Chapter 1. Introduction to the ART Vulnerability and Risk Assessment

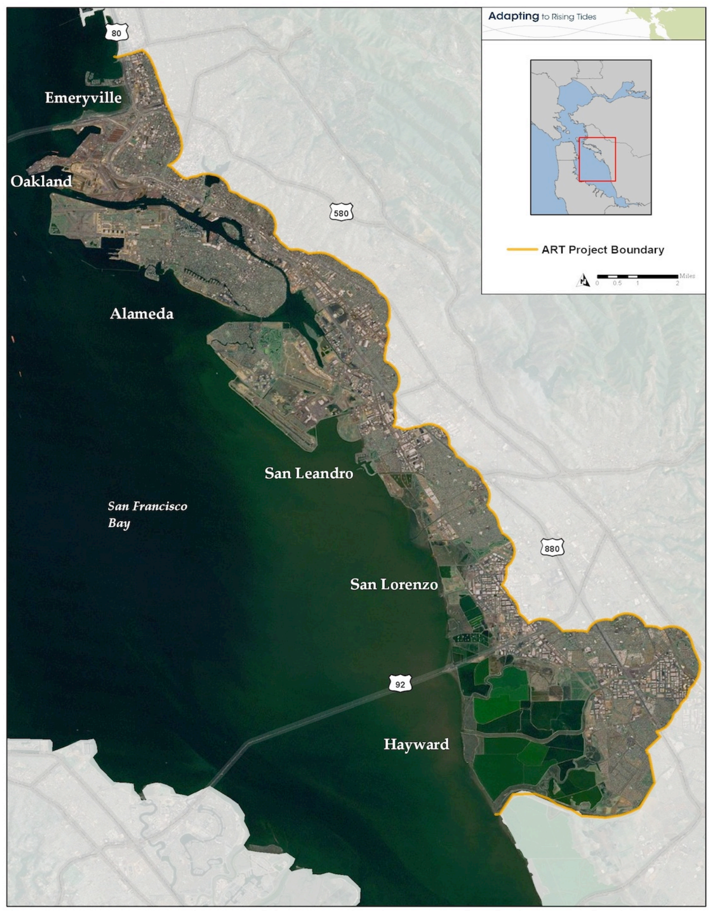
The Adapting to Rising Tides (ART) project is a collaborative effort to evaluate how the San Francisco Bay Area can become more resilient to climate change, in particular sea level rise and storm events. This project will ultimately provide guidance on two broad questions:

> *How will climate change impacts of sea level rise and storm events affect the future of Bay Area communities, infrastructure, ecosystems and economy?*
>
> *What strategies can we pursue, both locally and regionally, to reduce and manage these risks?*

The goal of the ART project is to increase the Bay Area's preparedness and resilience to sea level rise and storm events while protecting critical ecosystem and community services.

The project study area is a portion of the Alameda County shoreline, from Emeryville to Union City, and inland areas potentially exposed to mid- and end-of-century sea level rise and storm event impacts (Figure 1). This area was selected based on local community and stakeholder interest and capacity for participation, its diverse shoreline features, and presence of regionally significant transportation infrastructure.

Figure 1. The ART project area is located in Alameda County on the eastern shoreline of San Francisco Bay.



The ART is evaluating twelve asset categories[1], including:

- Airport
- Community land use, services & facilities
- Contaminated lands
- Energy infrastructure & pipelines
- Ground transportation
- Hazardous materials
- Natural areas
- Parks & recreation areas
- Seaport
- Structural shorelines
- Stormwater
- Wastewater

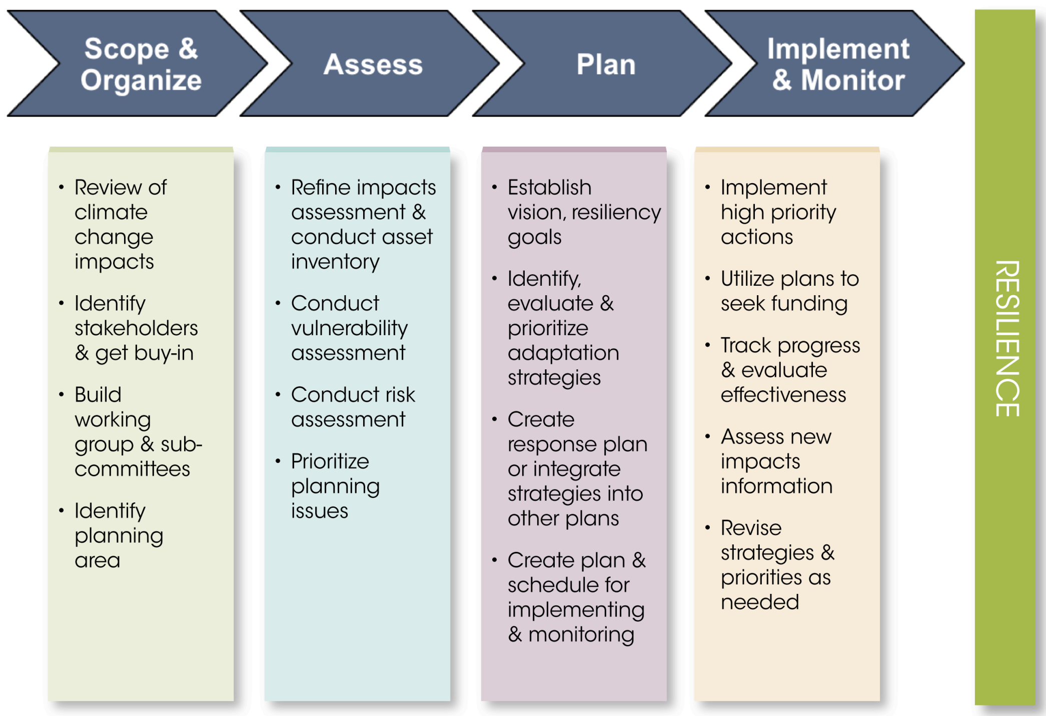
This report presents the methods, data and findings of a vulnerability and risk assessment conducted for assets in each of these twelve categories.

[1] A detailed description of each asset category is provided in the Existing Conditions and Stressors Report available along with other ART project resources at www.adaptingtorisingtides.org.

Purpose of the Assessment

The purpose of the assessment is to identify the underlying causes and components of vulnerability and risk of shoreline and community assets in the ART project area to sea level rise and storm events. Conducting a vulnerability and risk assessment is a key part of the Assess step in the project's planning process (see Figure 2). The assessment provides a foundation for the remaining two project steps in which appropriate adaptation response and implementation strategies will be considered.

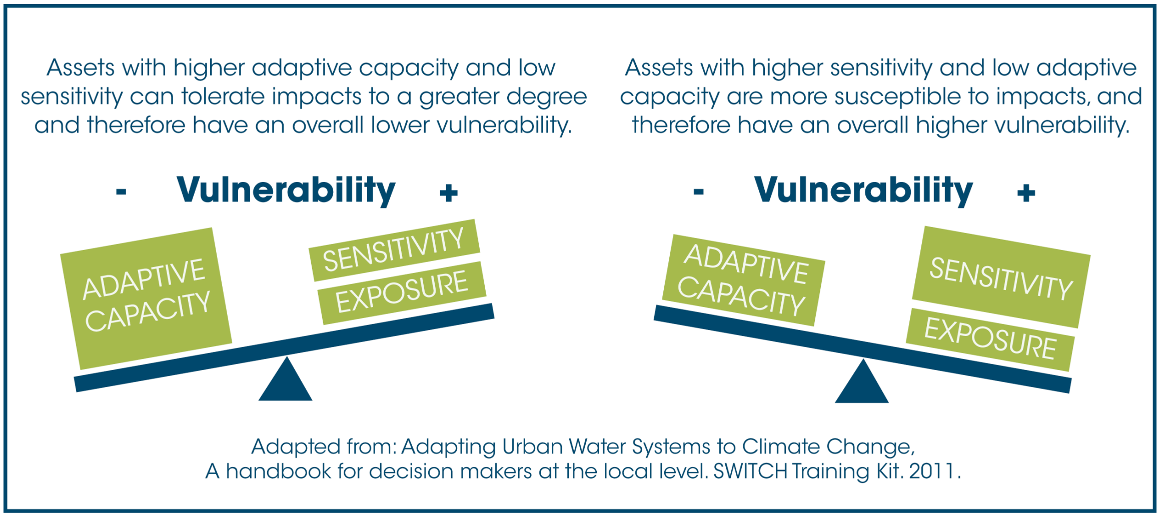
Figure 2. The ART adaptation planning process is based on a model developed by ICLEI Local Governments for Sustainability.



Key Concepts of Vulnerability and Risk

Vulnerability is the degree to which assets – services, facilities and systems – are susceptible to or unable to accommodate adverse impacts of climate change, and is defined by three primary factors: exposure, sensitivity and adaptive capacity (ICLEI 2009). In the ART project, which is focused on the climate impacts of sea level rise and storm events, **exposure** is defined as whether and to what degree a geographic area will be inundated. **Sensitivity** is the degree to which an asset is impaired by a climate impact. **Adaptive capacity** is the ability of an asset to accommodate or adjust to an impact to maintain its primary function. In general, assets with high sensitivity and low adaptive capacity are more susceptible to impacts and therefore have a higher overall vulnerability. Alternatively, assets with high adaptive capacity and low sensitivity can tolerate impacts to a greater degree, and therefore have a lower overall vulnerability (Figure 3).

Figure 3. Vulnerability is in general determined by the relationship among three components: exposure, sensitivity and adaptive capacity.



Risk is the threat posed by an adverse climate impact and is a function of two components: the magnitude of the consequences should an impact occur and the likelihood of impact occurring. Consequence was evaluated through four key assessment frames: economy, environment, governance, and society and equity. For example, there may be significant consequences to the economy if energy distribution infrastructure is disrupted, however depending on the location of the asset there may not be direct consequences on the environment. Alternatively, if a wastewater treatment plant impaired there could be consequences on the economy and the environment, as well as on society and equity and potentially governance.

To evaluate vulnerability and risk the ART project assessed both the potential for adverse effects on each asset's physical condition as well as its function. In addition, the evaluation considered individual assets as well as systems of assets within the larger shoreline community. Evaluation of both physical condition and function will enable a broader discussion of vulnerability and risk across the asset categories that is necessary to inform the development of integrated, cross-sectoral and cross-jurisdictional adaptation response strategies. It is also necessary to ensure that assets can continue to serve their current role or roles. For example, while the Port of Oakland's seaport may not be directly affected by sea level rise in the near term, the rail and roadways it relies on will be affected, which in turn will have a significant effect on goods movement, which will affect seaport operations.

Assessment Approach

The ART assessment provided an opportunity to develop, test and refine approaches and methods that could be used by others to plan for climate change adaptation. In developing the approach used in this assessment, ART project staff reviewed over 25 journal articles, regional frameworks and community-driven assessments. These assessments were evaluated for their transparency, replicability and clarity of adaptation outcomes. Based on the results of this review, and with input from working group members, both quantitative and qualitative approach was developed to evaluate the vulnerability and risk of assets in all categories. ART project staff conducted a data-driven desktop analysis and elicited best professional judgment through a survey, individual interviews, and input from working group members and other topical experts.

The qualitative and quantitative approaches of the assessment both addressed a number of guiding vulnerability and risk questions that were broad enough to be relevant to all of the asset categories, yet specific enough to inform the future consideration of adaptation strategies.

> **Laying the Groundwork**
>
> The ART assessment served as an opportunity to develop, test and refine adaptation planning methods and approaches that can be used by others. A number of aspects of the assessment methods and approach were explored:
>
> *Identifying overarching key questions that can inform the physical and functional vulnerability of a variety of asset types.*
>
> *Integrating four, overarching frames – economy, environment, governance, and society and equity – into the evaluation of vulnerability and risk for all assets.*
>
> *Standardizing the analysis of vulnerability and risk across diverse asset types.*
>
> *Supplementing desktop analyses conducted by project staff and partners with expert input (best professional judgment) from local asset managers.*

Guiding vulnerability questions:

- If exposed to a climate impact, would the asset be physically impaired?
- If exposed to a climate impact, would the asset be functionally impaired?
- If compromised would the asset maintain function?
- If disrupted or disabled, could the asset be restored to function quickly, easily, or in a low-cost manner?
- Is there the ability to improve the asset's capacity to cope with a climate impact quickly, easily, or in a low-cost manner?

Guiding risk question:

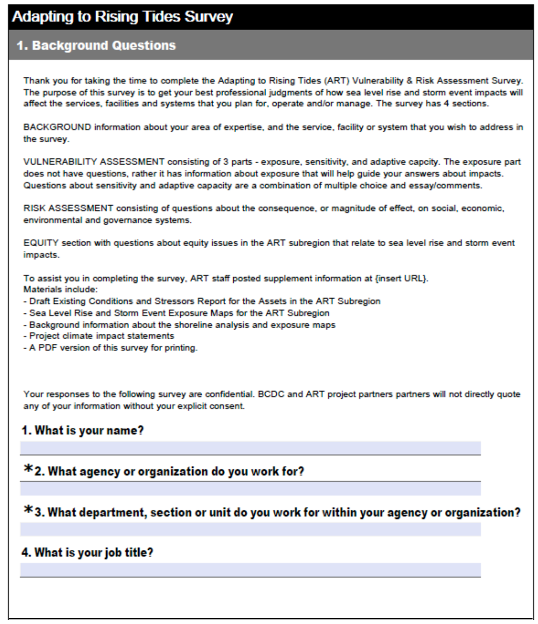
- If exposed to a climate impact, what is the expected magnitude of consequences on the economy, environment, governance, society and equity?

<u>Quantitative Data-driven Desktop Analysis</u>
Project staff, with assistance and input from working group members, project partners and consultants, conducted analyses informed by the Existing Conditions and Stressors Report completed by project staff Fall 2011, asset-specific metrics (characteristics and conditions), a

shoreline study, a socio-economic evaluation, a parks and recreation area economic analysis, and a GIS-based exposure analysis[2].

In addition, two white papers were developed in support of the ART project assessment. The first, ***Addressing Social Vulnerability and Equity in Climate Change Adaptation Planning***[3], addresses issues of social vulnerability and equity to provide a more accurate picture of the consequences of sea level rise and storm impacts, and to facilitate the development of equitable adaptation strategies. The second, ***Addressing the Role of Institutions in Climate Change Adaptation,*** examines the implications of planning for climate change on governance and institutions not only in the ART project area but also for the larger Bay Area region.

Figure 4. The ART Survey was completed by over 50 asset managers and topical experts.



Adapting to Rising Tides Survey

1. Background Questions

Thank you for taking the time to complete the Adapting to Rising Tides (ART) Vulnerability & Risk Assessment Survey. The purpose of this survey is to get your best professional judgments of how sea level rise and storm event impacts will affect the services, facilities and systems that you plan for, operate and/or manage. The survey has 4 sections.

BACKGROUND information about your area of expertise, and the service, facility or system that you wish to address in the survey.

VULNERABILITY ASSESSMENT consisting of 3 parts - exposure, sensitivity, and adaptive capcity. The exposure part does not have questions, rather it has information about exposure that will help guide your answers about impacts. Questions about sensitivity and adaptive capacity are a combination of multiple choice and essay/comments.

RISK ASSESSMENT consisting of questions about the consequence, or magnitude of effect, on social, economic, environmental and governance systems.

EQUITY section with questions about equity issues in the ART subregion that relate to sea level rise and storm event impacts.

To assist you in completing the survey, ART staff posted supplement information at {insert URL}.
Materials include:
- Draft Existing Conditions and Stressors Report for the Assets in the ART Subregion
- Sea Level Rise and Storm Event Exposure Maps for the ART Subregion
- Background information about the shoreline analysis and exposure maps
- Project climate impact statements
- A PDF version of this survey for printing.

Your responses to the following survey are confidential. BCDC and ART project partners partners will not directly quote any of your information without your explicit consent.

1. What is your name?

***2. What agency or organization do you work for?**

***3. What department, section or unit do you work for within your agency or organization?**

4. What is your job title?

Qualitative Vulnerability and Risk Survey

To solicit best professional judgment on vulnerability and risk, a survey was developed and administered to the working group and other topical experts (Figure 4). The survey was based on a similar effort led by ICLEI Local Governments for Sustainability[4] that assessed San Diego Bay. The survey consisted of questions about the sensitivity and adaptive capacity of the particular assets operated, managed or owned by the respondent. The survey also asked for input on the potential consequences to the asset, or to the larger system or community that relies on the asset, if impacts were to occur. Lastly, the survey included a section focused on the potential for equity issues, such as disproportionate burden on vulnerable populations if an impact were to occur (see Appendix A).

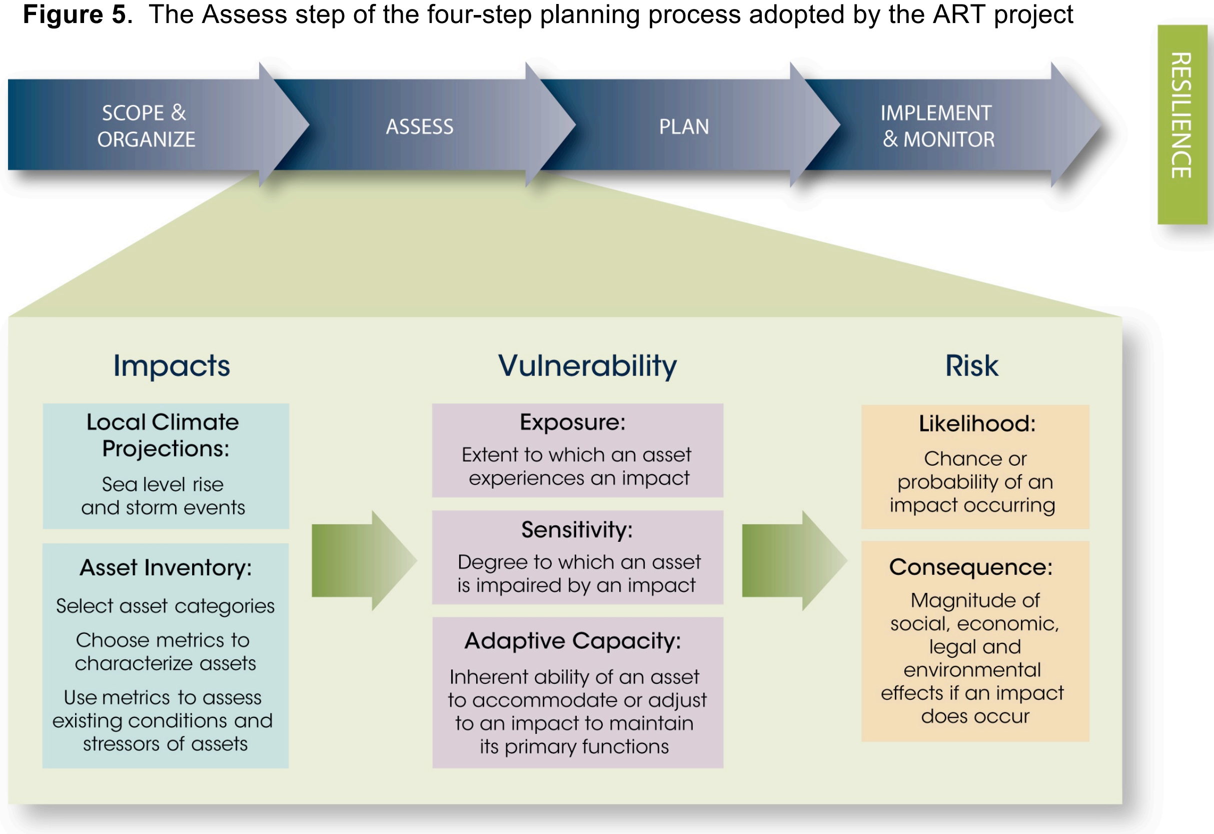
Survey respondents were provided with background information including the project's climate impact statements, Existing Conditions and Stressors Report, and the sea level rise and storm event inundation maps to assist them in answering the questions. Survey respondents were asked to draw on their knowledge of the geographic area, the asset, and any past experience with flooding or storms in considering vulnerability and risk.

Specific Components of the Vulnerability and Risk Assessment

There are three elements of the "Assess" step of the adaptation planning process (Figure 5). The first element - Impacts - included selecting local climate projections and impacts, and identifying and describing shoreline and community assets to be evaluated. The impacts assessment completed by project staff and working group members is summarized in the project's Climate Impact Statements and Existing Conditions and Stressors Report[5].

[2] Detailed technical information on these analyses is provided in the appendices to this report.
[3] http://www.adaptingtorisingtides.org/equity/
[4] ICLEI SD Bay survey reference
[5] Available at www.adaptingtorisingtides.org

Figure 5. The Assess step of the four-step planning process adopted by the ART project



The remaining two elements of the Assess step, vulnerability and risk, are the subject of this report. The individual components of vulnerability and risk, and how the ART project both defined and evaluated them, are described in detail below.

<u>Exposure</u>

Exposure is the extent to which an asset experiences a specific climate impact. Five impacts associated with sea level rise and storm events are defined in the scope of the ART vulnerability and risk assessment:

- More frequent extreme high sea level events cause more frequent flooding in areas that are already flood-prone
- With longer duration extreme high sea level events, flooding lasts longer
- Higher high tides, shifts in tidal range, and increases in depth and duration of tidal inundation cause frequent or permanent inundation of areas that are not currently in the daily tidal range
- Higher Bay water level causes changes in wave activity in the Bay leading to increased shoreline erosion and waves over-topping shoreline protection
- Higher Bay water level leads to elevated groundwater levels and salinity

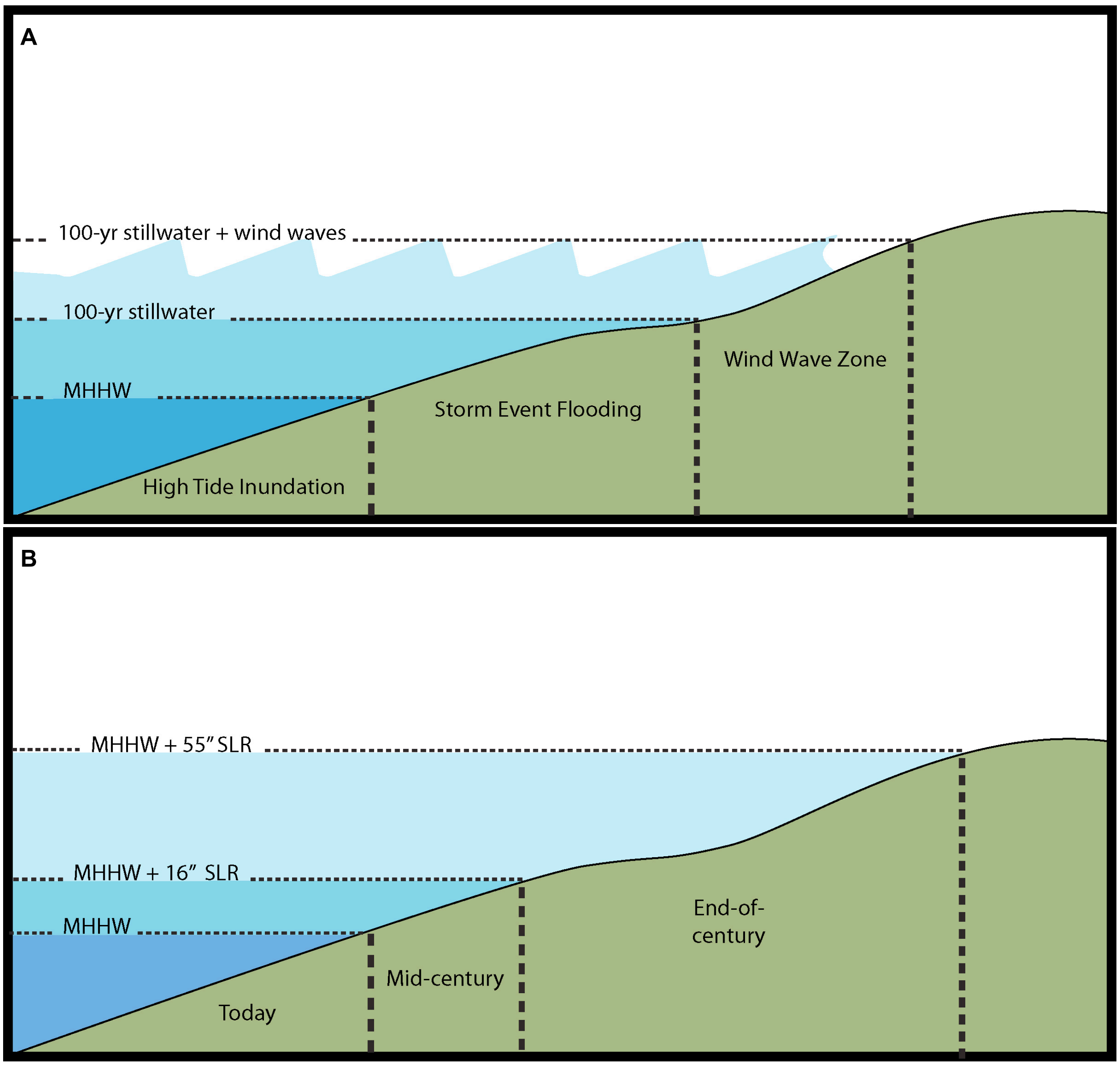
Refined sea level rise maps were developed for six future climate scenarios (AECOM 2011 and Chapter 2) in order to evaluate exposure to four of the five climate impacts[6]. The six scenarios are based on two sea level rise projections and three Bay water levels (Figure 6). The two sea level rise projections, 16 inches (40 cm) and 55 inches (140 cm), correlate approximately to mid- and end-of-century timeframes. These projections are consistent with the October 2010 State of

[6] Changes in groundwater levels due to sea level rise were not evaluated.

California Sea Level Rise Interim Guidance[7] and are within the range of projections recently reported by a National Academy of Science study of sea level rise on the west coast (NRC 2012). The NRC study found that the potential range of projected sea level rise values is fairly wide. For the Bay Area, the range of values is 4.7 to 24 inches (12 to 61 cm) at mid-century and 16.5 to 65.7 inches (42-167 cm) at end-of-century.

The Bay water levels selected correspond to three tide and storm conditions: the highest average daily high tide represented by mean higher high water (MHHW), hereafter "high tide" or "daily high tide"; the 100-year extreme water level, also known as the 100-year stillwater elevation (100-year SWEL), hereafter "100-year storm" or "storm event"; and the 100-year extreme water level coupled with wind-driven waves, hereafter "storm event with wind waves", or "wind waves."

Figure 6. Conceptual diagram of the three Bay water levels evaluated in the ART project (A) and the increase in the extent and depth of high tide inundation from 16 inches of sea level rise (B).



[7] CO-CAT 2010

The daily high tide was selected to inform which shoreline areas not currently exposed to tidal action could be exposed to the high tide with sea level rise. This scenario is important because exposure to the daily high tide would result in frequent or permanent inundation, potentially leading to the slow yet chronic degradation of an asset's physical condition or function.

In contrast, shoreline areas exposed to a 100-year storm event with sea level rise could be subjected to infrequent and temporary, but potentially severe, inundation. Extreme storms can cause overtopping and erosion of shoreline protection assets, exposing large inland areas to fairly deep flood depths and high velocity flows. Wind waves can elevate water levels significantly above stillwater levels, potentially increasing the severity of flooding. It is critical, therefore, to consider the effect wind driven waves could have on inland inundation during a coastal storm event.

During a storm event with wind waves the inland extent of flooding could be greater (than the area exposed to storm event inundation), and the depth of flooding in areas already exposed could be deeper. Because waves both propagate and dissipate as they move over land, it was not possible to estimate the additional depth of inundation due to wind waves in areas already exposed to storm event flooding, nor was it possible to determine the depth of inundation in areas exposed to wind waves only. Therefore, the storm event with wind wave scenario results were interpreted as (1) all assets exposed to storm event flooding could also be exposed to potentially deeper inundation due to wind waves, and (2) assets exposed to wind waves only could potentially be inundated with shallow depths for short durations.

While these water levels were selected because they represent a reasonable range of Bay conditions that will affect flooding and inundation along the shoreline, other tide/storm scenarios could also be informative. For example, the "King Tide" is an extreme high tide, higher than MHHW, which occurs annually when the sun and moon's gravitational forces reinforce each other[8], while a 10 or 25-year return period storm occurs more frequently, and is less sever then, a 100-year storm. The tide and storm condition used in an exposure analysis should be selected during the "Scope and Organize" phase of an adaptation planning project, and will depend on the type of shoreline assets under investigation, and the type of scenarios that are most useful to developing adaptation strategies.

Coastal Storm Events

Source: Mark Taylor, EBRPD

In California, coastal storms generally occur in the winter. Low air pressure during a storm increases wind activity, which in turn generates wind-driven waves (Bromirski and Flick 2008). The strength and frequency of coastal storms is influenced by climate patterns such as the El Niño Southern Oscillation, which generally results in persistent low air pressure, high winds, and increased rainfall (Cayan et al. 2008).

Storm activity is not projected to intensify or appreciably change this century, making sea level rise the dominant factor controlling increased shoreline flooding and erosion. Rising sea levels will not only increase tide levels, causing flooding of inland areas, but will allow erosive wave energy to reach farther inland.

With sea level rise, by the end of the century flooding caused by today's 100-year storm event is projected to occur annually along the California coast (Bromirski et al. 2012).

[8] For information about King Tides visit californiakingtides.org/

Sensitivity
Sensitivity is the degree to which an asset is impaired by a climate impact. Metrics used to guide the analysis of sensitivity for both built and natural assets include:

- Type of land use or service provided, e.g., residential land uses, facilities that are critical for emergency response, or provide key community services to at-risk or vulnerable, less mobile populations
- Susceptibility of structures due to design or function, e.g., foundation type, flood-proofing, below-ground entrances or uses
- Historic effects of flooding, e.g., loss of function, disruption or delay of service
- Current depth to groundwater
- Seismic susceptibility due to increased liquefaction potential
- Presence of contaminated soil or groundwater
- Elevation relative to current Bay water level, e.g., low, mid, or high marsh habitat
- Capacity to keep up with sea level rise, e.g., vertical accretion and subsidence rates
- Capacity for horizontal (inland) migration, lateral accommodation space available
- Species value - biodiversity, unique, sensitive, state or federally listed species
- Habitat value - wildlife corridor, high tide refugia, part of landscape mosaic

Adaptive Capacity
Adaptive Capacity is the ability of an asset to accommodate or adjust to an impact and thus to maintain its primary functions. Metrics used to guide the analysis of adaptive capacity for both built and natural assets include:

- Potential for partially compromised asset to maintain key functions and continue to provide necessary community services
- Asset redundancy, e.g., alternative comparable asset available
- Capacity of the system to function without an asset or if an asset is compromised
- Ability to restore asset function quickly, easily, or in a low-cost manner if compromised
- Disaster or emergency response resources, e.g., onsite staff, backup power, equipment for cleanup, temporary flood protection, pumps, "friends of" organizations or volunteers
- Operation and maintenance costs
- Capital improvement costs
- Potential for reengineering or redesign
- Status of existing plans, e.g., emergency or disaster response plan, master plans, etc
- Complexity of regulations governing operations, maintenance or capital improvements
- Complexity of decision-making regarding operations, maintenance or capital improvement planning and implementation

Consequences
The expected magnitude of the economic, environmental, governance, societal and equity consequences if an impact were to occur was evaluated in a qualitative manner for all assets. The consequences of an impact on the primary function of an asset and on the system of assets (if one exists) were considered in evaluating magnitude. For example, the loss of an essential sewage pumping station could be significant not only to the managing agency or organization, but to the greater community or system as well. The magnitude and type of consequences are important when identifying and prioritizing adaptation response strategies.

A number of general considerations were developed to guide the assessment of consequences including:

- The potential scale of impact, e.g., the population size, land area, and resources that would be affected.
- The potential severity of impact, e.g., total physical loss or complete disruption of function versus frequent minor damage that could be repaired.
- Cumulative costs/harm due to frequent but relatively minor events
- Cumulative costs/harm due to infrequent but extreme events

Specific considerations were developed to help frame the approach to each of the guiding risk questions.

Guiding Risk Questions	Specific considerations
What is the expected magnitude of consequences on the economy?	• Is there a disruption to the goods movement network? • Is there a disruption to job / employment centers? • What are the costs associated with repair, replacement and reopening of the asset?
What is the expected magnitude of consequences on the environment?	• Will there be an impact or disruption to ecosystem services such as flood protection? • Will populations of threatened or endangered species be impaired? • Does the asset serve as an important ecological corridor or serve as an important link in a large habitat network
What is the expected magnitude of consequences on governance?	• Will there be an impact on land use, facility, or public planning processes? • Will the impact require inter-agency coordination beyond existing agreements (if they exist)? Will the impact make existing agreements inadequate or inappropriate? • Will the impact result in an unclear legal or regulatory situation (e.g., unclear legal responsibilities, authorities, or compliance/enforcement dilemmas)?
What is the expected magnitude of consequences on society and equity?	• Is there a potential for public health and safety related impacts? • Is there a loss of recreational opportunities/shoreline access? • Does the asset serve an underserved community? • Does the asset serve individuals/communities with limited mobility such as elderly, disabled or transit dependent populations?

In addition to the qualitative assessment of consequences conducted for all of the asset categories, a quantitative assessment of the potential economic consequences to park and recreation areas was evaluated using a benefits transfer model with assistance from the Eastern Research Group (ERG)[9].

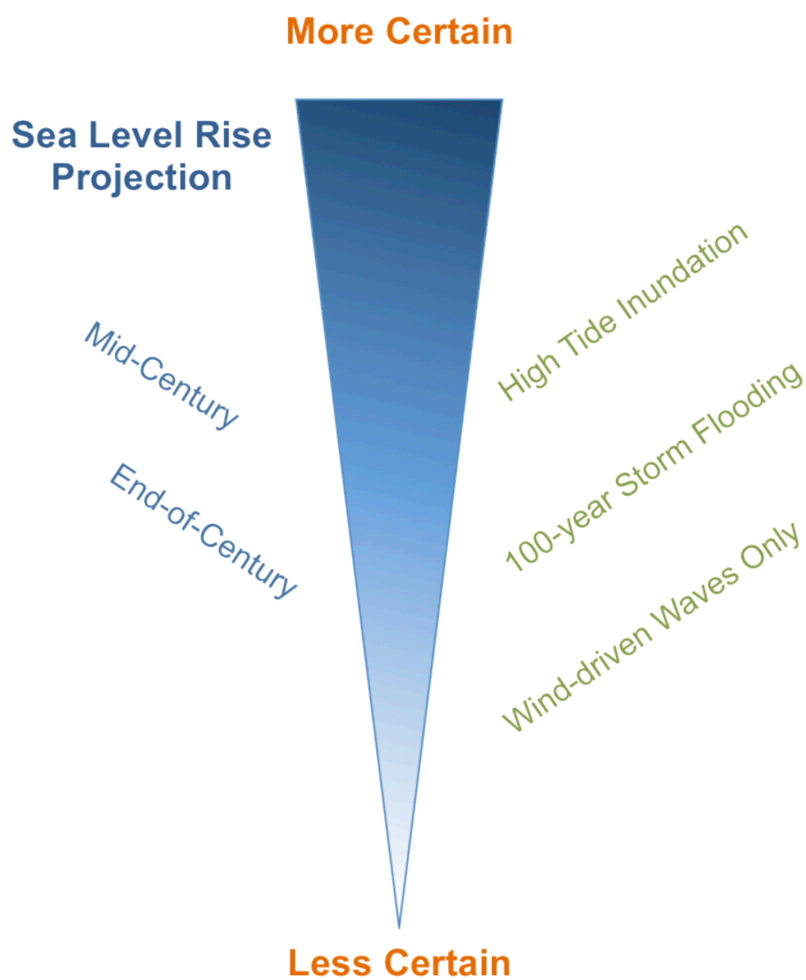
[9] *Economic Analysis of Recreational and Other Values of Parks in the Adapting to Rising Tides Project Area* prepared by the Eastern Research Group for the Adapting to Rising Tides project.

<u>Likelihood</u>

The likelihood of a climate impact is based on the certainty, or confidence, that the sea level rise projection and Bay water level evaluated will occur. Among the six future climate scenarios selected for the ART project, there is a greater certainty of the impacts occurring at mid-century (i.e. 16 inches of sea level rise by 2050) then at the end-of-century (i.e., 55 inches of sea level rise by 2100). There is also greater certainty that high tide inundation will occur then will flooding due to an extreme storm event (Figure 7). In addition, due to the dynamic nature of wind wave processes, there is less certainty in the potential impacts that could be caused by wind-driven waves during a storm event than for high tide or a storm event without wind wave impacts.

Likelihood can also be understood as the potential that an asset will be exposed if the climate impact does occur. For the ART project, this component of likelihood was informed by an analysis of shoreline overtopping potential. This analysis is a high-level screening tool that helps identify areas of the shoreline that are not of adequate height to prevent inland inundation if the future climate scenarios occur. This analysis, described in Chapter 2, was conducted for the ART project area in general as well as for specific representative shoreline areas (see Chapter 6, Structural Shorelines).

Figure 7. There is more certainty, and therefore a greater likelihood, in the mid-century climate change predictions then in the end-of-century predictions, and for Bay water level conditions that are more frequent such as high tide verses an extreme storm event tide.



Organization of the ART Vulnerability and Risk Assessment Report

This report presents the data, methods, and results of the vulnerability and risk assessment conducted for shoreline and community assets in the ART project area. Project staff and working group members will use the findings of this assessment to consider adaptation response strategies and implementation options.

In *Chapter 2. Sea Level Rise Mapping and Shoreline Potential Overtopping Analysis* the evaluation of exposure is described, and the inundation maps and shoreline analysis results are presented. *Chapter 3. Cross-Cutting Issues* provides an overview of the vulnerability and risk assessment findings, and highlights the cross-sectoral, cross-jurisdictional issues that will be key in considering integrated and multi-beneficial adaptation response strategies.

Chapter 4. Vulnerability and Risk Classification sets the stage for the consideration of adaptation response strategies and implementation options. Vulnerabilities and risks identified in the assessment have been classified according to characteristics that will help project participants (1) prioritize management issues, (2) guide them towards evaluating adaptation strategies, and (3) highlight where better or new coordination is needed. This chapter describes the classification approach developed by the ART project and presents the results of this last step in the Assess part of the adaptation planning process.

The vulnerability and risk of individual assets or systems of assets are detailed in the following twelve asset category chapters. For each category a summary of the exposure, physical and functional sensitivity and adaptive capacity is provided. Additionally, the potential consequences of the climate impacts on the assets are discussed through the four assessment frames (economic, environmental, governance, society and equity). At the end of each chapter, key findings are provided that summarize the asset-specific vulnerabilities and risks.

References

Adapting to Rising Tides: Transportation Vulnerability and Risk Assessment Pilot Project. November 2011. Prepared by AECOM and Arcadis for the San Francisco Bay Conservation and Development Commission, Metropolitan Transportation Commission and the California Department of Transportation. Available at http://www.mtc.ca.gov/news/current_topics/10-11/sea_level_rise.htm.

Bromirski, P. D., D. R. Cayan, N. Graham, R. E. Flick, and M. Tyree (Scripps Institution of Oceanography). 2012. Coastal Flooding Potential Projections: 2000-2100. California Energy Commission. CEC-500-2012-011.

Bromirski, P.D. and R.E. Flick. 2008. Storm surge in the San Francisco Bay/Delta and nearby coastal locations. Shore & Beach. 76(3): 29-37.

Cayan, D.R., P.D. Bromirski, K. Hayhoe, M. Tyree, M.D. Dettinger, and R.E. Flick. 2008. Climate Change Projections of Sea Level Extremes Along the California Coast. Climatic Change. 87 Suppl 1): S57-S73. Doi: 10.1007/s10584-007

National Research Council. Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future. 2012. Prepared by the Committee on Sea Level Rise in California, Oregon, and Washington; Board on Earth Sciences and Resources; Ocean Studies Board; Division on Earth and Life Studies; National Research Council. Available from the National Academies Press at www.nap.edu/catalog.php?record_id=13389

Chapter 2. Sea Level Rise Mapping and Shoreline Potential Overtopping Analysis

To support the ART vulnerability and risk assessment a coastal engineering team conducted an analysis and developed maps to illustrate the potential extent and depth of inland inundation, and the potential location and depth of shoreline overtopping for the six future climate scenarios considered (AECOM 2011). The analysis and resulting maps are based on modeling of Bay hydrodynamics and shoreline topography. Models are simplifications of complex processes, and are therefore inherently limited in how well they can accurately represent real-world conditions (TNC and NOAA, 2011). Models can, however, provide a framework for understanding possible future conditions, and are therefore useful and necessary for decision-making undertaken in climate adaptation planning.

The analysis conducted for the ART project is based on model outputs that do not account for complex and dynamic Bay processes, future conditions such as erosion or subsidence, or the improvement or construction of shoreline protection. The resulting maps are therefore appropriate for higher-level planning studies such as the ART project, but are not intended to represent or replace detailed studies that may ultimately be necessary to address sea level rise at a local or site-specific scale.

> The ART sea level rise maps are a refinement of previous efforts completed for San Francisco Bay* because the analyses:
>
> - Used recently collected, high resolution topographic data
> - Considered wind waves
> - Determined the depth and extent of potential inundation
> - Identified hydraulically disconnected areas
>
> ** Maps based on data developed by the USGS at http://cal-adapt.org/sealevel/*

Sea Level Rise Inundation Mapping

Sea level rise inundation maps are generally constructed using a four-step process (NOAA CSC 2009). The four steps are:

Obtain and Prepare elevation data that will serve as the mapping base layer

Prepare Water Levels based on model outputs or a single value

Map Inundation using elevation data and water levels

Visualize Results using simple maps, online GIS, or interactive viewers

The data and methods used to complete each of these steps for the ART project are summarized below. See Appendix B for a detailed description of the analytical methods used.

<u>Obtain and Prepare Elevation Data</u>
Elevation data was obtained from the California Coastal Mapping Project[1], a state-federal-industry partnership. As a project partner, the U.S. Geological Survey (USGS) collected Light Detecting and Ranging (LIDAR) data for the southern portion of San Francisco Bay in 2010. This LIDAR data provided complete coverage of the ART project area up to the 16-foot (5-meter) elevation contour and had a vertical accuracy of +/- 2.8 inches (0.07 m), which exceeds USGS Guidelines and Base Specifications.

The bare-earth LIDAR[2] from the 2010 USGS collection was used to create a 2-meter horizontal grid resolution Digital Elevation Model (DEM) that served as the base layer for the ART project inundation mapping. The DEM was of sufficient resolution and detail to capture the shoreline

[1] www.opc.ca.gov/2012/03/coastal-mapping-lidar-data-available
[2] The bare-earth LIDAR had all building, structures and vegetation removed during processing

levees and flood protection assets in the project area with the exception of floodwalls, which are generally narrower than the DEM's 2-meter horizontal resolution.

Prepare Water Levels

Water level data was obtained from existing and readily available model outputs from two large-scale San Francisco Bay efforts: (1) TRIM2D modeling completed by the USGS for the Computational Assessments of Scenarios of Change for the Delta Ecosystem Project, (CASCaDE) and (2) MIKE21 modeling completed by DHI for the Federal Emergency Management Agency (FEMA) San Francisco Bay coastal hazard analysis and mapping.

The TRIM2D and MIKE21 modeled water levels provided two independent estimates of tide levels along the Alameda County shoreline. These two estimates are not directly comparable, however because the time periods of records used were different (a 100-year projection vs. a 30-year hindcast), and because only one of the models (MIKE21) accounted for wind effects. Development of water levels for the project's storm and wind wave scenarios took advantage of these differences by combining the results of the two modeling efforts. In particular, the MIKE21 model was used to account for wind setup, wave setup and wave height. Wind setup is a component of storm surge that results in an increase in water level due to wind blowing across the water surface and "piling up" water at the shoreline. Similarly, wave setup is an increase in water level at the shoreline due to the presence of breaking waves. These two processes will increase water levels at the shoreline above the extreme tide level.

Current water levels for mean higher high water (daily high tide), 100-year extreme water level (100-year storm), and 100-year extreme water level with wind-driven waves (100-year storm with wind waves) were determined for specific model output points within the project area. These water levels were then projected to future conditions by adding either 16 or 55 inches of sea level rise. The resulting water levels were then interpolated and extrapolated to create water surface maps for each of the six future climate scenarios.

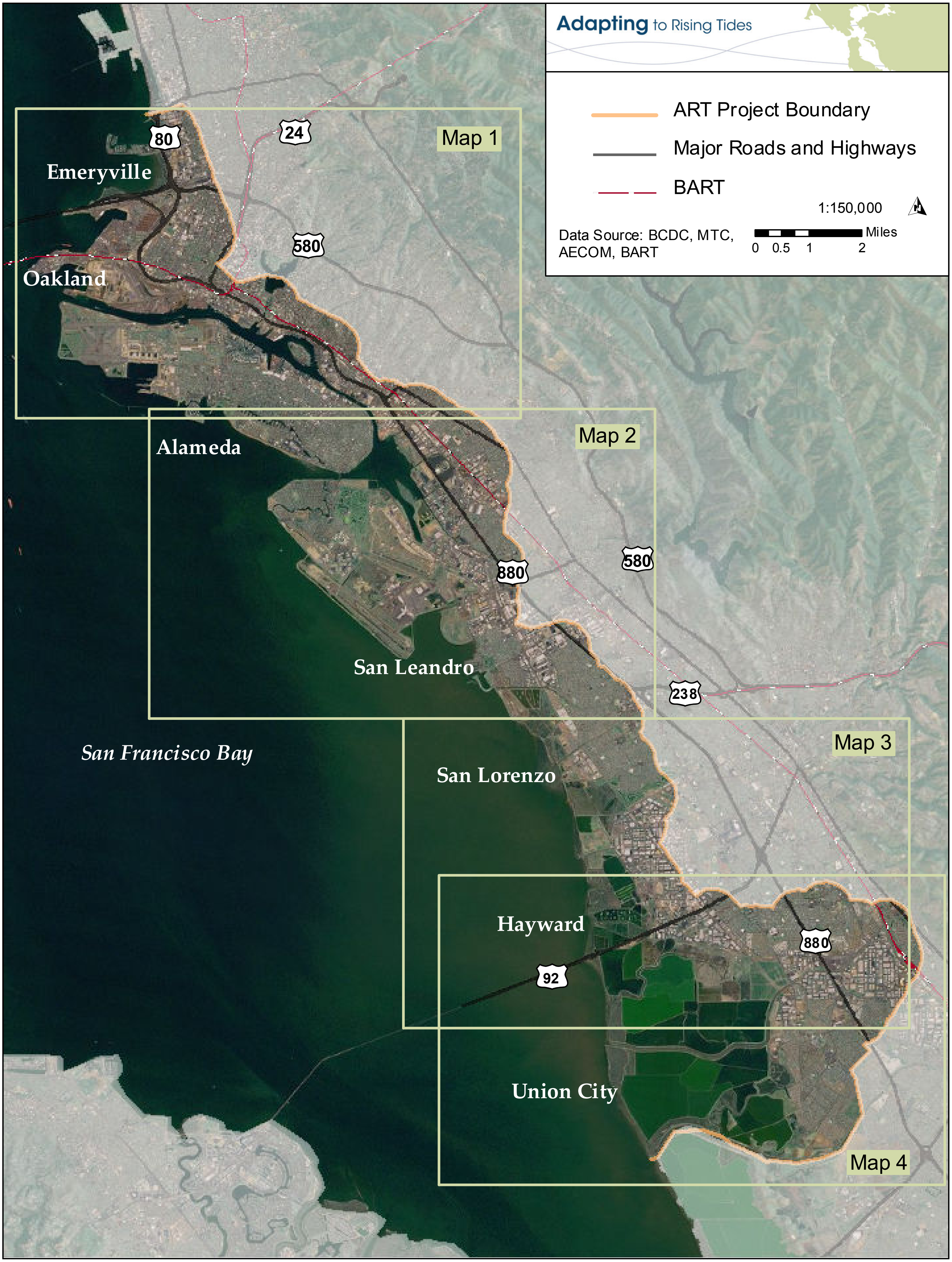
Inundation Mapping

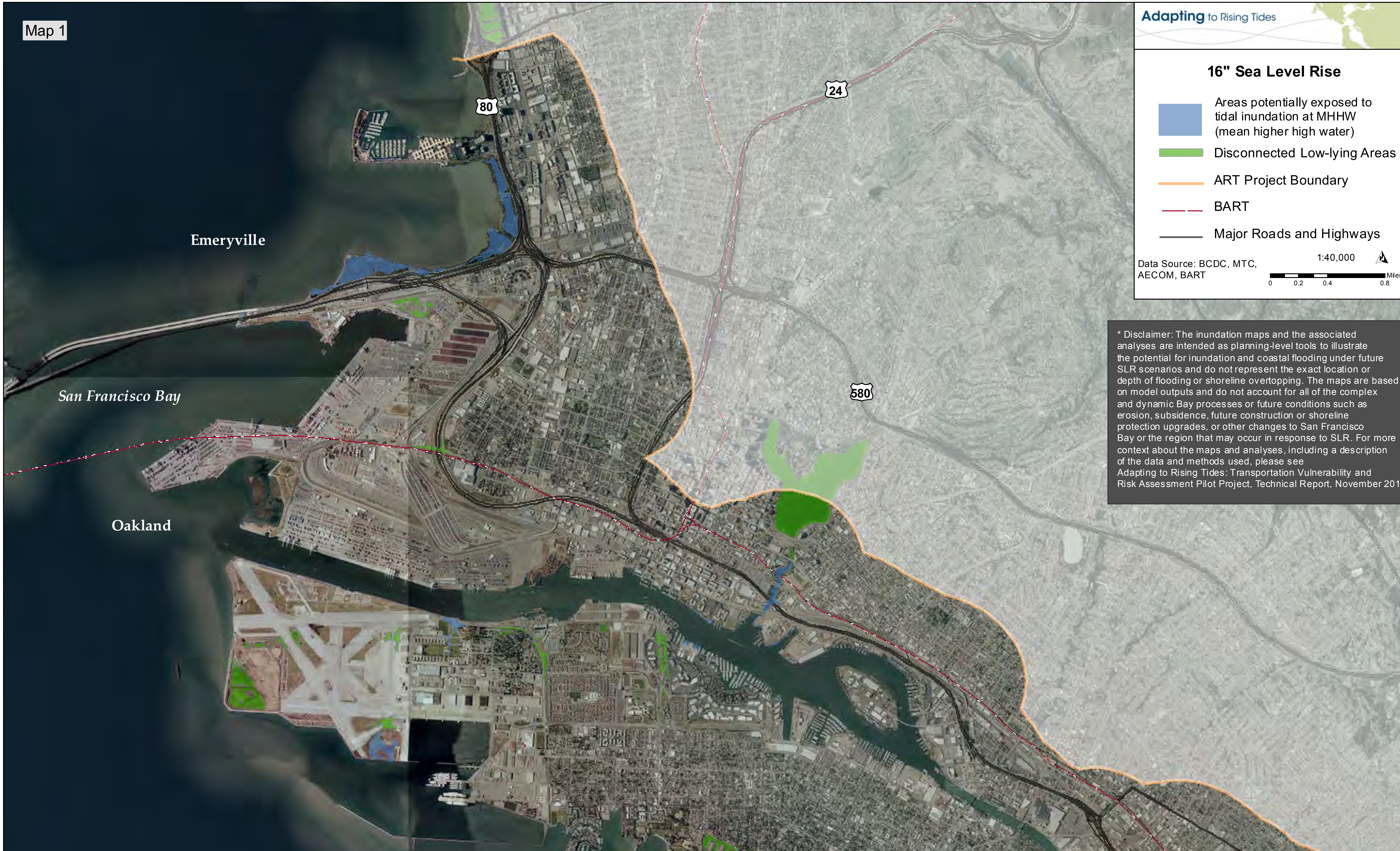
Inundation maps for six future climate scenarios were developed from the 2-meter horizontal grid resolution Digital Elevation Model (DEM) and water surface maps described above using mapping methods developed by the National Oceanic and Atmospheric Administration Coastal Services Center (Marcy et al. 2011). The methods include an assessment of hydraulic connectivity that identifies low-lying areas that are not connected to adjacent inundated areas because they are protected by levees or other topographic features, and therefore would not be flooded. These areas were uniquely identified on the final maps created for the ART project because while they are not directly exposed to sea level rise or storm event impacts, they are at risk of flooding if the topographic feature protecting them fails or breaches.

Visualize Results

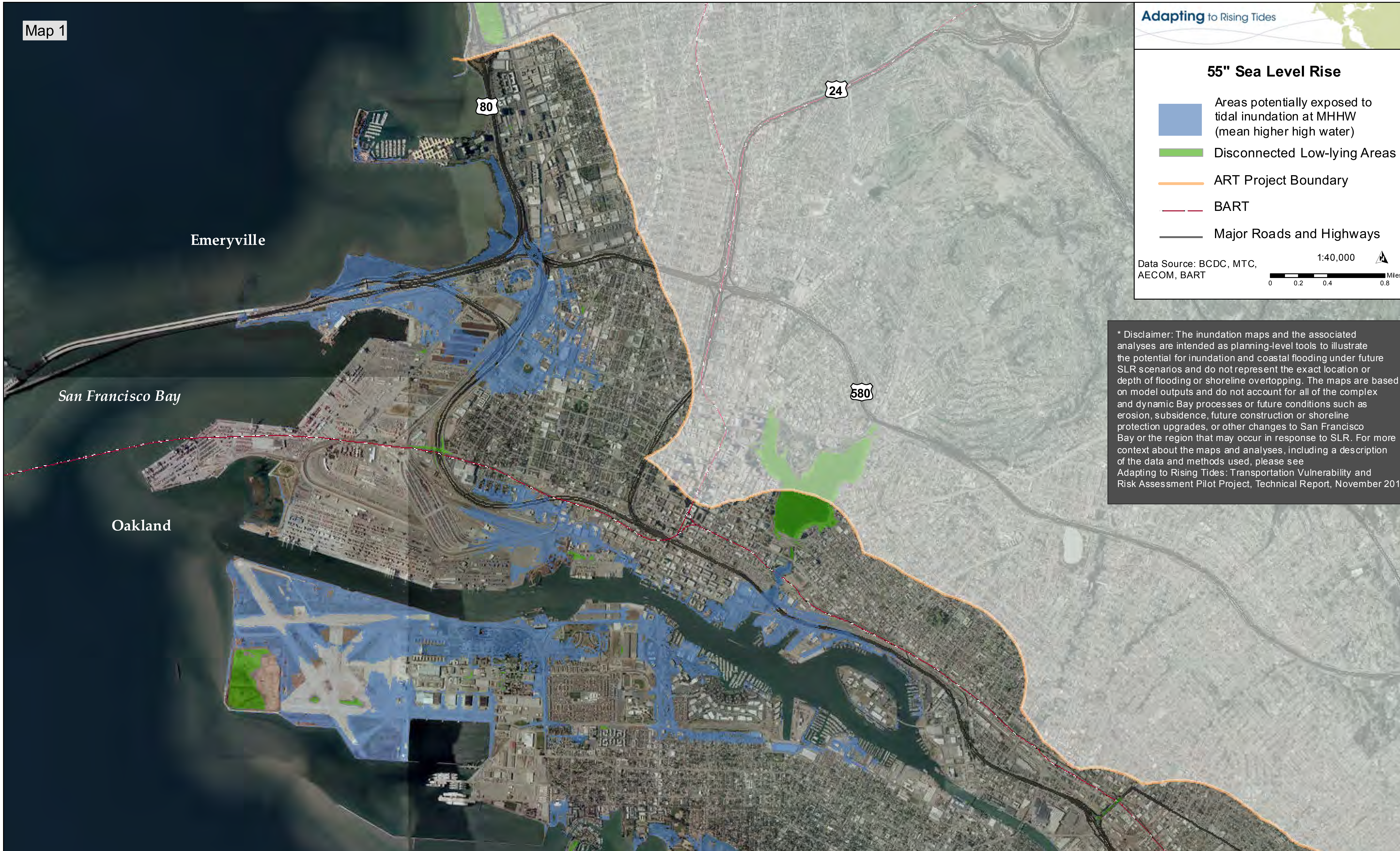
Maps visualizing the inundation analysis were developed for all six future climate scenarios. The extent and depth of inundation is depicted for the two sea level rise projections (16 and 55 inches) and for two Bay water levels - the daily high tide and the 100-year storm. Because overland wave propagation and dissipation which could significantly affect inundation depth were not evaluated, only the extent of inundation was depicted for the 100-year storm with wind waves. Based on the uncertainty of the topographic data and the modeling results, inundation depths are presented in 1-foot increments, and depths of less than 0.5 foot were not considered. Lastly, areas determined by the hydraulic connectivity analysis to be "disconnected low-lying areas "were uniquely identified on the final maps.

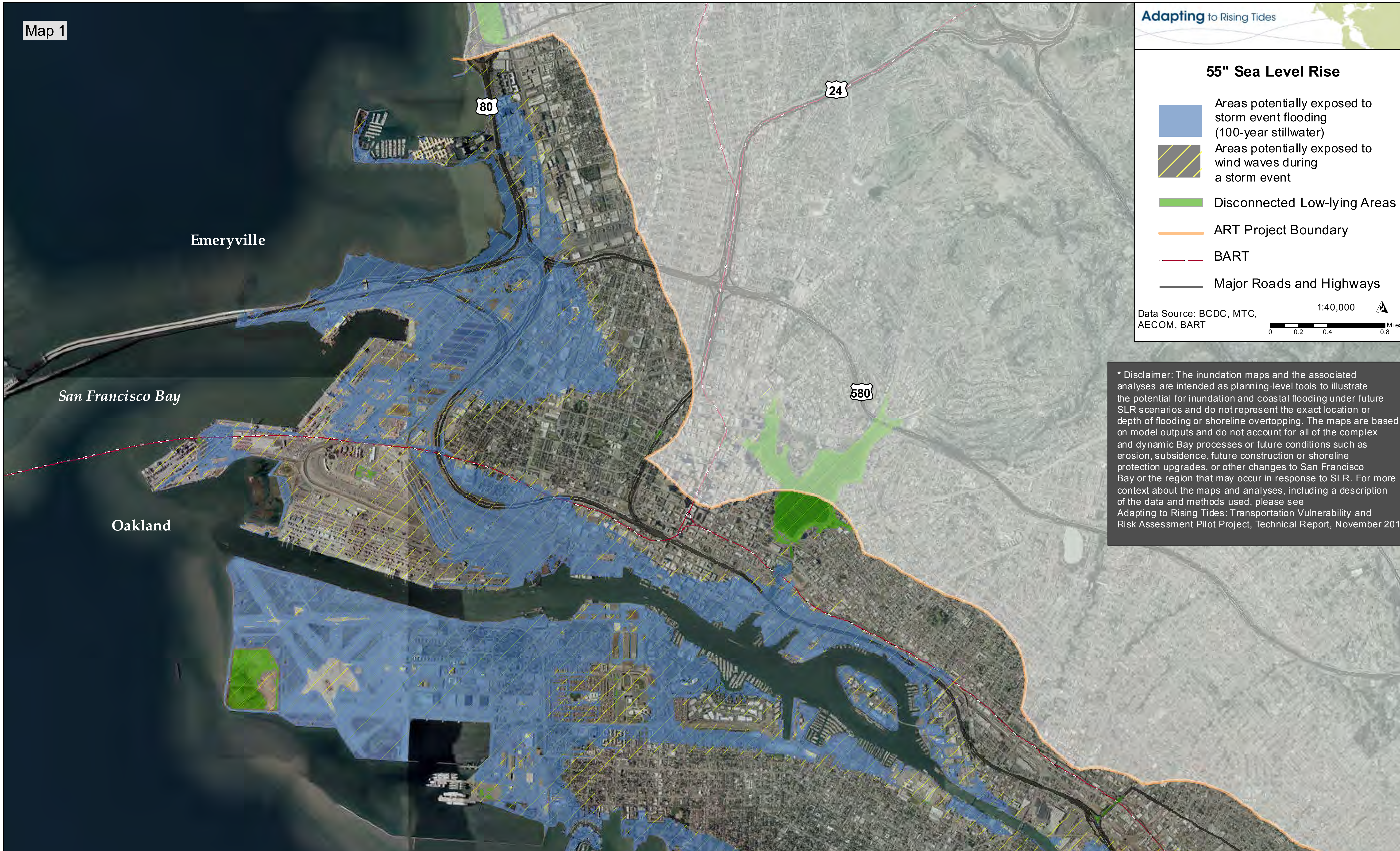
Sea Level Rise Maps


Adapting to Rising Tides
ART Project Boundary
Major Roads and Highways
BART
1:150,000
Data Source: BCDC, MTC, AECOM, BART
0 0.5 1 2 Miles
Map 1
Map 2
Map 3
Map 4
80
24
580
880
238
92
Emeryville
Oakland
Alameda
San Leandro
San Francisco Bay
San Lorenzo
Hayward
Union City


Map 1
Adapting to Rising Tides
16" Sea Level Rise
Areas potentially exposed to tidal inundation at MHHW (mean higher high water)
Disconnected Low-lying Areas
ART Project Boundary
BART
Major Roads and Highways
Data Source: BCDC, MTC, AECOM, BART
1:40,000
0 0.2 0.4 0.8 Miles
* Disclaimer: The inundation maps and the associated analyses are intended as planning-level tools to illustrate the potential for inundation and coastal flooding under future SLR scenarios and 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 see Adapting to Rising Tides: Transportation Vulnerability and Risk Assessment Pilot Project, Technical Report, November 2011.
80
24
580
Emeryville
San Francisco Bay
Oakland


Map 1
Adapting to Rising Tides
16" Sea Level Rise
Areas potentially exposed to storm event flooding (100-year stillwater)
Areas potentially exposed to wind waves during a storm event
Disconnected Low-lying Areas
ART Project Boundary
BART
Major Roads and Highways
Data Source: BCDC, MTC, AECOM, BART
1:40,000
0 0.2 0.4 0.8 Miles
* Disclaimer: The inundation maps and the associated analyses are intended as planning-level tools to illustrate the potential for inundation and coastal flooding under future SLR scenarios and 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 see Adapting to Rising Tides: Transportation Vulnerability and Risk Assessment Pilot Project, Technical Report, November 2011.
Emeryville
San Francisco Bay
Oakland
80
24
580

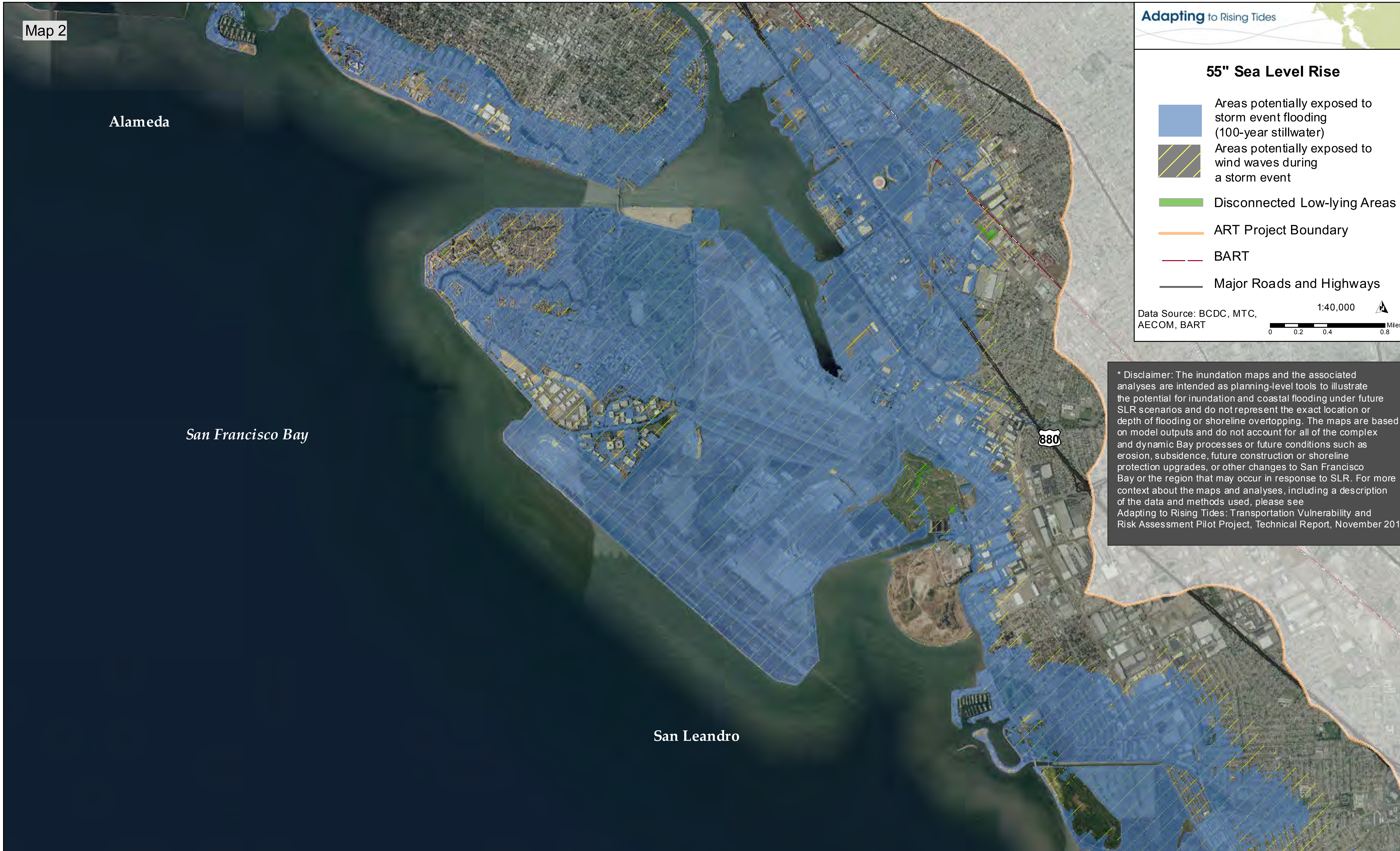

Map 1
Adapting to Rising Tides
55" Sea Level Rise
Areas potentially exposed to tidal inundation at MHHW (mean higher high water)
Disconnected Low-lying Areas
ART Project Boundary
BART
Major Roads and Highways
Data Source: BCDC, MTC, AECOM, BART
1:40,000
0 0.2 0.4 0.8 Miles
* Disclaimer: The inundation maps and the associated analyses are intended as planning-level tools to illustrate the potential for inundation and coastal flooding under future SLR scenarios and 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 see Adapting to Rising Tides: Transportation Vulnerability and Risk Assessment Pilot Project, Technical Report, November 2011.
Emeryville
San Francisco Bay
Oakland
80
24
580

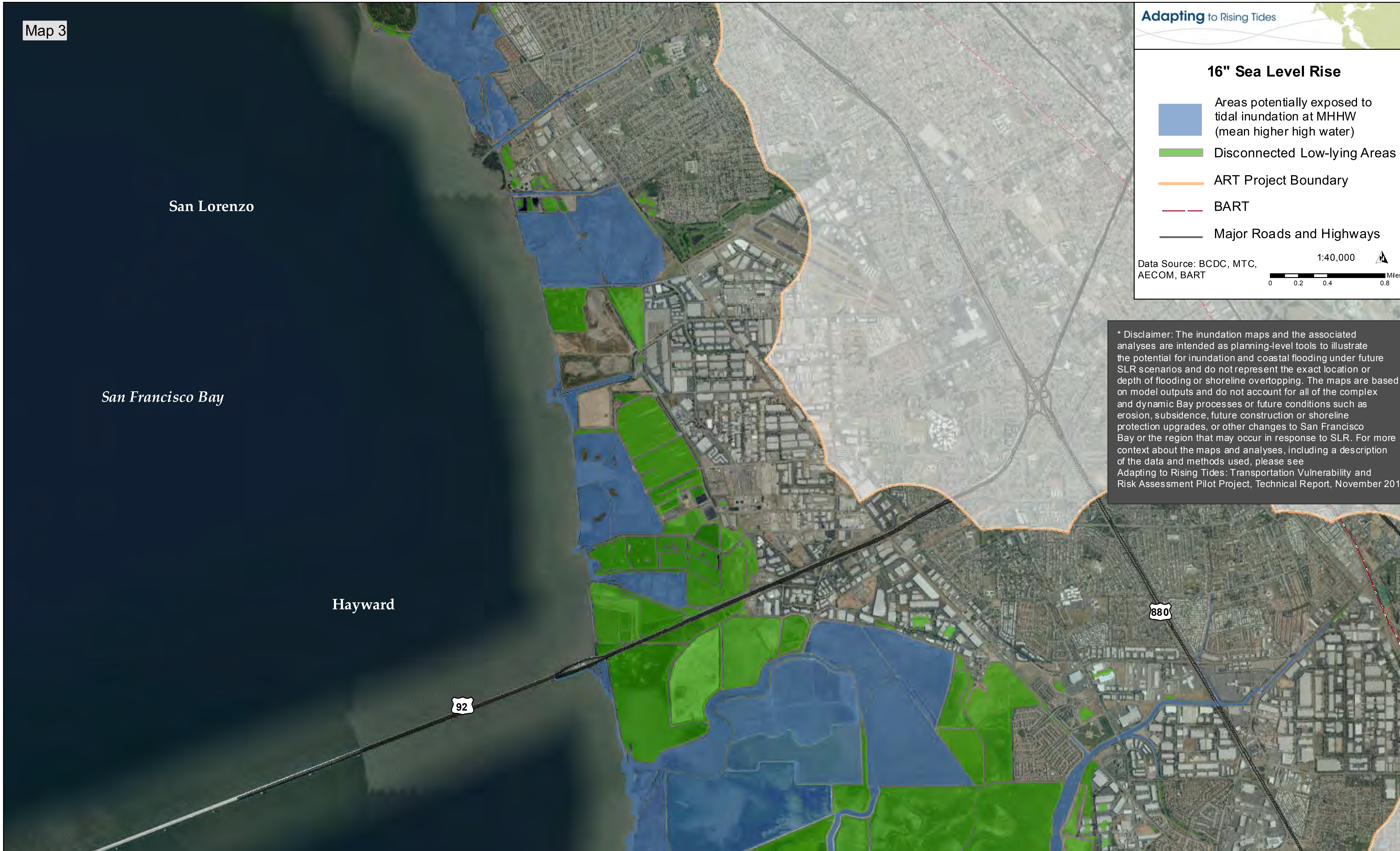

Map 1
Adapting to Rising Tides
55" Sea Level Rise
Areas potentially exposed to storm event flooding (100-year stillwater)
Areas potentially exposed to wind waves during a storm event
Disconnected Low-lying Areas
ART Project Boundary
BART
Major Roads and Highways
Data Source: BCDC, MTC, AECOM, BART
1:40,000
0 0.2 0.4 0.8 Miles
* Disclaimer: The inundation maps and the associated analyses are intended as planning-level tools to illustrate the potential for inundation and coastal flooding under future SLR scenarios and 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 see Adapting to Rising Tides: Transportation Vulnerability and Risk Assessment Pilot Project, Technical Report, November 2011.
Emeryville
San Francisco Bay
Oakland
80
24
580


Map 2
Adapting to Rising Tides
16" Sea Level Rise
Areas potentially exposed to tidal inundation at MHHW (mean higher high water)
Disconnected Low-lying Areas
ART Project Boundary
BART
Major Roads and Highways
Data Source: BCDC, MTC, AECOM, BART
1:40,000
Miles
0
0.2
0.4
0.8
* Disclaimer: The inundation maps and the associated analyses are intended as planning-level tools to illustrate the potential for inundation and coastal flooding under future SLR scenarios and 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 see Adapting to Rising Tides: Transportation Vulnerability and Risk Assessment Pilot Project, Technical Report, November 2011.
Alameda
San Francisco Bay
San Leandro
880

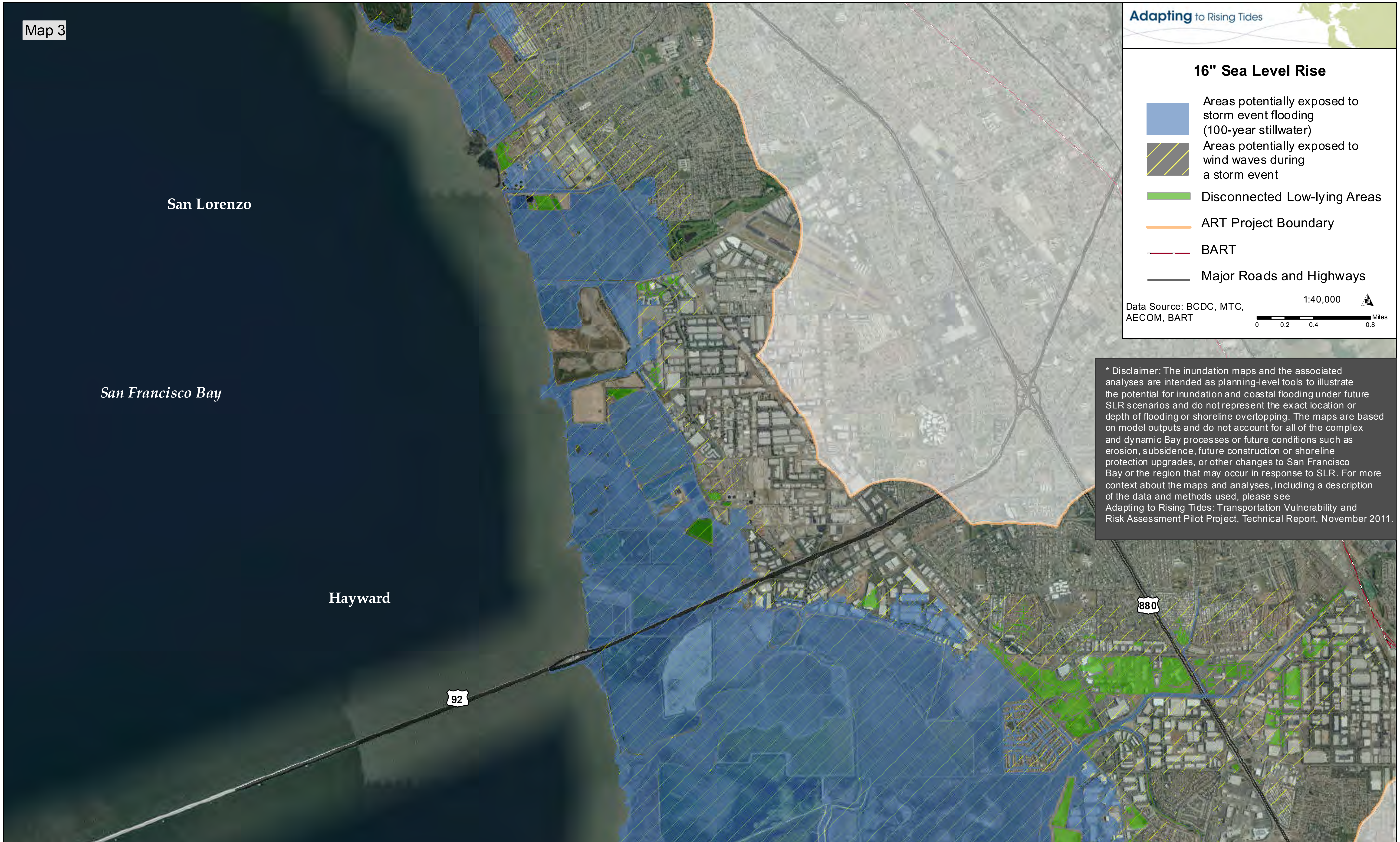
Map 2
Adapting to Rising Tides
16" Sea Level Rise
Areas potentially exposed to storm event flooding (100-year stillwater)
Areas potentially exposed to wind waves during a storm event
Disconnected Low-lying Areas
ART Project Boundary
BART
Major Roads and Highways
Data Source: BCDC, MTC, AECOM, BART
1:40,000
0 0.2 0.4 0.8 Miles
Alameda
San Francisco Bay
San Leandro
880
* Disclaimer: The inundation maps and the associated analyses are intended as planning-level tools to illustrate the potential for inundation and coastal flooding under future SLR scenarios and 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 see Adapting to Rising Tides: Transportation Vulnerability and Risk Assessment Pilot Project, Technical Report, November 2011.

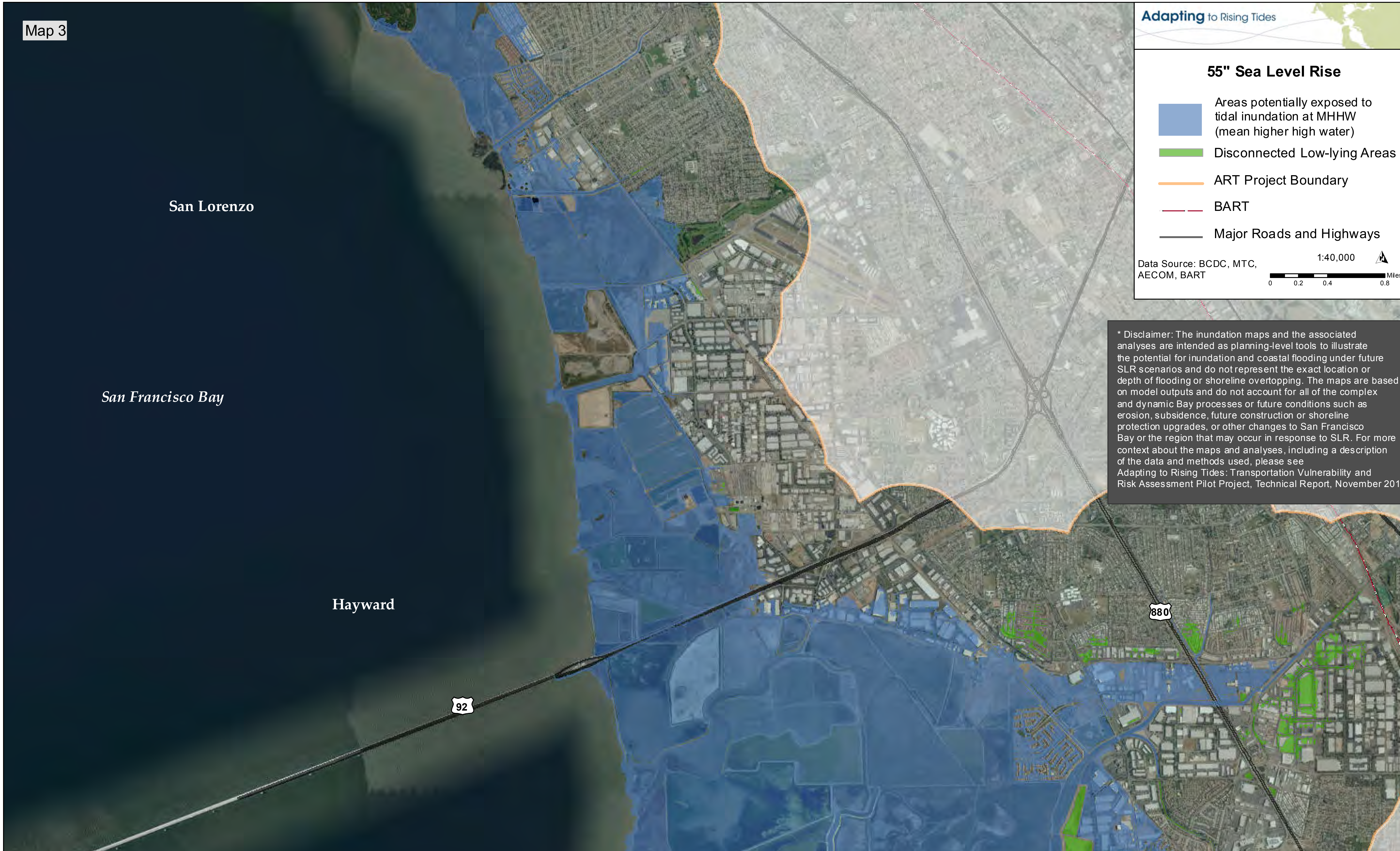

Map 2
Adapting to Rising Tides
55" Sea Level Rise
Areas potentially exposed to tidal inundation at MHHW (mean higher high water)
Disconnected Low-lying Areas
ART Project Boundary
BART
Major Roads and Highways
Data Source: BCDC, MTC, AECOM, BART
1:40,000
0 0.2 0.4 0.8 Miles
* Disclaimer: The inundation maps and the associated analyses are intended as planning-level tools to illustrate the potential for inundation and coastal flooding under future SLR scenarios and 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 see Adapting to Rising Tides: Transportation Vulnerability and Risk Assessment Pilot Project, Technical Report, November 2011.
Alameda
San Francisco Bay
San Leandro
880

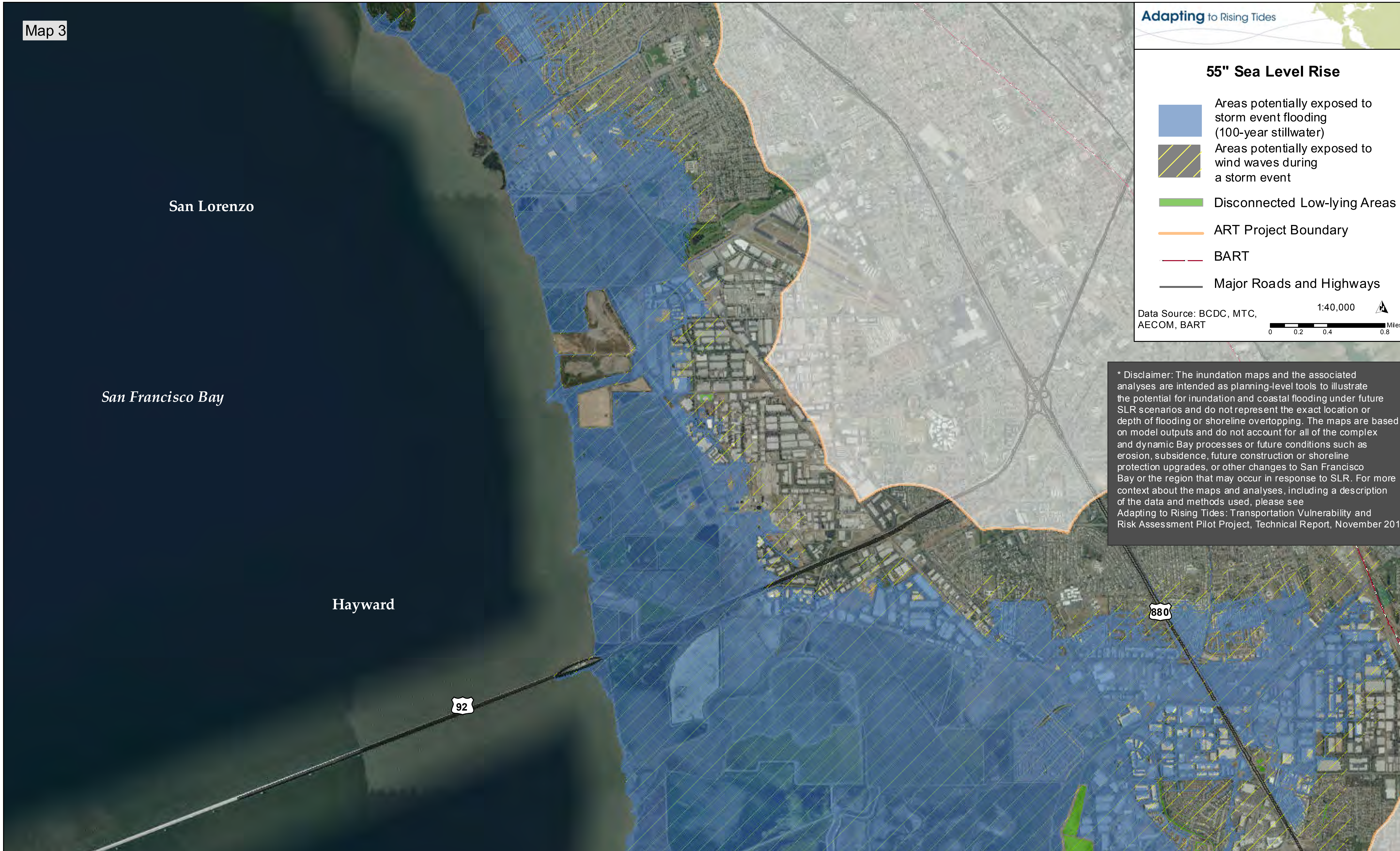

Map 2
Adapting to Rising Tides
55" Sea Level Rise
Areas potentially exposed to storm event flooding (100-year stillwater)
Areas potentially exposed to wind waves during a storm event
Disconnected Low-lying Areas
ART Project Boundary
BART
Major Roads and Highways
Data Source: BCDC, MTC, AECOM, BART
1:40,000
0 0.2 0.4 0.8 Miles
* Disclaimer: The inundation maps and the associated analyses are intended as planning-level tools to illustrate the potential for inundation and coastal flooding under future SLR scenarios and 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 see Adapting to Rising Tides: Transportation Vulnerability and Risk Assessment Pilot Project, Technical Report, November 2011.
Alameda
San Francisco Bay
San Leandro
880

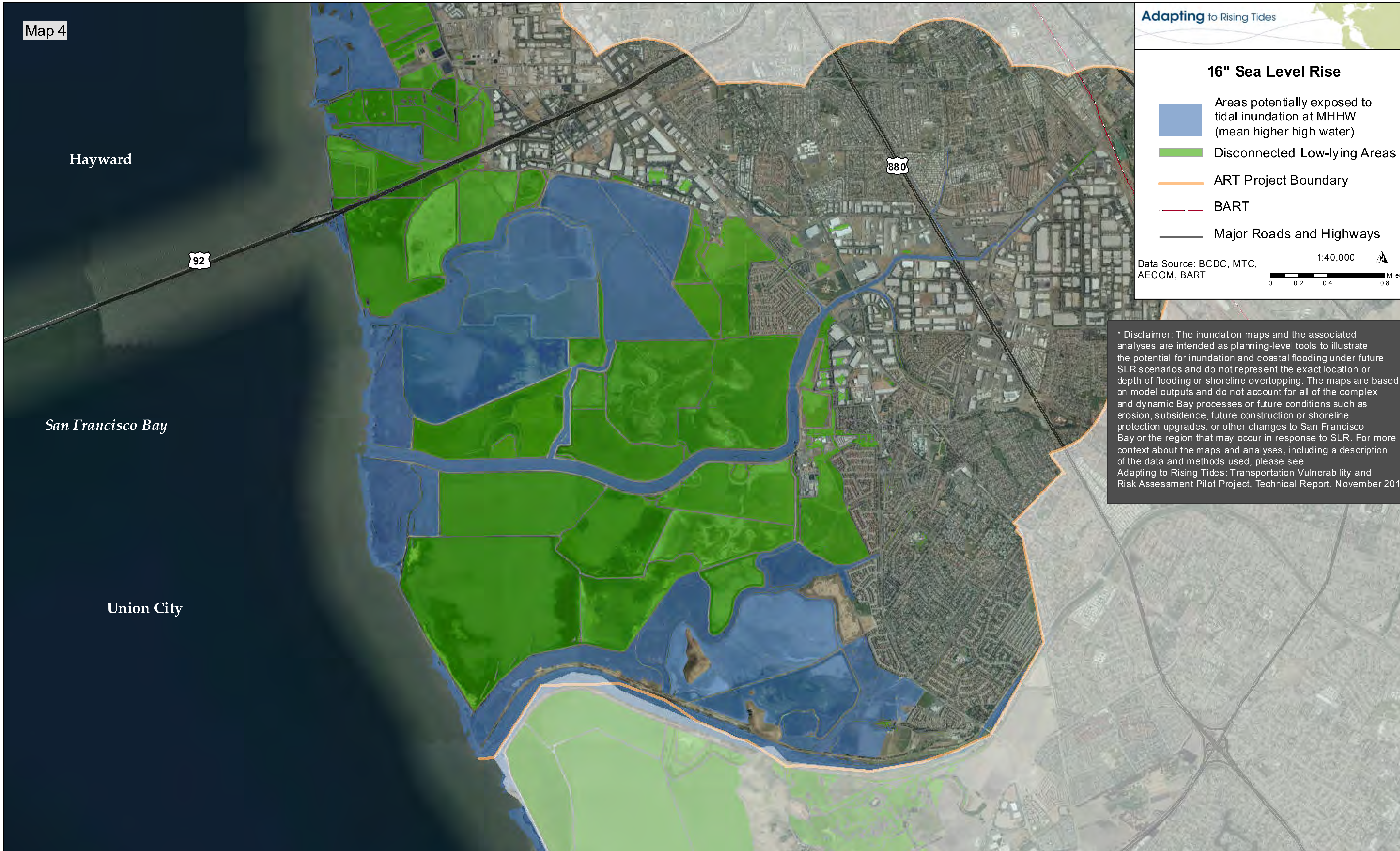


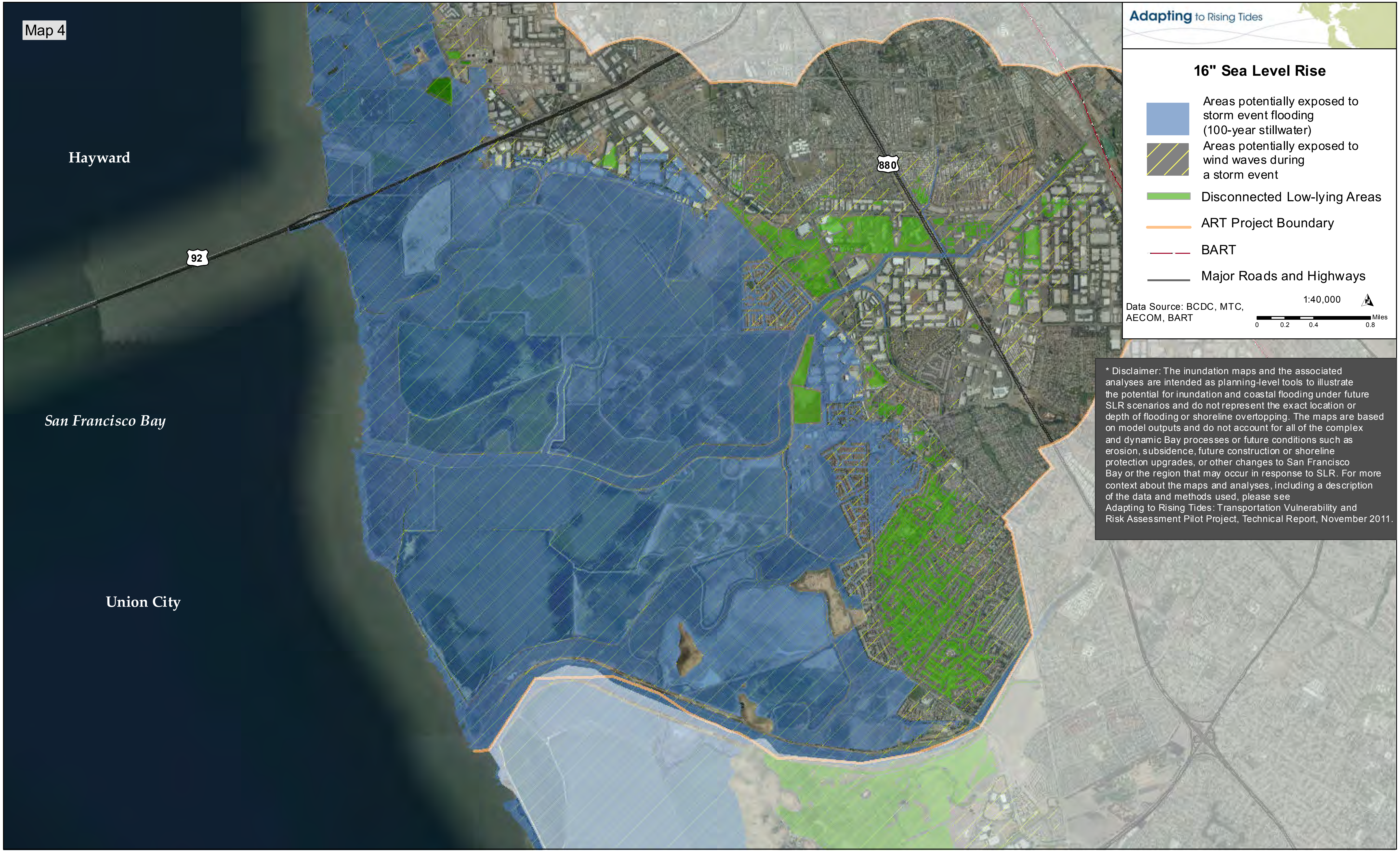
* Disclaimer: The inundation maps and the associated analyses are intended as planning-level tools to illustrate the potential for inundation and coastal flooding under future SLR scenarios and do not represent the exact location or depth of flooding or shoreline overtopping. The maps are based on model 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 see Adapting to Rising Tides: Transportation Vulnerability and Risk Assessment Pilot Project, Technical Report, November 2011.


Map 3
Adapting to Rising Tides
16" Sea Level Rise
Areas potentially exposed to storm event flooding (100-year stillwater)
Areas potentially exposed to wind waves during a storm event
Disconnected Low-lying Areas
ART Project Boundary
BART
Major Roads and Highways
Data Source: BCDC, MTC, AECOM, BART
1:40,000
0
0.2
0.4
0.8
Miles
* Disclaimer: The inundation maps and the associated analyses are intended as planning-level tools to illustrate the potential for inundation and coastal flooding under future SLR scenarios and 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 see Adapting to Rising Tides: Transportation Vulnerability and Risk Assessment Pilot Project, Technical Report, November 2011.
San Lorenzo
San Francisco Bay
Hayward
880
92


Map 3
Adapting to Rising Tides
55" Sea Level Rise
Areas potentially exposed to tidal inundation at MHHW (mean higher high water)
Disconnected Low-lying Areas
ART Project Boundary
BART
Major Roads and Highways
Data Source: BCDC, MTC, AECOM, BART
1:40,000
0 0.2 0.4 0.8 Miles
* Disclaimer: The inundation maps and the associated analyses are intended as planning-level tools to illustrate the potential for inundation and coastal flooding under future SLR scenarios and 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 see Adapting to Rising Tides: Transportation Vulnerability and Risk Assessment Pilot Project, Technical Report, November 2011.
San Lorenzo
San Francisco Bay
Hayward
92
880


Map 3
Adapting to Rising Tides
55" Sea Level Rise
Areas potentially exposed to storm event flooding (100-year stillwater)
Areas potentially exposed to wind waves during a storm event
Disconnected Low-lying Areas
ART Project Boundary
BART
Major Roads and Highways
Data Source: BCDC, MTC, AECOM, BART
1:40,000
0 0.2 0.4 0.8 Miles
* Disclaimer: The inundation maps and the associated analyses are intended as planning-level tools to illustrate the potential for inundation and coastal flooding under future SLR scenarios and 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 see Adapting to Rising Tides: Transportation Vulnerability and Risk Assessment Pilot Project, Technical Report, November 2011.
San Lorenzo
San Francisco Bay
Hayward
92
880


Map 4
Adapting to Rising Tides
16" Sea Level Rise
Areas potentially exposed to tidal inundation at MHHW (mean higher high water)
Disconnected Low-lying Areas
ART Project Boundary
BART
Major Roads and Highways
1:40,000
Data Source: BCDC, MTC, AECOM, BART
0
0.2
0.4
0.8
Miles
* Disclaimer: The inundation maps and the associated analyses are intended as planning-level tools to illustrate the potential for inundation and coastal flooding under future SLR scenarios and 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 see Adapting to Rising Tides: Transportation Vulnerability and Risk Assessment Pilot Project, Technical Report, November 2011.
Hayward
San Francisco Bay
Union City
92
880


Map 4
Adapting to Rising Tides
16" Sea Level Rise
Areas potentially exposed to storm event flooding (100-year stillwater)
Areas potentially exposed to wind waves during a storm event
Disconnected Low-lying Areas
ART Project Boundary
BART
Major Roads and Highways
Data Source: BCDC, MTC, AECOM, BART
1:40,000
0 0.2 0.4 0.8 Miles
Hayward
San Francisco Bay
Union City
92
880
* Disclaimer: The inundation maps and the associated analyses are intended as planning-level tools to illustrate the potential for inundation and coastal flooding under future SLR scenarios and 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 see Adapting to Rising Tides: Transportation Vulnerability and Risk Assessment Pilot Project, Technical Report, November 2011.


Map 4
Adapting to Rising Tides
55" Sea Level Rise
Areas potentially exposed to tidal inundation at MHHW (mean higher high water)
Disconnected Low-lying Areas
ART Project Boundary
BART
Major Roads and Highways
Data Source: BCDC, MTC, AECOM, BART
1:40,000
Miles
0 0.2 0.4 0.8
* Disclaimer: The inundation maps and the associated analyses are intended as planning-level tools to illustrate the potential for inundation and coastal flooding under future SLR scenarios and 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 see Adapting to Rising Tides: Transportation Vulnerability and Risk Assessment Pilot Project, Technical Report, November 2011.
Hayward
San Francisco Bay
Union City
92
880


Map 4
Adapting to Rising Tides
55" Sea Level Rise
Areas potentially exposed to storm event flooding (100-year stillwater)
Areas potentially exposed to wind waves during a storm event
Disconnected Low-lying Areas
ART Project Boundary
BART
Major Roads and Highways
Data Source: BCDC, MTC, AECOM, BART
1:40,000
0 0.2 0.4 0.8 Miles
Hayward
San Francisco Bay
Union City
92
880
* Disclaimer: The inundation maps and the associated analyses are intended as planning-level tools to illustrate the potential for inundation and coastal flooding under future SLR scenarios and 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 see Adapting to Rising Tides: Transportation Vulnerability and Risk Assessment Pilot Project, Technical Report, November 2011.

Analysis of Shoreline Overtopping Potential

For the ART project analysis, "overtopping potential" refers to the condition where the water surface elevation from a particular inundation scenario exceeds the elevation of the existing shoreline, potentially causing flooding of inland low-lying areas. The analysis of overtopping potential identified where the shoreline may not be high enough to control inland inundation relative to the six future climate scenarios evaluated. The analysis did not account for the physics of wave setup and runup, the condition of the shoreline asset, or the potential for the to asset fail due to scour, undermining or a breach after the initial overtopping occurs[3].

The analysis identified the location and depth of inundation at the shoreline, and determined the total length of shoreline that is potentially overtopped. While the analysis informs an understanding of relative vulnerability, even small areas of shoreline overtopping could lead to flooding of large inland areas. And, if the overtopping leads to a structural failure then even larger areas could be inundated at deeper depths. Therefore, the analysis of overtopping potential should be used a screening level tool to help direct resources to specific shoreline areas where further study is necessary and not as a direct indicator of the risk.

Figure 1. Shoreline systems are contiguous reaches that act together to prevent inundation of inland areas. For example, system #9, shown in red, is located at the Martin Luther King Regional Shoreline just south of Arrowhead Marsh.

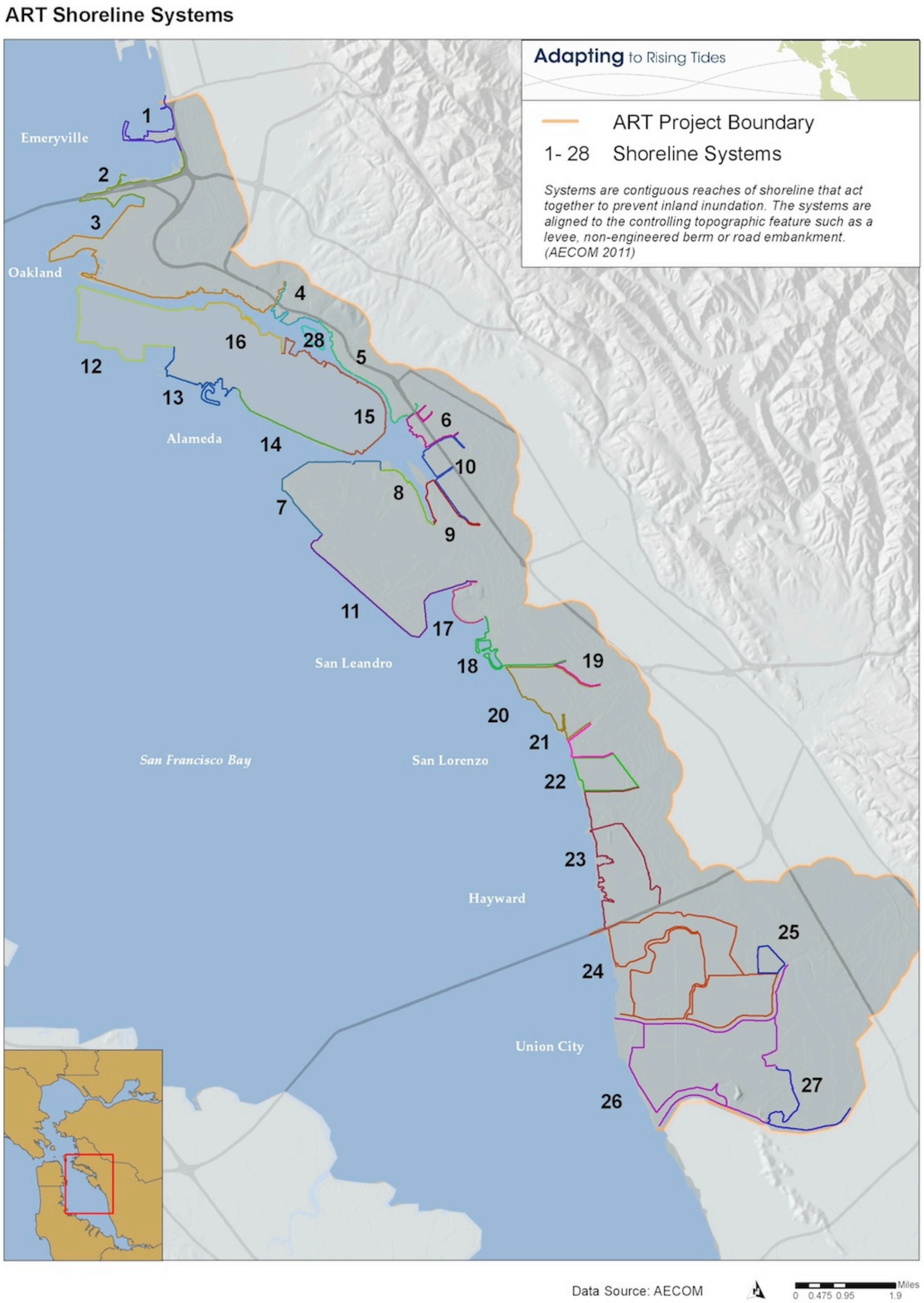
To conduct the overtopping potential analysis the shoreline was subdivided into distinct "systems" (Figure 1). The systems were defined as contiguous reaches of shoreline that act together to prevent inundation of inland areas. The exact location and alignment of each system was based on the topographic feature (based on ground elevation) that would prevent inundation, such as a levee, non-engineered berm or road embankment. In areas where the shoreline was comprised of wetlands and beaches, the system was aligned along an inland topographic feature that acts as a barrier to inland inundation[4].

Depending on the complexity of the shoreline, systems in the ART project area are either comprised of a single shoreline type, such as a reach of levee between two Bay tributaries, or multiple types, a combination of levee, non-engineered berm, and road embankment.

[3] Overtopping potential does not refer to the wave overtopping process, whereby breaking or non-breaking waves reach and overtop a shoreline feature. The depth of inundation due to the 100-year storm with wind waves was determined for shoreline assets but not for inland areas because the physics associated with overland wave propagation and dissipation was beyond the scope of the study.
[4] The analysis did not use wetland or beach systems as the topographic feature because dynamic coastal process such as erosion, organic matter accumulation and sediment deposition/resuspension were not accounted for.

The ART project shoreline was subdivided into 28 systems (Figure 2) with a combined length of 126 miles that represents the complex, and in some areas parallel or redundant features that protect inland areas. The division of the shoreline into the 28 systems was based in part on the scope, scale and objectives of the ART project. In general, the systems are small enough to provide meaningful information about specific shoreline vulnerabilities and risk, but are few enough in number to be manageable for the entire project area.

Figure 2. The 28 shoreline systems identified in the ART project area.



The overtopping potential analysis identified specific locations within each system that could be overtopped by the six future climate scenarios. The results of the analysis both inform both an understanding of the relative sensitivity of each system and the likelihood that an inland area protected by a specific shoreline system could be exposed. Based on the uncertainty of the topographic data and the modeling results, only areas overtopped by depths of 0.5 feet or greater were included in the analysis. Specific details on the methods of the overtopping potential analysis are included in Appendix B.

A summary of the overtopping potential results is provided below. Overtopping potential metrics were calculated for each system, and in some cases are summarized for the entire project area. These metrics include: **length of the shoreline overtopped**, the **percent of the shoreline length overtopped**, and the **average and maximum depth of overtopping**.

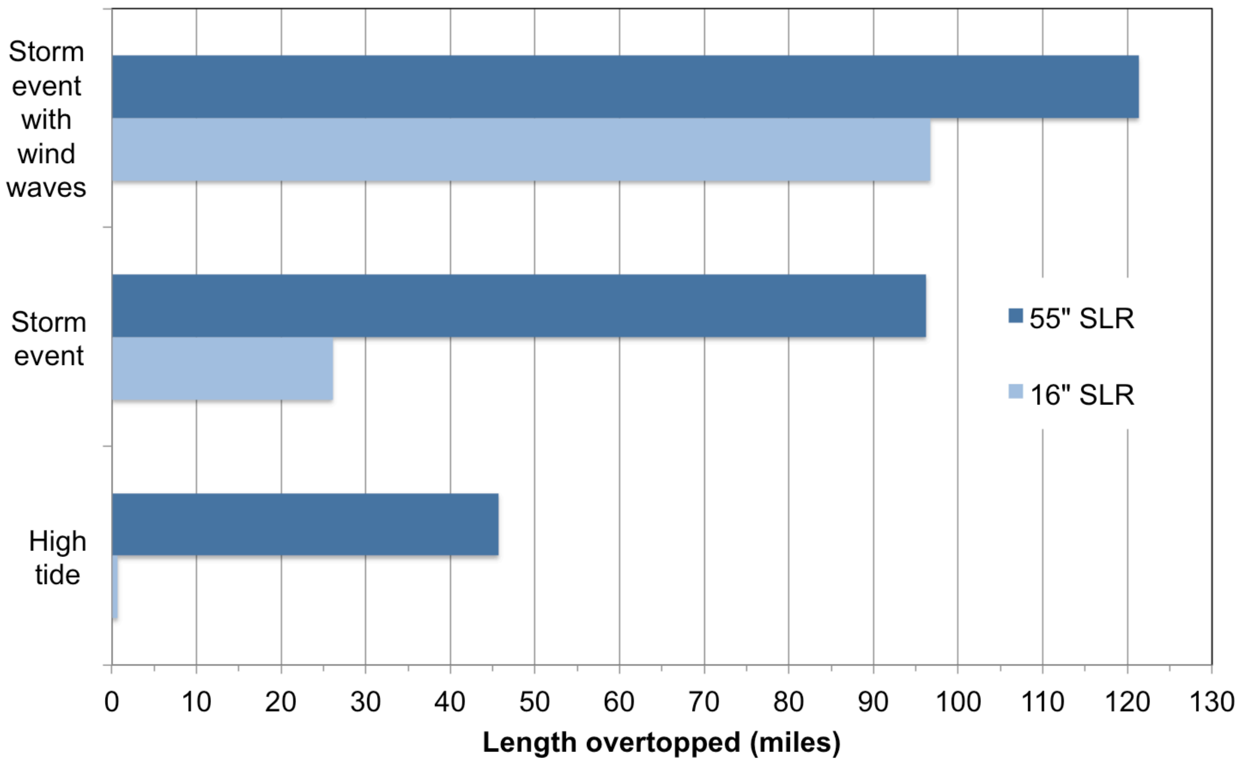
Length Overtopped

The length of shoreline overtopped within each system helps inform analysis of the likelihood that assets protected by the system would be exposed to sea level rise and storm events. It is also an indication of how vulnerable the shoreline system is to a future climate impact. For example, assets protected by a system with 1,000 feet of overtopping have a greater likelihood of exposure than those protected by a system with 10 feet of overtopping. Similarly, a system that has a greater length of overtopping is more vulnerable than one with less overtopping. As the exposure to overtopping increases across a system the potential for erosion, scour, and failure will increase, and the capacity to quickly, easily or in a low-cost manner either modify the system or improve its ability to accommodate the impact will diminish.

Approximately one mile of shoreline will be overtopped with 16 inches of sea level rise at high tide. This overtopping will occur mostly within two systems: #2 on the north side of the San Francisco-East Bay Bridge peninsula, and #23 at the Hayward Regional Shoreline (Figure 2). During a storm event with 16 inches of sea level rise, the total length of shoreline overtopped increases to 28 miles, with overtopping occurring in all but one system (#19). With the addition of wind waves during the storm event, all of the systems are overtopped, and the length of overtopping more than triples to a total of 97 miles (Figure 3).

With 55 inches of sea level rise all 28 systems are overtopped for each Bay water level evaluated. A total of 46 miles are overtopped at high tide, 96 miles during a storm event, and 121 miles during a storm event with wind waves (Figure 3).

Figure 3. Total length of shoreline system overtopped by the six future climate scenarios evaluated. The total length of project shoreline systems is 126 miles.



Percent of Length Overtopped

Because the length of each system varies widely, from 1.2 to 18 miles[5], it is important to also consider overtopping relative to system length. The chosen metric, the percent of the length overtopped, is an indication of the relative amount of exposure potentially experienced within each system.

Only 1% of the shoreline will overtop with 16 inches of sea level rise at high tide (Figure 4). Of the fourteen systems overtopped by this scenario, only three are greater than 1% overtopped (#2, 4, and 23, Figure 5). During a storm event, the percent length overtopped increases to 21%. More than half of the systems will have less than 50% of their length overtopped, and only one system (#8) will have greater than 75% of its length overtopped. With the addition of wind waves during the storm event the percent of length overtopped increases dramatically to 77%, with the majority of systems having 75% of their overtopped and only one system (#17) having less than 10% of its length overtopped.

With 55 inches of sea level rise at high tide, 36% of the shoreline will overtop. Only four systems will have less than 10% of their length overtopped (#11, 14, 17 and 19). During a storm event the percent of length overtopped increases to 76%, and if there are wind waves nearly all of the shoreline is overtopped (96%). Only one system (#27) has less than 75% of its length overtopped (54%) during a storm with wind waves (Figure 4 and 5).

[5] The shortest system, #19 (1.2 miles), is in San Leandro, and the longest, #24 (18 miles), is in Hayward.

Figure 4. The percent length overtopped on average for the 28 ART project shoreline systems by the six future climate scenarios evaluated.

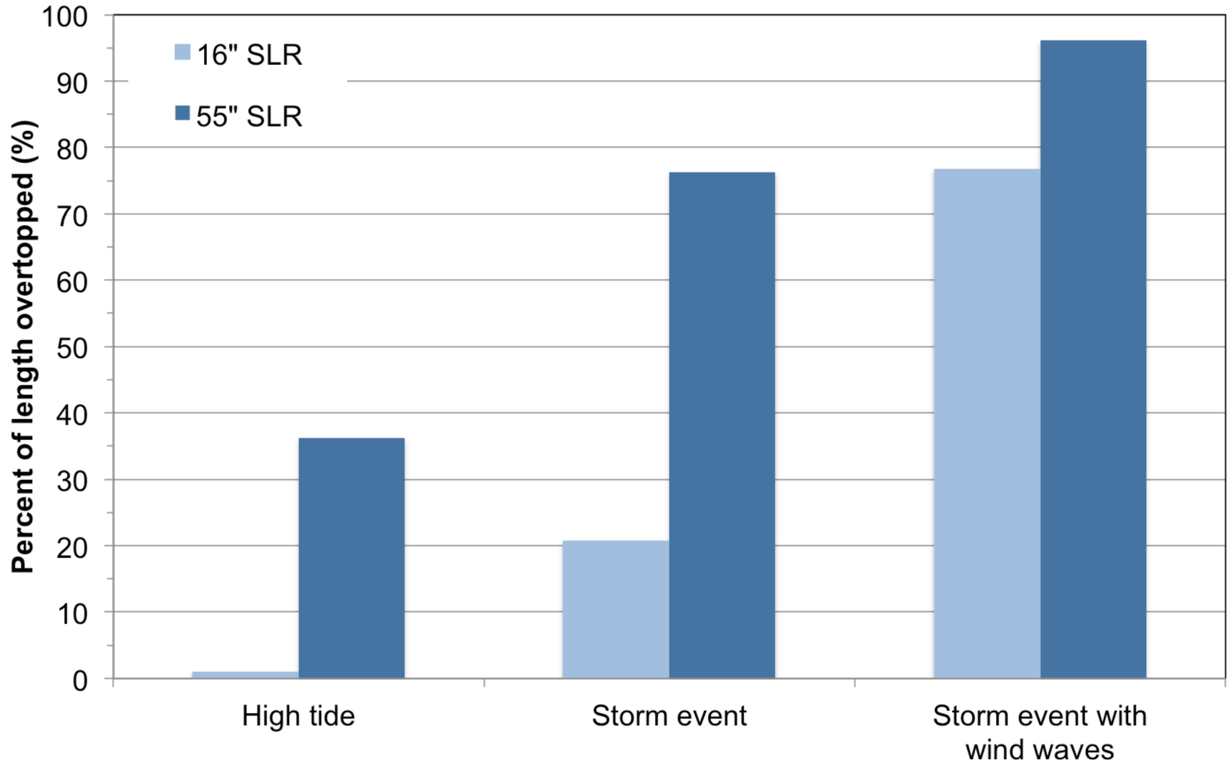
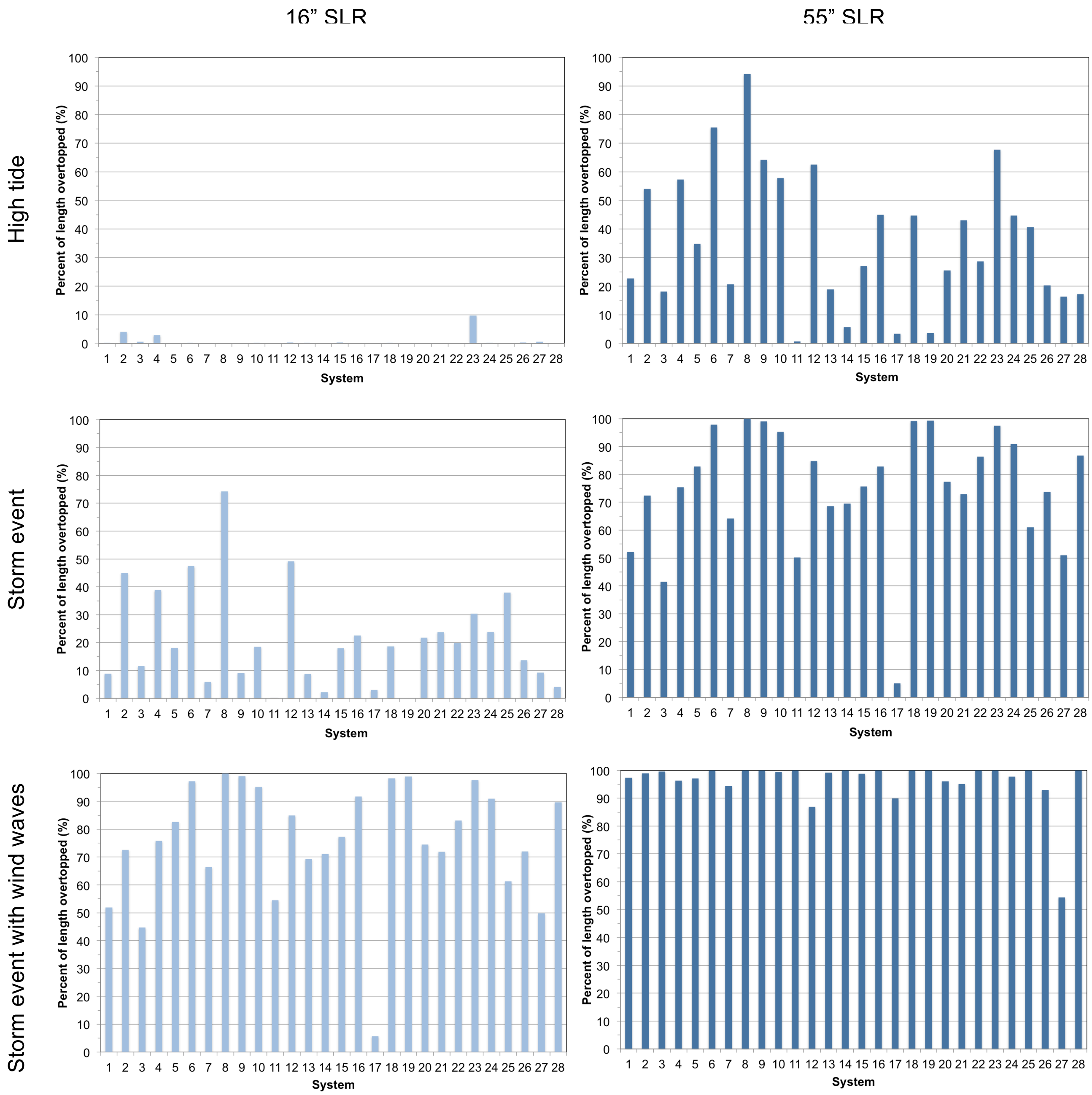


Figure 5. Percent length overtopped for each system by the six future climate scenarios evaluated.



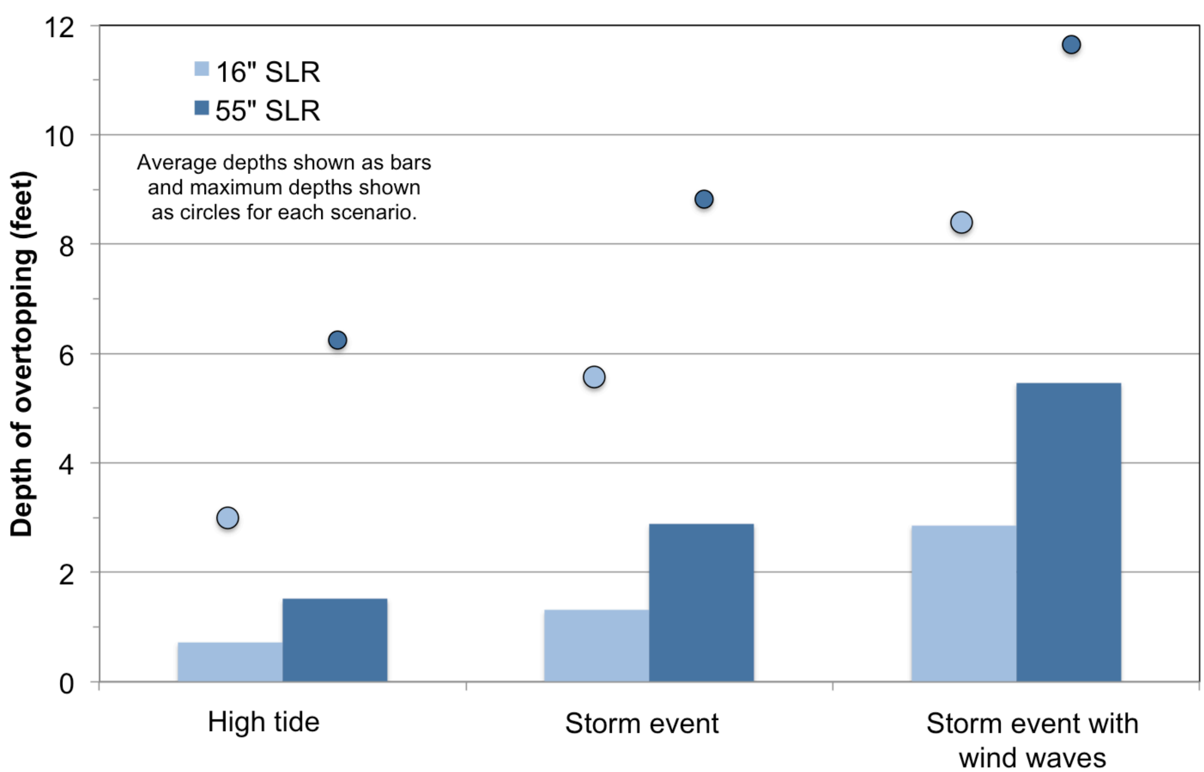
Average and Maximum Depth of Overtopping

The potential overtopping within a shoreline system is a useful screening-level tool that informs an understanding of the specific locations where additional study is necessary. To better understand where further efforts should be focused[6], and to more clearly define where the likelihood of an impact to inland areas could be, a segment level analysis was completed that determined the specific location(s) of potential overtopping along the shoreline. The analysis was summarized for each system as the average and maximum depth of overtopping that could occur due to the six future climate scenarios evaluated.

Across all 28 systems, the average depth of overtopping with 16 inches of sea level rise at high tide is less than one foot (Figure 6). During a storm event, the average depth increases to slightly more than 1 foot, and with wind waves to almost 3 feet. The maximum overtopping depths observed across all 28 systems occur within system #23 (Figure 2), with potentially 3 feet at high tide, 6 feet during a storm event, and 8 feet during a storm event with wind waves.

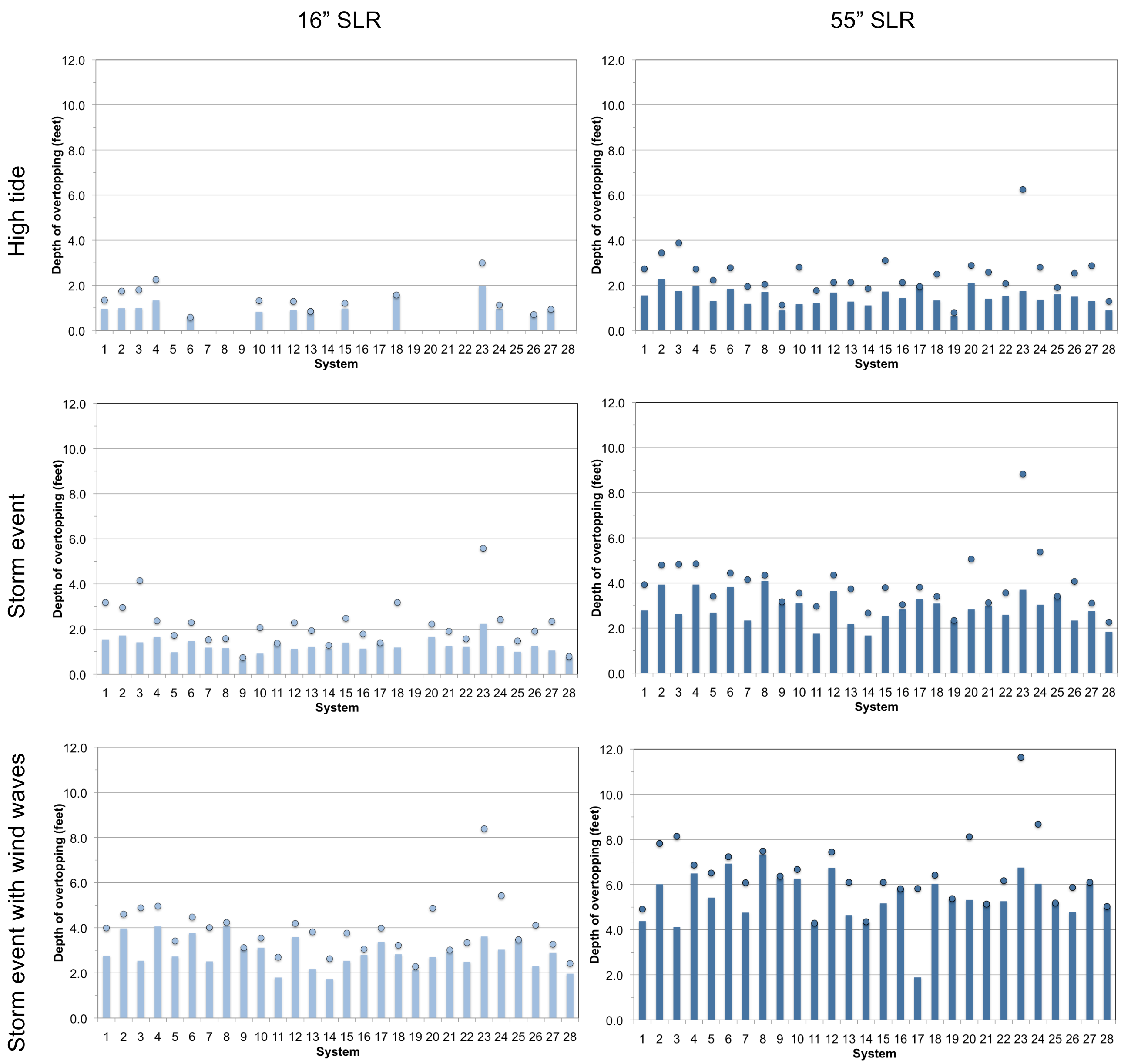
With 55 inches of sea level rise the majority of systems are overtopped on average by 1.5 feet at high tide, while during a storm event the average depth doubles to almost 3 feet. If there are wind waves during the storm event the average depth of overtopping increases to 5.5 feet. The maximum overtopping depths observed also occur within system #23, with potentially 6 feet at high tide, 9 feet with a storm event, and 12 feet during a storm event with wind waves.

Figure 6. Average (bars) and maximum (circles) depth of overtopping across the 28 ART project shoreline systems for the six future climate scenarios evaluated.

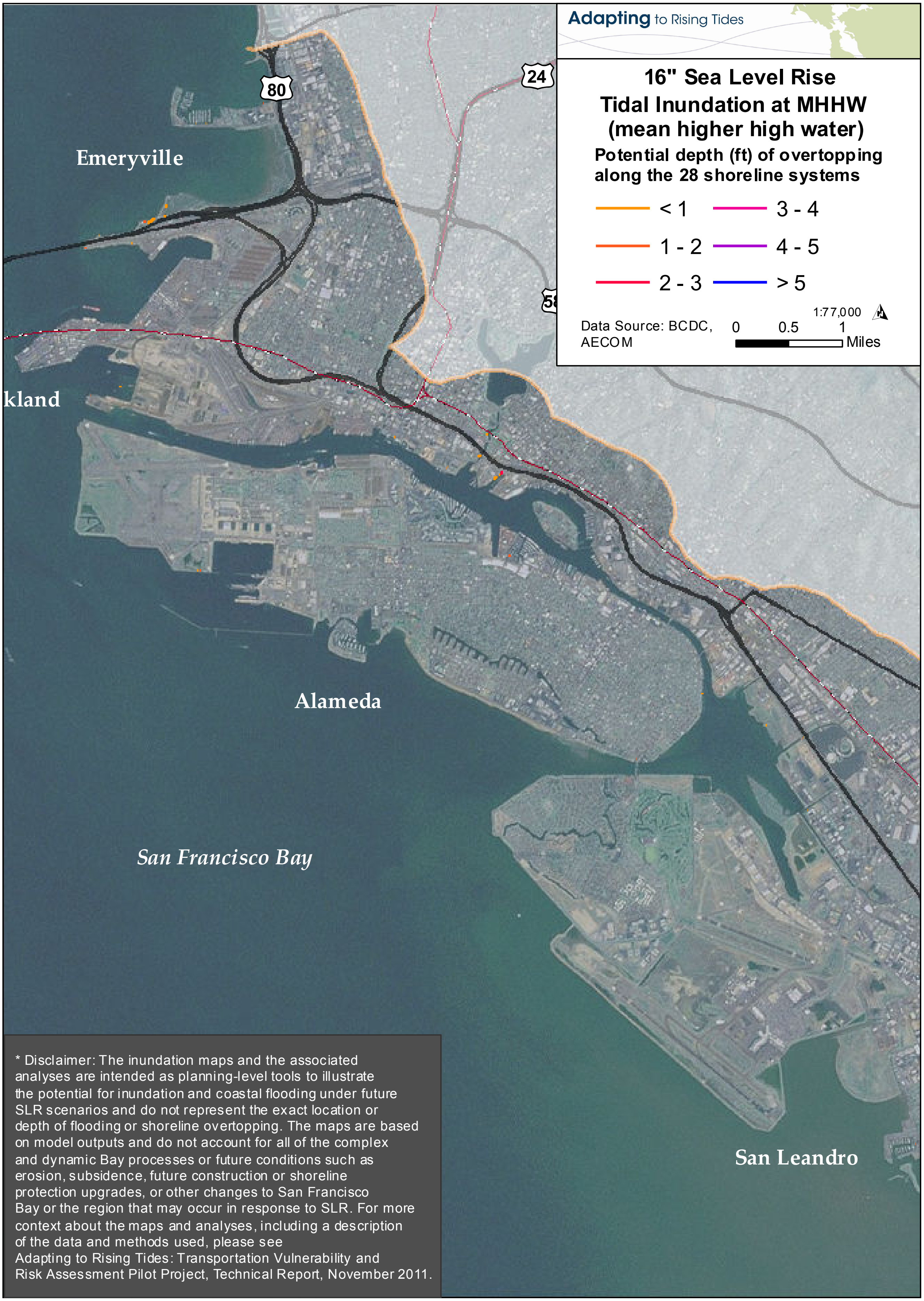


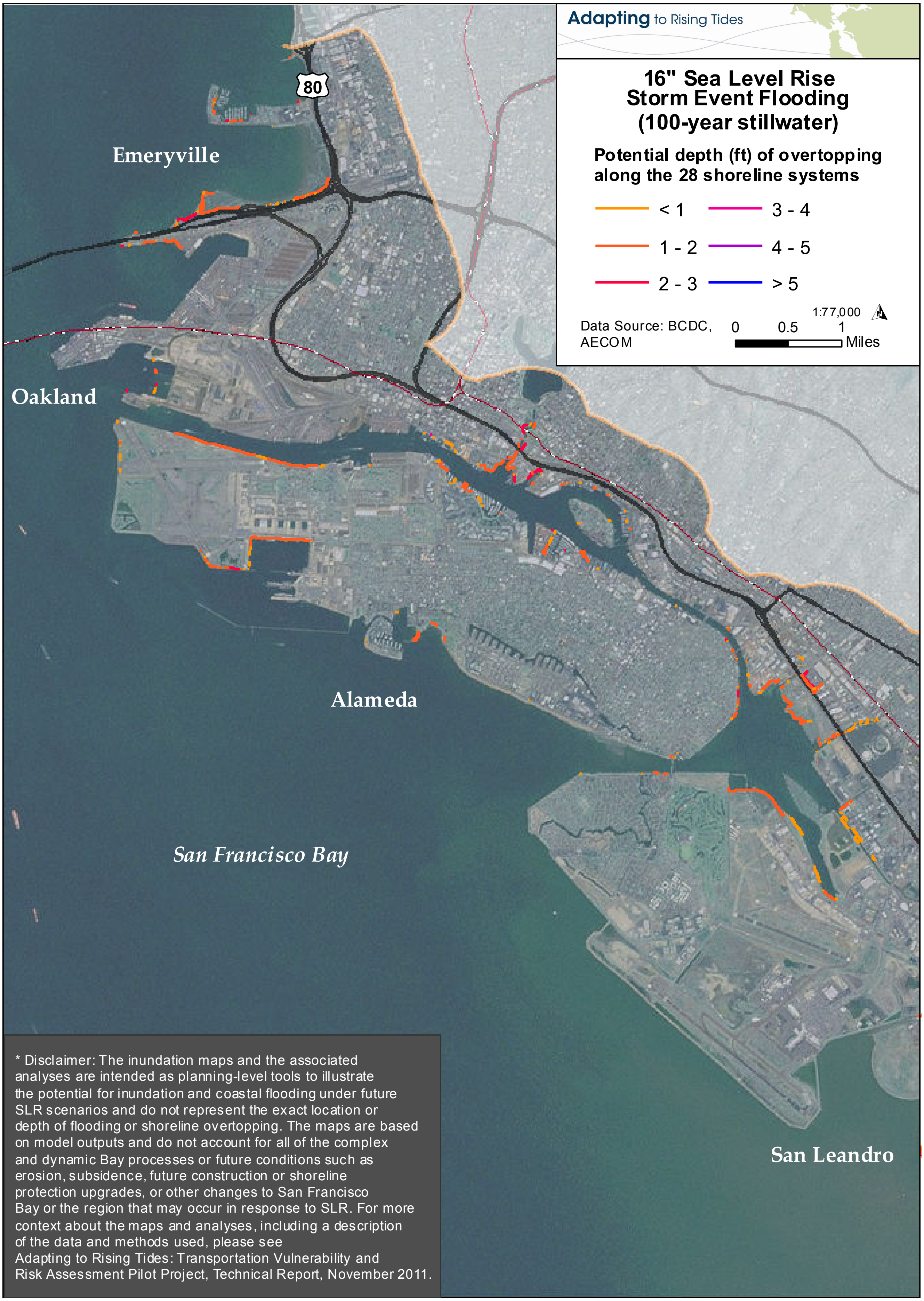
[6] See Chapter 6, Structural Shorelines, for specific examples of how the segment-level analysis was used to understand vulnerability and risk of representative shoreline areas.

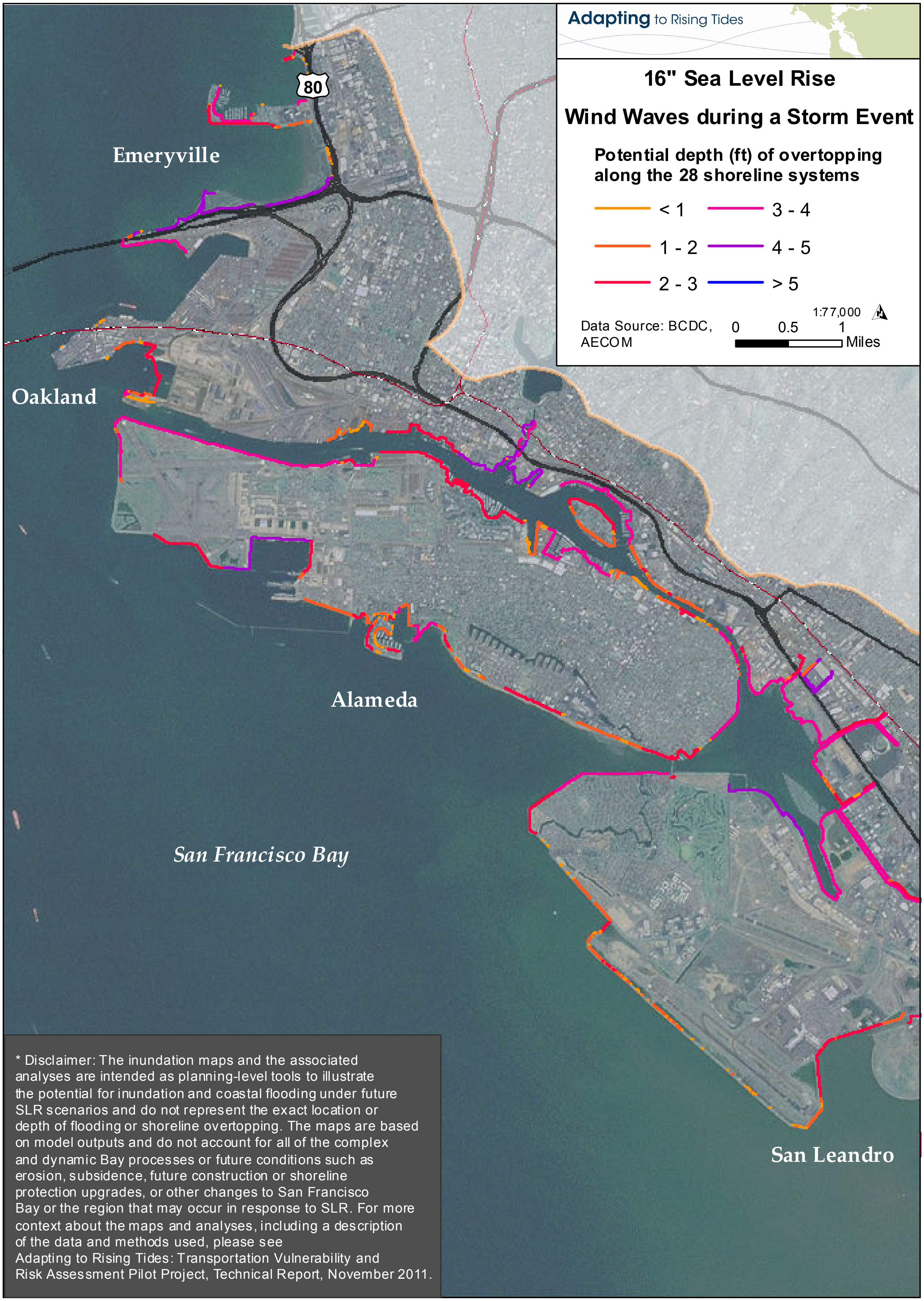
Figure 7. Average (bars) and maximum (circles) depth of overtopping within each system for the six future climate scenarios evaluated.

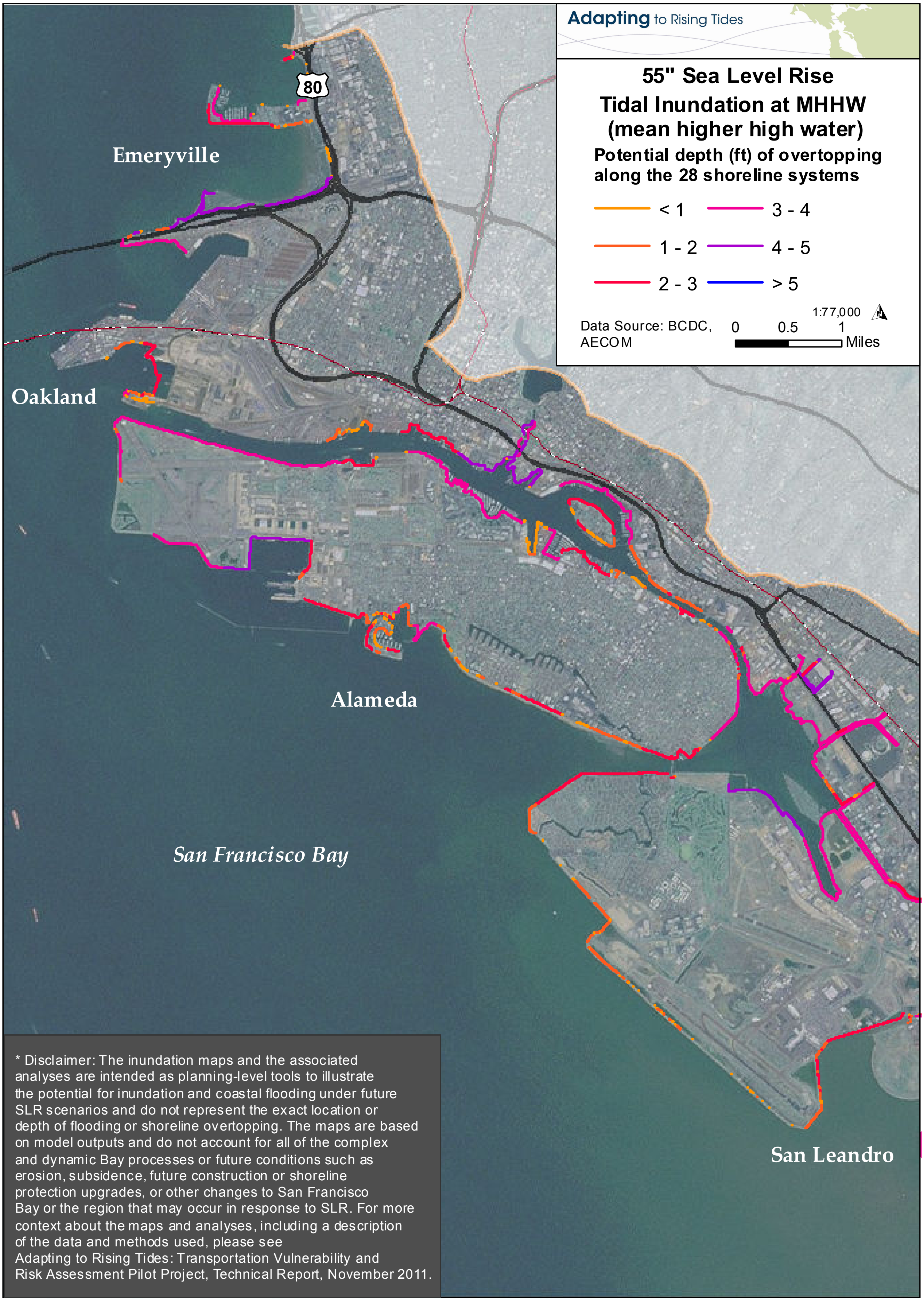


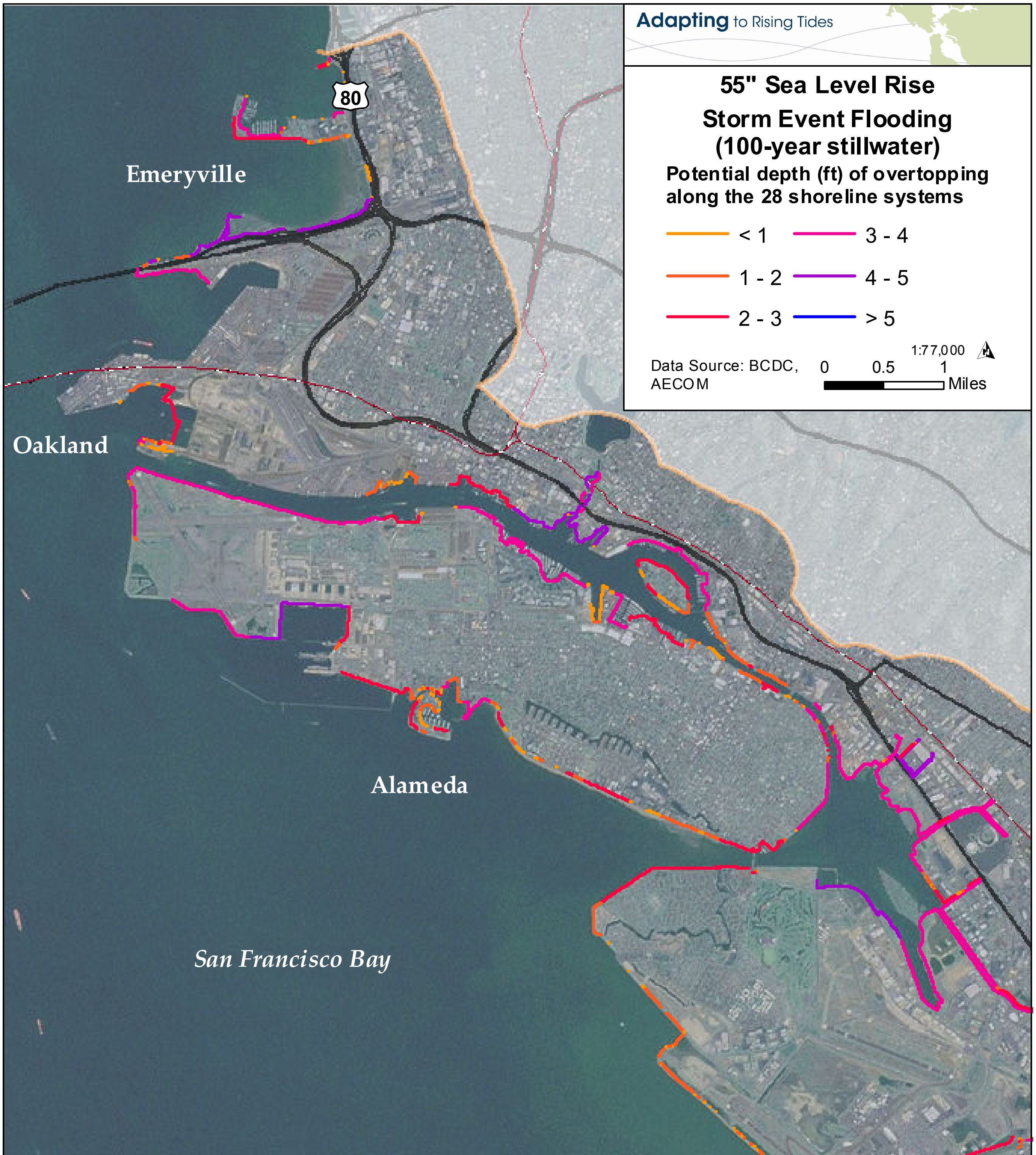
Maps Depicting Average Depth of Potential Overtopping


Adapting to Rising Tides
16" Sea Level Rise
Tidal Inundation at MHHW
(mean higher high water)
Potential depth (ft) of overtopping along the 28 shoreline systems
< 1
1 - 2
2 - 3
3 - 4
4 - 5
> 5
Data Source: BCDC, AECOM
1:77,000
0 0.5 1 Miles
80
24
Emeryville
kland
Alameda
San Francisco Bay
San Leandro
* Disclaimer: The inundation maps and the associated analyses are intended as planning-level tools to illustrate the potential for inundation and coastal flooding under future SLR scenarios and 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 see Adapting to Rising Tides: Transportation Vulnerability and Risk Assessment Pilot Project, Technical Report, November 2011.

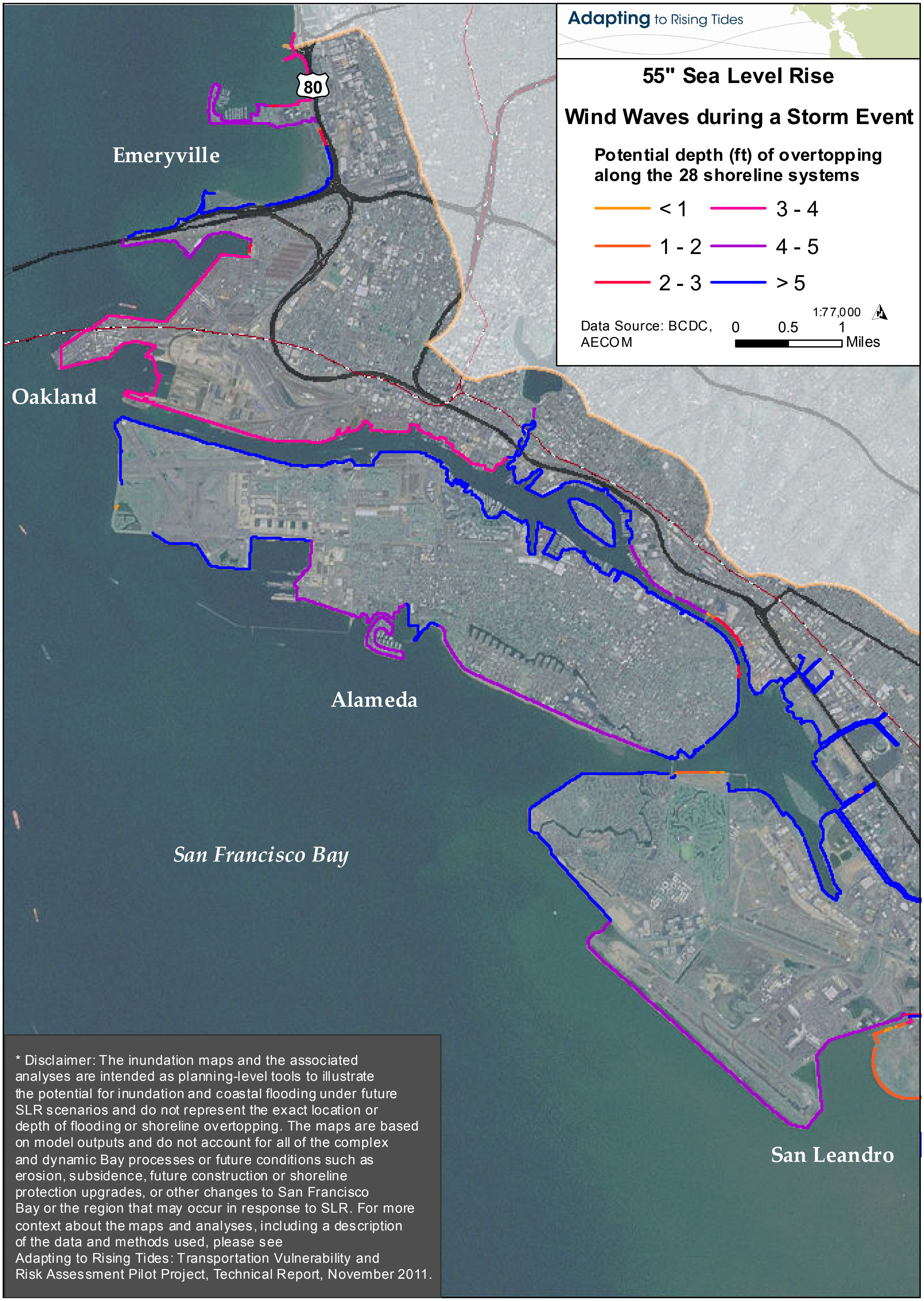

Adapting to Rising Tides
16" Sea Level Rise
Storm Event Flooding
(100-year stillwater)
Potential depth (ft) of overtopping along the 28 shoreline systems
< 1
1 - 2
2 - 3
3 - 4
4 - 5
> 5
Data Source: BCDC, AECOM
1:77,000
0 0.5 1 Miles
80
Emeryville
Oakland
Alameda
San Francisco Bay
San Leandro
* Disclaimer: The inundation maps and the associated analyses are intended as planning-level tools to illustrate the potential for inundation and coastal flooding under future SLR scenarios and 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 see Adapting to Rising Tides: Transportation Vulnerability and Risk Assessment Pilot Project, Technical Report, November 2011.


Adapting to Rising Tides
16" Sea Level Rise
Wind Waves during a Storm Event
Potential depth (ft) of overtopping along the 28 shoreline systems
< 1
3 - 4
1 - 2
4 - 5
2 - 3
> 5
Data Source: BCDC, AECOM
1:77,000
0 0.5 1 Miles
80
Emeryville
Oakland
Alameda
San Francisco Bay
San Leandro
* Disclaimer: The inundation maps and the associated analyses are intended as planning-level tools to illustrate the potential for inundation and coastal flooding under future SLR scenarios and 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 see Adapting to Rising Tides: Transportation Vulnerability and Risk Assessment Pilot Project, Technical Report, November 2011.

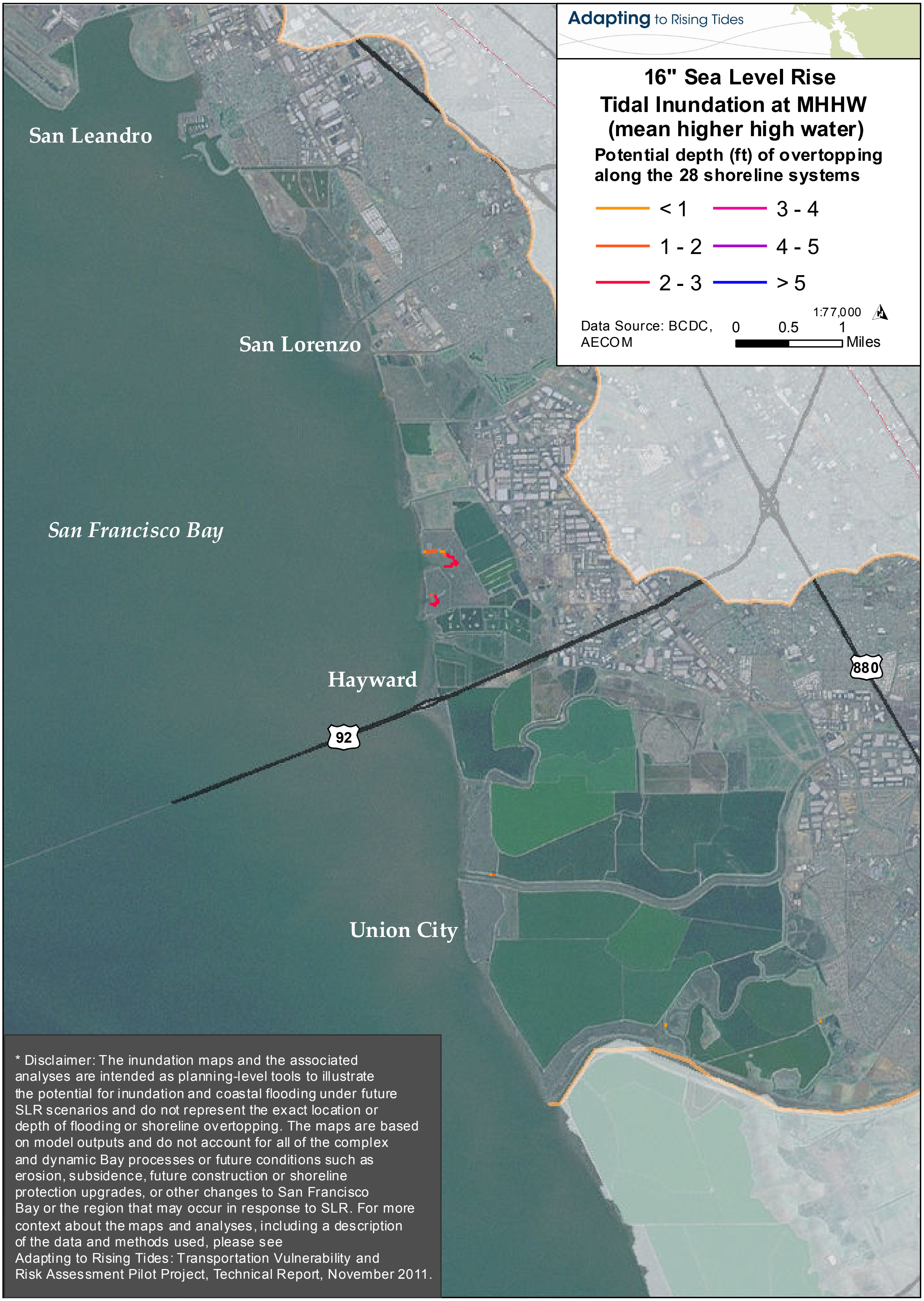

Adapting to Rising Tides
55" Sea Level Rise
Tidal Inundation at MHHW
(mean higher high water)
Potential depth (ft) of overtopping
along the 28 shoreline systems
< 1
3 - 4
1 - 2
4 - 5
2 - 3
> 5
1:77,000
Data Source: BCDC, AECOM
0 0.5 1 Miles
80
Emeryville
Oakland
Alameda
San Francisco Bay
San Leandro
* Disclaimer: The inundation maps and the associated analyses are intended as planning-level tools to illustrate the potential for inundation and coastal flooding under future SLR scenarios and 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 see Adapting to Rising Tides: Transportation Vulnerability and Risk Assessment Pilot Project, Technical Report, November 2011.

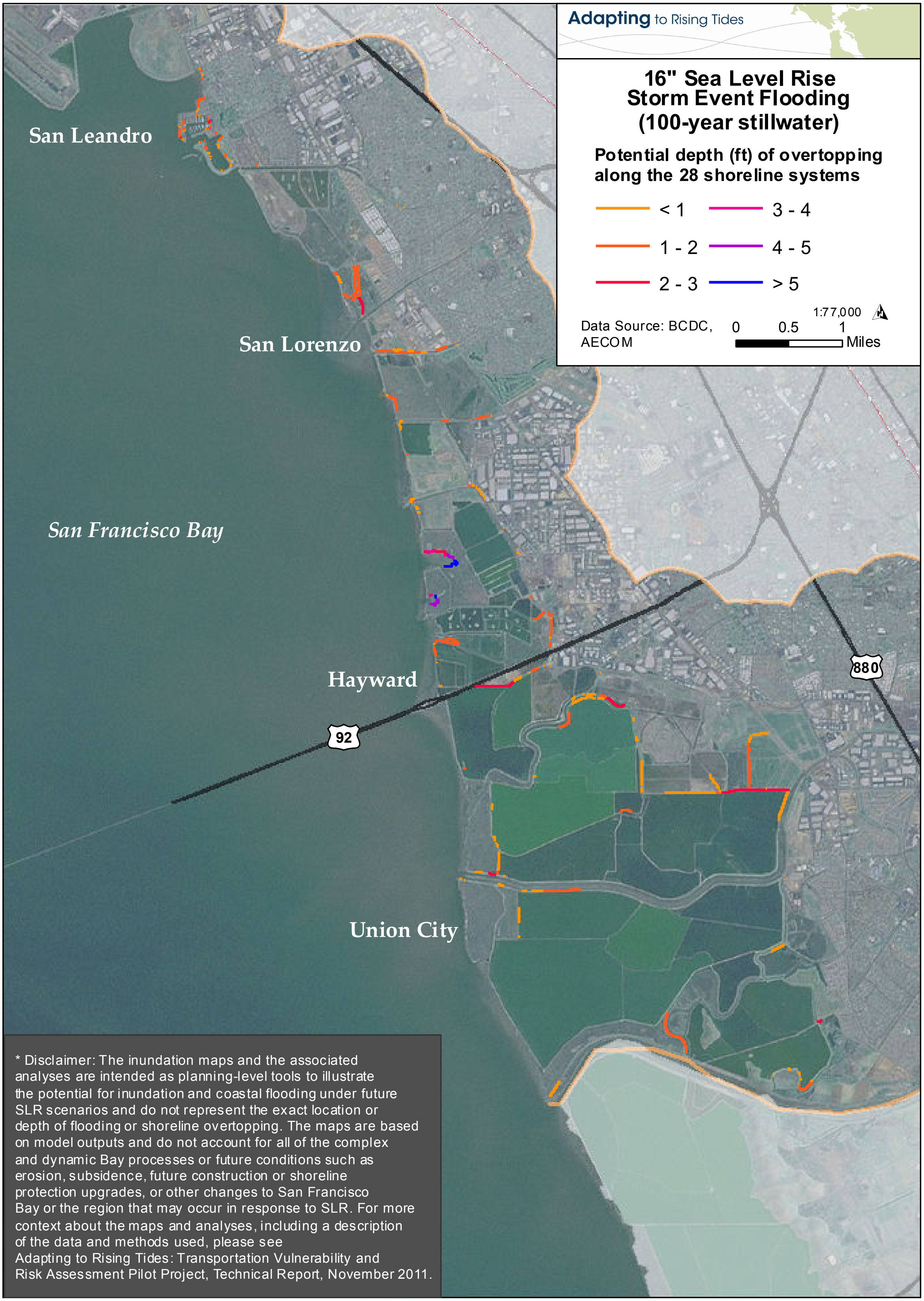


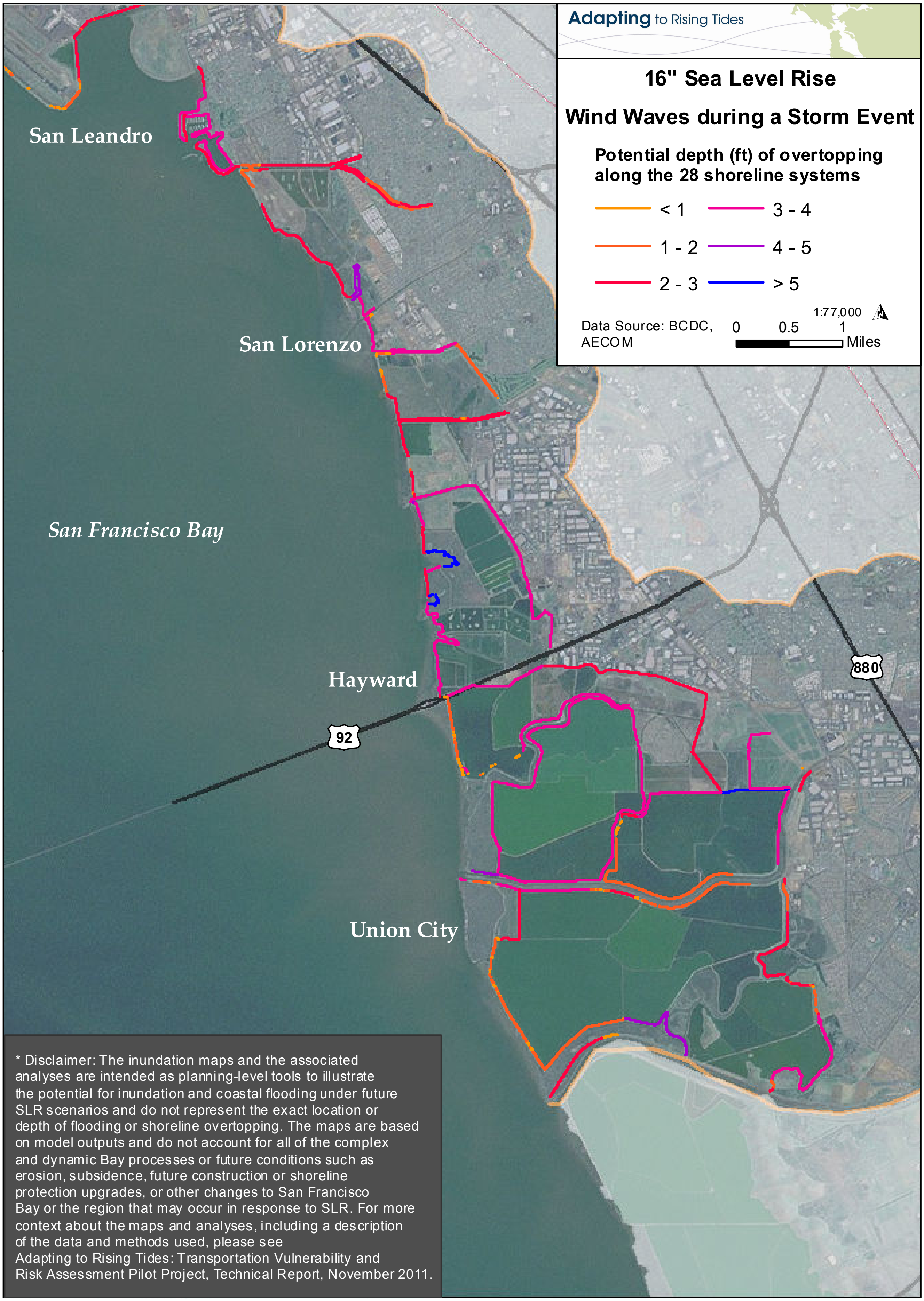
* Disclaimer: The inundation maps and the associated analyses are intended as planning-level tools to illustrate the potential for inundation and coastal flooding under future SLR scenarios and do not represent the exact location or depth of flooding or shoreline overtopping. The maps are based on model 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 see Adapting to Rising Tides: Transportation Vulnerability and Risk Assessment Pilot Project, Technical Report, November 2011.

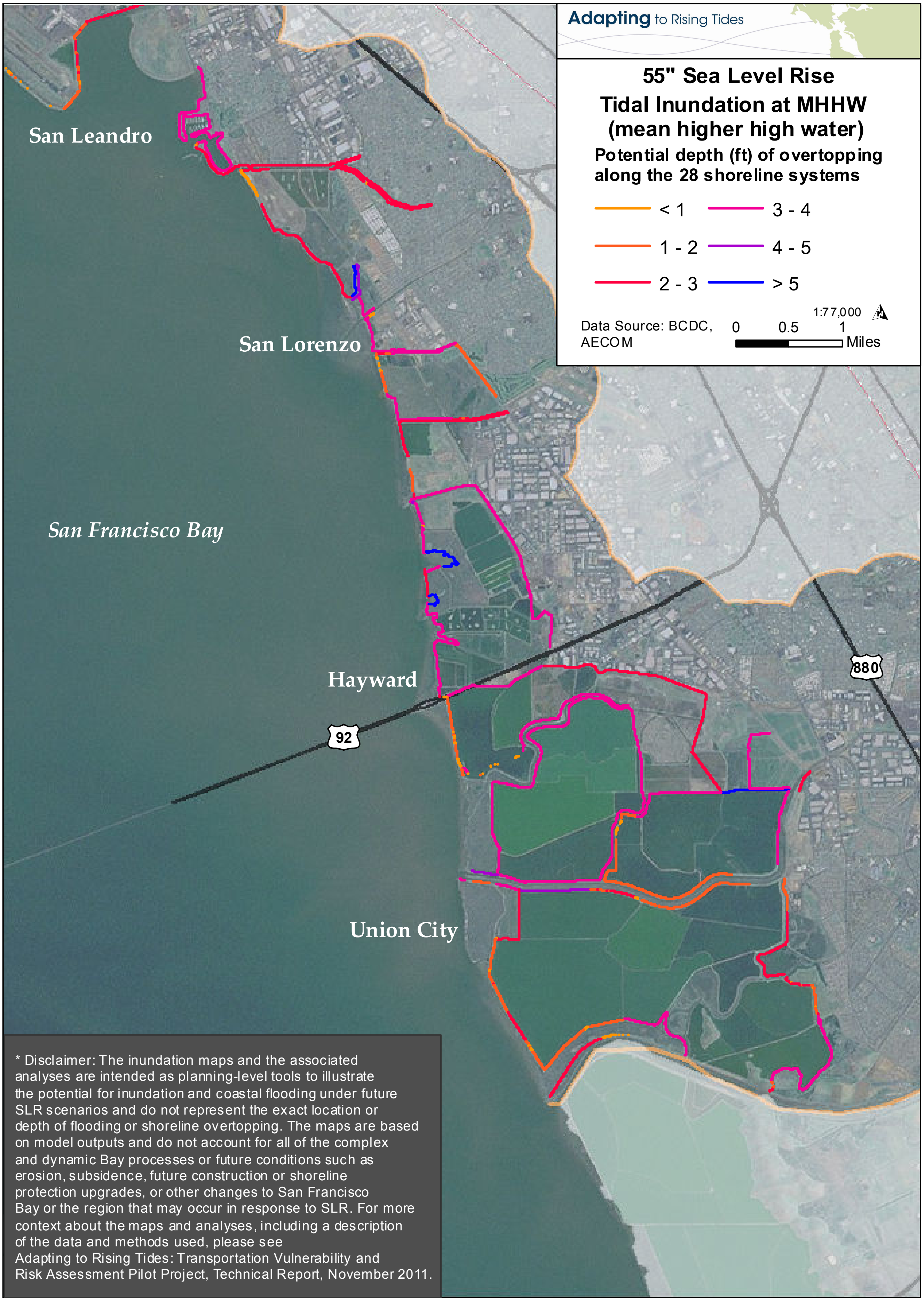


Adapting to Rising Tides
55" Sea Level Rise
Wind Waves during a Storm Event
Potential depth (ft) of overtopping along the 28 shoreline systems
< 1
1 - 2
2 - 3
3 - 4
4 - 5
> 5
Data Source: BCDC, AECOM
1:77,000
0 0.5 1 Miles
80
Emeryville
Oakland
Alameda
San Francisco Bay
San Leandro
* Disclaimer: The inundation maps and the associated analyses are intended as planning-level tools to illustrate the potential for inundation and coastal flooding under future SLR scenarios and 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 see Adapting to Rising Tides: Transportation Vulnerability and Risk Assessment Pilot Project, Technical Report, November 2011.

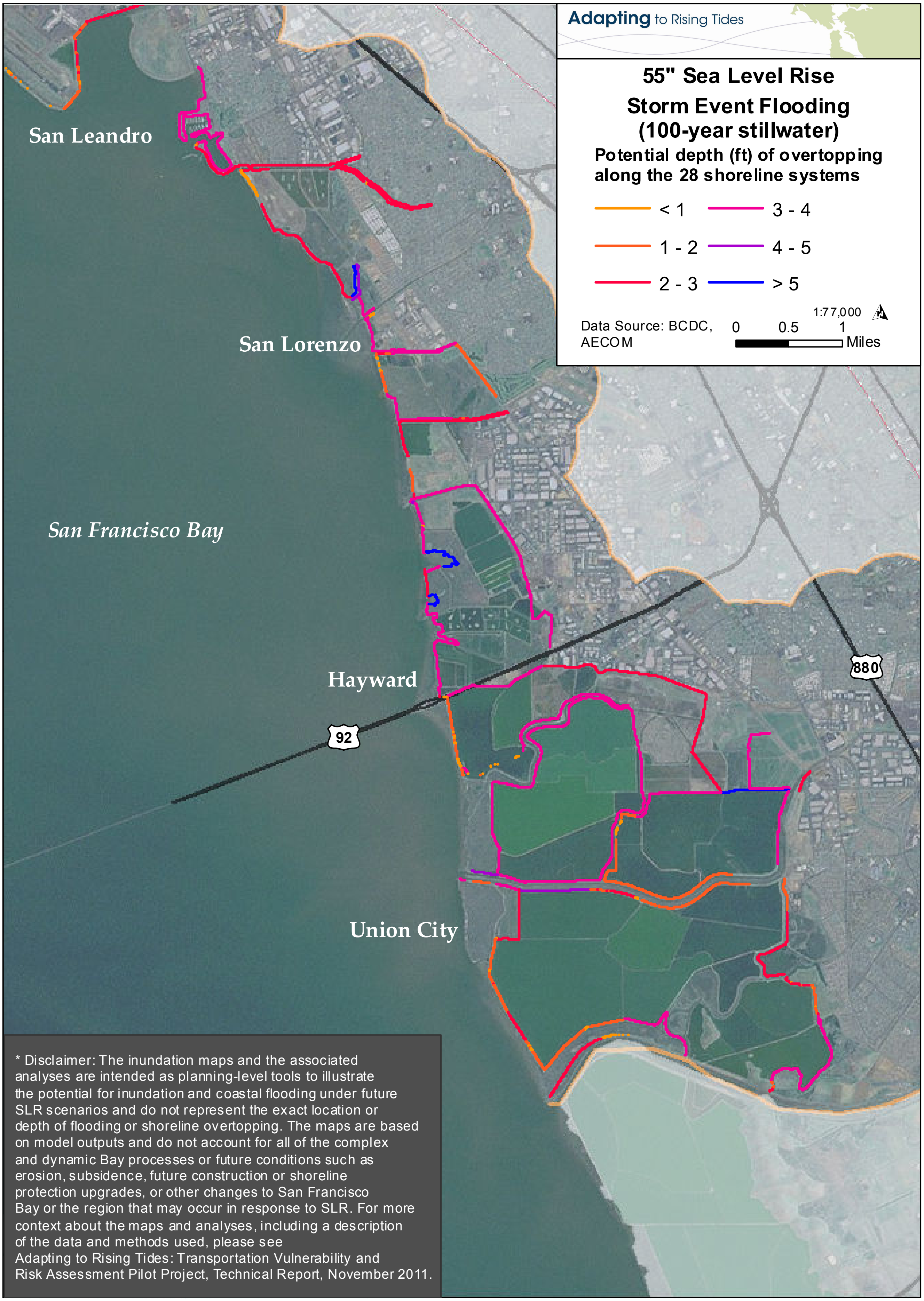

Adapting to Rising Tides
16" Sea Level Rise
Tidal Inundation at MHHW
(mean higher high water)
Potential depth (ft) of overtopping
along the 28 shoreline systems
< 1
3 - 4
1 - 2
4 - 5
2 - 3
> 5
1:77,000
Data Source: BCDC, AECOM
0
0.5
1
Miles
San Leandro
San Lorenzo
San Francisco Bay
Hayward
880
92
Union City
* Disclaimer: The inundation maps and the associated analyses are intended as planning-level tools to illustrate the potential for inundation and coastal flooding under future SLR scenarios and 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 see Adapting to Rising Tides: Transportation Vulnerability and Risk Assessment Pilot Project, Technical Report, November 2011.

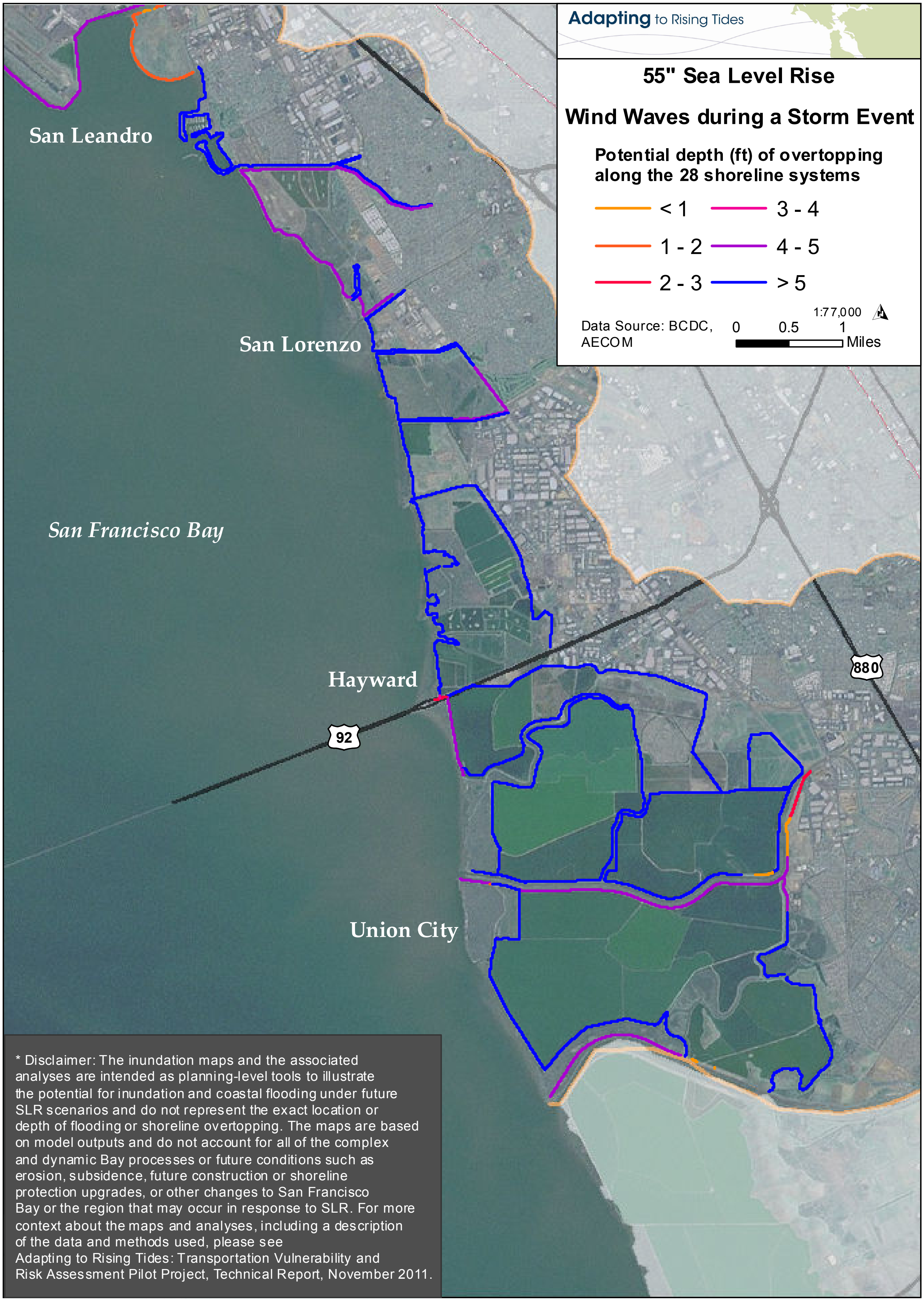

Adapting to Rising Tides
16" Sea Level Rise
Storm Event Flooding
(100-year stillwater)
Potential depth (ft) of overtopping along the 28 shoreline systems
< 1
1 - 2
2 - 3
3 - 4
4 - 5
> 5
Data Source: BCDC, AECOM
1:77,000
0 0.5 1 Miles
San Leandro
San Lorenzo
San Francisco Bay
Hayward
92
880
Union City
* Disclaimer: The inundation maps and the associated analyses are intended as planning-level tools to illustrate the potential for inundation and coastal flooding under future SLR scenarios and 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 see Adapting to Rising Tides: Transportation Vulnerability and Risk Assessment Pilot Project, Technical Report, November 2011.


Adapting to Rising Tides
16" Sea Level Rise
Wind Waves during a Storm Event
Potential depth (ft) of overtopping along the 28 shoreline systems
< 1
1 - 2
2 - 3
3 - 4
4 - 5
> 5
1:77,000
Data Source: BCDC, AECOM
0 0.5 1 Miles
San Leandro
San Lorenzo
San Francisco Bay
Hayward
Union City
92
880
* Disclaimer: The inundation maps and the associated analyses are intended as planning-level tools to illustrate the potential for inundation and coastal flooding under future SLR scenarios and 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 see Adapting to Rising Tides: Transportation Vulnerability and Risk Assessment Pilot Project, Technical Report, November 2011.



Adapting to Rising Tides
55" Sea Level Rise
Tidal Inundation at MHHW
(mean higher high water)
Potential depth (ft) of overtopping
along the 28 shoreline systems
< 1
1 - 2
2 - 3
3 - 4
4 - 5
> 5
Data Source: BCDC, AECOM
1:77,000
0 0.5 1
Miles
San Leandro
San Lorenzo
San Francisco Bay
Hayward
Union City
92
880
* Disclaimer: The inundation maps and the associated analyses are intended as planning-level tools to illustrate the potential for inundation and coastal flooding under future SLR scenarios and 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 see Adapting to Rising Tides: Transportation Vulnerability and Risk Assessment Pilot Project, Technical Report, November 2011.


Adapting to Rising Tides
55" Sea Level Rise
Storm Event Flooding
(100-year stillwater)
Potential depth (ft) of overtopping along the 28 shoreline systems
< 1
1 - 2
2 - 3
3 - 4
4 - 5
> 5
Data Source: BCDC, AECOM
1:77,000
0 0.5 1 Miles
San Leandro
San Lorenzo
San Francisco Bay
Hayward
92
880
Union City
* Disclaimer: The inundation maps and the associated analyses are intended as planning-level tools to illustrate the potential for inundation and coastal flooding under future SLR scenarios and 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 see Adapting to Rising Tides: Transportation Vulnerability and Risk Assessment Pilot Project, Technical Report, November 2011.


Adapting to Rising Tides
55" Sea Level Rise
Wind Waves during a Storm Event
Potential depth (ft) of overtopping along the 28 shoreline systems
< 1
3 - 4
1 - 2
4 - 5
2 - 3
> 5
Data Source: BCDC, AECOM
1:77,000
0 0.5 1 Miles
San Leandro
San Lorenzo
San Francisco Bay
Hayward
92
880
Union City
* Disclaimer: The inundation maps and the associated analyses are intended as planning-level tools to illustrate the potential for inundation and coastal flooding under future SLR scenarios and 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 see Adapting to Rising Tides: Transportation Vulnerability and Risk Assessment Pilot Project, Technical Report, November 2011.

Caveats and Assumptions

There are a number of caveats and assumptions to be considered when using and interpreting the analysis and mapping conducted for the ART project. A summary of these is provided below. A more detailed description of the data, methods, caveats, and assumptions is provided in Appendix B.

- The analysis does not account for potential future changes in Bay hydrodynamics or bathymetry, shoreline topography, erosion, subsidence, future construction, levee upgrades, wetland organic matter accumulation, sediment supply, or sediment deposition/resuspension rates.
- Only the location and height of shoreline protection features was considered. Other criteria, including condition, age, maintenance status, potential for future or planned upgrades, or failure outcomes, were not evaluated.
- The height of topographic features (levee, road embankment, etc) was derived from LIDAR data, downsampled from a 1-meter to a 2-meter horizontal grid resolution. Although this data set represents the best available topographic data, and has undergone rigorous quality assurance/quality control, it has not been extensively ground-truthed. Therefore, levee crests or embankment heights may be overrepresented or underrepresented in the DEM used for the inundation mapping.
- The inundation depth and extent for daily high tide was based on the mean higher high water (MHHW) tidal elevation. This approximates future inundation from the highest 'average' daily high tide. Because there are two high and two low tides in San Francisco Bay on any given day the high tide may be more or less than MHHW.
- The inundation depth and extent for the 100-year storm event was based on the extreme tide level with a 1-percent chance of occurring in any given year. Extreme tide levels with greater return intervals (i.e., 500-year event, with a 0.2-percent chance of occurring in a given year) can also occur, and would result in greater inundation depths and extents.
- The depth of inundation was not determined for storm event with wind waves because the physics associated with overland wave propagation and dissipation were not accounted for due to resource limitations. These processes could have a significant effect on the ultimate depth of inundation associated with large coastal wave events.
- The existing 10-year wave heights were used in the analysis. As sea level rises and Bay water depths increase, the potential for larger waves to develop in nearshore areas will increase, potentially resulting in increased inundation and overtopping.
- The inundation maps do not account for changes in rainfall patterns, frequency or intensity, nor do they consider the effect of localized flooding due to rainfall-runoff events or overbank flooding from local tributaries.
- Based on the uncertainty of the topographic data and the modeling results, only areas inundated or overtopped by depths of 0.5 foot or greater were included in the analyses.
- The analysis of overtopping potential does not account for the physics of wave setup and runup, the condition of the shoreline asset, or the potential the asset will fail due to scour, undermining or a breach after the initial overtopping occurs.
- The overtopping potential analysis does not fully capture the potential consequences on inland areas. Short lengths of overtopped shoreline can potentially cause large inland areas to be inundated, and if overtopping causes a structural failure then even larger areas could be inundated with deeper depths.

Summary and Conclusions

The sea level rise analysis and mapping conducted for the ART project was the foundation for understanding exposure of shoreline communities and assets to sea level rise and storm events. The potential overtopping analysis, which built off of the inundation analysis, provided a high level understanding of the likelihood that specific assets will be exposed if a future climate impacts occur, and helps identify specific shoreline vulnerabilities and risks that need to be further evaluated.

Taken together, the analysis and mapping results provide a generalized picture of exposure along the ART project area, and support the more detailed asset-by-asset analysis of exposure that is necessary for the completion of a vulnerability and risk assessment. In the near-term (i.e., mid-century) exposure of the shoreline to sea level rise will be observed first during storm events, and in particular storm events when extreme water levels are combined wind-driven waves, for example, during a winter storm that coincides with an annual high tide such as the king tide, or during an El Nino year. Further evaluation of specific shoreline areas most vulnerable to near-term climate impacts such as 16 inches of sea level rise can be informed by an analysis of overtopping potential such as the one conducted for the ART project.

The majority of the ART project shoreline is adequately protected against 16 inches of sea level rise at high tide. However there are specific locations, representing less than 1% of the total shoreline evaluated (1.2 miles), that will overtop with depths of less then one foot on average. The level of flood protection is greatly reduced if there is a storm event, and even further if there are wind waves during the storm event. For the particular storm event evaluated (i.e., a storm resulting in a 100-year extreme water level) the extent of shoreline exposed and the depth of overtopping increases (21%, or 26 miles, with an average depth of 1 foot); however, with the addition of wind waves 77% of the shoreline (96.7 miles) will overtop with average depths of 3 feet. The widespread and relatively significant depth of inundation of the shoreline system due to overtopping during a storm event with wind waves translates to large inland areas potentially exposed.

With 55 inches of sea level rise, a little more than one third of the shoreline will overtop (36%). However this represents a fairly significant length of shoreline protection (45.7 miles). During a storm event 75% of the shoreline will overtop (96.2 miles), and if there are wind waves nearly the entire shoreline will overtop (96%, 121 miles). On average, there will be 3 feet of overtopping during a storm event (with a range of 1.7 to 4.2 feet). However, this will increase to 5 feet (with a range of 1.9 to 7.3 feet) if there are wind waves. For the worst case observed (system #23, located at the Hayward Regional Shoreline), the average depth of overtopping during a storm event is 3.7 feet, with a maximum depth of 8.8 feet. These depths, which increase with wind waves to an average of 6.8 and a maximum of 11.6 feet, are significant and reflect the potential challenges this portion of the shoreline will face in developing long-term adaptation response strategies.

The results of the overtopping potential analysis do not necessarily correlate to the magnitude of the potential consequences to inland areas from the future climate scenarios evaluated. Not only could shoreline protection systems be improved or enhanced, but they also could be subjected to failure due to repeated exposure to higher tides, stronger currents and increased wave activity. Depending on the location of the overtopping, and if there is a partial or total failure of a shoreline protection asset, the impact on inland areas could be much greater with larger inland areas inundated at greater depths then determined in the current analysis.

The effect of rising sea levels on the shoreline will be observed on a regular basis during the highest of high tides. Further assessments of sea level rise and storm events impacts in the ART project area would benefit from a decision-based approach that uses specific scenarios focused on known thresholds of impact or asset-specific tolerance levels. For example, based on the overtopping potential analysis it may become clear that specific reaches of shoreline are vulnerable to threshold amounts of sea level rise. Using that information, further analysis of the specific tide and storm conditions, and the potential timing and likelihood of those events, would help to prioritize further evaluation of vulnerabilities and development of specific adaptation response solutions.

The analysis and mapping conducted for the ART project used a scenario-based planning approach, with six scenarios focused on two future time frames evaluated. Longer term and more in-depth planning processes that include more detailed and refined studies of particular thresholds of impacts, including specific tide and storm event conditions, will be required to adequately plan for end-of-century climate impacts.

References

Adapting to Rising Tides: Transportation Vulnerability and Risk Assessment Pilot Project. November 2011. Prepared by AECOM and Arcadis for the San Francisco Bay Conservation and Development Commission, Metropolitan Transportation Commission and the California Department of Transportation. Available at http://www.mtc.ca.gov/news/current_topics/10-11/sea_level_rise.htm.

Marcy, Douglas, William Brooks, Kyle Draganov, Brian Hadley, Chris Haynes, Nate Herold, John McCombs, Matt Pendleton, Sean Ryan, Keil Schmid, Mike Sutherland, and Kirk Waters. 2011. "New Mapping Tool and Techniques for Visualizing Sea Level Rise and Coastal Flooding Impacts." In *Proceedings of the 2011 Solutions to Coastal Disasters Conference, Anchorage, Alaska, June 26 to June 29, 2011*, edited by Louise A. Wallendorf, Chris Jones, Lesley Ewing, and Bob Battalio, 474–90. Reston, VA: American Society of Civil Engineers.

The Nature Conservancy and NOAA National Ocean Service Coastal Services Center, 2011, Marshes on the move: A manager's guide to understanding and using model results depicting potential impacts of sea level rise on coastal wetlands. Available at: www.csc.noaa.gov/publications/Marshes_on_the_move.pdf

National Oceanic and Atmospheric Administration Coastal Services Center. August 2009. Coastal Inundation Mapping Guidebook. Available online at: