State Route 37 Integrated Traffic, Infrastructure and Sea Level Rise Analysis: Final Report

Road Ecology Center
University of California, Davis
http://hwy37.ucdavis.edu

State Route 37 Integrated Traffic, Infrastructure and Sea Level Rise Analysis

Task 1 Technical Memorandum: Sea Level Rise Assessment

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Executive Summary

In recognition of the potential effects of sea level rise on State Route 37 (SR 37) and surrounding marshes and communities, Caltrans has engaged the Road Ecology Center (UC Davis) to assist with initial stages of planning for adaptive actions associated with the highway. One critical analysis for planning adaptation is understanding the potential inundation due to sea level rise (SLR) and storm surges. AECOM was contracted by the Road Ecology Center to model the potentially-affected areas and stretches of highway from SLR and elevation changes due to storm surges.

The modeling approach relied on a combination of high-resolution elevation data obtained by light detection and ranging (LiDAR) by the US Geological Survey (USGS) and the National Oceanic and Atmospheric Administration's (NOAA) California Shoreline Mapping Project (CSMP). The model uses a "contagion" method which basically means that for any area on the landscape, if it is immediately adjacent to an area that is inundated and is lower elevation than that area, it will also become inundated. Mean higher high water ("high tide") elevations in the San Pablo Bay were used to describe current conditions. Additional water elevations due to SLR or storm surge were added to these elevations to indicate a potential future condition. These potential water elevations were then used to project potential inundation inland from the shoreline. Certain areas are protected by levees or berms and remain protected until the water elevation is higher than the lowest point on the levee or berm, at which point water enters the protected area and inundation proceeds until land elevations are higher than the water elevation. One consequence of this approach is that the inundated area may be over-estimated at lower than high-tide, unless water remains behind after the high-tide recedes.

The inundation modeling and mapping was the first step in understanding extent and magnitude of potential risks to SR 37 and surrounding landscapes and infrastructure. The vulnerability of SR 37 to SLR and the risks to continuing use of SR 37 were assessed (see Report 2) based on the inundation modeling and mapping step described here. The following memorandum describes the methods and results from the modeling and mapping. Maps corresponding to different SLR and storm surge scenarios are also available here:

http://hwy37.ucdavis.edu/resource/potential-inundation-maps-various-scenarios.

1. Introduction and Background

The University of California, Davis (UC Davis) is carrying out a collaborative project with Caltrans to examine the potential impacts of sea level rise (SLR) on North Bay infrastructure, with a focus on California State Route 37 (HWY 37). The study area covers 21 miles from the HWY 37/Route 101 interchange (west) to the Interstate 80/HWY 37-Columbus Parkway interchange (east). As part of this project, AECOM was retained by UC Davis to develop a series of SLR and storm surge inundation maps for the area surrounding HWY 37. Inundation maps are a valuable tool for evaluating potential exposure to future SLR and storm surge conditions. The maps are typically used to evaluate when (i.e., under which SLR and/or storm surge scenario) and by how much (i.e., what depth of inundation) a given asset will be exposed. The maps presented in this memorandum use topographic and water level data to estimate the depth and extent of inundation for a range of existing and future SLR and storm surge conditions. In a subsequent phase of the project, AECOM and UC Davis will complete a vulnerability and risk assessment of the HWY 37 alignment, and develop conceptual-level engineering drawings and cost estimates for potential adaptation strategies.

This memorandum documents the inundation maps and the mapping methodology. The risk assessment, conceptual-level engineering drawings, and cost estimates will be documented in future memorandums. The sections below present the SLR projections (Section 2), inundation map development (Section 3), preliminary vulnerability assessment (Section 4), and mapping assumptions and caveats (Section 5).

2. Sea Level Rise Projections

In 2011, Caltrans released its Sea Level Rise Guidance for use in the planning and development of Project Initiation Documents (Caltrans 2011). The Caltrans guidance was based on interim SLR scenarios developed by the California Climate Action Team. In 2012 the National Research Council (NRC) published *Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future* (NRC 2012). This report included discussions of historical SLR observations, three SLR projections of likely SLR for the coming century, high and low extremes for SLR, and insight into the potential impacts of a rising sea for the California coast. In March 2013, the Ocean Protection Council adopted the NRC report as the best available science on SLR for the state (Ocean Protection Council 2013). The California Coastal Commission also supported the use of the NRC 2012 report as best available science (California Coastal

Commission 2013). 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 SLR (IPCC 2013).

Table 1 presents the NRC SLR projections for San Francisco relative to the year 2000. These projections represent the likely SLR 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, 5 to 24 inches for 2050) represent unlikely but possible levels of SLR using both low and very high emissions scenarios and, at the high end, also 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 SLR that include contributions from the local thermal expansion of seawater, wind driven components, land ice melting, and vertical land motion.

Table 1. Sea Level Rise Estimates for San Francisco 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 Coast 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.

At this time, the use of NRC projections and ranges is appropriate for this study because they encompass the best available science, have been derived considering local and regional processes and conditions, and their use is consistent with current state guidance. The specific SLR scenarios selected for inundation mapping are presented in Section 3.3.1.

3. Inundation Modeling and Mapping

This section presents the methods used to develop the detailed inundation maps presented in Appendix A. The following sections present the topographic and hydrodynamic model data obtained for the project (Section 3.1), the water level analysis to determine daily and extreme tide (i.e., high tide plus storm surge) levels (Section 3.2), and development of the inundation maps (Section 3.3).

3.1. Data Sources

The inundation mapping required topographic and water level data which were obtained from the following sources:

- Topographic LiDAR from the U.S. Geological Survey (USGS) and National Oceanic Atmospheric Administration (NOAA) California Shoreline Mapping Project (CSMP) (Section 3.1.1)[1]
- Water levels from the Federal Emergency Management Agency (FEMA) San Francisco Bay Area Coastal Study (Section 3.1.2)[2]

3.1.1. Topographic Data Development

The topographic data used for this analysis were derived from topographic light detection and ranging (LiDAR) data from the USGS and NOAA CSMP. NOAA managed the data collection in the North Bay. The SLR inundation mapping was completed on a 5-ft (1.5-meter) digital elevation model (DEM) derived from the bare-earth LiDAR data.

In the bare-earth LiDAR dataset, all buildings and structures (including bridges and overpasses) have been removed. All vegetation has also been removed as part of the bare-earth LiDAR processing. The resultant DEM is of sufficient resolution and detail to capture the shoreline levees and flood protection assets. Although care was taken to capture all relevant topographic features and coastal structures that may impact coastal inundation, it is possible that structures narrower than the 5-ft horizontal DEM scale may not be fully represented.

AECOM also obtained Real Time Kinematic (RTK) GPS survey data of the marshlands in north San Pablo Bay, which was collected by USGS researchers over the summers of 2008, 2009, and 2010. This dataset was compared against the LiDAR data to identify any differences in elevation and ground-truth the topographic DEM derived from the LiDAR dataset. The LiDAR-derived DEM shows higher elevations in the marsh areas, with differences of approximately one to two feet. This difference is thought to be due to the influence of the dense and tall vegetation in the vegetated marsh areas. This difference in the marsh areas does not have an effect on the extent of flooding of HWY 37 because the marsh is not the controlling topographic feature for landward inundation (landward inundation is typically controlled by levees and berms). It should be noted that the depth, extent, and timing of inundation of the marshplain surface may

[1] California Ocean Protection Council, California Shoreline Mapping Project: http://www.opc.ca.gov/2010/11/the-california-shoreline-mapping-project/

[2] FEMA San Francisco Bay Area Coastal Study: http://www.r9map.org/Pages/San-Francisco-Coastal-Bay-Study.aspx

be misrepresented by the maps. For example, in areas of dense marsh vegetation, elevations may be overestimated and therefore inundation may occur at lower SLR scenarios than indicated. It is also noted that there may be some areas of dense vegetation cover on levee and berm features that do control landward inundation; however, these topographic features were not surveyed by the USGS marsh surveys so a direct comparison of elevations was not possible.

A stakeholder meeting was held on January 29, 2015 to discuss the draft SLR inundation mapping process and solicit feedback. As follow-up to that meeting, stakeholders provided information on recent development and restoration work that had taken place in the areas surrounding the highway since the time of the LiDAR collection (e.g., 2010). Input was provided by Environmental Science Associates, Ducks Unlimited, the Coastal Conservancy, and Caltrans staff with familiarity of the study area, including recent levee breaches, new levees, and water control structure operations. The bare-earth LiDAR DEM was manually adjusted to account for these features and their effects on inundation using the information provided. The specific DEM modifications are described below.

Levee breaches were placed at the following sites that have been restored to tidal wetlands or are tidally connected to the Bay through water control structures:

- The levee surrounding the Napa Plant site was breached in two locations
- Cullinan Ranch was breached in two locations
- The bayfront levee of Hamilton Airfield was breached in one location
- The bayfront levee surrounding the Sears Point site was breached in two locations to reflect a current restoration project (in construction)
- A breach was placed in the levee of the West End area to represent a culvert connection with Sonoma Creek
- A breach was placed in the levee of the White Slough area to represent a culvert connection with the Napa River

Levees were placed at the following sites that have recently been restored to tidal wetlands. At both sites, the 50-year design elevation (including effects of settlement) was used:

- A levee was placed at the Cullinan Ranch site, running 3,800 feet along the north side of HWY 37 at an elevation of 10 ft NAVD88.
- A levee was placed at the Sears Point site, running 2.3 miles along the northwest edge of the site at an elevation of 10.6 ft NAVD88.

In addition, structures were placed at three locations where the bare-earth LiDAR-based DEM did not accurately represent existing levees or structures:

- At Bel Marin Keys, the two locks were added at two locations (north and south) by assuming a lock crest elevation equal to the surrounding levee crest.

- At Camp 2, the levee was extended to close a tidal connection to the site, which is a California Department of Fish and Wildlife managed pond that is not open to tidal action.
- In Novato, the Leveroni Tide Gate structure was added to the channel that drains Pacheco Pond at the confluence with Novato Creek at an elevation of 9.5 ft NAVD88.

The inundation modeling and mapping did not take into account future planned restoration activities (for example, breaching levees to managed pond areas) beyond those actions described above.

<u>Hydrodynamic Modeling Data</u>

The inundation mapping effort leveraged existing and readily available model output from a large-scale MIKE21 San Francisco Bay hydrodynamic modeling effort completed as part of FEMA's San Francisco Bay Area Coastal Study (DHI 2011). The model was driven by hourly water levels at the Golden Gate that simulated conditions over a 31-yr time period from January 1, 1973 through December 31, 2003. The model takes into account water level variations associated with astronomical tides, storm surge, and El Nino effects. The FEMA model output was used to determine the daily and extreme tide levels throughout the study area. The use of model output for this study was preferred over individual tide gage analyses because of the high spatial density provided in the model output for the entirety of the HWY 37 study area. This model output has been leveraged and used for several similar studies in San Francisco Bay, including the Adapting to Rising Tides project in Alameda County and ongoing coastal vulnerability assessments (AECOM et al. 2011; AECOM 2014).

The FEMA MIKE21 modeled water level output was provided in 15-minute time steps and consisted of water surface elevations relative to the North American Vertical Datum of 1988 (NAVD88). A 31-yr time series of modeled water level output was obtained at 22 points along the North Bay shoreline (Figure 1, top panel).

3.2. Water Level Analysis

The general approach for the water level analysis included first evaluating daily high tide and extreme tide water levels under existing conditions, and then projecting these water levels into the future by adding a specified amount of SLR. The validity of this approach was documented in the Adapting to Rising Tides project (AECOM et al. 2011). At each model output point shown on Figure 1, daily and extreme tide levels were calculated for the 31-yr simulated time series. The mean higher high water (MHHW) tidal datum was selected to represent the typical daily high tide. The MHHW tide level is defined as the average of the higher high tides of each day recorded during the National Tidal Datum Epoch, which is a specific 19-yr period adopted by

NOAA to perform tidal computations. MHHW was calculated at each model output point using the portion of the model output timeseries corresponding to the most recent National Tidal Datum Epoch (1983 through 2001). MHHW elevations for existing conditions range from 6.0 feet to 6.3 feet NAVD within the study area (Figure 1, middle panel). The water level statistic used to represent the extreme tide is the 1-percent-annual-chance stillwater elevation (extreme tide level due to coincidence of high tide and storm surge) commonly referred to as the 100-yr SWEL. The 100-yr SWEL was selected as an appropriate extreme tide level because it is consistent with FEMA's regulatory mapping guidelines. The 100-yr SWEL was calculated at each model output point using statistical analysis of the 31 annual maxima water levels from the simulated time series. 100-yr SWEL elevations for existing conditions range from 9.3 to 9.9 ft NAVD within the study area (Figure 1, bottom panel). The MHHW and 100-yr SWEL elevations at each FEMA MIKE21 model output point are shown in Figure 1. Daily and extreme tide levels (including other recurrence intervals) are tabulated in Table 2.

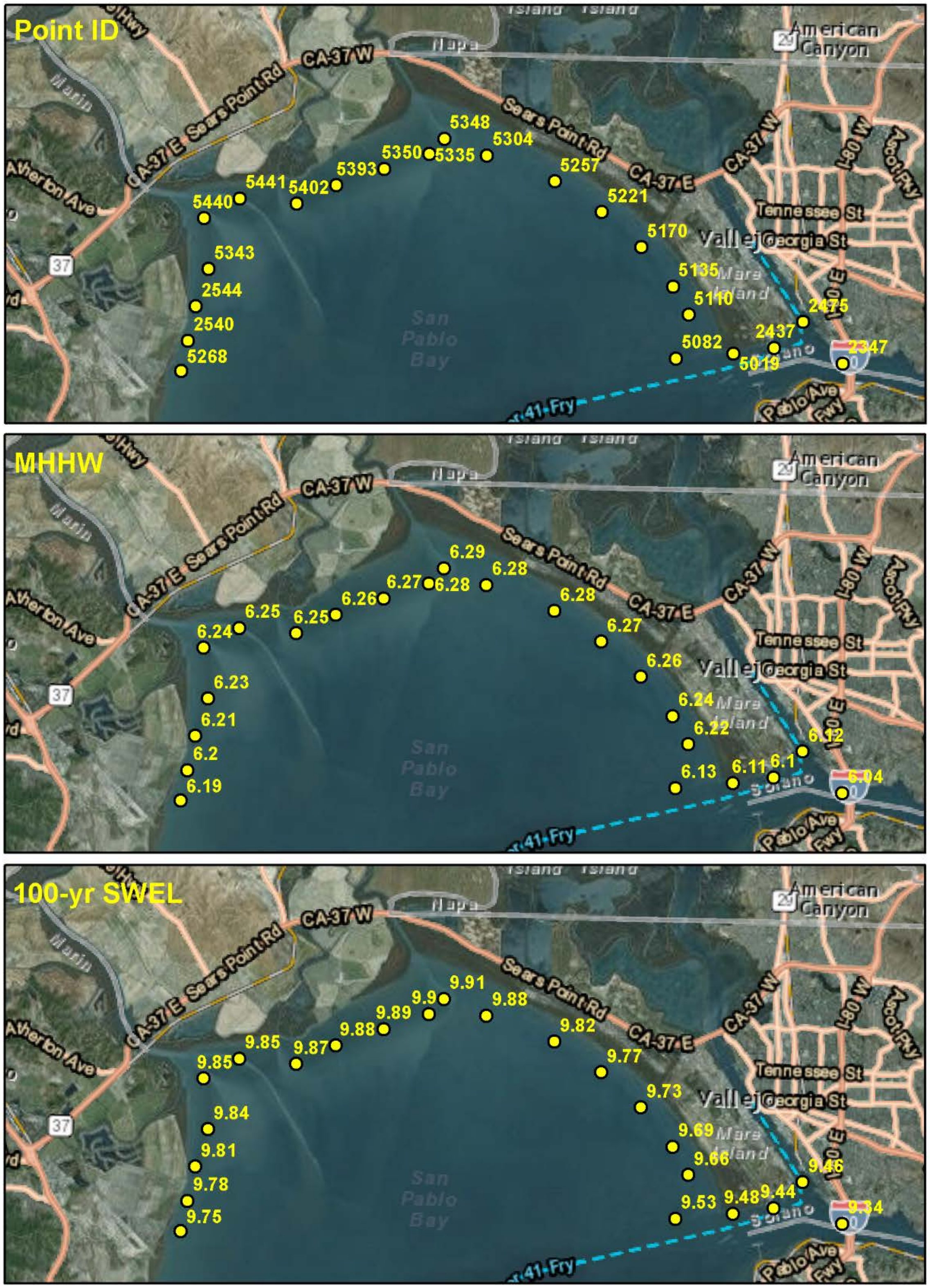

Figure 1. Summary of North Bay Water Level Statistics

Note: MHHW and 100-yr SWEL elevations referenced to NAVD88 datum (feet).

Table 2. Daily and Extreme Tide Water Levels at DHI Model Output Points

	Water Surface Elevation (feet NAVD88)							
Point ID	MHHW	2-yr SWEL	5-yr SWEL	10-yr SWEL	25-yr SWEL	50-yr SWEL	100-yr SWEL	500-yr SWEL
5268	6.19	7.75	8.18	8.50	8.96	9.34	9.75	10.86
2540	6.20	7.76	8.20	8.52	8.98	9.36	9.78	10.90
2544	6.21	7.78	8.21	8.54	9.01	9.39	9.81	10.96
5343	6.23	7.80	8.24	8.57	9.03	9.42	9.84	10.98
5440	6.24	7.85	8.28	8.61	9.07	9.44	9.85	10.92
5441	6.25	7.85	8.28	8.61	9.07	9.44	9.85	10.95
5402	6.25	7.84	8.27	8.60	9.06	9.45	9.87	11.02
5393	6.26	7.84	8.28	8.61	9.07	9.46	9.88	11.03
5350	6.27	7.85	8.29	8.61	9.08	9.47	9.89	11.05
5335	6.28	7.87	8.30	8.62	9.09	9.48	9.90	11.06
5348	6.29	7.88	8.31	8.64	9.10	9.49	9.91	11.05
5304	6.28	7.87	8.30	8.62	9.08	9.46	9.88	11.00
5257	6.28	7.86	8.28	8.60	9.05	9.42	9.82	10.91
5221	6.27	7.85	8.27	8.58	9.02	9.38	9.77	10.82
5170	6.26	7.82	8.24	8.55	8.99	9.35	9.73	10.76
5135	6.24	7.80	8.21	8.52	8.95	9.31	9.69	10.71
5110	6.22	7.78	8.19	8.50	8.93	9.28	9.66	10.67
5082	6.13	7.65	8.07	8.38	8.81	9.16	9.53	10.53
5019	6.11	7.63	8.05	8.35	8.77	9.12	9.48	10.43
2437	6.10	7.62	8.03	8.33	8.75	9.09	9.44	10.37
2475	6.12	7.64	8.05	8.35	8.77	9.10	9.46	10.37
2347	6.04	7.54	7.96	8.26	8.67	9.00	9.34	10.23
Avg.	**6.21**	**7.78**	**8.20**	**8.52**	**8.97**	**9.34**	**9.73**	**10.80**

Note: MHHW is the mean higher high water level (the average of the higher of two high tides each day). SWEL is the extreme stillwater elevation, a tide elevation based on model simulations (not including local wind effects, which may increase SWEL above this estimate), calculated from statistical analysis of modeled annual maximum water levels. Point IDs are sorted from west to east along the North Bay shoreline.

3.3. Inundation Map Development

3.3.1. Mapping Scenarios

Sea level rise is often visualized using inundation maps; however, selecting the most appropriate SLR scenario for mapping to support project planning, exposure analysis, and SLR vulnerability and risk assessment is not simple. Typically, a series of maps is created that represents specific SLR scenarios added to MHHW, as well as paired with a specific extreme tide or storm surge event (such as the 100-yr SWEL). This approach requires pre-selecting specific SLR scenarios that will meet all project needs.

Rather than pre-selecting specific SLR scenarios for the HWY 37 project, six individual inundation maps were developed to represent a range of possible scenarios associated with extreme tide levels and SLR, ranging from 12 to 66 inches. The goal of the scenario selection was to identify a suite of scenarios that could represent the current NRC (2012) SLR projections and ranges as well as approximate a range of combinations of SLR and extreme tide events. The four SLR amounts selected relate directly to the NRC SLR estimates and capture a broad range of scenarios between the most likely scenario and the high range of uncertainty.

In consideration of the NRC (2012) SLR projections, four SLR scenarios were considered: the likely and the high end of the range for 2050 (+12” and +24”) and 2100 (+36” and +66”). The likely and high-end scenarios were evaluated with a daily high tide (MHHW). The extreme high tide (100-yr SWEL) was evaluated with the likely SLR scenarios for 2050 and 2100 (+12” and +36”, respectively). In total, this produced six scenarios (in addition to the existing conditions MHHW and 100-yr SWEL scenarios):

- MHHW + 12 in (NRC most likely 2050)
- MHHW + 24 in (NRC high-end 2050)
- MHHW + 36 in (NRC most likely 2100)
- MHHW + 66 in (NRC high-end 2100)
- 100-yr SWEL + 12 in (NRC most likely 2050 + 100-yr SWEL)
- 100-yr SWEL + 36 in (NRC most likely 2100 + 100-yr SWEL)

These six maps represent a range of possible scenarios associated with daily and extreme tide levels coupled with different amounts of SLR. As discussed above, each individual map can also represent various combinations of SLR and tide level. Table 3 lists the six mapped scenarios and the associated reference water level used for each inundation map (relative to MHHW). It is important to note that the reference water levels listed for each scenario can occur due to a variety of hydrodynamic conditions by combining different amounts of SLR with either a daily or extreme high tide (for example, a water level of MHHW + 42 inches is roughly equivalent to the

100-yr SWEL). A +/- 3 inch tolerance was added to each reference water level to increase the applicable range of each mapped scenario. For example, Scenario 3 (MHHW + 36 in) is assumed to be representative of all extreme tide/SLR combinations that produce a water level in the range of MHHW + 33 to 39 inches.

Table 3. Sea Level Rise Inundation Mapping Scenarios

Mapping Scenario	Reference Water Level	Applicable Range for Mapping Scenario (Reference +/- 3 in)
Scenario 1	MHHW + 12 in	MHHW + 9 to 15 in
Scenario 2	MHHW + 24 in	MHHW + 21 to 27 in
Scenario 3	MHHW + 36 in	MHHW + 33 to 39 in
Scenario 4	MHHW + 66 in	MHHW + 63 to 69 in
Scenario 5	100-yr SWEL + 12 in (MHHW + ~54 in)	100-yr SWEL+ 9 to 15 in (MHHW + 51 to 57 in)
Scenario 6	100-yr SWEL + 36 in (MHHW + ~78 in)	100-yr SWEL + 33 to 39 in (MHHW + 75 to 81 in)

Note: The MHHW and 100-yr SWEL values vary spatially throughout the study area. The MHHW-equivalent values listed for Scenarios 5 and 6 are approximate and based on the average values of MHHW and the 100-yr SWEL for all model output points in the study area (see Table 2, "Avg." values). See Table 4 for application of mapping scenario "color coding".

By combining different amounts of SLR and tide levels, a matrix of water level scenarios was developed to identify the various combinations represented by each inundation map for the study area. The resulting SLR and extreme tide matrix is shown in Table 4. The values in Table 4 are shown in inches above the existing conditions MHHW tide level (taken as the average of all model output points in the study area). The colors match the colors shown in Table 3 and indicate the different combinations of SLR and tide scenarios. The "Existing Conditions" and "100-yr SWEL" rows of the matrix show values of MHHW and 100-yr SWEL for existing conditions (with no SLR). For example, the MHHW + 36 in inundation map (Scenario 3), could also represent a 5-yr extreme tide + 12 in SLR, a 10-yr extreme tide + 6 in SLR, or a 25-yr extreme tide under existing conditions. Equivalent combinations for the MHHW + 12 in, MHHW + 24 in, MHHW + 36 in, 100-yr SWEL + 12 in and 100-yr + 36 in scenarios can be determined similarly by tracking the color coding through the table.

Table 4. Daily and Extreme Tide and Sea Level Rise Matrix for HWY 37 Study Area

Mapped Scenario	Daily Tide Inches above MHHW (SLR)	Extreme Tide Levels (inches above MHHW) 2-yr	5-yr	10-yr	25-yr	50-yr	100-yr	500-yr
Existing	0	19	24	28	33	37	42	55
MHHW + 6	6	25	30	34	39	43	48	61
MHHW + 12	12	31	36	40	45	49	54	67
MHHW + 24	24	43	48	52	57	61	66	79
MHHW + 36	36	55	60	64	69	73	78	91
100-yr SWEL (MHHW + 42)	42	61	66	70	75	79	84	97
MHHW + 48	48	67	72	76	81	85	90	103
100-yr SWEL + 12 (MHHW + 54)	54	73	78	82	87	91	96	109
MHHW + 60	60	79	84	88	93	97	102	115
MHHW + 66	66	85	90	94	99	103	108	121
MHHW + 72	72	91	96	100	105	109	114	127
100-yr + 36	78	97	102	106	111	115	120	133

Notes: Color coding indicates which combinations of SLR and extreme tides are represented by each mapping scenario. Cells with no color coding do not directly correspond to any of the mapping scenarios shown in Table 3.

For each mapped scenario, the extent of inundation can be interpreted as showing either areas of *permanent inundation* or *temporary flooding*. Permanent inundation refers to the daily tidal inundation caused by the daily high tide (MHHW). Temporary flooding refers to the short duration flooding associated with extreme tide or storm events. For example, the MHHW + 24 inch map represents possible future permanent inundation associated with daily high tides under a 24 inch SLR scenario or the temporary flooding associated with a 2-yr tide under a 6 inch SLR scenario or a 5-yr tide under existing conditions. All three of these scenarios can be represented by the MHHW + 24 inch map.

Using the approach described above, the six selected inundation scenarios can be used to represent 32 different combinations of SLR and tide events. These scenarios provide a richer data set with which to evaluate SLR vulnerabilities and risk – and more importantly to better define the timing for implementation of effective adaptation strategies.

3.3.2. Water Surface DEM Creation

Once the relevant water level statistics were generated for each inundation mapping scenario, the inundation maps were developed using the methods developed by the NOAA Coastal Services Center (Marcy et al. 2011).

The initial step in creating the inundation maps was to create the inundated water surface DEM. Daily and extreme high tide elevations derived from the FEMA MIKE 21 model output points (Table 2) were used to define the water surface elevations for the existing conditions MHHW and 100-yr SWEL. The water surface elevations were then extended inland to project the water surface over the inundated topography. To project the water surface inland, shore perpendicular transects were drawn inland beyond the expected limit of inundation. Transects were spaced at an appropriate density to capture variations in the tidal surface elevation and changes in orientation of the shoreline. The water surface DEMs were developed with a grid spacing of 5-ft (1.5-m) to match the resolution of the topographic DEM.

To produce the future conditions water surface DEMs, the appropriate amount of SLR (i.e., 12, 24, 36, 66 inches) was added to the model output data generated for the MHHW or 100-yr SWEL tide levels for each inundation map scenario.

The resulting water surface DEM is an extension of the tidal water surface at the shoreline over the inland topography. This represents a conservative estimate of the inland inundated water surface. 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 SLR, 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 or certain results.

3.3.3. Depth and Extent of Flooding

Depth of flooding raster files were created by subtracting the land-surface DEM from the water surface DEM. Both DEMs were generated using a 5-ft horizontal resolution with the same grid spacing in order to allow for grid cell to grid cell subtraction. The resultant DEM provides both the inland extent and the depth of inundation (in the absence of considering hydrologic connectivity).

The final step used in creating the depth and extent of flood maps relies on an assessment of hydraulic connectivity. The methodology described by Marcy et al. (2011) employs two rules for assessing whether or not 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 methodology 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).

The assessment of hydraulic connectivity removes areas from the inundation zone if they are protected by levees or other topographic features that are not overtopped. It also removes areas that are low-lying but inland and not connected to an adjacent flooded area. When this approach is used along controlling topographic features such as levees, the inland disconnected area remains dry until the water surface elevation exceeds the lowest point of the levee. Once this point is overtopped by Bay floodwaters, the low-lying area is converted from a disconnected area to an area of inundation.

4. Preliminary Vulnerability Assessment

Attachment A presents the inundation maps for each of the six scenarios. The maps show the extent and depth of inundation, mapped with a color scale from light blue (0-2 feet depth) to dark blue (greater than 12 foot depth). Low-lying areas that are not hydraulically connected to the Bay are shown in green and labeled as "Disconnected Areas" in the legend. The green areas indicate low-lying areas that would be inundated under a given scenario if the higher topographic land feature (such as a levee or berm) which separates the low-lying area from the Bay were removed. This means that for that particular scenario, there is not an overland (or over-levee) pathway for Bay flood waters to reach the disconnected low-lying area. Since the mapping does not take into account water control structures such as culverts and tide gates which may convey water into these areas, they may potentially be vulnerable despite being shown as hydraulically disconnected. Additionally, it should not be assumed that hydraulically disconnected areas would be dry under existing or future conditions, as some of these areas (such as restored salt ponds) are managed systems which are already inundated under existing conditions.

HWY 37 is protected from inundation by a complex interconnected system of levees along Novato Creek, the Petaluma River, Tolay Creek, Sonoma Creek, the Napa River, and San Francisco Bay. The study area can be divided into five reaches to aid in the examination of vulnerability to inundation due to SLR. A brief discussion of the inundation mapping results and preliminary vulnerability assessment within each reach is presented below. A more detailed examination of vulnerabilities to inundation and flooding will be presented in the vulnerability and risk assessment.

- **Reach A1. Highway 101 to Petaluma River.** Located east of the town of Novato, north of Bel Marin Keys, and west of the Petaluma River. The western and eastern limits of the reach are bounded by uplands but the middle segment from approximately Novato Creek to Atherton Avenue is relatively low-lying (approximately 4 to 6 ft NAVD) and protected by the Novato Creek levees which range in elevation from approximately 10 to 13 ft NAVD. This reach of HWY 37 is protected from inundation until the MHHW + 36 inch scenario at which point nearly the entire reach is inundated (Note: As shown in Table 4, the MHHW + 36 inch SLR mapping scenario corresponds to a number of different storm surge/SLR combinations, including a 5-yr extreme tide with 12 inches of SLR or a 25-yr extreme tide under existing conditions). Potential sources of flooding for further investigation include overland flooding at Black Point and levee overtopping near the mouth of Novato Creek.

- **Reach A2. Petaluma River to Highway 121.** Located east of the Petaluma River and west of the HWY 37/HWY 121 junction in the vicinity of Sears Point. The western half of the reach is relatively low-lying (approximately 2 to 4 ft NAVD) and the eastern half is uplands. This reach of HWY 37 is protected from inundation by levees along the eastern bank of the Petaluma River, the landward edge of the Sonoma Baylands restoration site, and the western bank of Tolay Creek. This reach of HWY 37 is protected from inundation until the MHHW + 24 inch scenario at which point the entire western portion of the reach is inundated. (Note: As shown in Table 4, the MHHW + 24 inch SLR mapping scenario corresponds to a number of different storm surge/SLR combinations, such as a 5-yr extreme tide under existing conditions). Potential sources of flooding for further investigation include overland flooding of low points around the perimeter of the Port Sonoma marina and the relatively low elevation levee (9-10 ft NAVD) along the eastern bank of the Petaluma River.

- **Reach B1. Highway 121 to Sonoma Creek.** Located east of HWY 121 and west of Sonoma Creek. The HWY 37 road grade is relatively high elevation in this area, ranging from approximately 9 ft NAVD at the western end to 8 ft NAVD at the eastern end. This reach of HWY 37 is protected by levees along the eastern bank of Tolay Creek and the western bank of Sonoma Creek. These creek levees tie-in to a bayfront levee to the south and form a continuous system of flood protection. This reach of HWY 37 is protected from inundation until the MHHW + 36 inch scenario at which point the entire reach is inundated. Potential sources of flooding for further investigation include overland flooding of low spots at the western end from Tolay Creek and at the eastern end from Sonoma Creek.

- **Reach B2. Sonoma Creek to Mare Island.** Located east of Sonoma Creek and west of the Napa River along the San Francisco Bay shoreline. In general, there is no bayfront levee protecting HWY 37 in this area and the road is constructed to a high enough elevation (approximately 11 ft NAVD) to prevent inundation and flooding. This reach of HWY 37 is protected from inundation through the 100-yr SWEL scenario with only minor flooding of a few low-lying areas, with the exception of the eastern end of the reach near Mare Island, where the road elevation is much lower at approximately 7 to 8 ft NAVD. The 100-yr SWEL + 12 inch scenario shows much larger stretches of inundation along the roadway. Potential sources of flooding for further investigation include overland flooding directly from San Francisco Bay.

- **Reach C. Mare Island to Interstate 80.** Located east of Mare Island and west of the Interstate 80 interchange. In general, there is no bayfront levee protecting HWY 37 in this area and the road is constructed to a high enough elevation (approximately greater than 13 ft NAVD) to prevent inundation and flooding, with the exception of the western end of the reach at Mare Island, where the road elevation is much lower at approximately 7 to 8 ft NAVD. The majority of the reach is protected from inundation until the MHHW + 66 inch scenario at which point a low spot in the road is inundated at Austin Creek.

In summary, HWY 37's vulnerability to SLR inundation and flooding varies along the length of the study area. Each of the five reaches examined in this memorandum varies in elevation from relatively low (2 to 4 ft NAVD near Sonoma Baylands) to relatively high (greater than 100 ft NAVD near Sonoma Raceway). A variety of shoreline protection infrastructure prevents inundation and flooding of the roadway and in some cases where a riverine or bayfront levee does not exist, the roadway itself is elevated to prevent inundation by Bay floodwaters. Further analysis will be required to determine the exact location, extent, and timing of overtopping and the inundation pathways responsible for inundation and flooding. The results of that further analysis will be presented in the vulnerability and risk assessment.

5. Mapping Assumptions and Caveats

The inundation maps created for the project area represent advancement over previous inundation maps that characterized the extent of inland inundation due to SLR. The inundation maps produced for the HWY 37 study area adopted SLR values that are consistent with the NRC (2012) most likely and high-end ranges for the San Francisco region. The maps incorporate water level analysis in a manner that produces multi-purpose maps in which each mapped scenario can represent a range of potential SLR and extreme tide combinations. This approach creates a richer dataset for completing a vulnerability assessment and developing adaptation strategies along the HWY 37 corridor. Most notably, the new maps include:

- The depth and extent of inundation.
- New topographic information from the 2010 NOAA LIDAR data. Flood protection levees and other features that could impede flood conveyance are accurately captured in this dataset (except in areas of dense vegetation cover – an issue common to all LiDAR-based SLR inundation mapping efforts).

- An assessment of hydraulic connectivity, using inundation mapping methodologies developed by the NOAA Coastal Services Center to exclude low-lying areas that are below the inundated water surface elevation, but are not hydraulically connected to the inundated areas.

The new inundation maps are intended as a screening-level tool to assess vulnerability to SLR. Although the inundation maps do account for additional processes compared to previous maps, and they rely on new data, they are still associated with a series of assumptions and caveats:

- The bathymetry of San Francisco Bay and the topography of the landward areas, including levees and other flood and shore protection features, would not change in response to SLR and increased inundation (e.g., the morphology of the region is constant over time).
- The maps do not account for the accumulation of organic matter in wetlands, or potential sediment deposition and/or resuspension that could alter San Francisco Bay hydrodynamics and/or bathymetry.
- The maps do not account for erosion, subsidence, future construction, or levee upgrades.
- The maps do not account for the existing condition or age of the shore protection assets. No degradation or levee failure modes have been analyzed as part of the inundation mapping effort.
- The 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 NOAA 2010 LIDAR data, downsampled from a 1- meter to a 1.5-meter horizontal grid resolution. Although this data set represents the best available topographic data, and the data have undergone a rigorous quality assurance/quality control process by a third party, the data have not been extensively ground-truthed. Levee crests may be overrepresented or underrepresented by the LIDAR data.
- 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,” as it represents the area that would be inundated regularly. Tides in San Francisco Bay exhibit two highs and two lows in any given day, and the daily high tide on any given day may be higher or lower than the MHHW tidal elevation.
- The inundation depth and extent shown on the 100-yr SWEL maps is associated with a 100-yr extreme water level condition—in other words, an extreme tide level with a 1-percent chance of occurring in any given year. This inundation is considered episodic inundation or “flooding” because the newly inundated areas (the areas not inundated under the MHHW scenario) would be inundated only during extreme high tides. It

should be noted that extreme tide levels with greater return intervals (i.e., 500-yr SWEL with a 0.2-percent chance of occurring in a given year) can also occur, and would result in greater inundation depths and a larger inundated area.

- The depth 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 focus on the potential for coastal flooding associated with SLR for daily and extreme tide events. The inundation maps do not account for localized inundation associated with rainfall-runoff events, or the potential for riverine overbank flooding in the local tributaries associated with large rainfall events.
- The maps do not account for inundation associated with changing rainfall patterns, frequency, or intensity as a result of climate change.
- The water level analysis and evaluation of future daily and extreme tide levels do not take into account future changes to Bay hydrodynamics as a result of SLR (e.g., changes in tide range due to changing tidal wave propagation physics).

6. Attachments

Attachment A. Sea Level Rise Inundation Maps for HWY 37 Project Area

7. References

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

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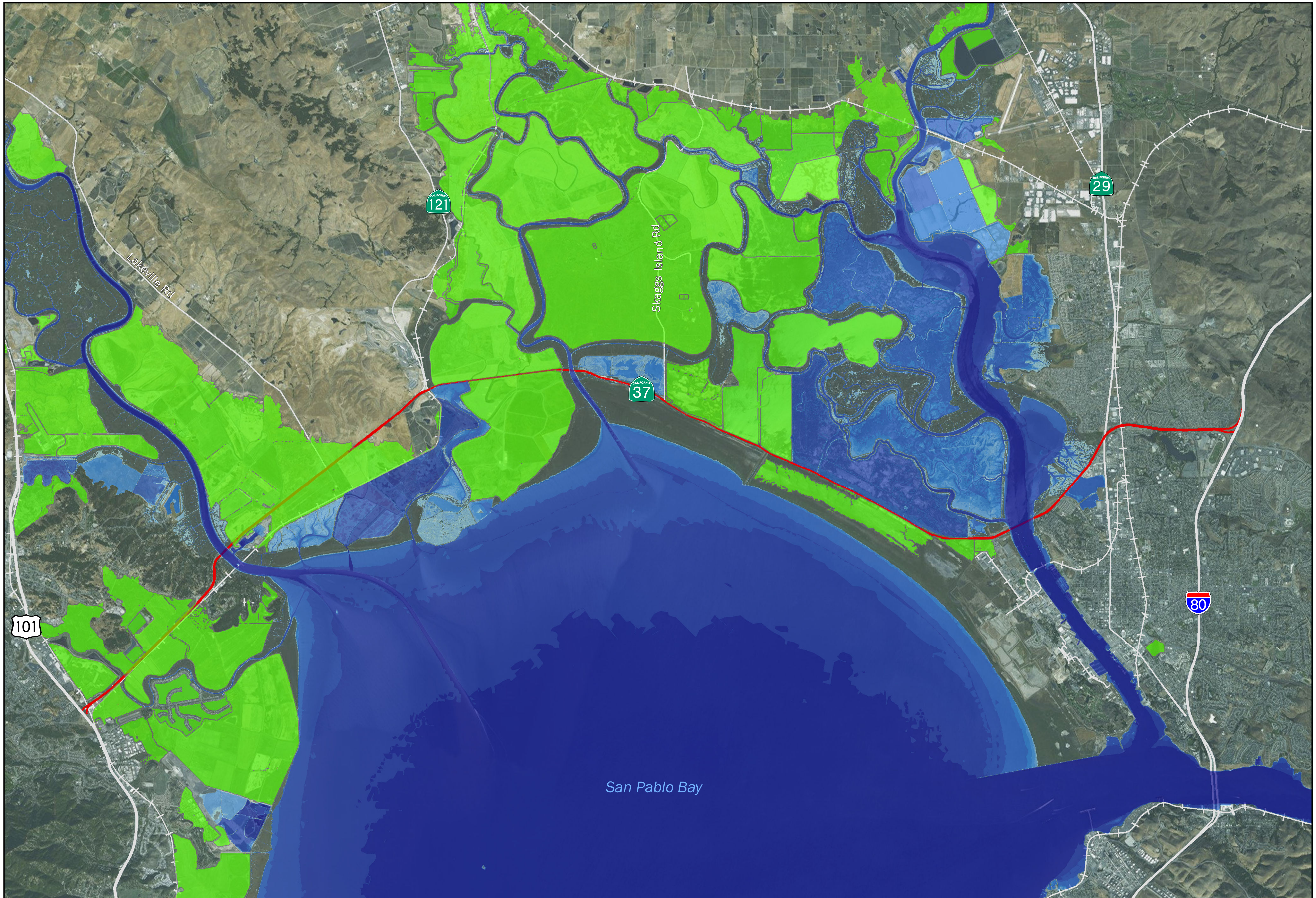
California State Route 37
Inundation Mapping

MHHW (EXISTING CONDITIONS)



Inundation

Depth in Feet

- 0 - 0.5
- 0.5 - 1
- 1 - 1.5
- 1.5 - 2
- 2 - 2.5
- 2.5 - 3
- 3 - 5
- 5 - 7
- 7 - 10
- 10 +
- Lowlying Areas > 1 Acre

0 1 2 Miles

0 5,000 10,000 Feet

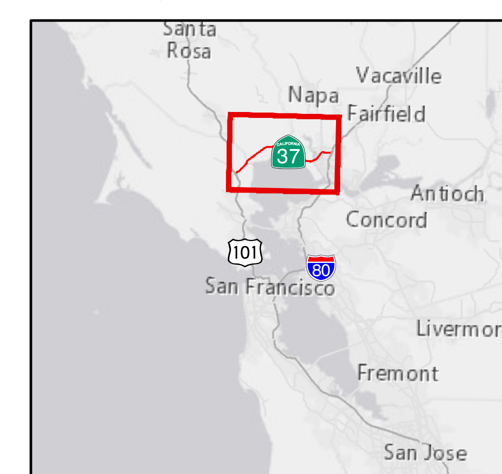
N

AECOM

CALIFORNIA 37

Projection:
NAD 1983 California III; North American Datum 1983

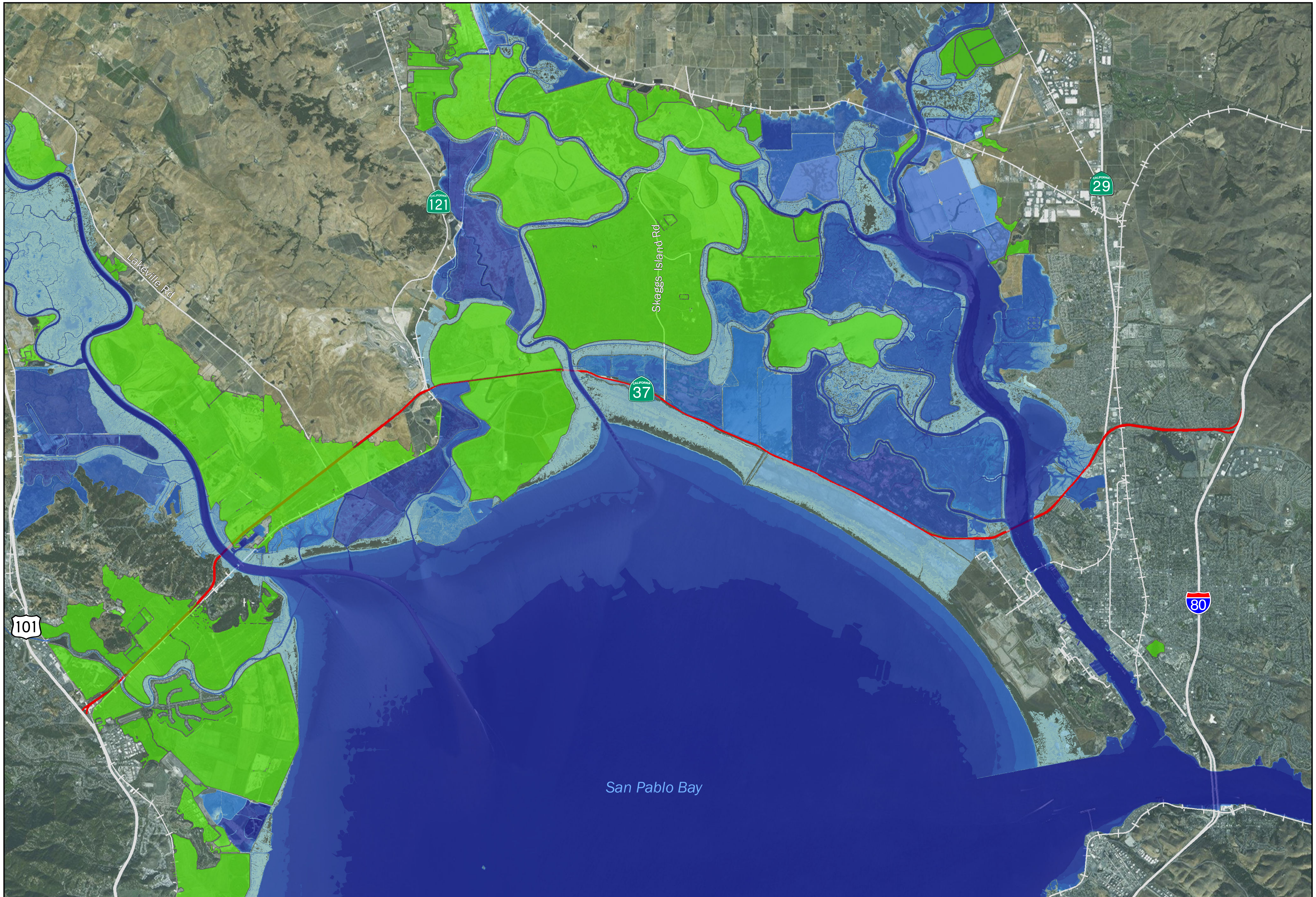
Date: 8/21/2015



Disclaimer: The inundation maps and the associated analyses are intended as planning level tools to illustrate the potential for inundation and coastal flooding under a variety of future sea level rise and storm surge scenarios. The maps depict possible future inundation that could occur if nothing is done to adapt or prepare for sea level rise over the next century. The maps do not represent the exact location or depth of flooding. The maps relied on a 5-ft digital elevation model created from LiDAR data collected in 2010. Although care was taken to capture all relevant topographic features and coastal structures that may impact coastal inundation, it is possible that structures narrower than the 5-ft horizontal map scale may not be fully represented. In addition, inundation and flooding of bridges along the SR 37 alignment was not evaluated. The maps are based on model outputs and do not account for all of the complex and dynamic San Francisco Bay processes or future conditions such as erosion, subsidence, future construction or shoreline protection upgrades, or other changes to San Francisco Bay or the region that may occur in response to sea level rise. For more context about the maps and analyses, including a description of the data and methods used, please see project documentation for the State Route 37 Integrated Traffic, Infrastructure and Sea Level Rise Analysis Study (UC Davis Road Ecology Center and Caltrans District 4).

California State Route 37
Inundation Mapping

MHHW + 12" SEA LEVEL RISE



Inundation

Depth in Feet

- 0 - 0.5
- 0.5 - 1
- 1 - 1.5
- 1.5 - 2
- 2 - 2.5
- 2.5 - 3
- 3 - 5
- 5 - 7
- 7 - 10
- 10 +

Lowlying Areas > 1 Acre

N

0 1 2 Miles

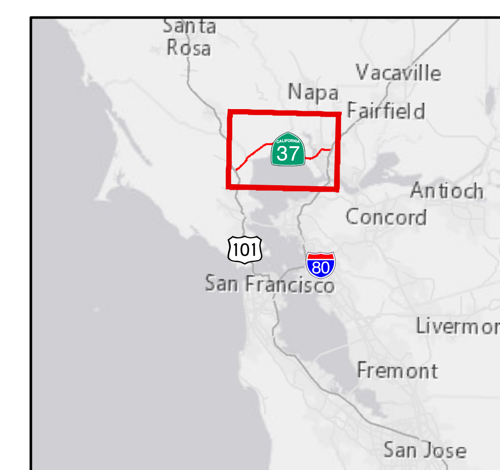
0 5,000 10,000 Feet

AECOM

CALIFORNIA 37

Projection:
NAD 1983 California III; North American Datum 1983

Date: 8/21/2015



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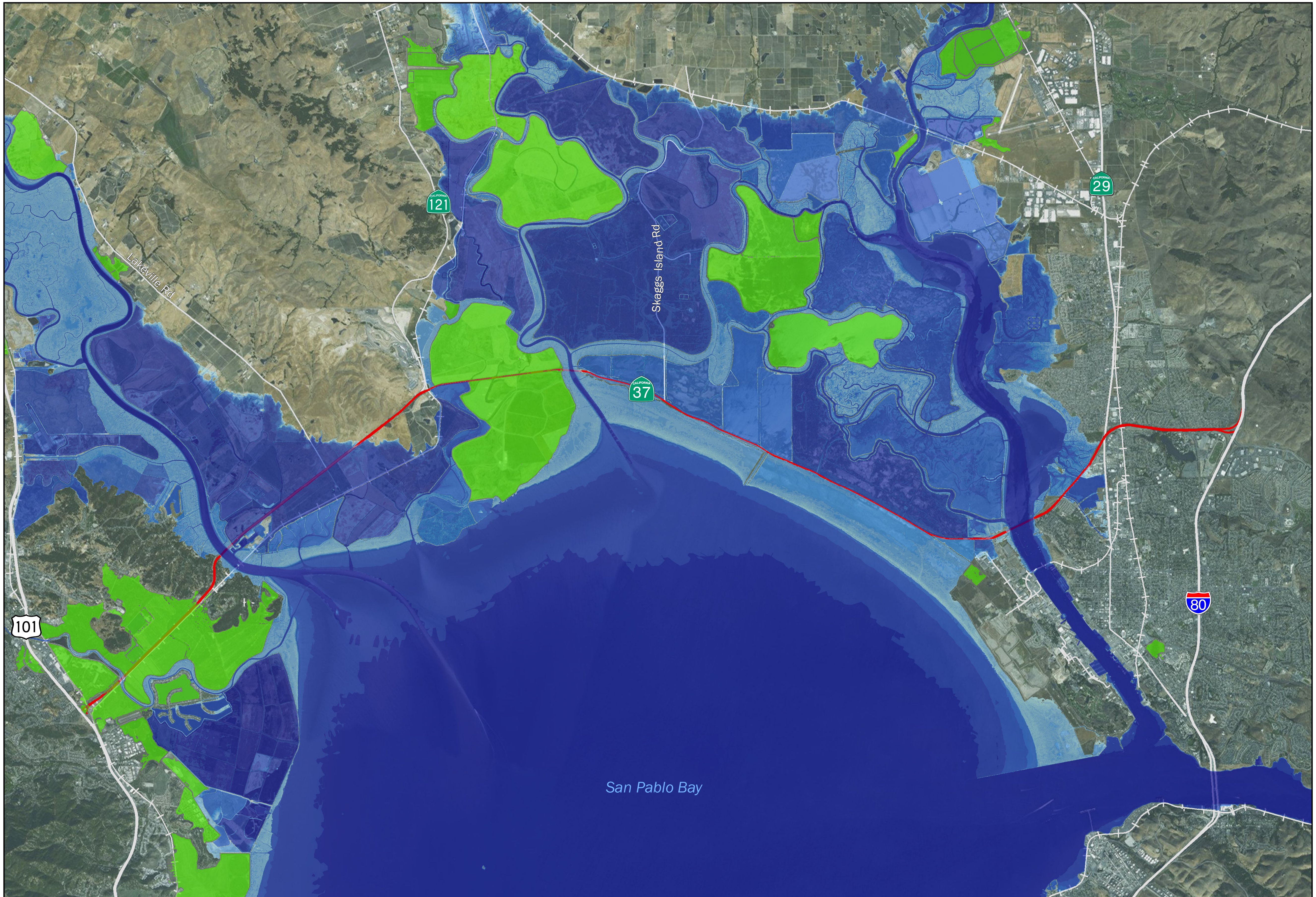
California State Route 37
Inundation Mapping

MHHW + 24" SEA LEVEL RISE

6" SLR + 2-yr Storm Surge
0" SLR + 5-yr Storm Surge



Inundation

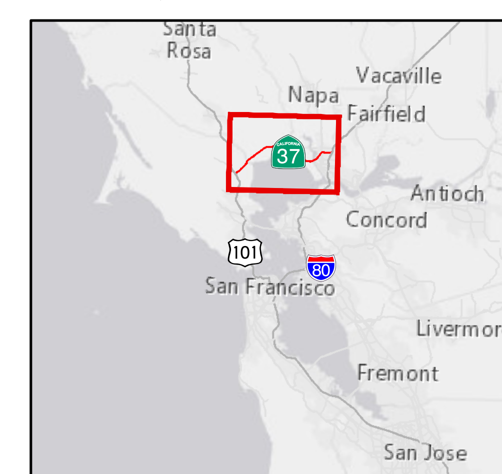
Depth in Feet
0 - 0.5
0.5 - 1
1 - 1.5
1.5 - 2
2 - 2.5
2.5 - 3
3 - 5
5 - 7
7 - 10
10 +
Lowlying Areas > 1 Acre

0 1 2 Miles
0 5,000 10,000 Feet

AECOM

Projection:
NAD 1983 California III; North American Datum 1983

Date: 8/21/2015



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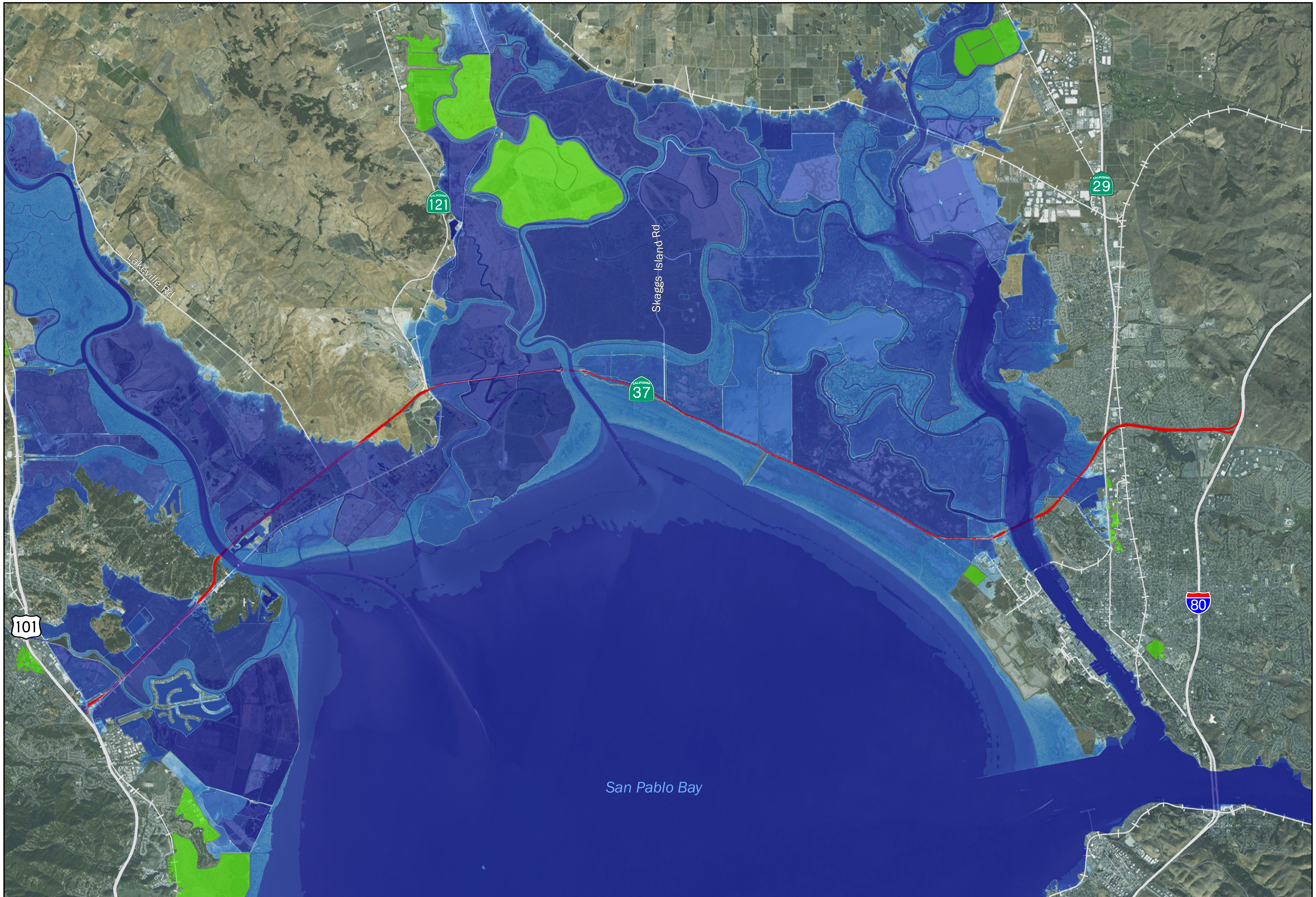
California State Route 37
Inundation Mapping

MHHW + 36" SEA LEVEL RISE

12" SLR + 5-yr Storm Surge
6" SLR + 10-yr Storm Surge
0" SLR + 25-yr Storm Surge



Inundation

Depth in Feet
0 - 0.5
0.5 - 1
1 - 1.5
1.5 - 2
2 - 2.5
2.5 - 3
3 - 5
5 - 7
7 - 10
10 +
Lowlying Areas > 1 Acre

N

0 1 2 Miles

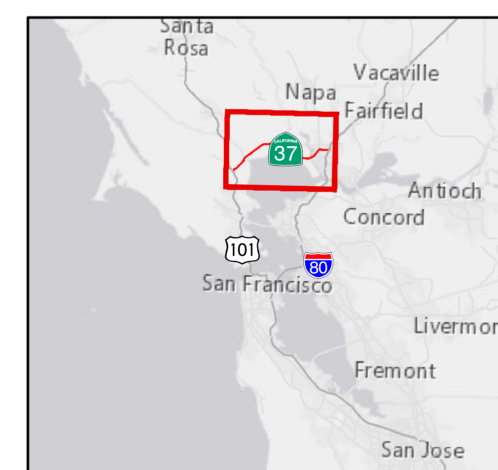
0 5,000 10,000 Feet

AECOM

CALIFORNIA 37

Projection:
NAD 1983 California III; North American Datum 1983

Date: 8/21/2015



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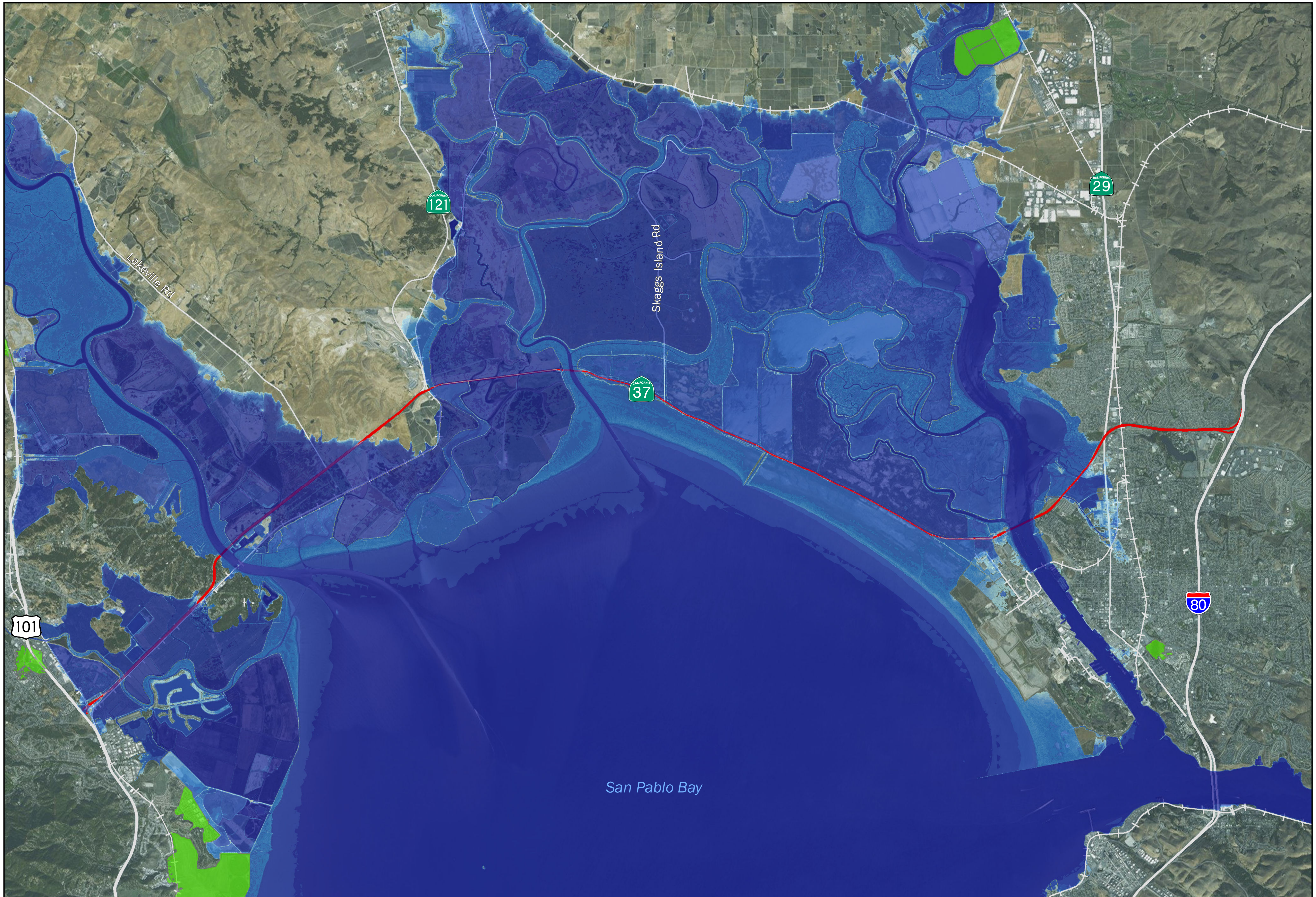
California State Route 37
Inundation Mapping

100 YEAR STORM SURGE
(EXISTING CONDITIONS)



Inundation

Depth in Feet
0 - 0.5
0.5 - 1
1 - 1.5
1.5 - 2
2 - 2.5
2.5 - 3
3 - 5
5 - 7
7 - 10
10 +
Lowlying Areas > 1 Acre

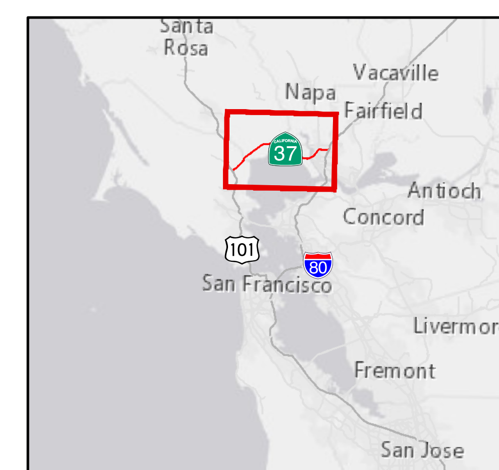
0 1 2 Miles

0 5,000 10,000 Feet

AECOM

Projection:
NAD 1983 California III; North American Datum 1983

Date: 8/21/2015



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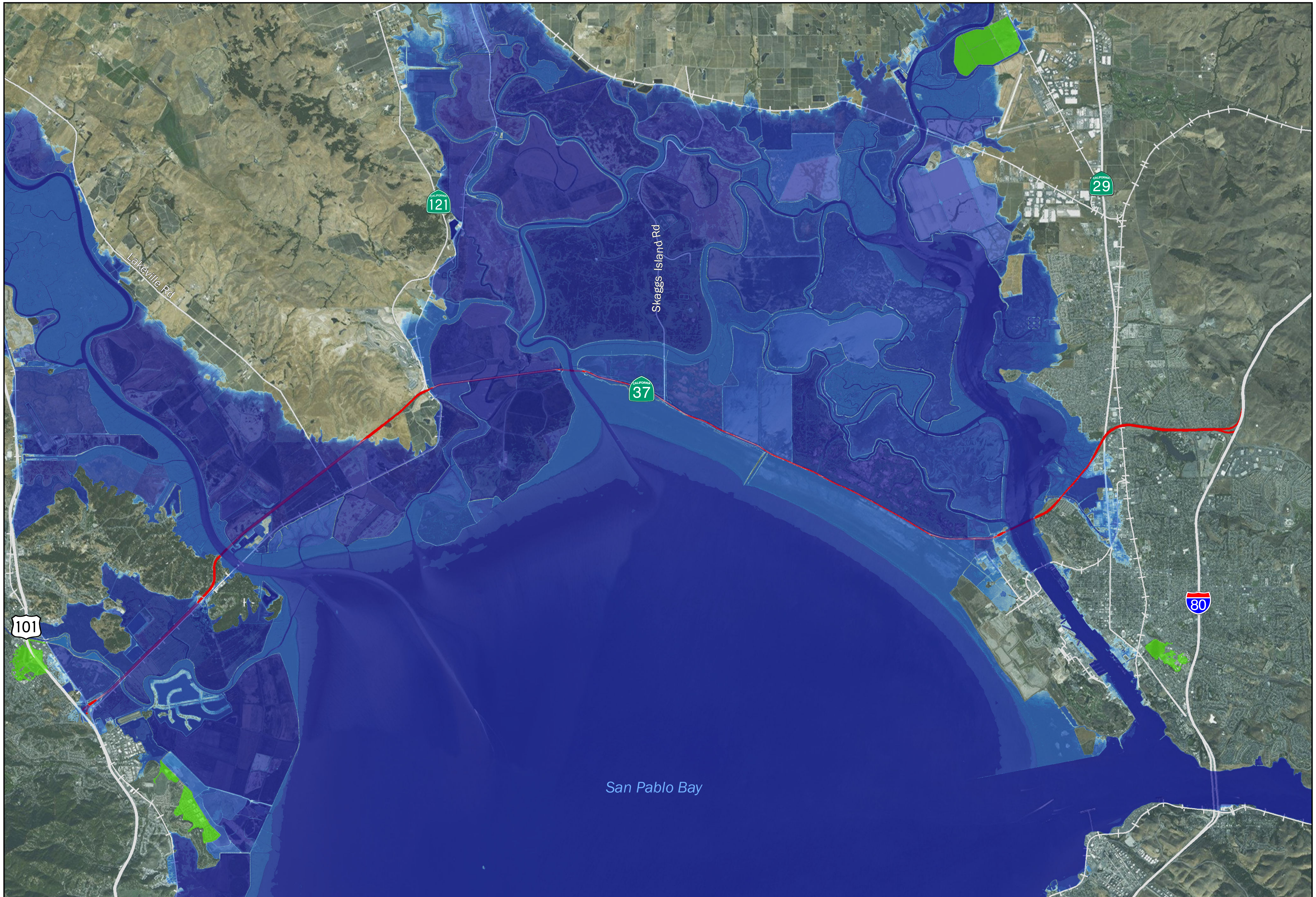


California State Route 37
Inundation Mapping

100 YEAR STORM SURGE
+ 12" SEA LEVEL RISE

36" SLR + 2-yr Storm Surge
24" SLR + 10-yr Storm Surge
12" SLR + 100-yr Storm Surge
0" SLR + 500-yr Storm Surge

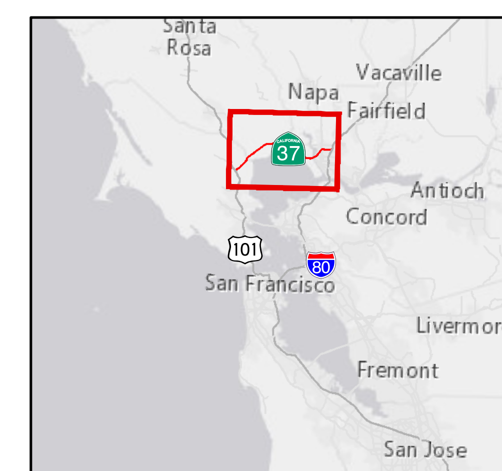
Inundation

Depth in Feet
0 - 0.5
0.5 - 1
1 - 1.5
1.5 - 2
2 - 2.5
2.5 - 3
3 - 5
5 - 7
7 - 10
10 +
Lowlying Areas > 1 Acre

N
0 1 2 Miles
0 5,000 10,000 Feet

Projection:
NAD 1983 California III; North American Datum 1983

Date: 8/21/2015



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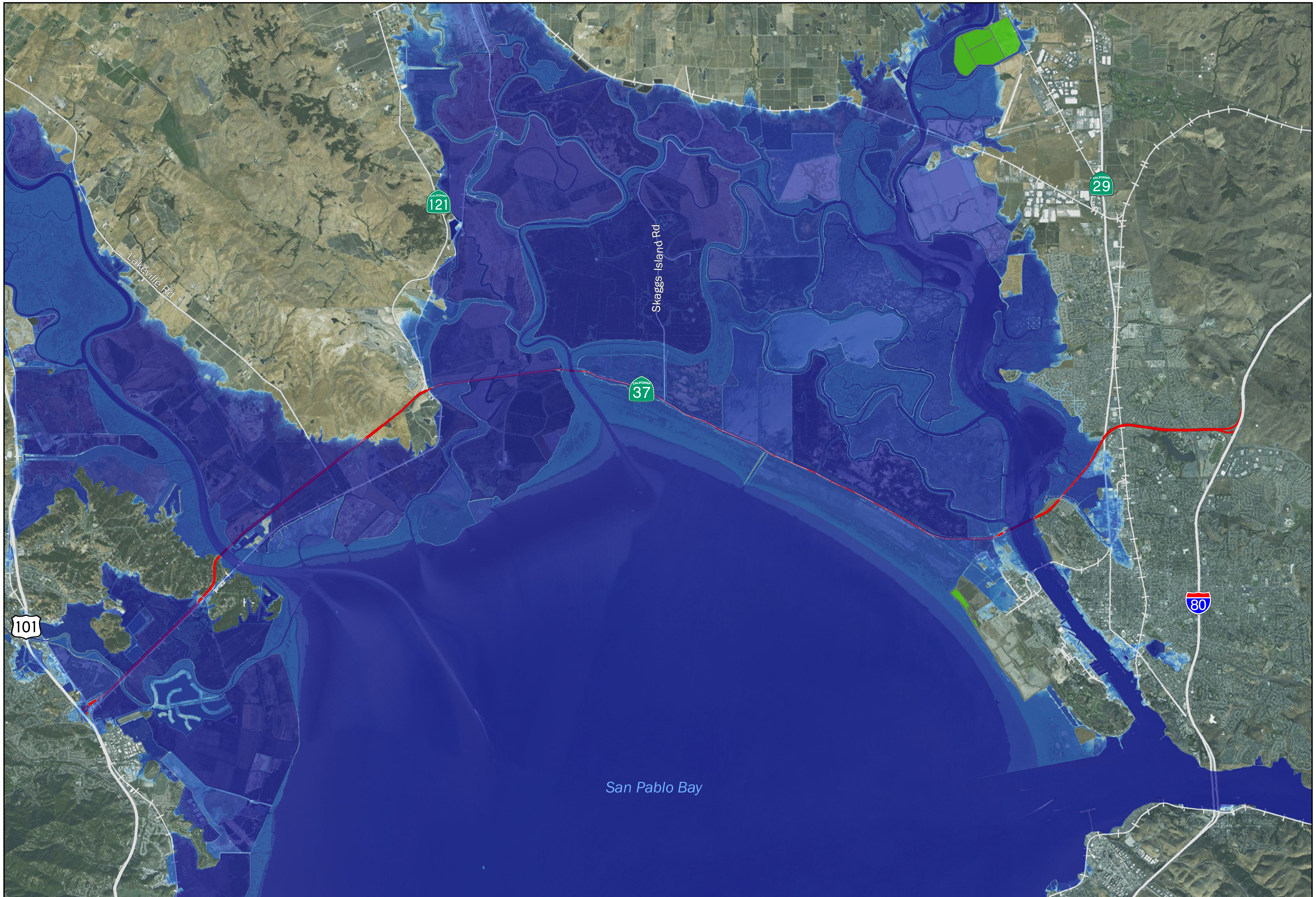
California State Route 37
Inundation Mapping

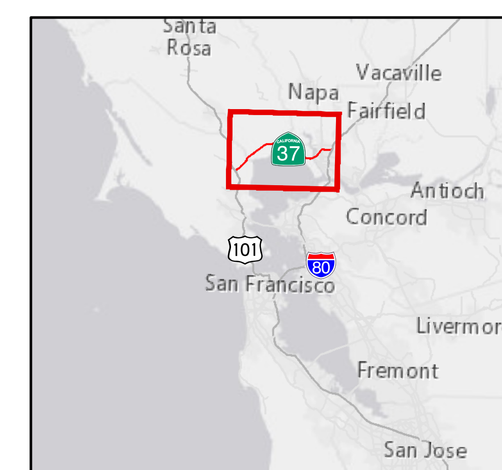
MHHW + 66" SEA LEVEL RISE

48" SLR + 2-yr Storm Surge
42" SLR + 5-yr Storm Surge
36" SLR + 10-yr Storm Surge
24" SLR + 100-yr Storm Surge
12" SLR + 500-yr Storm Surge



Projection:
NAD 1983 California III; North American Datum 1983

Date: 8/21/2015



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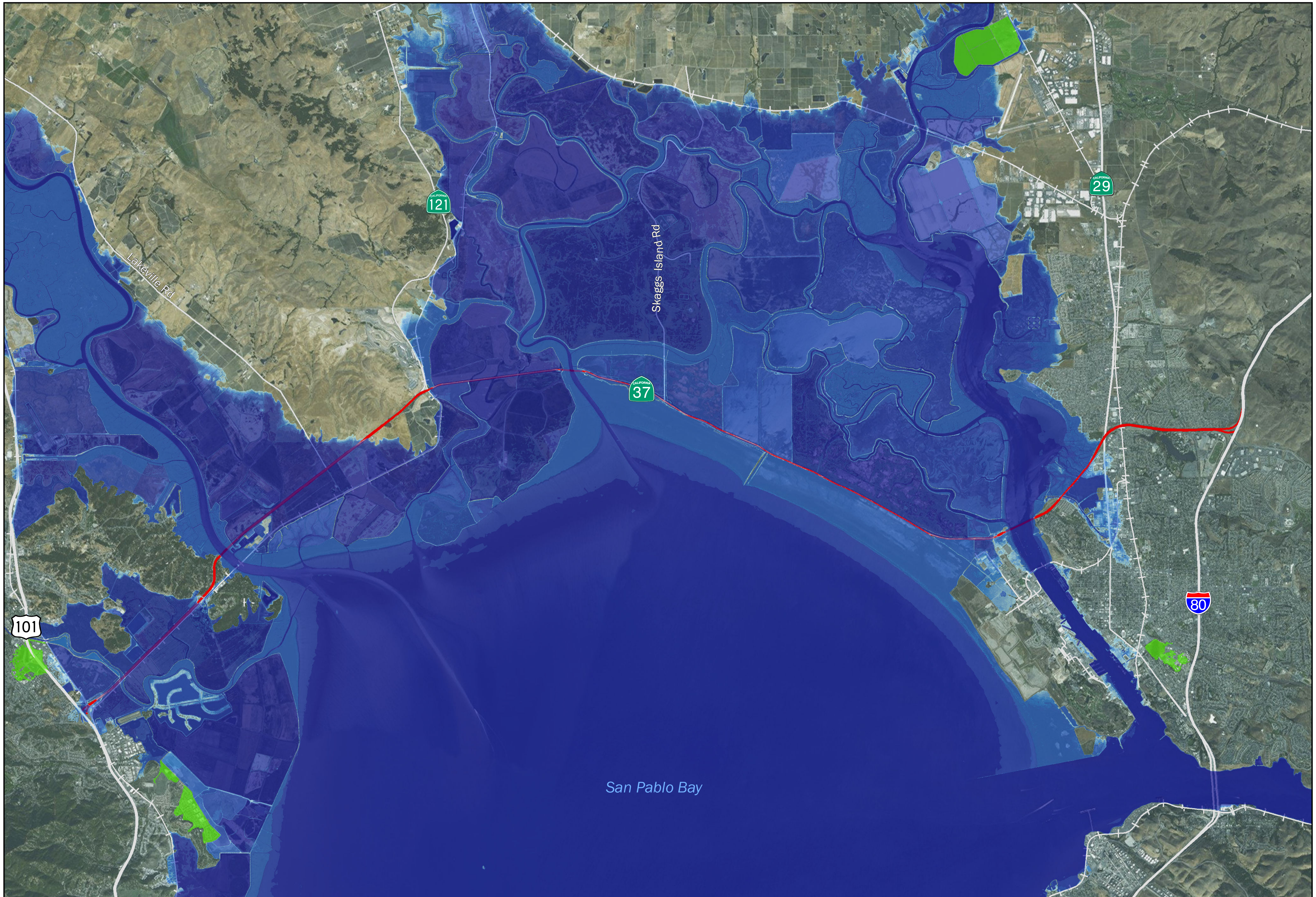
California State Route 37
Inundation Mapping

100 YEAR STORM SURGE
+ 36" SEA LEVEL RISE

60" SLR + 2-yr Storm Surge
54" SLR + 5-yr Storm Surge
48" SLR + 10-yr Storm Surge
42" SLR + 25-yr Storm Surge
36" SLR + 100-yr Storm Surge



Inundation

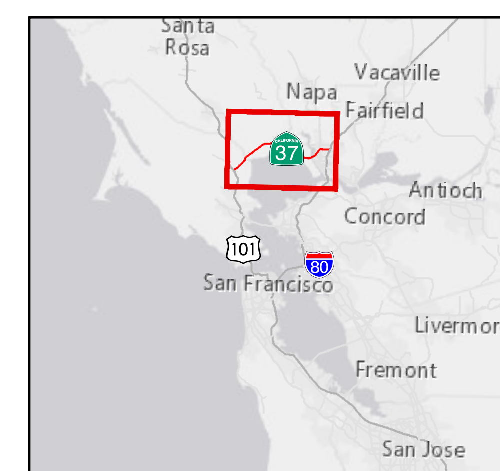
Depth in Feet
0 - 0.5
0.5 - 1
1 - 1.5
1.5 - 2
2 - 2.5
2.5 - 3
3 - 5
5 - 7
7 - 10
10 +
Lowlying Areas > 1 Acre

0 1 2 Miles
0 5,000 10,000 Feet

AECOM

Projection:
NAD 1983 California III; North American Datum 1983

Date: 8/21/2015



Disclaimer: The inundation maps and the associated analyses are intended as planning level tools to illustrate the potential for inundation and coastal flooding under a variety of future sea level rise and storm surge scenarios. The maps depict possible future inundation that could occur if nothing is done to adapt or prepare for sea level rise over the next century. The maps do not represent the exact location or depth of flooding. The maps relied on a 5-ft digital elevation model created from LiDAR data collected in 2010. Although care was taken to capture all relevant topographic features and coastal structures that may impact coastal inundation, it is possible that structures narrower than the 5-ft horizontal map scale may not be fully represented. In addition, inundation and flooding of bridges along the SR 37 alignment was not evaluated. The maps are based on model outputs and do not account for all of the complex and dynamic San Francisco Bay processes or future conditions such as erosion, subsidence, future construction or shoreline protection upgrades, or other changes to San Francisco Bay or the region that may occur in response to sea level rise. For more context about the maps and analyses, including a description of the data and methods used, please see project documentation for the State Route 37 Integrated Traffic, Infrastructure and Sea Level Rise Analysis Study (UC Davis Road Ecology Center and Caltrans District 4).