the bridge touchdown and toll plaza would not likely be adequate to address the projected inundation. Given the potential consequences of this impact, the following more drastic adaptation measures can be considered:

- **Raise road surface**—Rather than raising the road during regularly scheduled maintenance, a more proactive approach could address greater inundation levels. The entire freeway could be elevated above the end-of-century 100-year storm level. Although this is described as an asset-specific measure, it might also provide benefits to the region because the raised road could serve as a levee protecting West Oakland.
- **Build causeway**—The freeway leading up to the Bay Bridge could be transformed into a causeway bridging the low-lying areas, similar to the Hayward–San Mateo Bridge that spans part of the bay. It would be very expensive, however, to accommodate a toll plaza on a causeway.

REGIONAL ADAPTATION

For the midcentury scenario, with only minor modifications to the landscape, most of the bridge touchdown, the toll plaza, and I-80 leading up to the bridge could be protected from inundation, which would also protect a wider area. Note that these adaptation measures would become part of a flood control system that might extend beyond the immediate area to create a closed flood protection system:

- **Create berm**—Along the perimeter of the freeway and the off- and on-ramps, a berm could be constructed to keep rising tides back. With this measure, the drainage system of the freeway and toll plaza would need to be altered, and pumps might be needed to pump out stormwater. This berm could be constructed such that it allows for modifications in the future to withstand greater SLR.
- **Support wetland growth**—Wetlands are able to absorb wave action and can reduce flood elevations at the asset. Wetlands are located along the north side of the toll plaza and I-80. If wetlands are able to grow organically with SLR (through sediment deposition, for example) they provide a natural and attractive form of flood protection. Note that fringing wetlands can reduce the flooding only associated with waves. High tide and storm stillwater levels would still inundate the shoreline unimpeded. A recent study by PRBO Conservation Science (PLoS 2011), however, indicates that it is unlikely that Bay Area marshes will be able to keep pace with anticipated SLR at the end of the century.
- **Construct floodwall**—A small floodwall could be constructed along the perimeter of the freeway to prevent flooding and wave overtopping at the asset. A floodwall would impair the existing drainage system, which would therefore have to be modified as well (e.g., installation of pumps).

Regional adaptation at the end of the century would require greater interventions to deal with the potential inundation scenarios. Without major interventions, it is unlikely that wetlands would be able to address a 55-inch SLR scenario and would reduce the impacts of flooding associated only with waves.

- **Construct levees**—A berm built at midcentury could be reconstructed as a levee. As discussed under asset-specific adaptation, an elevated freeway could also be built on top of a new levee, which would also serve a regional flood protection function.
- **Construct floodwall**—A flood wall built at midcentury could be strengthened and raised.
- **Support wetland growth/build wetlands**—As stated earlier wetlands are able to absorb wave action and can reduce flood elevations at the asset. It is unlikely that wetlands will accrete to the end of century level of SLR. Therefore, wetland growth could be supported by beneficial use of dredged material. However, to provide proper flood protection, this measure likely should be integrated with the construction of a levee or floodwall further inland.

Residential Development as Flood Protection Barrier

NONSTRUCTURAL ADAPTATION

As stated earlier, given the importance of this asset, temporary closure, rerouting traffic, using an alternative mode of transportation, or even abandoning the asset are not considered viable options for non-structural adaptation measures. Measures specific to this asset include:

- **Changes to building codes and design guidance**—As new designs and plans are made for construction, retrofitting, or maintenance, they should include guidance on how to adapt to SLR. This guidance can help enable the implementation of structural measures, such as improving drainage, raising the road surface, or making structures around the touchdown and toll plaza more resilient to flooding.
- **Modification of policies and planning guidelines**—For proactive planning and to facilitate adaptation to rising sea levels, existing policies for SLR and flood management for this asset should be reviewed and revised.
- **Multi-Jurisdictional Partnerships**—Since areas inland of the San Francisco-Oakland Bay Bridge peninsula are vulnerable to flooding that originates at the shoreline of this facility, exploring partnerships with the Port of Oakland, City of Oakland, and City of Emeryville may facilitate cost-sharing or implementation of structural solutions needed to address vulnerabilities and risks identified in the risk profile. The Bay Bridge Peninsula is currently the subject of a collaborative planning effort being conducted by Caltrans, the Bay Area Toll Authority, the Port of Oakland, City of Oakland, BCDC, the East Bay Regional Park District and East Bay Municipal Utility District to facilitate redevelopment of the peninsula for a mix of uses. This partnership could expand its focus to address adaptation solutions in conjunction with other planning initiatives.

7.4.2 NONSTRUCTURAL REGIONAL ADAPTATION MEASURES

An integrated regional adaptation strategy should also involve nonstructural measures. Some of the regional nonstructural measures relevant for both the example assets that could be considered by transportation and planning agencies in developing SLR adaptation plans include:

- **Stakeholder and community awareness and input**—To gain critical public understanding of, and support for, implementation of climate change adaptation plans, public education and outreach could be conducted. Stakeholder input is also essential to help identify and shape the most appropriate adaptation measures for a given asset and location, particularly if the measure may have regional impacts.
- **Increased technical knowledge and capacity**—To allow agencies to better understand the impacts of climate change and the different options for adaptation, further research and education is needed. Building up the level of knowledge and technical capacity through research and education would allow for development of new climate change adaptation plans and smoother implementation.
- **Planning and policy making**—Many existing government policies do not yet take SLR into account and need to do so. This applies to planning policy and guidance documents, building codes, design standards, and zoning requirements, for example.
- **Funding**—Funding is needed to conduct further vulnerability assessments and adaptation planning analyses and implement climate change adaptation plans for both example assets. Adapting to rising tides will inevitably bring additional costs to their capital improvement projects. Funding can be sought through traditional mechanisms, but also new funding methods could be considered, such as through public private partnerships and new or other user fees. Planning proactively for SLR now should avoid major unexpected costs in the future. In addition, being prepared for the risk of climate change should attract new investments and make the Bay Area more competitive compared to other regions around the world.
- **New and innovative partnerships**—To research, fund, and implement climate change adaptation planning, new partnerships should be fostered to explore and establish cooperation among research institutions, governments, nonprofit organizations, and business entities to prepare for climate change.

7.5 NEXT STEPS IN ADAPTATION PLANNING

This chapter provides preliminary suggestions for potential climate change adaptation measures for the Alameda County subregion, but this is only the first step in developing an adaptation plan. The wealth of information that has been generated in this pilot project can be more thoroughly analyzed for all the selected representative assets to inform further decision making on adaptation measures. Stakeholder consultation will be a vital part of this process. The Adapting to Rising Tides program will take the outputs from this study to inform the 2012 and 2013 adaptation planning efforts for all sectors within the subregion. As it specifically relates to transportation planning, the following potential projects are recommended:

- Prepare further vulnerability and risk assessments of some of the transportation assets that could not be included in this study because of time and budget constraints, using the methodology developed as part of the pilot project and drawing on the new inundation mapping. In addition, a more in-depth analysis of the inundation mapping and shoreline overtopping information for specific transportation assets could be carried out to better understand the potential impacts under different storm scenarios and to inform the selection of adaptation measures.
- Conduct a more detailed alternatives analysis and feasibility study of different climate change adaptation measures at selected locations, reviewing all the criteria (relative to economy, ecology, equity, and governance) outlined in Table 7.1 This study could be accompanied by visualizations of adaptation measures under different SLR scenarios. These results can then be discussed with stakeholders to identify the most appropriate and cost-effective solutions.
- Conduct traffic flow and economic impact analyses to understand the primary and secondary effects of reduced mobility in the Bay Area attributable to SLR inundation of transportation assets.
- Ensure that all assets due for upgrade, repair, or retrofit in the near future are reviewed for adaptation opportunities, particularly in terms of new materials, drainage, and waterproofing improvements.
- Develop a SLR or climate change preparedness plan for the Metropolitan Transportation Commission that serves as a guidance document for local and other regional transportation agencies on how they can incorporate SLR into their own transportation planning.

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