Adapting to Rising Tides

Alameda County Shoreline Vulnerability Assessment

Final Report • May 2015

Flood Control & Water Conservation District

bcdc

Acknowledgments

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EXECUTIVE SUMMARY

Alameda County has been the focus of several collaborative efforts between the Alameda County Flood Control and Water Conservation District (ACFCWCD), San Francisco Bay Conservation and Development Commission (BCDC), Metropolitan Transportation Commission (MTC), California Department of Transportation District Number 4 (Caltrans District 4), and San Francisco Bay Area Rapid Transit (BART). The purpose of these efforts is to understand, refine, and enhance our understanding of climate change related risks, with an emphasis on future sea level rise and storm surge impacts. Through these collective efforts, a stepwise and systematic approach for investigating shoreline resilience has been developed:

1. Use regional sea level rise and storm surge inundation maps to conduct high-level shoreline assessments.
2. Ground truth findings with local experts, and flag locations where the inundation maps do not represent local, on the ground knowledge of past flood events.
3. Conduct refined shoreline analyses to assess more-detailed vulnerabilities and identify locations where short-term actions would provide benefits.
4. Identify resilience building actions and implementation options that can reduce shoreline vulnerabilities.
5. Investigate the feasibility of resilience building actions.

The Adapting to Rising Tides Transportation Vulnerability and Risk Assessment Pilot Project, funded through a grant with the Federal Highway Administration (FHWA), focused on Step 1 of this process for a portion of Alameda County. This effort was completed in November 2011. Through this initial pilot project, three focus areas were selected for more detailed analysis (Steps 2 through 5). However, based on lessons learned from the Adapting to Rising Tides project, additional exposure information was required to complete a more robust shoreline assessment, and to inform the timing and need of potential climate adaptation projects and resilience building actions. Alameda County, through collaboration with BCDC, completed the additional analyses required to inform the focus area analyses, while also providing an overall enhanced data set for understanding county-wide shoreline vulnerabilities. BCDC's contributions to this report were funded through a Coastal Impacts Assessment Program grant[1]. Alameda County's contributions were funded through the Alameda County Public Works Agency. These combined efforts are the focus this report.

To support the stepwise approach for investigating shoreline, new sea level rise and storm surge inundation maps were created for Alameda County using an innovative approach that allows one map to represent multiple potential future sea level rise and storm surge scenarios. This approach considers sea level rise scenarios from 6 to 60 inches, and storm surge events from the 1-year extreme tide to the 500-year coastal storm surge event. In addition, a shoreline delineation approach was used to assess shoreline type and overtopping potential. This information is used to highlight where along the shoreline adaptation strategies may be warranted, and to inform when in time intervention may be required to reduce potential future inland flooding risks, and what type of strategies may be appropriate based on the existing shoreline features and topology. The final appendix of this report provides an illustrative example of how these data sets can support Steps 2 through 5 for a focus area within the county -- from the initial shoreline assessment, through identification of potential conceptual adaptation options, to

[1] The work completed by the San Francisco Bay Conservation and Development Commission was funded with qualified outer continental shelf oils and gas revenues by the Coastal Impacts Assessment Program, Fish and Wildlife Service, and the U.S. Department of the Interior.

an assessment of implementation feasibility and next steps. The focus area (the San Francisco-Oakland Bay Bridge Touchdown Focus Area) was completed under the Climate Change and Extreme Weather Adaptation Options Pilot Project, funded through a grant with the FHWA. This project was led by MTC, in partnership with BCDC, Caltrans District 4, and BART.

Although the work presented in this report can inform near-term actions to address sea level rise and storm surge vulnerabilities along the shoreline, it can also inform when (i.e., at what level of sea level rise), we pass a tipping point where discrete actions along the shoreline are no longer sufficient to address these growing threats. As sea levels rise past this tipping point, regional solutions that include collaboration across broad geographic scales will be required. This study, and the regional and agency collaboration that has occurred to date, are an important step for expanding these discussions. At the time of publication of this report, two Bay Area wide efforts are already in progress to expand the work completed in Alameda County to a regional scale: the U.S. Department of Homeland Security's Federal Emergency Management Agency (FEMA) is completing a tidal datums study for the entire San Francisco Bay, and the San Francisco Estuary Institute is completing the shoreline delineation by type as part of their Flood Infrastructure Mapping Project for seven of the nine Bay Area counties (the Alameda County shoreline delineation was completed as part of this report, and the San Francisco County shoreline delineation was completed as part of the San Francisco Public Utilities Commission's Sewer System Improvement Program Climate Adaptation Plan).

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Jack London Square at the end of Broadway during a King Tide

1.0

INTRODUCTION

1. INTRODUCTION

Alameda County has been the focus of several collaborative efforts between the Alameda County Flood Control and Water Conservation District (ACFCWCD), San Francisco Bay Conservation and Development Commission (BCDC), Metropolitan Transportation Commission (MTC), California Department of Transportation District Number 4 (Caltrans District 4), and San Francisco Bay Area Rapid Transit (BART). The purpose of these efforts is to understand, refine, and enhance our understanding of climate change related risks, with an emphasis on future sea level rise and storm surge impacts. The report builds upon the award-winning Adapting to Rising Tides Transportation Vulnerability and Risk Assessment Pilot Project (ART)[1], completed in November 2011 (AECOM 2011). In addition, this report provides the updated exposure information that supported the follow-on Climate Change and Extreme Weather Adaptation Options for Transportation Assets in the Bay Area Pilot Project (AECOM 2014b).[2]

Based on lessons learned from the ART Project, additional exposure information was required to complete a more robust shoreline assessment, and to inform the timing and need of potential climate adaptation projects and resilience building actions. Alameda County, through collaboration with BCDC, completed the additional analyses required to inform more detailed focus area analyses, while also providing an overall enhanced data set for understanding county-wide shoreline vulnerabilities. BCDCs contributions to this report were funded through a Coastal Impacts Assessment Program grant[3]. Alameda County's contributions were funded through the Alameda County Public Works Agency. These combined efforts are the focus this report.

This study includes a broader assessment of shoreline exposure than the predecessor ART project, including consideration of sea level rise scenarios ranging from 6 to 60 inches, and storm surge events from the 1-year extreme tide event to the 500-year coastal storm surge event. Shoreline exposure to oceanic climate change stressors (e.g., sea level rise and storm surge) can be characterized by the magnitude and frequency of inundation. Permanent *inundation* occurs when an area is regularly covered by daily tidal fluctuations. As sea level rises, additional areas will potentially be subjected to permanent inundation. In contrast, *flooding* occurs when an area is exposed to episodic, short duration, extreme tide events of greater magnitude than normal tide levels. Inland areas may be temporarily flooded during an extreme tidal event, while maintaining at least a portion of their functionality once the floodwaters recede. The analyses presented in this report show that, as sea levels rise, shoreline assets will become increasingly exposed to extreme tide levels, and will no longer provide the same level of flood protection as they do today. For example, the analysis demonstrates that with 20 inches of sea level rise, the Bay water level associated with today's 100-year extreme tide level will occur with, approximately, a 20-year extreme tide event. Such shifts in the frequency of extreme tide levels will have important design implications for flood protection infrastructure, and for the resilience and persistence of valuable shoreline habitats. The datasets and information provided in this report can inform design and operational

[1] MTC, in partnership with the BCDC and Caltrans District 4, were awarded a grant from the Federal Highway Administration for a pilot study to assess the vulnerability of transportation assets within the Alameda County sub-region to climate change impacts. The final report was released in Nov 2011. This work won three prestigious awards in 2012 from the American Planning Association, Northern California Section; Association of Environmental Professionals, California Chapter; and the Climate Chance Business Journal.

[2] MTC, in partnership with BCDC, Caltrans District 4, and BART, were awarded a grant from the Federal Highway Administration for a pilot study to assess climate change and extreme weather vulnerability and adaptation options for transportation infrastructure in the Alameda County sub-region. The final report was released in December 2014. This work won a prestigious Award of Excellence for Best Practices in 2015 from the American Planning Association, Northern California Section.

[3] The work completed by the San Francisco Bay Conservation and Development Commission was funded with qualified outer continental shelf oils and gas revenues by the Coastal Impacts Assessment Program, Fish and Wildlife Service, and the U.S. Department of the Interior.

strategies, assist in managing climate change-related risks, and help identify trigger points for implementing adaptation strategies to increase the likelihood that a consistent level of flood protection can be provided over the coming decades and into the next century.

1.1 STUDY GOALS

Through the collective efforts of the various project partners, a stepwise and systematic approach for investigating shoreline resilience has been developed:

1. Use regional sea level rise and storm surge inundation maps to conduct high-level shoreline assessments.
2. Ground truth findings with local experts and flag locations where the inundation maps do not represent local, on the ground knowledge of past flood events.
3. Conduct refined shoreline analyses to assess more-detailed vulnerabilities and identify locations where short-term actions would provide benefits.
4. Identify resilience building actions and implementation options that can reduce shoreline vulnerabilities.
5. Investigate the feasibility of resilience building actions.

The ART Project focused on Step 1 of this process for a portion of Alameda County. The goal of this study was to develop the datasets and tools needed to support Steps 1, 2 and 3, and to expand the coverage of the datasets and tools to the entire Alameda County shoreline. To meet these goals, new sea level rise and storm surge inundation maps were created for Alameda County using an innovative approach that allows one map to represent multiple potential future sea level rise and storm surge scenarios (supports Step 1). Using local knowledge, areas where the maps do not accurately represent past coastal flood events, such as inundation that occurs along the shoreline during King Tides, the underlying data can be examined to refine the maps to more truthfully portray existing vulnerabilities (Step 2). In addition, the shoreline delineation approach developed for the ART Project to assess both shoreline type and overtopping potential can be used to highlight where along the shoreline adaptation strategies may be warranted, and to inform when intervention may be required to reduce potential future inland flooding risks, and what type of strategies may be appropriate based on the existing shoreline features and topology (Step 3).

1.2 OVERVIEW OF REPORT

The following sections summarize the sea level rise science,

- **Section 2. Sea Level Rise Science** provides an overview of the sea level rise and coastal hazards, a summary of the state of the science, and a discussion of sea level rise scenario selection.
- **Section 3. Inundation Mapping** describes the leveraged model data, water level analysis, topographic data, and the inundation mapping methods used to create the sea level rise inundation maps.
- **Section 4. Shoreline Delineation** describes the shoreline delineation approach by type (e.g., engineered flood protection structure, non-engineered berm, etc.)
- **Section 5. Shoreline Overtopping Potential** describes the methods used to calculate overtopping potential along the shoreline (and adjacent areas) and outlines applications of the maps to identity potential shoreline vulnerabilities.
- **Section 6. Shoreline Exposure Analysis** presents the normalized shoreline approach for assessing shoreline exposure and vulnerabilities in between mapped inundation scenarios.

- **Section 7. Mapping Assumptions and Caveats** provides key caveats associated with the overall approach for developing sea level rise and storm surge inundation maps that are appropriate as a screening-level tool for assessing exposure.
- **Section 8. Conclusions and Next Steps** provides a summary of the developed approach, as well as an introduction to the more detailed focused area analyses completed using these data. The focus area studies are included as additional appendices.
- **Section 9.** References

1.3 ACRONYMS/ABBREVIATIONS

ACFCWCD	Alameda County Flood Control and Water Conservation District
AFCC	Alameda Flood Control Channel
AR5	The IPCC's Fifth Assessment Report (IPCC 2013)
ART	Adapting to Rising Tides project
BART	Bay Area Rapid Transit
Bay	San Francisco Bay
Bay Area	San Francisco Bay Area
BCDC	San Francisco Bay Conservation and Development Commission
Caltrans	California Department of Transportation, District 4
CCC	California Coastal Commission
CCAMP	California Coastal Analysis and Mapping Project
CCMP	California Coastal Mapping Program
DEM	digital elevation model
FEMA	U.S. Department of Homeland Security's Federal Emergency Management Agency
FHWA	Federal Highway Administration
ft	feet
GEV	Generalized Extreme Value
GHG	greenhouse gas
GIS	Geographic Information System
IPCC	International Panel on Climate Change
LiDAR	light detection and ranging
m	meter(s)
MHHW	mean higher high water
MLLW	mean lower low water
MLI	Midterm Levee Inventory
MTC	Metropolitan Transportation Commission
NAVD88	North American Vertical Datum of 1988
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NTDE	National Tidal Datum Epoch
RMSE	Root Mean Square Error
SFEI	San Francisco Estuary Institute
USGS	United States Geological Survey

1.4 GLOSSARY

Annual Maxima: The highest water level recorded during each year in a time series based on a July through June “storm year.”

El Niños (within the ENSO cycle): a phenomenon in the Pacific Ocean characterized by warmer than usual waters in the Eastern Pacific. They are caused by specific changes in winds and currents across the equatorial Pacific, driven by an oscillation in air pressure differences across the Eastern and Western Pacific called the Southern Oscillation (SO). El Niños may result in higher sea levels and larger, more frequent storms over the affected region.

Extreme Tide: Extreme tides are relatively infrequent water level events that are a result of relatively high astronomical tides coupled with a storm surge event. The absolute elevations reached during these events are due to short-term meteorological processes (such as low atmospheric pressure due to storms) and large-scale oceanographic conditions (such as King Tides or El Niño-Southern Oscillation). The extreme tide elevations discussed in this assessment do not include any wave effects.

Hydrodynamic Zones: Due to the Bay’s geometry and hydrodynamics, tidal characteristics vary spatially. Tides are amplified in the South Bay, and daily Mean High Higher Water (MHHW) and extreme tide elevations increase from north to south along the Alameda County shoreline. Regions of roughly similar hydrodynamic characteristics are referred to as “hydrodynamic zones.” The analysis within each hydrodynamic zone is averaged to simplify application of the results.

Mean Higher High Water (MHHW): Average height of the higher high tides of each day during the current National Tidal Datum Epoch.

Normalized Extreme Tide Curves: Normalizing elevation data allows the original data to be compared using a different scale. Elevation data is normalized by dividing each elevation value by a common denominator. For example, in San Francisco Bay, both the MHHW tide level and the 100-year tide level vary spatially. The absolute elevation of both daily and extreme tides increases from north to south within Alameda County; however, the ratio of a given extreme tide to MHHW is relatively constant across large geographic areas. For example, the ratio of the 100-year tide level divided by the MHHW tide level (the common denominator) is approximately constant within each hydrodynamic zone identified in this study (approximately 10.0 ft / 6.5 ft = 1.5). Normalized extreme tide curves were created to show the elevations of a 1-year through 100-year extreme tide event normalized to the MHHW elevation for both existing conditions and future conditions with sea level rise. The normalized elevation data allows comparisons across different spatial areas.

Normalized Shoreline Elevation: Similar to the approach taken to normalize the extreme tide curves, shoreline elevation data can also be normalized by dividing each shoreline elevation value by the local MHHW tide level. By normalizing the shoreline asset elevations, the asset’s flooding threshold can be determined by comparing the “normalized shoreline elevation” to the normalized extreme tide curve. A normalized elevation value of 1.0 indicates an elevation equal to the local MHHW tide level. A normalized elevation value greater than 1.0 indicates an elevation above the local MHHW tide level, while a value less than 1.0 is below MHHW. The normalized shoreline elevation maps and extreme tide curves can be used together to assess exposure to flooding.

Overtopping Potential Calculation: Overtopping potential refers to the condition where the water surface elevation associated with a particular sea level rise scenario exceeds the elevation of the shoreline asset. Overtopping potential does not account for the physics of wave runup and overtopping. It also does not account for potential vulnerabilities along the shoreline protection infrastructure that could result in complete failure of the flood protection infrastructure through scour, undermining, or breach after the initial overtopping occurs. The overtopping potential results visually show which segments of the shoreline are first impacted, and the depth that each segment is overtopped during the mapped scenarios.

Storm Surge: A storm surge is an abnormal rise of water generated by high winds and low atmospheric pressure in the presence of a storm, over and above the predicted astronomical tide. The magnitude of a storm surge and the height of an astronomical tide are additive: when the sum of the two is unusually large, an Extreme Tide occurs.

Tidal Datum: A tidal datum is the daily tide water level computed using records observed during the current National Tidal Datum Epoch (NTDE), which is a specific 19-year period (1983-2001) adopted by the National Oceanic and Atmospheric Administration (NOAA) to perform tidal computations.

Tides: The regular upward and downward movement of the level of the ocean due to the gravitational attraction of the moon and the sun and the rotation of the earth. Also called “astronomical tides.” The San Francisco Bay experiences two high tides and two low tides each day.

2.0

SEA LEVEL RISE SCIENCE

2. SEA LEVEL RISE SCIENCE

2.1 SUMMARY OF THE SCIENCE

The science associated with sea level rise is continually being updated, revised, and strengthened. Although there is no doubt that sea levels have risen and will continue to rise at an accelerated rate over the coming century, it is difficult to predict with certainty what amount of sea level rise will occur within any given time frame. The uncertainties increase over time (e.g., the uncertainties associated with 2100 projections are greater than with 2050 projections) because of uncertainties in future greenhouse gas (GHG) emissions trends, the sensitivity of climate conditions to GHG concentrations, and the overall capabilities of climate models. The sea level rise projections presented in this document draw on the best available science on the potential effects of sea level rise in California as of April 2015.

In March 2013, the California Ocean Protection Council adopted the 2012 National Research Council (NRC) Report *Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future* as the best available science on sea level rise for the state (Ocean Protection Council 2013). The California Coastal Commission also supported the use of the NRC 2012 report as best available current science, noting that the science of sea level rise is continually advancing and future research may enhance the scientific understanding of how the climate is changing, resulting in the need to regularly update sea level rise projections (California Coastal Commission 2013). The NRC report includes discussions of historic sea level rise observations, three likely sea level rise projections for the coming century, high and low extremes for sea level rise, and insight into the potential impacts of a rising sea for the California coast. After the release of the NRC report and the development of the draft Coastal Commission guidance, the International Panel on Climate Change (IPCC) released the Fifth Assessment Report (AR5), *Climate Change 2013: The Physical Science Basis*, which provides updated consensus estimates of global sea level rise (IPCC 2013).

Table 2-1 presents the NRC sea level rise projections for San Francisco relative to the year 2000, which can be applied to Alameda County. The table presents the local *projections* (mean ± 1 standard deviation). These projections (for example, 6 ± 2.0 inches in 2030) represent the *likely* sea level rise values based on a moderate level of greenhouse gas emissions and extrapolation of continued accelerating land ice melt patterns, plus or minus one standard deviation. The extreme limits of the *ranges* (for example, 2 and 12 inches for 2030) represent *unlikely but possible* levels of sea level rise using both low and very high emissions scenarios and, at the high end, including significant land ice melt that was not anticipated at the time of publication but were acknowledged as having potential to occur. The NRC report is also notable for providing regional estimates of *net sea level rise* for the Oregon, Washington, and California coastlines that include the sum of contributions from the local thermal expansion of seawater, wind-driven components, land ice melting, and vertical land motion. The chief differentiator among net sea level rise projections along the western coast derives from vertical land motion estimates, which show uplift (reducing net sea level rise) of lands north of Cape Mendocino and subsidence (increasing net sea level rise) of lands south of Cape Mendocino.

The NRC ranges are higher than the global estimates presented in IPCC AR5, while the projections in the NRC report are similar to IPCC estimates. At this time, the use of NRC projections and ranges is appropriate for Alameda County because they encompass the best available science, they have been derived considering local and regional processes and conditions, and their use is consistent with current state guidance.

Table 2-1. Sea Level Rise Estimates Relative to the Year 2000

Year	Projections	Ranges
2030	6 ± 2 in	2 to 12 in
2050	11 ± 4 in*	5 to 24 in
2100	36 ± 10 in	17 to 66 in

Source: NRC, 2012. *Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future*.

* As a simplifying assumption, the 2050 most likely value selected for the inundation mapping effort is 12 inches rather than the 11-inch value noted in the table.

2.2 SEA LEVEL RISE AND COASTAL HAZARDS

In addition to sea level rise, consideration must be given to storm surge and waves along the Alameda County shorelines. Understanding the additive impact of large waves and high tides to produce inundation and flooding is crucial for planning in the coastal environment. Table 2-2 provides an overview of factors affecting existing water levels in the San Francisco Bay and the Alameda County shoreline. The typical range shown for the components that can build up extreme water levels represents how the magnitude of these components can vary, and are not referenced to an elevation datum.

Table 2-2. Factors That Influence Local Water Level Conditions in Addition to Sea Level Rise

Factors Affecting Water Level	Typical Range[1,2,3]	Period of Influence	Frequency
Tides	5 to 7 ft	Hours	Twice daily
Storm Surge	0.5 to 4 ft	Days	Several times a year
Storm Waves	0.5 to 4 ft	Hours	Several times a year
El Niños (within the ENSO cycle)	<1.5 ft	Months to Years	2 to 7 years

1 DHI. 2010. *Regional Coastal Hazard Modeling Study for North and Central San Francisco Bay*. Prepared for Federal Emergency Management Agency.
2 DHI. 2012. *Regional Coastal Hazard Modeling Study for South San Francisco Bay*. Prepared for Federal Emergency Management Agency.
3 BakerAECOM. 2013. *Central San Francisco Bay Coastal Flood Hazard Study for Alameda County*. Prepared for Federal Emergency Management Agency.

Alameda County is susceptible to sea level rise, storm surge, and wave hazards from San Francisco Bay. The shoreline is comprised of a variety of shoreline features, including natural tidal marshes and mudflats, a network of non-engineered berms, engineered flood protection structures (e.g., levees) and engineered shoreline protection features (e.g., bulkheads, revetments, and rip-rap) all serving as the first line of defense to protect the densely built inland areas from coastal hazards. Some areas along the shoreline, including the Bay Bridge / I-80 touchdown area, the Bay Farm Bridge touchdown area on Bay Farm Island, and the salt ponds, already experience inundation due to coastal hazards, such as the annual extreme tides, or King Tides. Areas of the shoreline that have been filled, such as Bay Farm Island and Oakland International Airport, are especially at risk, as rising sea levels may influence groundwater levels, resulting in increased subsidence and liquefaction hazards.

The following coastal flood hazards may increase due to sea level rise and other atmospheric-oceanic processes:

- **Daily tidal inundation:** As sea level rises, the amount of land and infrastructure subjected to daily inundation by high tides – also known as increases in MHHW – will increase. This would result in increased permanent future inundation of low-lying areas.
- **Annual high tide inundation (King Tides):** King tides are abnormally high, predictable astronomical tides that occur approximately twice per year. King Tides are the highest tides that occur each year during the winter and summer when the Earth, moon and sun are aligned. In the winter (December, January, and February), King Tides may be amplified by winter weather, making these events more dramatic. King Tides result in temporary inundation, particularly associated with nuisance flooding, such as inundation of low-lying roads, boardwalks, and waterfront promenades.
- **Extreme high tide inundation (storm surge):** When Pacific Ocean storms coincide with high tides, storm surge due to meteorological effects can elevate Pacific Ocean and San Francisco Bay water levels and produce extreme high tides, resulting in temporary inundation. Such storm surge events have occurred in January 27, 1983, December 3, 1983, February 6, 1998, January 8, 2005, and December 31, 2006. Extreme high tides can cause severe inundation of low-lying roads, boardwalks, and promenades; can exacerbate coastal and riverine flooding and cause upstream flooding; and can interfere with stormwater outfalls.
- **El Niño winter storms:** During El Niño[4] winters, atmospheric and oceanographic conditions in the Pacific Ocean produce severe winter storms that impact the San Francisco shorelines. Pacific Ocean storms follow a more southerly route and bring intense rainfall and storm conditions to the Bay Area. Tides are often elevated 0.5 to 1.0-feet above normal along the coast, and wind setup can elevate water levels even further. El Niño winter conditions prevailed in 1977–1978, 1982–1983, 1997–1998, and 2009–2010. Typical impacts include severe inundation of low-lying roads, boardwalks and waterfront promenades; storm drain backup; wave damage to coastal structures; and erosion of natural shorelines.
- **Ocean swell and wind-wave events (storm waves):** Pacific Ocean storms and strong thermal gradients can produce strong winds that blow across the ocean and the Bay. When the wind blows over long reaches of open water, large waves can be generated that impact the shoreline and cause damage. Typical impacts include wave damage along the shoreline, particularly to coastal structures such as levees, docks and piers, wharves, and revetments; backshore inundation due to wave overtopping of structures; and erosion of natural shorelines.

[4] El Niño–Southern Oscillation is a natural oceanic-atmospheric cycle. El Niño conditions are defined by prolonged warming in the Pacific Ocean sea surface temperatures. Typically, this happens at irregular intervals of two to seven years, and it can last anywhere from nine months to two years.

2.3 SCENARIOS

Sea level rise is often visualized using inundation maps; however, selecting the most appropriate sea level rise scenario to map in support of project planning, exposure analysis, and sea level rise vulnerability and risk assessment is not simple. Typically, maps represent specific sea level rise scenarios (e.g., 16 inches of sea level rise above MHHW) or extreme tide water level (e.g., the 1-percent-annual-chance event, a.k.a. the 100-year event). This approach requires pre-selecting appropriate sea level rise and extreme tide scenarios that meet all project needs.

Rather than pre-selecting specific sea level rise scenarios for Alameda County, six individual inundation maps were developed to represent a range of possible scenarios associated with extreme tide levels and sea level rise, ranging from 12 inches to 96 inches, and the 1-year extreme tide event to the 100-year extreme tide (i.e., storm surge) events. The scenario selection relied on the extreme water level analysis described in Section 3.3. The goal of scenario selection was to identify six scenarios that could represent the current NRC sea level rise projections, as presented in Section 2.1, as well as approximate a range of storm surge events. The first four scenarios (12-, 24-, 36-, and 48-inches of sea level rise) relate directly to the NRC sea level rise estimates (sea level rise above MHHW), and they capture a broad range of scenarios between the most likely scenario and the high of the uncertainty range at both mid- and end-of-century.

1. 12-inch sea level rise ≈ 2050 most likely sea level rise scenario
2. 24-inch sea level rise = 2050 high end of the range; ≈ 2100 lower 15% confidence interval
3. 36-inch sea level rise = 2100 most likely sea level rise scenario
4. 48-inch sea level rise ≈ 2100 upper 85% confidence interval

Each of the above scenarios can approximate either permanent inundation scenarios that are likely to occur before 2100, or temporary flooding events which could occur from specific combinations of sea level rise and extreme tides. For example, the water elevation associated with 36 inches of sea level rise is similar to the water elevation associated with a combination of 24 inches of sea level rise and a 1-year extreme tide (king tide). Therefore, a single map can be used to visualize either event. The primary difference between the two scenarios is that 36” of sea level rise above MHHW represent possible future *permanent* inundation by daily tides, and the 24” of sea level rise coupled with a 1-year extreme tide event represents the *temporary* inundation that would likely occur at least once in any given year. However, when the inundation maps are used to approximate the flooding extent associated with an extreme tide or storm surge scenarios, it should be noted that the maps do not consider the duration of flooding, or the potential mechanism for draining the floodwaters from the inundated areas once the extreme high tide levels recede. Figure 2-1 presents a representative cross section of a shoreline that illustrates the distinction between permanent inundation and temporary flooding.

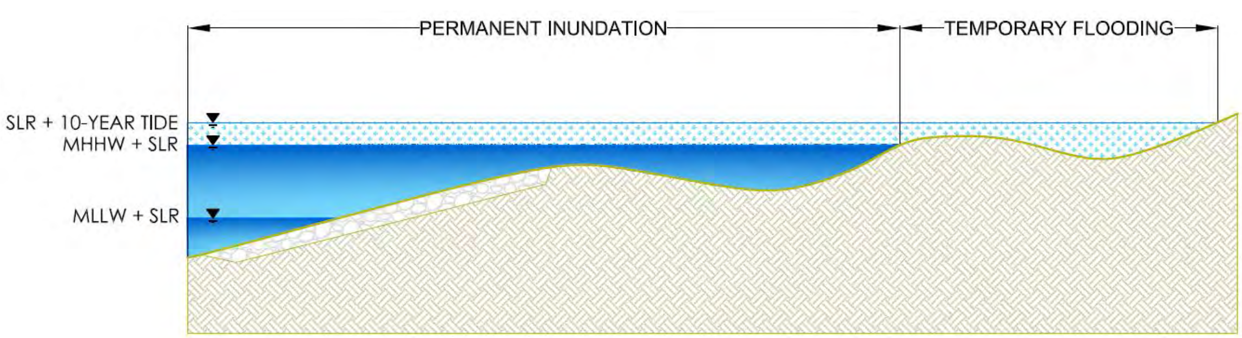


Figure 2-1. Shoreline Cross Section showing Permanent Inundation and Temporary Flooding

In addition to the first four scenarios listed above, 72- and 96-inches above MHHW were also evaluated, but these water levels are outside the range of current scientific predictions for sea level rise and, therefore, do not correspond with permanent inundation scenarios that are likely to occur before 2100. They illustrate short-term flooding that could occur when extreme tides are coupled with higher levels of sea level rise (see bullets 5 and 6 below).

5. 72-inch above MHHW = extreme flooding scenario (e.g., 50-year storm surge with 36-inches of sea level rise)
6. 96-inch above MHHW = extreme flooding scenario (e.g., 100-year storm surge with 54-inches of sea level rise)

The water levels along the shoreline were binned using a tolerance of ± 3-inch to increase the applicable range of the mapped scenarios. For example, Scenario 3 (MHHW + 36 inches) can be used to approximate all extreme tide/sea level rise combinations that produce a water level in the range of MHHW + 33 inches to MHHW + 39 inches (See Table 2-3).

While Table 2-3 presents the ten mapped scenarios, Table 2-4 presents 30 combinations of sea level rise with extreme tides levels represented by the mapped scenarios. For example, from Table 2-4, the inundation map of Scenario 3 (MHHW + 36 inches), represents all of these combinations:

- 1-year extreme tide coupled with 24 inches of sea level rise,
- 2-year extreme tide coupled with 18 inches of sea level rise,
- 5-year extreme tide event coupled with 12 inches of sea level rise,
- 25-year extreme tide event coupled with 6 inches of sea level rise, and
- 50-year extreme tide event under existing conditions (no sea level rise).

It should be noted that Table 2-4 is appropriate for northern Alameda County, and Section 3.8 provides additional matrices for the full Alamaeda County shoreline. The colors shown in Table 2-3 are replicated in the matrix of water levels shown in Table 2-4 to indicate the combinations represented by each inundation map. As noted above, Scenarios 5 and 6 are outside the range of NRC permanent sea level rise estimates expected to occur by 2100. Table 2-4 also identifies the combinations of sea level rise and extreme tide which may produce flooding at the higher end of the spectrum at the end of the century. For example, Scenario 6 (96 inches above MHHW) approximates:

- 66 inches of sea level rise with a 25-year extreme tide event,
- 60 inches of sea level rise with a 50-year extreme tide event, and
- 54 inches of sea level rise with a 100-year extreme tide event.

These scenarios provide a rich data set with which to evaluate vulnerabilities and risk from sea level rise, and to better define the timing for effective adaptation strategies.

Table 2-3. Sea Level Rise Mapping Scenario (inches above MHHW)

Mapping Scenario	Reference Water Level	Applicable Range for Mapping Scenario (Reference +/- 3 inches)
Scenario 1	MHHW + 12-inch	MHHW + 9 – 15 inch
Scenario 2	MHHW + 24-inch	MHHW + 21 – 27 inch
Scenario 3	MHHW + 36-inch	MHHW + 33 – 39 inch
Scenario 4	MHHW + 48-inch	MHHW + 45 – 51 inch
Scenario 5	MHHW + 72-inch	MHHW + 69 – 75 inch
Scenario 6	MHHW + 96-inch	MHHW + 93 – 99 inch

Table 2-4. Sea Level Rise and Extreme Tide Matrix

Sea Level Rise Scenario	Daily Tide *Permanent Inundation*	Extreme Tide (Storm Surge) *Temporary Flooding*						
	+SLR	1-yr	2-yr	5-yr	10-yr	25-yr	50-yr	100-yr
	Water Level above MHHW (in)							
Existing Conditions	0	14	19	23	27	33	37	42
MHHW + 6 inch	6	20	25	29	33	39	43	48
MHHW +12 inch	12	26	31	35	39	45	49	54
MHHW +18 inch	18	32	37	41	45	51	55	60
MHHW +24 inch	24	38	43	47	51	57	61	66
MHHW +30 inch	30	44	49	53	57	63	67	72
MHHW +36 inch	36	50	55	59	63	69	73	78
MHHW +42 inch	42	56	61	65	69	75	79	84
MHHW +48 inch	48	62	67	71	75	81	85	90
MHHW +54 inch	54	68	73	77	81	87	91	96
MHHW +60 inch	60	74	79	83	87	93	97	102
HYDRODYNAMIC ZONE 1								

3.0

INUNDATION MAPPING

3. INUNDATION MAPPING

3.1 LEVERAGED DATA SOURCES

Inundation maps are a valuable tool for evaluating potential exposure to future sea level rise and storm surge conditions, and the most up-to-date maps should be referenced during project planning and design. The maps are typically used to evaluate when (under what amount of sea level rise and/or storm surge) and by how much (what depth of inundation) an asset will be exposed. This section presents the overall methods and data sources used to develop the detailed inundation maps presented in Appendix B. The Alameda County sea level rise and storm surge inundation mapping relied on two primary data sources:

- **Hydrodynamic Modeling Data:** Hydrodynamic model output was required to assess daily and extreme tide levels throughout Alameda County. The use of modeled water levels was preferred over individual tide gage analyses because of the high spatial density provided in the model output for the entirety of the Alameda County shoreline. This study leveraged water levels from a regional San Francisco Bay hydrodynamic modeling study completed as part of the FEMA San Francisco Bay Area Coastal Study (DHI 2011, 2013). The modeling was conducted in two stages. The first stage focused on the North and Central Bay (north of the Hayward - San Mateo Bridge) and the second stage focused the South Bay[5]. The boundary between the two study areas falls within the Alameda County shoreline near the Oakland International Airport. As a result, the model output points for Alameda County span both study areas. The modeled water levels from both studies were used, as appropriate, in each geographic region.

  The FEMA model output was archived in 15-minute time steps, as described in DHI (2011, 2013). In the North and Central Bays, the water level simulations extended from January 1, 1973 to December 31, 2003 (31 years). In the South Bay, the water level simulations extended from January 1, 1956 to December 31, 2009 (54 years). The regional model was calibrated and validated to observed historical data from nine tide stations within the Bay. Nineteen output points along the Alameda County shoreline were selected to characterize the spatial variability of water levels throughout the study area (see Figure 3-3). The North and Central Bay model output was used for Points 1-8 to north of the Oakland International Airport, and the South Bay model output was used for Points 9-19. The model output points correspond to the same locations analyzed for the ART Project (BCDC et al. 2011).

- **Topographic Data:** High quality topographic data was leveraged for the shoreline delineation task. The primary data set was the LiDAR[6] data collected by the U.S. Geological Survey (USGS) and the National Oceanic Atmospheric Administration (NOAA) as part of the California Coastal Mapping Program (CCMP)[7]. The USGS managed the data collection in southern San Francisco Bay, and NOAA managed additional data collection in northern and central San Francisco Bay. The northern and central Bay LiDAR were collected in February–April 2010. The South Bay LiDAR data were collected in June, October, and November 2010. Together, both data sets provide complete coverage of the coastal areas, up to the 16-foot (5-meter) elevation contour. The collected LiDAR data for the South Bay have a vertical accuracy of +/- 0.06 m, and the

[5] The FEMA San Francisco Bay regional hydrodynamic modeling studies were completed in two stages due to the nature in which the FEMA studies were originally contracted. The first stage covered the entire San Francisco Bay, with an emphasis on accurately modeling tide and wave processes in the North and Central Bays, north of the Hayward San Mateo Bridge. The regional model was later refined to better characterize the more complex South Bay bathymetry and hydrodynamics.

[6] LiDAR is Light Detection and Ranging, an aerial based topographic survey method that uses optical sensors to map topographic landforms and elevations.

[7] http://www.opc.ca.gov/2012/03/coastal-mapping-lidar-data-available/

LiDAR data for North and Central bay have a vertical accuracy of +/- 0.05 m, based on the tested RMSE for all checkpoints (Dewberry 2011). This accuracy exceeds the USGS National Geospatial Program LiDAR Guidelines and Base Specifications[8].

The USGS and NOAA LiDAR and the associated Digital Elevation Model (DEM) derived from the LiDAR data provided the topographic base data for the mapping and shoreline delineation effort. The bare-earth LiDAR was used, which means that all vegetation, buildings, and structures (i.e., bridges and buildings) have been removed. The shoreline delineation effort was completed on a 1-meter DEM derived from the USGS LiDAR, while the inundation mapping and associated analyses were completed on a 2-meter DEM derived from the USGS and NOAA LiDAR. The DEMs are of sufficient resolution and detail to capture the shoreline levees and flood protection assets.

3.2 EXTREME HIGH TIDES (STORM SURGE)

Extreme high tides can cause significant inundation throughout the Bay Area. The extreme high tides can remain elevated above MHHW for several hours when storm surge conditions coincide with high tide, and these levels can persist over several high tide cycles. The highest water level conditions typically occur during El Niño winters, such as those that occurred in the winter of 1982–83, and 1983–84. Table 3-1 presents the maximum observed water levels recorded at the NOAA tide station in Alameda (9414750)[9], along with the predicted tide levels in the absence of storm surge. Table 3-1 also shows the magnitude of storm surge that occurred at the peak of each event, and the approximate duration (in hours) that the extreme tide persisted above MHHW and a typical King Tide elevation. For this assessment, the King Tide water level elevation was approximated by a tidal water level with a 1-year recurrence interval.

The 1983 events resulted in the highest water levels recorded at the Alameda tide station. Although the December 1983 event was the highest recorded event at the Alameda tide station, other locations along the Alameda County shoreline experienced the highest water levels during the January 1983 event (see Figure 3-3). During the January 1983 event, storm surge conditions occurred after several days of heavy rainfall and coincided with the highest astronomical tides of the year. High water levels were elevated above predicted MHHW by up to 1.5 feet for approximately seven hours over a two-day period (see Figure 3-4). The storm surge conditions in December 1983 were larger than observed in January 1983; however, the peak storm-surge conditions did not coincide with the highest high tide conditions, and the duration of elevated water levels was shorter by approximately four hours. If a strong El Niño had persisted over the 1983–84 winter, or if heavy rainfall had coincided with the December 1983 event, flood impacts could have been intensified across the Bay. The largest storm-surge conditions for the four events presented in Table 3-1 occurred in February 1998. If these conditions had been associated with higher high tide conditions (such as during a strong spring tide), extreme tide water levels would have exceeded those observed during the 1983 events.

The timing of storm events with the tidal cycle has a significant impact on the maximum observed water levels associated with the coastal storm surge event. The severity of each event could have increased with shifts in the timing (i.e., coincident storm surge and high tide) or the joint occurrence of other processes (e.g., rainfall). As sea levels rise, these high water levels will be reached and exceeded with less intense storms, highlighting the importance of considering both sea level rise and extreme tides in the assessment of existing and future shoreline vulnerabilities.

[8] http://lidar.cr.usgs.gov/USGS-NGP%20Lidar%20Guidelines%20and%20Base%20Specification%20v13%28ILMF%29.pdf

[9] Observed tides recorded at the Alameda station during the December 31, 2006 event were found to have errors, and are not presented.

Figure 3-1. FEMA Model Output Locations Used for Alameda County

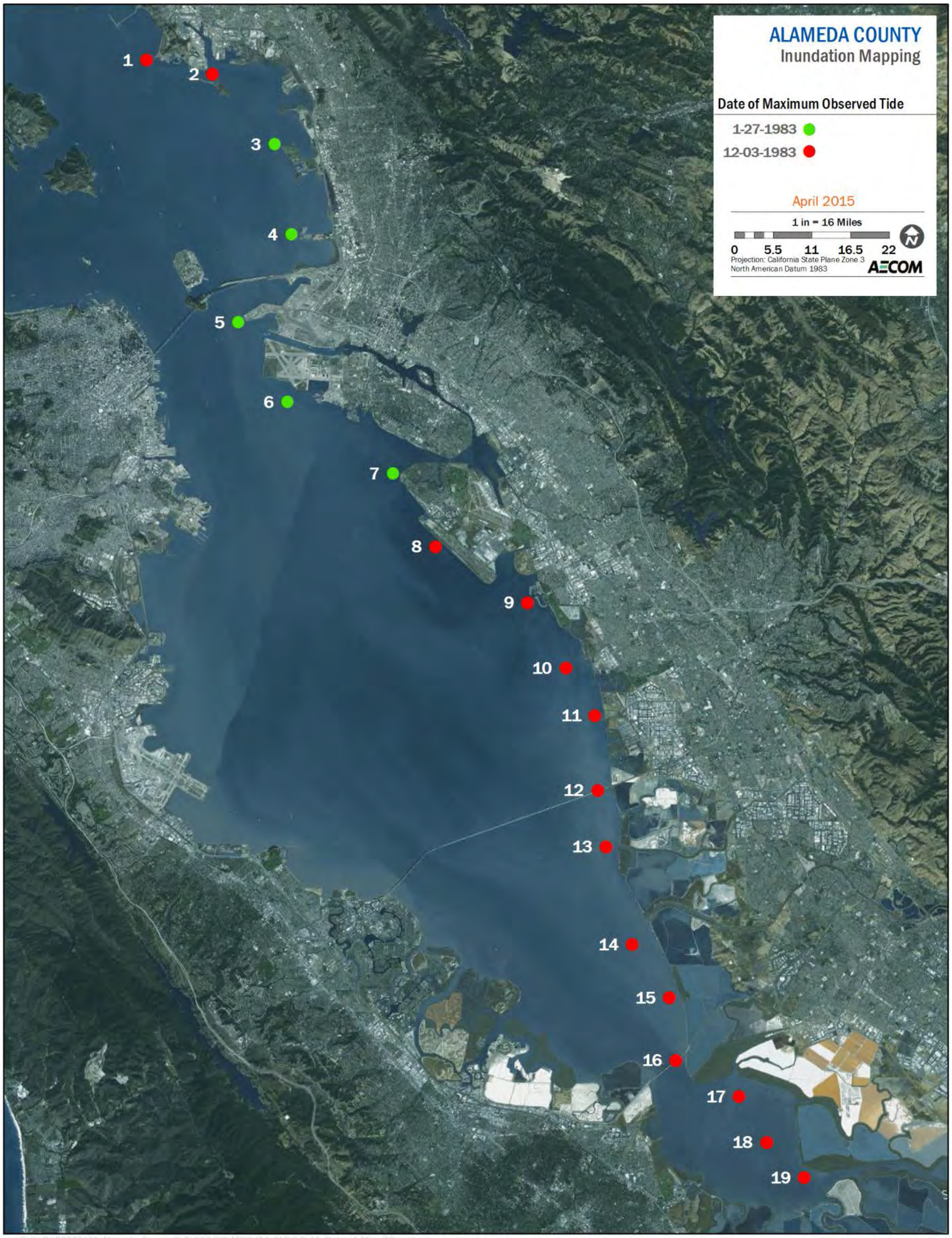


Figure 3-2. Date of Highest Simulated Tide at FEMA Model Output Locations

Table 3-1. Extreme High Tide Inundation (NOAA Alameda Tide Station - 9414750)

Event	Predicted Tide	Max. Water Level	Storm Surge at Peak Water Level	Approximate Duration Above MHHW (6.37 ft NAVD)	Approximate Duration Above King Tide[1] (7.7 ft NAVD)
	Feet-NAVD	Feet-NAVD	Feet[2]	Hours	Hours
Jan. 27, 1983	7.57	9.19	1.61	10.5	7.0[3]
Dec. 3, 1983	7.00	9.21	2.20	6.0	4.0
Feb. 6, 1998	6.68	9.02	2.33	7.0	4.5
Jan. 8, 2005	7.40	8.70	1.29	5.0	4.0

Notes:
[1] King Tides, on average, can be approximately by the 1-year extreme tide elevation.
[2] Storm surge is not referenced to a topographic datum, and is calculated as the observed minus the predicted tide at one time step.
[3] Duration above King Tide for this event includes tide levels on Jan. 28, 1983.

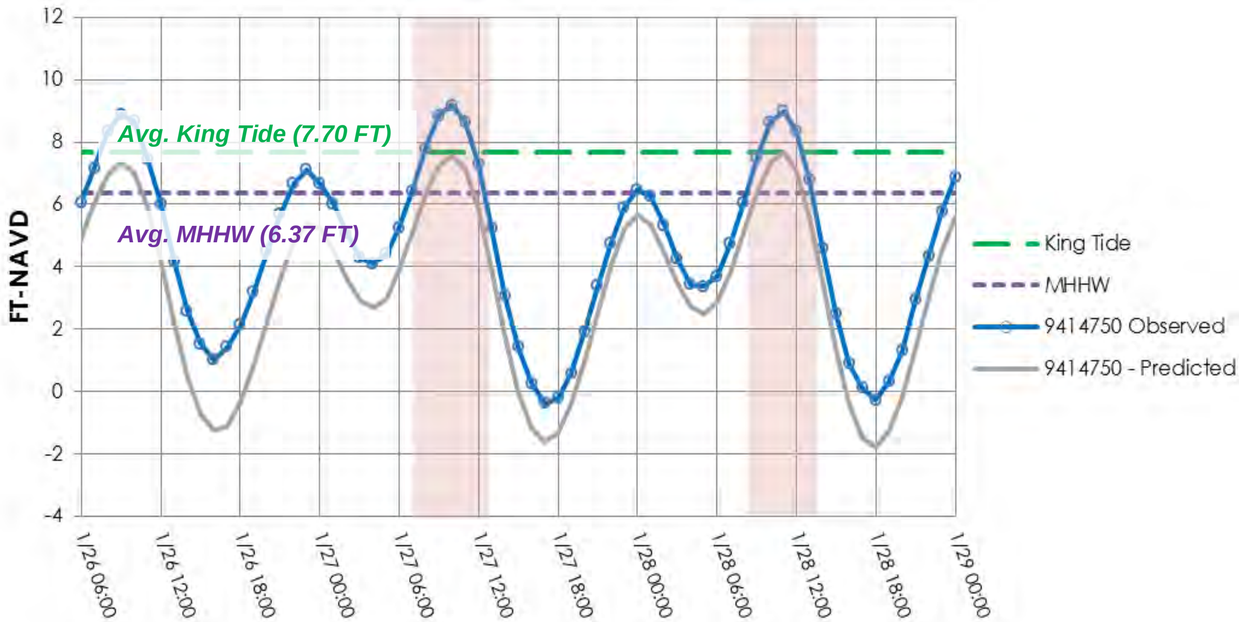


Figure 3-3. January 1983 Water Levels Observed at NOAA Alameda Tide Station #9414750)

3.3 TIDAL DATUMS AND EXTREME TIDE LEVELS

This section describes the calculation of the existing conditions daily and extreme tide levels at each model output point along the Alameda County shoreline. The daily and extreme tide levels are one of the primary datasets used to develop the normalized extreme tide curves (Section 6.1 and 6.2) and normalized shoreline elevation maps (Section 6.3).

The MHHW tide level was selected to represent the typical daily high tide. The MHHW tide level for existing conditions was computed using model hindcast data corresponding to the most recent National Tidal Datum Epoch (NTDE) which is a specific 19-year period adopted by NOAA to perform tidal computations, from 1983 through 2001. The MHHW tide level is defined as the average of the higher high tides of each day recorded during the NTDE.

The extreme tide levels were computed using either the 31-year record (Central Bay model output) or 54-year record (South Bay model output) of the simulated time series. The water level statistics used to represent the extreme tides include the 2-, 5-, 10-, 25-, 50-, 100-, and 500-year extreme tide levels. The 500-year extreme tide levels are presented for reference and to convey to stakeholders that the potential exists for events with greater than 100-year severity to occur. It should be noted that these estimates of the 500-year tide level are only approximate, given the relatively short duration of the hydrodynamic model hindcast. These values are consistent with the values FEMA will use for the upcoming Flood Insurance Rate Maps (FIRMs) and Flood Insurance Studies (FISs) for Alameda County.

The following steps were performed to determine the extreme tide elevations using the timeseries of modeled water levels from each model output point:

- Annual maxima water levels were extracted based on a July–June "storm year," consistent with the FEMA coastal hazard analysis.
- A Generalized Extreme Value (GEV) probability distribution was fit to the annual maxima dataset, and extreme tide elevations were calculated at each return period.
- The 1-year extreme tide elevation for each model output point was determined by extrapolating the extreme tide curves out to the 1-year level.
- An example water level time series and the extracted annual maxima for one model output point are shown in Figure 3-4. Computed daily and extreme tide levels at each model output point are shown in Table 3-2.

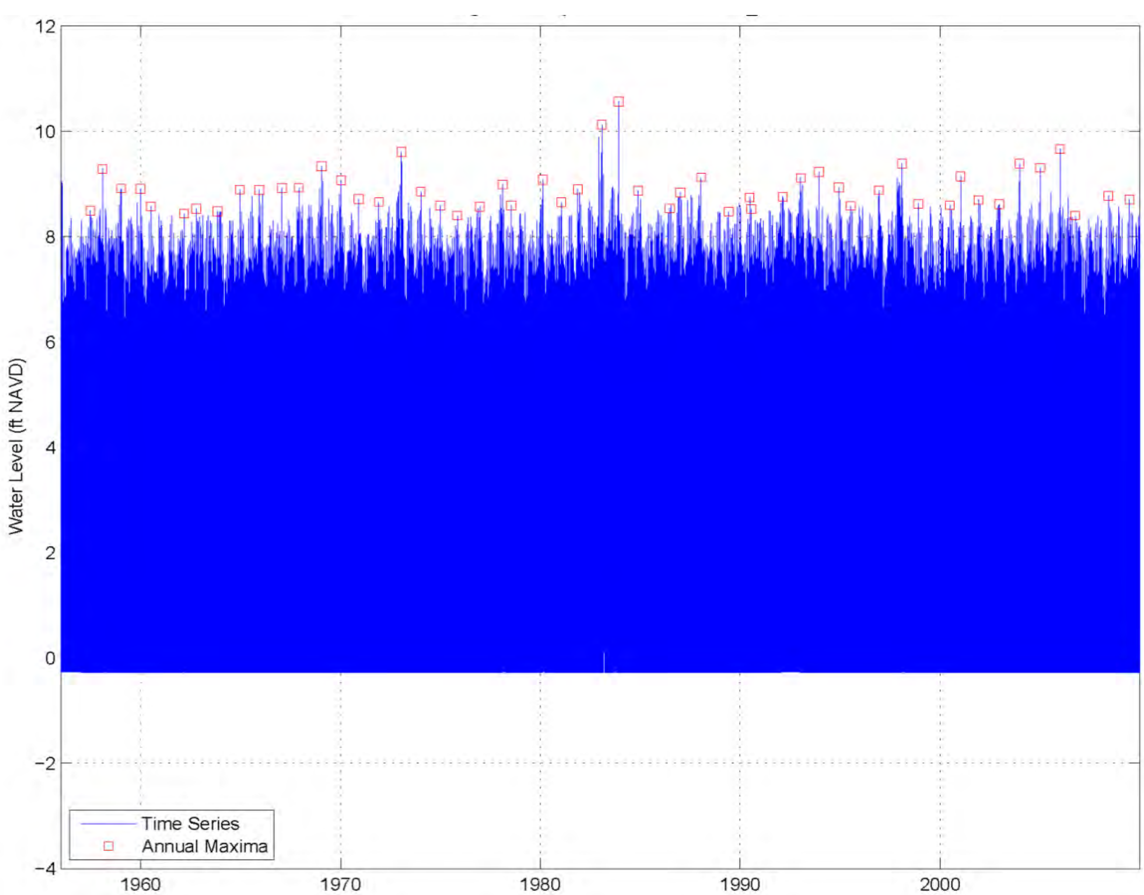


Figure 3-4. Example Water Level Time Series and Annual Maxima Dataset

Table 3-2. Existing Conditions Daily and Extreme Tide Elevations

Point ID	MHHW (ft NAVD)	Extreme Tide Elevations (ft NAVD)							
		1-yr	2-yr	5-yr	10-yr	25-yr	50-yr	100-yr	500-yr
1	6.10	7.25	7.62	8.03	8.34	8.77	9.14	9.54	10.63
2	6.16	7.30	7.71	8.13	8.45	8.91	9.31	9.75	10.98
3	6.20	7.34	7.75	8.15	8.47	8.93	9.32	9.75	10.96
4	6.21	7.38	7.76	8.16	8.47	8.91	9.28	9.68	10.80
5	6.27	7.47	7.82	8.21	8.51	8.92	9.26	9.63	10.62
6	6.42	7.62	7.98	8.36	8.65	9.07	9.42	9.81	10.89
7	6.62	7.82	8.20	8.56	8.85	9.27	9.63	10.03	11.17
8	6.75	7.95	8.34	8.70	8.98	9.41	9.78	10.19	11.40
9	6.89	8.21	8.53	8.88	9.14	9.52	9.83	10.17	11.10
10	6.94	8.24	8.57	8.92	9.19	9.57	9.89	10.24	11.21
11	6.97	8.26	8.60	8.95	9.22	9.61	9.94	10.31	11.33
12	7.02	8.26	8.64	8.99	9.26	9.68	10.03	10.43	11.59
13	7.06	8.30	8.69	9.04	9.32	9.74	10.10	10.52	11.73
14	7.16	8.38	8.79	9.14	9.43	9.87	10.26	10.71	12.06
15	7.21	8.42	8.85	9.21	9.50	9.95	10.35	10.83	12.28
16	7.27	8.47	8.92	9.27	9.56	10.01	10.42	10.90	12.39
17	7.35	8.57	9.02	9.37	9.67	10.12	10.54	11.03	12.56
18	7.38	8.62	9.05	9.40	9.71	10.21	10.68	11.25	13.11
19	7.42	8.61	9.09	9.44	9.76	10.29	10.81	11.46	13.70

3.4 TIDAL AMPLIFICATION AND SEA LEVEL RISE

Daily and extreme tides vary spatially throughout the Bay, and these variations are primarily driven by complex interactions between the tides, winds, and the Bay's bathymetry and complex shoreline. This section describes how the tides vary within the Bay. In addition, this section presents a discussion on adding sea level rise to daily and extreme tide levels to examine future conditions in the Bay.

3.4.1 TIDAL VARIATION

Tides within the Bay are generally amplified with increasing distance from the Golden Gate, with the greatest rate of increase seen in the South Bay. Tidal amplification is a result of interactions between tidal processes (i.e., wave reflection), changes in bathymetry, bottom friction, freshwater inflows, and shoreline position. Within the Bay, the tide manifests in two general wave patterns: progressive and standing waves. In a progressive wave, flood tides move progressively forward from the mouth of the Bay inland. Standing waves in the Bay can be described as an incoming tidal wave that reflects upon itself after interacting with a landform (i.e., the convergent shoreline in the South Bay), resulting in tidal amplification. Standing wave characteristics dominate in the South Bay, and the tide range increases to the south. In the North Bay, a progressive wave dominates, and tidal amplification is not as pronounced. MHHW increases northward from the Golden Gate and into San Pablo Bay, and then decreases within the

Carquinez Straight. Beyond the Carquinez Straight and into Suisun Bay, high water levels become heavily influenced by freshwater riverine inflows from the Sacramento River.

Figure 3-5 presents MHHW along a longitudinal profile in the Bay, using model output from the FEMA San Francisco Bay regional model[10]. Geographical landmarks are provided for reference, including the approximate limits of Alameda County. In addition to MHHW, mean lower low water (MLLW) and the January 27th and December 3rd, 1983 extreme water levels are shown. MHHW and MLLW are calculated using the current 19-year NTDE (see Section 3.2). The amplification of the daily tide range (the distance between MHHW and MLLW) in the South Bay is evident in Figure 3-5.

The extreme water levels that occurred during the January and December 1983 storm events are similar, but the storm events were driven by different processes. For example, heavy rainfall preceded the January 1983 event, resulting in higher water levels in the North Bay. Strong winds from the west-northwest accompanied the December 1983 event, resulting in increased water levels in South Bay. Due to the size, orientation, and variable hydrodynamic and meteorological conditions present in the Bay Area, to date there is no single storm event that has led to the highest observed water elevations throughout the Bay.

3.4.2 SEA LEVEL RISE

Tide levels (tidal amplitude and range) in the Bay generally remain stationary over time, and this has been confirmed with the FEMA San Francisco Bay regional modeling effort, as well as by modeling efforts completed by Holleman and Stacy (2014) that consider both existing conditions and future sea level rise. Based on current modeling, and neglecting significant changes to the landscape such as constructing levees around large portions of the Bay, sea level rise does not result in a significant change to the tidal hydraulics. Therefore, future Bay water levels can be approximated by linearly adding sea level rise to existing MHHW. Holleman and Stacey (2014) showed that this linear approach is appropriate within the Bay, although small changes in tidal range were observed, the changes were small compared to the amounts of sea level rise.

For simplicity, this linear approach has also been used to approximate future extreme tide levels (i.e., sea level rise has been added to the existing 100-year extreme tide levels). However, it should be noted that this may be a conservative estimate for future extreme condition. This approach does not consider climate change factors that may increase the frequency and severity of extreme events over time. However, at the present time, trends in increasing storm surge severity and intensity associated with climate change are not clear for the Northern California coast and the San Francisco Bay Area (NRC, 2012).

3.5 WATER SURFACE DIGITAL ELEVATION MODEL CREATION

The first step in creating the inundation maps was to create the MHHW water surface DEM. The calculated MHHW water level at each model output point was projected inland along shore perpendicular transects to provide complete coverage across the entire shoreline delineation. The transects were drawn inland beyond the expected extent of inundation under the highest sea level rise scenario, and were spaced at an appropriate density to capture the variation in tidal surface and the underlying topography. The resulting MHHW DEM has a horizontal resolution of 2-meters to match the resolution of the topographic DEM. Each sea level rise scenario (i.e., 12-, 24-, 36-, 48-, 72-, 96-inches) was added to the MHHW water surface to develop the future conditions tidal water surfaces.

[10] Model output was provided by DHI, leveraged from the FEMA San Francisco Bay regional model. Output along the longitudinal axis was not extracted or analyzed for the FEMA San Francisco Bay Area Coastal Study.

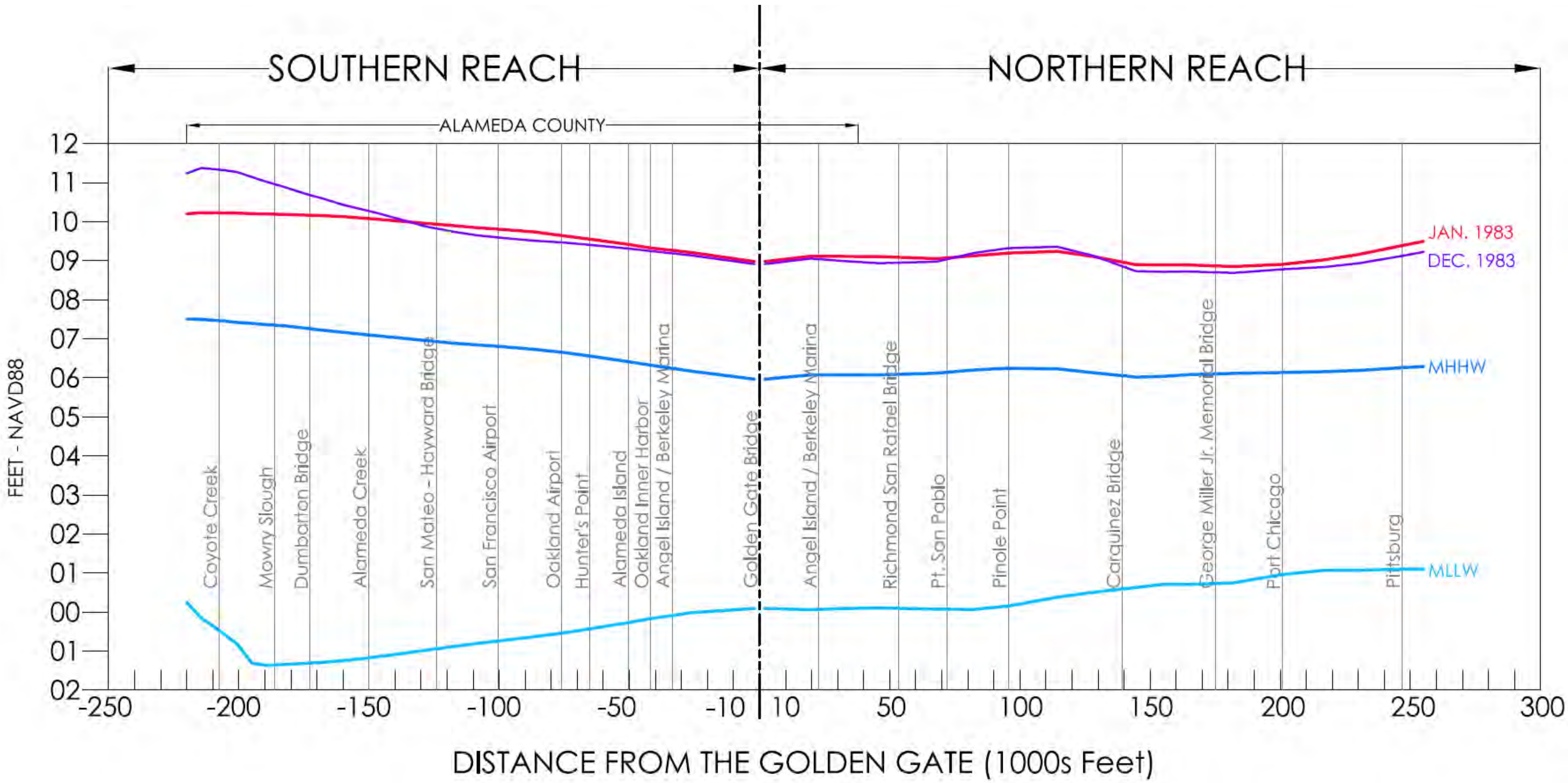


Figure 3-5. Water Surface Profile in San Francisco Bay for Daily and Extreme Tides

The resulting water surface DEMs are an extension of the tidal water surface at the shoreline over the inland topography. This represents a conservative estimate of the inland area that may be inundated every day by tidal action. The MHHW tidal water surface represents an average of the daily high tide conditions over the 19-year NTDE, and therefore daily high tide levels may exceed this average elevation approximately 50 percent of the time.

This exercise does not take into account the associated physics of overland flow, dissipation, levee overtopping, storm duration, or potential shoreline or levee erosion associated with extreme water levels and waves. To account for these processes, a more sophisticated modeling effort would be required. However, given the uncertainties associated with sea level rise, as well as future land use changes, development, and geomorphic changes that will occur over the next 100 years, a more sophisticated modeling effort may not necessarily provide more accurate results.

3.6 DEPTH AND EXTENT OF FLOODING

Depth of flooding raster[11] files were created by subtracting the land surface DEM from the water surface DEM. Both DEMs were generated using a 2-meter horizontal resolution with the same grid spacing to allow for grid cell to grid cell subtraction. The resultant DEM (or “inundation depth raster”) provides both the inland extent and the depth of inundation without considering hydraulic connectivity.

The final step used in creating the depth and extent of flood maps is an assessment of hydraulic connectivity. The method described by Marcy et al. (2011) employs two rules for assessing whether a grid cell is inundated. A cell must be below the assigned water surface DEM elevation value, and it must be connected to an adjacent grid cell that was either flooded or open water. NOAA’s method applies an “eight-side rule” for connectedness, where the grid cell is considered “connected” if any of its cardinal or diagonal directions are connected to a flooded grid cell. This approach decreases the inundated area over earlier inundation mapping efforts that considered a grid cell to be inundated solely based on its elevation (i.e., even if there was no hydraulic pathway to the Bay to allow flooding). This assessment removes areas from the inundation zone if they are protected by levees or other topographic features that prevent inland inundation. It also removes areas that are low lying, but inland, and not directly connected to an adjacent inundated area.

The six sea level rise inundation maps are presented in Appendix B. The shades of blue represent various depths of inundation, shown in two-foot depth increments, ranging from 0-feet to greater than 16-feet of inundation. In addition, hydraulically disconnected low-lying areas are displayed in green. These areas do not have an effective overland flow path to allow water to reach the area, although these areas have topographic elevations below the inundated water surface. It is possible that the low-lying areas are, or may become, connected through culverts, storm drains, or other hydraulic features that are not captured within the DEM; therefore, it is important to note that there may be an existing or future flood risk within these areas. In addition, these low-lying areas may be at risk of flooding from below due to increasing groundwater elevations. Figure 3-6 illustrates an inland disconnected low-lying area.

[11] A raster consists of a matrix of pixels organized into a surface area grid where each cell contains a value representing information (e.g., water depth values).

Figure 3-6. Example Shoreline Cross Section Showing Disconnected Low-lying Area

3.7 HYDRODYNAMIC ZONES

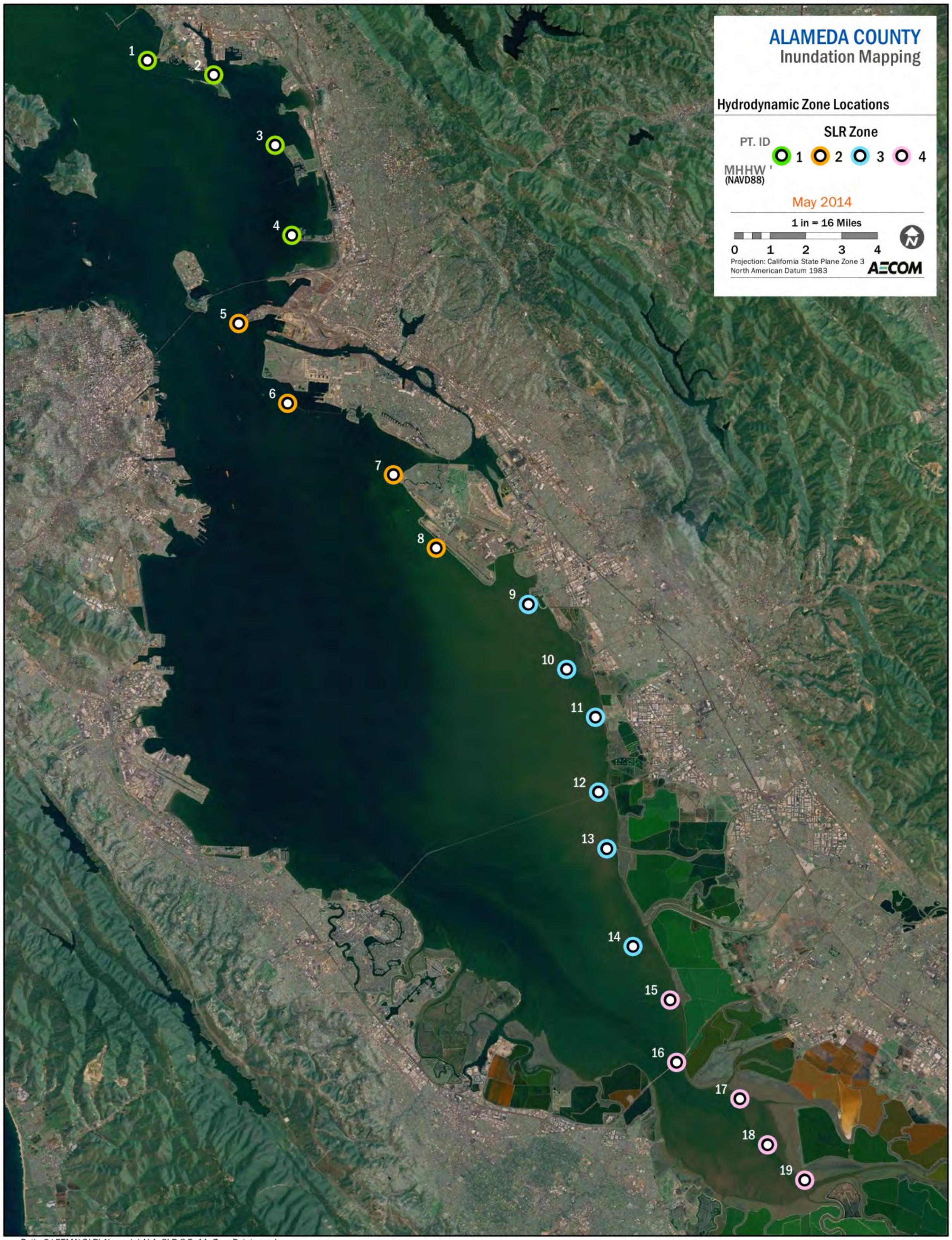
Due to the Bay's geometry and hydrodynamics, tidal characteristics vary spatially. In general, tides are amplified in the South Bay and daily and extreme tide elevations increase from north to south along the Alameda County shoreline. For example, the MHHW tide level increases from approximately 6.1-feet NAVD to 7.2-feet NAVD along the limits of the original ART Project area. Similarly, the 100-year tide level increases from 9.5-feet NAVD to 10.7-feet NAVD. The model output points were used to assess the spatial variability of tidal characteristics along the shoreline, and to identify four regions with roughly similar hydrodynamics referred to as "hydrodynamic zones". Within each hydrodynamic zone, the water levels were averaged to simplify application of the results. The hydrodynamic zone designation for Alameda County is a continuation of the work completed for BCDC within the ART Project boundary (AECOM 2014a). The hydrodynamic zones are consistent with prominent geographic features that influence circulation patterns within the Bay. The hydrodynamic zones presented in Figure 3-7 are defined as:

- Zone 1: Point Richmond to the San Francisco-Oakland Bay Bridge (Points 1-4)
- Zone 2: San Francisco-Oakland Bay Bridge to the Oakland International Airport (Points 5-8)
- Zone 3: Oakland International Airport to the Alameda County Flood Control Channel (Alameda Creek) (Points 9-14)
- Zone 4: Alameda County Flood Control Channel to Coyote Creek (Points 15-19)

The relationship between extreme tide levels and MHHW along the Alameda County shoreline is relatively uniform over large spatial areas, so the boundaries of the hydrodynamic zones are approximate.

3.8 SEA LEVEL RISE AND EXTREME TIDE MATRIX

As described in Section 2.3, a matrix approach was developed to relate Bay water levels associated with combinations of sea level rise and extreme tides. Table 2-4 presented an example of this approach for hydrodynamic zone 1 in northern Alameda County. This matrix is repeated in Table 3-3 for ease of comparison with hydrodynamic zones 2 – 4 presented in Table 3-4 to Table 3-6, respectively. With this approach, the six selected inundation scenarios can be used to represent over 30 combinations of sea level rise and storm surge events. These scenarios will therefore provide a richer data set with which to evaluate sea level rise vulnerabilities and risk – and more importantly to better define the timing for implementation of effective adaptation strategies.



Path: C:\FEMA\SLR\Alameda\ALA_SLR 8.5x11_ZonePoints.mxd

Figure 3-7. Hydrodynamic Zone Locations for Alameda County

Table 3-3. Sea Level Rise and Extreme Tide Matrix (Hydrodynamic Zone 1)

Sea Level Rise Scenario	Daily Tide *Permanent Inundation*	Extreme Tide (Storm Surge) *Temporary Flooding*						
	+SLR	1-yr	2-yr	5-yr	10-yr	25-yr	50-yr	100-yr
	Water Level above MHHW (in)							
Existing Conditions	0	14	19	23	27	33	37	42
MHHW + 6 inch	6	20	25	29	33	39	43	48
MHHW +12 inch	12	26	31	35	39	45	49	54
MHHW +18 inch	18	32	37	41	45	51	55	60
MHHW +24 inch	24	38	43	47	51	57	61	66
MHHW +30 inch	30	44	49	53	57	63	67	72
MHHW +36 inch	36	50	55	59	63	69	73	78
MHHW +42 inch	42	56	61	65	69	75	79	84
MHHW +48 inch	48	62	67	71	75	81	85	90
MHHW +54 inch	54	68	73	77	81	87	91	96
MHHW +60 inch	60	74	79	83	87	93	97	102
HYDRODYNAMIC ZONE 1								

Table 3-4. Sea Level Rise and Extreme Tide Matrix (Hydrodynamic Zone 2)

Sea Level Rise Scenario	Daily Tide *Permanent Inundation*	Extreme Tide (Storm Surge) *Temporary Flooding*						
	+SLR	1-yr	2-yr	5-yr	10-yr	25-yr	50-yr	100-yr
	Water Level above MHHW (in)							
Existing Conditions	0	14	19	23	27	32	36	41
MHHW + 6 inch	6	20	25	29	33	38	42	47
MHHW +12 inch	12	26	31	35	39	44	48	53
MHHW +18 inch	18	32	37	41	45	50	54	59
MHHW +24 inch	24	38	43	47	51	56	60	65
MHHW +30 inch	30	44	49	53	57	62	66	71
MHHW +36 inch	36	50	55	59	63	68	72	77
MHHW +42 inch	42	56	61	65	69	74	78	83
MHHW +48 inch	48	62	67	71	75	80	84	89
MHHW +54 inch	54	68	73	77	81	86	90	95
MHHW +60 inch	60	74	79	83	87	92	96	101
HYDRODYNAMIC ZONE 2								

Table 3-5. Sea Level Rise and Extreme Tide Matrix (Hydrodynamic Zone 3)

Sea Level Rise Scenario	Daily Tide *Permanent Inundation*	Extreme Tide (Storm Surge) *Temporary Flooding*						
	+SLR	1-yr	2-yr	5-yr	10-yr	25-yr	50-yr	100-yr
	Water Level above MHHW (in)							
Existing Conditions	0	15	20	24	27	32	36	41
MHHW + 6 inch	6	21	26	30	33	38	42	47
MHHW +12 inch	12	27	32	36	39	44	48	53
MHHW +18 inch	18	33	38	42	45	50	54	59
MHHW +24 inch	24	39	44	48	51	56	60	65
MHHW +30 inch	30	45	50	54	57	62	66	71
MHHW +36 inch	36	51	56	60	63	68	72	77
MHHW +42 inch	42	57	62	66	69	74	78	83
MHHW +48 inch	48	63	68	72	75	80	84	89
MHHW +54 inch	54	69	74	78	81	86	90	95
MHHW +60 inch	60	75	80	84	87	92	96	101
HYDRODYNAMIC ZONE 3								

Table 3-6. Sea Level Rise and Extreme Tide Matrix (Hydrodynamic Zone 4)

Sea Level Rise Scenario	Daily Tide *Permanent Inundation*	Extreme Tide (Storm Surge) *Temporary Flooding*						
	+SLR	1-yr	2-yr	5-yr	10-yr	25-yr	50-yr	100-yr
	Water Level above MHHW (in)							
Existing Conditions	0	15	20	24	28	33	39	45
MHHW + 6 inch	6	21	26	30	34	39	45	51
MHHW +12 inch	12	27	32	36	40	45	51	57
MHHW +18 inch	18	33	38	42	46	51	57	63
MHHW +24 inch	24	39	44	48	52	57	63	69
MHHW +30 inch	30	45	50	54	58	63	69	75
MHHW +36 inch	36	51	56	60	64	69	75	81
MHHW +42 inch	42	57	62	66	70	75	81	87
MHHW +48 inch	48	63	68	72	76	81	87	93
MHHW +54 inch	54	69	74	78	82	87	93	99
MHHW +60 inch	60	75	80	84	88	93	99	105
HYDRODYNAMIC ZONE 4								

4.0

SHORELINE DELINEATION

4. SHORELINE DELINEATION

4.1 APPROACH

The shoreline for Alameda County was delineated using Geographic Information System (GIS) tools to delineate the shoreline using an expanded version of the shoreline types defined in the ART Project (AECOM 2011) (e.g., “Engineered Shoreline Protection Structures” or “Wetland”, see Section 4.2). For this assessment, the ART Project shoreline types were expanded to include additional shoreline types that may impact floodwater conveyance and inland inundation (e.g., transportation structures – major roads and rail). The expanded shoreline types provide a more robust dataset for evaluating primary levels of shoreline and flood protection. The expanded approach was developed in collaboration with the San Francisco Estuary Institute (SFEI). SFEI is using the approach developed for Alameda County to create a bay-wide shoreline delineation, expected to be completed in 2015.

The shoreline was classified into shoreline types to collapse a highly-varied and diverse shoreline into distinct classes that will support vulnerability and risk assessments in Alameda County. Identification of shoreline types can enhance the understanding of how the shorelines may respond in a future climate condition. For example, stretches of erodible shoreline (e.g., beaches) will react to sea level rise differently than an engineered flood protection structure (e.g., levee armored with revetment). Assets behind more erodible shoreline features will be more susceptible to exposure from rising sea levels than if they were protected by a flood protection levee that includes consideration of freeboard within its design.

The shoreline from Emeryville to the Alameda Flood Control Channel (AFCC) was delineated for the ART Project. The areas north of Emeryville and south of the AFCC were delineated for this Project to provide consistent coverage to the full Alameda County shoreline. The complete shoreline delineation underwent intensive QA/QC using high-resolution oblique imagery made available by Alameda County. Major features that could provide flood protection up to a Bay water level of 120 inches (10 feet) above existing MHHW[12] were delineated, including channel embankments along open channels. In many cases, the original ART Project delineation was extended further upstream. The 1-meter horizontal grid resolution DEM was used as the primary source for locating and delineating the shoreline, in conjunction with high-resolution aerial photography. Levees databases from both Alameda County and FEMA (Midterm Levee Index, MLI) were also used for reference (FEMA 2012).

The shoreline segments were delineated on, or around, an absolute scale of 1:1,200. A combination of both high-resolution planar and oblique imagery was also crucial in distinguishing both location and type of feature. Aerial imagery (planar) from ArcGIS Online was used while digitizing in GIS. This imagery was flown in October 2010 (10/26/2010), and has a 0.3-meter horizontal resolution. Due to the visual absence of tidal flats in the imagery, it is likely that the imagery was flown at or near high tide. Oblique imagery was used from a number of free sources available online to assist in delineating and reviewing shoreline segments. Sources of oblique imagery included: Bing maps (“birds' eye” – low-resolution Pictometry imagery) and Google maps (45 degree).

Since the shoreline was used to identify overtopping potential (and possible inundation) risk, the shoreline was delineated at its highest point (or crest). The crest of each levee and/or high ground feature constituting the existing shoreline was determined using the 3D line profile tool in Esri's ArcGIS 3D Analyst extension. In locations where shorelines had natural features in the foreshore (i.e., wetlands), as well as man-made or natural features in the backshore (e.g., Engineered Shoreline Protection

[12] This scenario was not selected for inundation mapping as part of this assessment, but is used by SFEI to complete the shoreline delineation for the entire Bay, and represents an upper boundary beyond the extent inundation and flooding expected for the remainder of the century.

Structures), both features were delineated. In these cases, the shoreline feature at the backshore was used to evaluate overtopping. For natural shorelines, the shoreline is delineated at the “crest” of the beach (usually at the boundary of vegetation). In these cases, additional shorelines, including hardscapes (e.g., path, road, etc.) or softscapes (e.g., cliff, bluff, etc.), were delineated above these natural shorelines. In areas with narrow fringe wetlands, beaches, or natural shorelines that were too narrow to delineate, the primary shoreline in the backshore was assigned a “frontage” shoreline sub-category that tracks these features.

Additional man-made shoreline features were also delineated, such as salt pond berms or dikes that were inland of similar features located at the foreshore, if they were at similar or higher elevations than the more bayward shoreline. These features may provide additional flood protection. Gaps in the shoreline, such as wetland or flood control channels, remain as gaps in the shoreline segments. Finally, flood barriers (i.e., tide gates) located in channels, major roads, rail lines, and embankments were either delineated or re-classified from the previous ART Project delineation.

The central portion of the Alameda County shoreline delineated for the ART Project in 2011 was reviewed and edited for both geometry and type classification errors. These sections of the shoreline were edited to improve attribute and spatial accuracy using the high-resolution oblique imagery from Pictometry (6 inch resolution from 2009) provided by Alameda County. This imagery provided a high level of detail (and image orientation) for evaluating the spatial accuracy and type designations for each shoreline segment (see Figure 4-1 and Figure 4-2). Once edits were made to the central portion of the shoreline, they were combined with the northern and southern sections to create a comprehensive and seamless shoreline for the overtopping potential and normalized shoreline analyses.

Figure 4-1. High Resolution Oblique Imagery – Looking North at East Creek Point/East Creek Slough, Oakland

Figure 4-2. High Resolution Oblique Imagery – Looking South at Marina Park, Emeryville

4.2 SHORELINE BY TYPE DELINEATION

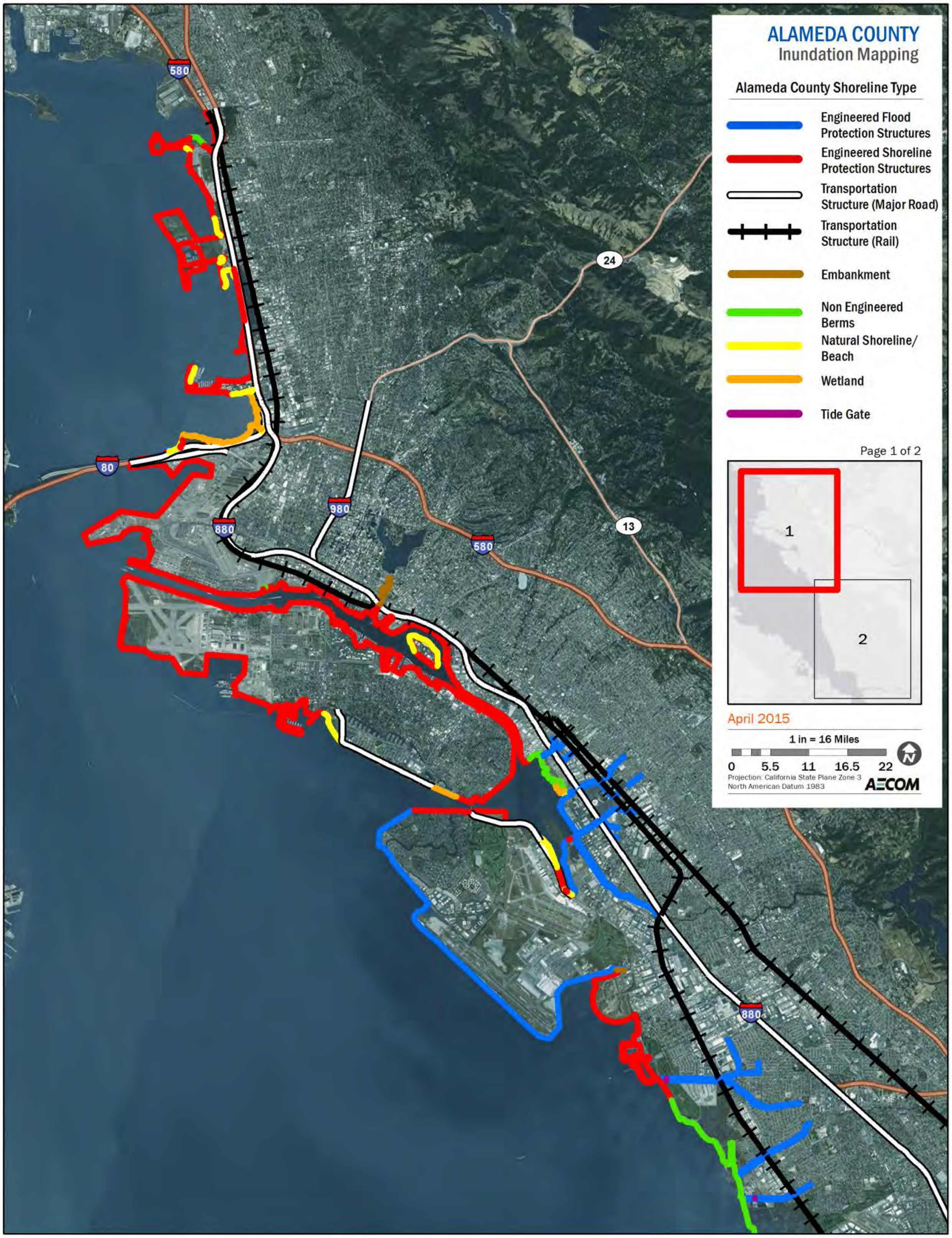
The shoreline categorization focused on identifying the main line of shoreline defense and seven categories were identified for the purposes of this study. These are: Engineered Flood Protection Structures (Levees or Flood Walls), Engineered Shoreline Protection Structures (Bulkheads or Revetments), Embankments (Upstream Channel Banks), Transportation Structures (Major Roads and Railways), Non Engineered Berms, Wetlands, and Natural Shoreline/Beach (Non-wetland). A brief description of each shoreline by type category is presented below. Additional descriptions and example images are included in Section 2.4 (Shoreline Asset Categorization) in the ART Project Technical Report (AECOM 2011). The final shoreline by type delineation for Alameda County is presented in Figure 4-3.

- **Engineered Flood Protection Structures:** These structures protect inland areas from flooding and inundation. These are defined as existing levees or flood walls. A coastal levee prevents inland flooding from major storm events and extreme water levels that may also be accompanied by large, powerful waves. A flood wall is a vertical barrier with a similar design standard to that of a levee. Structures with a FEMA Accreditation Date in the FEMA MLI Database were categorized into this shoreline type. These structures were delineated along the high point of the DEM profile.
- **Engineered Shoreline Protection Structures – Revetment/Bulkheads:** These structures harden the shoreline to reduce erosion and prevent land loss, and consist of bulkheads or shoreline revetments. However, they do not provide a standard level of flood protection like *Engineered Flood Protection Structures*. Revetments are a cover, or facing, of erosion resistant material (e.g., concrete or riprap) placed on an existing slope or an engineered embankment to protect the area from waves. A bulkhead is a vertical retaining structure designed to reduce land loss and protect inland areas from wave damage. Revetments and bulkheads were delineated

along the high point in structure profile where revetments (riprap) have been placed along the shore or those sections defined by the hardscape behind *Natural Shoreline* segments.

- **Embankments:** These barrier features do not provide a standard level of flood protection, but serve as a line of defense against flood hazards during storm events. Embankments are typically an earthen slope that transitions to heavy development (e.g., channel banks upstream of the coastal shoreline). These features were delineated at the high point on the DEM profile.
- **Transportation Structures – Major Roads/Rail:** These features were built for transportation purposes and do not provide a standard level of flood protection, but can serve as a line of defense against flood hazards during storm events. Only major roads (Rt. 80, 580, 880, 980) and rail lines (Amtrak) were delineated for this assessment to evaluate potential hazards to these assets. These features were delineated following the high point on the DEM profile.
- **Non Engineered Berms:** These features do not provide a standard level of flood protection, but still serve as a line of defense against flood hazards during storm events. Non Engineered Berms include other levees or levee-like structures that do not have current or previous FEMA Accreditation, and often resemble the shape of a levee. These features were delineated following the high point on the DEM profile.
- **Wetland:** Boundaries were defined by identifying the high point on the DEM either adjacent to a channel or tidal flat and digitizing an isoline (contour) to terminus with the nearest identified levee or protection structure. The hardscape behind each wetland has also been defined primarily by the most bay-ward levee.
- **Natural Shoreline/Beaches:** These are areas where Engineered Flood Protection or Shoreline Protection Structures are absent, and a clear landward structure that provides a level of flood protection is not visible. This includes areas that have permanent vegetation and may have a defined high point in the DEM profile, but are not engineered structures. The hardscape behind the natural shoreline has also been defined as an "Engineered Shoreline Protection Structure" or “Embankment” and, where applicable, consists of the nearest engineered path or road.
- **Tide Gates:** These structures are barriers that span creeks or channels, but allow tidal flushing to occur and can provide a level of flood protection for upstream areas. Major tide gates were identified using a GIS shapefile of tide barriers provided by ACFCWCD for the ART Project. The top of tide gate structures were delineated using the ArcGIS Online aerial imagery layer.

In addition to the maps contained in this report, the shoreline delineation layer for Alameda County is also available as a digital shapefile. The digital shapefile contains information on the most bayward shoreline type (*Frontage*) for each of the major shoreline types listed above. Features that are too narrow to be useful for this assessment, such as fringe wetlands, beaches, or combination of the two, are only identified under the primary backshore shoreline segment and are not delineated. For example, narrow fringe wetlands in front of a Non Engineered Berm segment of the shoreline are only tagged under the *Frontage* sub-category, and were not delineated in GIS. In addition, fortified shoreline segments (i.e., with riprap or concrete on the bayward slope) are attributed within the digital shoreline shapefile.


ALAMEDA COUNTY
Inundation Mapping
Alameda County Shoreline Type
Engineered Flood Protection Structures
Engineered Shoreline Protection Structures
Transportation Structure (Major Road)
Transportation Structure (Rail)
Embankment
Non Engineered Berms
Natural Shoreline/ Beach
Wetland
Tide Gate
Page 1 of 2
1
2
April 2015
1 in = 16 Miles
0 5.5 11 16.5 22
Projection: California State Plane Zone 3
North American Datum 1983
AECOM
580
24
80
980
880
13

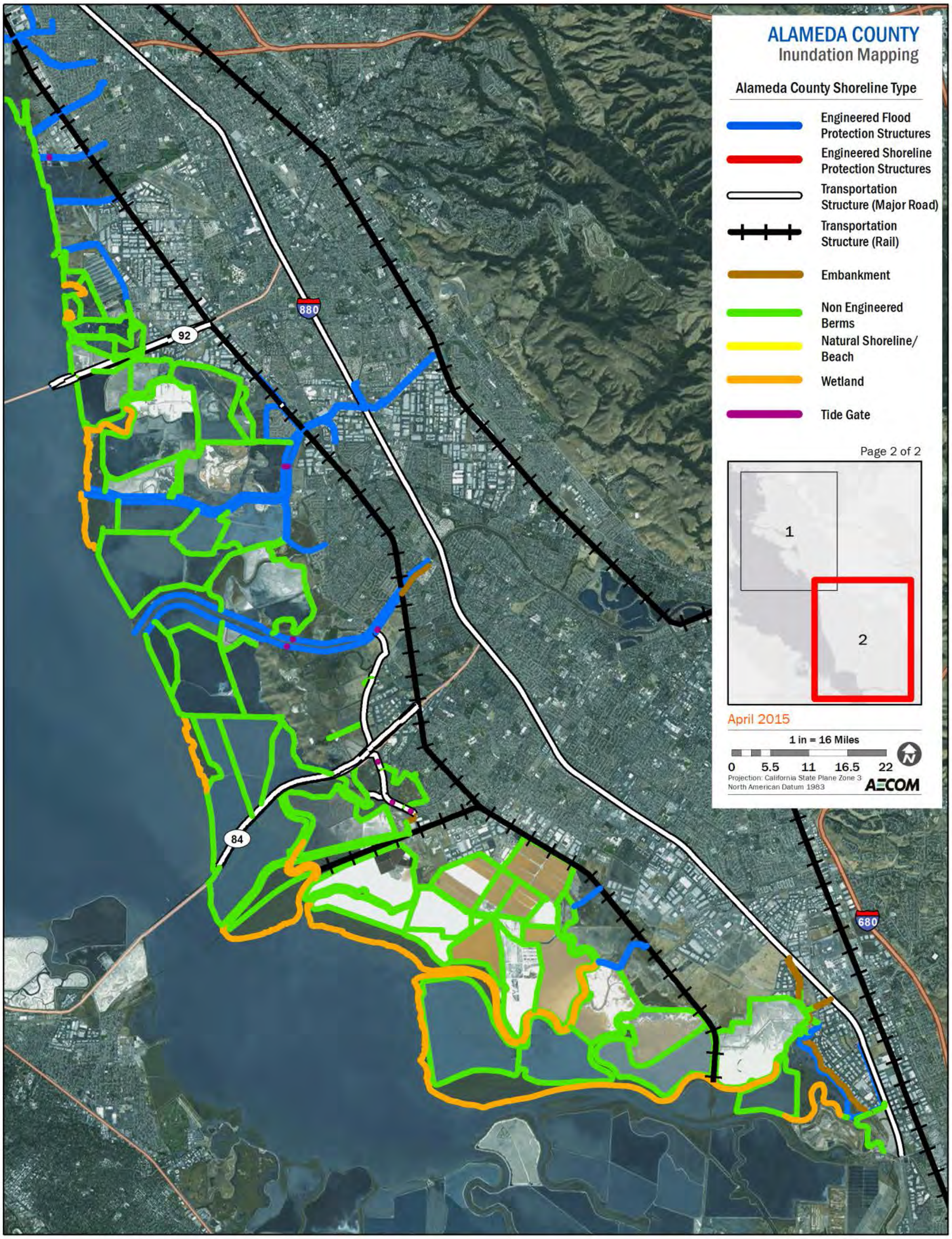


Figure 4-3. Shoreline by Type Delineation for Alameda County

5.0

SHORELINE OVERTOPPING POTENTIAL

5. SHORELINE OVERTOPPING POTENTIAL

5.1 METHODS

Information on the depth of inundation was extracted along each segment of the Alameda County shoreline to provide a high-level assessment of the potential for shoreline overtopping. “Overtopping potential” refers to the condition where the water surface elevation associated with a particular sea level rise scenario exceeds the elevation of the shoreline. The average depth of inundation along the shoreline assets was evaluated on a segment level, looking at the actual areas where the shoreline assets could be overtopped. This metric is useful for identifying the initial flow path for the inland inundation. For example, for the Oakland International Airport, the engineered flood protection levees on the inland edge of Bay Farm Island are overtopped first, resulting in inundation of the airport. Portions of the shoreline that are not overtopped (overtopping depth = 0) were not included in the average overtopping depth calculation. As sea level rises from the MHHW + 12 inch to the MHHW + 96 inch sea level rise scenario, additional lengths of shoreline are inundated within each system; therefore, the average overtopping depth increase between the two scenarios is less than the 84-inch increase in sea level.

Calculating overtopping potential provides insight to what locations on the shoreline are overtopped, causing inundation of low-lying areas landward of the current shoreline. The pathways for inundation from the Bay and overland cannot be determined from viewing the inundation maps by themselves. The addition of the overtopping potential delineation provides insight into the sources of inland flooding, so that the most vulnerable locations along the shoreline can be identified and prioritized for potential adaptation strategies.

GIS based tools were used to extract inundation depths for each scenario to create the overtopping potential dataset. To calculate overtopping potential, the shoreline delineation described in Section 4 was overlain on each of the six inundation depth rasters (i.e., one raster for each of the six inundation scenarios described in Section 2), and average depth values along each shoreline segment were extracted from the rasters. Figure 5-1 illustrates overtopping depth (i.e., water level exceeds the shoreline elevation) and freeboard (i.e., shoreline elevation exceeds the water level).

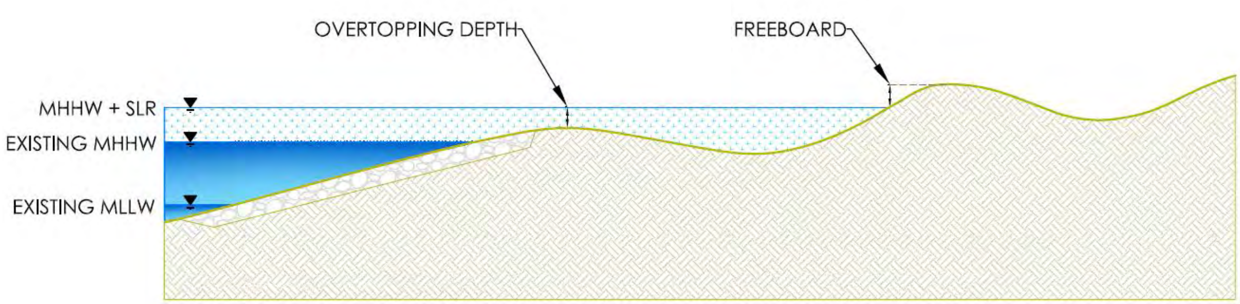


Figure 5-1. Representative Shoreline Cross Section Illustrating Overtopping Depth and Freeboard

5.2 APPLICATION OF OVERTOPPING POTENTIAL MAPS

Given the uncertainty in the modeling results and topography datasets, overtopping depths of less than 0.5 foot (0.2 meter) were excluded from the results. Therefore, it is possible for inundation to be shown in the overtopping potential maps over a particular shoreline segment without an associated depth of overtopping potential value.

The overtopping potential maps for each of the six inundation scenarios are presented in Appendix C. It should be noted that in the overtopping potential maps, the legends for the shoreline elevations were classified into 1-foot increments for visualization purposes only (excluding depths less than 0.5-feet) and the overtopping depths are more varied than shown. In addition to the maps contained in this report, the shoreline overtopping potential data layers are also available as digital shapefile.

This assessment should be considered a planning-level tool only, as it does not account for the physics of wave runup and overtopping. It also does not account for potential vulnerabilities along the shoreline protection infrastructure that could result in partial or complete failure of the flood protection infrastructure through scour, undermining, or breach after the initial overtopping occurs.

6.0

SHORELINE EXPOSURE ANALYSIS

6. SHORELINE EXPOSURE ANALYSIS

6.1 NORMALIZED EXTREME TIDE CURVES (EXISTING)

The concept of "normalized elevation" is a key component of this study. Normalizing elevation data allows the original data to be compared using a different scale. Elevation data is normalized by dividing each elevation value by a common denominator, which allows for comparisons across different spatial areas. For example, in San Francisco Bay, both the MHHW tide level and the 100-year tide level vary spatially. As previously discussed, the absolute elevation of both daily and extreme tides increases from north to south along Alameda County; however, the ratio of a given extreme tide to MHHW is relatively constant across large geographic areas. For example, the ratio of the 100-year tide level divided by the MHHW tide level (the common denominator) is approximately constant within each hydrodynamic zone identified in this study (approximately 10.0-ft / 6.5-ft = 1.5). A higher normalized extreme tide level reflects a greater difference between an extreme tide elevation and the local MHHW at a particular model output point. As can be seen in Table 6-1, while there is moderate spatial variability in the elevation of the MHHW tide level throughout Alameda County, the ratio of a specified return period extreme tide level to MHHW (elevation/MHHW) remains remarkably constant, especially for adjacent model output points. This finding further justifies the consolidation of the extreme tide elevations into several hydrodynamic zones, as discussed previously in Section 3.

An example extreme tide curve is shown in Figure 6-1a. The extreme tide curve shows the extreme tide elevations for corresponding return periods (from 1- to 100-years). A normalized extreme tide curve is similar to the extreme tide curve, except the extreme tide elevations are now normalized based on MHHW. An example normalized extreme tide curve is shown in Figure 6-1b (this normalized extreme tide curve is derived directly from the extreme tide curve and MHHW elevation shown in Figure 6-1a).

The existing conditions normalized extreme tide values for the corresponding points were also averaged to create a set of four consolidated curves – one for each zone. The four extreme tide curves for existing conditions are derived from normalizing the results from the daily and extreme tide level analysis presented in Table 6-1. This was done by dividing the extreme tide levels in Table 6-1 by the local MHHW. The resulting normalized extreme tide levels for each hydrodynamic zone are shown in Table 6-1. Using this normalized extreme tide data, graphical curves were produced for each hydrodynamic zone to represent existing conditions. The curves for Zones 1, 2, 3, and 4 are presented in Figure 6-2 to Figure 6-4. The black curve represents the extreme tide curve derived from model output data for existing conditions. The colored curves represent the extreme tide curves for future conditions under specific sea level rise scenarios. Normalized extreme tides curves were not created for the 500-year extreme tide level, but normalized extreme tide levels are presented in Table 6-1 for informational purposes. As discussed previously in Section 3.3, the 500-year normalized extreme tide values are meant to convey to stakeholders that the potential exists for events greater than the 100-year severity to occur.

The same concepts used to normalize the existing conditions extreme tide curves were also applied in developing the future conditions normalized extreme tide curves with a range of sea level rise scenarios (from 6 to 60 inches), which are discussed in the next section. The application of these extreme tide curves with the normalized shoreline elevation maps presented in Appendix D is presented in the following sections.

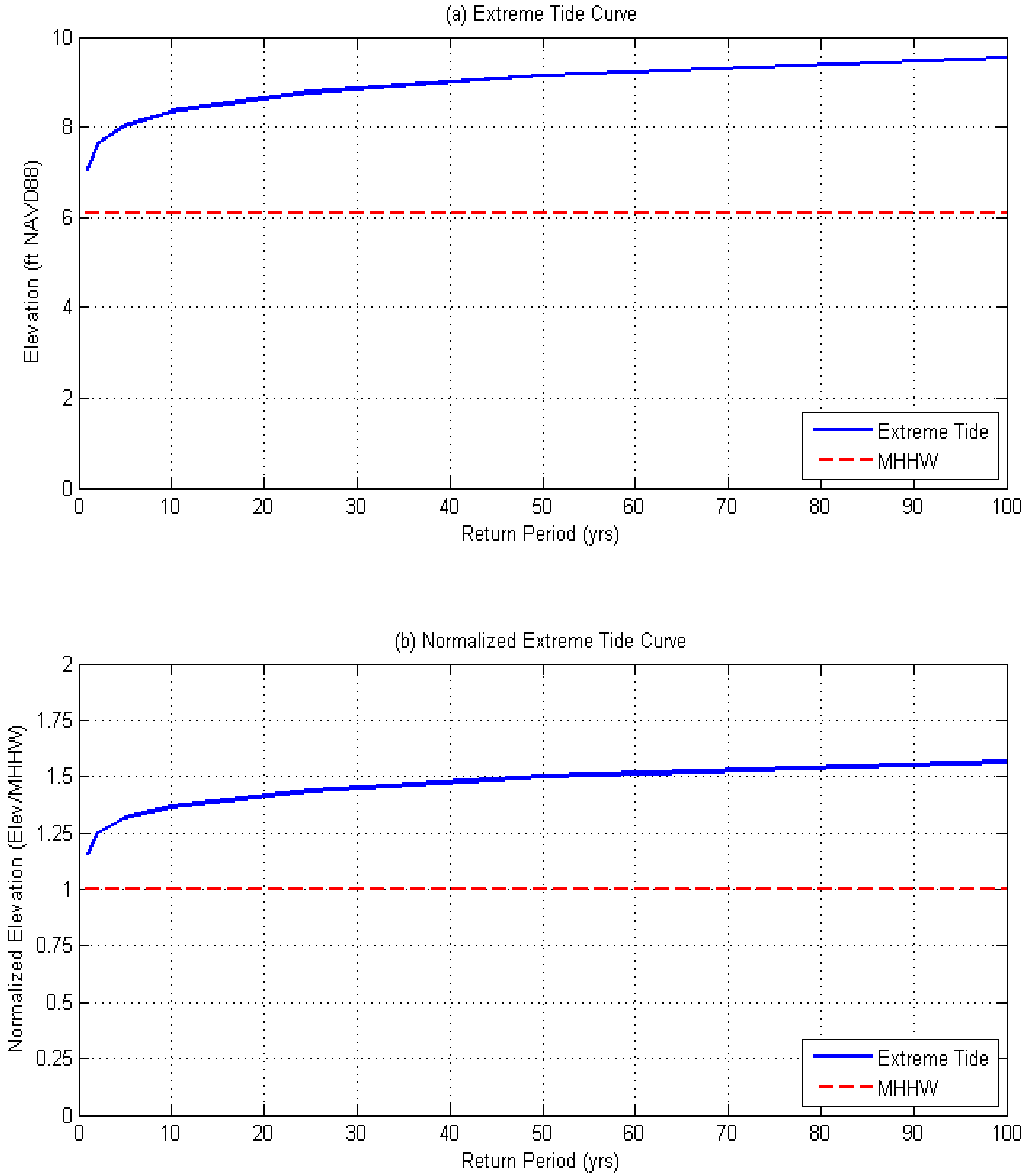


Figure 6-1. Example Tide Curves in San Francisco Bay:
(a) Extreme Tide Curve and (b) Normalized Extreme Tide Curve

Table 6-1. Existing Conditions Normalized Extreme Tide Levels

ZONE	Point ID	MHHW (ft NAVD)	Normalized Extreme Tide Level (Elev./MHHW) 1-yr	2-yr	5-yr	10-yr	25-yr	50-yr	100-yr	500-yr
Zone 1	1	6.10	1.19	1.25	1.32	1.37	1.44	1.50	1.56	1.74
	2	6.16	1.19	1.25	1.32	1.37	1.45	1.51	1.58	1.78
	3	6.20	1.19	1.25	1.32	1.37	1.44	1.50	1.57	1.77
	4	6.21	1.19	1.25	1.31	1.36	1.43	1.49	1.56	1.74
Zone 1 Average		6.17	1.19	1.25	1.32	1.37	1.44	1.50	1.57	1.76
Zone 2	5	6.27	1.19	1.25	1.31	1.36	1.42	1.48	1.54	1.69
	6	6.42	1.19	1.24	1.30	1.35	1.41	1.47	1.53	1.70
	7	6.62	1.18	1.24	1.29	1.34	1.40	1.45	1.52	1.69
	8	6.75	1.18	1.24	1.29	1.33	1.39	1.45	1.51	1.69
Zone 2 Average		6.51	1.18	1.24	1.30	1.34	1.41	1.46	1.52	1.69
Zone 3	9	6.89	1.19	1.24	1.29	1.33	1.38	1.43	1.48	1.61
	10	6.94	1.19	1.24	1.29	1.32	1.38	1.43	1.48	1.62
	11	6.97	1.18	1.23	1.28	1.32	1.38	1.43	1.48	1.63
	12	7.02	1.18	1.23	1.28	1.32	1.38	1.43	1.49	1.65
	13	7.06	1.18	1.23	1.28	1.32	1.38	1.43	1.49	1.66
	14	7.16	1.17	1.23	1.28	1.32	1.38	1.43	1.49	1.68
Zone 3 Average		7.01	1.18	1.23	1.28	1.32	1.38	1.43	1.48	1.64
Zone 4	15	7.21	1.17	1.23	1.28	1.32	1.38	1.44	1.50	1.70
	16	7.27	1.17	1.23	1.28	1.32	1.38	1.43	1.50	1.70
	17	7.35	1.17	1.23	1.28	1.31	1.38	1.43	1.50	1.71
	18	7.38	1.17	1.23	1.27	1.32	1.38	1.45	1.52	1.78
	19	7.42	1.16	1.22	1.27	1.31	1.39	1.46	1.54	1.85
Zone 4 Average		7.33	1.17	1.23	1.27	1.32	1.38	1.44	1.51	1.75

6.2 NORMALIZED EXTREME TIDE CURVES (FUTURE)

To transform the existing conditions extreme tide curves to future conditions, the entire range of sea level rise values from 6 to 60 inches was added to the existing conditions tide elevations presented in Table 6-1 and the resulting curves were normalized using the present day MHHW elevations. The future conditions normalized extreme tide curves for each hydrodynamic zone are presented in Table 6-2 to Table 6-5 for sea level rise amounts from 6 to 60 inches. All normalized extreme tide levels are reported relative to the existing conditions MHHW tide level for the specified hydrodynamic zone. The curves for Zones 1, 2, 3, and 4 are presented in Figure 6-2 to Figure 6-5. The black curve represents the extreme tide curve derived from model output data for existing conditions. Each of the colored curves represents the future conditions normalized extreme tide curve for each sea level rise projection from 6 to 60 inches.

It is worthwhile to note that as sea levels rise, it is possible for the increase in depth to be attenuated due to the inundation of new low-lying areas at the shoreline (e.g., perimeter sloughs, salt ponds, salt marshes, and other developed areas). It is also possible for an increase in depth to respond non-linearly if the presence of hard shoreline protection is increased in one region of the bay, and not others. At this time future changes to the shoreline are unknown, however they will most likely change throughout the remainder of the century. Therefore, there is still uncertainty in how some of the normalized extreme tide curves, especially for the higher sea level rise scenarios (i.e., 54 and 60 inches), may respond to these changes. These normalized extreme tide curves and subsequent analyses are based on existing conditions water levels and shoreline conditions, and should be used for planning purposes only as they are subject to change along with the existing shoreline.

Table 6-2. Future Conditions Normalized Extreme Tide Curves – Zone 1

			Inches of Sea Level Rise Above Existing MHHW									
	Return Period	Ex.	+6"	+12"	+18"	+24"	+30"	+36"	+42"	+48"	+54"	+60"
Zone 1	Ex.	1.00	1.08	1.16	1.24	1.32	1.41	1.49	1.57	1.65	1.73	1.81
	1	1.19	1.27	1.35	1.43	1.51	1.59	1.67	1.75	1.84	1.92	2.00
	2	1.25	1.33	1.41	1.49	1.57	1.66	1.74	1.82	1.90	1.98	2.06
	5	1.32	1.40	1.48	1.56	1.64	1.72	1.80	1.88	1.96	2.05	2.13
	10	1.37	1.45	1.53	1.61	1.69	1.77	1.85	1.93	2.02	2.10	2.18
	25	1.44	1.52	1.60	1.68	1.76	1.85	1.93	2.01	2.09	2.17	2.25
	50	1.50	1.58	1.66	1.74	1.83	1.91	1.99	2.07	2.15	2.23	2.31
	100	1.57	1.65	1.73	1.81	1.89	1.97	2.06	2.14	2.22	2.30	2.38
	500	1.76	1.84	1.92	2.00	2.08	2.16	2.24	2.33	2.41	2.49	2.57

Table 6-3. Future Conditions Normalized Extreme Tide Curves – Zone 2

			Inches of Sea Level Rise Above Existing MHHW									
	Return Period	Ex.	+6"	+12"	+18"	+24"	+30"	+36"	+42"	+48"	+54"	+60"
Zone 2	Ex.	1.00	1.08	1.15	1.23	1.31	1.38	1.46	1.54	1.61	1.69	1.77
	1	1.18	1.26	1.34	1.41	1.49	1.57	1.65	1.72	1.80	1.88	1.95
	2	1.24	1.32	1.39	1.47	1.55	1.62	1.70	1.78	1.86	1.93	2.01
	5	1.30	1.38	1.45	1.53	1.61	1.68	1.76	1.84	1.91	1.99	2.07
	10	1.34	1.42	1.50	1.57	1.65	1.73	1.80	1.88	1.96	2.03	2.11
	25	1.41	1.48	1.56	1.64	1.71	1.79	1.87	1.94	2.02	2.10	2.18
	50	1.46	1.54	1.62	1.69	1.77	1.85	1.92	2.00	2.08	2.15	2.23
	100	1.52	1.60	1.68	1.75	1.83	1.91	1.98	2.06	2.14	2.21	2.29
	500	1.69	1.77	1.85	1.92	2.00	2.08	2.15	2.23	2.31	2.38	2.46

Table 6-4. Future Conditions Normalized Extreme Tide Curves – Zone 3

	Return Period	Ex.	+6"	+12"	+18"	+24"	+30"	+36"	+42"	+48"	+54"	+60"
			Inches of Sea Level Rise Above Existing MHHW									
Zone 3	Ex.	1.00	1.07	1.14	1.22	1.29	1.36	1.43	1.50	1.57	1.65	1.72
	1	1.18	1.25	1.32	1.40	1.47	1.54	1.61	1.68	1.75	1.82	1.90
	2	1.23	1.30	1.38	1.45	1.52	1.59	1.66	1.73	1.80	1.88	1.95
	5	1.28	1.35	1.43	1.50	1.57	1.64	1.71	1.78	1.85	1.93	2.00
	10	1.32	1.39	1.46	1.54	1.61	1.68	1.75	1.82	1.89	1.96	2.04
	25	1.38	1.45	1.52	1.59	1.66	1.74	1.81	1.88	1.95	2.02	2.09
	50	1.43	1.50	1.57	1.64	1.71	1.79	1.86	1.93	2.00	2.07	2.14
	100	1.48	1.56	1.63	1.70	1.77	1.84	1.91	1.98	2.06	2.13	2.20
	500	1.64	1.71	1.78	1.86	1.93	2.00	2.07	2.14	2.21	2.28	2.36

Table 6-5. Future Conditions Normalized Extreme Tide Curves – Zone 4

	Return Period	Ex.	+6"	+12"	+18"	+24"	+30"	+36"	+42"	+48"	+54"	+60"
			Inches of Sea Level Rise Above Existing MHHW									
Zone 4	Ex.	1.00	1.07	1.14	1.20	1.27	1.34	1.41	1.48	1.55	1.61	1.68
	1	1.17	1.23	1.30	1.37	1.44	1.51	1.57	1.64	1.71	1.78	1.85
	2	1.23	1.29	1.36	1.43	1.50	1.57	1.64	1.70	1.77	1.84	1.91
	5	1.27	1.34	1.41	1.48	1.55	1.62	1.68	1.75	1.82	1.89	1.96
	10	1.32	1.38	1.45	1.52	1.59	1.66	1.72	1.79	1.86	1.93	2.00
	25	1.38	1.45	1.52	1.59	1.65	1.72	1.79	1.86	1.93	1.99	2.06
	50	1.44	1.51	1.58	1.65	1.71	1.78	1.85	1.92	1.99	2.06	2.12
	100	1.51	1.58	1.65	1.72	1.79	1.86	1.92	1.99	2.06	2.13	2.20
	500	1.75	1.82	1.88	1.95	2.02	2.09	2.16	2.23	2.29	2.36	2.43

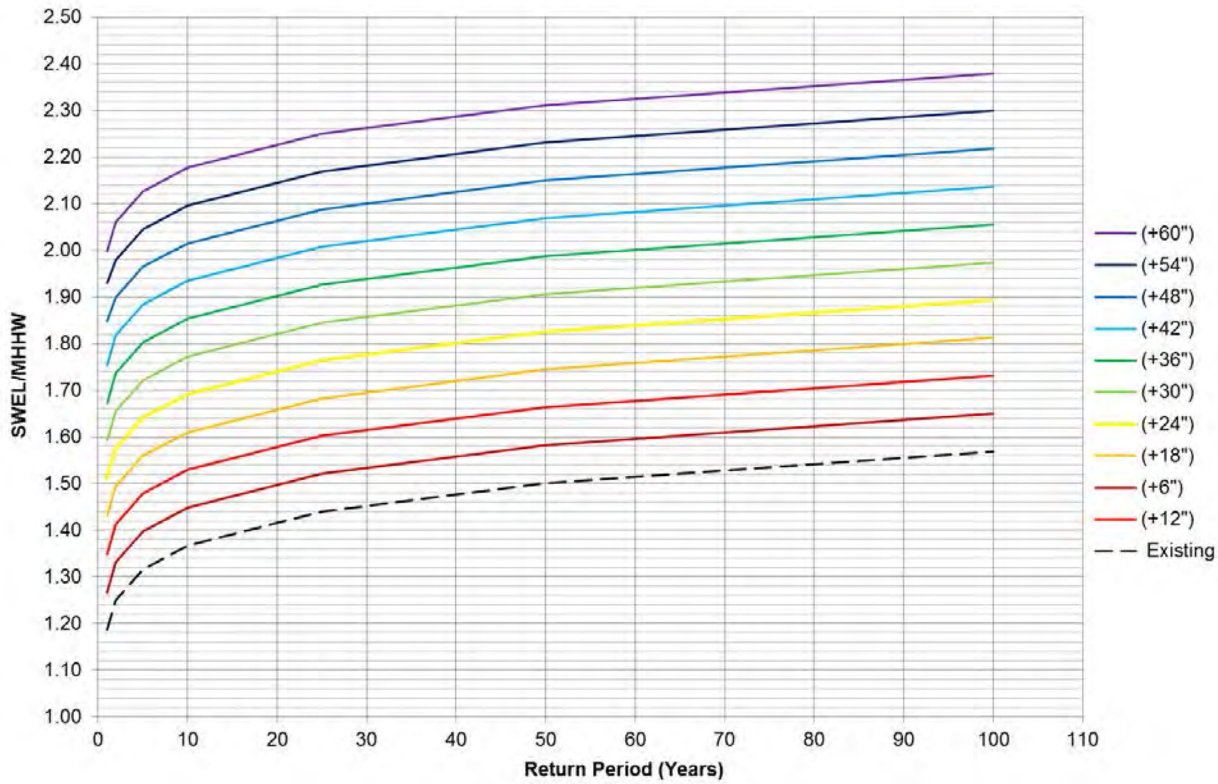


Figure 6-2. Existing and Future Conditions Normalized Extreme Tide Curves – Zone 1

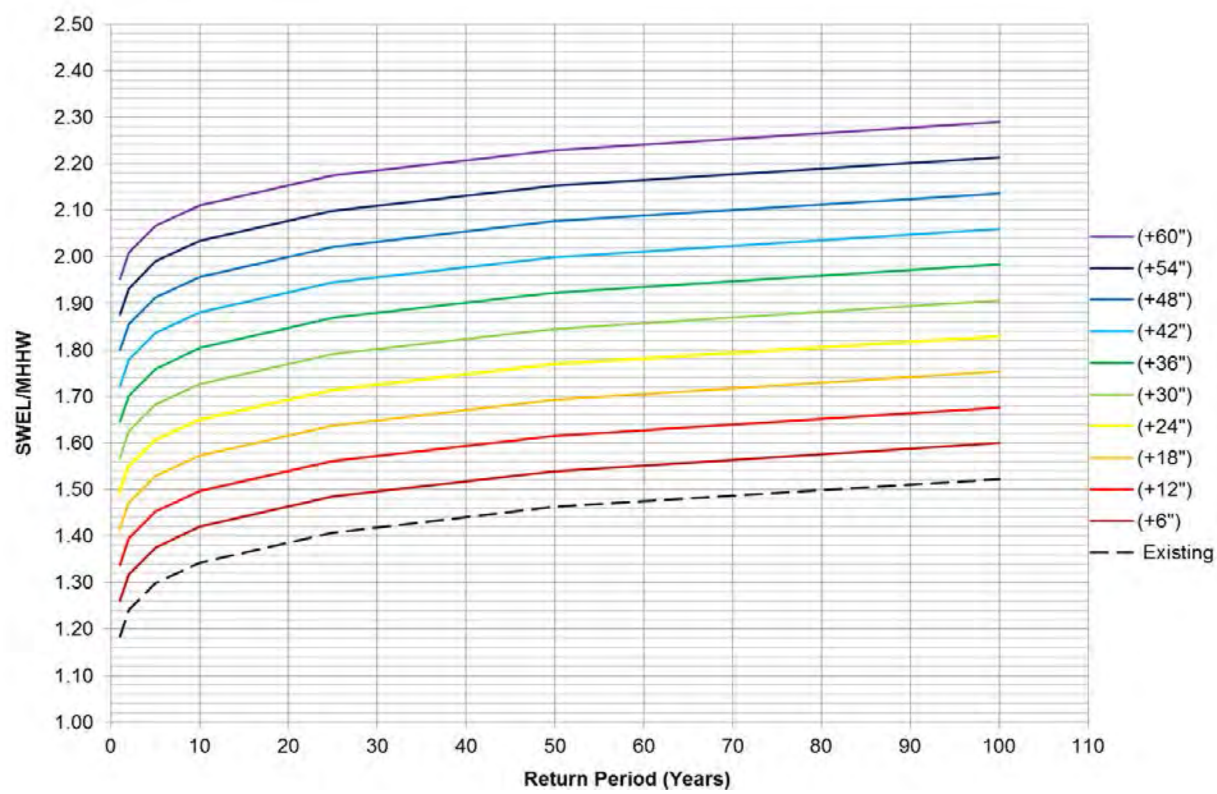


Figure 6-3. Existing and Future Conditions Normalized Extreme Tide Curves – Zone 2

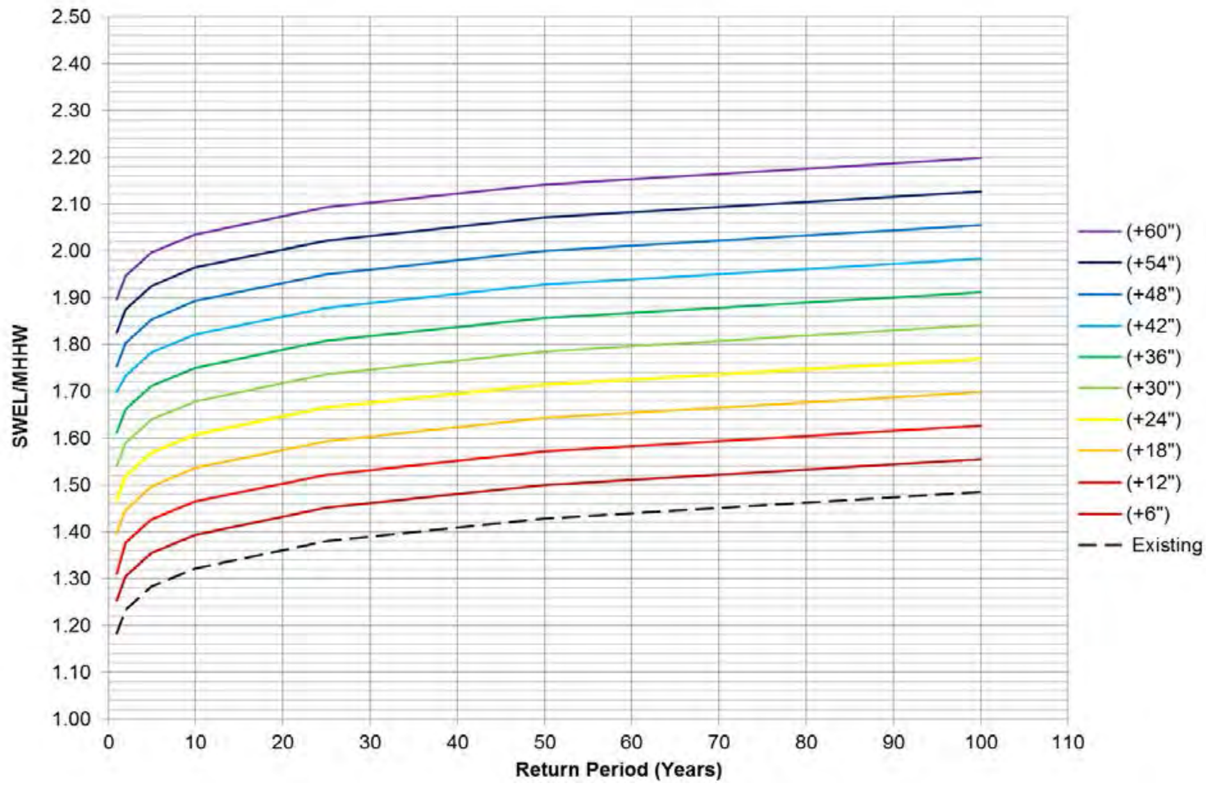


Figure 6-4. Existing and Future Conditions Normalized Extreme Tide Curves – Zone 3

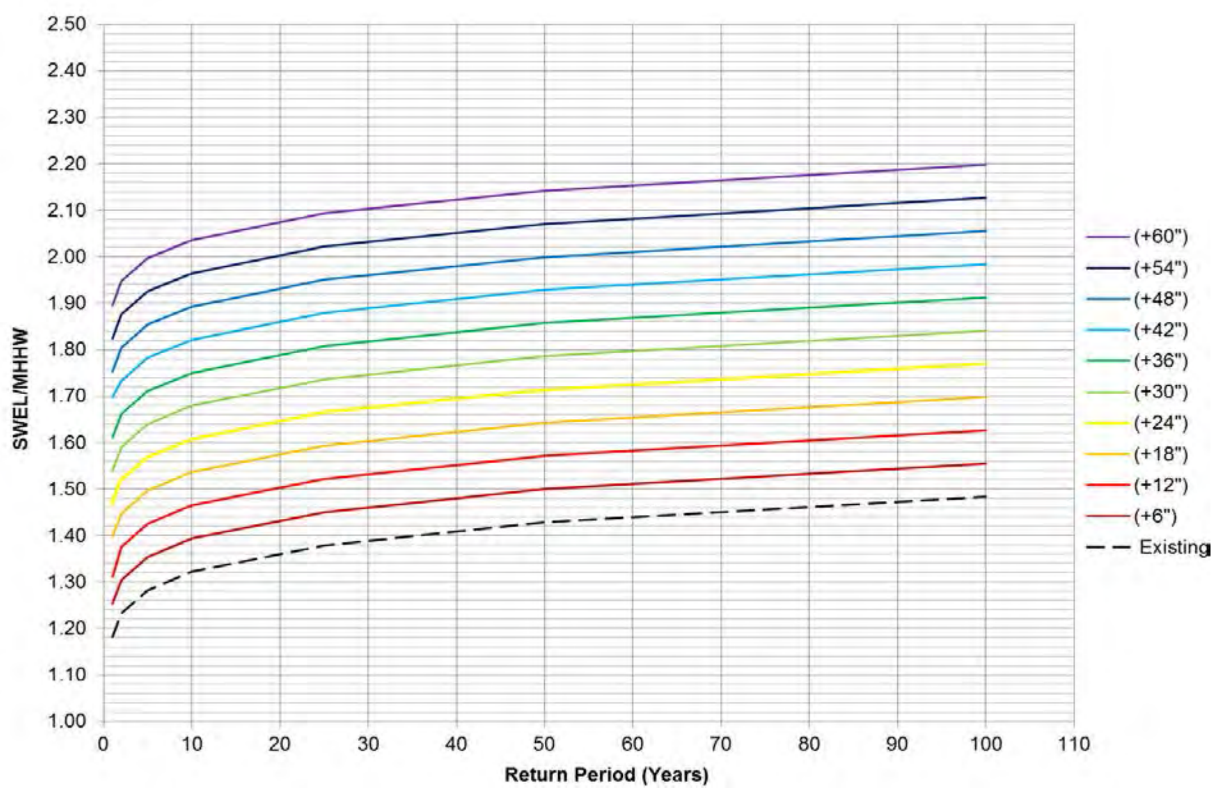


Figure 6-5. Existing and Future Conditions Normalized Extreme Tide Curves – Zone 4

6.3 NORMALIZED SHORELINE ELEVATIONS

A significant component of the study was the development of shoreline delineation maps that depict the elevation of the shoreline assets and features relative to MHHW ("normalized shoreline elevation"). Similar to the approach taken to normalize the extreme tide curves, shoreline elevation data can also be normalized by dividing each shoreline elevation value by the local MHHW tide level. The normalized shoreline elevation maps are presented in Appendix D, and can be used in combination with the normalized extreme tide curves to assess flooding thresholds for shoreline assets under existing and future conditions. By normalizing the shoreline asset elevations, the asset's flooding threshold can be determined by comparing the normalized shoreline elevation to the normalized extreme tide curve. A normalized elevation value of 1.0 indicates an elevation equal to the local MHHW tide level. A normalized elevation value greater than 1.0 indicates an elevation above the local MHHW tide level, while a value less than 1.0 is below MHHW.

The shoreline delineation layer described in Section 4 was used as a basis for calculating the normalized shoreline elevations. Two sets of elevation data were extracted along the shoreline delineation – the topographic elevations from the LiDAR-based DEM and the MHHW elevations calculated along the shoreline at the model outpoint points. Development of the normalized shoreline elevation maps was comprised of three steps. First, an existing conditions MHHW water surface DEM was developed using the results from the daily tide analysis of the model output data (Section 3). Second, the shoreline delineation was overlaid on the MHHW water surface DEM, and the topographic DEM to extract the average values of MHHW and land elevation along each shoreline segment. Third, the shoreline segment elevations were normalized by the local MHHW to produce a map of normalized shoreline elevation (Section 6). It should be noted that the water surface DEM is simply an extension of the Bay tidal water surface over the inland topography and not an explicit modeling of the hydrodynamics within the landward marsh channels and creeks.

GIS based tools were used to extract the land and water surface elevations and create the normalized shoreline elevation dataset. The detailed steps to create this dataset are as follows:

- The shoreline delineation layer was subdivided into segments with a maximum length of 100-feet
- The segmented shoreline delineation layer was overlaid on the MHHW water surface DEM
- The average value of the MHHW water surface within each shoreline segment was computed
- The averaging process was repeated with the topography DEM to determine the average land elevation within each shoreline segment
- The normalized shoreline elevation for each segment was computed by dividing the segment's average elevation by its average MHHW value

The shoreline elevation maps in Appendix D are reported relative to the NAVD88 vertical datum. It should be noted that in the normalized shoreline elevation maps, the legends for the shoreline elevations were classified into 0.2-foot increments for visualization purposes only, and the shoreline elevations are more varied than shown. In addition to the maps contained in this report, the normalized shoreline elevation data layer is also available as a digital shapefile. Further use of the normalized shoreline elevations as a tool to assess vulnerabilities on the Alameda County shoreline is described in the following section.

6.4 APPLICATION OF TIDE CURVES AND SHORELINE MAPS

The existing and future conditions normalized extreme tide curves have been presented in tabular and graphical format (Section 6.1 and 6.2). The future conditions normalized extreme tide curves for each of the four hydrodynamic zones along the Alameda County shoreline should be used in tandem with the normalized shoreline elevation maps presented in Appendix D. The information that can be extracted from the normalized extreme tide curves and corresponding values in tabular format are similar to the sea level rise matrix presented for each of the four hydrodynamic zones for Alameda County presented in Section 3.8. The normalized extreme tide curves in Figure 6-2 to Figure 6-5 are a graphical representation of combinations of sea level rise and storm surge scenarios that can impact a selected shoreline segment. Table 6-2 to Table 6-5 show the same information in tabular format -combinations of sea level rise and storm surge scenarios that can inundate shoreline segments above the same normalized extreme tide value.

The maps and curves can be used in various ways to assess flooding thresholds for existing and future conditions. Two potential scenarios for application are outlined below:

1. Determine the flooding threshold for a particular shoreline segment given a specified amount of sea level rise
2. Determine the approximate design elevation for a shoreline asset given a specified amount of sea level rise and preferred/required level of flood protection

In the first scenario, a stakeholder might be interested in the level of flood protection provided by a particular shoreline asset for some future condition with sea level rise. For example, an asset might provide 100-year flood protection under existing conditions, but with sea level rise, it is expected that the level of protection would decrease over time. Figure 6-6a illustrates this example for a shoreline asset with a normalized shoreline elevation of 1.5 (which indicates an elevation of 1.5 times MHHW). The flooding threshold can be evaluated by plotting a horizontal line at a normalized elevation of 1.5 and intersecting it with the selected extreme tide curve. For the selected extreme tide curve this asset's flooding threshold would be reduced to the 50-year level for future conditions with sea level rise.

In the second scenario, a stakeholder might be interested to know approximately to what elevation a shoreline asset would need to be raised to provide a specified level of flood protection under future conditions with sea level rise. Continuing the example above, the stakeholder may wish to elevate the shoreline asset to continue providing 100-year flood protection in the future. Figure 6-6b illustrates this example. The approximate design elevation can be evaluated by plotting a vertical line at a return period of 100 years, and intersecting it with the extreme tide curve. For the selected return period, a normalized shoreline elevation of 1.54 would be required. Using the local MHHW for the selected hydrodynamic zone to convert the normalized elevation to an absolute elevation (i.e., relative to NAVD88), an approximate design elevation for the shoreline asset could be determined. It should be noted that asset elevations determined in this manner would only be appropriate for planning level assessments and not engineering design.

An additional application of the normalized shoreline elevation maps shown in Attachment D is to visually identify existing and near term vulnerable reaches of existing shoreline. For example, one vulnerable area along the Alameda County shoreline is the San Leandro Bay shoreline, along the backside of Bay Farm Island and directly opposite Arrowhead Marsh (along Doolittle Drive). The normalized shoreline elevations in this area range from 1.03 to 1.74. Using this elevation range with the normalized extreme tide curves for Zone 2, it is apparent that sections of this shoreline that are below a value of 1.18 are already exposed to inundation during a 1-year extreme tide level under existing conditions. This area may be subjected to future daily inundation with sea level rise of 12 to 18 inches.

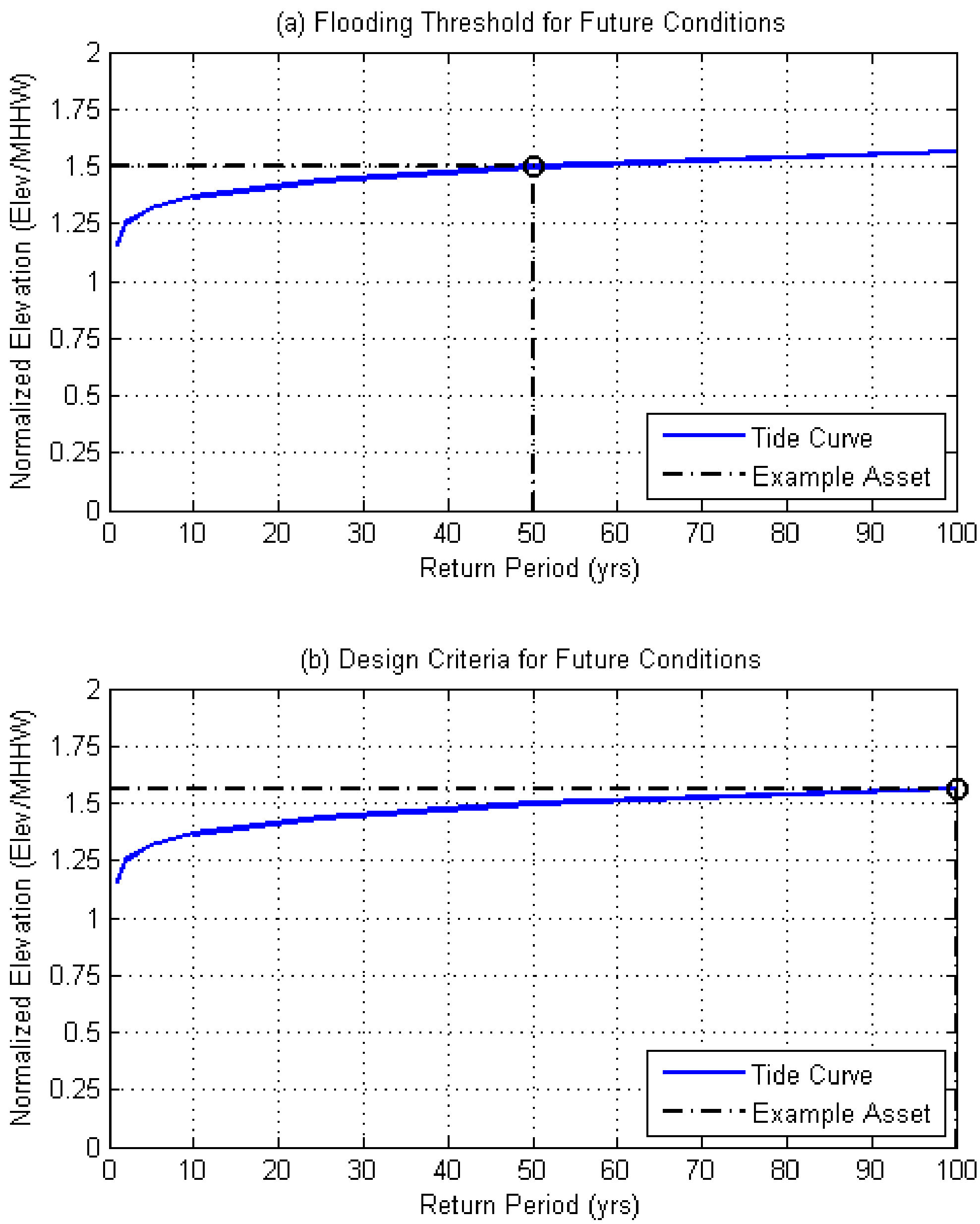


Figure 6-6. Example Application of Future Conditions Normalized Extreme Tide Curves

In summary, to interpret the flooding thresholds for a particular area of interest, the following steps can be used:

1. Identify the shoreline segment of interest and its normalized elevation using the shoreline maps in Attachment D,
2. Identify the hydrodynamic zone corresponding to the segment of interest,
3. Select the appropriate set of existing or future conditions normalized extreme tide curves for the hydrodynamic zone of interest from Figures 7 through 10,
4. Select an existing or future conditions normalized extreme tide curve for evaluation,
5. Intersect the existing or future conditions normalized extreme tide curve with either a horizontal or vertical line to determine the resulting normalized elevation or return period of interest.

7.0

MAPPING ASSUMPTIONS + CAVEATS

7. MAPPING ASSUMPTIONS AND CAVEATS

The inundation maps are intended as a screening-level tool to assess exposure to future sea level rise and extreme tide/storm surge induced coastal flooding. These maps represent a “do nothing” future scenario, and although they rely on the best available and current information and data sources, they are still associated with a series of assumptions and caveats as detailed below.

- The inundation scenarios associated with an increase in future MHHW (sea level rise above MHHW) represent areas that could be inundated permanently on a regular basis by tidal action. The inundation scenarios associated with extreme tide levels and storm surge represent periodic or temporary inundation associated with a coastal flooding condition. The inundation maps for extreme tide and storm surge scenarios do not consider the duration of flooding, or the potential mechanism for draining the floodwaters from the inundated land once the extreme high tide levels recede.
- The bathymetry of San Francisco Bay and the topography of the landward areas, including levees and other flood and shore protection features, are assumed to remain the same over time. No erosion, build up, or other shoreline changes in response to sea level rise and increased inundation is included in the analysis and mapping. The accumulation of organic matter in wetlands, or potential sediment deposition and/or resuspension, or subsidence that could alter San Francisco Bay hydrodynamics and/or bathymetry are not captured within the sea level rise scenarios.
- The maps do not account for future construction, or levee upgrades. The mapping methods also do not consider the existing condition or age of the shore protection assets. No degradation or levee failure modes have been analyzed as part of the inundation mapping effort.
- The maps do not account for flooding from potential increases in the groundwater table as sea levels rise.
- The maps do not account for water flow through water control structures such as culverts or tide gates.
- The levee heights and the heights of roadways and/or other topographic features that may affect floodwater conveyance are derived from the USGS and NOAA 2010 LiDAR data. Although this data set represents the best available topographic data, the data have not been extensively ground-truthed, and levee crests may be overrepresented or underrepresented by the LiDAR data. It is possible that features narrower than the 2-m horizontal map scale may not be fully represented.
- The inundation depth and extent shown on the MHHW maps are associated with the typical high tide, in an attempt to approximate the maximum extent of future daily tidal inundation. This level of inundation can also be referred to as “permanent inundation” because it represents the area that would be inundated regularly. Tides in San Francisco Bay exhibit two highs and two lows in any given day, and the daily high tide on any given day may be higher or lower than the MHHW tidal elevation.
- The depth and extent of inundation for an extreme coastal storm event (i.e., including local wind and wave effects) was not included in this study. These processes could have a significant effect on the ultimate depth of inundation associated with a large coastal wind/wave event, especially near the shoreline.
- The inundation maps do not account for localized inundation associated with any freshwater inputs, such as rainfall-runoff events, or the potential for riverine overbank flooding in the local

tributaries associated with large rainfall events. Inundation associated with changing rainfall patterns, frequency, or intensity as a result of climate change is also not included in this analysis.

- The science of climate change is constantly evolving, and sea level rise projections have a wide range of values.

8.0

CONCLUSIONS + NEXT STEPS

8. CONCLUSIONS + NEXT STEPS

This shoreline vulnerability assessment for Alameda County led to the development of a variety of geo-spatial tools and data layers that can assist with the next steps of identifying shoreline vulnerabilities and formulating and implementing adaptation strategies where necessary. These tools and data layers include the following:

- Sea level rise inundation maps
- Shoreline overtopping potential maps
- Sea level rise and extreme tide matrices
- Shoreline by type delineation maps
- Daily and extreme tide elevations
- Normalized shoreline elevation maps
- Normalized existing and future extreme tide curves

The sea level rise inundation and overtopping potential maps provide the first method for identifying assets that will be exposed to inundation from rising sea levels, as well as the primary inundation pathways from the Bay and over land. The depth of potential inundation over shoreline segments can be extracted from the overtopping potential maps for each inundation scenario. The normalized extreme tide curves coupled with the normalized shoreline elevation maps also provides a useful tool for landowners and managers to identify flooding thresholds for existing and future conditions with sea level rise. The future conditions normalized extreme tide curves are applicable over a range of extreme tide levels, from the 1-year to 100-year events, and a range of sea level rise projections, from 0 to 60 inches. To simplify the application of the daily and extreme tide levels and normalized curves, homogeneous hydrodynamic zones were created for Alameda County. Using these tools, stakeholders can further understand shoreline asset exposure to a much broader range of sea level rise projections than previously assessed. In addition to identifying where shoreline vulnerabilities may exist, these tools can help roughly identify a timing for adaptation in order to maintain an existing level of flood protection along the shoreline areas. As sea levels increase over time, the level of flood protection for these areas will decrease and flooding will occur at a higher frequency. The application of the sea level rise and extreme tide matrices created for each hydrodynamic zone can highlight when existing levels of flood protection will be eliminated, and when adaptation strategies might need to be implemented.

In order to continue this analysis, these tools and datasets could be applied to specific focus areas within Alameda County to understand the sources, mechanisms, and timing of inundation and flooding. This information would further support the development of appropriate adaptation strategies. With these tools, critical areas of vulnerabilities can be identified, and floodplain and shoreline asset managers can determine whether a localized or regional approach is necessary to maintain an existing level of flood protection against higher tide levels and more frequent flooding from storm surge.

Currently in Alameda County, some of these geo-spatial tools and data layers have been leveraged to identify shoreline vulnerabilities and the timing of inundation at four focus areas. These focus areas include: (1) Bay Farm Island and the existing vulnerabilities along the Doolittle Drive and Harbor Bay Club shorelines; (2) Damon Sough and the upstream tributaries which flow adjacent to the Oakland Coliseum, Amtrak, and BART transportation assets; (3) the San Francisco-Oakland Bay Bridge touchdown area; and (4) the San Mateo-Highway 92 Bridge touchdown area. The technical memorandum for one focus area is provided in Appendix F to illustrate how the products developed from this assessment can be used to evaluate shoreline vulnerabilities in greater detail and inform adaptation strategies.

The application of these tools and data layers should be used for planning-level assessments only, and should not be used directly for engineering design or construction purposes without further detailed analysis in consultation with a qualified engineering professional. However, these products are very useful for identifying where additional detailed information may be needed to confirm the shoreline vulnerabilities highlighted in the maps, and to identify what next steps are needed to perform more detailed analyses.

Beyond these tools, additional evaluations to strengthen the shoreline vulnerability assessment include examining the combined impact of coastal storm surge, waves, groundwater interactions, and roadway drainage and runoff. The inclusion of wave hazards in this analysis, including wave processes such as wave runup and overtopping, will enhance the overall understanding of shoreline vulnerability. The cumulative impacts of rainfall runoff and storm events occurring during periods of extreme tide levels were not considered in this analysis; however, these events will further exacerbate inland flooding and can be examined with more detailed modeling efforts. Changes in storm frequency and magnitude due to climate change were also not examined, but an evaluation of these dynamics may provide further insight to timing of when adaptation strategies need to be implemented at specific shorelines or inland areas. Rising groundwater tables, primarily associated with static sea level rise, can impact flooding and drainage by reducing infiltration and sub-surface storage of runoff. The impacts of rising groundwater tables on watershed flooding in Alameda County is not known, but can be explored as a next step. With higher groundwater tables and rising sea levels at the shoreline, the existing highway drainage systems will become less effective over time, and they may become completely ineffective with higher levels of sea level rise. These additional impacts were not considered in this assessment, but evaluation of these factors is recommended.

9.0

REFERENCES

9. REFERENCES

AECOM 2010. Adapting to Rising Tides Transportation Vulnerability and Risk Assessment Pilot Project. Prepared for the Metropolitan Transportation Commission, San Francisco Bay Conservation and Development Commission, Caltrans District No. 4, and the Federal Highway Administration. November 2011.

AECOM 2014a. BCDC Alameda County Sea Level Rise Enhanced Shoreline Exposure Analysis. Prepared for the San Francisco Bay Conservation and Development Commission. Final Report, March, 2014.

AECOM 2014b. Climate Change and Extreme Weather Adaptation Options for Transportation Assets in the Bay Area Pilot Project Technical Report. Prepared for the Metropolitan Transportation Commission, San Francisco Bay Conservation and Development Commission, Caltrans District No. 4, Bay Area Rapid Transit and the Federal Highway Administration. December 2014.

Dewberry. 2011. Project Report for the USGS San Francisco LIDAR-ARRA LIDAR. USGS Contract G10PC00013. Prepared for the USGS, March 4, 2011.

Dewberry. 2011. LiDAR Quality Assurance (QA) Report San Francisco Bay. LiDAR Project NOAA Coastal Services Center. April 21, 2011.

DHI Water and Environment (DHI). 2011. Regional Coastal Hazard Modeling Study for North and Central San Francisco Bay. FEMA. Final Draft Report, October 2011. Prepared for Federal Emergency Management Agency as part of the FEMA Services Group (DHI, Nolte Associates and Fugro).

DHI Water and Environment (DHI), 2012. Regional Coastal Hazard Modeling Study for South San Francisco Bay. FEMA. Final Draft Report, January 2013. Prepared for Alameda County Flood Control District and Federal Emergency Management Agency, Region IX.

Federal Emergency Management Agency (FEMA). 2012. *Midterm Levee Inventory (MLI) Project Report.* Washington, D.C.

Holleman R. C. and M. T. Stacey. 2014. Coupling of Sea Level Rise, Tidal Amplification, and Inundation. *J. Phys. Oceanogr.*, 44, 1439–1455.

Marcy, D., B. William, K. Dragonoz, B. Hadley, C. Haynes, N. Herold, J. McCombs, M. Pendleton, S. Ryan, K. Schmid, M. Sutherland, and K. Waters, 2011. New Mapping Tool and Techniques or Visualizing Sea Level Rise and Coastal Flooding Impacts. Proceedings of the 2011 Solutions to Coastal Disasters Conference. June 2011. Anchorage, AK.

National Research Council. 2012. Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future. Prepared by the Committee on Sea Level Rise in California, Oregon, and Washington and the National Research Council Board on Earth Sciences and Resources and Ocean Studies Board Division on Earth and Life Studies.

San Francisco Bay Conservation and Development Commission, NOAA, Metropolitan Transportation Commission, and California Department of Transportation District 4. 2011. Adapting to Rising Tides: Transportation Vulnerability and Risk Assessment Pilot Project. Accessed at http://www.mtc.ca.gov/planning/climate/RisingTides-TechnicalReport.pdf.

A

SUMMARY OF CLIMATE SCIENCE

A-1. Introduction

In 2013, the Intergovernmental Panel on Climate Change (IPCC) reiterated in its Fifth Assessment Report (AR5) that the evidence of climate change is "unequivocal" and that "the human influence on the climate system is clear" (IPCC 2013). Over the past several centuries, the composition of the atmosphere has changed as a result of human activity: there has been an increase in the concentration of different types of greenhouse gases, aerosols (small airborne solid or liquid particles), and tropospheric ozone in the atmosphere. Additionally, human activity has also resulted in land use change globally. These factors have contributed in various ways to altering the climate system by exerting either a warming or a cooling effect on the climate. For example, aerosols exert a net cooling effect on the atmosphere. On the other hand, the emissions of greenhouse gases in the atmosphere (primarily, the emissions of carbon dioxide from the combustion of fossil fuels) exert a significant warming effect on the climate. The cumulative impact of human activity has resulted in a net warming of the earth's surface at the global scale, which has led to detectable climate change or climate variability expressed in unusual weather patterns and events as well as sea level rise (USGCRP 2009). At the continental and regional scale, these observed effects from climate change include sea level rise, changes in precipitation patterns and coastal storms, and extreme heat events, among others (USGCRP 2009).

This climate science summary presents the relevant climate science data in order to establish the scientific basis for evaluating climate change impacts from using the best, readily available, scientific information, as it relates to sea level rise. The data and information gathered for each climate change parameter include time horizons whenever possible (e.g., 2050 and 2100), as well as relevant ranges in the parameters that account for uncertainty in the future climate scenarios. Observed climatic changes (i.e., changes sea level) that have occurred as a result of normal climatic variability and anthropogenic-driven change, as well as projected climatic changes that are expected to occur as a result of future increases in greenhouse gas emissions, are presented. These observed and projected climatic changes are identified for California and the San Francisco Bay Area (Bay Area). For the various greenhouse gas emission scenarios, this climate science summary also examines potential time horizons and trigger points/levels for expected climatic changes in sea level. Uncertainties associated with observed and projected climatic changes are identified for consideration within the overall evaluation of sea level rise impacts in Alameda County. When planning for adaptation strategies to protect valuable assets from exposure to rising sea levels and more frequent storm surge events, it is helpful to understand the science behind the projections, so that better informed decisions can be made throughout the planning process.

A-1.1 ACRONYMS/ABBREVIATIONS

AR4	Fourth Assessment Report of the Intergovernmental Panel on Climate Change
AR5	Fifth Assessment Report of the Intergovernmental Panel on Climate Change
Bay	San Francisco Bay
Bay Area	San Francisco Bay Area
CCC	California Coastal Commission
CCCC	California Climate Change Center
CEC	California Energy Commission
CMIP	Coupled Model Intercomparison Project
CNRA	California Natural Resources Agency
CO_2	carbon dioxide
CO_{2e}	carbon dioxide equivalent
ENSO	El Niño–Southern Oscillation
FEMA	Federal Emergency Management Agency
GCM	general circulation model
GHG	greenhouse gas
IPCC	Intergovernmental Panel on Climate Change
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
PDO	Pacific Decadal Oscillation
ppm	part(s) per million
RCP	representative concentration pathway
SF	San Francisco
SREX	Special Report on Extreme Events
USGCRP	United States Global Change Research Program
USGS	United States Geological Survey
W/m^2	watt(s) per square meter

A-1.2 AVAILABLE DATA SOURCES

Several resources have been made available by the state of California on assessing statewide vulnerability to climate change, and on building resilience against these vulnerabilities. For example, the California Climate Change Center, a division of the California Energy Commission, which was enacted in 2005 pursuant to Executive Order S-3-05[1], is responsible for preparing periodic reports on the science of climate change and the impacts of climate change on various sectors. To date, the California Climate Change Center has conducted three assessments, the latest of which was released in July 2012. Each assessment highlights the major findings and implications of climate change for the state, based on a collection of studies from academic institutions and state agencies. The first assessment, released in 2006, examined the potential impacts of climate change on key state resources, such as the water supply, public health, agriculture, coastal areas, forestry, and electricity production and demand (CCCC 2006). The assessment contributed to the passage of Assembly Bill 32, the California Global Warming Solutions Act of 2006. The second assessment, released in 2008, provided initial estimates of the economic impacts of climate change (CCCC 2008); it formed the basis for the 2009 California Adaptation Strategy, which is the State's guidance for decision makers on how best to respond to and plan for climate change. The third assessment consisted of more than 30 peer-reviewed papers from the University of California and other research organizations, with a stronger focus on climate change vulnerability and statewide adaptation options (CCCC 2012). In addition to the research that has been published by the California Climate Change Center, this climate science summary also draws from the research conducted by other key agencies at the regional, state, federal, and international level that have contributed to advancing the understanding of climate science, vulnerabilities, and solutions at various scales. Key sources of information (shown with year of most recent publication reviewed) include:

- California Climate Change Center (2012)
- Cal-Adapt (2013)
- California Coastal Commission (2013, in review)
- California Energy Commission (2012)
- California Natural Resources Agency (2009)
- California Ocean Protection Council (2013)
- Environment California Research & Policy Center (2007)
- Intergovernmental Panel on Climate Change (2013)
- National Aeronautics and Space Administration (2009)
- National Oceanic and Atmospheric Administration (NOAA) (2013)
- National Research Council (2012)
- San Francisco Bay Conservation and Development Commission (2009)
- Vermeer and Rahmstorf (2009)

[1] Executive Order S-3-05 recognizes California's vulnerability to climate change and sets greenhouse gas reduction targets for California to 2000 levels by 2010, 1990 levels by 2020, and 80 percent below 1990 levels by 2050.

A-1.3 MODELING CLIMATE SYSTEMS

Modeling of climate systems is a common practice to assess how greenhouse gas emissions could influence climatic changes. Numerical models known as general circulation models (GCMs) simulate the physical processes of the atmosphere, ocean, and land surface to calculate the response of climate systems to increasing greenhouse gas levels. These models are based on well-established physical principles, and have been demonstrated to reproduce observed features of recent climate and past climate changes (IPCC 2007d). They are used to investigate the processes responsible for maintaining the general circulation of the atmosphere and the oceans, as well as the factors contributing to natural influences versus externally forced climate variability, such as an increase of anthropogenic greenhouse gases. Additionally, GCMs are also used to assess the role of various forcing factors in statistically significant climatic changes that have already been observed, and to provide projections of the response of climate systems to scenarios of future external forcing (IPCC 2007e). There are various global climate models ranging from atmosphere-ocean general circulation models to earth system models of intermediate complexity to simple climate models. There is considerable confidence that atmosphere-ocean general circulation models provide credible quantitative estimates of future climate change, particularly at continental and larger scales (IPCC 2007d).

A-1.4 GREENHOUSE GAS EMISSION SCENARIOS AS CLIMATE MODEL INPUTS

To model the impact of greenhouse gas emissions on the climate systems, the rate of increase and future amount of emissions need to be entered into the climate models. Various types of greenhouse gas emission scenarios were developed based on the premise that these rates depend on future human activity. Each scenario makes different assumptions for future greenhouse gas emission levels based on factors such as population, economic development, environmental changes, technology, and policy decisions. In 2000, IPCC published a special report on emissions scenarios, for which it developed global future greenhouse gas emission scenarios based on varying assumptions about economic development, population, regulation, and technology. All of these scenarios are considered “neutral” – none of them project future disasters or catastrophes (e.g., wars and conflicts, environmental collapse) (IPCC 2000). These scenarios were used by the IPCC in its Fourth Assessment Report (AR4) in 2007 (IPCC 2007f), and by numerous researchers modeling the impacts of climate change at various scales. The most relevant of these greenhouse gas emission scenarios are grouped into “families” termed as A1, B1, A2, and B2. Scenarios designated by the letter “A” generally emphasize economic development over environmental conservation, whereas “B” scenarios are generally more environmentally focused. Similarly, scenarios designated by the number “1” consider a more unified world focus, resulting in lower population, whereas scenarios designated by the number “2” are more regionally focused, and generally have higher population forecasts.

Researchers typically use high and low ends in the range of greenhouse gas emission levels to model the effects of greenhouse gas emissions on climate systems, and the scenarios representing these two possibilities are described in further detail below:

A2 - High-Emissions Scenario: The A2 future scenario represents a competitive world lacking cooperative development. It portrays a future in which economic growth is uneven, leading to a growing income gap between developed and developing nations. Under this scenario, world population exceeds 10 billion by 2050. Atmospheric carbon dioxide (CO_2) concentrations at the middle and end of the 21st century in this scenario would be about 575 and 870 parts per million (ppm), respectively, compared to pre-industrial levels of approximately 280 ppm, and today’s level of 397 ppm[2] .

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[2] http://www.esrl.noaa.gov/gmd/ccgg/trends/weekly.html

B1 - Low-Emissions Scenario: The B1 future scenario reflects a high level of environmental and social consciousness, combined with global cooperative and sustainable development and high economic growth. Global population would peak by mid-century, then decline. The low-emission scenario also includes a shift to less fossil fuel-intensive industries, and increased use of clean and resource-efficient technologies. Atmospheric CO_2 concentrations would reach 550 ppm by 2100, about double pre-industrial levels.

As the behavior and drivers of greenhouse gas emissions become clearer, the greenhouse gas emission scenarios may be revised periodically. Recently, in its AR5 (IPCC 2013), the IPCC used new scenarios for greenhouse gas emissions, called representative concentration pathways (RCPs). RCPs provide additional flexibility in climate modeling, and allow the incorporation of adaptation and mitigation measures to test the effectiveness of the measures relative to business-as-usual conditions. However, because these scenarios are fairly new and have only recently been published by the IPCC, they have not been used in most studies that have examined trends in climate change variables, particularly at the regional scale. Therefore, this memorandum will primarily summarize research that has been conducted on the basis of the former greenhouse gas emission scenarios that were developed in 2000.

The new RCP scenarios incorporate possible mitigation strategies, which were not included in AR4. They describe four potential climate futures, all of which are considered possible, depending on how much greenhouse gases are emitted in the years to come. The four RCPs – RCP2.6, RCP4.5, RCP6, and RCP8.5 – are named after a range of radiative forcing values in the year 2100 (+2.6, +4.5, +6.0, and +8.5 watts per square meter [W/m^2], respectively).

- **RCP 8.5**: Describes a world characterized by rapid economic growth. $\mathrm{CO_2 equivalent}$ (CO_{2e}) - concentrations reach ~1,370 ppm by end of the century. This is similar to the A1F1 scenario from IPCC AR4 (Table A- 1). This is also the worst-case scenario representing unabated emissions without implementing any mitigation measures.
- **RCP 6**: Represents a stabilization scenario. CO_{2e} concentrations reach ~850 ppm by the end of the century, followed by stabilization. This is similar to the A2 scenario from IPCC AR4.
- **RCP 4.5**: Represents a stabilization scenario where CO_{2e} concentrations reach ~650 ppm by the end of the century followed by stabilization. This is similar to the B1 scenario from IPCC AR4.
- **RCP 2.6**: Signifies a peak and decline scenario where CO_{2e} concentrations peak at ~490 ppm by mid-century, followed by rapid greenhouse gas emission reduction.

Table A-1 summarizes the CO2e concentrations expected by 2100 for the previous IPCC AR4 special report on emissions scenarios, and the representative concentration pathways adopted for the IPCC AR5. Out of the four RCP scenarios, only the lowest scenario (RCP 2.6) does not have an associated special report on emissions scenarios.

Table A-1: Summary of Special Report on Emissions Scenarios Emissions and RCP Scenarios – Approximate CO_2 Equivalent Concentrations by 2100 (ppm)

Family	Scenario	Approximate CO_2 equivalent concentrations by 2100 (ppm)	Note
High	A1F1	1,550	Fossil-fuel intensive economy. Rising emissions beyond 2100.
	RCP 8.5	1,370	Little effort to reduce emissions. Rising emissions beyond 2100.
	A2	1,250	Economic focus with regionally oriented economic development. Rising emissions beyond 2100.
Med-High	RCP 6.0	850	Stabilization after 2100.
	A1B	850	Economic focus with balanced emphasis on all energy sources. Stabilization after 2100.
	B2	800	Focus on local environmental sustainability. Stabilization after 2100.
Med-Low	RCP 4.5	650	Stabilization after 2100.
	B1	600	Focus on global environmental sustainability. Stabilization after 2100.
Low	RCP 2.6	490	Most ambitious effort. Peak in emissions before 2100, then decline. No similar scenario in special report on emissions scenarios.

Sources:

1. IPCC 2007b – Working Group I: The Physical Science Basis – Summary for Policymakers (Chapter 10 -Footnote #14)
2. Van Vuuren et al. 2011 – The Representative Concentration Pathways: An Overview.

A-1.5 DOWNSCALING OF GLOBAL CLIMATE MODELS

While models provide useful climate change projections at a global level, they do not provide detailed regional climate projections because the resolution – approximately 200 kilometers (km) – is typically too coarse for detailed regional climate projections (Hall et al. 2012). Therefore, models are often "downscaled" to provide additional regional detail. Downscaling is used to generate locally relevant data from GCMs by connecting global scale predictions and regional dynamics. There are multiple ways to downscale GCM data. One method, often referred to as dynamic downscaling, includes nesting a regional climate model within an existing GCM, thus generating local predictions that are informed by local processes and global models. Downscaled regional climate models can be developed to provide an evaluation of climate processes that are unresolved at the global model scale. There is a broad range of regional-based climate models from the sub-continental-scale with a resolution of approximately 50 kilometers, to a local-scale with resolution of approximately 1 to 5 kilometers (IPCC 2007e). The resolution is typically selected based on the size of the study area, computing power available, climate-relevant features, such as topography and land cover, and specific processes to be evaluated, such as runoff, infiltration, evaporation, and extreme events such as precipitation (IPCC 2007e).

Coupling the results of global climate models with regional models implies that uncertainties associated with both scales cascade through the ensemble modeling results, and are thus somewhat additive. Uncertainties and limitations of modeling are discussed in greater depth in subsequent sections.

GCM data can also be downscaled using statistical methods. One strategy relies on statistical regressions that can link local variables to particular large-scale variables in GCMs. These relationships are typically established for existing conditions, and then can be used to disaggregate the coarse-scale projections from the GCMs to a local/regional level. A second statistical strategy relies on stochastic weather generators that can reasonably predict the weather at a particular location using long-term weather data. The weather generator can be used to downscale GCM data by using GCM outputs, such as wind speed and/or temperature, as input to the weather generator, thereby generating a prediction of future local weather as a result of GCM predictions.

There are, of course, multiple downscaling techniques within each type – dynamic or statistical. All of the techniques are estimations, and none eliminate the uncertainties embedded in GCM output, but they can provide useful results for particular applications. Selecting the most appropriate downscaling technique requires a few elements to be considered, including the climate variables, desired time scale, and study domain of interest, as well as the availability of daily information (Maurer and Hidalgo 2009).

A-1.6 UNCERTAINTIES

Uncertainties associated with observed data are generally smaller than those associated with projections of future climate conditions. The range of uncertainty associated with future climate projections is much larger because there are uncertainties associated with multiple factors, including

- complex physical processes and their representation in global and regional climate models,
- predicting internal variability (e.g., El Niño/Southern Oscillation and the Pacific Decadal Oscillation),
- future greenhouse gas emissions,
- climate sensitivity to CO_2 forcing,
- model dependence (regional models rely on larger global models), and
- errors in the GCM initial conditions.

Evaluations of global climate models show that predictions of mean climate variables, such as the large-scale distributions of atmospheric temperature, precipitation, radiation and wind, and oceanic temperatures, currents, and sea ice cover are being represented with increasing skill over the past decade; however, numerous issues remain (IPCC 2007d). The latest AR5 assessment provides projections with a stated higher level of confidence compared to the previous AR4 projections, due to the enhanced method for evaluating future radiative forcing scenarios. However, uncertainty still exists in the global understanding of key processes, such as variations in volcanic activity, cloud feedback, ocean heat uptake, and the net change in global mean temperature as a result land use changes.

Uncertainties in predictions of climate change arise at all stages of the modeling process, but are partially overcome through evaluations of an ensemble of global climate models that sample different representative aspects of Earth processes. However, even this approach has limitations because some processes may be missing from the set of available models and alternative representations of other processes may share common systematic biases (IPCC 2007f).

A-2. Sea Level Rise

A-2.1 SEA LEVEL RISE INFORMATION SOURCES

This summary draws on the best available data for climate science, and the potential effects of sea level rise in California as of November 2013. In March 2013, the Ocean Protection Council adopted the 2012 National Research Council (NRC) Report *Sea-level rise for the Coasts of California, Oregon, and Washington: Past Present and Future* as the best available science on sea level rise for the state (OPC 2013). The California Coastal Commission also supported the use of the NRC 2012 report as best available current science, noting that the science of sea level rise is continually advancing, and future research may enhance the scientific understanding of how the climate is changing, resulting in updating sea level rise projections (CCC 2013, in review). The NRC report includes discussions of historic sea level rise observations, three sea level rise projections for the coming century, and insight into the potential impacts of a rising sea for the California coast.

Additional resources provide information on sea level rise and impacts specific to California and the Bay Area. These include peer-reviewed academic articles, the California Coastal Commission Sea Level Rise Policy Guidance (public review draft released on October 14, 2013), and globally relevant information from the latest release of the IPCC AR5, of which the summary for policymakers was released on September 27 2013.

The sections that follow summarize measured rates of sea level rise based on global (Section A-2.2) and regional (Section A-2.3) measurements, and global (Section A-2.4) and regional (Section A-2.5) sea level rise projections.

A-2.2 MEASURED GLOBAL SEA LEVEL RISE

Sea levels are one of the first indicators of Earth's evolving climate. Although global (also known as eustatic) sea levels have varied significantly throughout Earth's history, the end of the last glaciation, more than 20,000 years ago, marked the beginning of a progressively increasing trend of rising water levels experienced during the Holocene – the geologic period from 12,000 years ago to present (Alley et al. 2005). Increasing global atmospheric temperatures influence sea levels through two primary processes:

1) the melting of polar ice caps (land-based ice sheets and glaciers), which increases the volume of water stored in the oceans and

2) the warming of the oceans, causing water to expand, and thereby increasing the water column height (IPCC 2013), a process referred to as thermal expansion.

Evidence of historical sea level trends can be examined using a combination of reconstructed paleoclimate proxy-data (e.g., sediment and ice cores), ocean tide gauge records, and new satellite-based ocean elevation sensors.

Paleoclimate data are derived from natural sources, such as ocean sediment cores, marsh cores, and corals. These sources contain stratigraphic layers of geophysical and biological indicators of past climate conditions, and are used as proxies to reconstruct sea levels from hundreds to millions of years in the past. These records suggest that during the last deglaciation, which began 20,000 years ago, sea levels initially rose rapidly at an average rate of 10 millimeters (mm) or 0.4 inches per year (Chorley et al., 1984). These rates of glacial melt and sea level rise slowed significantly between 7,000 to 2,000 years ago, and eventually declined to a rate of zero change (Gehrels 2010). Sediment cores from salt marshes in both the Northern and Southern Hemispheres indicate another acceleration of sea level rise over the past 2,000 years. Rates increased from relatively low rates (>0.004 inches or >0.10 mm per year) to more modern rates on the order of 0.08 to 0.11 inches per year (2 to 3 mm per year), with the most robust of these changes occurring from 1840 to 1920 (IPCC 2013).

The water level data collected at a tide gauge can be averaged and filtered (to remove additional processes that may affect water levels such as atmospheric pressure, seasonal variations, wind, and tsunamis) to assess the relative sea level that has occurred at that location. All world-wide tide stations can be averaged together to remove regional variations and allow examination of sea level on a global scale.

Figure A-1 shows the average annual global sea level from 1870 to present. Evaluation of trends in global sea level captured by tide gauges reveals a rate of 0.07(± 0.01 inches) per year (1.7 (± 0.3 mm) per year) between 1901 and 2010 that produced a total sea level rise of 0.62 feet (0.19 meter [m]) (IPCC 2013). The fastest rates of increase in sea level occurred between 1920 and 1950 at a rate of 0.10 inches per year (2.5 mm per year), and between 1992 and 2002 at a rate of 0.13 inches per year (3.4 mm per year) (Jevrejeva et al. 2008).

High-precision global sea level observations from satellites began in 1992. Equipped with radar altimeters to measure the distance between the satellite and sea surface, these instruments make a complete set of repeated orbit observations every 10 to 35 days. After removing the approximately -0.01 inches per year (-0.3 mm per year) signal of deformation of ocean basins caused by the post-glacial rebound of the earth's crust (also referred to as glacial isostatic adjustment), global mean sea level can be computed by averaging data collected by all operating altimeters (Peltier 2009). From 1993 to 2002, satellite observations reveal the rate of increase in global sea levels to be 0.13 ± 0.02 inches per year (3.2 ± 0.4 mm per year) – a close agreement with tidal observations over the same period (IPCC 2013).

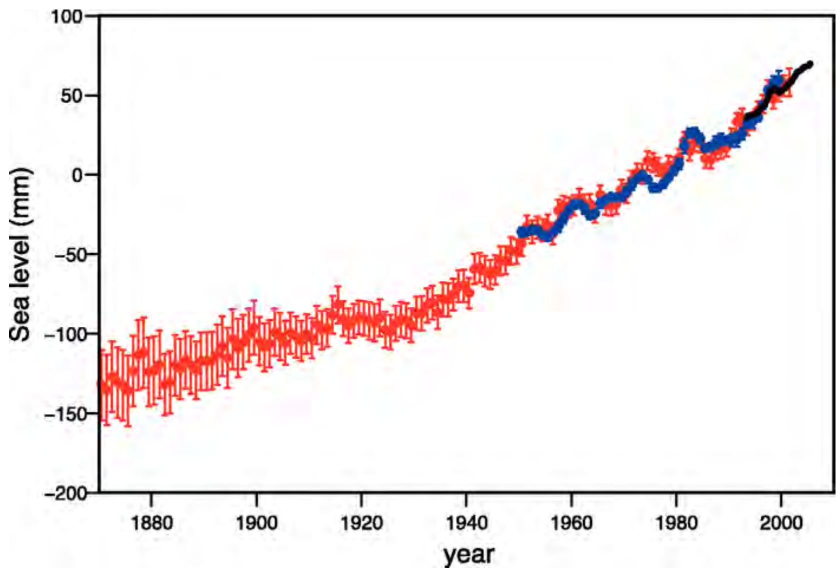


Figure A-1. Annual Averages of Global Sea Level

The red curve shows reconstructed sea levels since 1870, with error bars at the 90% confidence intervals, the blue curve shows coastal tide gauge measurements since 1950, and the black curve is based on satellite altimetry. Source: IPCC (2007)

A-2.3 MEASURED SEA LEVEL RISE ON THE CALIFORNIA COAST

Although estimating sea level on a global scale is useful for evaluating large-scale trends, various physical forces create regional and local variations in relative sea levels that may deviate from the average estimate. Large-scale climate patterns such as the El Niño–Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) are the dominant forces controlling sea level variability along the U.S. West Coast, and their effects can persist from years to decades (Bromirski et al. 2011).

Records from satellite altimeters, tide gauges, and ocean temperature measurements infer a long-term increase in sea levels of the Pacific Coast. It is estimated that on average, the coast of California has experienced 8 inches (20 centimeters [cm]) of sea level rise over the past century, which is comparable to the global average (CCC 2013, in review).

Although tide gauge records indicate an overall increase in sea level, multi-decadal variability trends for the California coast can fluctuate, and often correspond with large-scale PDO cycles (NRC 2012). For example, localized sea level increase rates in San Francisco were found to be nearly stationary from 1880–1930 and 1980–2010 (Bromirski et al. 2011). Studies suggest that large-scale wind patterns attributed to the PDO have maintained consistent northerly winds blowing along the coast, pushing coastal water to the west and replacing warm surface water with cooler deep-ocean water (Bromirski et al. 2011). Both of these processes create conditions for lowered, observed local sea level increase rates, potentially masking the appearance of sea level rise. However, as the PDO cycle reverses, conditions for locally elevated sea level may become more prevalent, allowing for accelerated sea level rates in the future (Bromirski et al. 2011; Bromirski et al. 2012; NRC 2012).

On inter-annual time scales, ENSO events have a large role in sea level conditions (Zervas 2009). During warm phases of ENSO (El Niño), coastal sea levels can be elevated by 3.9 to 7.9 inches (10 to 20 cm) for several months during the winters. Conversely, cool phases (La Niña) can result in lower than average sea levels (Komar et al. 2011; Bromirski et al. 2011). For California, the highest recorded sea levels in the tide gauge record are typically associated with El Niño events, due to warmer ocean surface temperatures and stronger storm activity. Local geologic processes (e.g., tectonic uplift/subsidence) also have a large role in relative sea levels by raising and lowering the coastal land surface, thereby controlling elevations exposed to waves and tides. The California coast north of Cape Mendocino is currently experiencing regional uplift at a rate of 0.06 to 0.1 inches per year (1.5 to 3.0 mm per year) due to the Pacific Plate subsidence beneath the North American Plate along the Cascadia Subduction Zone (NRC 2012). South of Cape Mendocino, rather than being uplifted, the North American Plate is sliding past the Pacific Plate along the San Andreas Fault Zone, causing little to no vertical land movement. Due to resource extraction of water and hydrocarbons from subsurface reservoirs, on average, the coast south of Cape Mendocino is sinking at a rate of approximately 0.04 inches (1 mm) per year, although the local rate varies from -0.15 to 0.02 inches (-3.7 to 0.6 mm) per year (NRC 2012).

Although regional-scaled projections of sea levels are often sufficient for assessing the impact at a local level, smaller-scale physical effects may still play a significant role in determining the actual sea level. Recent estimates of relative sea level rise at West Coast tide stations are available from NOAA (2012) and NRC (2012). Analysis of 109 years of tide data at the San Francisco tide station (#9414290) indicates long-term historic mean sea level rise of 0.08 ± 0.008 inches per year (2.01 ± 0.21 mm per year) – see Figure A-2.

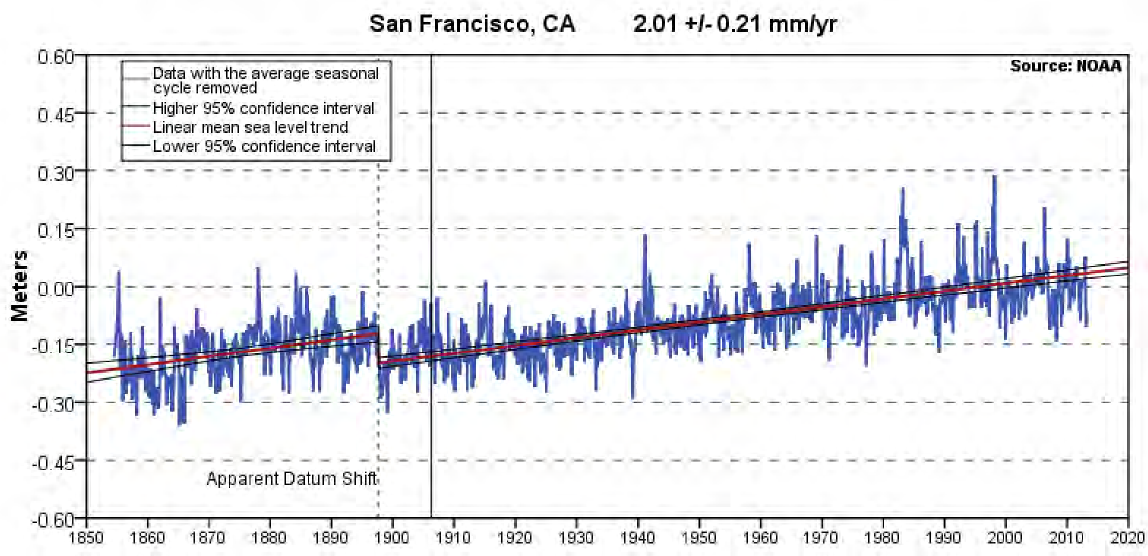


Figure A-2. Mean Sea Level Trend Tide Gauge Station 9414290 San Francisco, California

Source: NOAA; http://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?stnid=9414290, accessed February 2014. If present, solid vertical lines indicate times of any major earthquakes in the vicinity of the station and dashed vertical lines bracket any periods of questionable data.

The plot shows the monthly mean sea level without the regular seasonal fluctuations due to coastal ocean temperatures, salinities, winds, atmospheric pressures, and ocean currents. The long-term linear trend also is shown, including its 95% confidence interval. The plotted values are relative to the most recent mean sea level datum established by CO-OPS. The calculated trends for all stations are available as a table in millimeters/year or a table in feet/century (0.3 meters = 1 foot).

A-2.4 GLOBAL SEA LEVEL RISE PROJECTIONS

Projections of global sea levels are typically determined using one of the following methods:

1) extrapolations,
2) models of ocean-atmosphere-climate systems, or
3) semi-empirical models.

According to California's Ocean Protection Council Science Advisory Team, future sea level rise projections should not be based simply on linear extrapolation of historical sea level rise records. For estimates beyond one or two decades, linear extrapolation of sea level rise based on historical observations is considered inadequate. as it would likely underestimate the actual sea level rise. This is due to expected nonlinear increases in global temperature and the unpredictability of complex natural systems (Sea Level Rise Task Force of the Coastal and Ocean Working Group of the California Climate Action Team 2010).

Application of ocean-atmosphere-climate system models requires knowledge of the physical processes contributing to sea level rise based on future greenhouse gas concentration and climate scenarios. These models typically perform well for estimations of sea level rise contributions by thermal expansion due to warming surface waters; however, the complexities associated with ice dynamics often leads to an underestimation of contributions from glacial and ice sheet melt (NRC 2012). IPCC projections are based on this method, and a high degree of uncertainty in glacial processes and heat uptake in oceans caused an underestimation of observed sea levels for the AR4 estimates by up to 50 percent for the periods of 1990 to 2006 and 1961 to 2003 (Vermeer and Rahmstorf 2009). As discussed above, the more recent RCP scenarios developed in IPCC AR5 (IPCC 2013), provide an advancement of approaches for incorporation of dynamic ice sheets and glaciers.

Although greenhouse gas concentration scenarios are comparable between the two reports, the associated sea level rise is greater for AR5. The AR4 report estimated a 7.1 to 23.2 inch (18-59 cm) increase in sea levels by 2100, which has increased to 11.0 to 38.6 inches (28-98 cm) in AR5 (Figure A-3 and Table A-2).

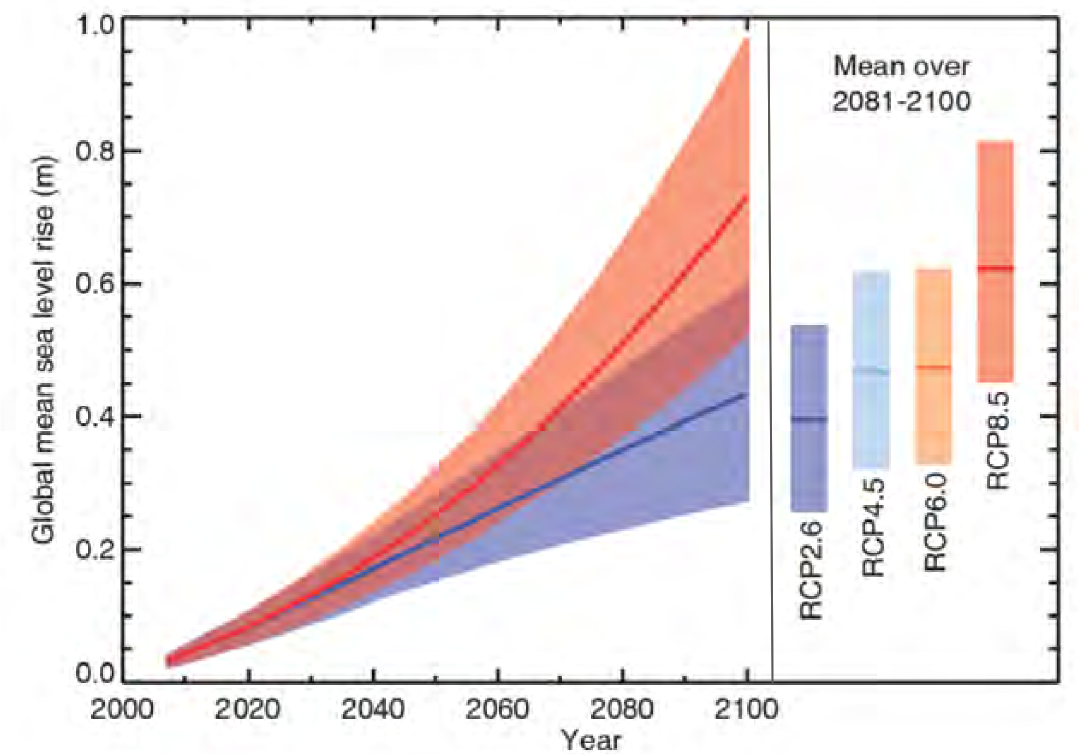


Figure A-3. Projected Rise in Global Sea Level until the Year 2100 for Each Representative Concentration Pathway Greenhouse Gas Concentration Scenario

Source: IPCC 2013.

Table A-2. Global Sea Level Rise by the Year 2100 as Projected by the Fifth Assessment Report of the Intergovernmental Panel on Climate Change

Scenario	Mean	Range
RCP2.6	17.3 in (44 cm)	11.0-24.0 in (28-61 cm)
RCP4.5	20.9 in (53 cm)	14.2-28.0 in (36-71 cm)
RCP6.0	21.7 in (55 cm)	15.0-28.7 in (38-73 cm)
RCP8.5	29.1 in (74 cm)	20.5-38.6 in (52-98 cm)

Values are relative to the mean over 1986-2005.

Semi-empirical methods avoid the difficulty of estimating the individual physical components contributing to sea level rise by using statistical relationships to relate past surface temperatures to sea levels. This approach relies on the simple physical concept that as the earth warms, sea levels rise. Rather than relying on a linear trend, multiple variations of this model have been developed to account for time-response relationships between sea levels and temperature forcings (Rahmstorf 2007; Vermeer and Rahmstorf 2009; Grinsted et al. 2009). All semi-empirical model projections greatly exceed those of IPCC, with many resulting in a 4.9 to 6.6 foot (1.5 to 2.0 m) increase in sea levels by 2100.

To consider the strengths and weaknesses of all methods, many scientists (including the NRC) have chosen to incorporate combinations of projections from the approaches previously described. Table A-3 provides an overview of global sea level rise projections obtained from process-based and semi-empirical models. Additionally, the table describes the ranges used by the NRC 2012 guidance. The projections used by the NRC reflect sea level rise values from the IPCC AR4, and not the most recent IPCC AR5 (2013) report.

Table A-3. Global Sea Level Rise Projections Relative to the Year 2000 from Process-Based, Semi-Empirical, and the National Research Council's Compilation of Approaches

Year	IPCC AR4 (2007)	Vermeer & Rahmstorf (2009)	NRC (2012)	IPCC AR5 (2013)
2030	-	5.5-8.7 in (14-22cm)	3.1-9.1 in (8-23cm)	-
2050	-	11- 18.5 in (28-47cm)	7.1-18.9 in (18-48cm)	-
2100	7.1-23.2 in (18-59cm)	30.7-68.9 in (78-175cm)	19.7-55.1 in (50-140cm)	11-38.6 in (28-98cm)

A-2.5 REGIONAL / SF BAY / SF COAST SEA LEVEL RISE PROJECTIONS

Mean sea level response along the San Francisco shoreline reflects the relative contributions of global sea level rise coupled with local and regional processes. Tasked with regulating the use of land and water in the coastal zone, the California Coastal Commission provides sea level rise recommendations for the state of California. The Coastal Commission recommends using projections provided in the NRC 2012 report for all coastal planning and permitting decisions, as this has been established as the best available science on sea level rise (CCC, in review). The NRC (2012) assessed historical and projected sea level rise for specific locations along the open Pacific coast and found that by the year 2100, sea levels on average are expected to increase by between 3.6 and 66 inches for the state of California. This study was further refined, dividing California into two sections, North of Cape Mendocino and South of Cape Mendocino, based on variations in tectonic uplift rates and subsidence. Table A-4 describes the rates of sea level rise expected for the two California regions through the end of the century.

Table A-4. Regional Sea Level Rise Projections for the California Coast Relative to the Year 2000

Period	North of Cape Mendocino	South of Cape Mendocino
2000-2030	-1.6 to 9 in (-4 to 23 cm)	1.56 to 11.8 in (4 to 30 cm)
2000-2050	-1.2 to 18.8 in (-3 to 48 cm)	4.68 to 24 in (12-61 cm)
2000-2100	3.6 to 56.28 in (10 to 143 cm)	16.6 to 65.8 in (42 to 167 cm)

Source: NRC (2012)

Because actual sea level rise for a particular location may vary based on vertical land motion and ocean circulation, it is important to also consider projections at a local level. Table A-5 presents the NRC sea level rise projections for San Francisco relative to the year 2000. The table presents the local *projections* (mean ± 1 standard deviation). These projections (for example, 6 ± 2.0 inches in 2030) represent the *likely* sea level rise values based on a moderate level of greenhouse gas emissions and extrapolation of continued accelerating land ice melt patterns, plus or minus one standard deviation[3]. The extreme limits of the *ranges* (for example, 2 and 12 inches for 2030) represent *unlikely but possible* levels of sea level rise using both low and very high emissions scenarios and, at the high end, include significant land ice melt that is not anticipated at this time, but could occur. The NRC report is also notable for providing regional estimates of *net sea level rise* for the Oregon, Washington, and California coastlines that include the sum of contributions from the local thermal expansion of seawater, wind driven components, land ice melting, and vertical land motion. The chief differentiator among net sea level rise projections along the western coast derives from vertical land motion estimates, which show uplift (reducing net sea level rise) of lands north of Cape Mendocino, and subsidence (increasing net sea level rise) of lands south of Cape Mendocino.

The NRC ranges are substantially higher than the global estimates presented in IPCC AR5, while the projections in the NRC report are similar to IPCC estimates. At this time, the use of NRC projections and ranges is appropriate for Alameda County because they encompass the best available science, they have been derived considering local and regional processes and conditions, and their use is consistent with current state guidance.

[3] One standard deviation roughly corresponds to a 15%/85% confidence interval, meaning that there is approximately 15% chance the value will exceed the high end of the projection (8 inches for the 2030 example given) and a 15% chance the value will be lower than the low end of the range (4 inches in the 2030 example).

Table A-5. Sea Level Rise Projections at San Francisco Relative to the Year 2000

Year	Projection	Range
2030	6 ± 2 in	2 to 12 in
2050	11 ± 4 in[1]	5 to 24 in
2100	36 ± 10 in	17 to 66 in

NRC. 2012. Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future.

[1] As a simplifying assumption, the 2050 most likely value selected for the inundation mapping effort is 12 inches rather than the 11 inch value noted in the table.

A-2.6 INCREASING STORM PROJECTIONS

There is a general consensus among scientists that climate change will affect the intensity, frequency, and paths of coastal storms and wave events; however, a clear consensus has not yet emerged on the nature of these changes in the North Pacific Ocean (NRC 2012). NRC (2012) summarizes recent research into changes in storminess in the North Pacific Ocean. Various physical processes are typically grouped together under the term “storminess,” including frequency and intensity of storms, shifts in storm tracks, magnitude of storm surges, and changes in mean and extreme wind speed and wave heights. Researchers have found some evidence of changes in storminess in both the 20th century historical record and in climate model projections of future conditions, but interpretation of these results is somewhat controversial and partly reflects changes due to natural climate variability. One common trend among these studies is a tendency toward increases in wind speed and wave height, especially in the northeast Pacific, from northern California to Washington. Even if storminess does not increase in the future, sea level rise will magnify the adverse impact of storm events and high waves on the coast.

A-2.7 POTENTIAL SEA LEVEL RISE AND STORM SCENARIOS

Sea level rise will increase the risk of flooding for a wide range of coastal infrastructure. This risk will be further elevated by large storms—particularly during the coincidence of large-wave and high-tide events. Understanding the additive impact of large waves and high tides to produce inundation and flooding is crucial for planning in the coastal environment. Table A-6 provides an overview of factors affecting the water levels in San Francisco Bay. With such a wide range of climate change projections, the debate then becomes to determine the future conditions scenarios that will be used for planning in the Bay Area. Using a range of scenarios of future conditions enables Alameda County to understand risk and vulnerability, while developing a framework that will support the adaptation and appropriate responses.

Table A-6. Factors That Influence Local Water Level Conditions

Factors Affecting Water Level	Typical Range[1,2,3]	Period of Influence	Frequency
Tides	5 to 7 feet	Hours	Twice daily
Storm Surge	0.5 to 4 feet	Days	Several times a year
Storm Waves	0.5 to 4 feet	Hours	Several times a year
El Niños (within the ENSO cycle)	<1.5 feet	Months to Years	2 to 7 years
Historic Sea Level, over 100 years	0.7 feet	Ongoing	Persistent
NRC State-wide Sea Level Projections 2000 – 2050	0.4 to 2 feet	Ongoing	Persistent
NRC State-wide Sea Level Projections 2000 - 2100	1.5 to 5.5 feet	Ongoing	Persistent

Sources:

[1]DHI. 2010. Regional Coastal Hazard Modeling Study for North and Central San Francisco Bay. Prepared for Federal Emergency Management Agency.

[2]DHI. 2011. Regional Coastal Hazard Modeling Study for South San Francisco Bay. Prepared for Federal Emergency Management Agency.

[3]BakerAECOM. 2013. *Central San Francisco Bay Costal Flood Hazard Study for Alameda County*. Prepared for Federal Emergency Management Agency.

A-2.8 SAN FRANCISCO BAY

Under existing conditions, daily tides inundate the intertidal mudflats and marshes at the edge of the bay, while storms and extreme tide events (e.g., King Tides and El Niño storms) cause increased flooding of inland areas. To evaluate the impact of sea level rise on future flooding and inundation events, a combination of local astronomical tides, projected sea level rise, and storm surge can be used to perform inundation analysis. The inundated area associated with daily high tides under each sea level rise scenario is representative of the area that would be subjected to frequent or permanent tidal inundation. This level of inundation could lead to slow and regular degradation of infrastructure, including shoreline protection. In addition to the daily high tide inundation, each sea level rise scenario will be evaluated under an extreme tide condition (e.g., the 100-year-tide level). Although storm conditions represent a lower-frequency event, they come with a larger potential flooded area, deeper flooded depths, higher velocities, and a greater likelihood of wind-driven waves that could overtop existing shore protection infrastructure, leading to permanent or catastrophic failure.

Recently completed and ongoing studies in the Bay Area were reviewed to inform the selection of sea level rise scenarios along the Alameda County shoreline. Leveraged studies may also provide additional tools and analyses to assess vulnerability to climate change. In the Bay Area, these studies include the following:

- *Adapting to Rising Tides: Transportation Vulnerability and Risk Assessment Pilot Project* (San Francisco Bay Conservation and Development Commission et al. 2011). Available data: Risk and vulnerability assessment analysis methods and framework; sea level rise inundation mapping methods.

- Potential Inundation Due to Rising Sea Levels in the San Francisco Bay Region (Knowles 2010). Available data: Regional hydrodynamic modeling for existing and future conditions.

- Federal Emergency Management Agency (FEMA) Regional Coastal Hazard Modeling Study for North and Central Bay (DHI 2010). Available data: Regional hydrodynamic and wind wave modeling for existing conditions.

- FEMA Region IX California Coastal Analysis and Mapping Project Bay Area Coastal Study. Available data: Delineation of existing conditions inundation and wave hazard zones and flood depths; extreme tide level estimates.

- Our Coast Our Future study. Available data: Method for future conditions assessments along the open coast; delineation of future conditions inundation and wave hazard zones and flood depths; online mapping data viewer. Website last updated February 2013.

A-3. References

Alley, R. B., Clark, P. U., Huybrechts, P., and Joughin, I. 2005. Ice-Sheet and Sea-Level Changes. *Science*, *310*(5747), 456-460.

BakerAECOM. 2012. *Intermediate Data Submittal #1. Scoping and Data Review. San Francisco County, California.* California Coastal Analysis and Mapping Project / Open Pacific Coast Study. Submitted to FEMA Region IX. February 13 2012.

Bromirski, P. D., Miller, A. J., Flick, R. E., and Auad, G. 2011. Dynamical Suppression of Sea Level Rise along the Pacific Coast of North America: Indications for Imminent Acceleration. *Journal of Geophysical Research: Oceans (1978–2012)*, *116*(C7).

Bromirski, P. D., Miller, A. J., & Flick, R. E. 2012. Understanding North Pacific sea level trends. *Eos*, Transactions American Geophysical Union,93(27) 249.

Cal-Adapt. 2013. Cal-Adapt Web Tool. Retrieved at http://cal-adapt.org/

California Climate Change Center. 2006. *First California Climate Change Assessment 2006*. http://climatechange.ca.gov/climate_action_team/reports/first_assessment.html.

California Climate Change Center. 2009 *Second California Climate Change Assessment 2010*. http://climatechange.ca.gov/climate_action_team/reports/second_assessment.html

California Climate Change Center. 2012. *Reports on the Third Assessment from the California Climate Change Center*. http://climatechange.ca.gov/climate_action_team/reports/third_assessment /index.html

California Coastal Commission. 2013, in review. *Draft Sea-Level Rise Policy Guidance*. Retrieved from http://www.coastal.ca.gov/climate/SLRguidance.html.

California Energy Commission. 2012. Our Changing Climate: Vulnerability & Adaptation to the Increasing Risks from Climate Change in California. A Summary Report on the Third Assessment from the California Climate Change Center. CEC-500-2012-007.

California Natural Resources Agency. 2009. 2009 California Climate Adaptation Strategy: A Report to the Governor of the State of California in Response to Executive Order S-13-2008. Available at http://www.energy.ca.gov/2009publications/CNRA-1000-2009-027/CNRA-1000-2009-027-F.PDF.

California Ocean Protection Council. 2010. State of California Sea-Level Rise Interim Guidance Document. http://www.opc.ca.gov/2011/07/sea-level-rise-task-force-interim-guidance-document/

California Ocean Protection Council. 2013. State of California Sea-Level Rise Guidance. Accessed at http://www.opc.ca.gov/webmaster/ftp/pdf/docs/2013_SLR_Guidance_Update_FINAL1.pdf.

Cayan, D. R., Tyree, M., Dettinger, M., Hildalgo, H., Das, T., Maurer, E., Bromirski, P., Graham, N., and Flick, R. 2009. *Climate Change Scenarios and Sea Level Rise Estimates for the California 2009 Climate Change Scenarios Assessment*. A Paper from California Climate Change Center, CEC-500-2009-014-F, August.

Cayan, D. R., Tyree, M., and Iacobellis, S. 2012. *Climate Change Scenarios for the San Francisco Bay Region*. California Energy Commission, Public Interest Energy Research Program. CEC-500-2012-042. Retrieved from http://www.energy.ca.gov/2012publications/CEC-500-2012-042/CEC-500-2012-042.pdf on November 21 2013.

Chorley, R. J., Schumm, S. A., and Sugden, D. E. 1984. *Geomorphology*. Metheun & Co., London.

DHI. 2010. Regional Coastal Hazard Modeling Study for North and Central Bay. Prepared for FEMA. September 2010.

Gehrels, R. 2010. Sea-Level Changes since the Last Glacial Maximum: An Appraisal of the IPCC Fourth Assessment Report. *Journal of Quaternary Science* 25(1) 26-38.

Grinsted, A., Moore, J. C., and Jevrejeva, S. 2009. Reconstructing Sea Level from Paleo and Projected Temperatures 200 to 2100 AD. *Climate Dynamics*, 1-12.

Intergovernmental Panel on Climate Change (IPCC). 2000. *Summary for Policymakers: Emissions Scenarios. A Special Report of IPCC Working Group III*. Based on a draft prepared by N. Nebojsa, O. Davidson, G. Davis, A. Grubler, T. Kram, E. Lebre La Rovere, B. Mets, T. Morita, W. Pepper, H. Pitcher, A. Sankovski, P. Shukla, R. Swart, R. Watson, and Z. Dadi. 2000. Cambridge University Press, Cambridge.

IPCC. 2007a. Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. R. K. Pachauri and A. Reisinger (eds.). IPCC, Geneva, Switzerland.

IPCC. 2007b. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller (eds.). Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA.

IPCC. 2007c. Climate Change 2007: Mitigation of Climate Change. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. B. Metz, O. R. Davidson, P. R. Bosch, R. Dave, and L.A. Meyer (eds.). Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA.

IPCC. 2007d. Climate Models and Their Evaluation. In Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. D. A. Randall, R. A. Wood, S. Bony, R. Colman, T. Fichefet, J. Fyfe, V. Kattsov, A. Pitman, J. Shukla, J. Srinivasan, R. J. Stouffer, A. Sumi, and K. E. Taylor. Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA.

IPCC. 2007e. Regional Climate Projections. In Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. J. H. Christensen, B. Hewitson, A. Busuioc, A. Chen, X. Gao, I. Held, R. Jones, R. K. Kolli, W.-T. Kwon, R. Laprise, V. Magaña Rueda, L. Mearns, C.G. Menéndez, J. Räisänen, A. Rinke, A. Sarr, and P. Whetton. Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA.

IPCC. 2007f. Global Climate Projections. In Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. G. A. Meehl, T. F. Stocker, W. D. Collins, P. Friedlingstein, A. T. Gaye, J. M. Gregory, A. Kitoh, R. Knutti, J. M. Murphy, A. Noda, S. C. B. Raper, I. G. Watterson, A. J. Weaver, and Z.-C. Zhao. Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA.

IPCC. 2012. Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Special Report of the Intergovernmental Panel on Climate Change. C. B. Field, V. Barros, T. F. Stocker, and Q. Dahe, (eds.). Cambridge University Press. Available at http://ipcc-wg2.gov/SREX/images/uploads/SREX-All_FINAL.pdf.

IPCC. 2013. *Climate Change 2013: The Physical Science Basis.* Retrieved from http://www.ipcc.ch/report/ar5/wg1/#.UpVXaOK3gyY.

Jevrejeva, S., Moore, J. C., Grinsted, A., and Woodworth, P. L. 2008. Recent Global Sea Level Acceleration Started over 200 Years Ago?. *Geophysical Research Letters*, *35*(8), L08715.

Komar, P. D., Allan, J. C., and Ruggiero, P. 2011. Sea Level Variations along the US Pacific Northwest Coast: Tectonic and Climate Controls. *Journal of Coastal Research* 27(5), 808-823.

National Aeronautics and Space Administration. 2009. Satellites Confirm Half-Century of West Antarctic Warming. Last updated January 21 2009. Available at http://www.nasa.gov/topics/earth/features/warming_antarctica.html.

NOAA. 2012. Sea Levels Online. LRevised: 10/15/2013. Available at http://tidesandcurrents.noaa.gov/sltrends/.

National Research Council. 2012. *Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future*. Prepared by the Committee on Sea Level Rise in California, Oregon, and Washington and the National Research Council Board on Earth Sciences and Resources and Ocean Studies Board Division on Earth and Life Studies.

Peltier, W. R. 2009. Closure of the Budget of Global Sea Level Rise over the GRACE Era: The Importance and Magnitudes of the Required Corrections for Global Glacial Isostatic Adjustment. *Quaternary Science Reviews 28*(17), 1658-1674.

Parris, A., P. Bromirski, V. Burkett, D. Cayan, M. Culver, J. Hall, R. Horton, K. Knuuti, R. Moss, J. Obeysekera, A. Sallenger, and J. Weiss. 2012. Global Sea Level Rise Scenarios for the US National Climate Assessment. NOAA Tech Memo OAR CPO-1.

Rahmstorf, S. 2007. A Semi-Empirical Approach to Projecting Future Sea-Level Rise. Originally published in *Science Express*, December 14 2006; *Science 315*(5810), 368-370. doi:10.1126/science.1135456.

San Francisco Bay Conservation and Development Commission. 2009. *Living with a Rising Bay: Vulnerability and Adaptation in San Francisco Bay and on its Shoreline*. April 7. Available at http://www.bcdc.ca.gov/planning/climate_change/SFBay_preparing_%20for_the_next_Level.pdf.

San Francisco Bay Conservation and Development Commission, NOAA, Metropolitan Transportation Commission, and California Department of Transportation District 4. 2011. *Adapting to Rising Tides: Transportation Vulnerability and Risk Assessment Pilot Project*. Available at http://www.mtc.ca.gov/planning/climate/RisingTides-TechnicalReport.pdf.

Sea-Level Rise Task Force of the Coastal and Ocean Working Group of the California Climate Action Team. 2010. *State of California Sea-Level Rise Interim Guidance Document*. Developed with science support provided by the Ocean Protection Council's Science Advisory Team and the California Ocean Science Trust, October 2010. Available at http://www.opc.ca.gov/webmaster/ftp/pdf/agenda_items/20100911/14.%20SLR/1011_COPC_SLR_Interim_Guidance.pdf.

United States Global Change Research Program (USGCRP) 2009. Global Climate Change Impacts in the United States. Cambridge University Press.

Van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., ... and Rose, S. K. 2011. The Representative Concentration Pathways: An Overview. *Climatic Change, 109*(1-2), 5-31.

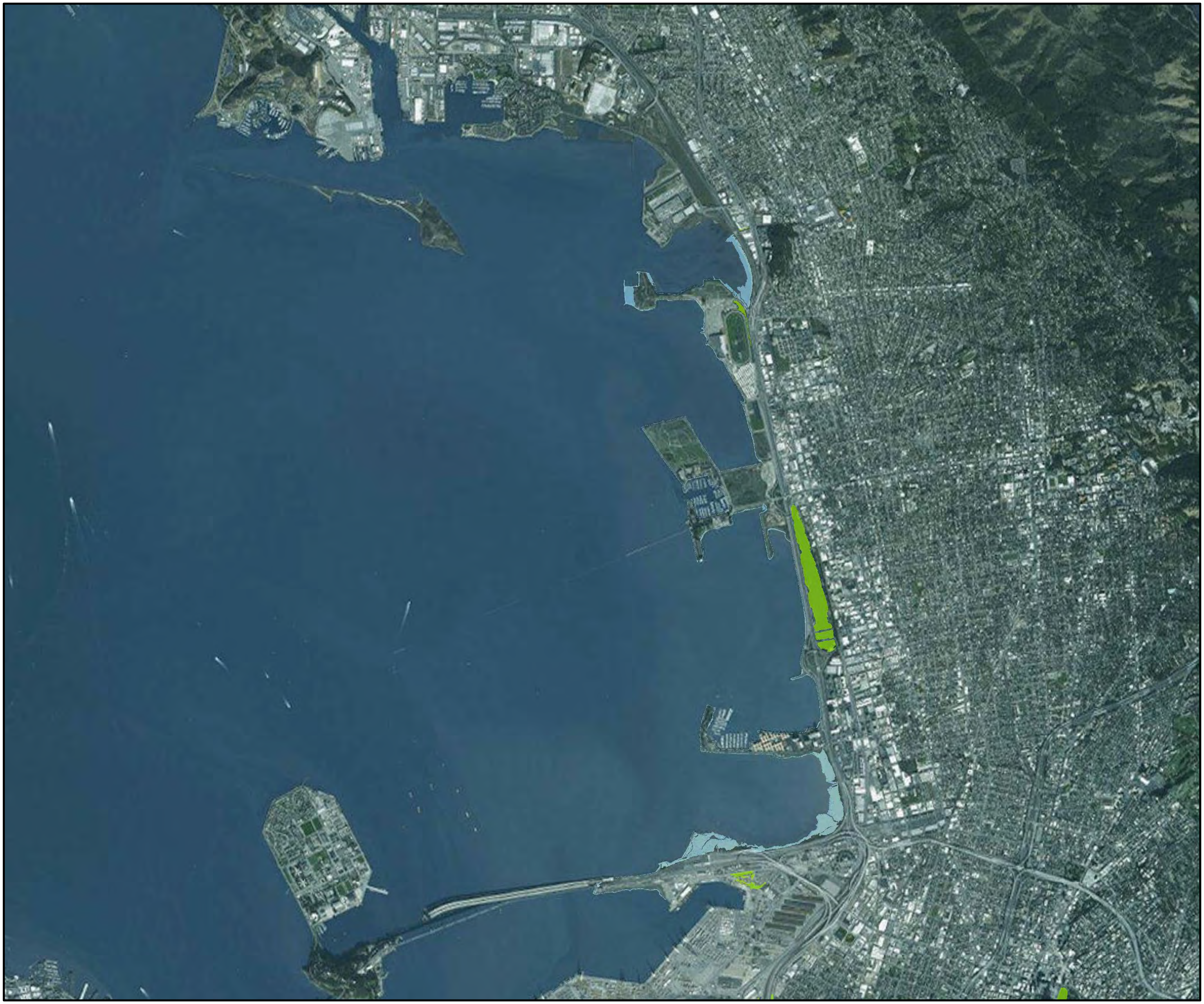
Vermeer, M. and Rahmstorf. S. 2009. *Proceedings of the National Academy of Sciences*. Published online before print December 7 2009. doi:10.1073/pnas.0907765106. *Proceedings of the National Academy of Sciences, 106* (51) 21527-21532. Available at http://www.pnas.org/content/106/51/21527.full.pdf+html.

Zervas, C. E. 2009. *Sea Level Variations of the United States, 1854-2006*. National Oceanic and Atmospheric Administration, U.S. Department of Commerce, National Ocean Service, Center for Operational Oceanographic Products and Services.

B

SEA LEVEL RISE INUNDATION MAPS

ALAMEDA COUNTY
Inundation Mapping



MHHW + 12” Sea Level Rise

Depth in Feet

- 0 - 2
- 2 - 4
- 4 - 6
- 6 - 8
- 8 - 10
- 10 - 12
- 12 - 14
- 14 - 16
- 16+
- Disconnected Areas > 1 Acre

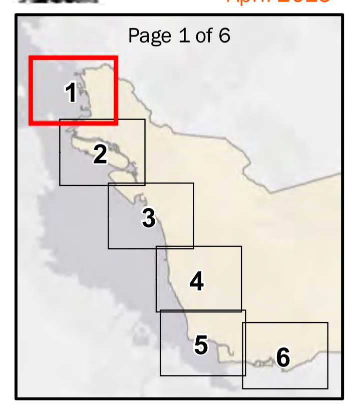
1 in = 20 Miles

0 10 20

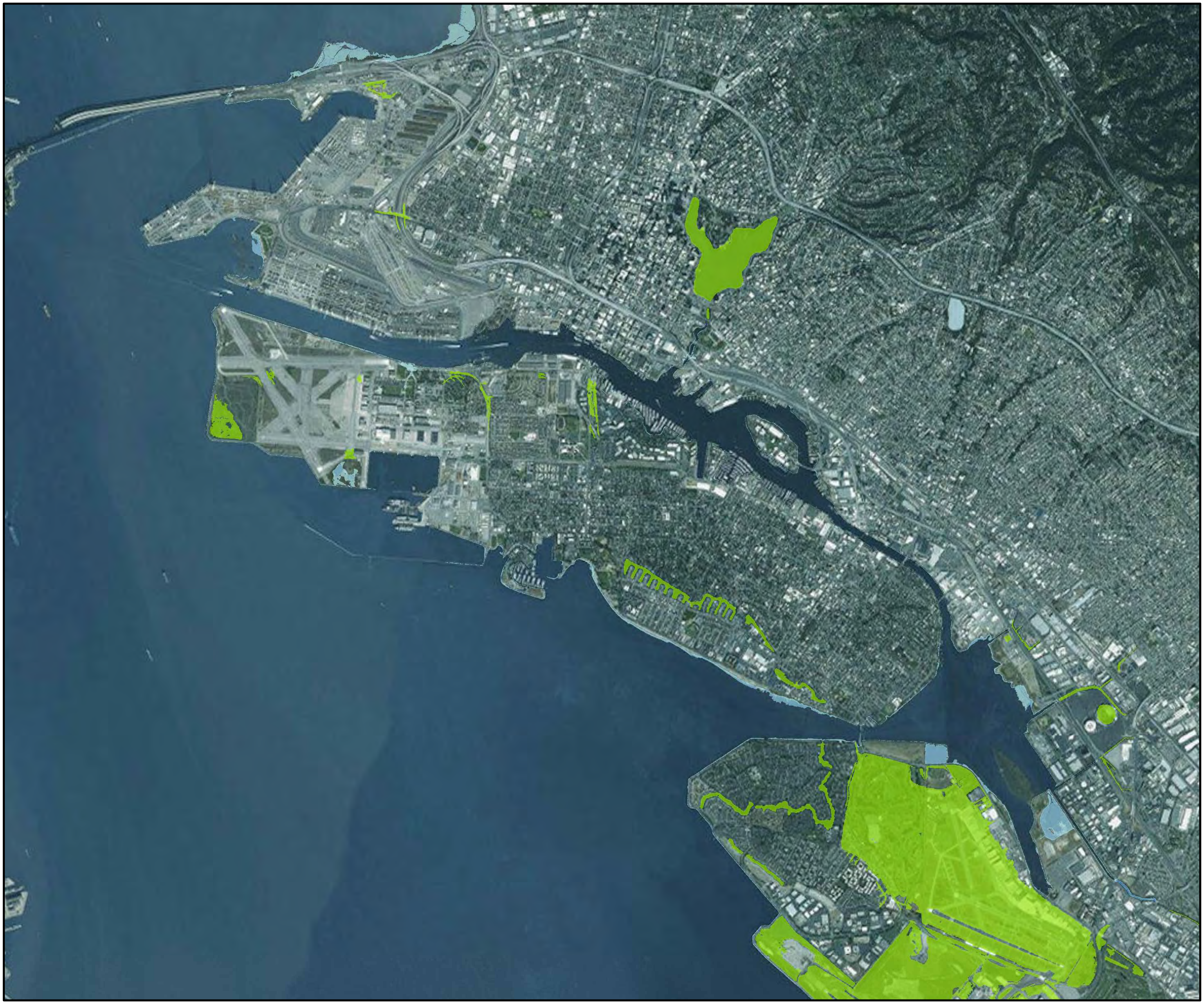
Projection:
California State Plane Zone III, North American Datum 1983

AECOM

April 2015



ALAMEDA COUNTY
Inundation Mapping



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AECOM

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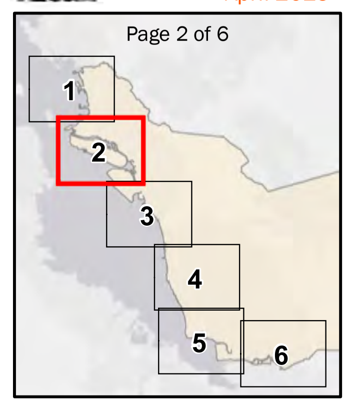
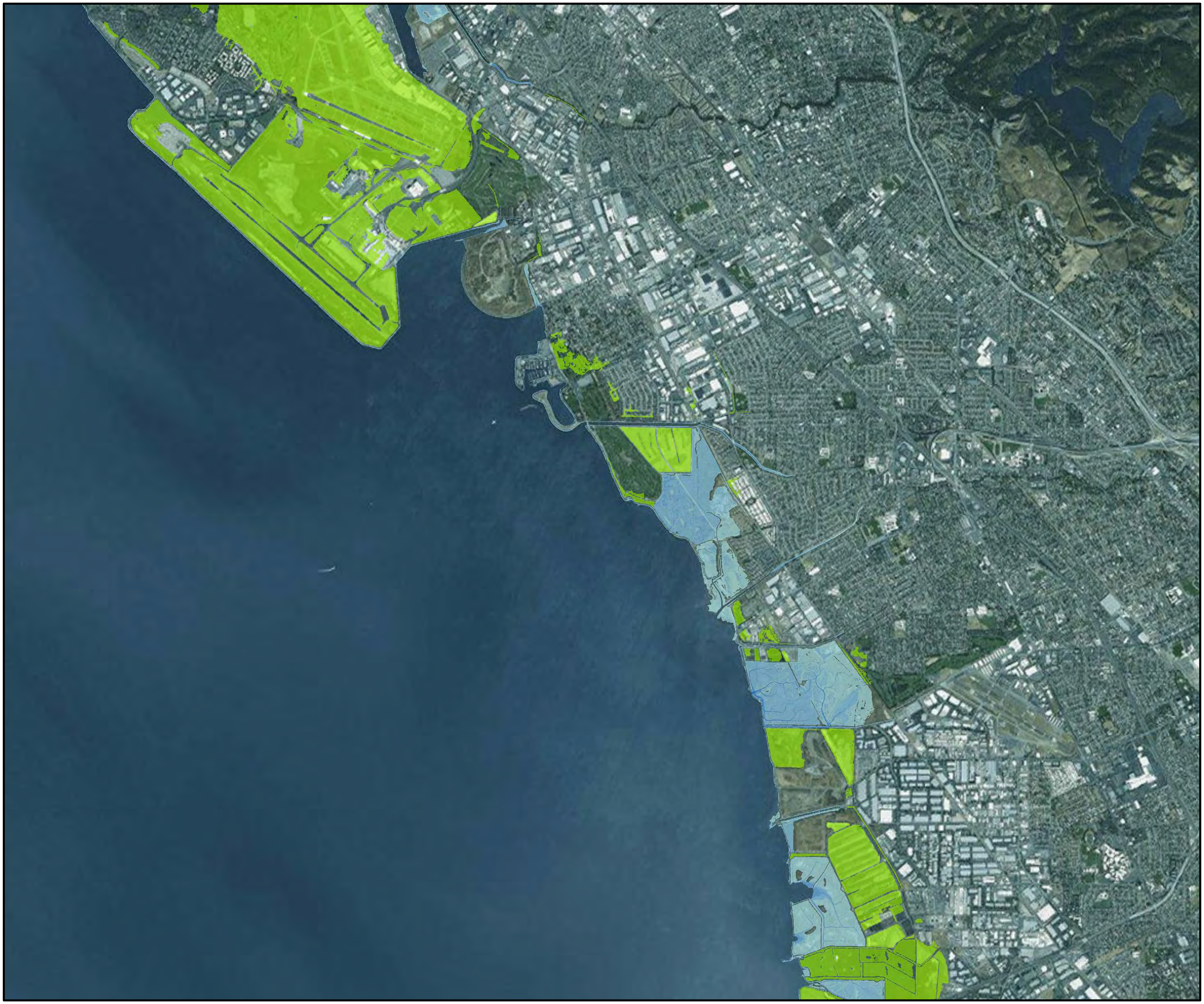


ALAMEDA COUNTY
Inundation Mapping



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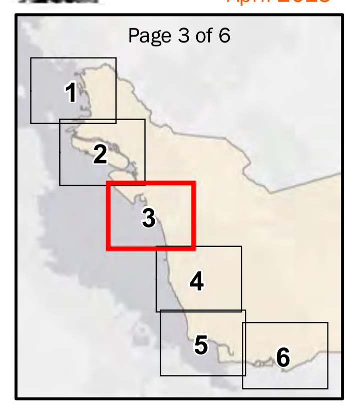

ALAMEDA COUNTY
Inundation Mapping

MHHW + 12” Sea Level Rise

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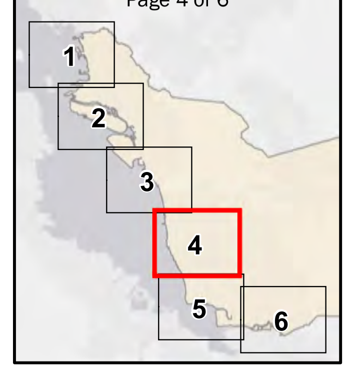

ALAMEDA COUNTY
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MHHW + 12" Sea Level Rise

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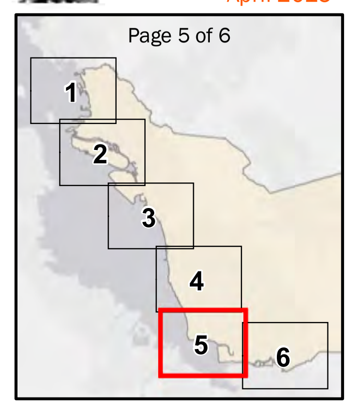

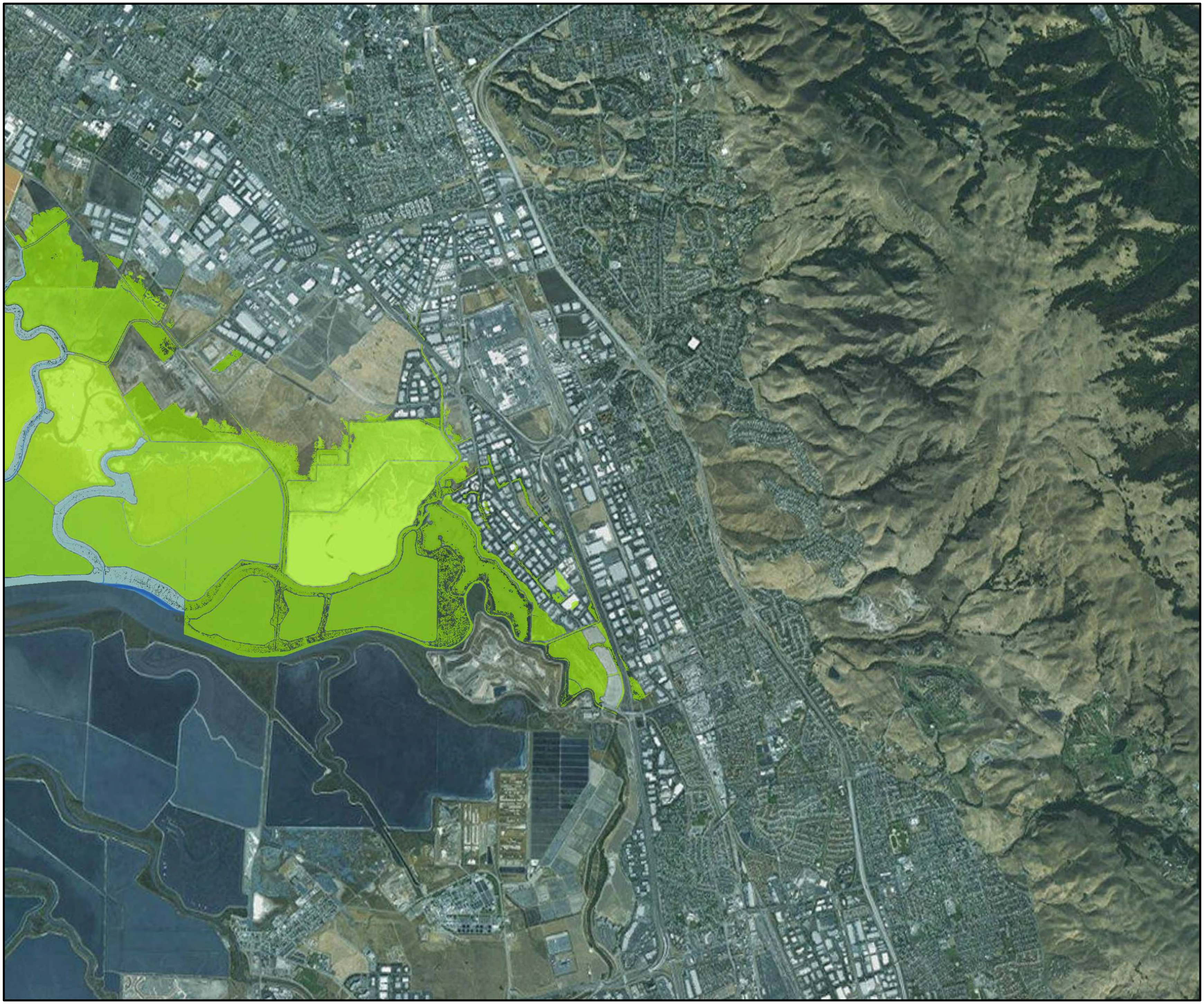

ALAMEDA COUNTY
Inundation Mapping

MHHW + 12" Sea Level Rise

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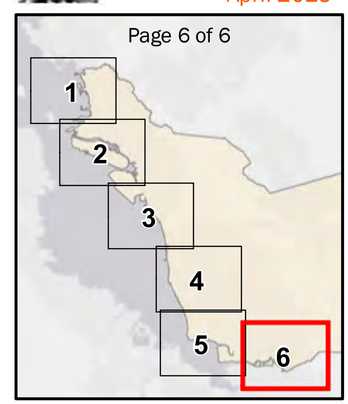
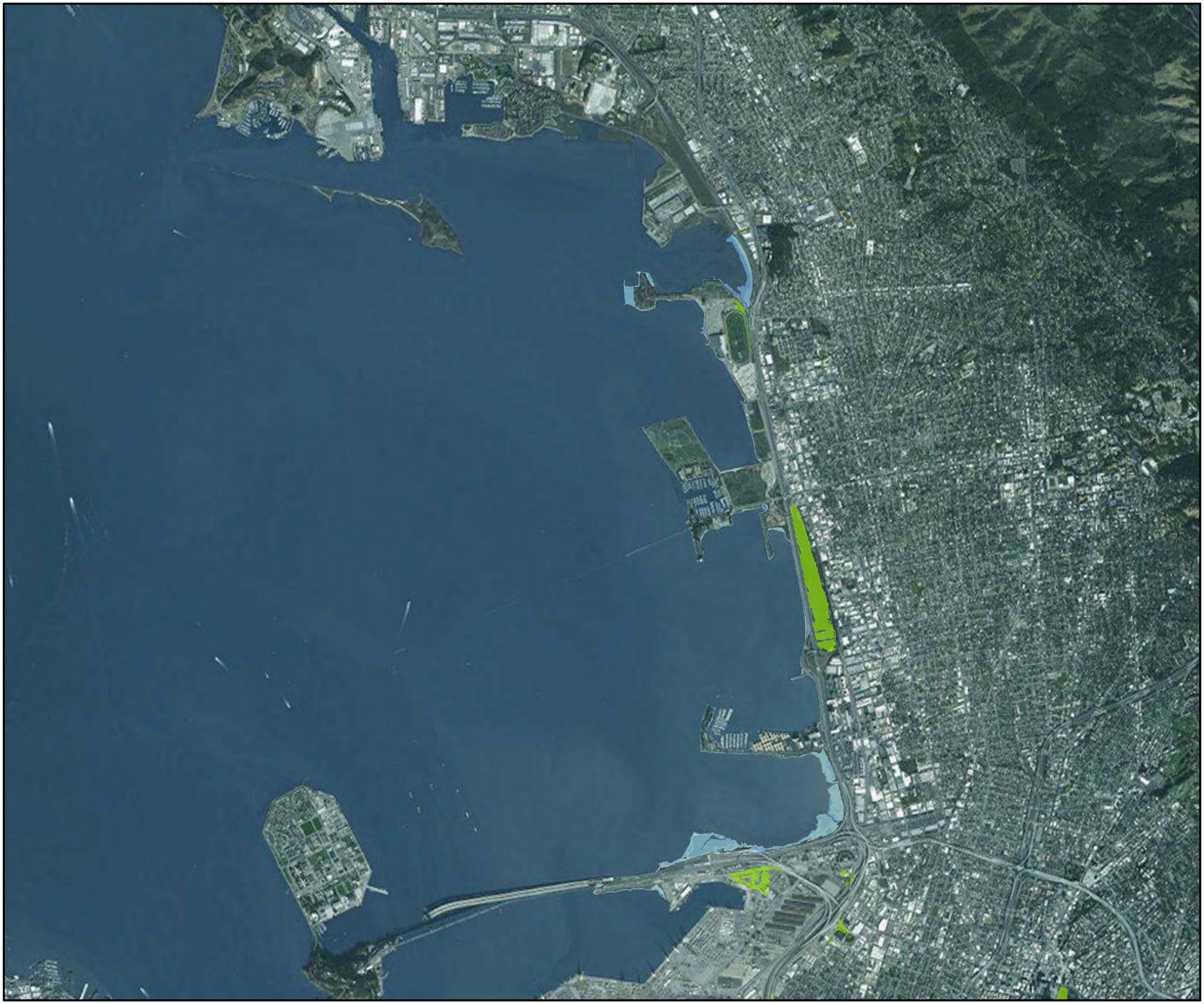
April 2015



ALAMEDA COUNTY
Inundation Mapping



MHHW + 24” Sea Level Rise

Depth in Feet

- 0 - 2
- 2 - 4
- 4 - 6
- 6 - 8
- 8 - 10
- 10 - 12
- 12 - 14
- 14 - 16
- 16+
- Disconnected Areas > 1 Acre

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1 in = 20 Miles

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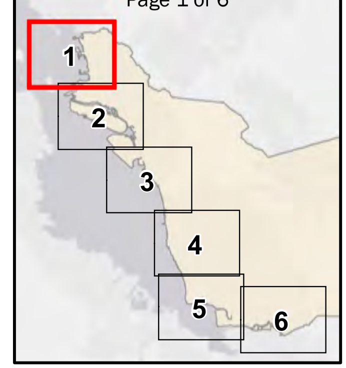
Projection:
California State Plane Zone III, North American Datum 1983

AECOM

April 2015



ALAMEDA COUNTY
Inundation Mapping

MHHW + 24" Sea Level Rise

Depth in Feet

- 0 - 2
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- 12 - 14
- 14 - 16
- 16+
- Disconnected Areas > 1 Acre

1 in = 20 Miles

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Projection:
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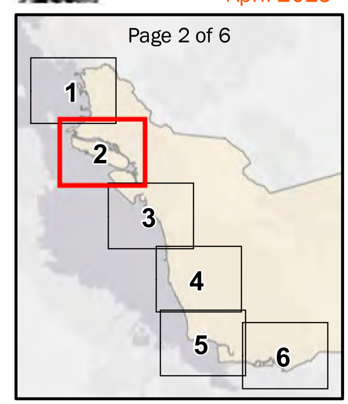
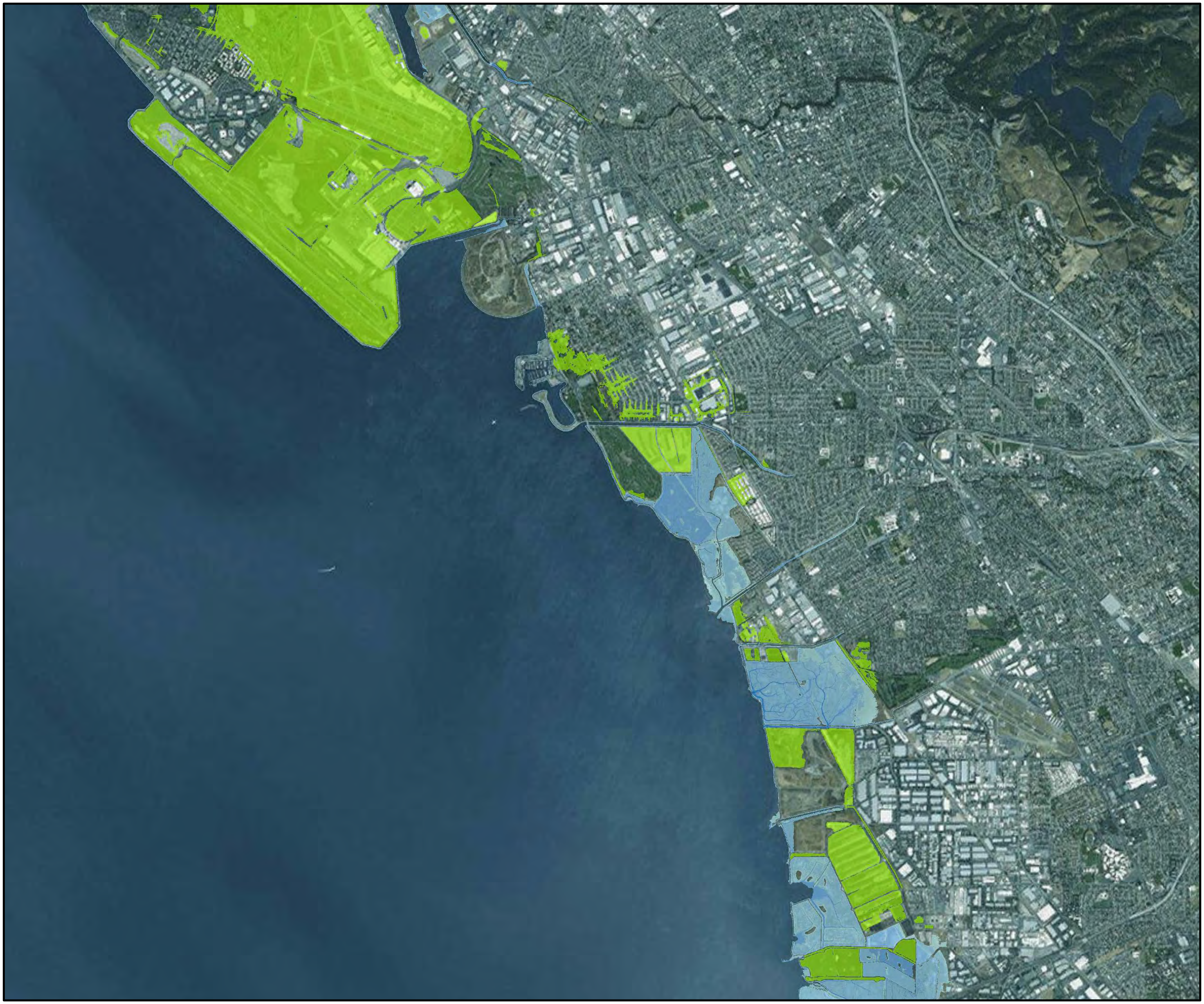
AECOM

April 2015



ALAMEDA COUNTY
Inundation Mapping



MHHW + 24” Sea Level Rise

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AECOM

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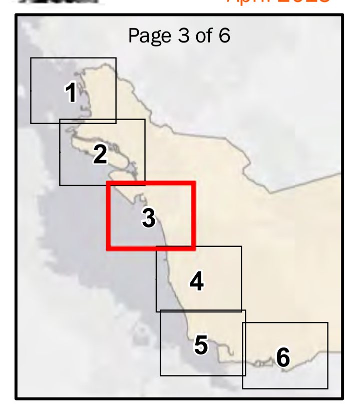

ALAMEDA COUNTY
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MHHW + 24” Sea Level Rise

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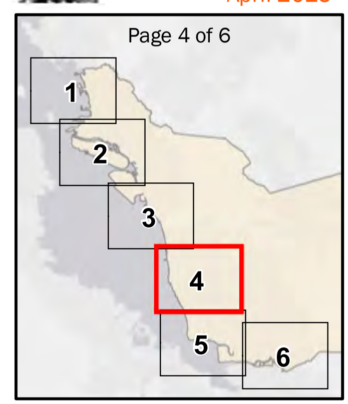

ALAMEDA COUNTY
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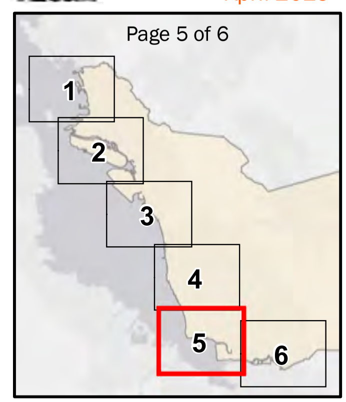

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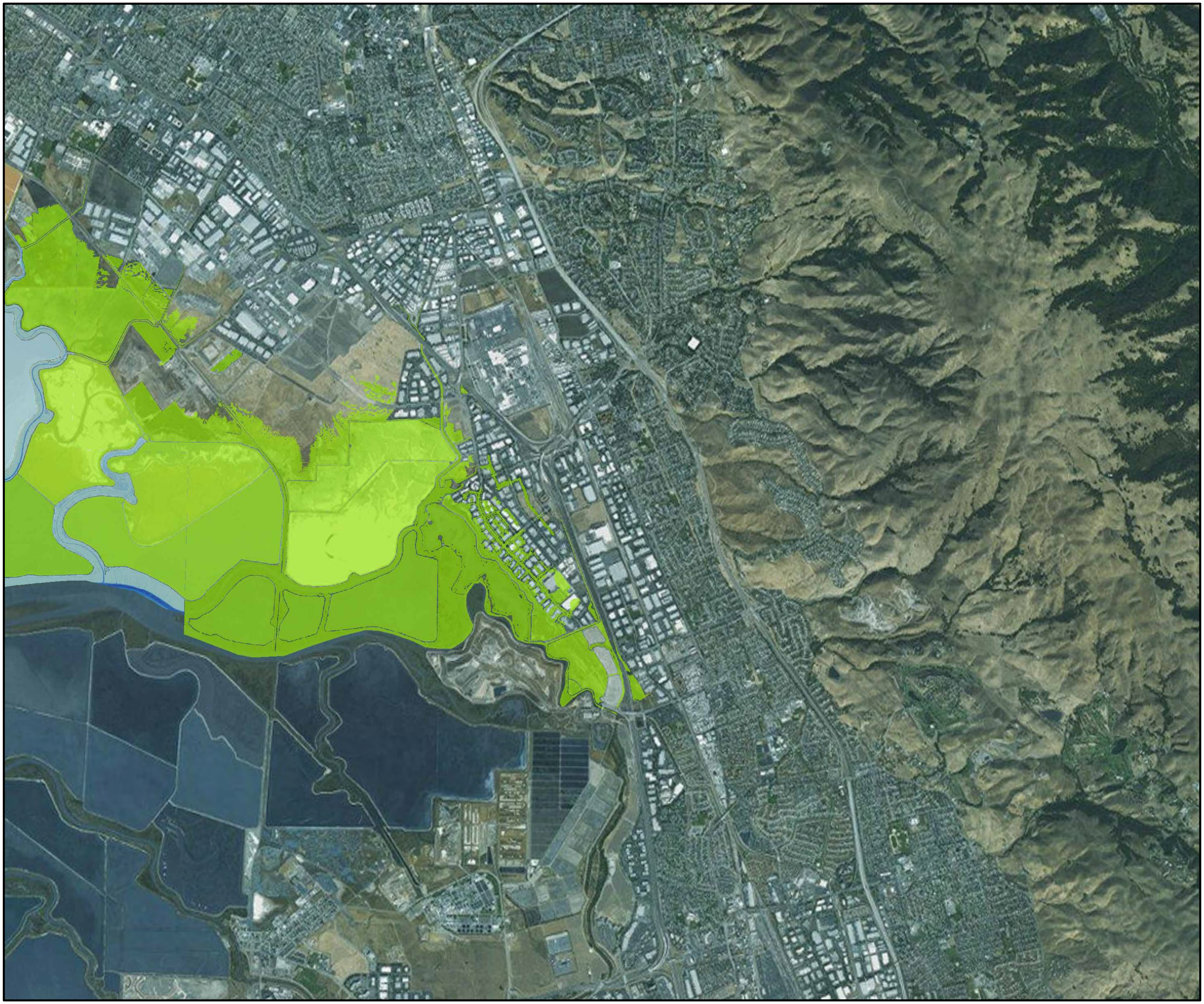

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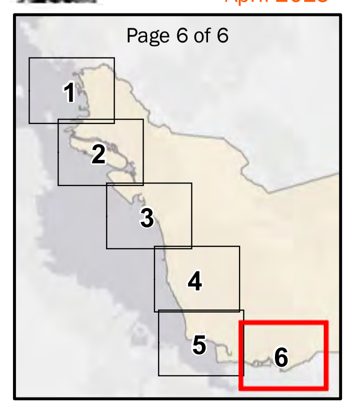

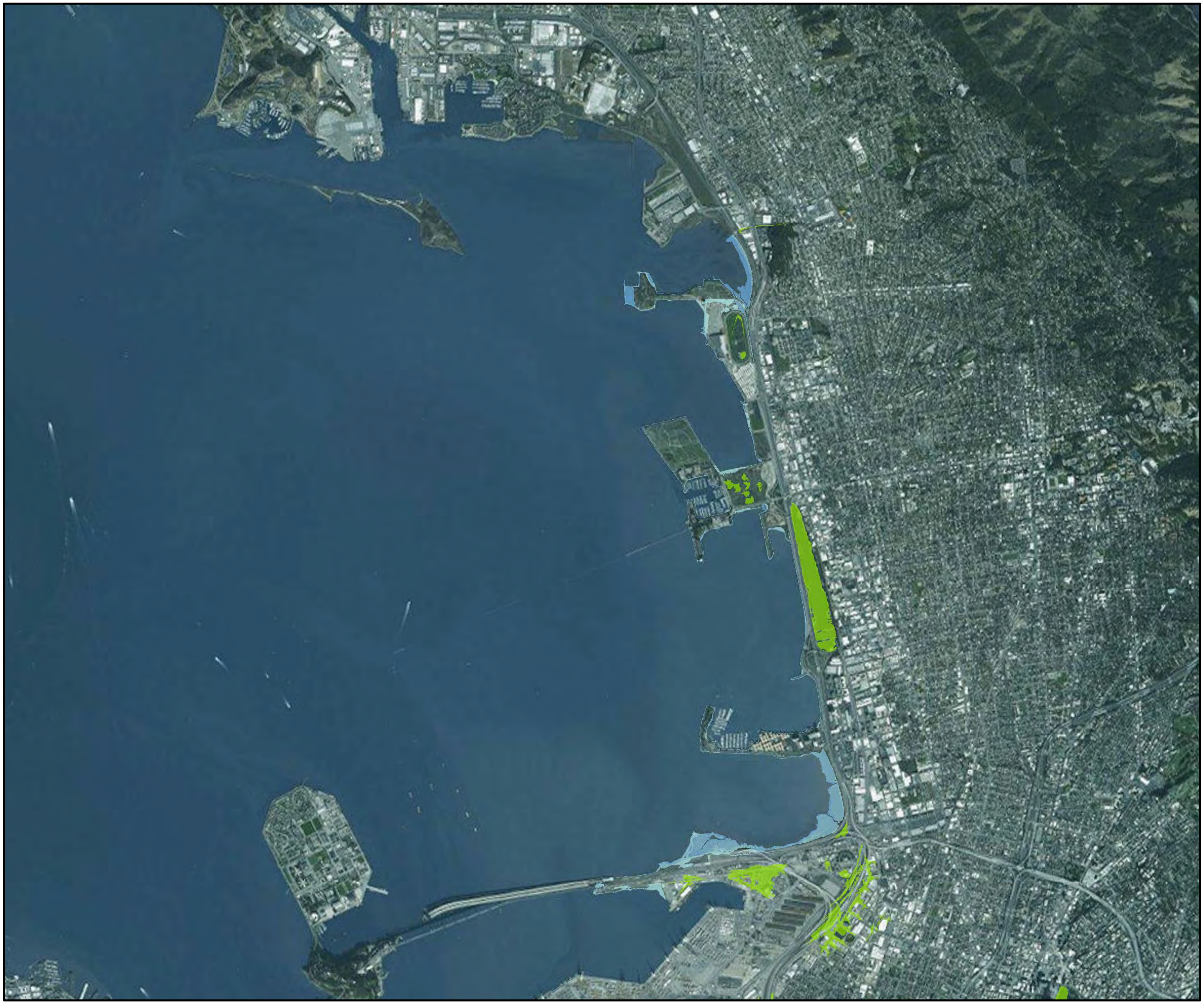

ALAMEDA COUNTY
Inundation Mapping

MHHW + 36” Sea Level Rise

Depth in Feet

- 0 - 2
- 2 - 4
- 4 - 6
- 6 - 8
- 8 - 10
- 10 - 12
- 12 - 14
- 14 - 16
- 16+
- Disconnected Areas > 1 Acre

1 in = 20 Miles

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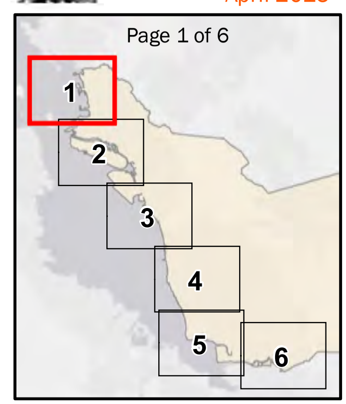
Projection:
California State Plane Zone III, North American Datum 1983

April 2015



ALAMEDA COUNTY
Inundation Mapping

MHHW + 36” Sea Level Rise

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Projection:
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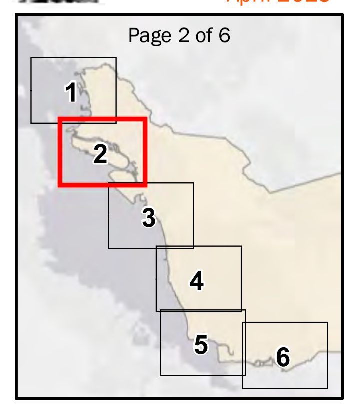
April 2015



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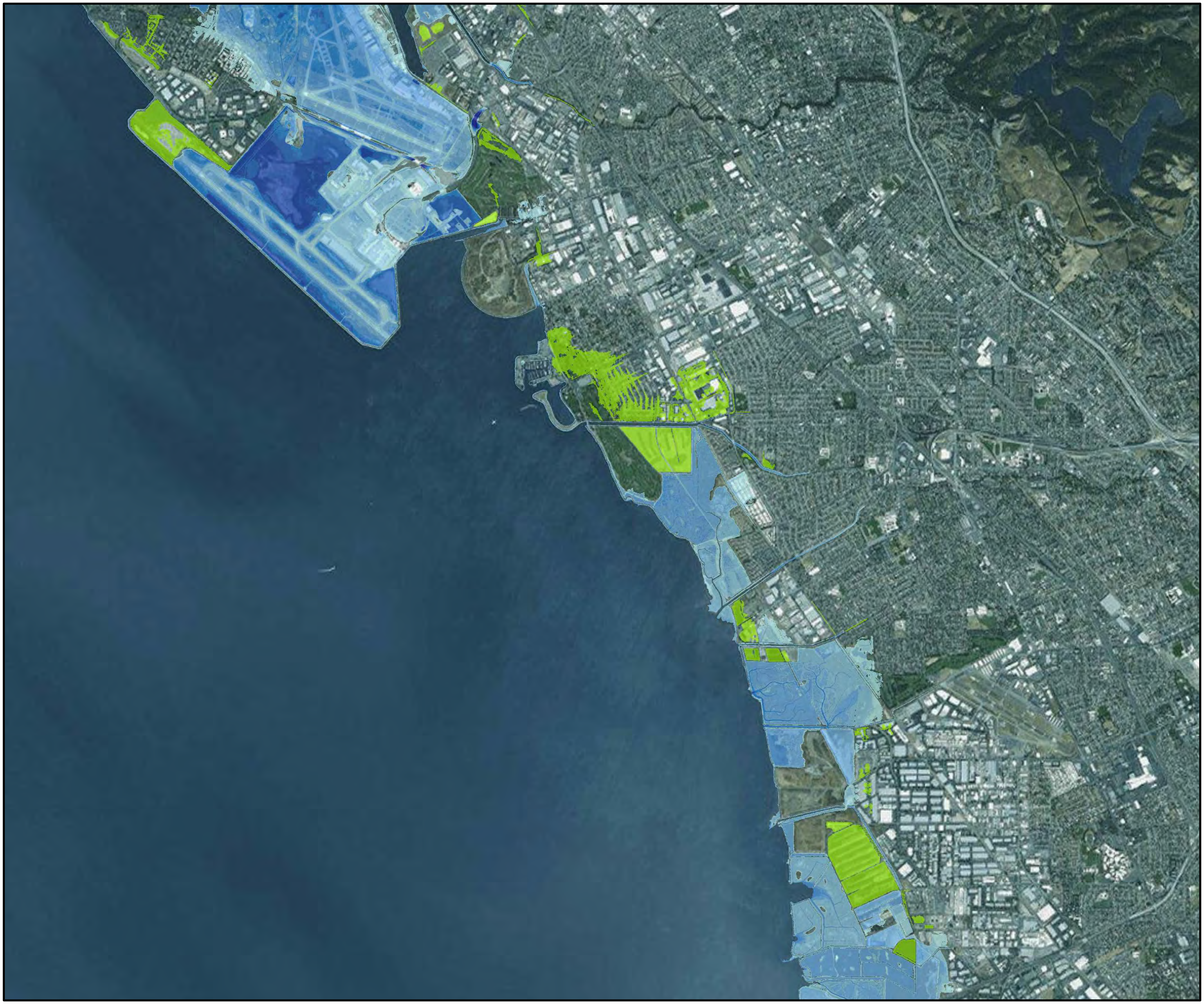

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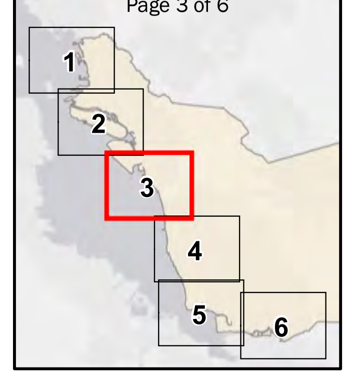

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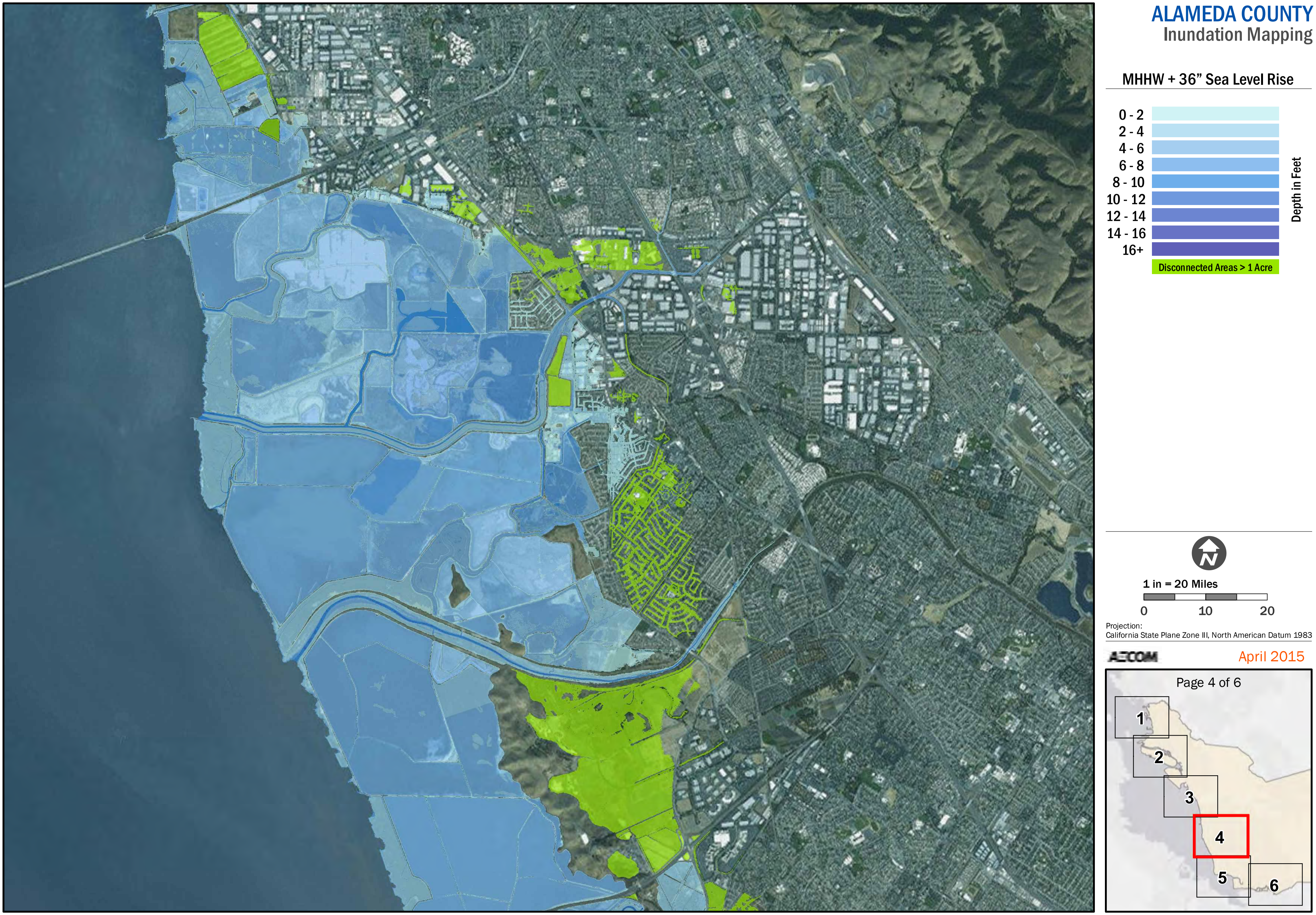

ALAMEDA COUNTY
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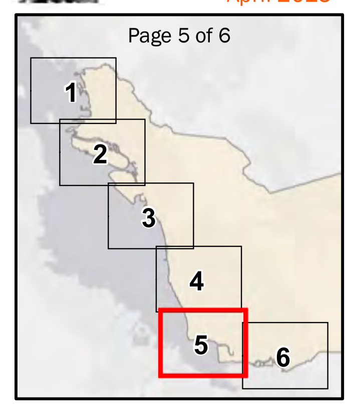

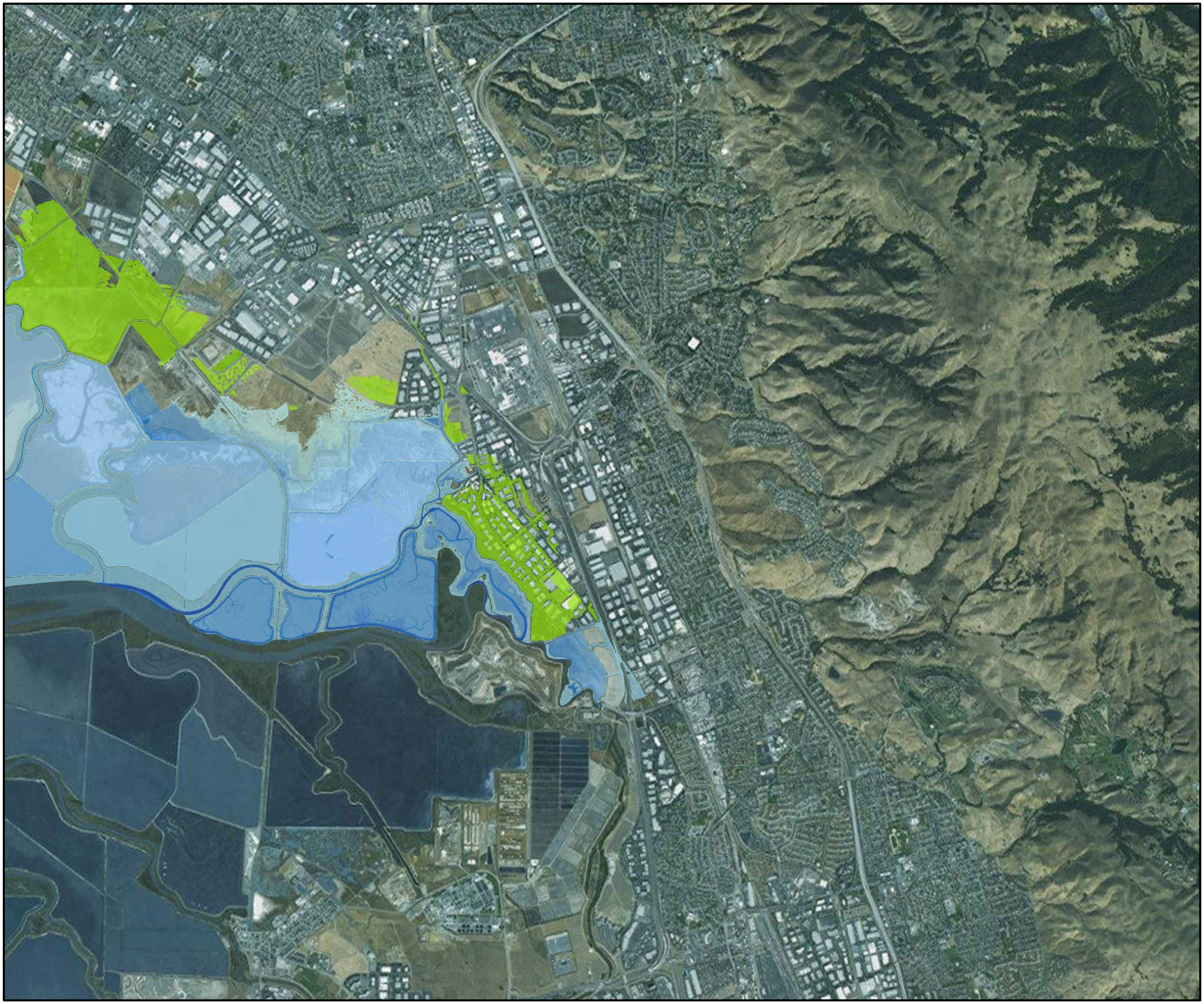

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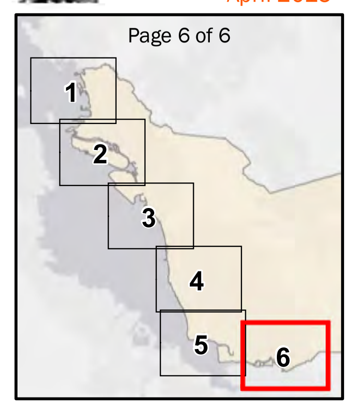
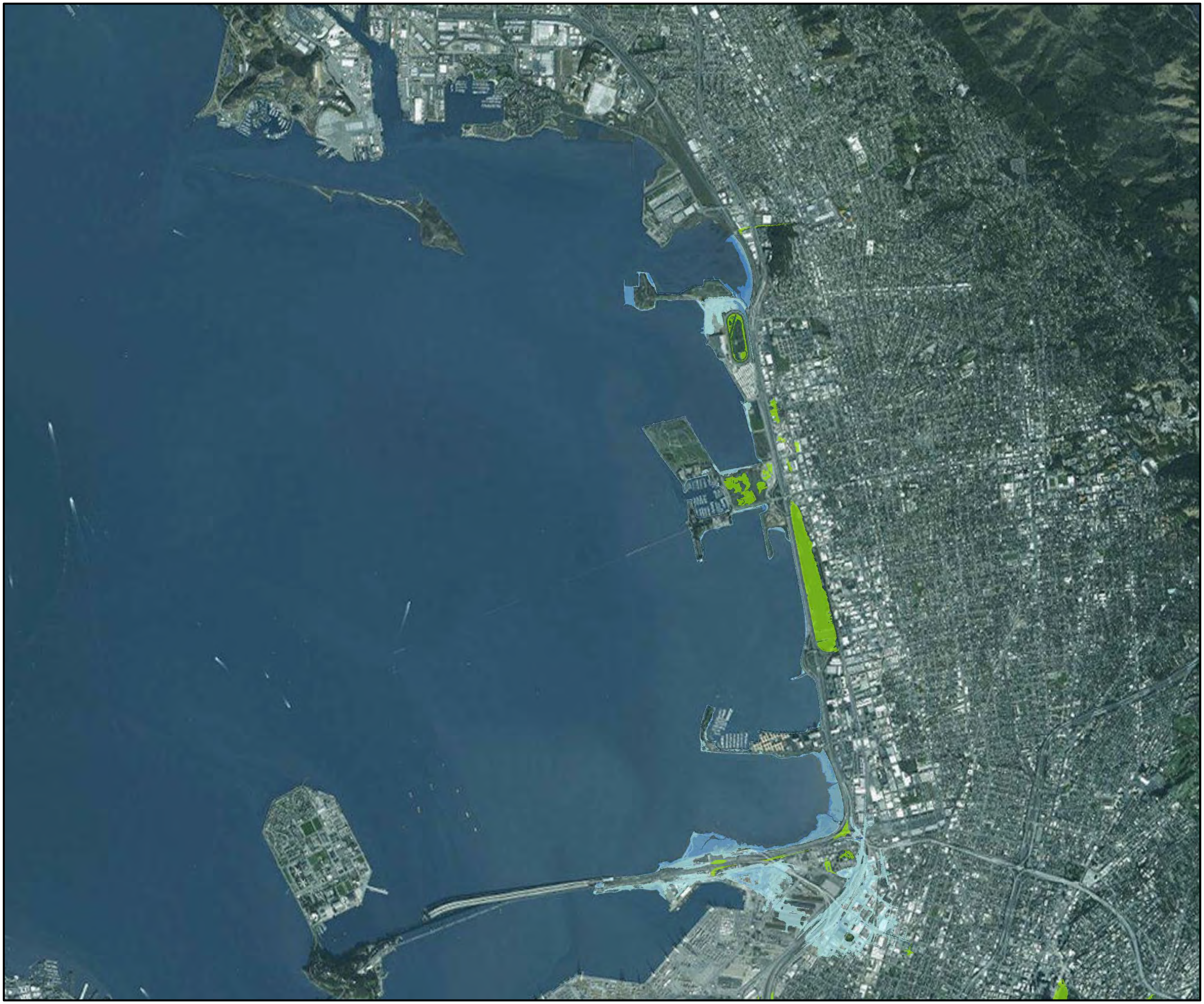
AECOM

April 2015



ALAMEDA COUNTY
Inundation Mapping



MHHW + 48” Sea Level Rise

Depth in Feet

0 - 2	
2 - 4	
4 - 6	
6 - 8	
8 - 10	
10 - 12	
12 - 14	
14 - 16	
16+	
	Disconnected Areas > 1 Acre

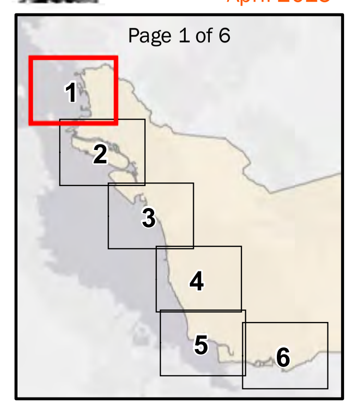
1 in = 20 Miles

0 10 20

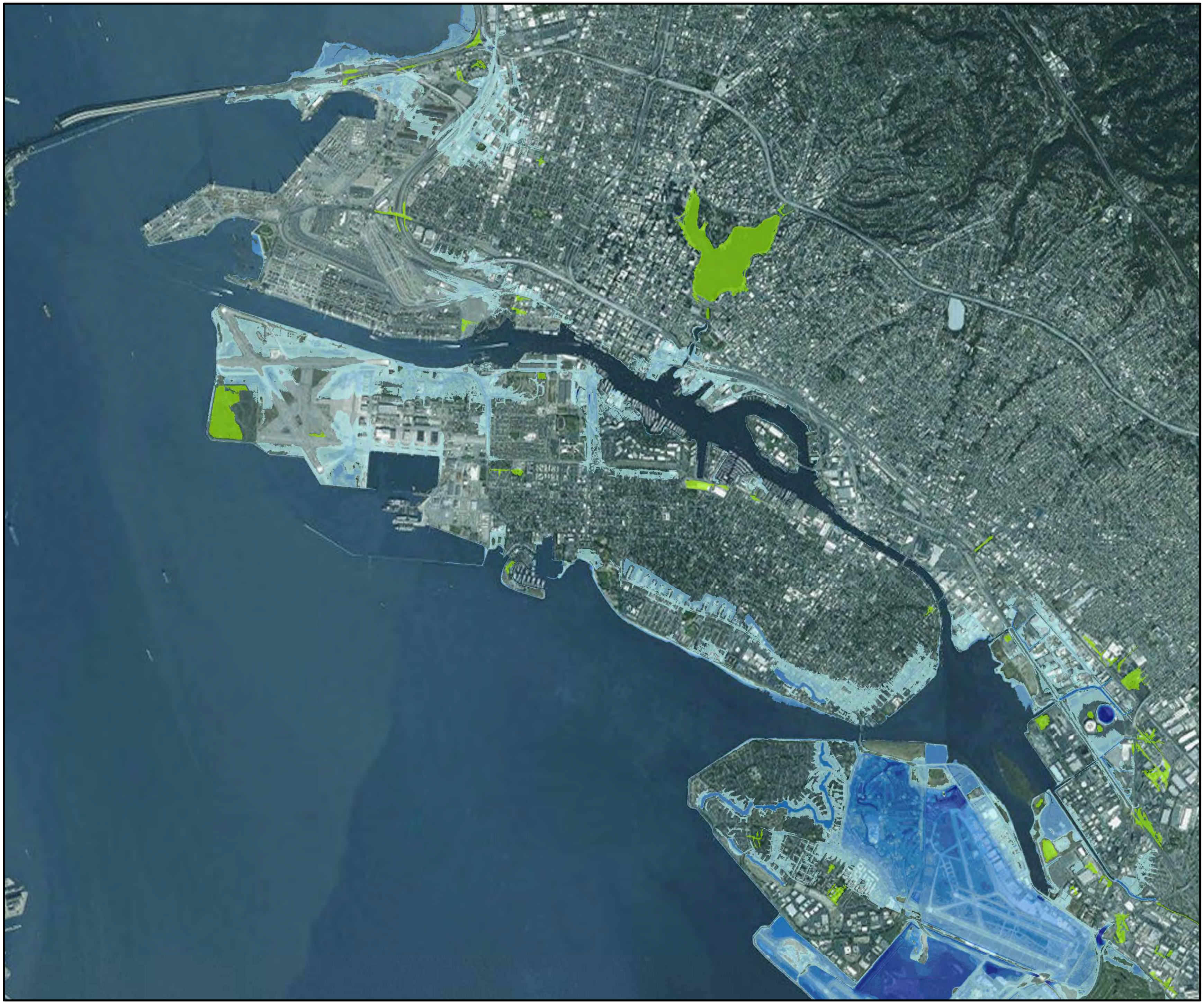
Projection:
California State Plane Zone III, North American Datum 1983

AECOM

April 2015



ALAMEDA COUNTY
Inundation Mapping



MHHW + 48” Sea Level Rise

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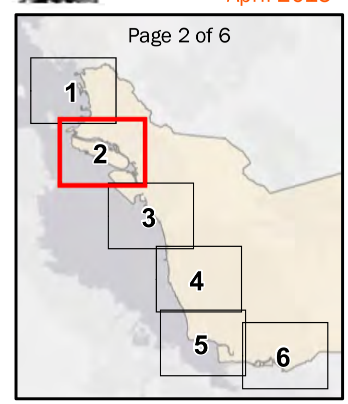
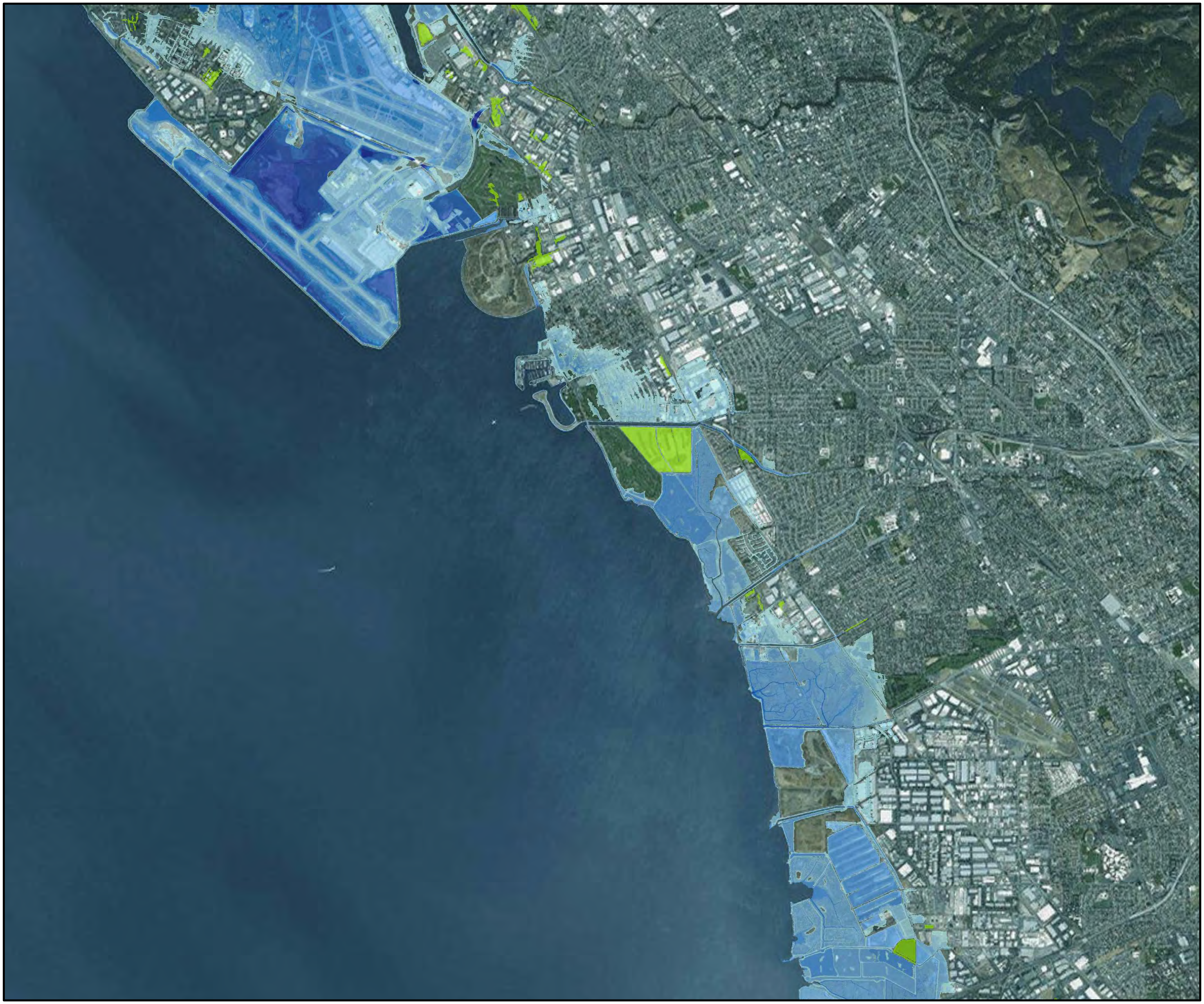
Projection:
California State Plane Zone III, North American Datum 1983

AECOM

April 2015



ALAMEDA COUNTY
Inundation Mapping



MHHW + 48” Sea Level Rise

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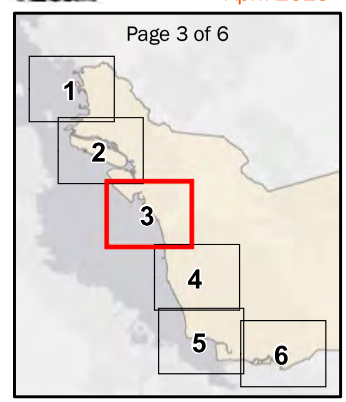
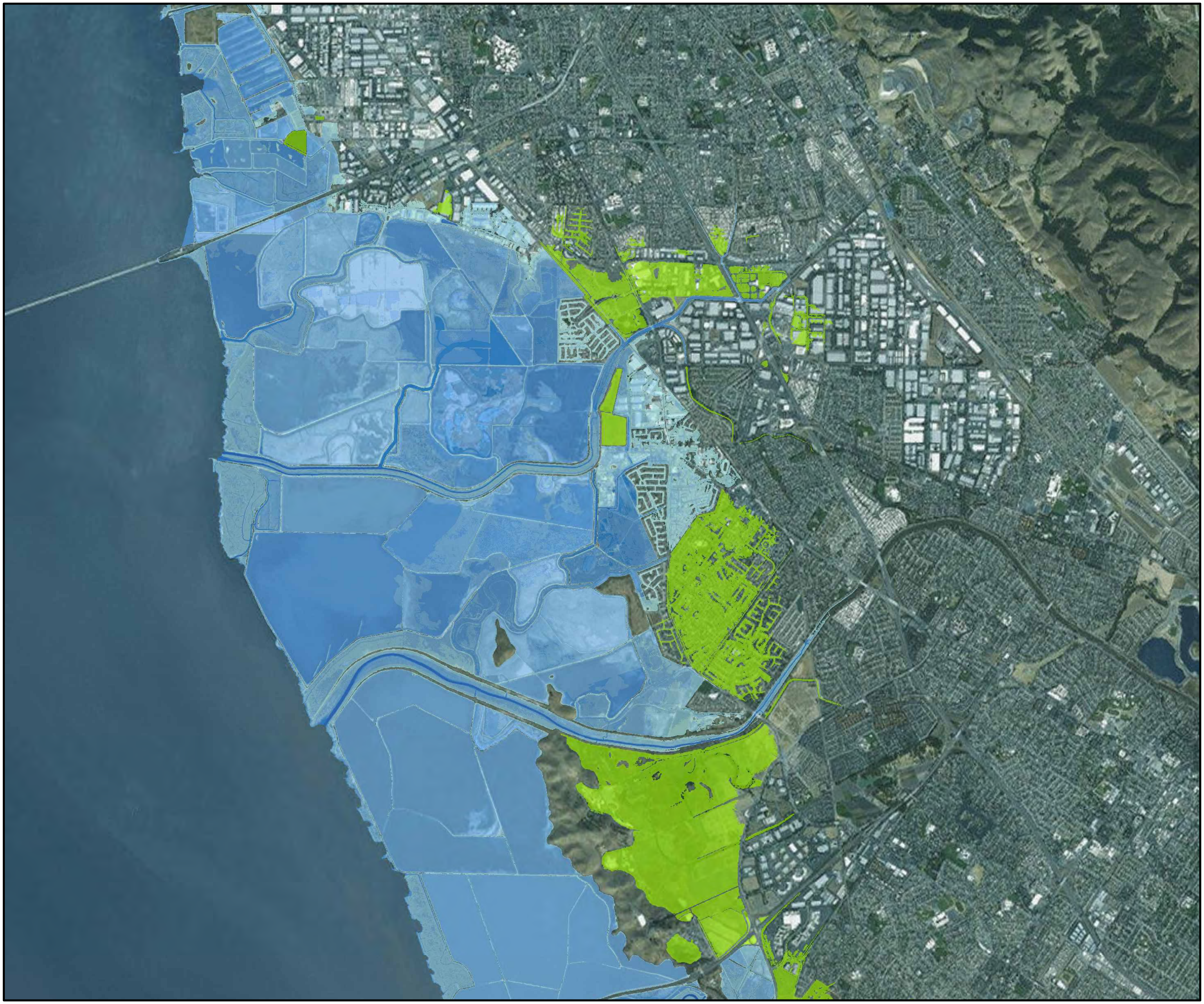
Projection:
California State Plane Zone III, North American Datum 1983

AECOM

April 2015



ALAMEDA COUNTY
Inundation Mapping



MHHW + 48” Sea Level Rise

Depth in Feet
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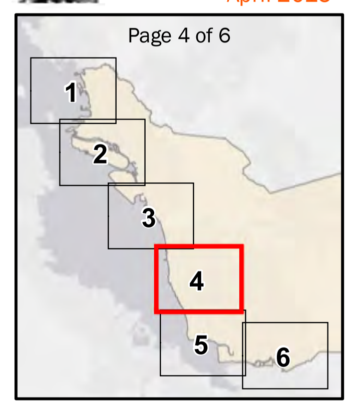
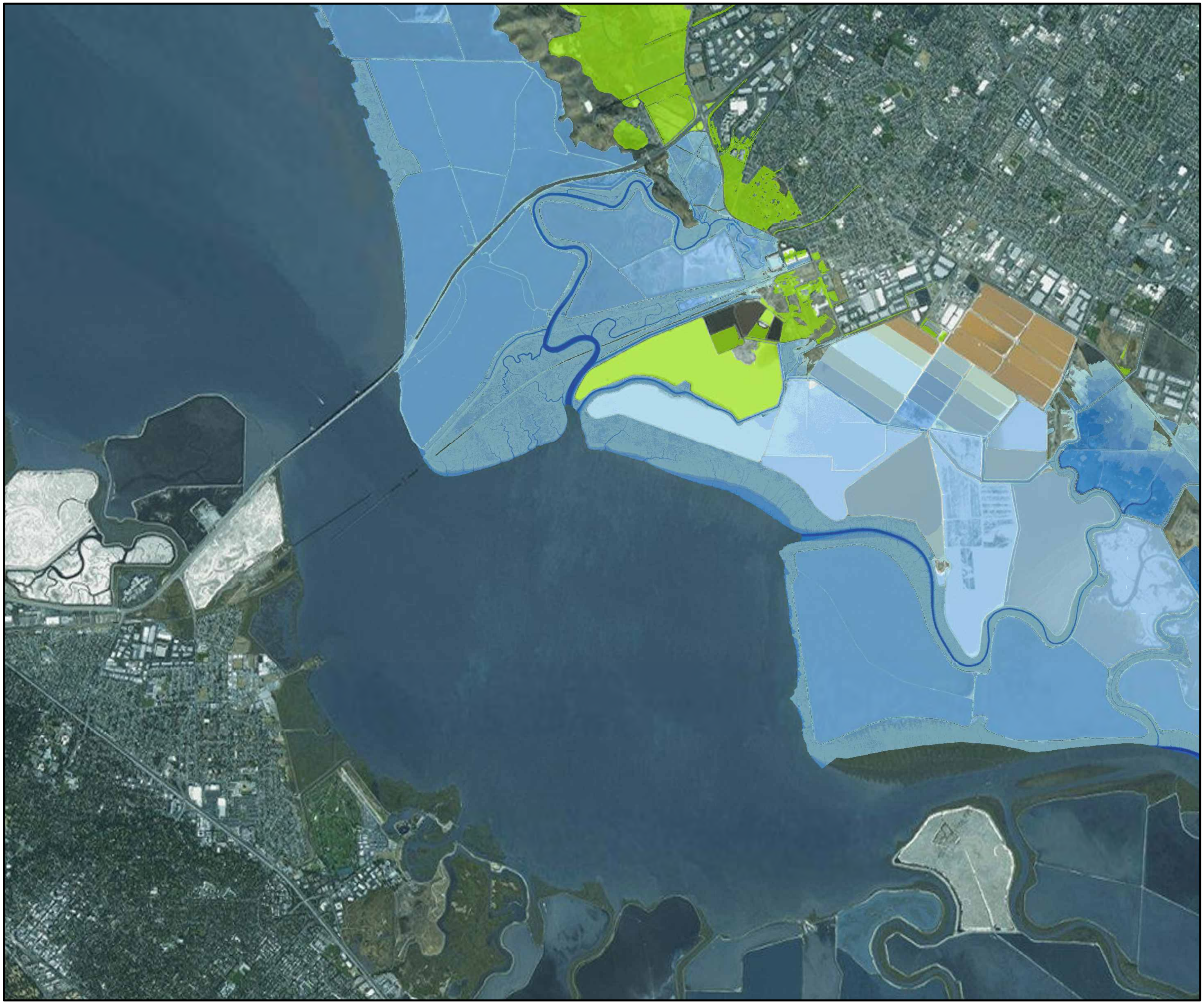
Projection:
California State Plane Zone III, North American Datum 1983

AECOM

April 2015



ALAMEDA COUNTY
Inundation Mapping



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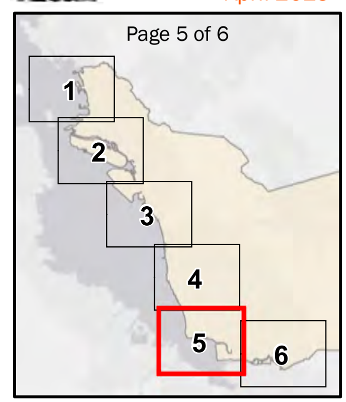
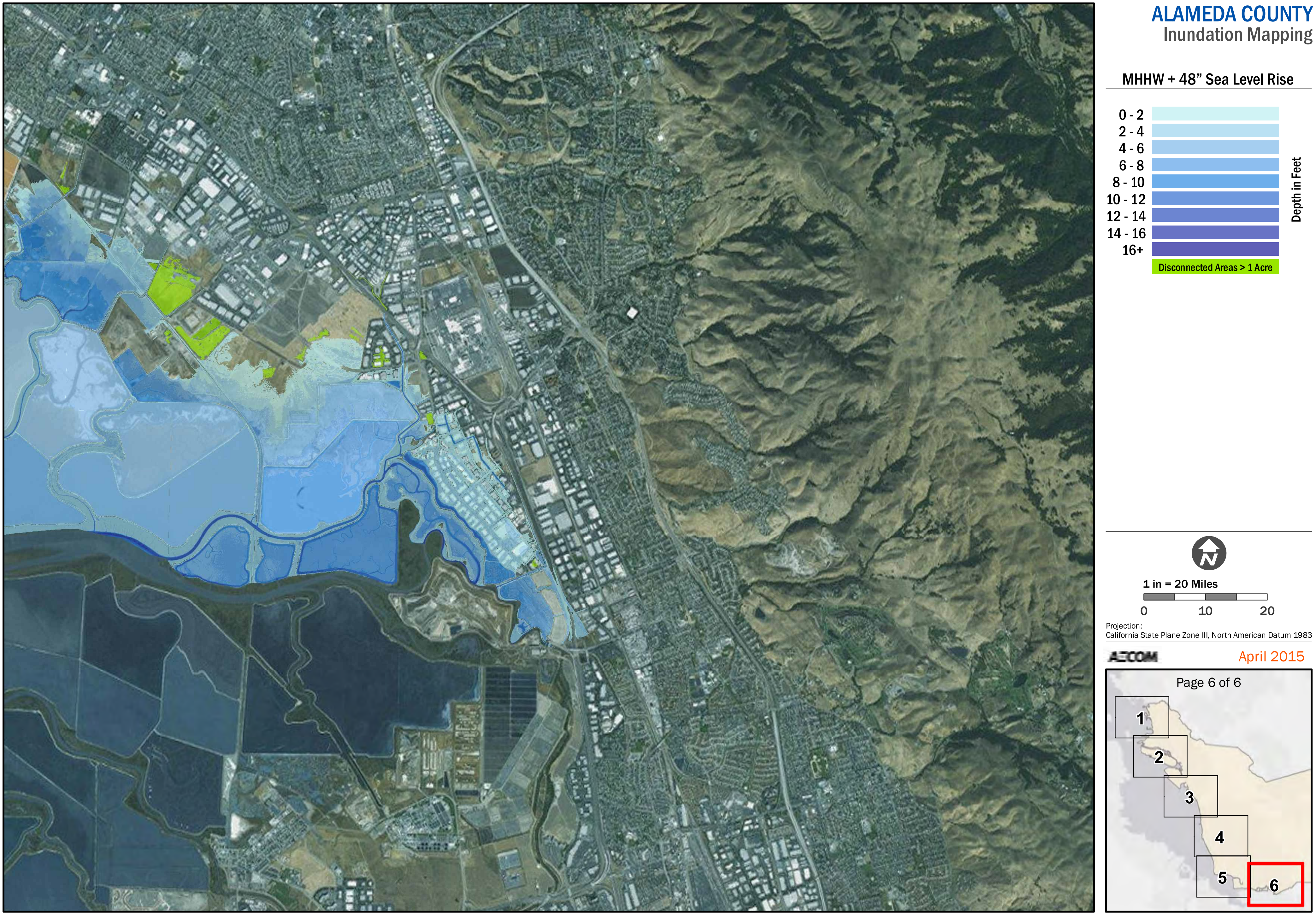
Projection:
California State Plane Zone III, North American Datum 1983

AECOM

April 2015




ALAMEDA COUNTY
Inundation Mapping
MHHW + 48" Sea Level Rise
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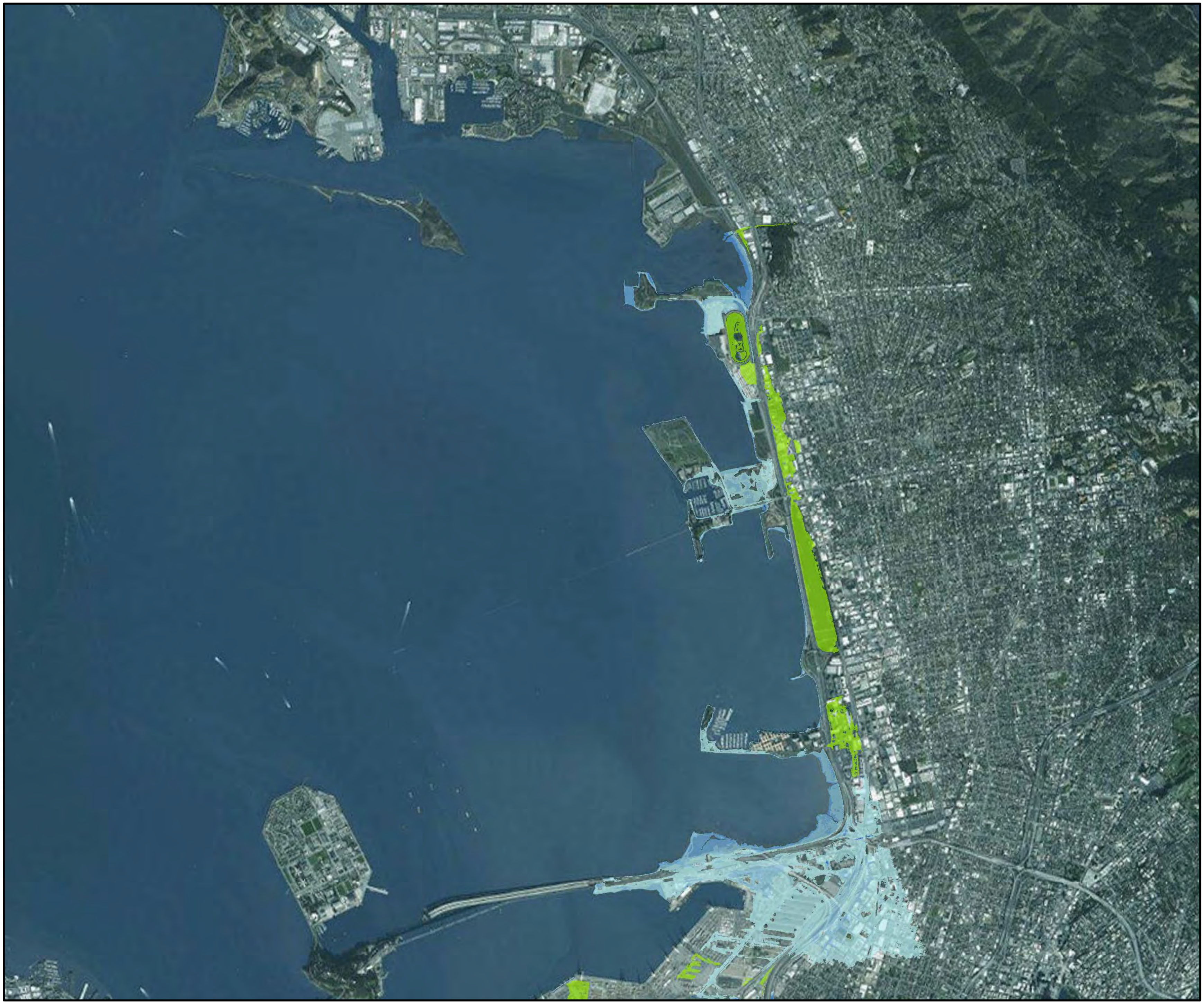
N
1 in = 20 Miles
0
10
20
Projection:
California State Plane Zone III, North American Datum 1983
AECOM
April 2015
Page 6 of 6
1
2
3
4
5
6

ALAMEDA COUNTY
Inundation Mapping



MHHW + 72" Sea Level Rise

Depth in Feet	
0 - 2	
2 - 4	
4 - 6	
6 - 8	
8 - 10	
10 - 12	
12 - 14	
14 - 16	
16+	
	Disconnected Areas > 1 Acre

1 in = 20 Miles

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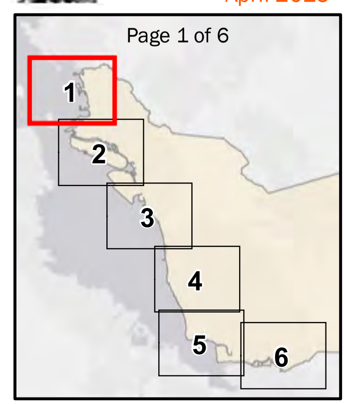
Projection:
California State Plane Zone III, North American Datum 1983

AECOM

April 2015



ALAMEDA COUNTY
Inundation Mapping

MHHW + 72” Sea Level Rise

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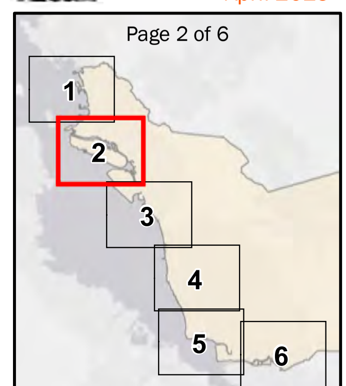
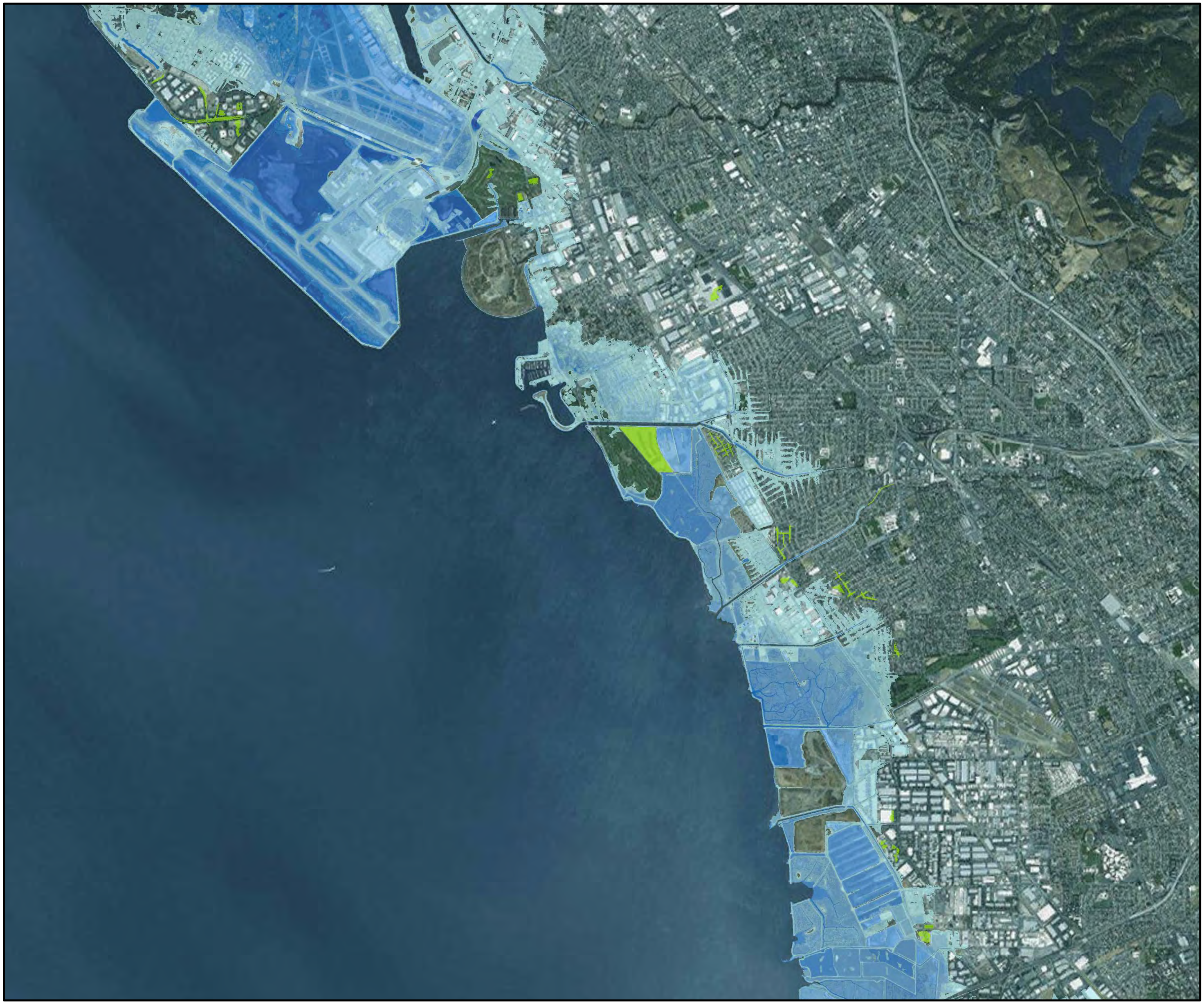
Projection:
California State Plane Zone III, North American Datum 1983

AECOM

April 2015



ALAMEDA COUNTY
Inundation Mapping



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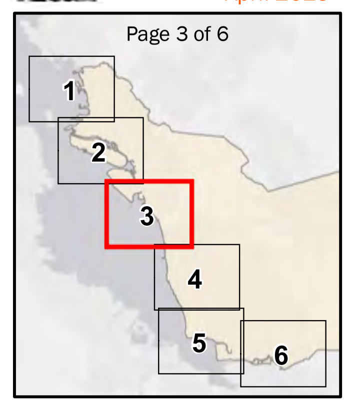
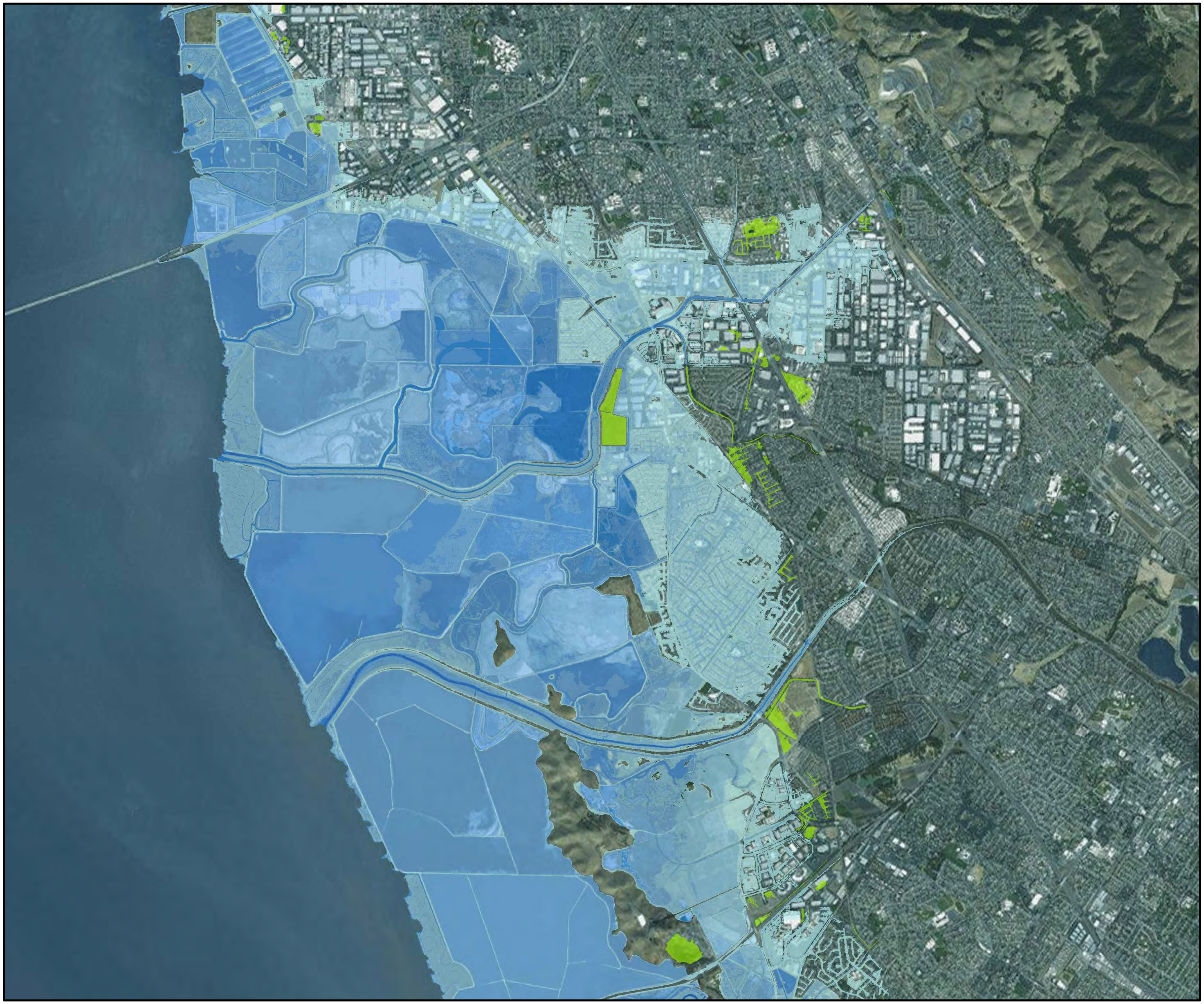
California State Plane Zone III, North American Datum 1983

AECOM

April 2015



ALAMEDA COUNTY
Inundation Mapping



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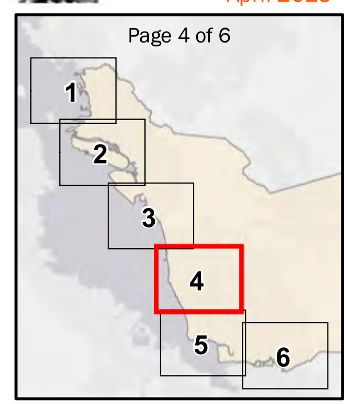

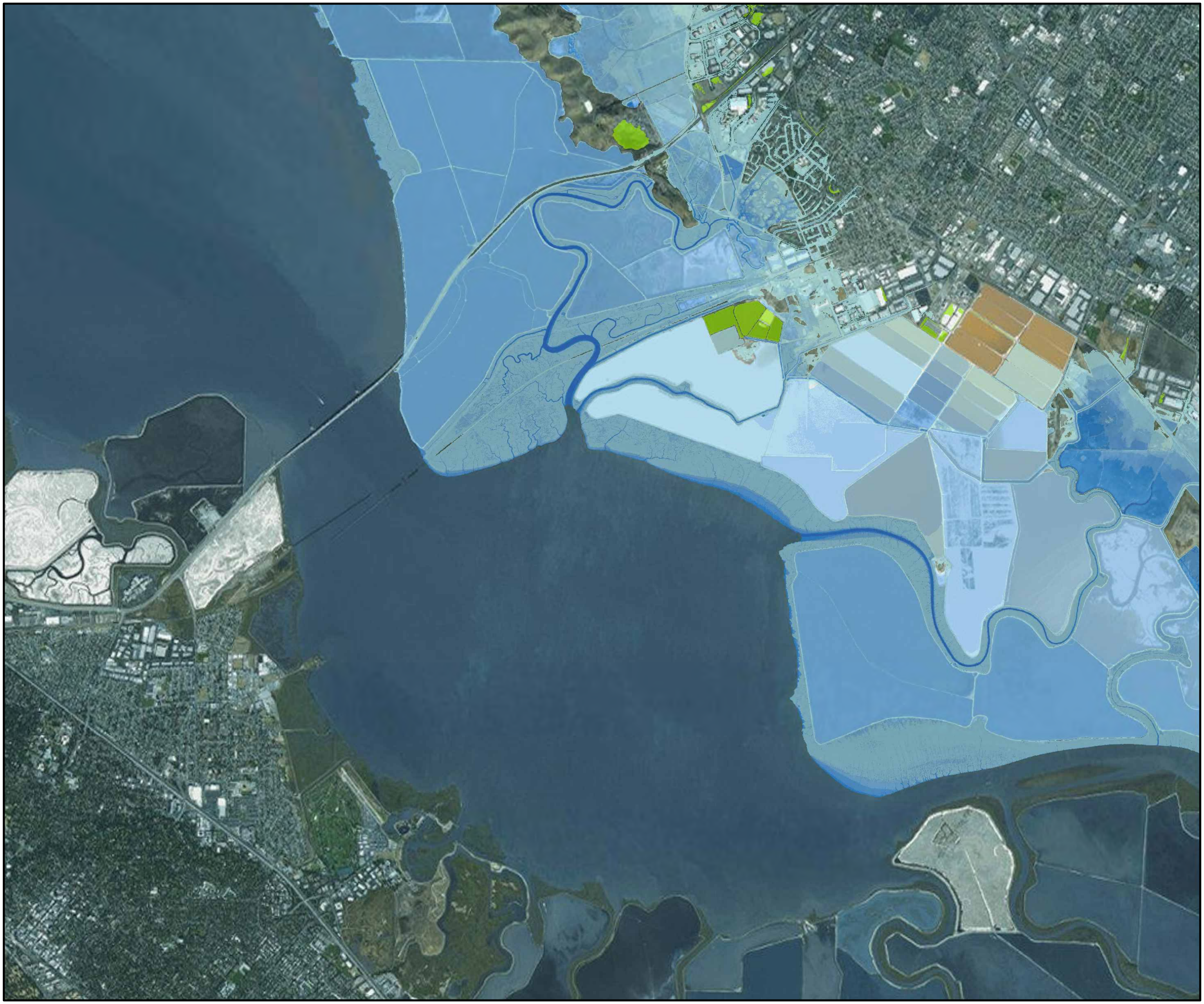

ALAMEDA COUNTY
Inundation Mapping

MHHW + 72" Sea Level Rise

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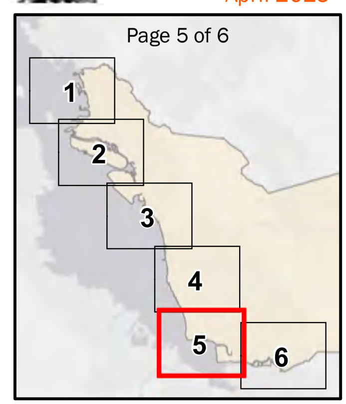

ALAMEDA COUNTY
Inundation Mapping

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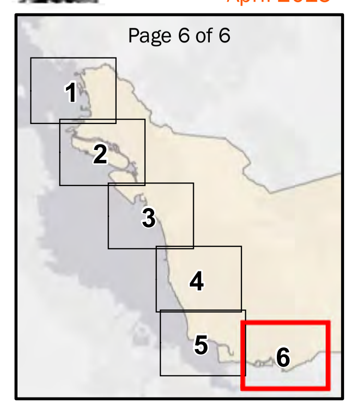
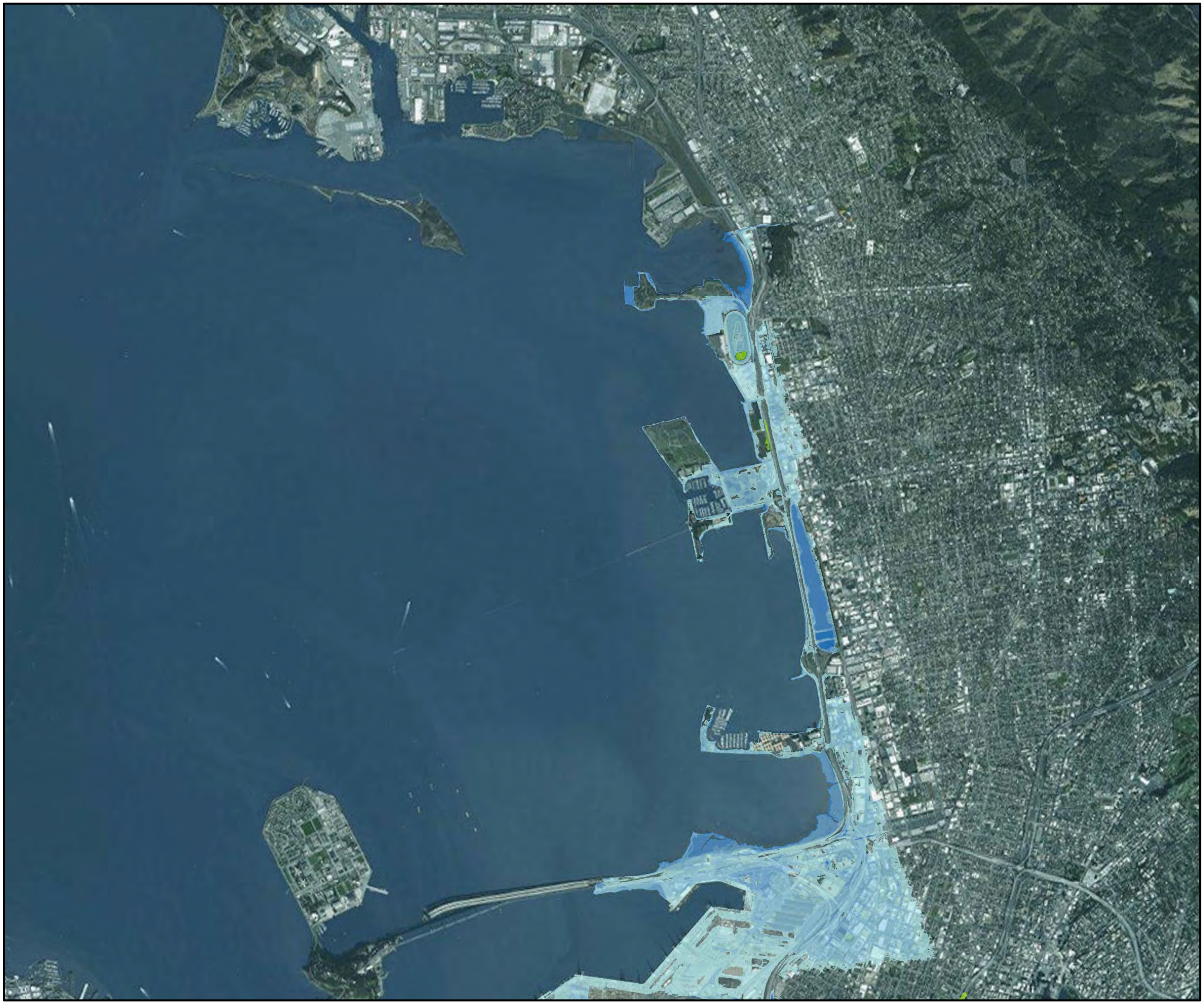




ALAMEDA COUNTY
Inundation Mapping

MHHW + 96” Sea Level Rise

Depth in Feet
0 - 2
2 - 4
4 - 6
6 - 8
8 - 10
10 - 12
12 - 14
14 - 16
16+
Disconnected Areas > 1 Acre

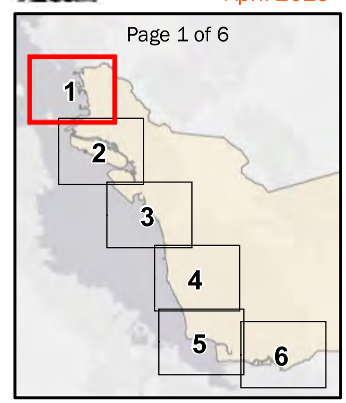
1 in = 20 Miles

0 10 20

Projection:
California State Plane Zone III, North American Datum 1983

AECOM

April 2015



ALAMEDA COUNTY
Inundation Mapping

MHHW + 96” Sea Level Rise

Depth in Feet

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Projection:
California State Plane Zone III, North American Datum 1983

AECOM

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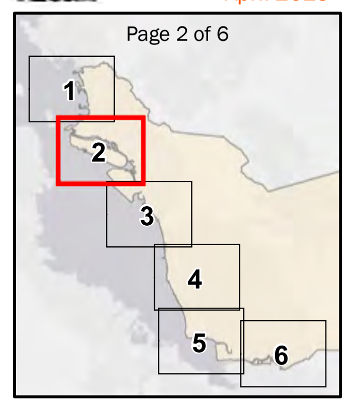

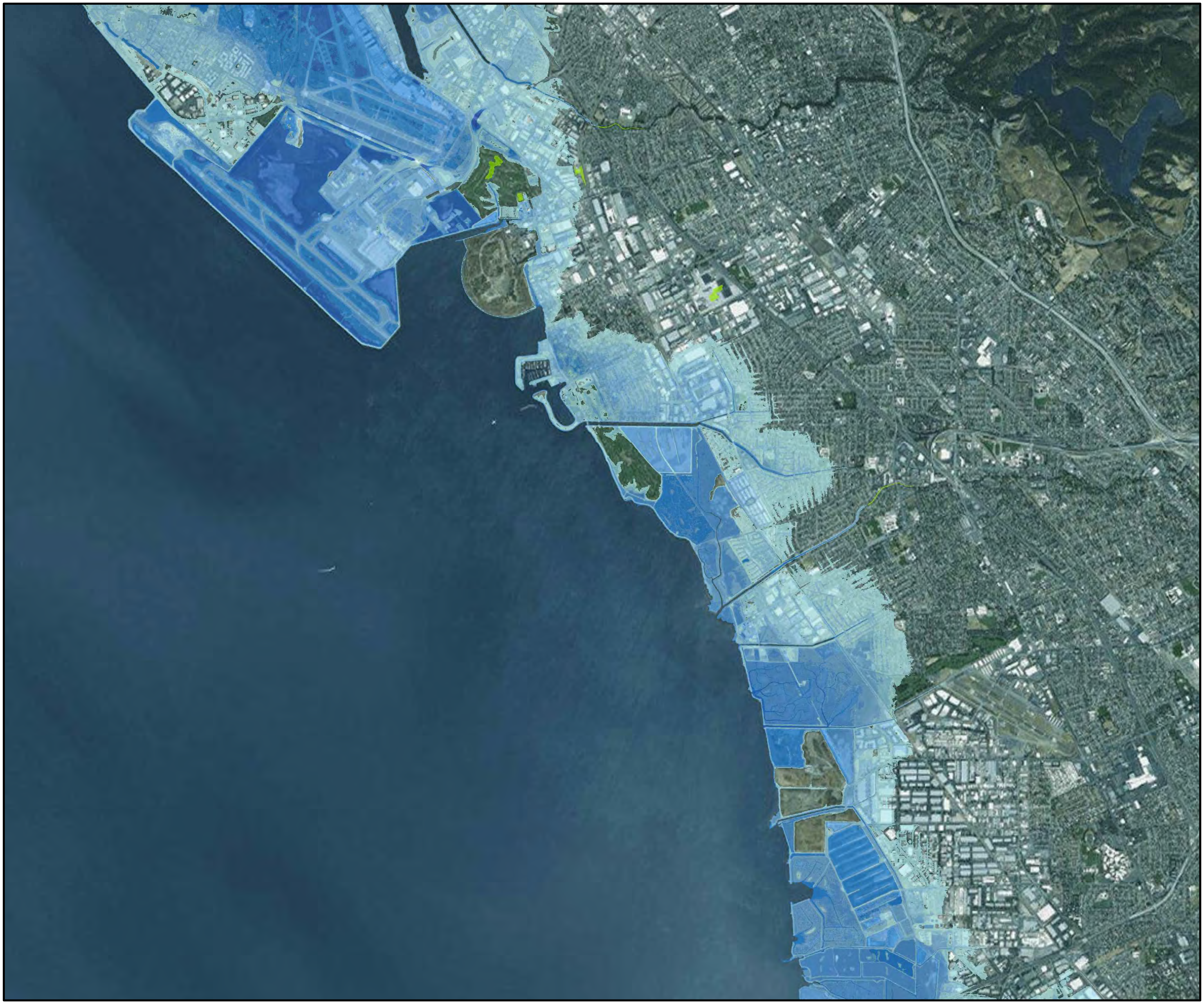

ALAMEDA COUNTY
Inundation Mapping

MHHW + 96" Sea Level Rise

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Projection:
California State Plane Zone III, North American Datum 1983

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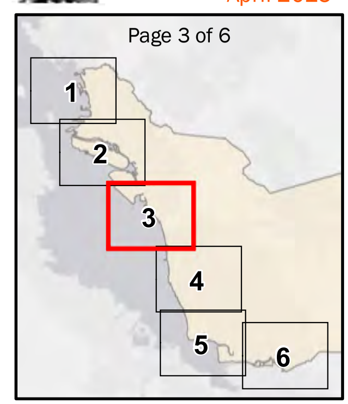

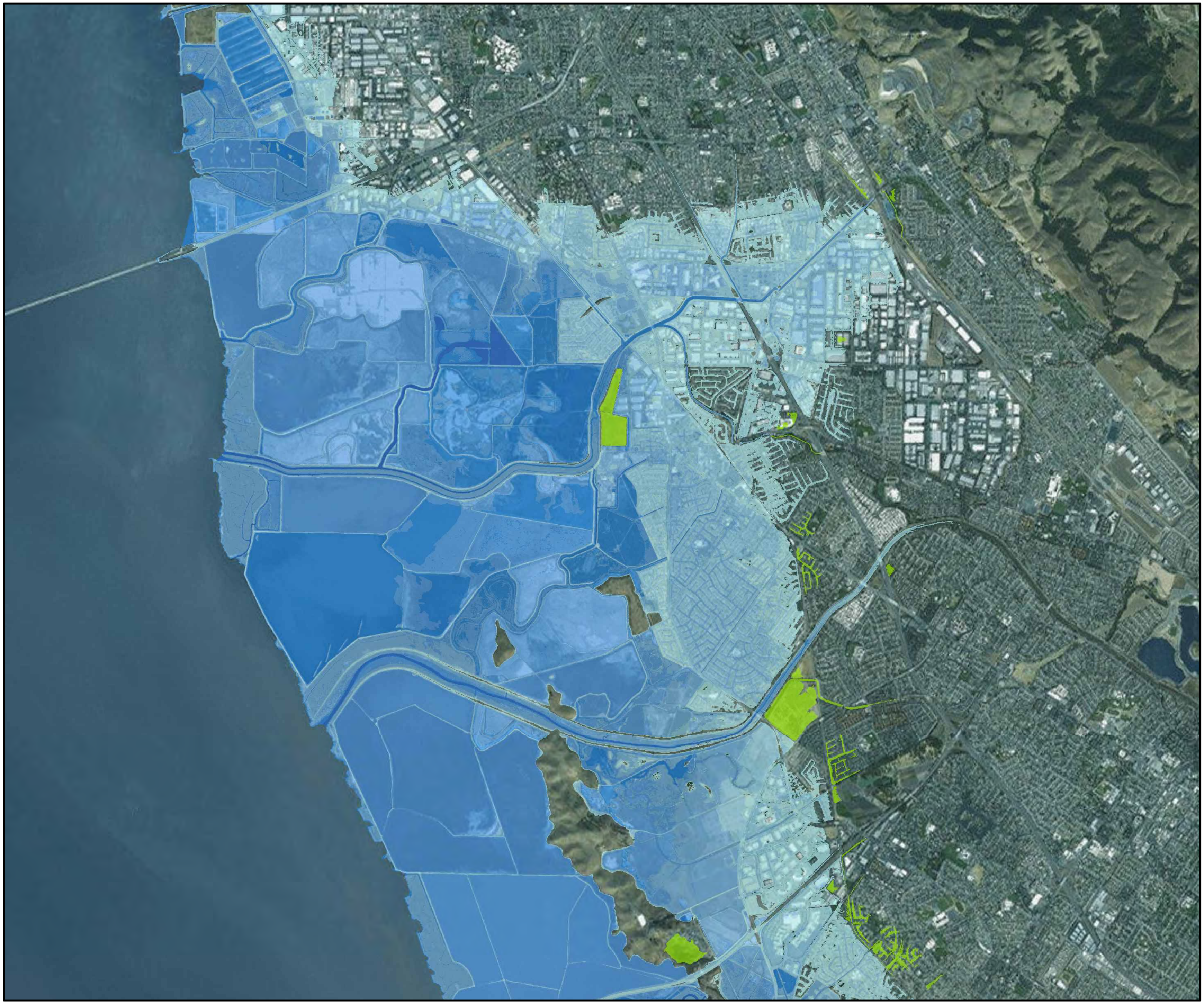

ALAMEDA COUNTY
Inundation Mapping

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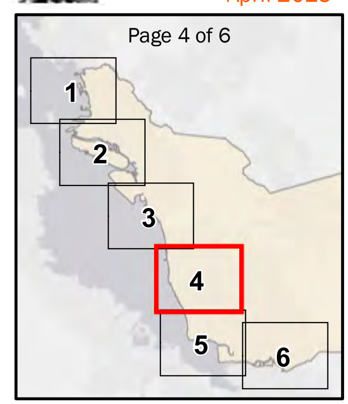
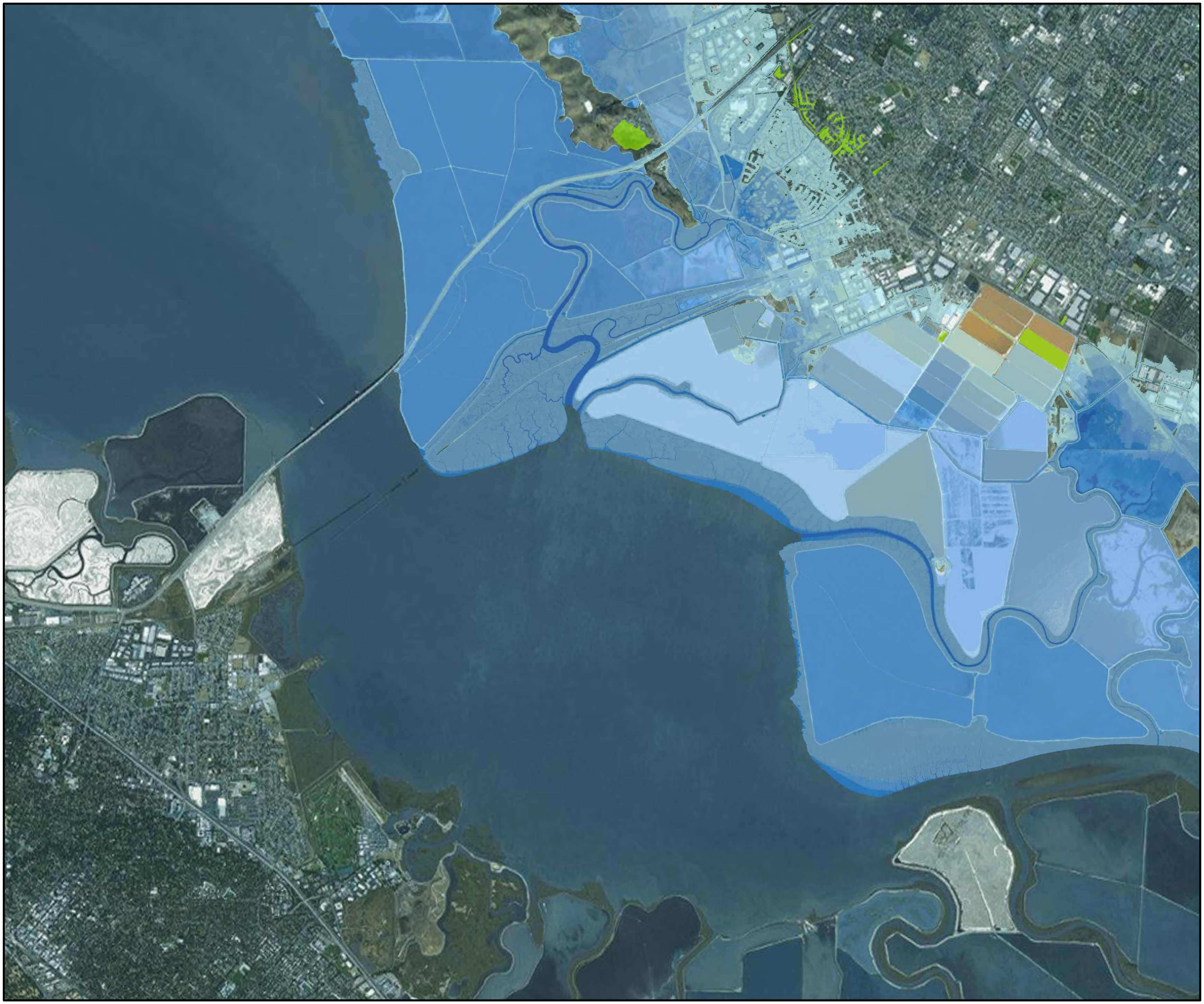


ALAMEDA COUNTY
Inundation Mapping



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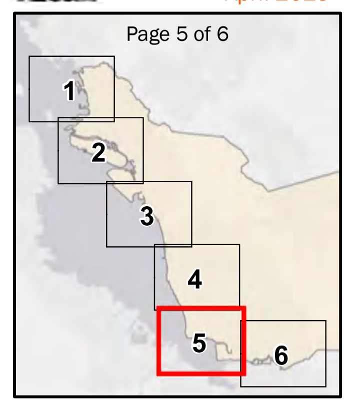

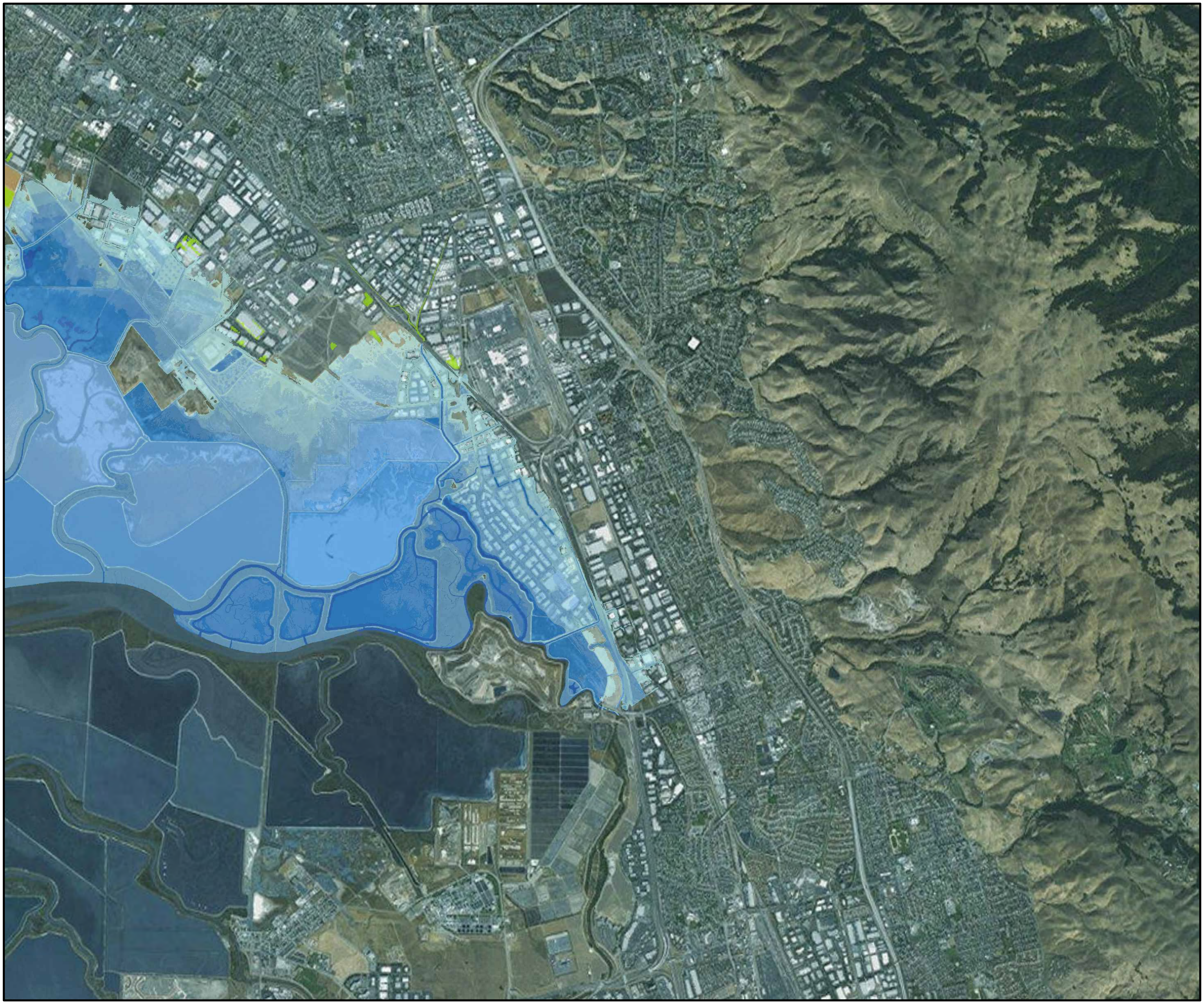

ALAMEDA COUNTY
Inundation Mapping

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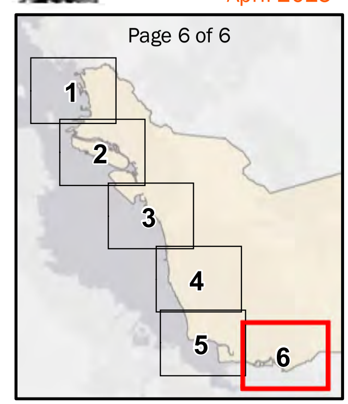
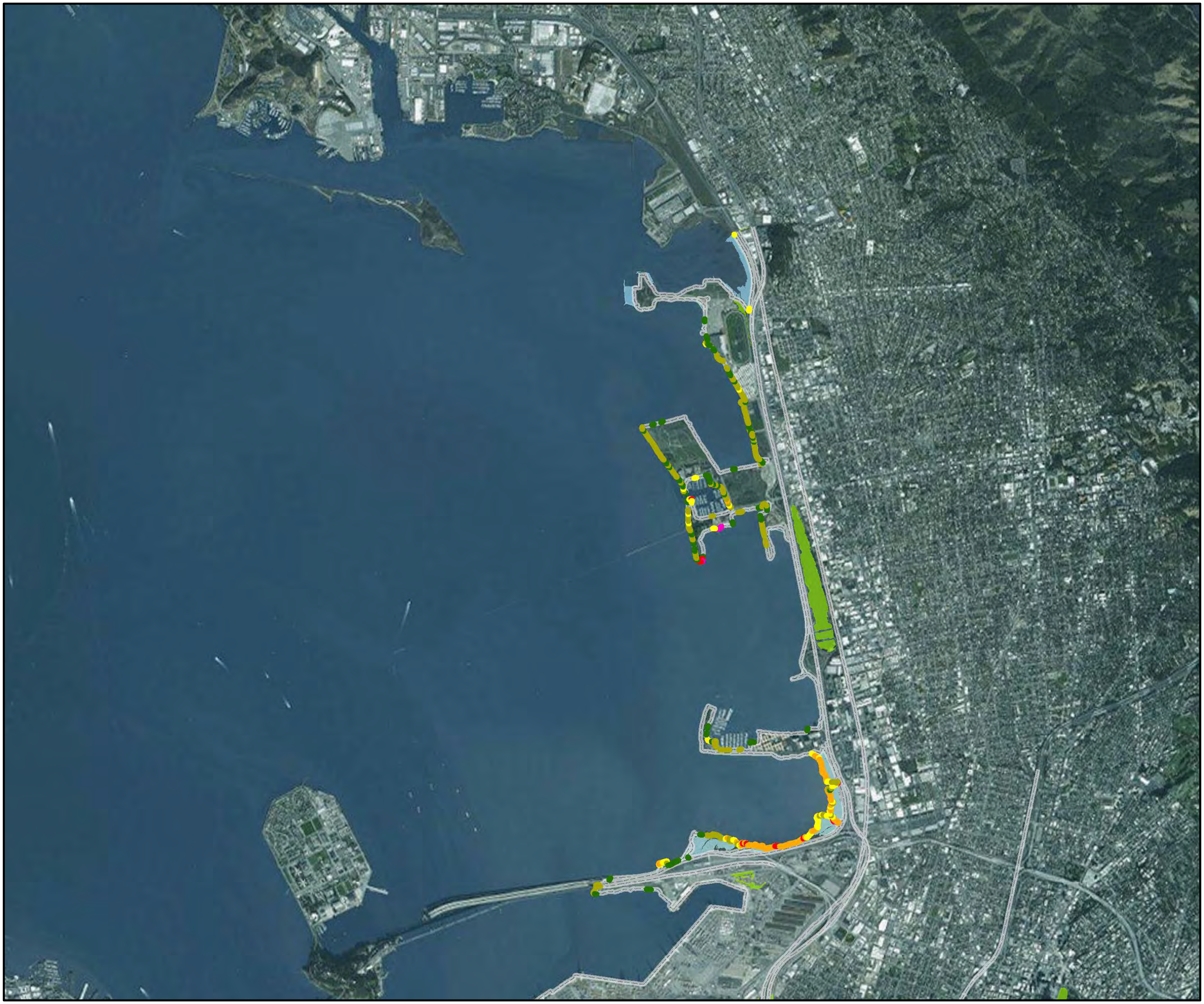


C

OVERTOPPING POTENTIAL MAPS



ALAMEDA COUNTY
Inundation Mapping

MHHW + 12” Sea Level Rise
Shoreline Overtopping Potential

Depth in Feet

- .5 - 1
- 1 - 2
- 2 - 3
- 3 - 4
- 4 - 5
- > 5
- No Overtopping

Depth in Feet

- 0 - 2
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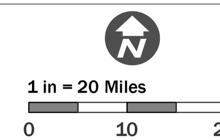

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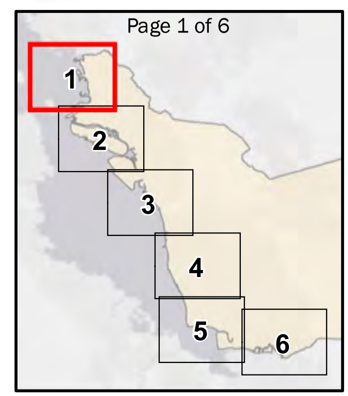

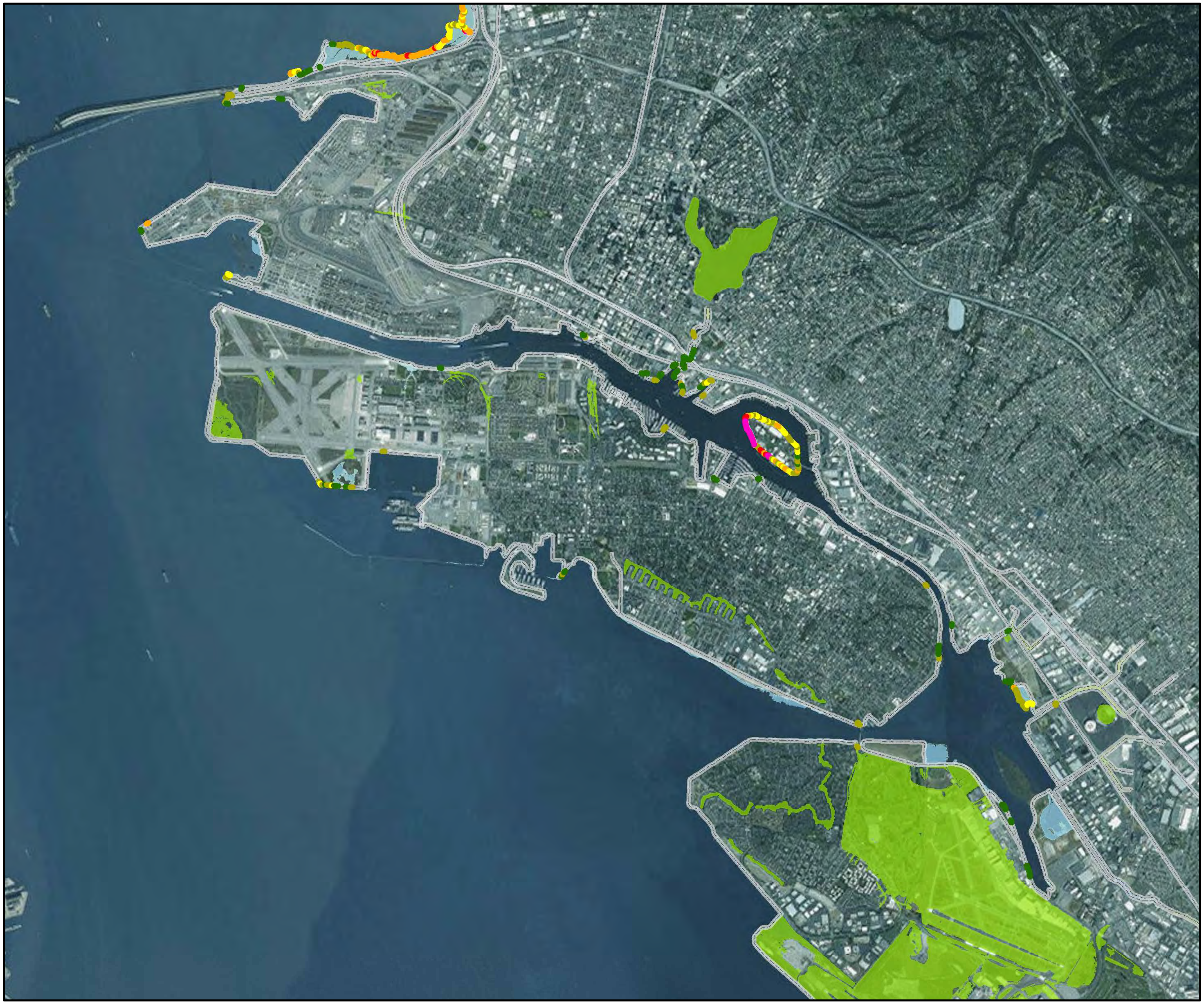

ALAMEDA COUNTY
Inundation Mapping

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Projection:
California State Plane Zone III, North American Datum 1983

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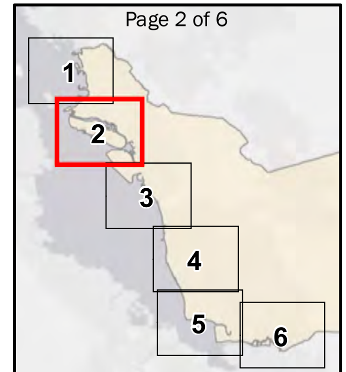

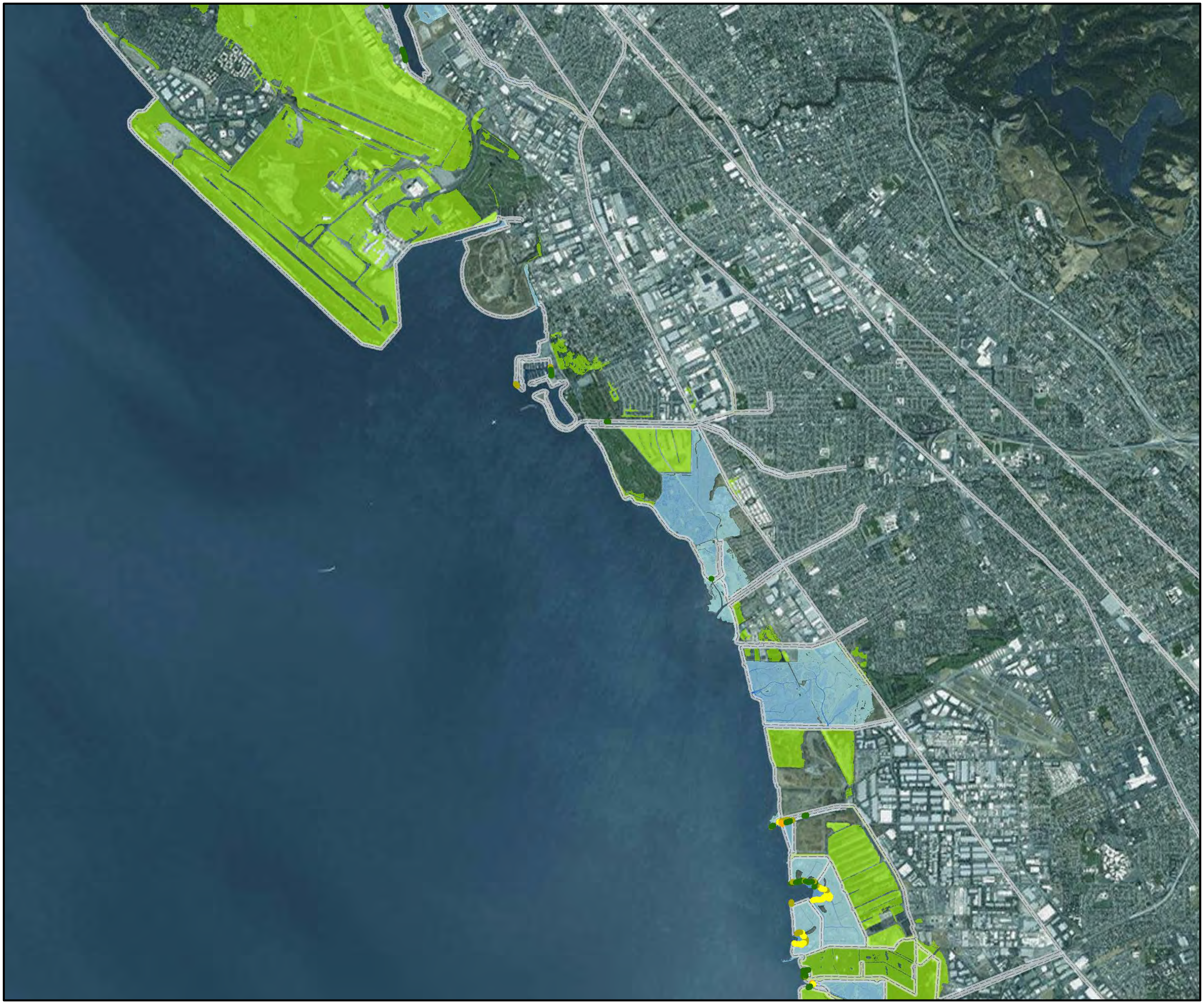

ALAMEDA COUNTY
Inundation Mapping

MHHW + 12" Sea Level Rise Shoreline Overtopping Potential

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Projection:
California State Plane Zone III, North American Datum 1983

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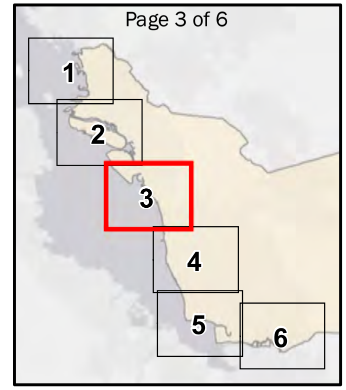
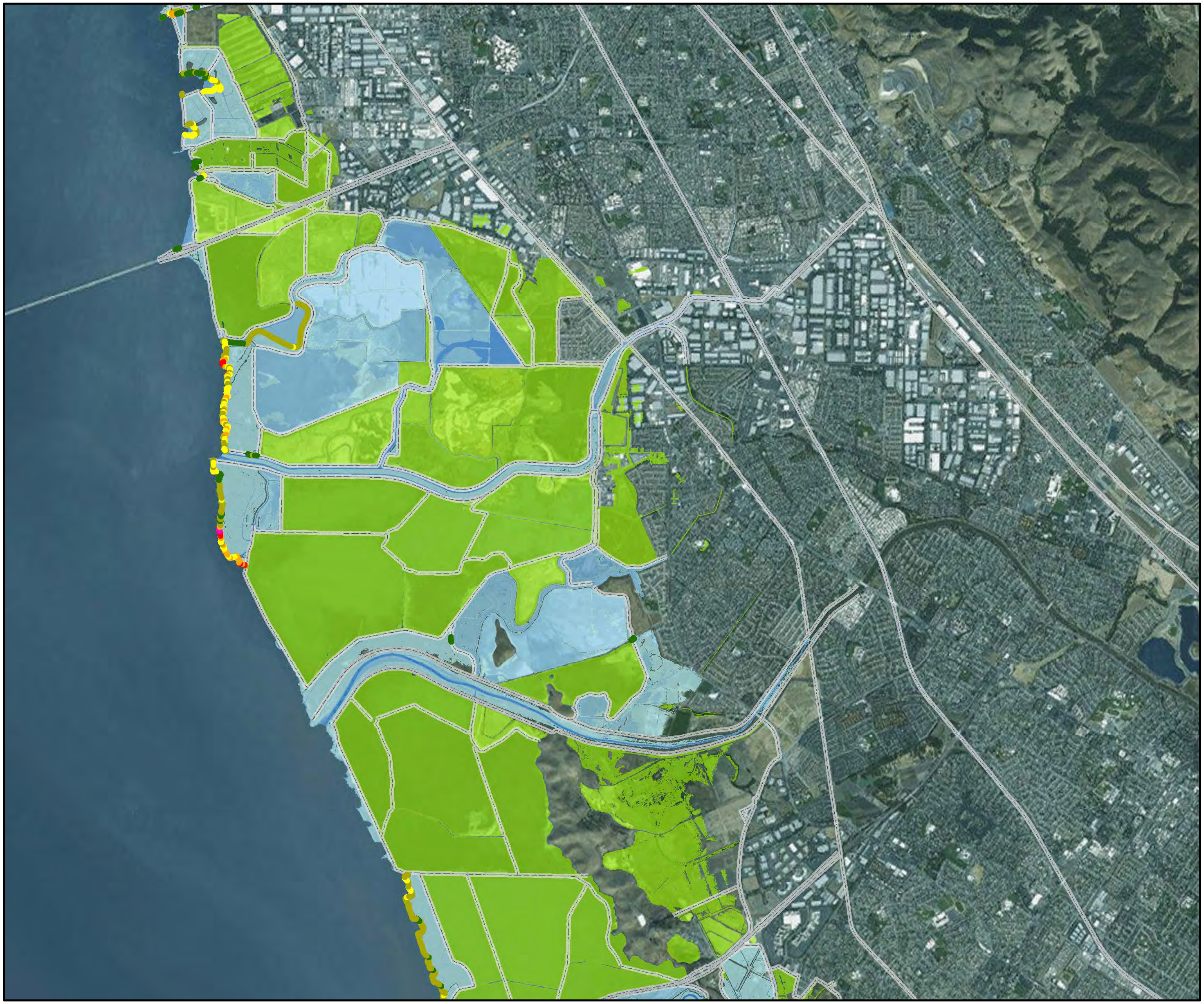


ALAMEDA COUNTY
Inundation Mapping



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California State Plane Zone III, North American Datum 1983

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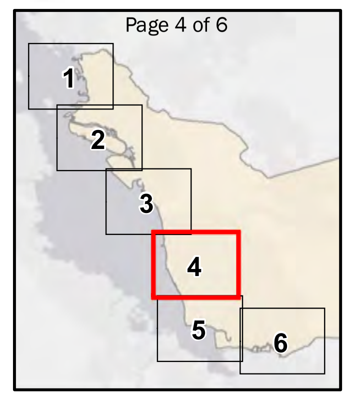
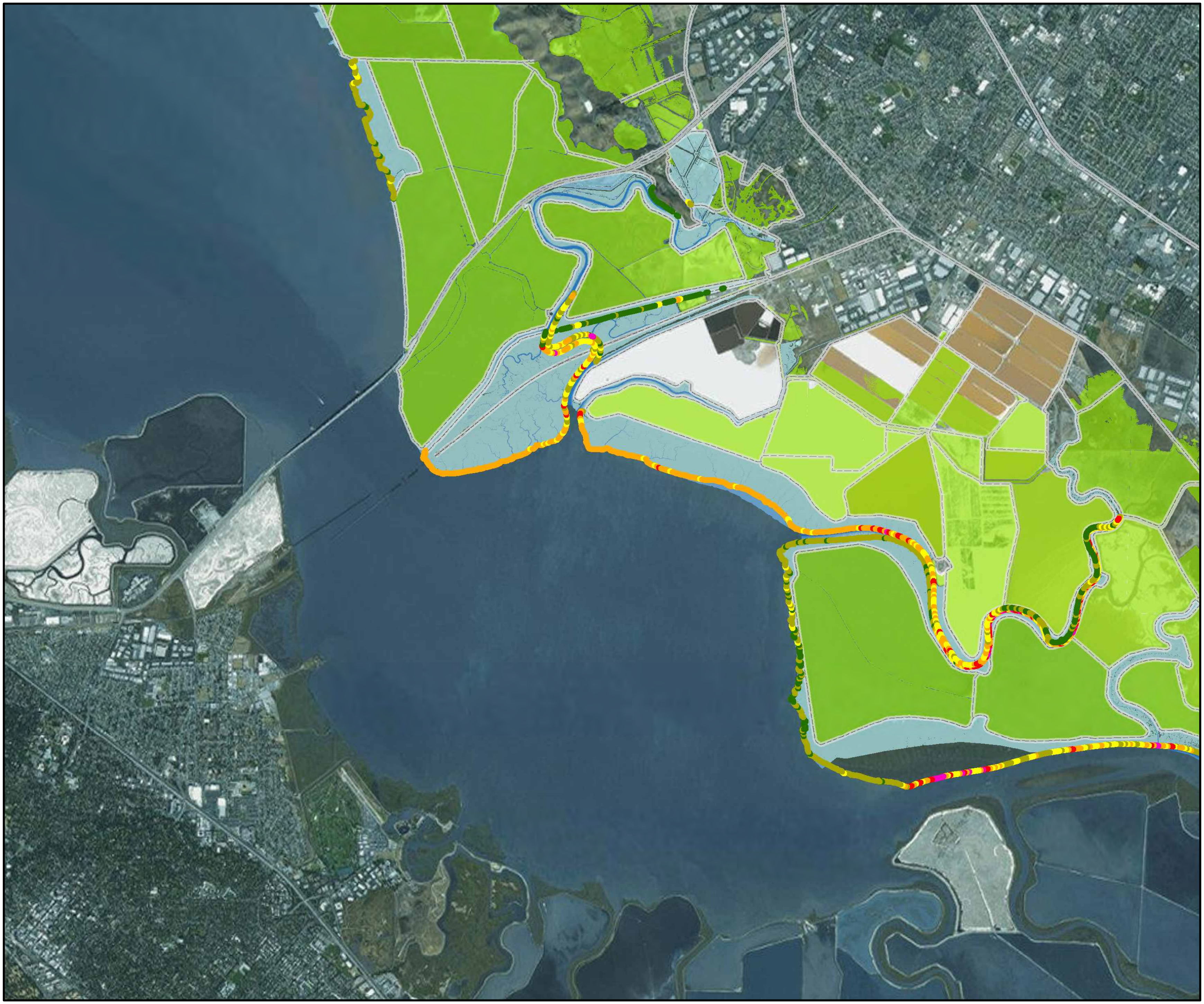
April 2015



ALAMEDA COUNTY
Inundation Mapping



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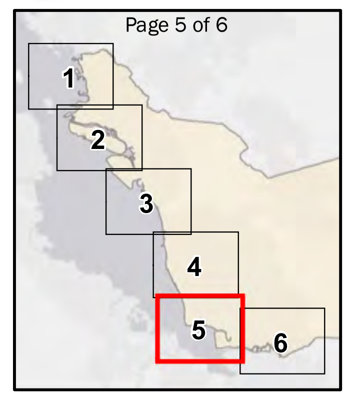
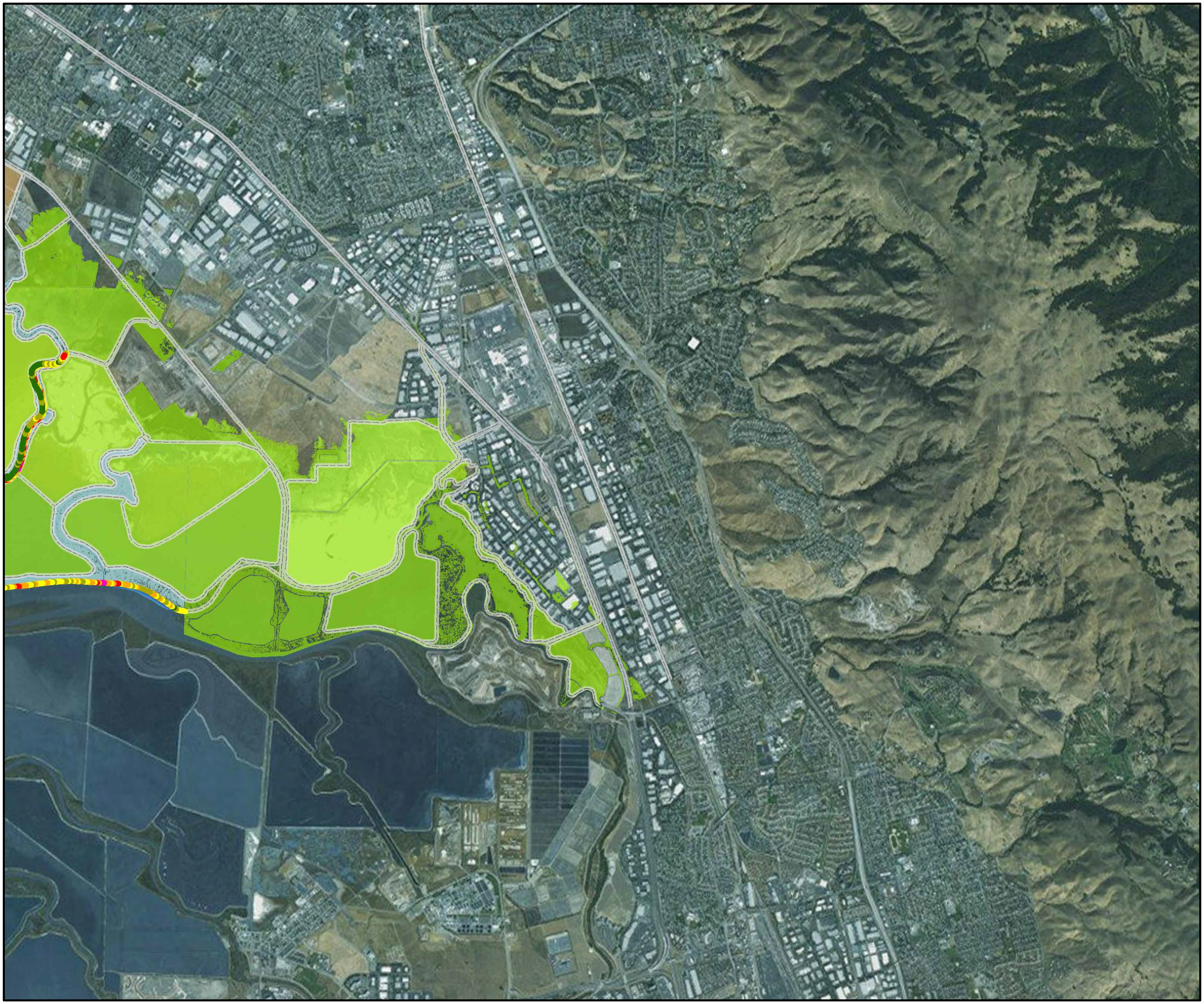


ALAMEDA COUNTY
Inundation Mapping



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- 12 - 14
- 14 - 16
- 16+
- Disconnected Areas > 1 Acre

N

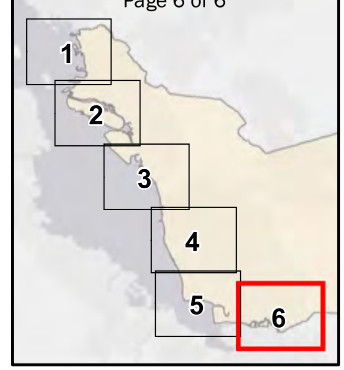
1 in = 20 Miles

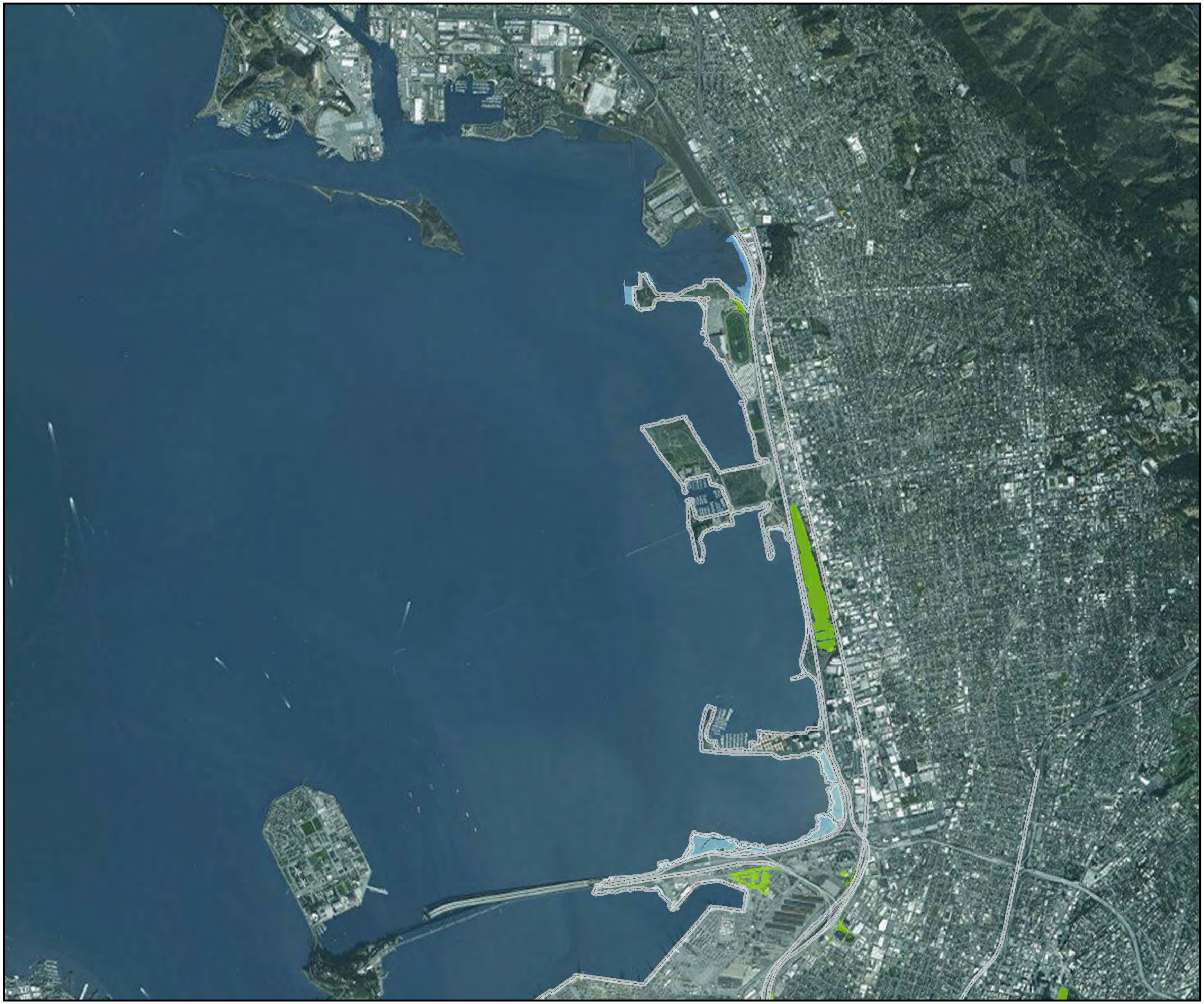
0 10 20

Projection:
California State Plane Zone III, North American Datum 1983

AECOM

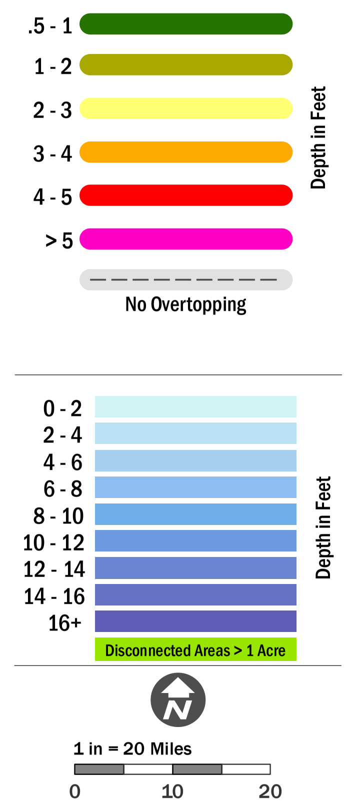
April 2015





ALAMEDA COUNTY
Inundation Mapping

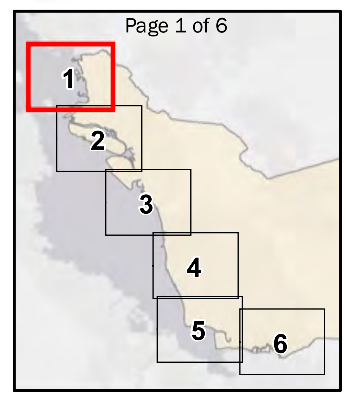
MHHW + 24" Sea Level Rise Shoreline Overtopping Potential



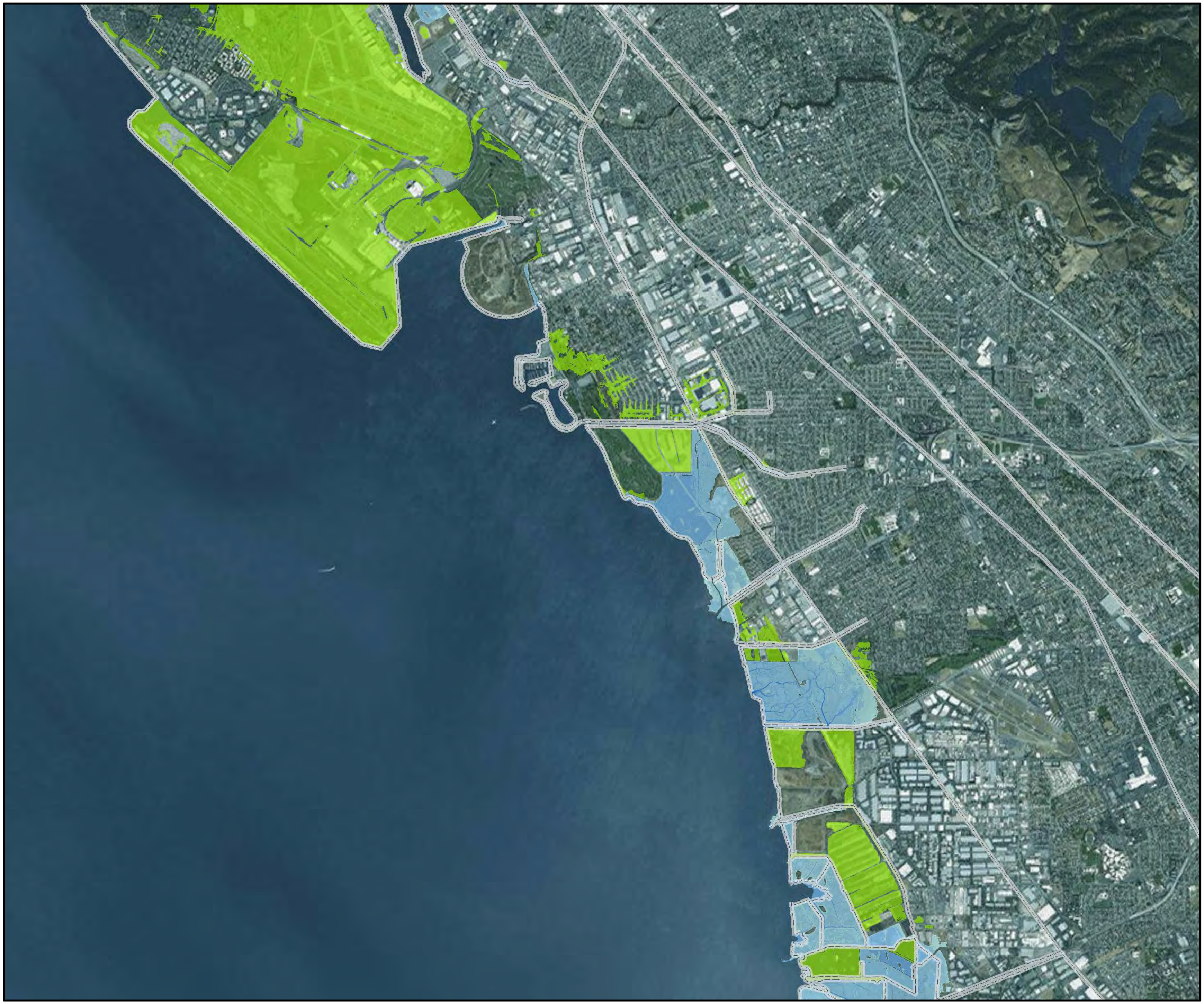
Projection:
California State Plane Zone III, North American Datum 1983

AECOM

April 2015




ALAMEDA COUNTY
Inundation Mapping
MHHW + 24" Sea Level Rise
Shoreline Overtopping Potential
.5 - 1
1 - 2
2 - 3
3 - 4
4 - 5
> 5
Depth in Feet
No Overtopping
0 - 2
2 - 4
4 - 6
6 - 8
8 - 10
10 - 12
12 - 14
14 - 16
16+
Depth in Feet
Disconnected Areas > 1 Acre
N
1 in = 20 Miles
0
10
20
Projection:
California State Plane Zone III, North American Datum 1983
AECOM
April 2015
Page 2 of 6
1
2
3
4
5
6



ALAMEDA COUNTY
Inundation Mapping

MHHW + 24” Sea Level Rise
Shoreline Overtopping Potential

Depth in Feet
- .5 - 1
- 1 - 2
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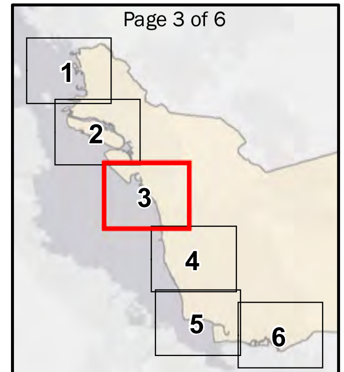
0 10 20

Projection:
California State Plane Zone III, North American Datum 1983

AECOM

April 2015

Page 3 of 6



ALAMEDA COUNTY
Inundation Mapping

MHHW + 24" Sea Level Rise
Shoreline Overtopping Potential

Depth in Feet

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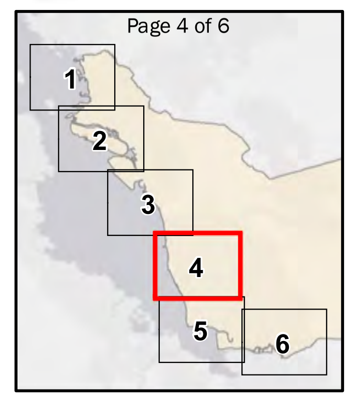
Projection:
California State Plane Zone III, North American Datum 1983

AECOM

April 2015



ALAMEDA COUNTY
Inundation Mapping

MHHW + 24" Sea Level Rise
Shoreline Overtopping Potential

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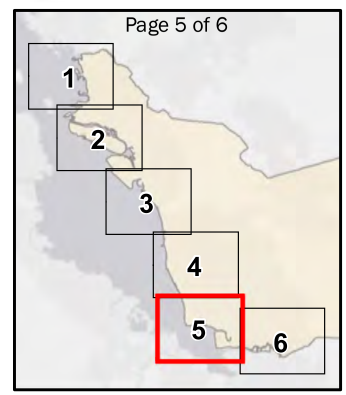
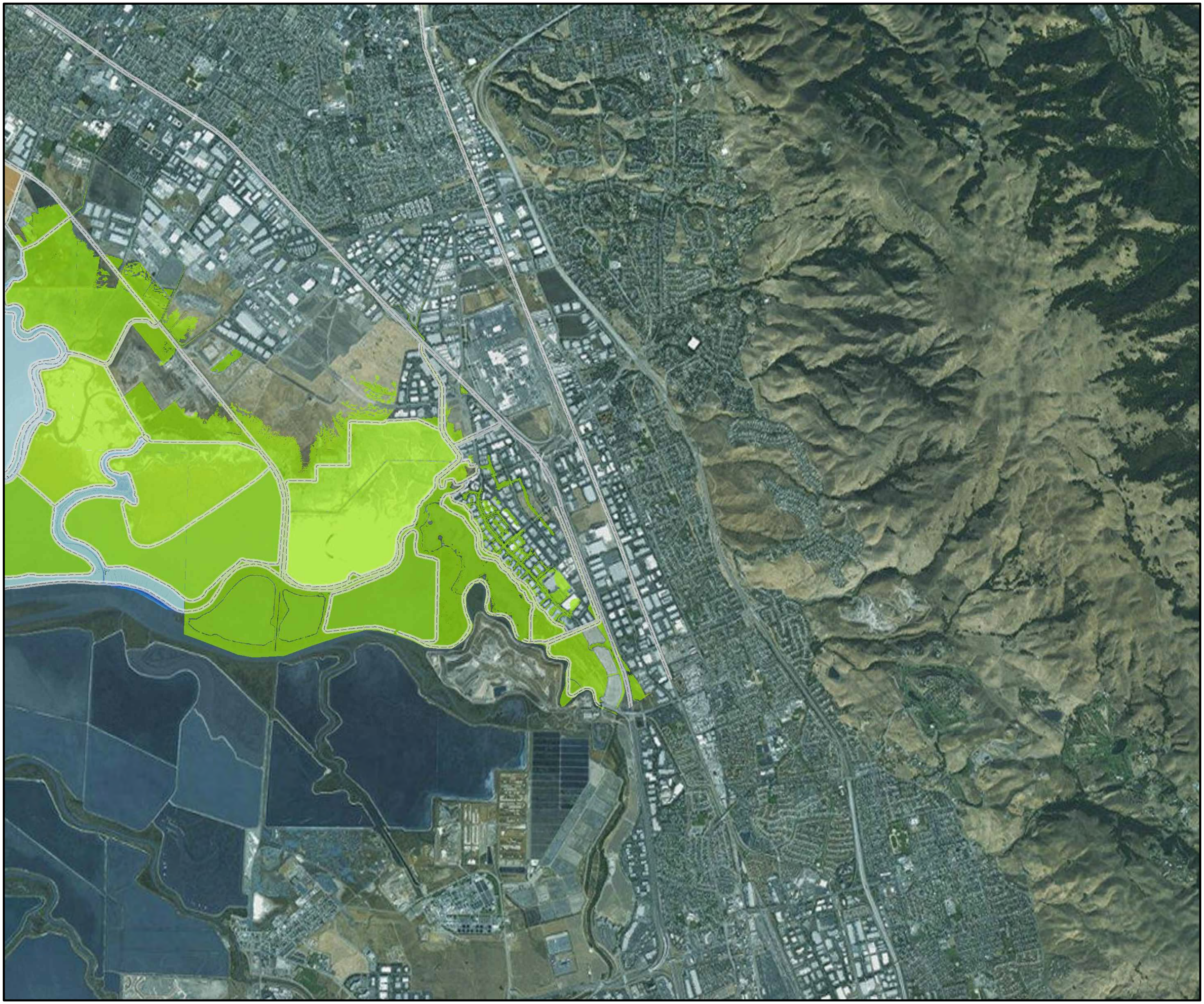
Projection:
California State Plane Zone III, North American Datum 1983

AECOM

April 2015





ALAMEDA COUNTY
Inundation Mapping

MHHW + 24" Sea Level Rise
Shoreline Overtopping Potential

Depth in Feet
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1 - 2
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No Overtopping

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Disconnected Areas > 1 Acre

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1 in = 20 Miles
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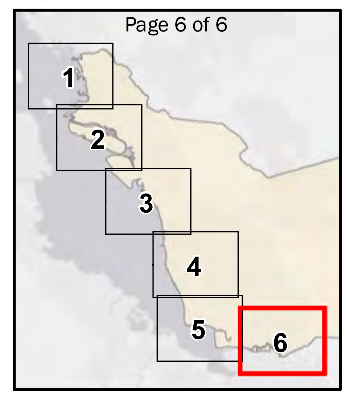
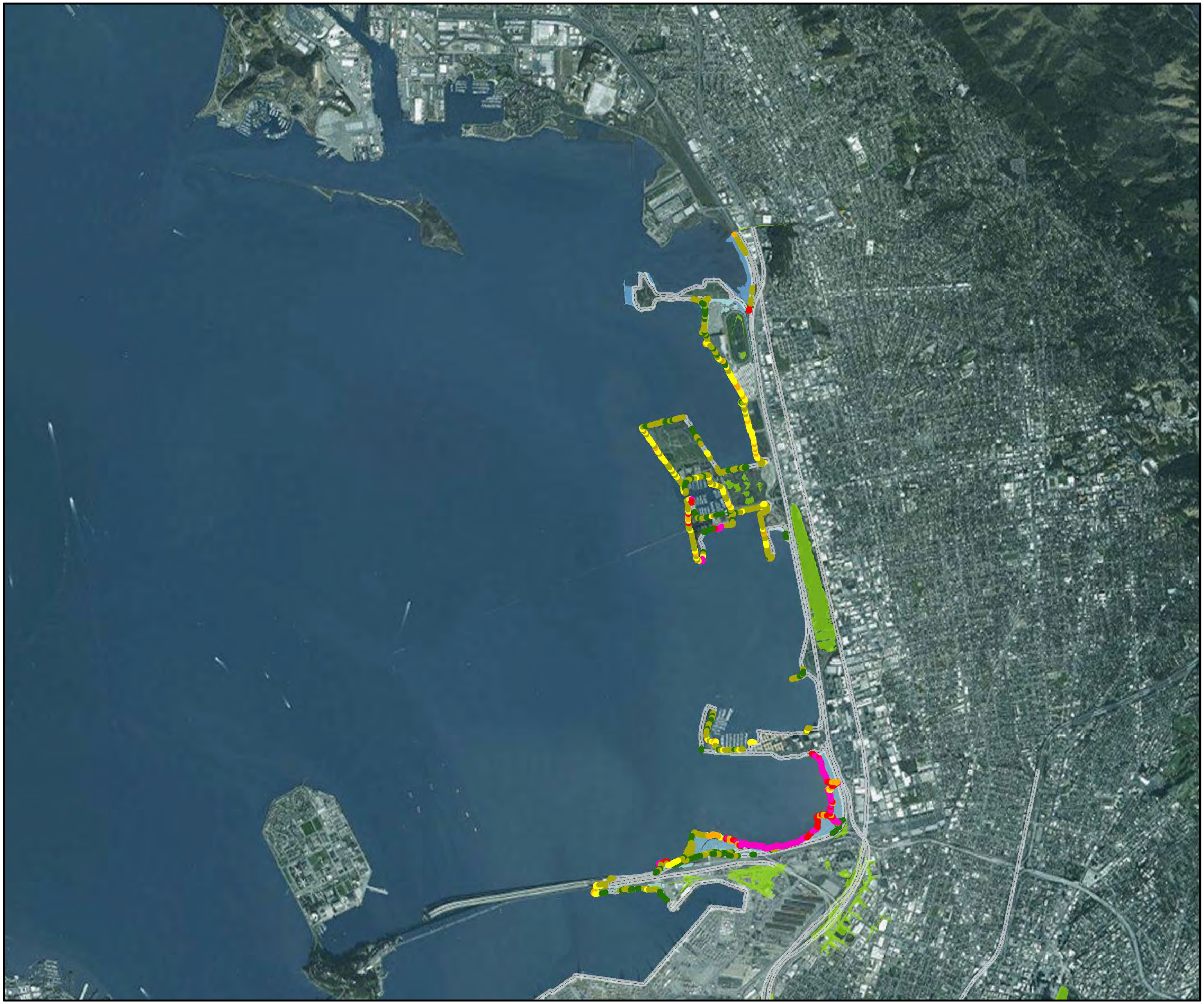
Projection:
California State Plane Zone III, North American Datum 1983

AECOM

April 2015





ALAMEDA COUNTY
Inundation Mapping

MHHW + 36" Sea Level Rise
Shoreline Overtopping Potential

Depth in Feet

- .5 - 1
- 1 - 2
- 2 - 3
- 3 - 4
- 4 - 5
- > 5
- No Overtopping

Depth in Feet

- 0 - 2
- 2 - 4
- 4 - 6
- 6 - 8
- 8 - 10
- 10 - 12
- 12 - 14
- 14 - 16
- 16+
- Disconnected Areas > 1 Acre

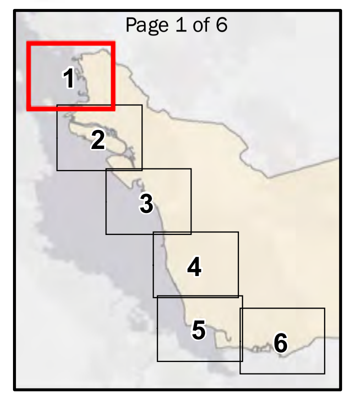
1 in = 20 Miles

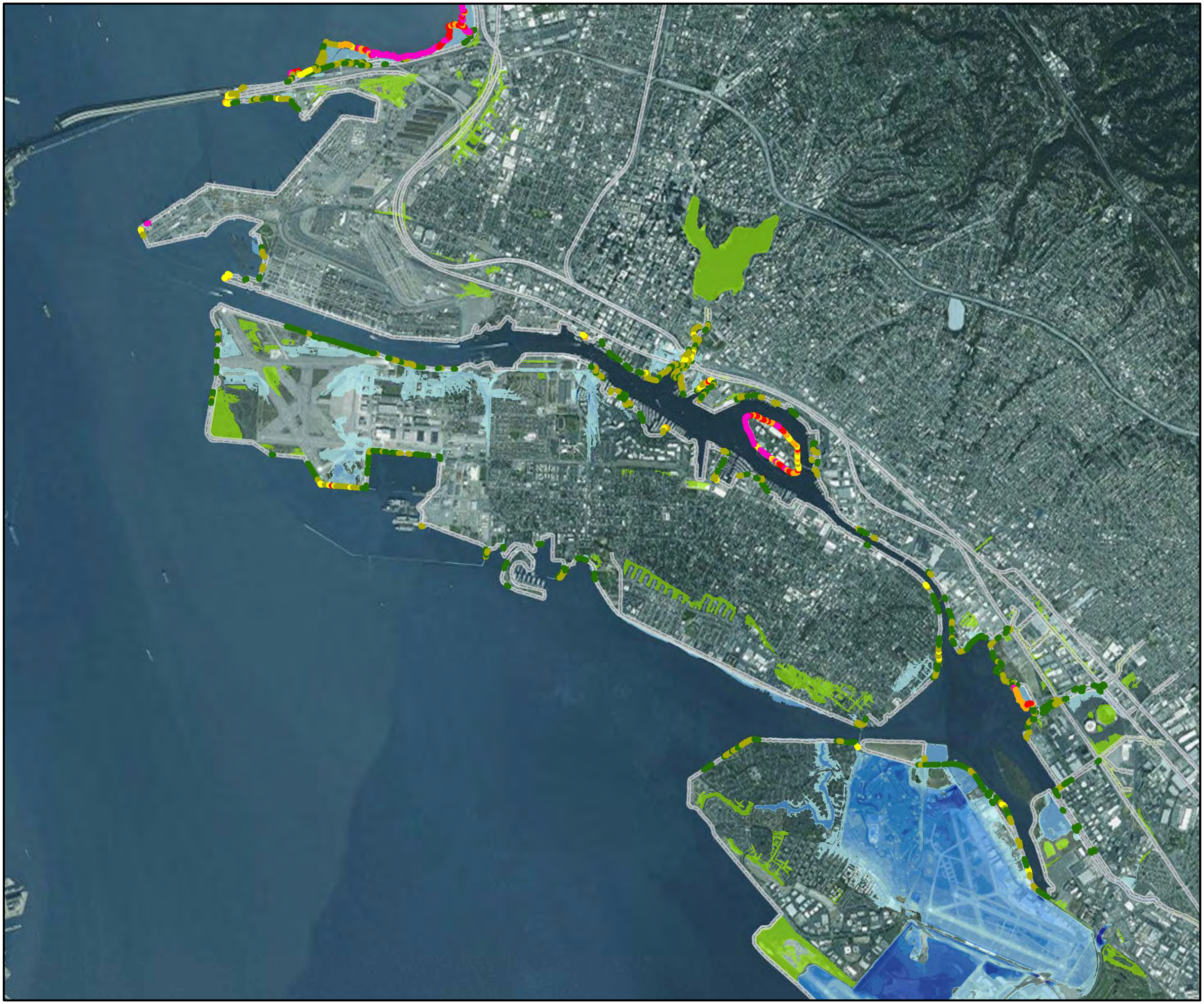
0 10 20

Projection:
California State Plane Zone III, North American Datum 1983

AECOM

April 2015





ALAMEDA COUNTY
Inundation Mapping

MHHW + 36" Sea Level Rise
Shoreline Overtopping Potential

Depth in Feet
- .5 - 1
- 1 - 2
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- 3 - 4
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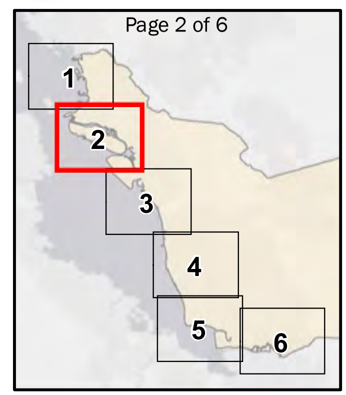
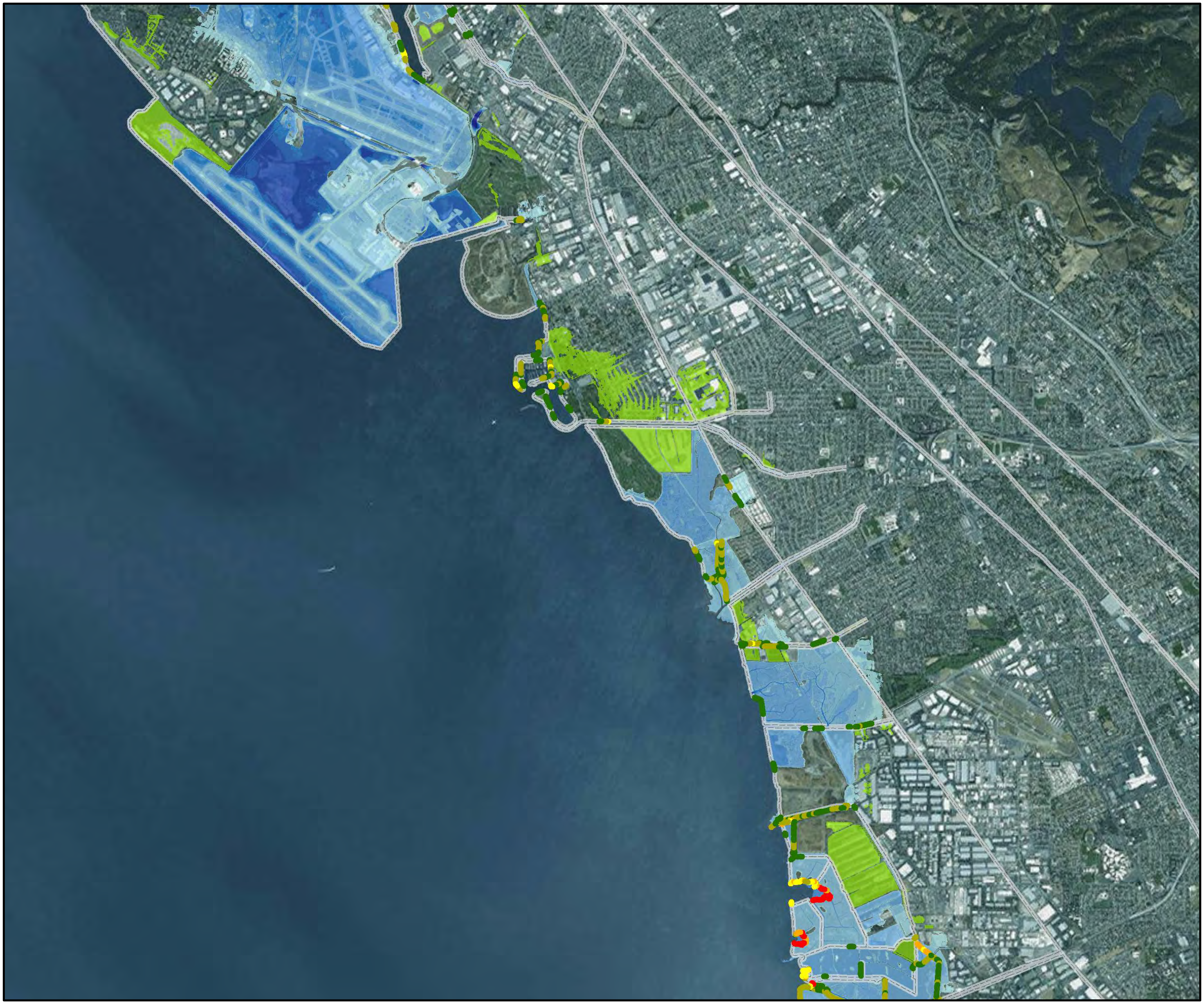
Projection:
California State Plane Zone III, North American Datum 1983

AECOM

April 2015



ALAMEDA COUNTY
Inundation Mapping



MHHW + 36" Sea Level Rise
Shoreline Overtopping Potential

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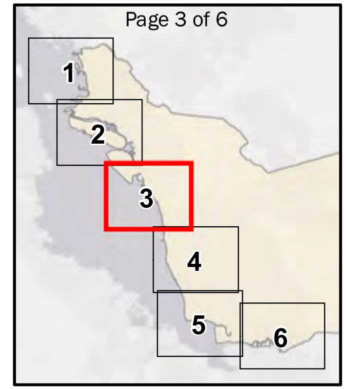
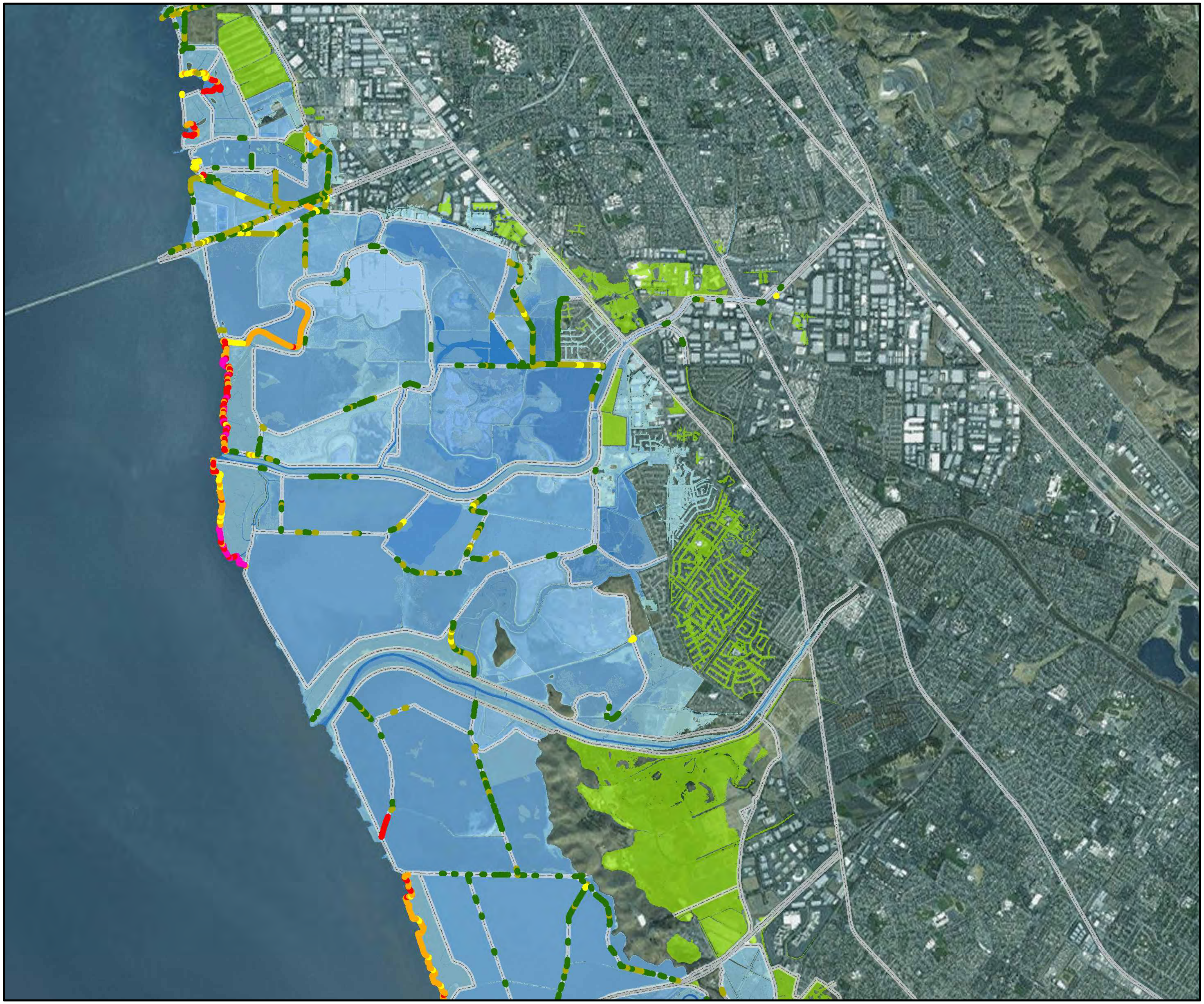
Projection:
California State Plane Zone III, North American Datum 1983

AECOM

April 2015



ALAMEDA COUNTY
Inundation Mapping



MHHW + 36" Sea Level Rise
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Projection:
California State Plane Zone III, North American Datum 1983

AECOM

April 2015

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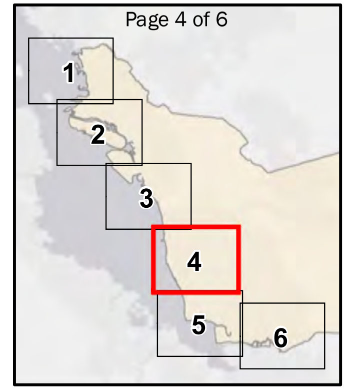

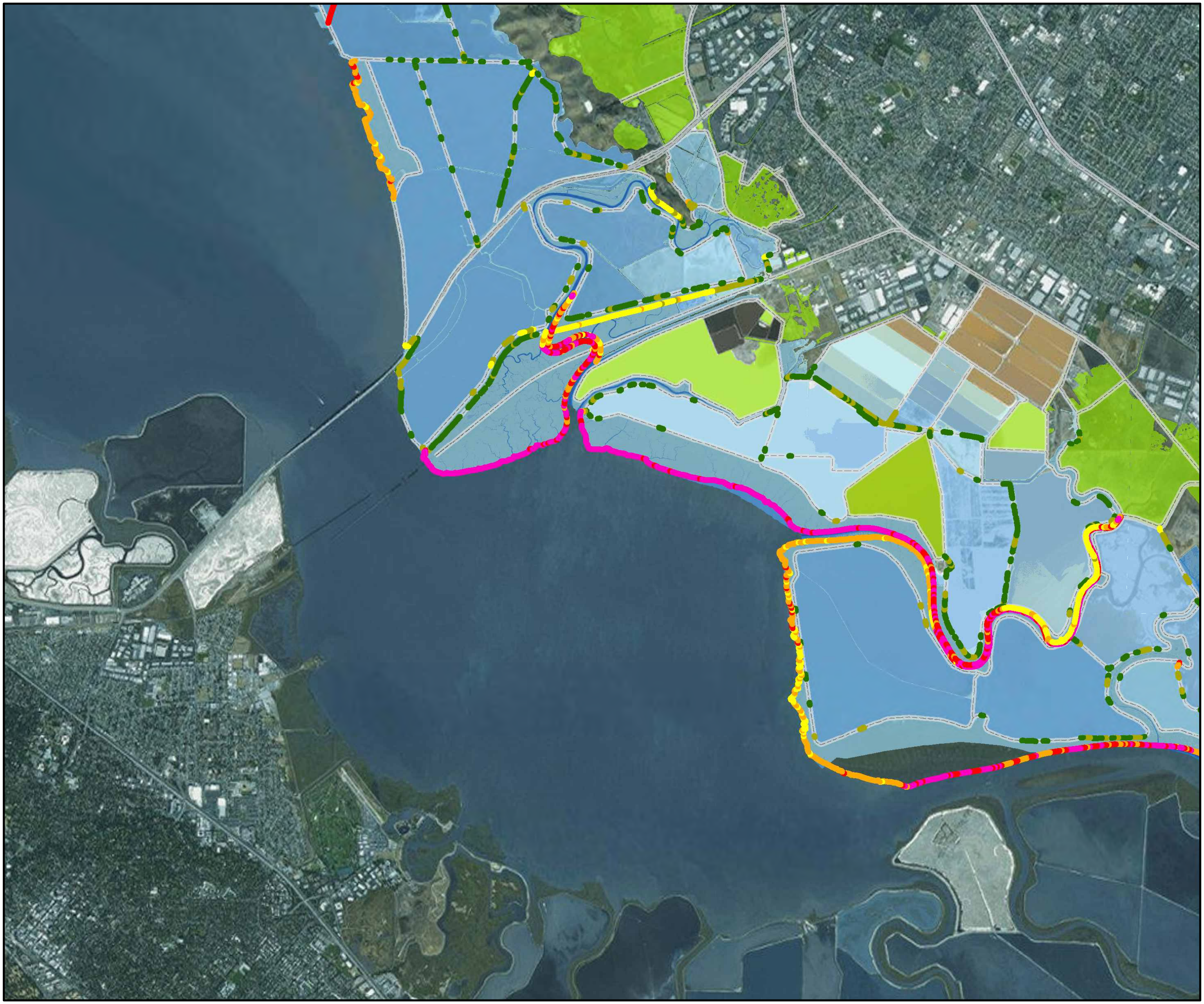

ALAMEDA COUNTY
Inundation Mapping

MHHW + 36" Sea Level Rise
Shoreline Overtopping Potential

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California State Plane Zone III, North American Datum 1983

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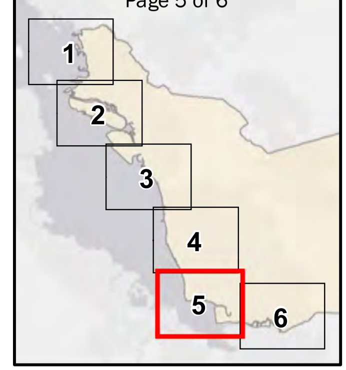
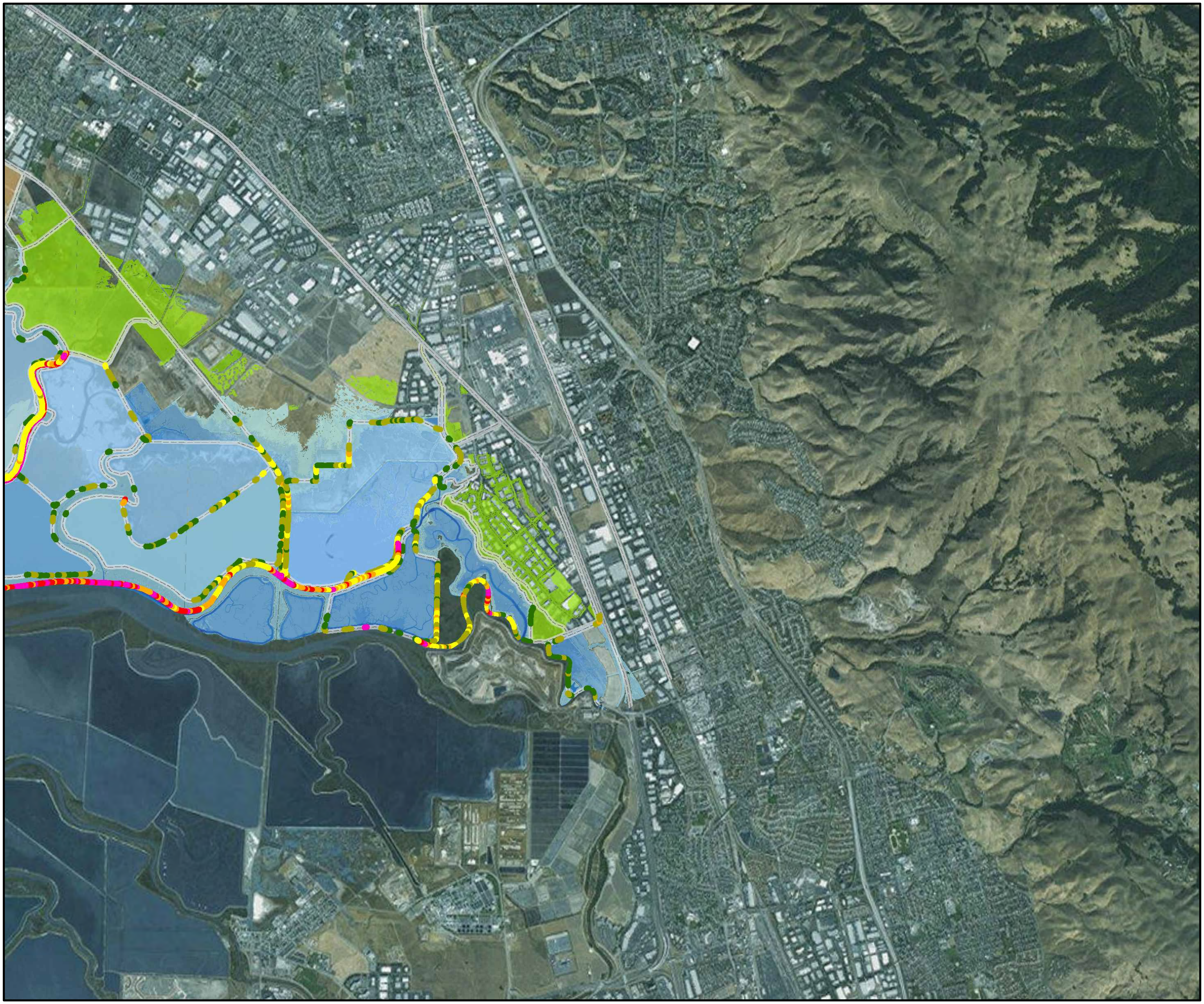
April 2015



ALAMEDA COUNTY
Inundation Mapping



MHHW + 36" Sea Level Rise
Shoreline Overtopping Potential

Depth in Feet
.5 - 1
1 - 2
2 - 3
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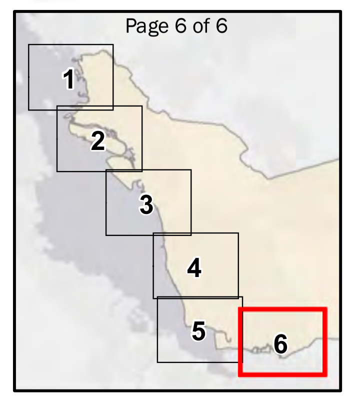
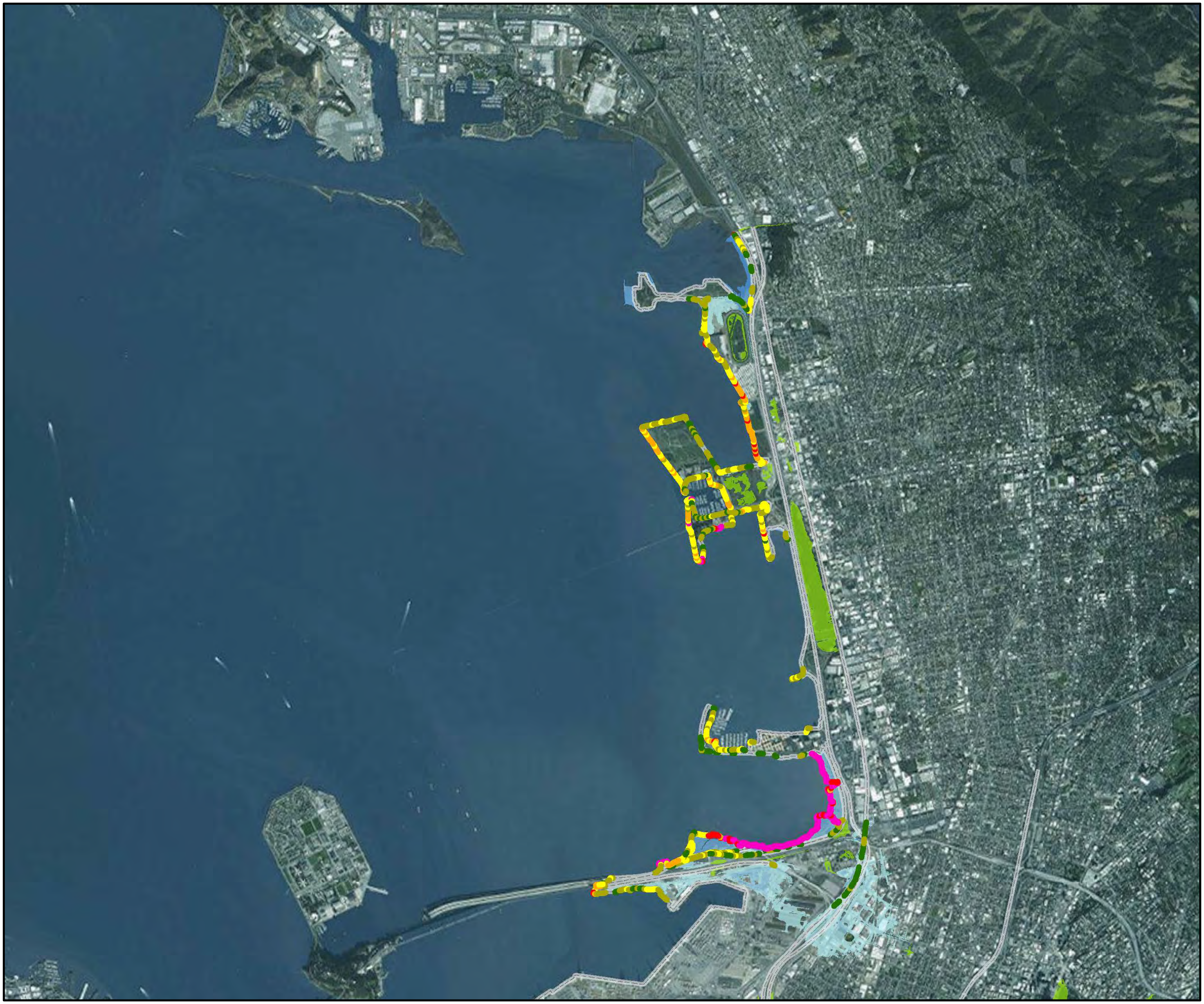
Projection:
California State Plane Zone III, North American Datum 1983

AECOM

April 2015





ALAMEDA COUNTY
Inundation Mapping

MHHW + 48” Sea Level Rise
Shoreline Overtopping Potential

Depth in Feet

- .5 - 1
- 1 - 2
- 2 - 3
- 3 - 4
- 4 - 5
- > 5
- No Overtopping

Depth in Feet

- 0 - 2
- 2 - 4
- 4 - 6
- 6 - 8
- 8 - 10
- 10 - 12
- 12 - 14
- 14 - 16
- 16+
- Disconnected Areas > 1 Acre

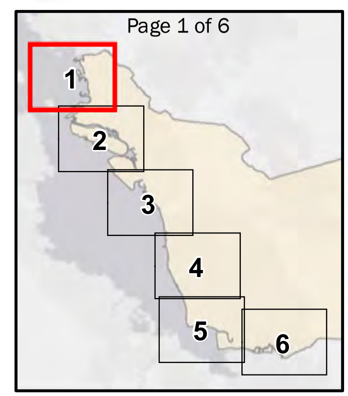
1 in = 20 Miles

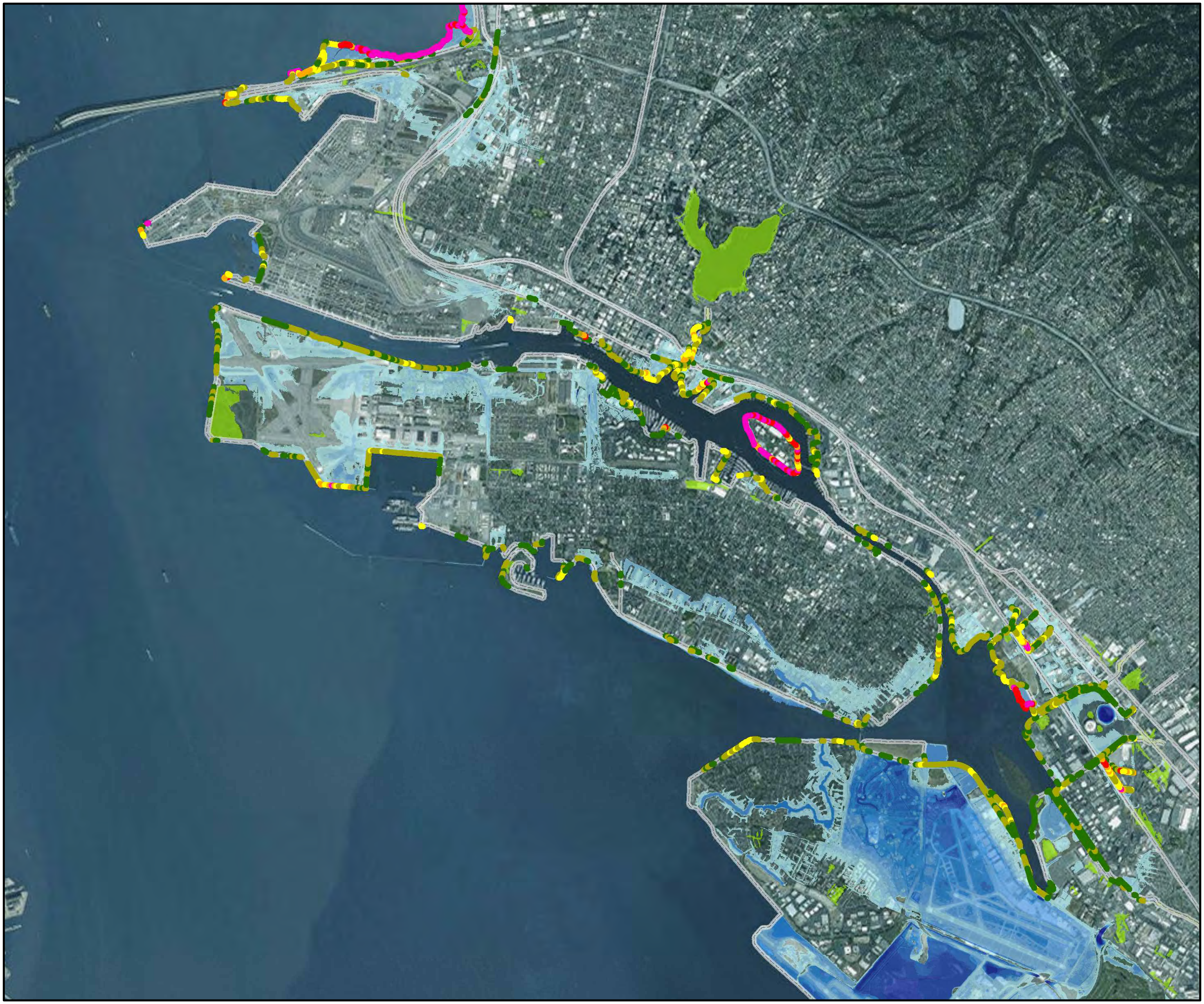
0 10 20

Projection:
California State Plane Zone III, North American Datum 1983

AECOM

April 2015





ALAMEDA COUNTY
Inundation Mapping

MHHW + 48” Sea Level Rise
Shoreline Overtopping Potential

Depth in Feet

- .5 - 1
- 1 - 2
- 2 - 3
- 3 - 4
- 4 - 5
- > 5
- No Overtopping

Depth in Feet

- 0 - 2
- 2 - 4
- 4 - 6
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- 8 - 10
- 10 - 12
- 12 - 14
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1 in = 20 Miles

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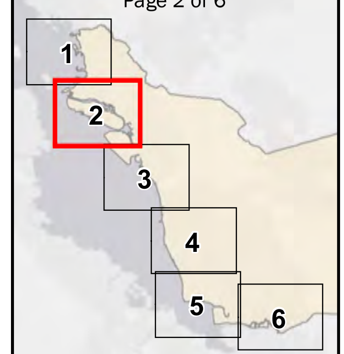
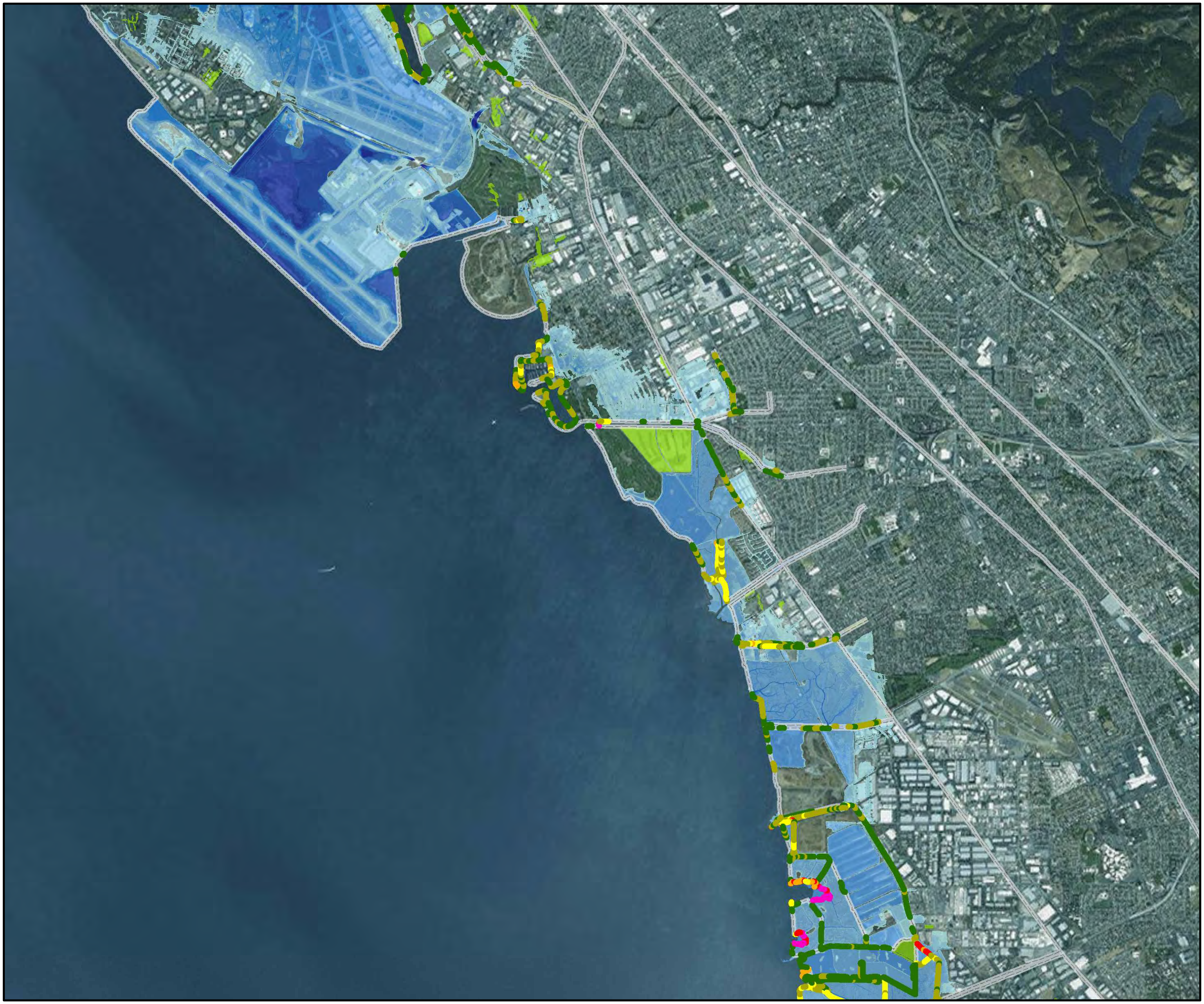
Projection:
California State Plane Zone III, North American Datum 1983

AECOM

April 2015



ALAMEDA COUNTY
Inundation Mapping



MHHW + 48" Sea Level Rise
Shoreline Overtopping Potential

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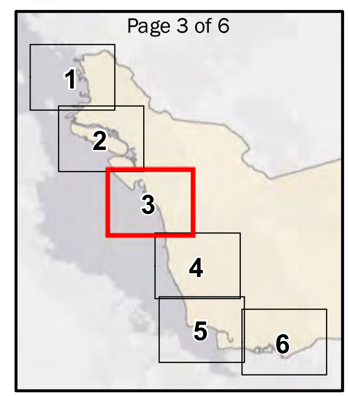
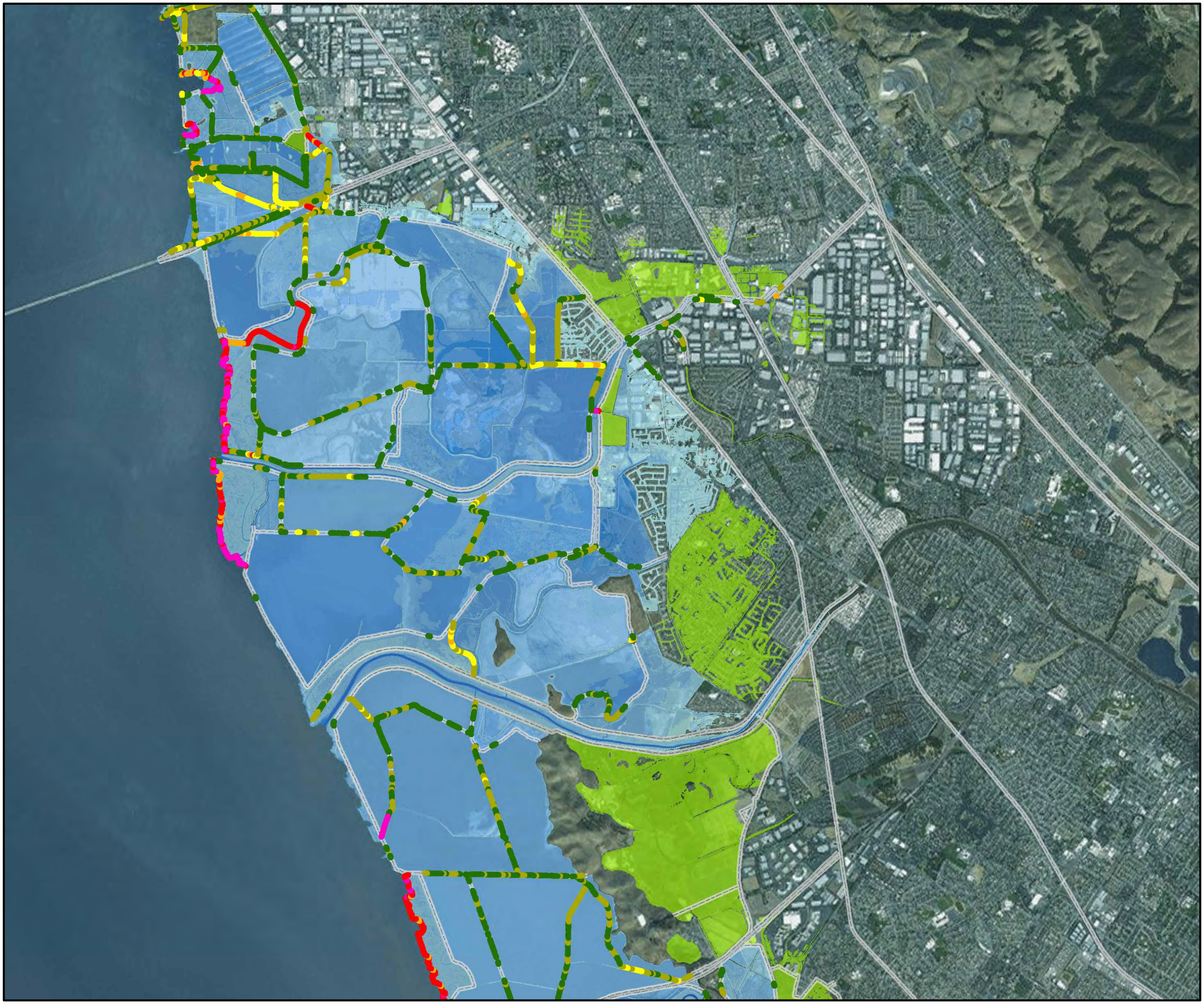
California State Plane Zone III, North American Datum 1983

AECOM

April 2015





ALAMEDA COUNTY
Inundation Mapping

MHHW + 48" Sea Level Rise
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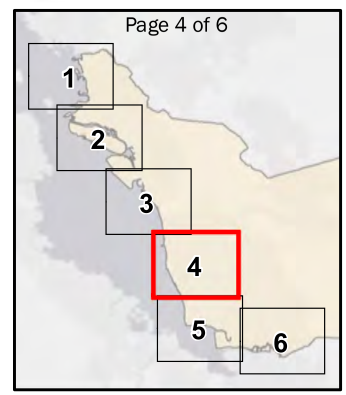
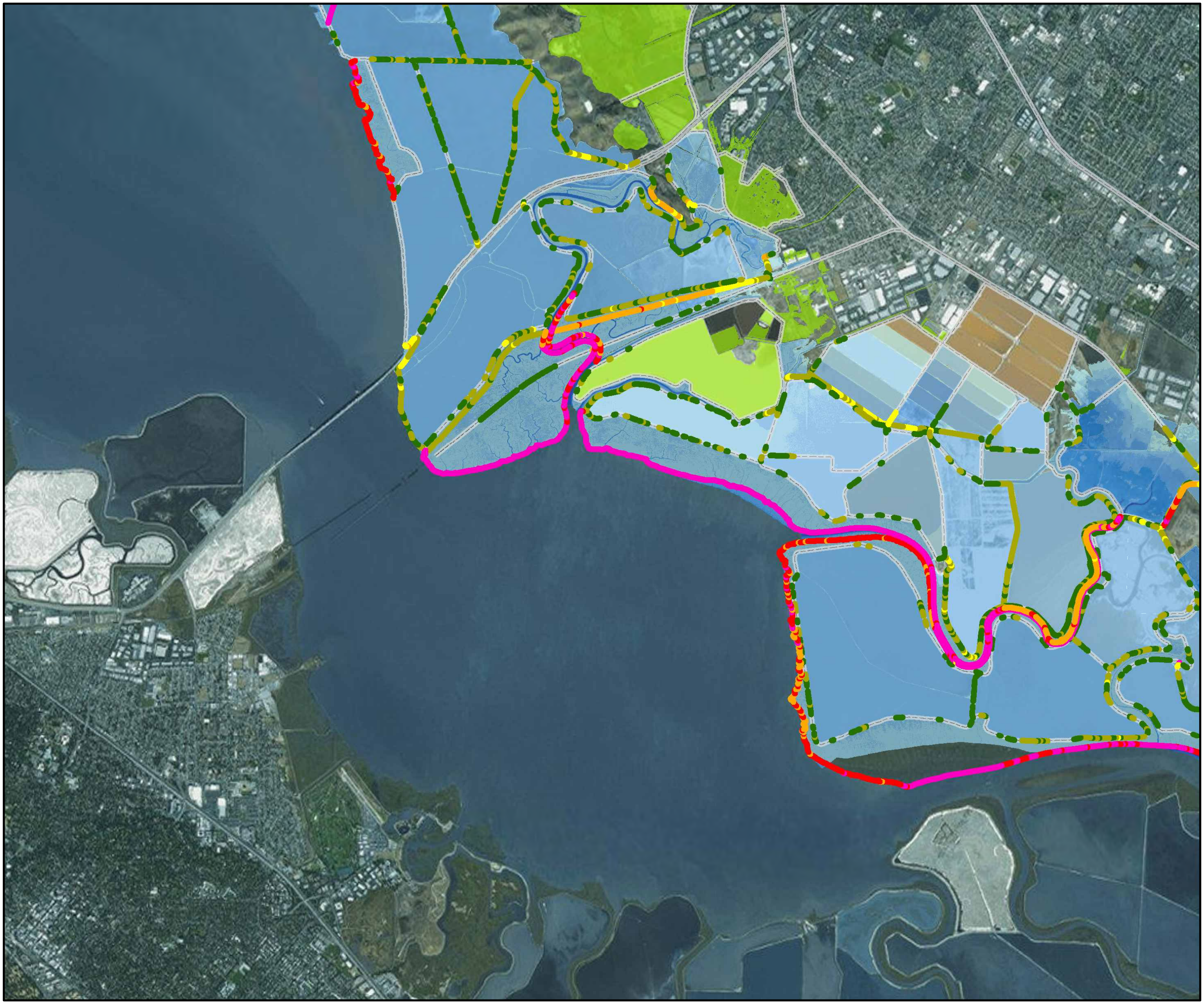
California State Plane Zone III, North American Datum 1983

AECOM April 2015





ALAMEDA COUNTY
Inundation Mapping

MHHW + 48" Sea Level Rise
Shoreline Overtopping Potential

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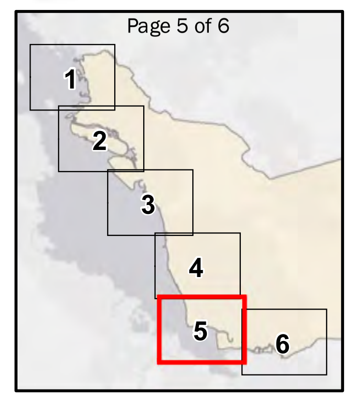
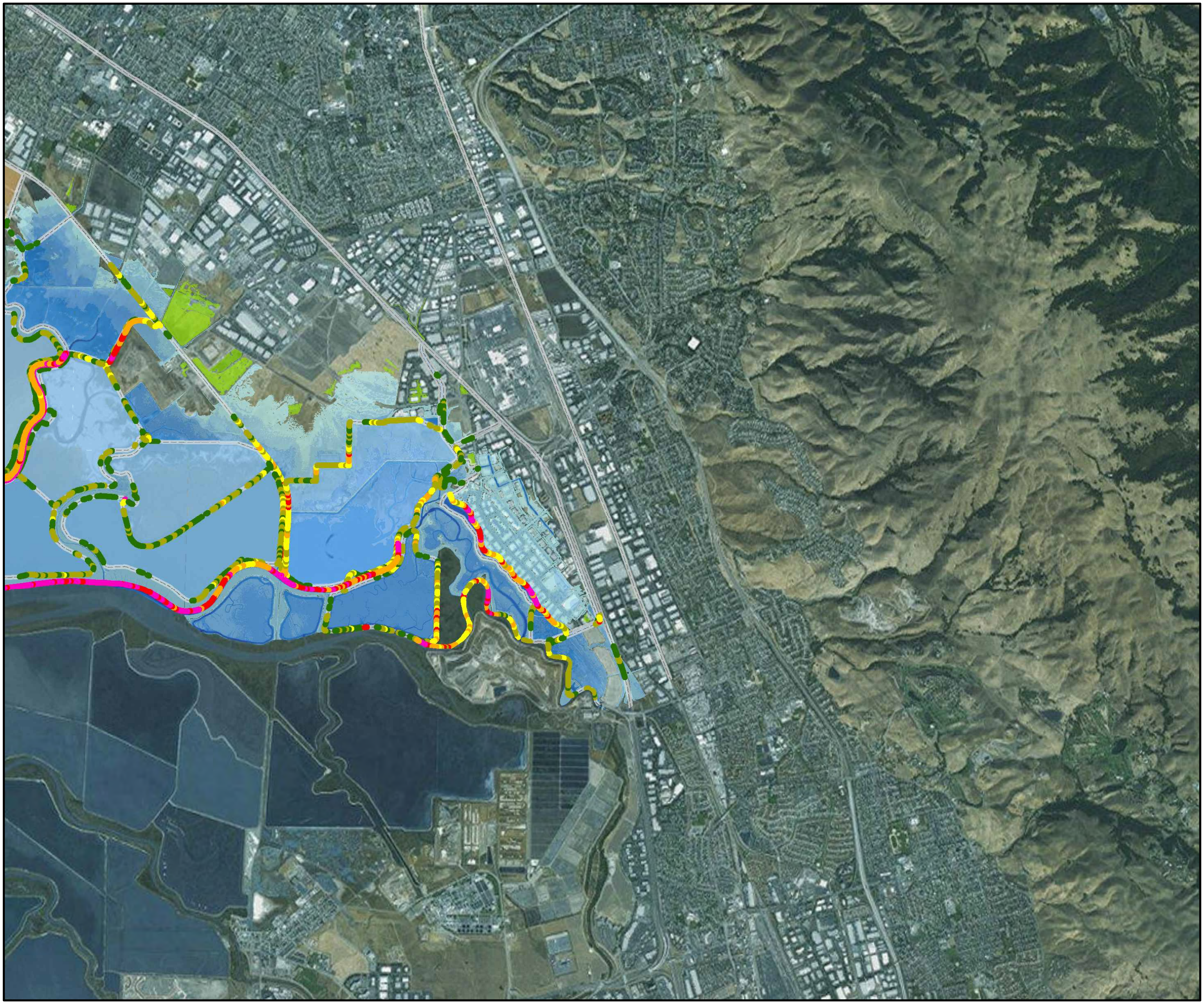
April 2015





ALAMEDA COUNTY
Inundation Mapping

MHHW + 48” Sea Level Rise
Shoreline Overtopping Potential

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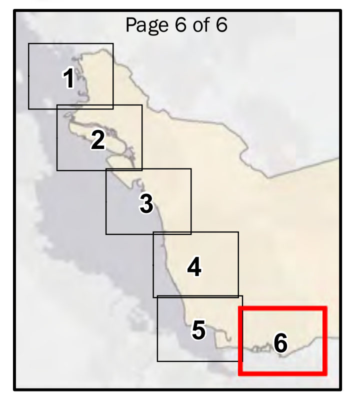
1 in = 20 Miles

0 10 20

Projection:
California State Plane Zone III, North American Datum 1983

AECOM

April 2015



ALAMEDA COUNTY
Inundation Mapping

MHHW + 72" Sea Level Rise
Shoreline Overtopping Potential

Depth in Feet

- .5 - 1
- 1 - 2
- 2 - 3
- 3 - 4
- 4 - 5
- > 5
- No Overtopping

Depth in Feet

- 0 - 2
- 2 - 4
- 4 - 6
- 6 - 8
- 8 - 10
- 10 - 12
- 12 - 14
- 14 - 16
- 16+
- Disconnected Areas > 1 Acre

N

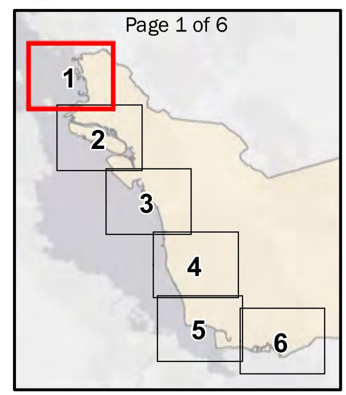
1 in = 20 Miles

0 10 20

Projection:
California State Plane Zone III, North American Datum 1983

AECOM

April 2015



ALAMEDA COUNTY
Inundation Mapping

MHHW + 72" Sea Level Rise
Shoreline Overtopping Potential

Depth in Feet

- .5 - 1
- 1 - 2
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- 3 - 4
- 4 - 5
- > 5
- No Overtopping

Depth in Feet

- 0 - 2
- 2 - 4
- 4 - 6
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- 10 - 12
- 12 - 14
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- 16+
- Disconnected Areas > 1 Acre

N

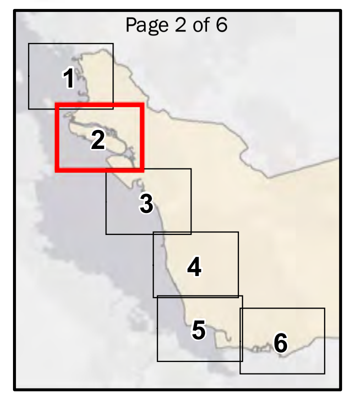
1 in = 20 Miles

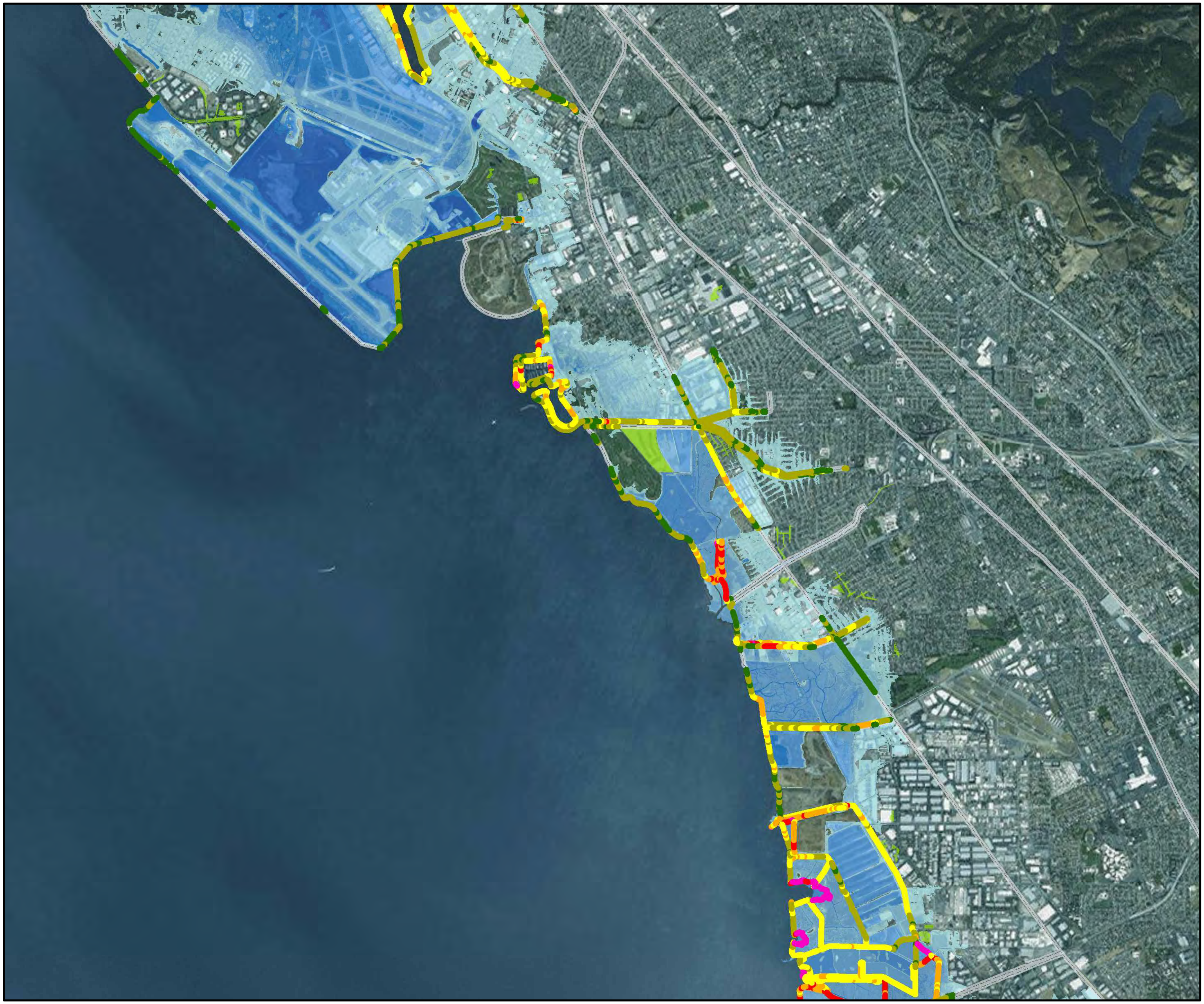
0 10 20

Projection:
California State Plane Zone III, North American Datum 1983

AECOM

April 2015





ALAMEDA COUNTY
Inundation Mapping

MHHW + 72” Sea Level Rise
Shoreline Overtopping Potential

Depth in Feet
- .5 - 1
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1 in = 20 Miles

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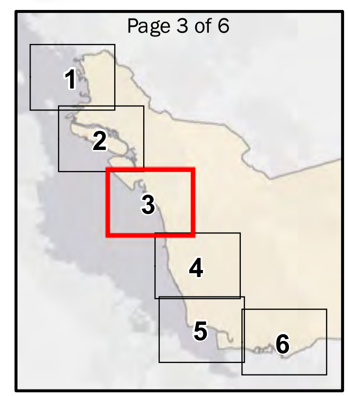
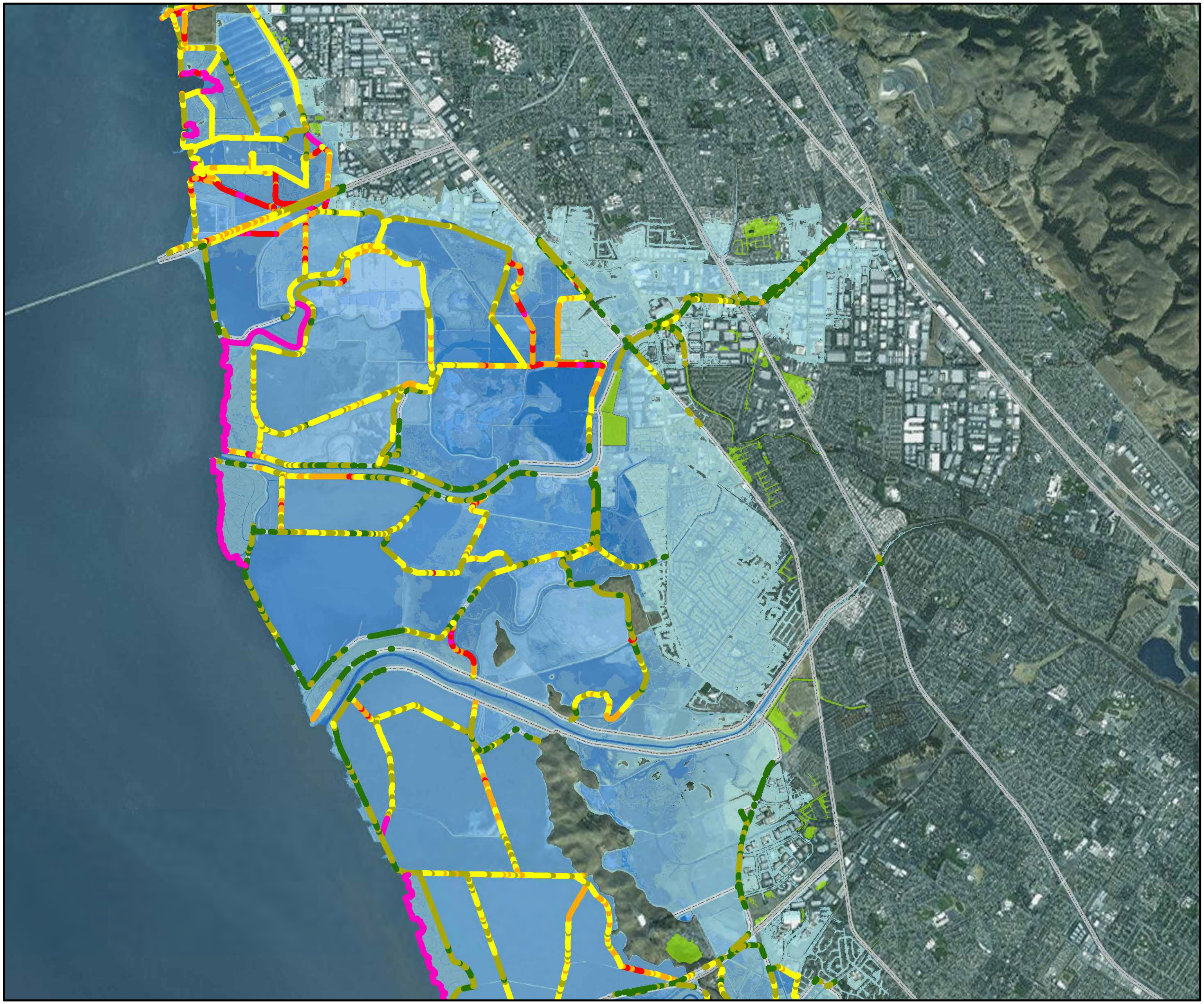
Projection:
California State Plane Zone III, North American Datum 1983

AECOM

April 2015





ALAMEDA COUNTY
Inundation Mapping

MHHW + 72" Sea Level Rise
Shoreline Overtopping Potential

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- 4 - 6
- 6 - 8
- 8 - 10
- 10 - 12
- 12 - 14
- 14 - 16
- 16+
- Disconnected Areas > 1 Acre

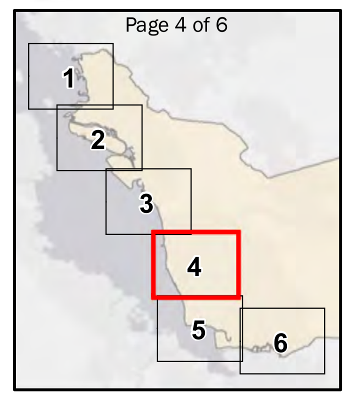
1 in = 20 Miles

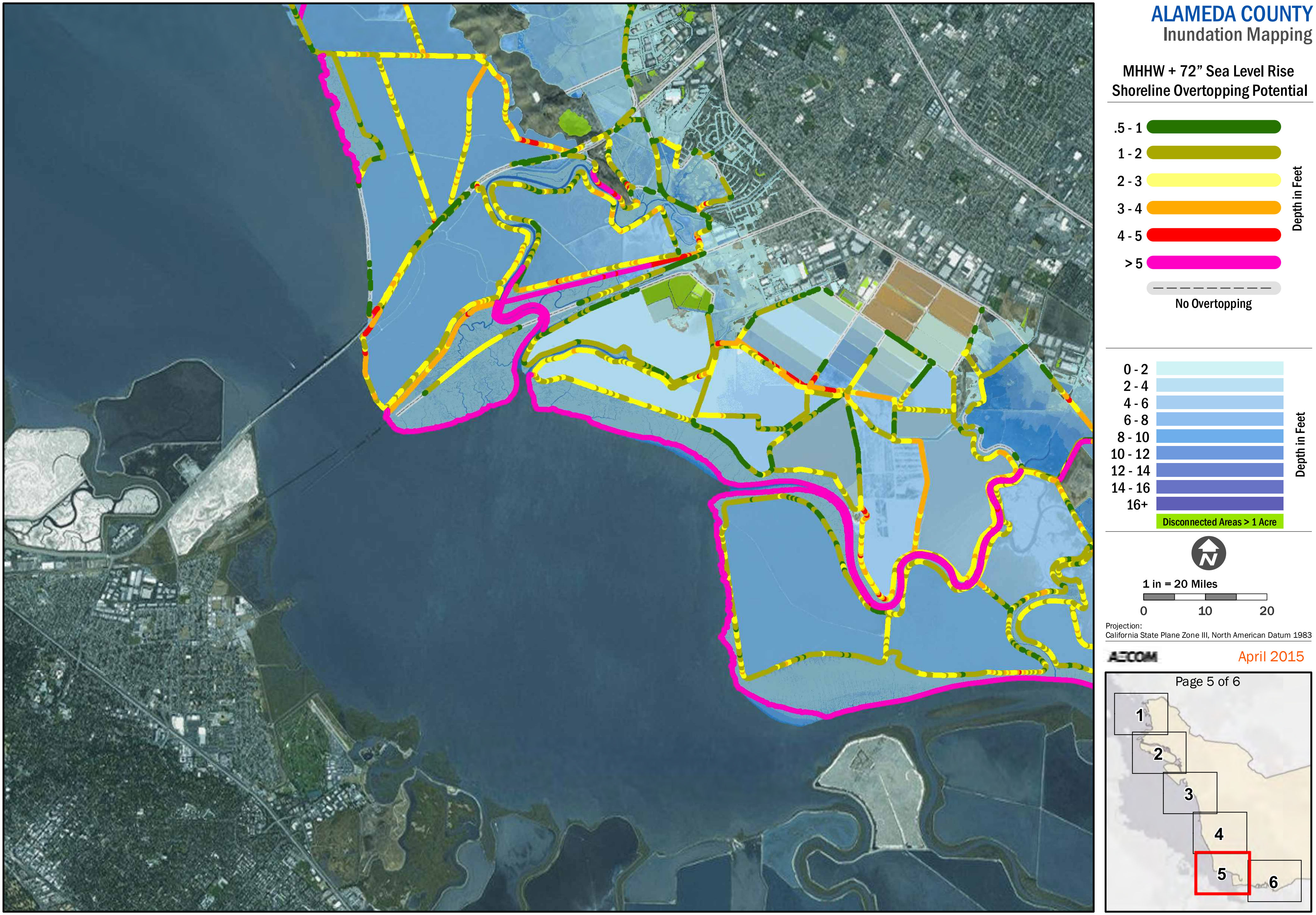
0 10 20

Projection:
California State Plane Zone III, North American Datum 1983

AECOM

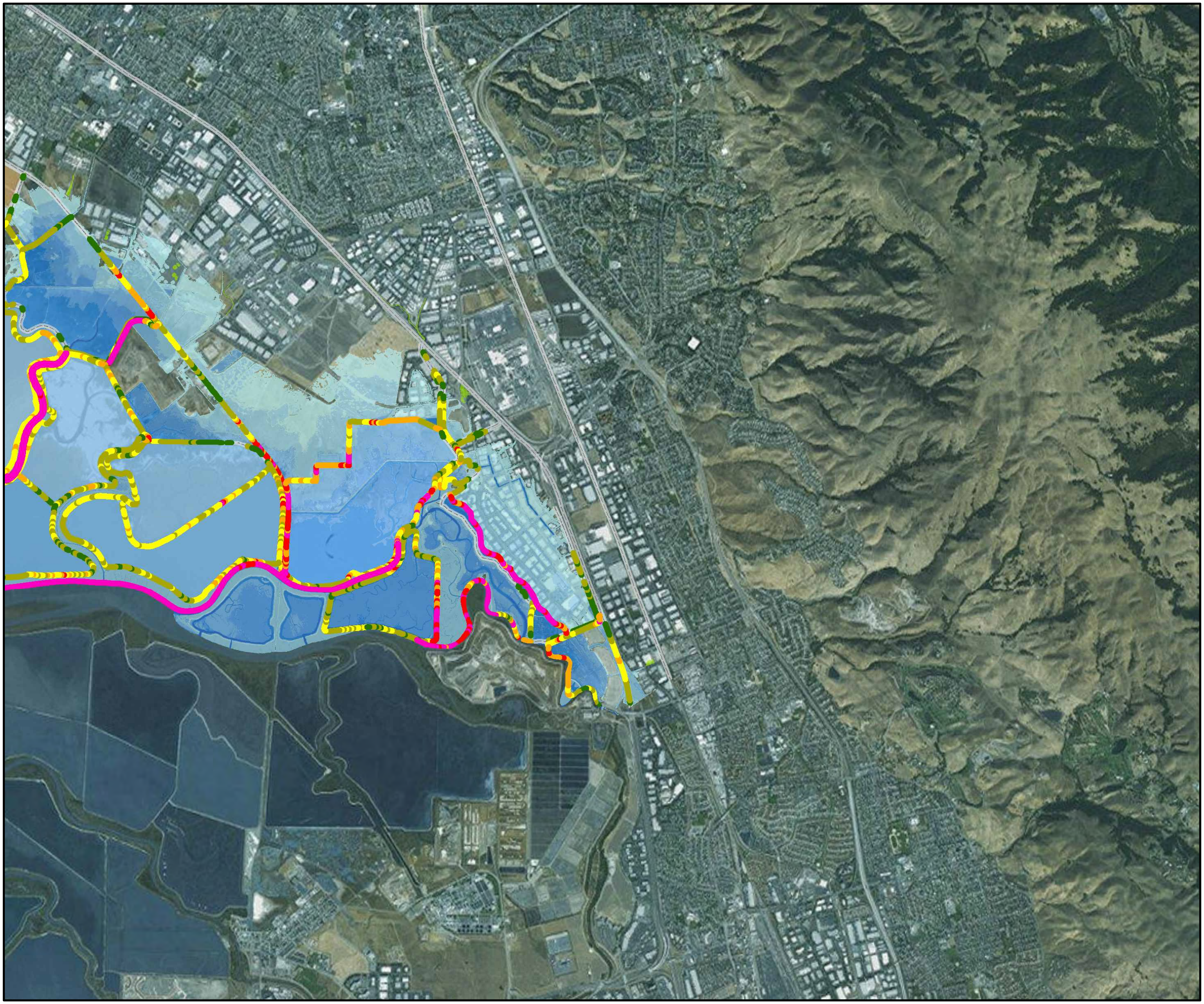
April 2015





ALAMEDA COUNTY
Inundation Mapping
MHHW + 72” Sea Level Rise
Shoreline Overtopping Potential
.5 - 1
1 - 2
2 - 3
3 - 4
4 - 5
> 5
Depth in Feet
No Overtopping
0 - 2
2 - 4
4 - 6
6 - 8
8 - 10
10 - 12
12 - 14
14 - 16
16+
Depth in Feet
Disconnected Areas > 1 Acre
N
1 in = 20 Miles
0
10
20
Projection:
California State Plane Zone III, North American Datum 1983
AECOM
April 2015
Page 5 of 6
1
2
3
4
5
6

ALAMEDA COUNTY
Inundation Mapping



MHHW + 72" Sea Level Rise
Shoreline Overtopping Potential

Depth in Feet

- .5 - 1
- 1 - 2
- 2 - 3
- 3 - 4
- 4 - 5
- > 5
- No Overtopping

Depth in Feet

- 0 - 2
- 2 - 4
- 4 - 6
- 6 - 8
- 8 - 10
- 10 - 12
- 12 - 14
- 14 - 16
- 16+
- Disconnected Areas > 1 Acre

N

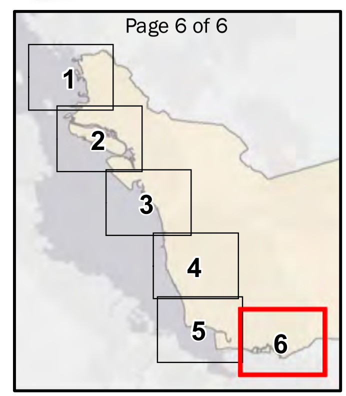
1 in = 20 Miles

0 10 20

Projection:
California State Plane Zone III, North American Datum 1983

AECOM

April 2015



ALAMEDA COUNTY
Inundation Mapping

MHHW + 96” Sea Level Rise
Shoreline Overtopping Potential

Depth in Feet

- .5 - 1
- 1 - 2
- 2 - 3
- 3 - 4
- 4 - 5
- > 5
- No Overtopping

Depth in Feet

- 0 - 2
- 2 - 4
- 4 - 6
- 6 - 8
- 8 - 10
- 10 - 12
- 12 - 14
- 14 - 16
- 16+
- Disconnected Areas > 1 Acre

N

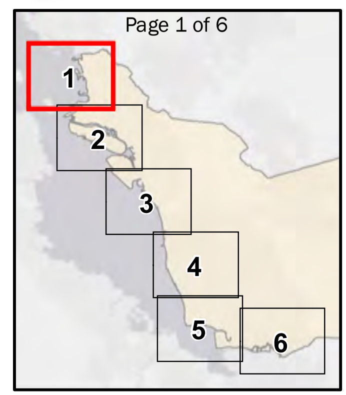
1 in = 20 Miles

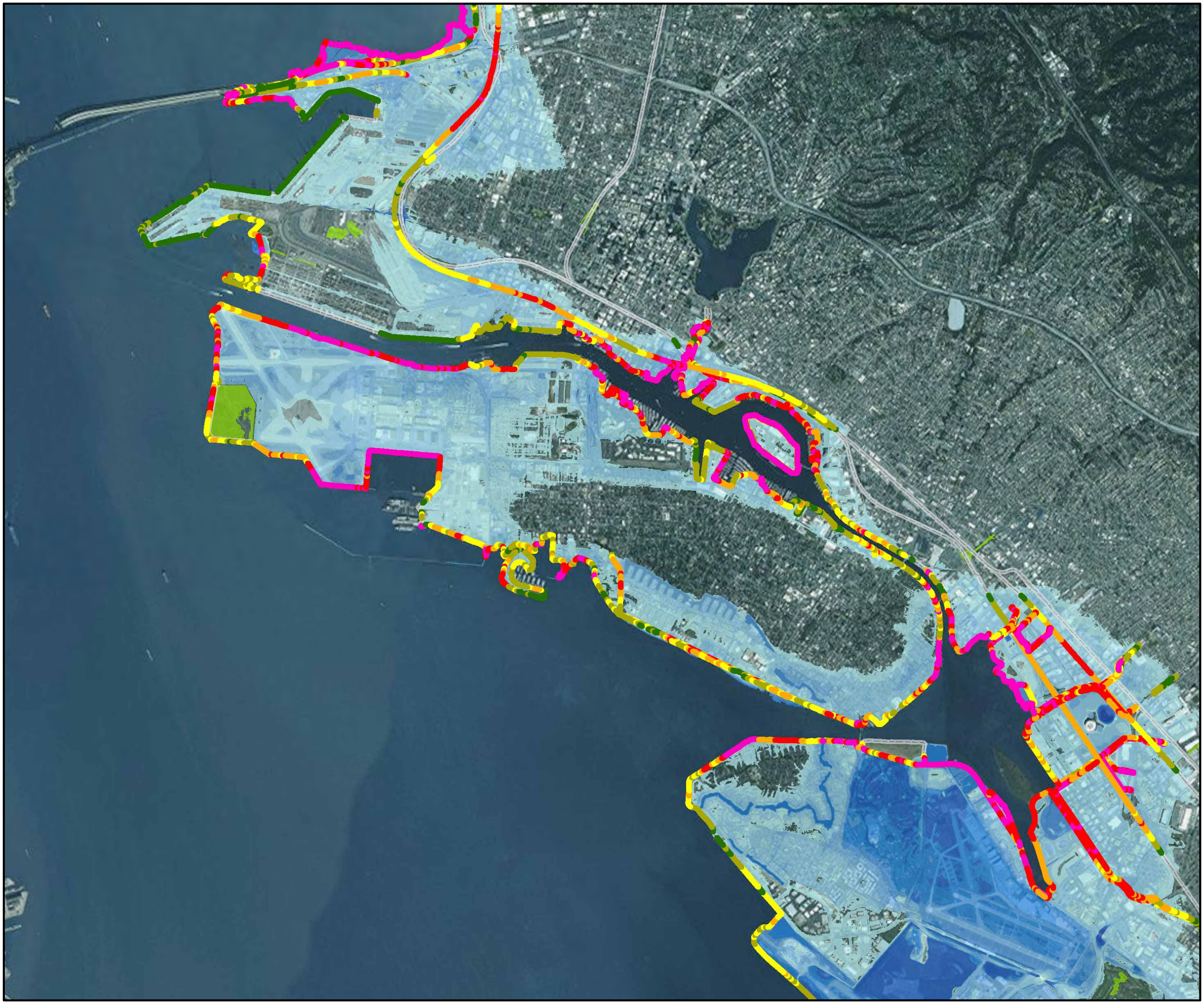
0 10 20

Projection:
California State Plane Zone III, North American Datum 1983

AECOM

April 2015





ALAMEDA COUNTY
Inundation Mapping

MHHW + 96" Sea Level Rise
Shoreline Overtopping Potential

Depth in Feet

- .5 - 1
- 1 - 2
- 2 - 3
- 3 - 4
- 4 - 5
- > 5
- No Overtopping

Depth in Feet

- 0 - 2
- 2 - 4
- 4 - 6
- 6 - 8
- 8 - 10
- 10 - 12
- 12 - 14
- 14 - 16
- 16+
- Disconnected Areas > 1 Acre

N

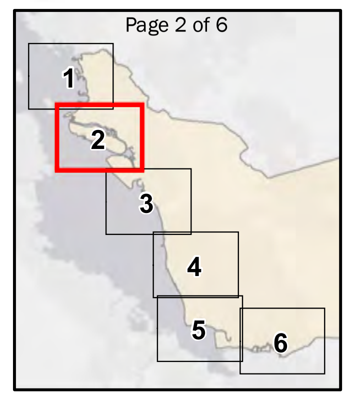
1 in = 20 Miles

0 10 20

Projection:
California State Plane Zone III, North American Datum 1983

AECOM

April 2015



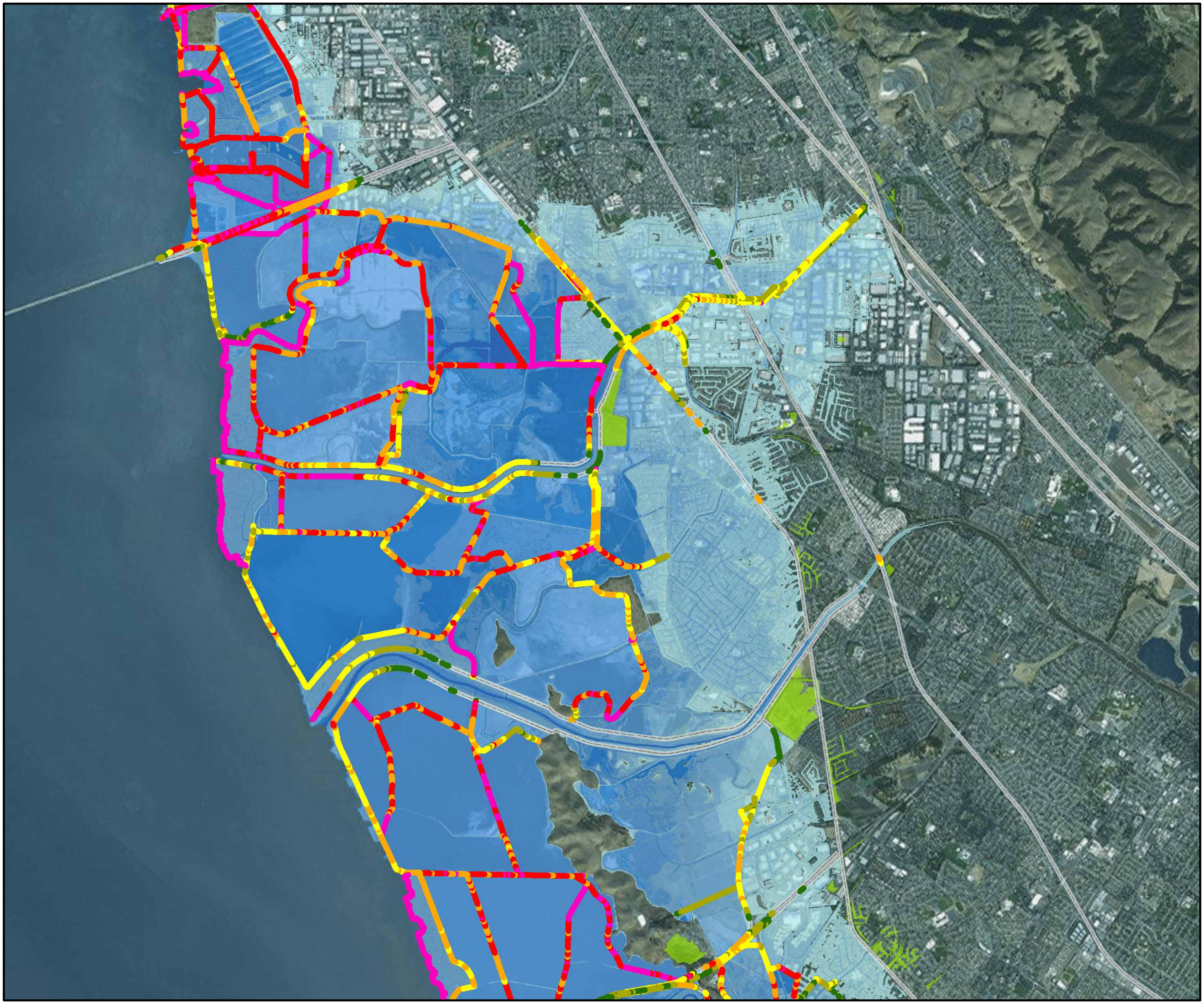
ALAMEDA COUNTY
Inundation Mapping

MHHW + 96" Sea Level Rise
Shoreline Overtopping Potential

Projection:
California State Plane Zone III, North American Datum 1983

AECOM

April 2015



ALAMEDA COUNTY
Inundation Mapping

MHHW + 96" Sea Level Rise
Shoreline Overtopping Potential

Depth in Feet
- .5 - 1
- 1 - 2
- 2 - 3
- 3 - 4
- 4 - 5
- > 5
- No Overtopping

Depth in Feet
- 0 - 2
- 2 - 4
- 4 - 6
- 6 - 8
- 8 - 10
- 10 - 12
- 12 - 14
- 14 - 16
- 16+
- Disconnected Areas > 1 Acre

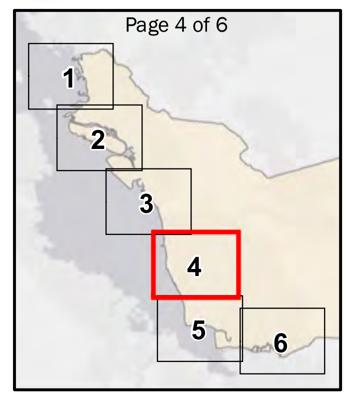
N

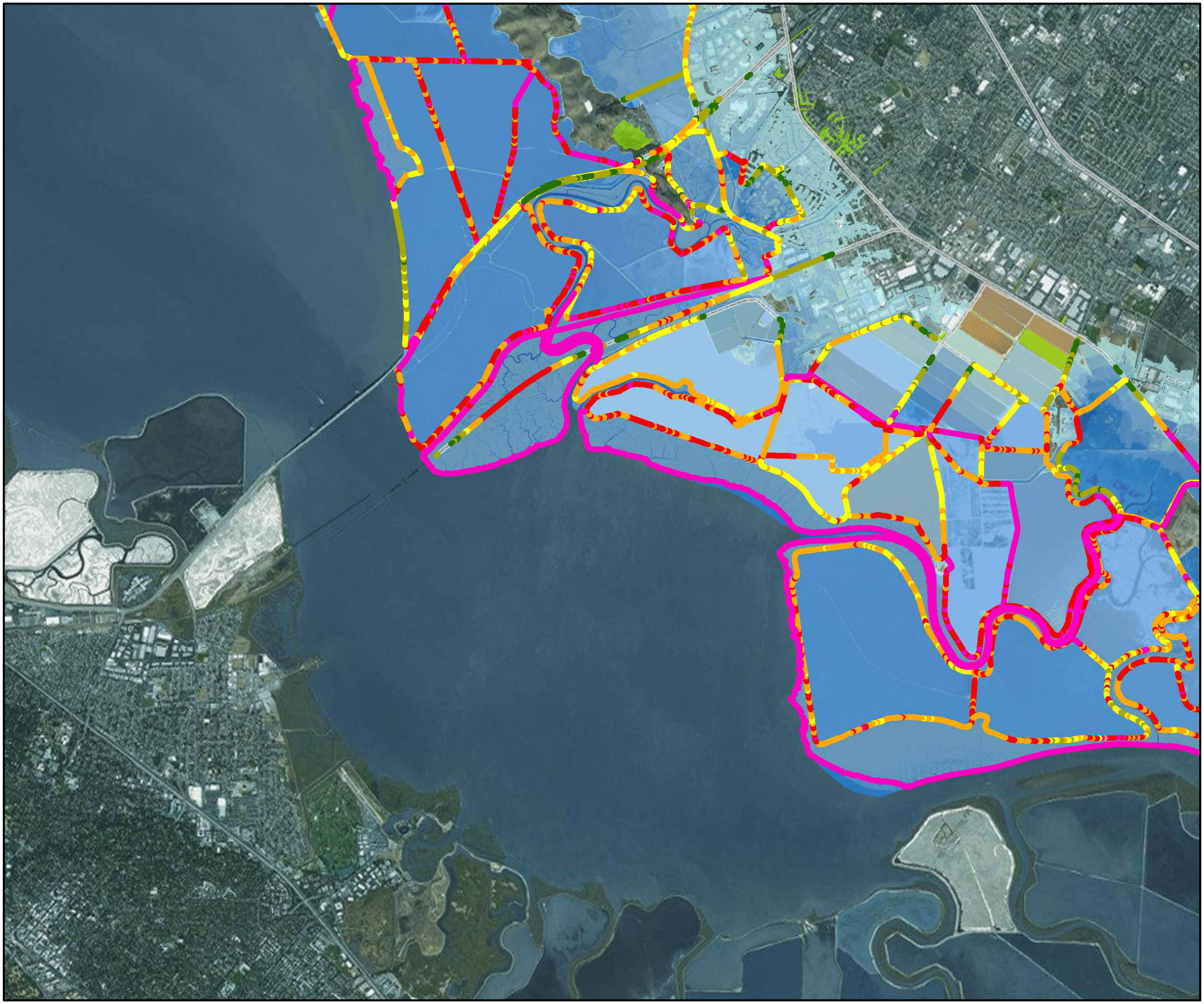
1 in = 20 Miles
0 10 20

Projection:
California State Plane Zone III, North American Datum 1983

AECOM

April 2015





ALAMEDA COUNTY
Inundation Mapping

MHHW + 96" Sea Level Rise
Shoreline Overtopping Potential

Depth in Feet

- .5 - 1
- 1 - 2
- 2 - 3
- 3 - 4
- 4 - 5
- > 5
- No Overtopping

Depth in Feet

- 0 - 2
- 2 - 4
- 4 - 6
- 6 - 8
- 8 - 10
- 10 - 12
- 12 - 14
- 14 - 16
- 16+
- Disconnected Areas > 1 Acre

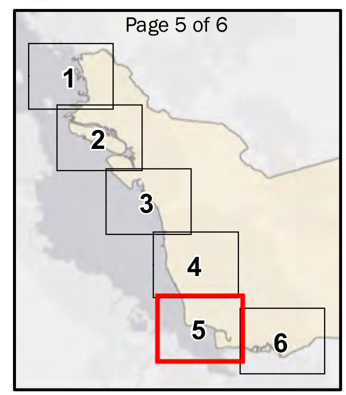
N

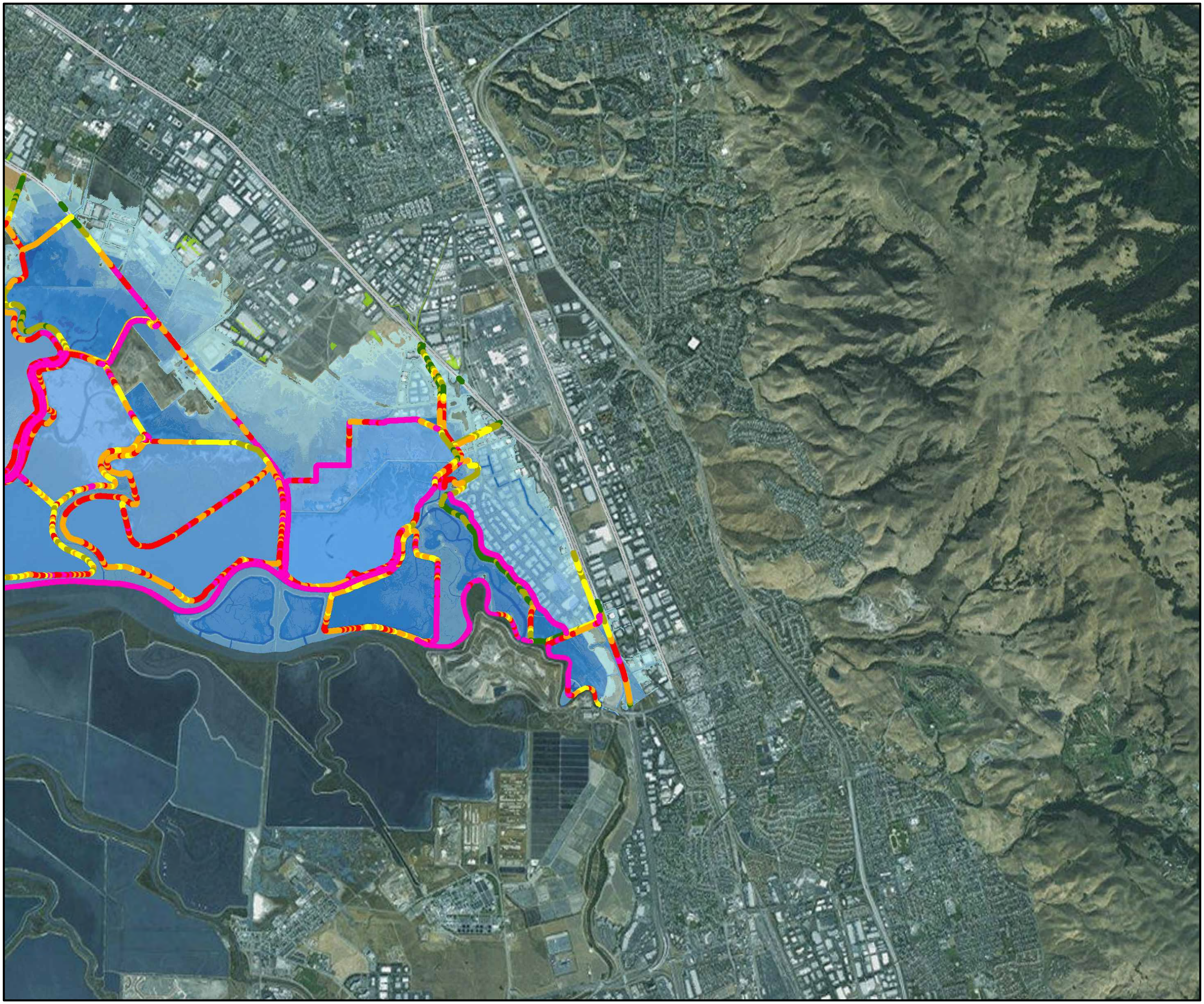
1 in = 20 Miles
0 10 20

Projection:
California State Plane Zone III, North American Datum 1983

AECOM

April 2015





ALAMEDA COUNTY
Inundation Mapping

MHHW + 96" Sea Level Rise
Shoreline Overtopping Potential

Depth in Feet
- .5 - 1
- 1 - 2
- 2 - 3
- 3 - 4
- 4 - 5
- > 5
- No Overtopping

Depth in Feet
- 0 - 2
- 2 - 4
- 4 - 6
- 6 - 8
- 8 - 10
- 10 - 12
- 12 - 14
- 14 - 16
- 16+
- Disconnected Areas > 1 Acre

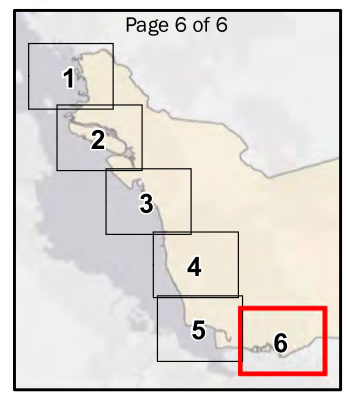
N

1 in = 20 Miles
0 10 20

Projection:
California State Plane Zone III, North American Datum 1983

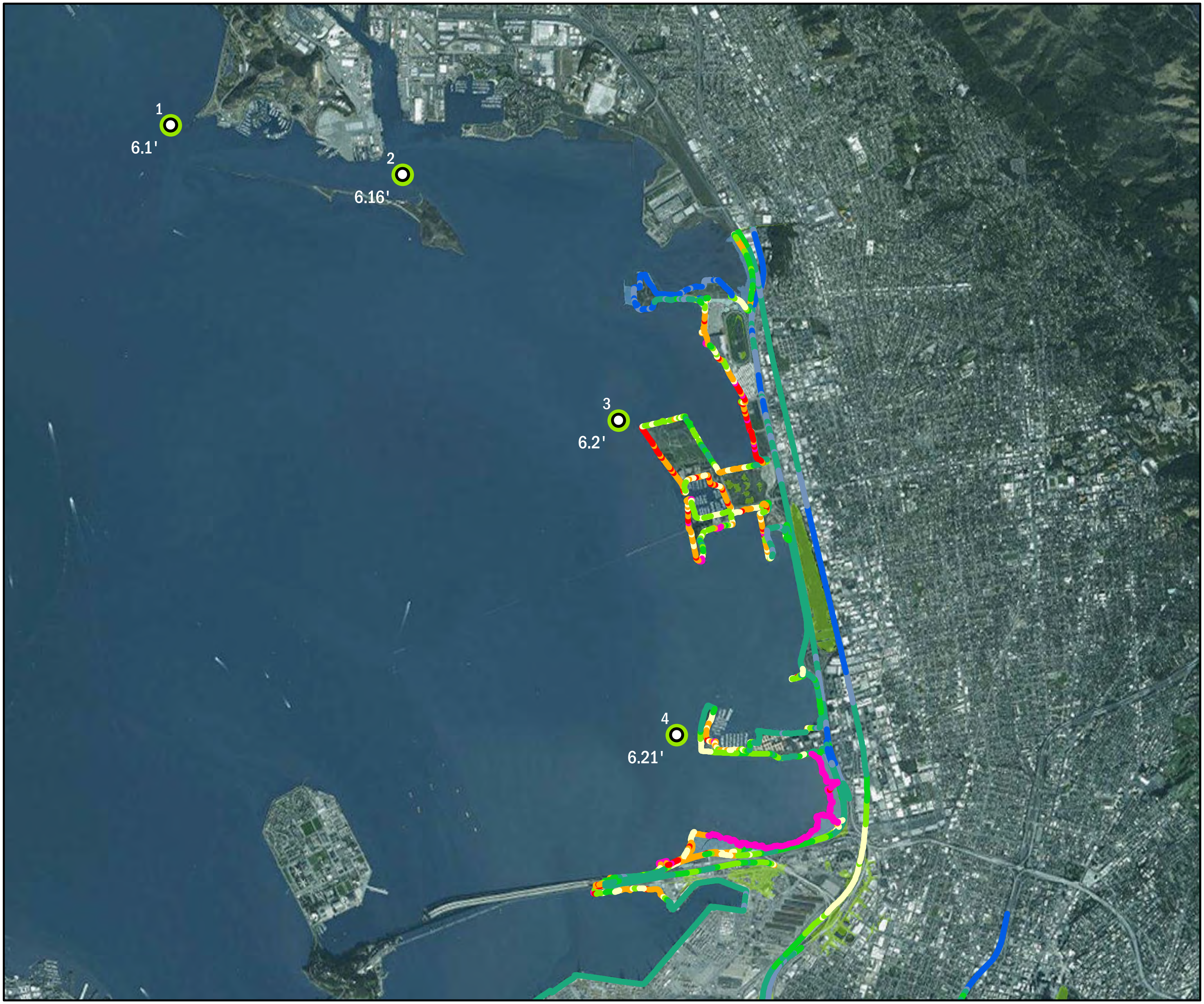
AECOM

April 2015



D

NORMALIZED SHORELINE ELEVATION MAPS



ALAMEDA COUNTY
Inundation Mapping

Normalized Elevation Relative to Mean Higher High Water Elevation / MHHW

- < 1.0
- 1.0 - 1.2
- 1.2 - 1.4
- 1.4 - 1.6
- 1.6 - 1.8
- 1.8 - 2.0
- 2.0 - 2.5
- 2.5 - 3.0
- > 3.0

Hydrodynamic Zone Locations

PT. ID
SLR Zone
1 2 3 4
MHHW '
(NAVD88)

MHHW + 36" Sea Level Rise

Depth in Feet

- 0 - 2
- 2 - 4
- 4 - 6
- 6 - 8
- 8 - 10
- 10 - 12
- 12 - 14
- 14 - 16
- 16+

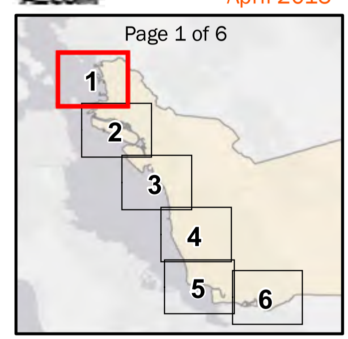
Disconnected Areas > 1 Acre

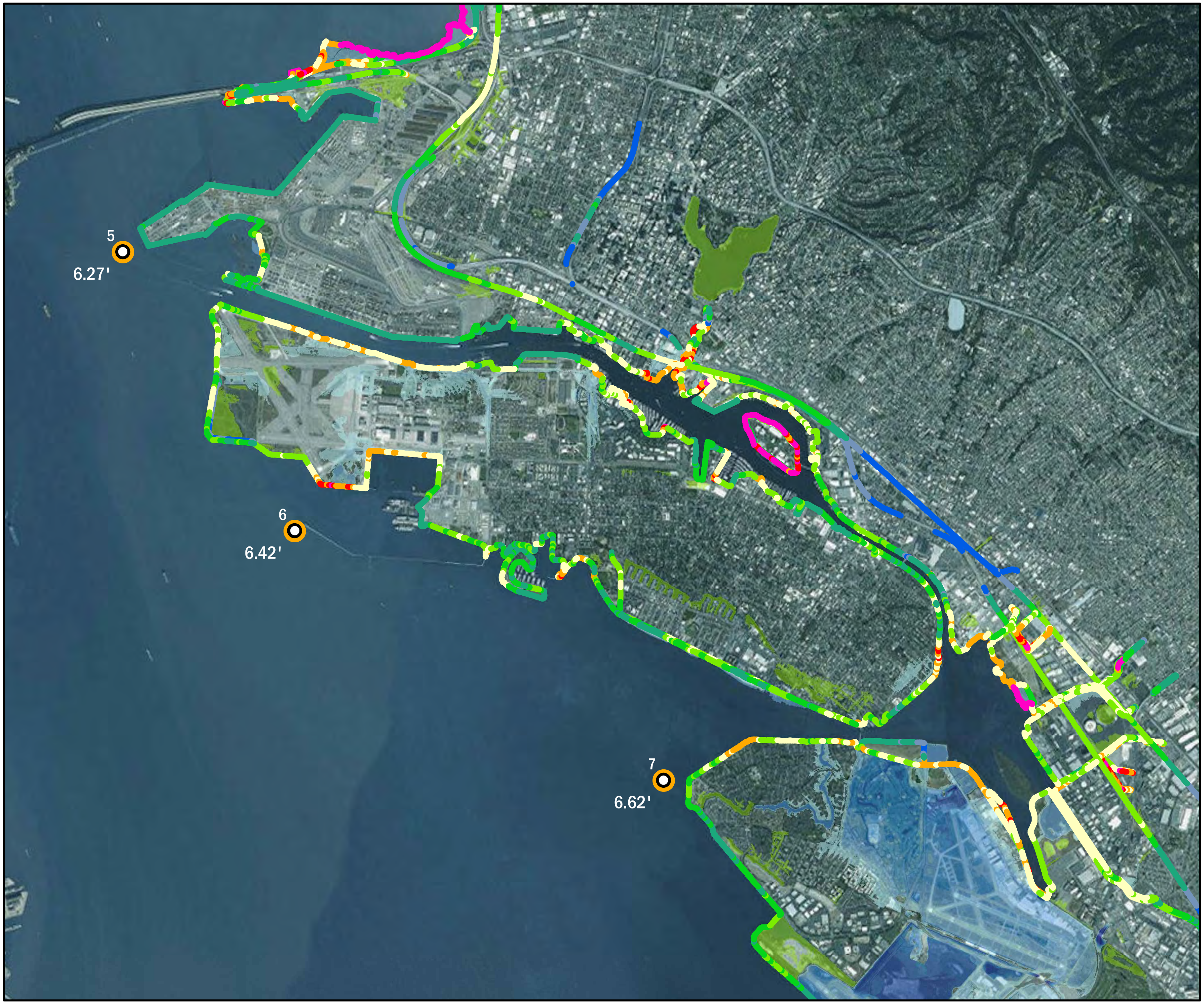
1 in = 20 Miles
0 10 20

Projection:
California State Plane Zone III, North American Datum 1983

AECOM

April 2015





ALAMEDA COUNTY
Inundation Mapping

Normalized Elevation Relative to Mean Higher High Water Elevation / MHHW

- < 1.0
- 1.0 - 1.2
- 1.2 - 1.4
- 1.4 - 1.6
- 1.6 - 1.8
- 1.8 - 2.0
- 2.0 - 2.5
- 2.5 - 3.0
- > 3.0

Hydrodynamic Zone Locations

PT. ID
MHHW ' (NAVD88)

SLR Zone
1 2 3 4

MHHW + 36" Sea Level Rise

Depth in Feet

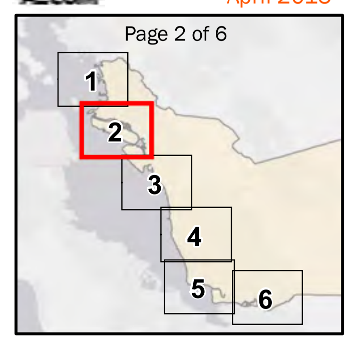
- 0 - 2
- 2 - 4
- 4 - 6
- 6 - 8
- 8 - 10
- 10 - 12
- 12 - 14
- 14 - 16
- 16+
- Disconnected Areas > 1 Acre

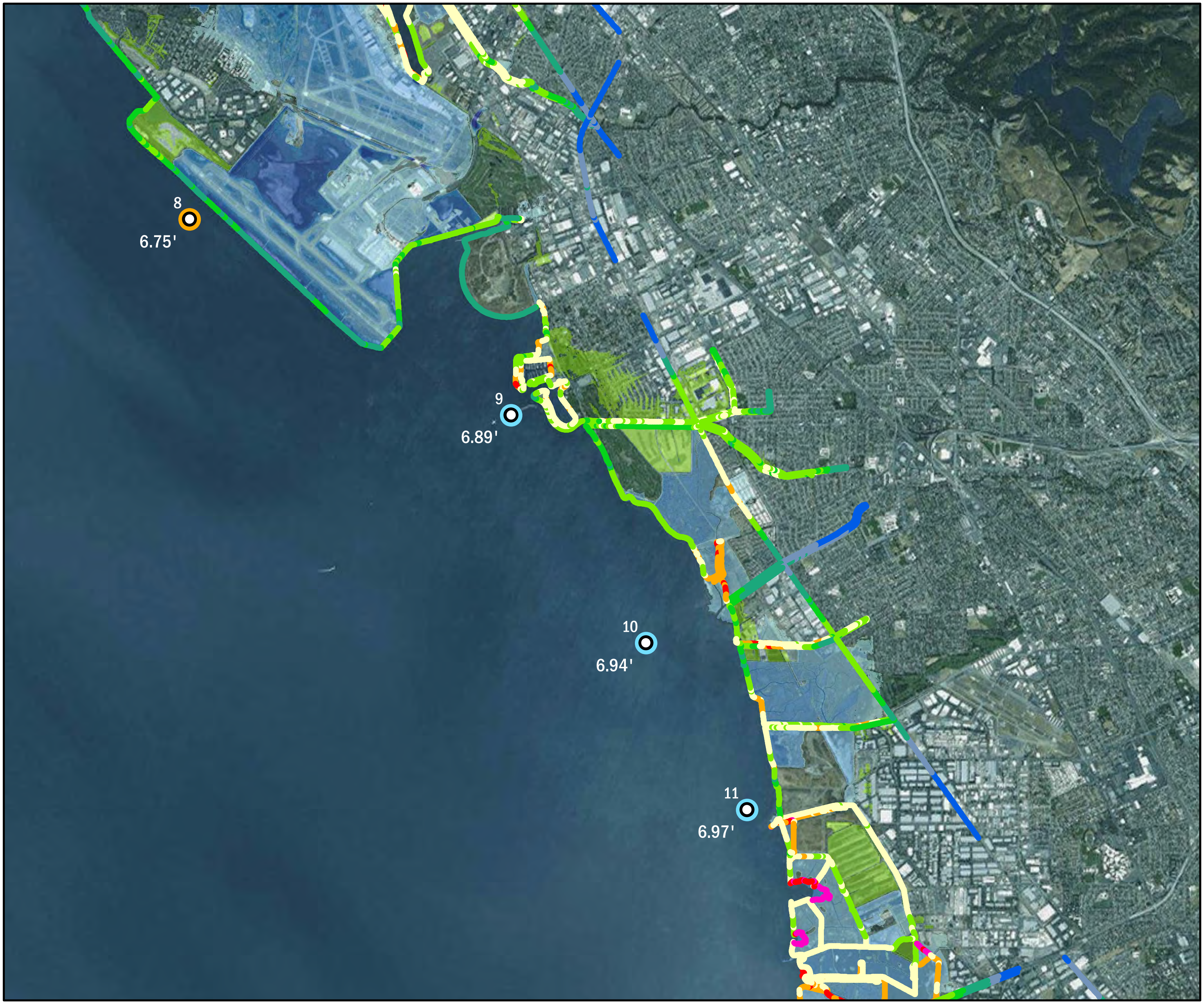
1 in = 20 Miles
0 10 20

Projection:
California State Plane Zone III, North American Datum 1983

AECOM

April 2015





ALAMEDA COUNTY
Inundation Mapping

Normalized Elevation Relative to Mean Higher High Water Elevation / MHHW

- < 1.0
- 1.0 - 1.2
- 1.2 - 1.4
- 1.4 - 1.6
- 1.6 - 1.8
- 1.8 - 2.0
- 2.0 - 2.5
- 2.5 - 3.0
- > 3.0

Hydrodynamic Zone Locations

PT. ID
MHHW ' (NAVD88)

SLR Zone: 1, 2, 3, 4

MHHW + 36" Sea Level Rise

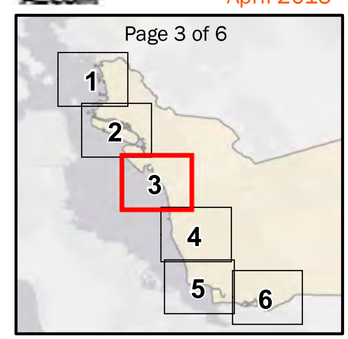
Depth in Feet
- 0 - 2
- 2 - 4
- 4 - 6
- 6 - 8
- 8 - 10
- 10 - 12
- 12 - 14
- 14 - 16
- 16+
- Disconnected Areas > 1 Acre

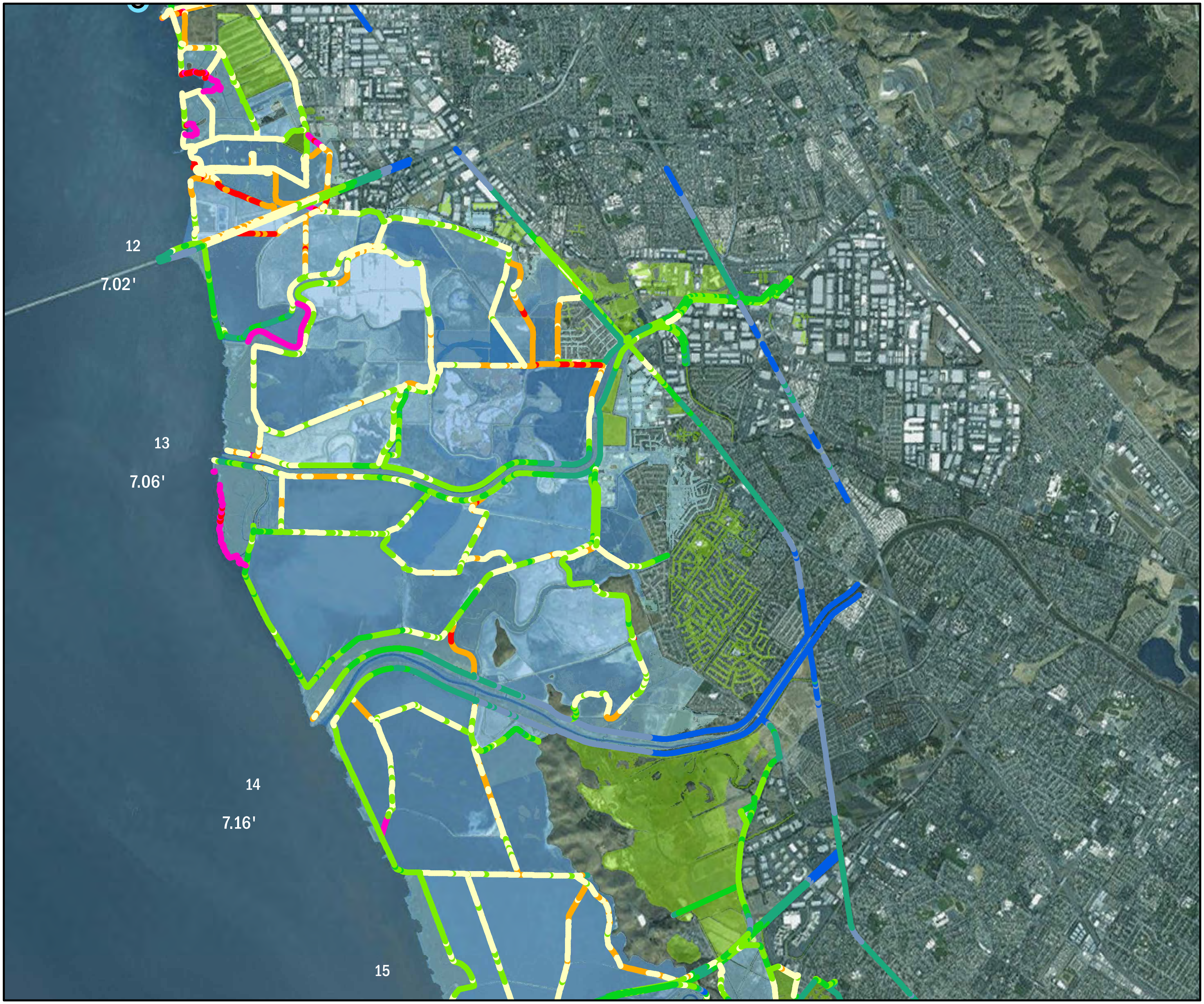
1 in = 20 Miles
0 10 20

Projection:
California State Plane Zone III, North American Datum 1983

AECOM

April 2015





ALAMEDA COUNTY
Inundation Mapping

Normalized Elevation Relative to Mean Higher High Water Elevation / MHHW

- < 1.0
- 1.0 - 1.2
- 1.2 - 1.4
- 1.4 - 1.6
- 1.6 - 1.8
- 1.8 - 2.0
- 2.0 - 2.5
- 2.5 - 3.0
- > 3.0

Hydrodynamic Zone Locations

PT. ID

SLR Zone: 1 2 3 4

MHHW ' (NAVD88)

MHHW + 36" Sea Level Rise

Depth in Feet

- 0 - 2
- 2 - 4
- 4 - 6
- 6 - 8
- 8 - 10
- 10 - 12
- 12 - 14
- 14 - 16
- 16+
- Disconnected Areas > 1 Acre

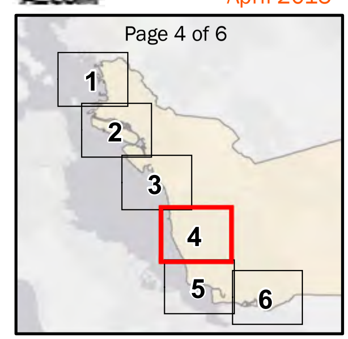
1 in = 20 Miles

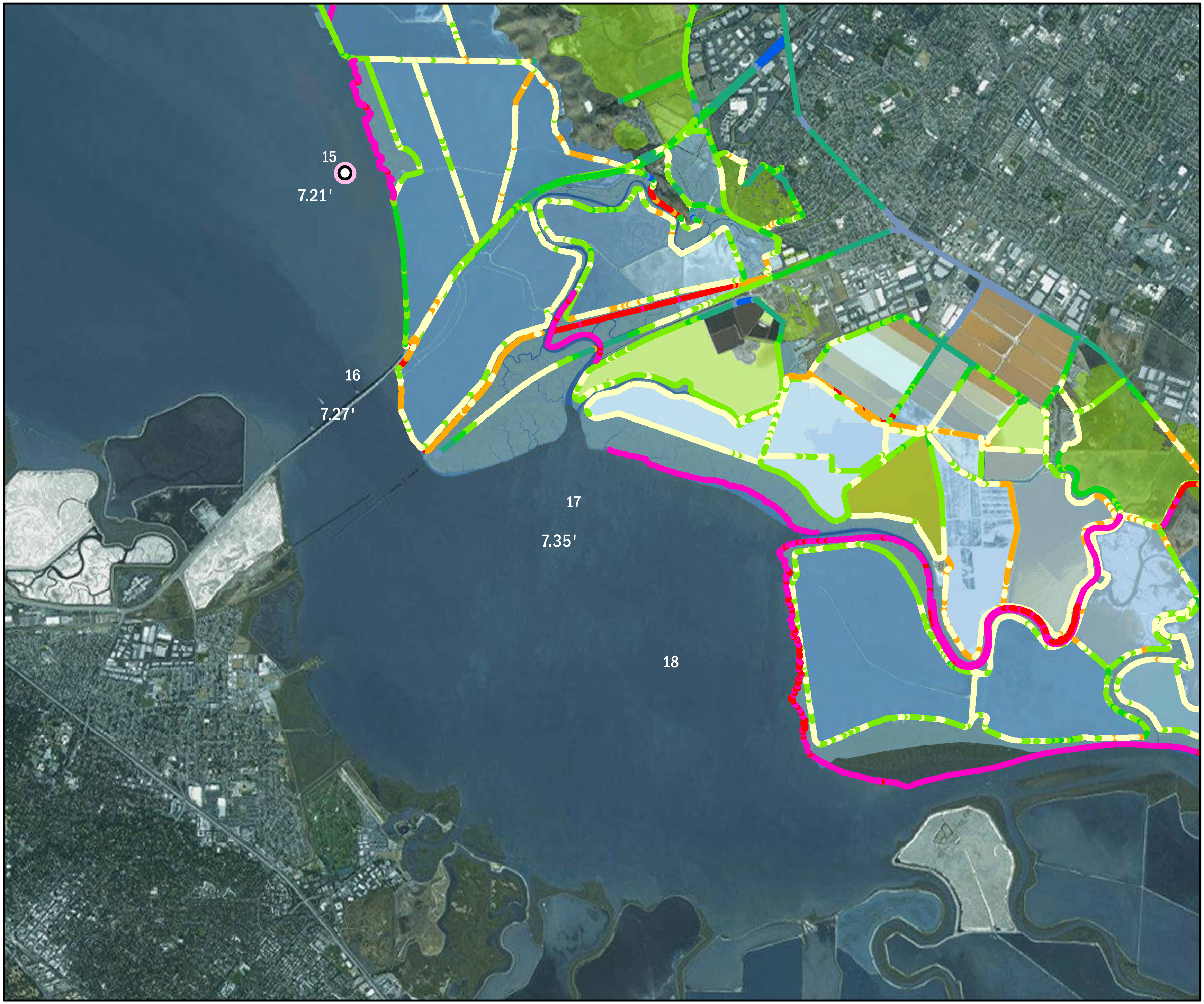
0 10 20

Projection:
California State Plane Zone III, North American Datum 1983

AECOM

April 2015





ALAMEDA COUNTY
Inundation Mapping

Normalized Elevation Relative to Mean Higher High Water Elevation / MHHW

- < 1.0
- 1.0 - 1.2
- 1.2 - 1.4
- 1.4 - 1.6
- 1.6 - 1.8
- 1.8 - 2.0
- 2.0 - 2.5
- 2.5 - 3.0
- > 3.0

Hydrodynamic Zone Locations

PT. ID
MHHW ' (NAVD88)

SLR Zone: 1 2 3 4

MHHW + 36" Sea Level Rise

Depth in Feet

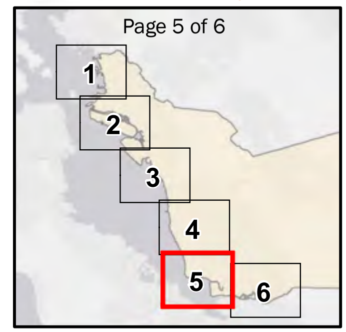
- 0 - 2
- 2 - 4
- 4 - 6
- 6 - 8
- 8 - 10
- 10 - 12
- 12 - 14
- 14 - 16
- 16+
- Disconnected Areas > 1 Acre

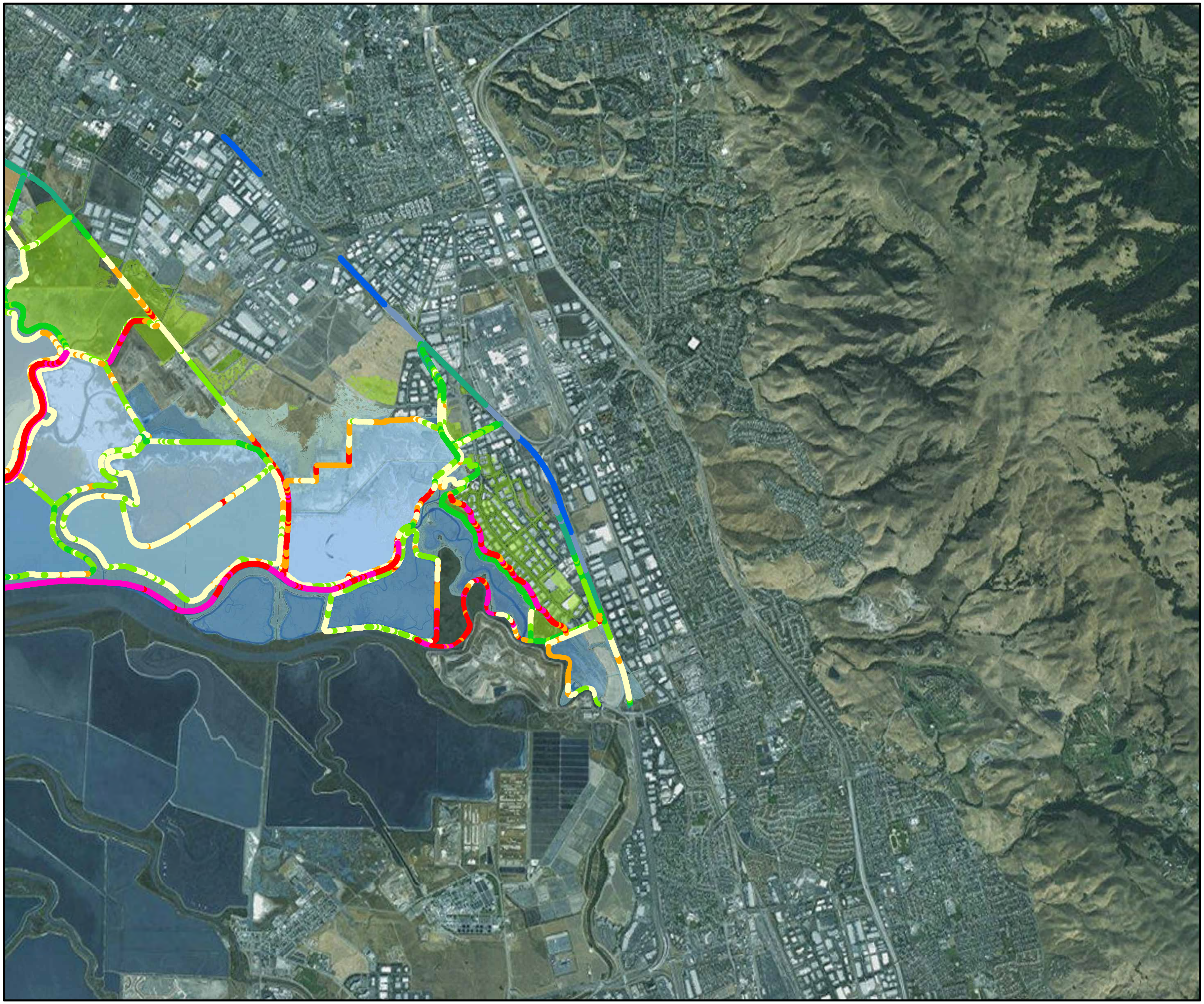
1 in = 20 Miles
0 10 20

Projection:
California State Plane Zone III, North American Datum 1983

AECOM

April 2015





ALAMEDA COUNTY
Inundation Mapping

Normalized Elevation Relative to Mean Higher High Water Elevation / MHHW

- < 1.0
- 1.0 - 1.2
- 1.2 - 1.4
- 1.4 - 1.6
- 1.6 - 1.8
- 1.8 - 2.0
- 2.0 - 2.5
- 2.5 - 3.0
- > 3.0

Hydrodynamic Zone Locations

PT. ID
MHHW '
(NAVD88)

SLR Zone
1 2 3 4

MHHW + 36" Sea Level Rise

Depth in Feet
- 0 - 2
- 2 - 4
- 4 - 6
- 6 - 8
- 8 - 10
- 10 - 12
- 12 - 14
- 14 - 16
- 16+

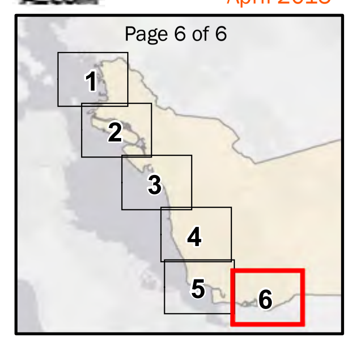
Disconnected Areas > 1 Acre

1 in = 20 Miles
0 10 20

Projection:
California State Plane Zone III, North American Datum 1983

AECOM

April 2015



E

GIS DATABASE CATALOG

E-1. GIS DATABASE CATALOG

This appendix describes the GIS datasets produced for the Alameda County shoreline vulnerability assessment. Metadata is included in .xml format, which is viewable (and exportable) in ArcGIS.

- Coordinate System: State Plane California III FIPS 0403 Feet
- Horizontal Datum: North American Datum 1983 (NAD83)
- Vertical Datum: North American Vertical Datum of 1988 (NAVD88)

The entire GIS Database produced for the sea level rise inundation and overtopping analysis is contained within a single folder entitled "Alameda_Co." Within the "Alameda_Co" folder are 4 sub-directories and 2 ESRI file geodatabases. These are described in more detail below:

/AlamedaCo_KMZ/

This folder contains a series of Google earth files (.kmz) of the Alameda County shoreline. These include: (a) shoreline segments by normalized elevation; (b) shoreline segments by overtopping potential under each of the six sea level rise scenarios; (c) shoreline segment average elevation value; and (d) shoreline segment by type.

/AlamedaCo_lyr/

This folder contains four ArcGIS layer files (.lyr) located within the /Alameda_Co/ directory. These layer files can be opened in ArcMap (.mxd) so that the shoreline file of Alameda County (found within the "AlamedaCo_Shoreline" geodatabase) can be easily classified with the symbology used in the report.

1. SLR_NORMALIZED_ELEVATION_RAMP.lyr

   For visualizing normalized shoreline elevations.

2. SLR_OVERTOPPING_RAMP.lyr

   For visualizing overtopping—this layer file uses the 48-inch sea level rise scenario. However, this classification ramp can be used for all of the sea level rise scenarios.

3. SLR_TYPE_RAMP.lyr

   For visualizing the shoreline type.

4. SLR_SHAPE_RAMP.lyr

   For visualizing the polygons produced for the sea level rise scenarios - this layer file used the 12-inch sea level rise scenario. However, this classification ramp can be used for all of the sea level rise scenarios.

AlamedaCo_Shoreline.gdb

This is an ArcGIS file geodatabase containing the shoreline and the outputs from the Alameda County shoreline vulnerability assessment. The geodatabase contains one feature class representing the shoreline of Alameda County (“AlamedaCo_Shoreline_Type_Overtopping_Normalized_Z”). The shoreline has been split into 100 foot segments to best assist in understanding potential overtopping and inundation. The attribute table contains fields for the following data produced from the analysis: shoreline type (e.g. “Engineered Shoreline Protection Structure”); average inundation depths for each sea level rise scenario; average elevation; and normalized (to MHHW) elevation. *The contents of this file geodatabase should only be viewed using ArcGIS (or other GIS software).* A detailed data dictionary for this shoreline geodatabase is included in Appendix E-2.

AlamedaCo_SLR_data.gdb

This is an ArcGIS file geodatabase containing the source data (four files) used for the shoreline vulnerability assessments. *The contents of this file geodatabase should only be viewed using ArcGIS (or other GIS software).* The geodatabase contains the following two feature classes and two raster files.

1. _Alameda_ART_DHI_pts_MHHW

   Point feature class of water elevation values;

2. alameda_dem_new

   Digital Elevation Model (DEM) raster with a cell resolution of 2 meters. This data set was used for the shoreline vulnerability assessment and to populate the Z_Mean field in the shoreline file. Elevation values (Z values) are in feet.

3. mhhw

   Mean Higher High Water (MHHW) raster used for the sea level rise inundation mapping and shoreline vulnerability assessment. This file was also used to calculate the normalized elevation field in the shoreline file. MHHW values (Z values) are in feet.

4. msl_shoreline_clip_poly

   Polygon file of Mean Sea Level (MSL) used for clipping model inputs.

/SLR_Rasters/

This folder includes eight sub-folders containing all the raster datasets that follow the eight-step process developed by the NOAA Coastal Services Center for sea level rise inundation mapping. The last folder (8_Land_Only_Extent_Rasters) contains the six inundation rasters (one for each of the six sea level rise scenarios).

Each of the eight sub-folders contains six raster files (in ESRI GRID format), one for each of the six sea level rise scenarios. The sea level rise scenarios are described in terms of inches above the mean higher high water (MHHW) tidal datum. These scenarios include: 12”, 24”, 36”, 48”, 72”, and 96” of sea level rise above MHHW. The sea level rise scenario is indicated by the number appended to the end of the filename. For example, the “condep_mhhw12” raster is the inundation grid (land only) for the 12” sea level rise scenario. The digital data contents and results associated with each of the eight steps in the NOAA inundation mapping process are outlined in each of the eight sub-folders listed below.

- NOAA Step 8: /SLR_Rasters/8_Land_Only_Extent_Rasters

  These rasters contain extent and depth of land-only inundation (in feet) of the Alameda County shoreline under various sea level rise scenarios. These rasters are clipped to show the land only extent of connected areas of inundation and disconnected low-lying areas.

- NOAA Step 7: /SLR_Rasters/7_Connected_Area_Depth_Grids

  These rasters contain extent and depth of inundation (in feet), including water, of the Alameda County shoreline under various sea level rise scenarios. These rasters are *not* clipped to the land only extent of connected areas of inundation and disconnected low-lying areas, and, therefore, also include areas of open water.

- NOAA Step 6: /SLR_Rasters/6_Lowlying_Areas_Over_1_Acre

  These rasters identify low-lying areas greater than one acre. These rasters depict areas that are below the inundated water surface elevation, but are not hydraulically-connected to the inundated areas. The cell values for each of these rasters are only used for identifying (and masking) low-lying areas under each sea level rise scenario.

- NOAA Step 5: /SLR_Rasters/5_Connected_Inundation_Area_Masks

  These rasters identify the extent of connected inundation under each sea level rise scenario. They were used to mask the “connected inundation areas” in Step 7 of the NOAA methodology. The cell values for these rasters are for identifying (and masking) inundation areas under each sea level rise scenario.

- NOAA Step 4: /SLR_Rasters/4_Connectivity_Extent_Rasters

  These rasters identify both the extent of connected inundation under and low-lying areas under each SLR scenario. These rasters were used as a mask to differentiate between the “connected inundation areas” in Step 5 and “low-lying areas” in Step 6 of the NOAA methodology..

- NOAA Step 3: /SLR_Rasters/3_Single_Value_Inundation_Extents

  These rasters identify the extent of connected inundation and low-lying areas under each sea level rise, *but do not distinguish between the two* (all cell values are the same). These rasters can be used to mask both the inundation and low-lying area.

- NOAA Step 2: /SLR_Rasters/2_Initial_Inundation_Depth_Grids

  These rasters contain the extent and initial depth of inundation (in feet) under each sea level rise scenario. They include both the inundation and low-lying areas under each sea level rise scenario.

- NOAA Step 1: /SLR_Rasters/1_SLR_Surfaces

  These rasters contain extent and height of the water surface (based on MHHW) under each sea level rise scenario. The height of the water surface was derived by adding the current MHHW surface (found in AlamedaCo_SLR_data.gdb) with a given sea level rise scenario.

/SLR_Shapefiles/

This folder includes two sub-folders containing shapefiles of both the extent of inundation as well as the low-lying areas under each of the six sea level rise scenarios. Each folder contains six ESRI shapefiles, one for each of the six sea level rise scenarios.

- NOAA Step 8: /SLR_Shapefiles/8_Land_Only_Extent_Rasters

  This folder contains six shapefiles identify the extent of inundation (land only) under each SLR scenario.

- NOAA Step 7: /SLR_Shapefiles/7_Connected_Area_Depth_Grids

  This folder contains six shapefiles depicting the extent of low-lying areas greater than one acre under each SLR scenario. These rasters depict areas that are below the inundated water surface elevation, but are not hydraulically-connected to the inundated areas.

E-2. DATA DICTIONARY

E-2.1 ALAMEDACO_SHORELINE.GDB

AlamedaCo_Shoreline_Type_Overtopping_Normalized_Z

This polyline feature class represents the shoreline of Alameda County as digitized for the shoreline vulnerability assessment. The shoreline was split into 100 foot segments to best assist in understanding potential overtopping and inundation. The attribute table contains fields for the following data: shoreline type (e.g. "Engineered Shoreline Protection Structure"); average inundation depths for each of the six sea level rise scenarios; average inundation under current MHHW; average elevation; and normalized (to MHHW) elevation. This feature class also contains an ESRI representation of shoreline type (stored in the "RepID" field). The shoreline can be symbolized according to the same classifications shown in the report by using the layer files files found in the /AlamedaCo_lyr/ sub directory (see description above). This data dictionary also applies to the KMZ files of the shoreline (overtopping, normalized, elevation mean, and type).

Field(s):

1. **[ID]:** Unique ID for each shoreline segment

2. **[Class]:** Contains the "type" of shoreline . Acceptable entries, described in detail within the report, include:
   a) Engineered Flood Protection Structure
   b) Engineered Shoreline Protection Structure
   c) Embankment
   d) Non Engineered Berm
   e) Transportation Structure
   f) Natural Shoreline/Beach
   g) Wetland
   h) Tide Gate

3. **[Subtype]:** Contains the "subtype" for each type of shoreline. Acceptable entries include:
   a) Levee
   b) Floodwall
   c) Bulkhead
   d) Revetment
   e) Non Engineered Berm
   f) Natural Wetland
   g) Managed Wetland
   h) Tidal Flat
   i) Natural Shoreline

5. **[Trans_Type]:** Contains the transportation structure type, if applicable. Acceptable entries include:
    a) Major Road
    b) Rail
    c) Null

6. **[Frontage]:** Contains frontage type in front of designated outboard shoreline, if applicable. Acceptable entries include:
    a) Wetland
    b) Beach
    c) Wetland and Beach
    d) Null

7. **[Fortified]**: Contains fortification type (e.g., rirap, concrete, buttressing) for designated shoreline, if applicable. Fortification of shoreline segments are found on the bayward slope. Acceptable entries include:
    a) Yes
    b) No
    c) Null

8. **[Comments]:** Contains a brief description and notes of important datasets that were used to digitize shoreline feature.

9. **[Condep12_MN]:** Contains the average inundation depth (in feet) for the shoreline segment under the 12 inch SLR scenario

10. **[Condep24_MN]:** Contains the average inundation depth (in feet) for the shoreline segment under the 24 inch SLR scenario

11. **[Condep36_MN]:** Contains the average inundation depth (in feet) for the shoreline segment under the 36 inch SLR scenario

12. **[Condep48_MN]:** Contains the average inundation depth (in feet) for the shoreline segment under the 48 inch SLR scenario

13. **[Condep72_MN]:** Contains the average inundation depth (in feet) for the shoreline segment under the 72 inch SLR scenario

14. **[Condep96_MN]:** Contains the average inundation depth (in feet) for the shoreline segment under the 96 inch SLR scenario

15. **[MHHW_Avg]:** Contains the average inundation depth (in feet) for the shoreline segment under current Mean Higher High Water (MHHW).

16. **[Z_Mean]:** Contains the average elevation value (in feet) for the shoreline segment using the DEM used for the SLR analysis (see above).

17. **[Normalize]:** Contains the normalized value for the shoreline segment (elevation values normalized to current MHHW). Please see the report for a more detailed description.

18. **[Shape_Length]:** The length of the shoreline segment (in feet).

19. **[RepID]:** The field used for the representation by type