B4.4 Inundation Mapping

Six inundation scenarios were evaluated as part of this effort. Each SLR scenario—16 inches (40 centimeters) by midcentury and 55 inches (140 centimeters) by the end of the century—is evaluated under three storm/tide conditions: inundation associated with high tides, also known as mean higher high water (MHHW); inundation associated with 100-year extreme water levels, also known as stillwater elevations (100-yr SWEL); and inundation associated with 100-year extreme water levels coupled with wind waves. The three storm/tide conditions were selected as they represent a reasonable range of potential inundation conditions. The inundated area associated with high tides under each SLR scenario is representative of the area that would be subjected to frequent or permanent tidal inundation. This level of inundation could correspond to slow and regular degradation of infrastructure, including shoreline protection. Although storm conditions represent a lower frequency event, they come with a larger potential flooded area with deeper flooded depths, higher velocities, and a greater likelihood of wind-driven waves that could overtop existing shore protection infrastructure. Most of the near-term damage that SLR is expected to cause on developed areas is from storm conditions that occur at the same time as high tides (SPUR 2011).

Three maps were created for each SLR scenario as described above:

- 16-inch SLR (MHHW)
- 16-inch SLR + 100-yr SWEL
- 16-inch SLR + 100-yr SWEL + wind waves
- 55-inch SLR (MHHW)
- 55-inch SLR + 100-yr SWEL
- 55-inch SLR + 100-yr SWEL + wind waves

The inundation maps are presented in Chapter 6, including overall maps for the project area, and five focus area maps that provide a more detailed look at the inundated depth and extent overlain with the selected transportation assets. New inundation maps were created for the pilot study region for several reasons.

- The previous inundation maps created by Knowles (2009, 2010) for the San Francisco Bay Area did not include depth of inundation. The new inundation maps provide the extent of inundation for each scenario, as well as the depth of inundation for the entire inundated area. The depth of inundation along the shoreline assets and at the transportation asset locations was considered to be an important factor in assessing vulnerability to SLR.
- The previous inundation maps did not account for the level of flood protection provided by the region's flood protection levees and other shoreline protection structures. Inundation maps that more accurately characterized the existing shoreline assets would provide a better understanding of the potential risk to future inundation.
- The previous inundation maps did not account for wind waves. Wind wave generation within San Francisco Bay is an important process to consider when evaluating the potential for shoreline overtopping and inundation in nearshore coastal areas.
- The new mapping effort also benefited from an assessment of hydraulic connectivity, using inundation mapping methodologies developed by the NOAA Coastal Services Center to exclude low-lying areas that are below the inundated water surface elevation, but would not be hydraulically connected to the inundated areas.
- The previous study relied on older Light Detection and Ranging (LIDAR) elevation data with less vertical and horizontal accuracy. This study benefits from the 2010 LIDAR data collected by USGS for south San Francisco Bay.

B4.4.1 SUMMARY OF HYDRODYNAMIC MODEL DATA

This section describes the modeling efforts leveraged for this analysis and presents the model output analysis methodology and results.

B4.4.1.1 LEVERAGED MODEL STUDIES

The inundation mapping effort leveraged existing and readily available model output from two, completed large-scale San Francisco Bay modeling efforts: (1) TRIM2D modeling completed by the USGS for the Computational Assessments of Scenarios of Change for the Delta Ecosystem Project, and (2) MIKE21 modeling completed by DHI for the Federal Emergency Management Agency (FEMA) San Francisco Bay coastal hazard analysis and mapping.

B4.1.1.1 USGS TRIM2D Model

The USGS used a TRIM2D hydrodynamic model to simulate water levels throughout San Francisco Bay over time as sea level rises. The goal of the modeling effort was to estimate potential inundation due to rising sea levels within the coastal areas of the nine San Francisco Bay area counties. The study was not intended to quantify the risk of inundation under future scenarios.

The TRIM2D model was validated over the 1996–2007 period. The hydrodynamic model was driven by hourly water levels at the Presidio that simulate conditions associated with 100 years of SLR. The model simulated a rise in sea level of 55 inches (139 centimeters) over the 100-year period. This projection was based on a combination of climate model outputs, and incorporates astronomical, storm surge, El Niño, and long-term SLR (Knowles 2010). The TRIM2D modeling effort does not include locally generated wind waves within San Francisco Bay. Additional details regarding the USGS TRIM2D modeling effort are available in Knowles (2010).

B4.4.1.1.2 FEMA MIKE21 Model

FEMA is performing new detailed coastal engineering analysis of San Francisco Bay. The goal of the study is to revise and update the flood and wave data for the coastal Flood Insurance Study reports and Digital Flood Insurance Rate Maps. A region-scale hydrodynamic, storm surge and wave model of San Francisco Bay was developed to provide 100-year SWEL (extreme water levels that are exceeded, statistically, once every 100 years), open ocean swells propagating through the Golden Gate, and locally generated wind waves. The region-scale models were developed to provide boundary conditions for onshore coastal hazard analyses.

The FEMA study used the MIKE 21 Hydrodynamic and MIKE 21 Spectral Wave models to simulate water levels and waves for a 31-year continuous period from 1973 to 2004 (Conner et al. 2011). Model input and boundary conditions include the ocean tide level, lower Sacramento River discharge, wind and pressure fields, and various river, creek and tributary discharges. The model was calibrated for tides and storm elevations throughout San Francisco Bay. The wave model was calibrated against a limited number of available wave measurements within the bay. Additional details regarding the FEMA modeling effort are available in DHI (2010) and Conner et al. (2011).

B4.4.1.2 MODEL OUTPUT ANALYSIS

The general approach followed in the analysis of the model output data was to first determine daily tide, extreme tide, and storm conditions for existing conditions at specific model output points within the study area. The derived water level statistics were then projected to future conditions by adding the specified amount of SLR for the midcentury and end-of-century MHHW SLR scenarios. The results at each model output point were then interpolated and extrapolated to create a water surface map for each of the six inundation scenarios. The water surface maps were then used as input in the inundation mapping. The water level analysis at the model output locations is described in this section. The creation of the water surface maps and inundation mapping efforts are described in Section B4.4.2.

B4.4.1.2.1 Model Extraction Points

Output from the USGS TRIM2D and FEMA MIKE21 hydrodynamic modeling efforts was obtained to develop the water surface maps for the inundation mapping scenarios. Noah Knowles (USGS) provided TRIM2D model output at 30 model extraction points, including points along the Alameda County shoreline and along the main San Francisco Bay channel. Figure B4.8 shows the location of the output points within the project area. The extraction points were selected to accurately characterize the spatial variability of water levels throughout the study area and facilitate development of the water surface maps. The extraction points along the Alameda County shoreline were also selected to coincide with model output locations from the existing FEMA MIKE21 model grid so that results from the two models could be compared and used together to more fully characterize the water level and wave conditions within the study area.

USGS TRIM2D model output was provided in 1-hour time steps from January 1, 2000, to December 31, 2099, and consisted of water surface elevations relative to the North American Vertical Datum of 1988 (NAVD88). FEMA MIKE21 model output was provided in 15-minute time steps for water level data and in 1-hour time steps for wave heights. The water level and wave records extended from January 1, 1973, to December 31, 2003. Water surface elevations were provided relative to NAVD88.

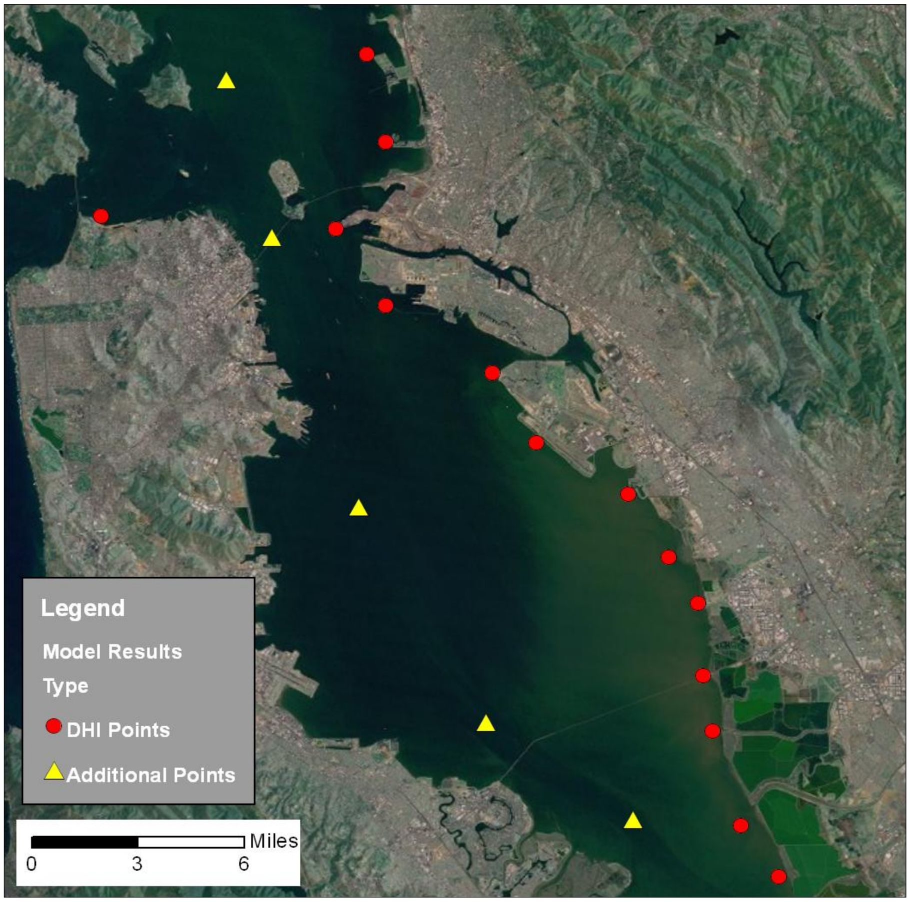

Figure B4.8. DHI and USGS Model Extraction Points within the Project Area

B4.4.1.2.2 USGS TRIM2D Stationarity Analysis

One of the fundamental assumptions in the Knowles (2010) inundation mapping was that of stationarity of the tidal hydraulics over the 100-year simulation period. This assumption was necessary given the methodology used to compute the daily tide and extreme tide statistics at each model output point. For example, under stationary conditions, the daily and extreme tides for existing conditions can be projected into the future simply by adding a specific amount of SLR (e.g., 16 inches [40 centimeters], 55 inches [140 centimeters]). This assumption does not account for factors that may modify the tidal hydraulics over the course of the 100-year simulation period. For example, as sea level rises the mean water depth of the bay will increase, which could affect the way in which the tidal wave propagates throughout the bay. Changes in tidal wave propagation could result in increases or decreases in the tide range at a particular location over time, which would invalidate the stationary assumption inherent in the statistical analysis used to determine daily and extreme tide levels within the study area.

To assess the stationarity assumption, the TRIM2D model time series at each output point was examined to determine if any long-term trends in the elevation of the MHHW tidal datum were observed in the 100-year time series. The following steps were performed at each model extraction point within the study area:

1. The 100-year water level time series was detrended to remove the long-term mean SLR trend (Figure B4.9, lower panel)
2. The detrended time series was segmented into 10-year decadal blocks (e.g., 2000–2010, 2010–2020)
3. The elevation of the MHHW tidal datum was calculated for each decadal block (Figure B4.9, upper panel)
4. A regression line was fit to the decadal MHHW values to determine the long-term trend (Figure B4.9, upper panel)

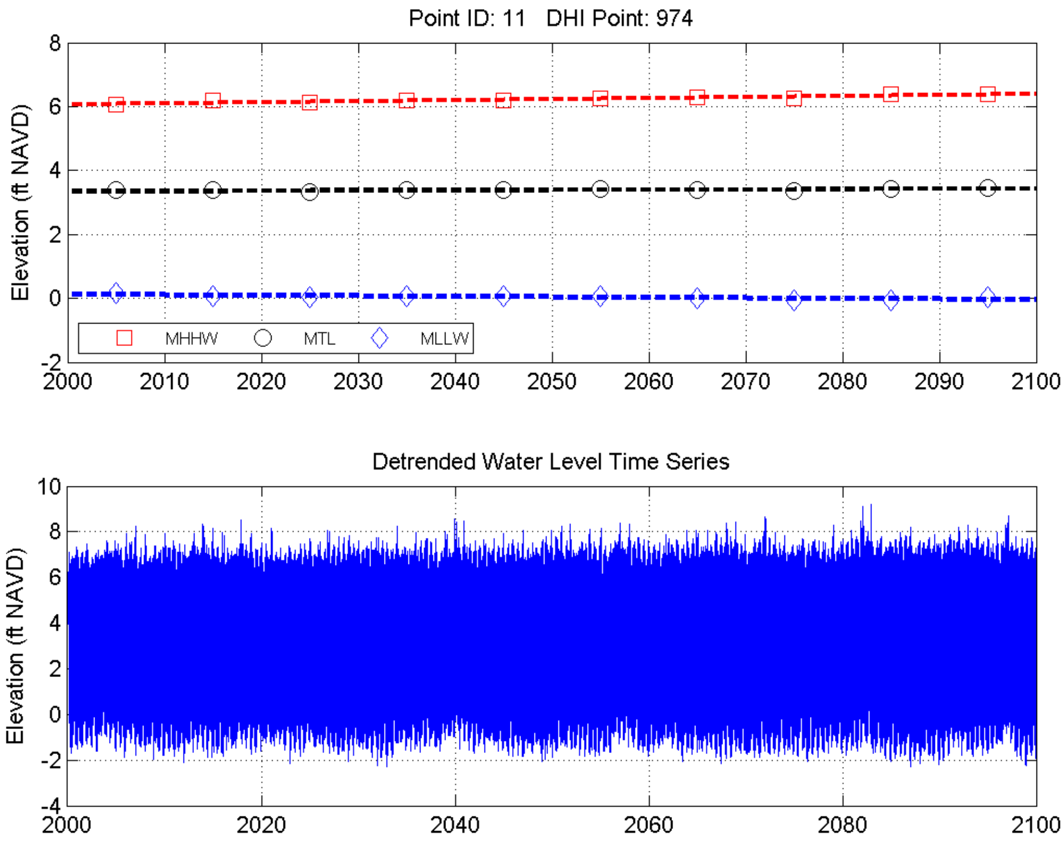

Figure B4.9. Stationarity Analysis and Trends for Sample Model Extraction Point along Alameda County Shoreline

Figure B4.9 shows an example of the analysis and trend determined from the decadal values of the MHHW tidal datum at an example point within the study area. The lower panel shows the 100-year time series with the mean SLR trend removed. The upper panel shows the decadal averaged tidal datums for MHHW, MTL, and MLLW. For each datum, the dashed line is the regression line from which the long-term trend was computed. An average trend of +0.33 foot (+0.1 meter) per century was determined for the MHHW tidal datum along the Alameda County shoreline. This result means that in the TRIM2D modeling, the MHHW tidal datum increased in elevation at a faster rate than mean sea level over the 100-year simulation period. Therefore, based on this analysis, the stationary assumption is not valid within the project area.

Given the importance of maintaining stationarity in the statistical analysis and the large uncertainty in potential future changes in tidal hydraulics due to SLR, it was decided to remove the MHHW trend from the USGS model output prior to statistical analysis. This procedure is described in more detail in Section B.4.4.1.2.3.

B4.4.1.2.3 Daily and Extreme Tide Analysis

Water level time series from the USGS TRIM2D and FEMA MIKE21 simulation periods were analyzed to determine daily and extreme tide levels for existing conditions throughout the study area. Methods of water level analysis are described below.

At each TRIM2D model output point, daily tide and extreme tide levels were computed. The MHHW tidal datum was selected to represent the average daily high tide. Average daily tide elevations for existing conditions were computed using the first 30 years of the detrended simulated time series (i.e., with the mean SLR trend removed). Only the first 30 years were used to avoid complications associated with the stationarity issue discussed in Section B.4.4.1.2.2. MHHW elevations for existing conditions ranged from approximately 6.1 feet to 7.0 feet NAVD from the northern to southern portions of the study area. Results of the daily tide analysis are shown in Figure B4.10.

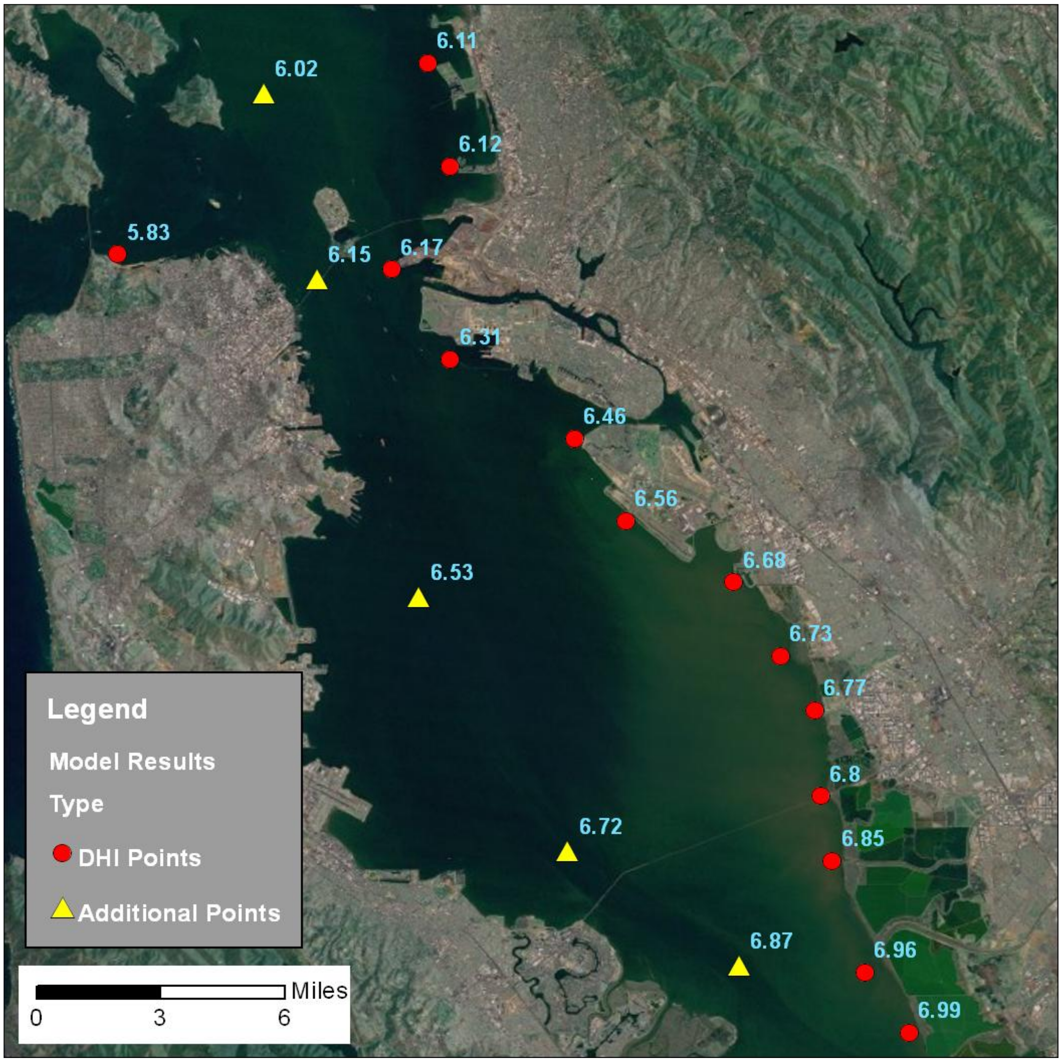

Figure B4.10. Average Daily Tide Elevations (MHHW Tidal Datum) for Existing Conditions Determined from USGS TRIM2D Modeling

Note: Elevations referenced to NAVD88.

The method presented by Knowles (2010) served as the basis for the determination of the extreme tide elevations, and is summarized below. The water level statistic used to represent the extreme tide in this study is the 1 percent-annual-chance water level, commonly referred to as the 100-year SWEL. The following steps were performed to determine the extreme tide elevation at each model extraction point:

1. The 100-year water level time series was detrended to remove the long-term mean SLR trend
2. Annual maxima were extracted based on a July–June “storm year”
3. Annual maxima were adjusted by removing the +0.33 feet per century MHHW trend determined from the stationarity analysis (Section B4.4.1.2.2)
4. A Weibull probability distribution was fit to the annual maxima dataset and extreme tide elevations were determined

Steps 1–3 are illustrated in Figure B4.11. Results of the extreme tide analysis for the USGS TRIM2D model output are shown in Figure B4.12.

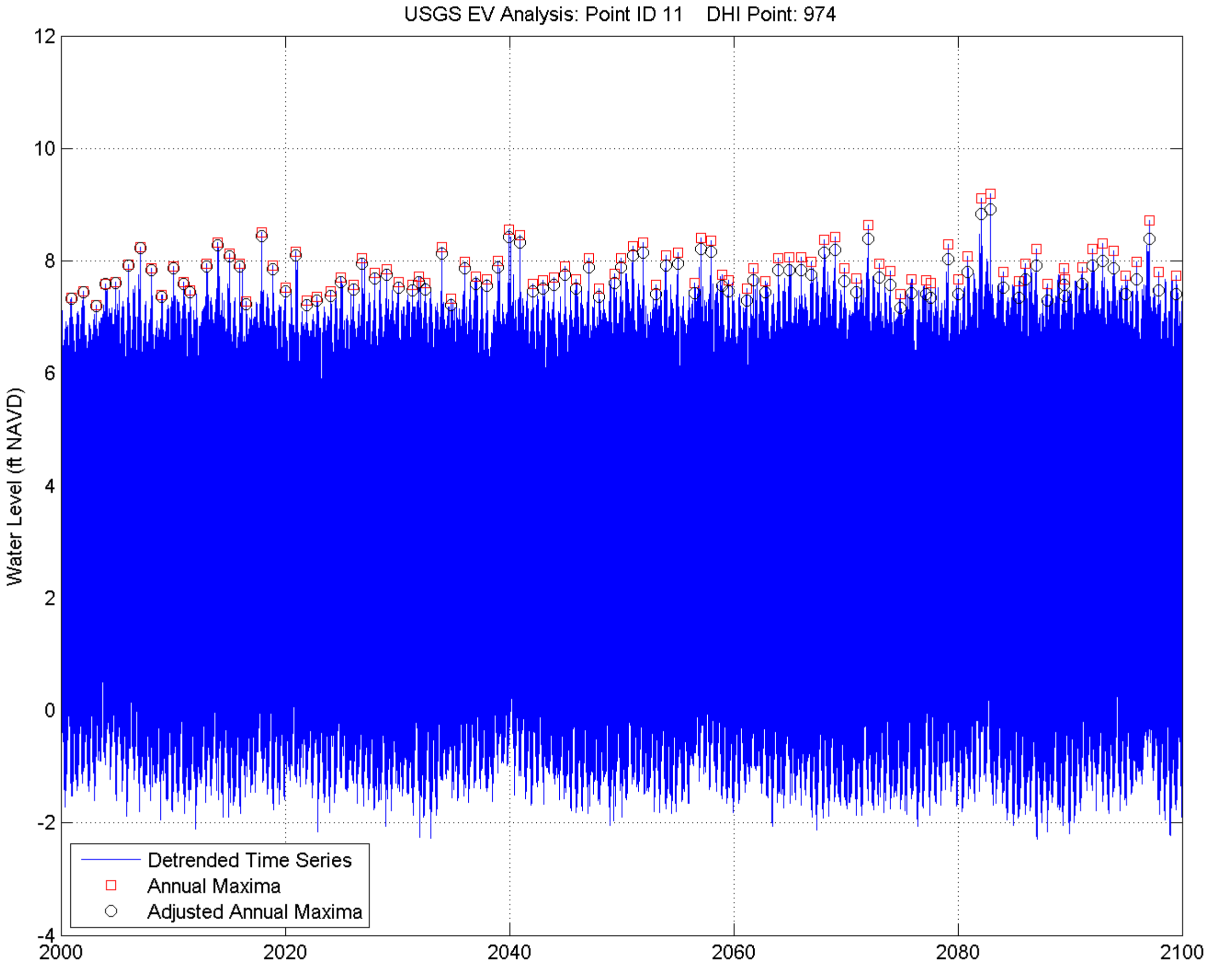

Figure B4.11. Extreme Value Analysis of Annual Maxima for Sample Model Extraction Point along Alameda County Shoreline

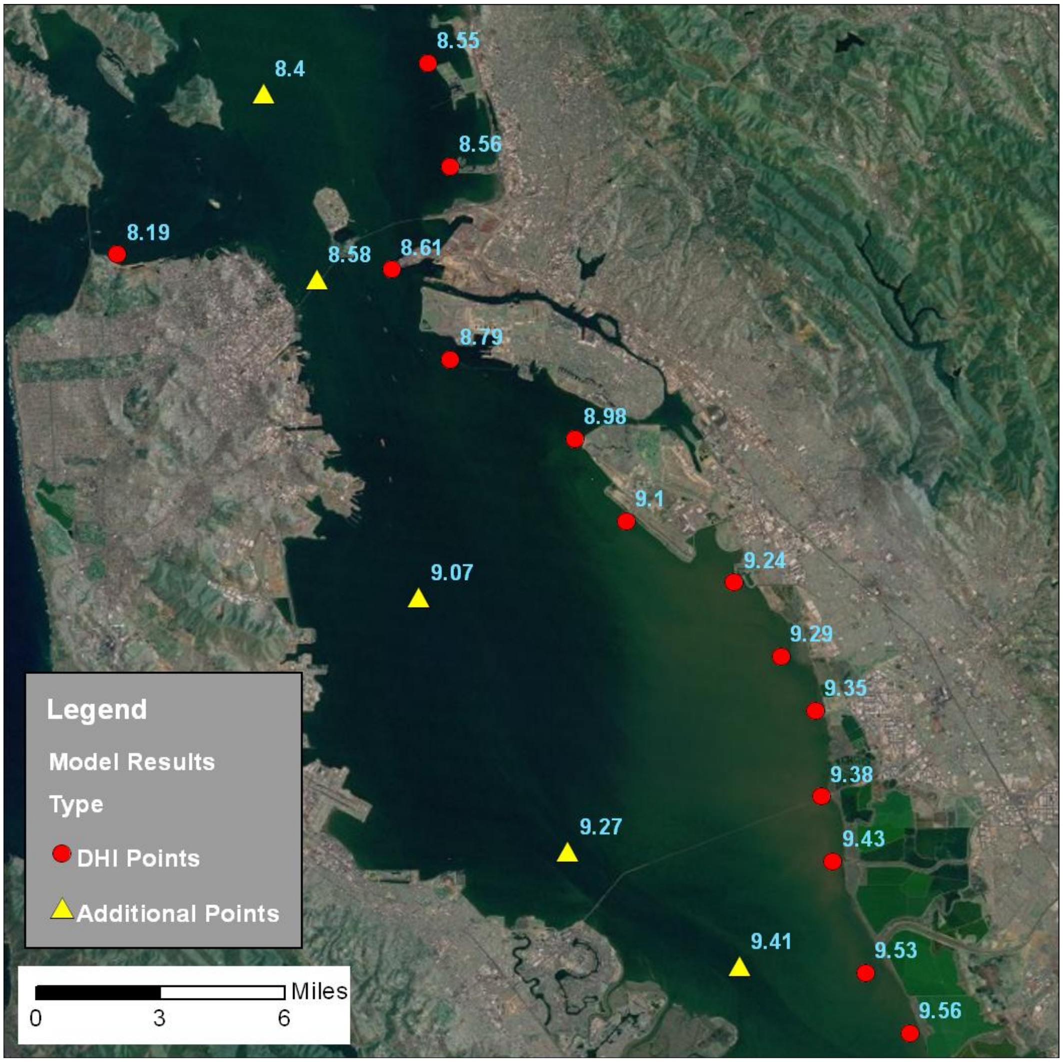

Figure B4.12. Extreme Tide Elevations for Existing Conditions Determined from USGS TRIM2D Modeling

Note: Elevations referenced to NAVD88.

Extreme tide levels were also computed at each of the FEMA MIKE21 model output points. Since the MIKE 21 model boundary condition was detrended to remove SLR in the original modeling effort, it was not necessary to detrend the water level time series prior to statistical analysis. Similarly, no adjustment for stationarity was required. Steps 2 and 4, listed above for the USGS TRIM2D analysis, were carried out to determine the extreme tide levels based on the FEMA water level time series. Results of the extreme tide analysis for the FEMA MIKE21 model output are shown in Figure B4.13.

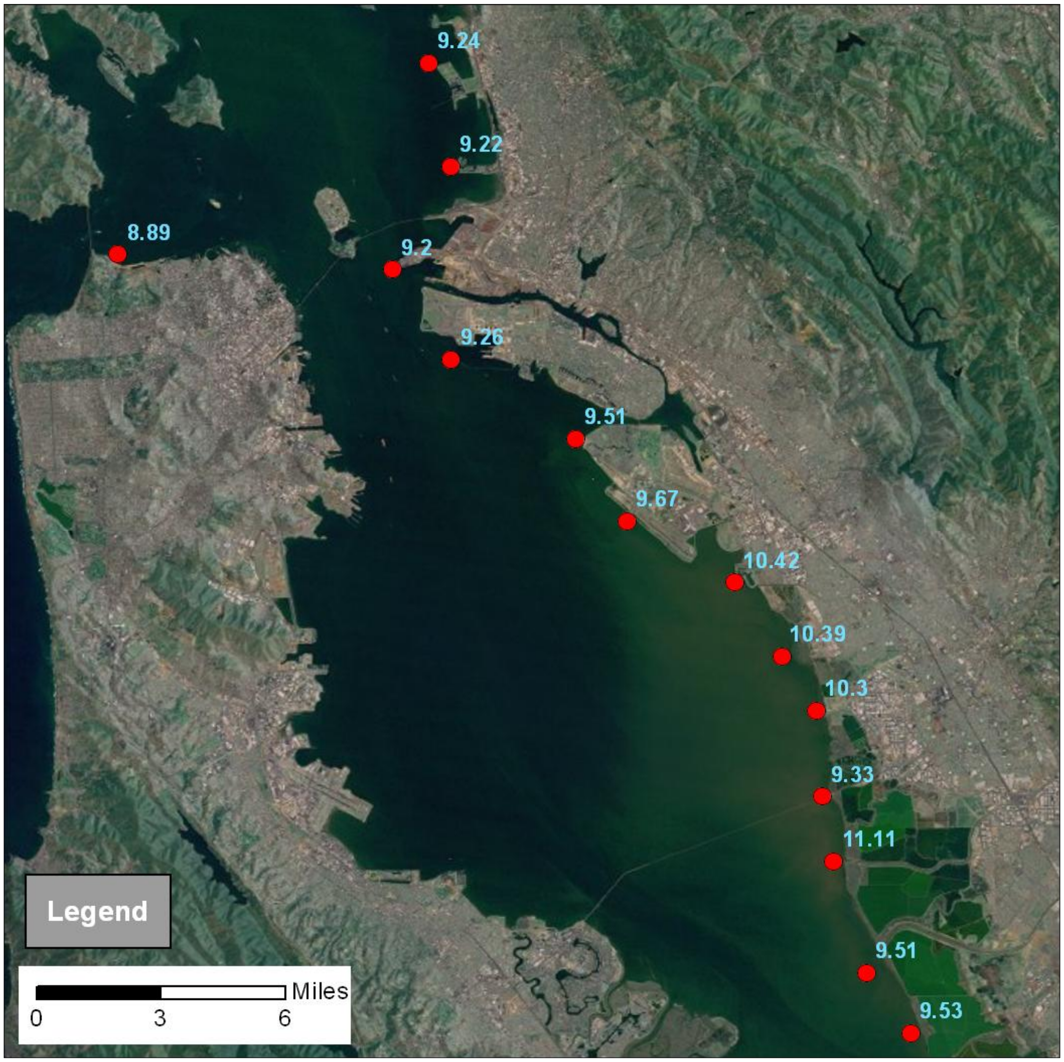

Figure B4.13. Extreme Tide Elevations for Existing Conditions Determined from FEMA MIKE21 Modeling

Note: Elevations referenced to NAVD88.

B4.4.1.2.4 Wind/Wave Storm Scenario Development

Analysis of the USGS TRIM2D and FEMA MIKE21 simulated water levels provides two independent estimates of the extreme tide level along the Alameda County shoreline; however, the two estimates are not directly comparable due to the specifics of each modeling effort. For example, the USGS and FEMA modeling efforts spanned different periods of record: a 100-year projection vs. a 30-year hindcast. Additionally, the FEMA modeling accounted for wind effects including wind setup and wind-wave generation within the bay, whereas the USGS modeling did not. The development of the wind/wave storm scenarios took advantage of these differences to combine the results of the two modeling efforts.

Since the USGS modeling effort spanned a longer period of record, use of the TRIM2D model results was preferable for the extreme tide statistical analysis; however, since theTRIM2D model did not include local wind and wave effects, these components were derived from the FEMA MIKE21 modeling. To develop the storm wave scenario the following additional processes needed to be accounted for along the Alameda shoreline: (1) wind setup, (2) wave setup, and (3) wave height. Wind setup is a component of storm surge that results in an increase in water level due to wind blowing across the water surface and "piling up" water at the shoreline. Similarly, wave setup is an increase in water level at the shoreline due to the presence of breaking waves. These two processes will increase water levels at the shoreline above the extreme tide levels determined from the statistical analysis presented in Section B4.4.1.2.3.

Wind Setup. Since the FEMA MIKE21 model includes wind effects and the USGS TRIM2D model does not, it was assumed the magnitude of wind setup could be estimated as the difference between the extreme tide estimates from the two models. The extreme tide level determined at each model output point from the FEMA MIKE21 and the USGS TRIM2D models was found to differ by -0.1 to 1.7 feet (-0.03 to 0.5 meter), with an average of approximately +0.5 feet (+0.2 meter) within the project area. The contribution of wind setup to the total surge level was therefore estimated to be approximately 0.5 foot (0.2 meter). This value was applied throughout the project area for the wind/wave storm scenarios.

Wave Height. In addition to the water level time series, the time series of wave height was provided at each model output point for the FEMA MIKE21 model. Steps 2 and 4 of the extreme tide statistical analysis were carried out with the wave height time series to determine extreme wave heights. The 10-year wave height was selected as an appropriate storm condition to pair with the 100-year water level to represent the wind/wave storm scenarios. Results of the wave height analysis are shown in Figure B4.14.

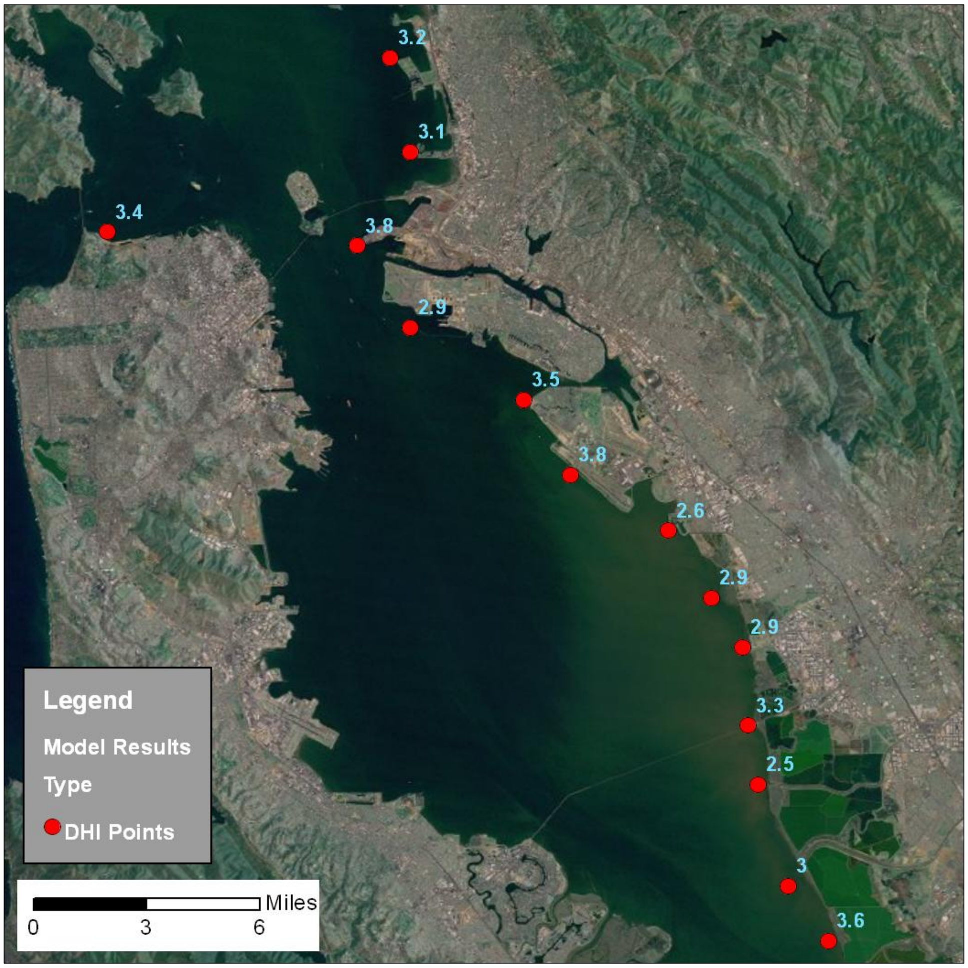

Figure B4.14. Storm Wave Heights for Existing Conditions Determined from DHI MIKE21 Modeling

Note: Wave heights shown in units of feet.

10-year wave heights along the Alameda County shoreline were found to range from 2.5 to 3.8 feet (0.8 to 1.2 meters), with an average of 3.5 feet (1.1 meters). For the purposes of FEMA flood mapping, it is assumed that 70 percent of the computed wave height contributes to the total stormwater level. In other words, the wave form is not symmetrical: 70 percent of the wave form is above the average water level, and 30 percent is below. To create the storm scenario water levels in this study, a value equal to 70 percent of the computed wave height from the FEMA MIKE21 model was added to the extreme tide level, along with wind and wave setup.

Wave Setup. While the DHI MIKE21 model simulates the generation of waves by local wind, it is not believed that wave setup is present in the water level time series at the model output points. Wave setup can be roughly estimated using a rule-of-thumb of 17 percent of the offshore wave height (Guza and Thornton 1981). Detailed wave analysis is beyond the scope of this study, so the wave heights at the output locations were used with no modification. Using the range of wave heights shown in Figure B4.14 and the wave setup rule-of-thumb, wave setup was computed to be approximately 0.5 foot (0.2 meter) within the project area. This value was applied throughout the project area for the wind/wave storm scenarios.

Stormwater Level. Once approximate values for wind setup, wave setup, and storm wave height were estimated, these additional water level components were combined with the extreme tide level to estimate the wind/wave storm scenario water levels for existing conditions. The storm scenario represents the coincident occurrence of a 100-year water level coupled with a 10-year wave event. The storm wave scenario is represented as follows:

[Stormwater level] = [100-yr extreme tide] + [wind setup] + [wave setup] + 0.7 x [10-yr wave height]

The resulting stormwater levels with waves for existing conditions are shown in Figure B4.15.

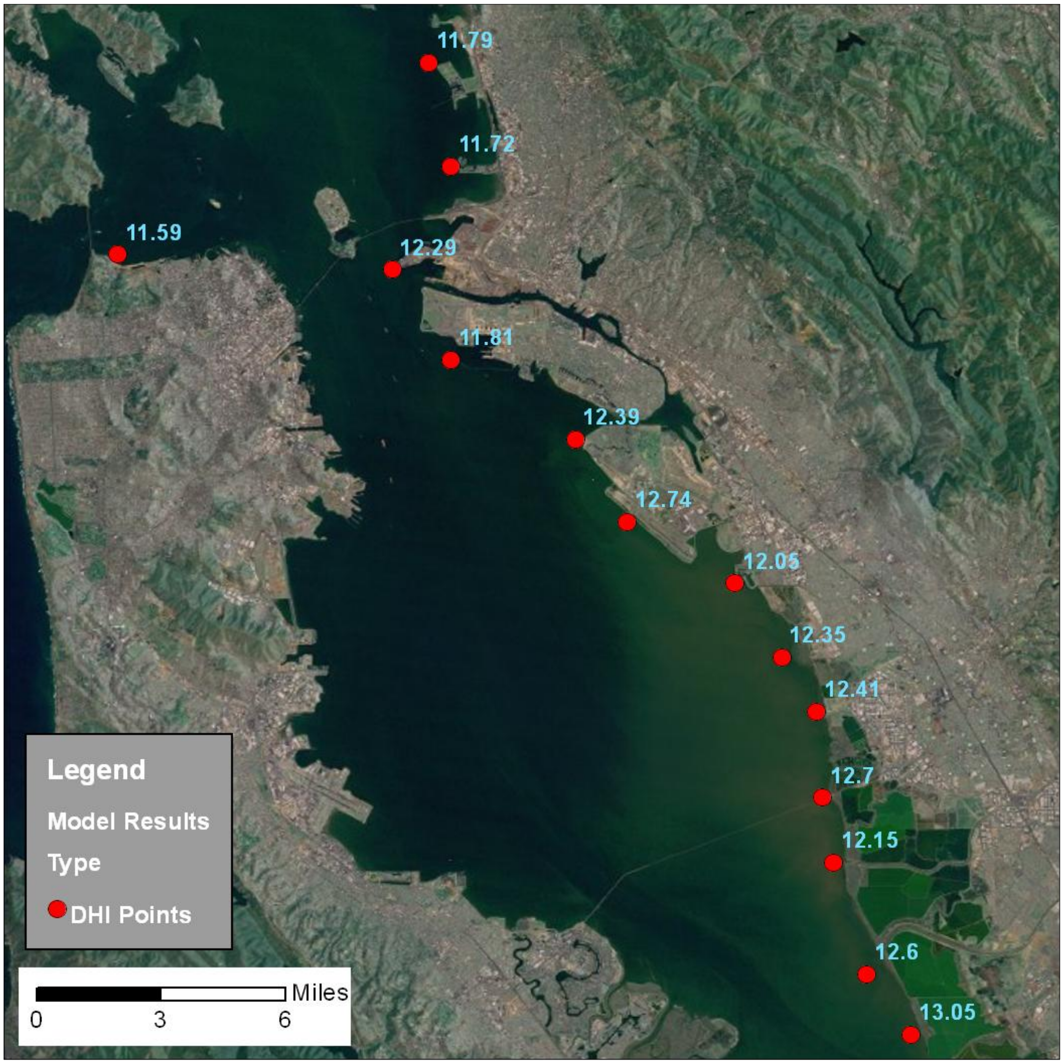

Figure B4.15. Storm Scenario Water Levels with Waves for Existing Conditions

Note: Elevations referenced relative to NAVD88.

B4.4.2 INUNDATION MAP DEVELOPMENT

Once the relevant statistics for the water levels had been generated for the six inundation mapping scenarios, the inundation maps were developed utilizing methodologies developed by the NOAA Coastal Services Center (Marcy et al. 2011).

B4.4.2.1 LEVERAGED TOPOGRAPHIC DATA

USGS managed the LIDAR data collection in south San Francisco Bay. The South Bay LIDAR data were collected in June, October, and November 2010 and provide complete coverage of the coastal areas of Alameda County, up to the 16-foot (5-meter) elevation contour.

The USGS LIDAR and associated Digital Elevation Model (DEM) provide the topographic data for the inundation mapping effort. The bare-earth LIDAR was used for the inundation mapping. In the bare-earth

LIDAR, all building and structures (i.e., bridges) 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.

B4.4.2.2 WATER SURFACE DEM CREATION

The initial step in creating the inundation maps relies on creating the inundated water surface, or DEM.

The appropriate amount of SLR (i.e., 16 and 55 inches [41 and 140 centimeters]) was added to the model output data generated for the daily tide (Figure B4.10), extreme tide (Figure B4.12 and 4.13), and extreme storm scenario with wind waves (Figure B4.15) in order to develop the tidal water surface over the open water portion of the bay along the Alameda County shoreline for the six inundation map scenarios:

- 16-inch SLR MHHW (high tide)
- 16-inch SLR + 100-yr SWEL (extreme tide)
- 16-inch SLR + 100-yr SWEL + wind waves (extreme coastal storm event)
- 55-inch SLR MHHW (high tide)
- 55-inch SLR + 100-yr SWEL (extreme tide)
- 55-inch SLR + 100-yr SWEL + wind waves (extreme coastal storm event)

The tidal water surface was then extended inland along a series of transects placed perpendicular to the shoreline to create the water surface elevation over the inundated topography. It should be noted that water surface DEM is simply 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, wave dissipation, levee overtopping, or potential shoreline or levee erosion associated with extreme water levels and waves. In order to account for these processes, a more sophisticated modeling effort would be required.

B4.4.2.3 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 2-meter 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 sea level (or the assigned final 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 efforts that considered a grid cell to be inundated solely based on its elevation.

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.

Chapter 6 presents the final inundation maps for the six scenarios. Low-lying areas that are not hydraulically connected to the inundated areas are shown in green.

The inundation mapping effort was associated with a series of challenges that required careful consideration and attention to detail. In order to develop credible inundation maps, it was important that the levees are adequately resolved in the topographic DEM. A DEM resolution of 2 meters was ultimately used to resolve the levees. However, this resolution was not sufficient to identify floodwalls. Levees that were stair stepped with respect to the DEM grid required the most attention to ensure they were appropriately resolved. The hydraulic connectivity analysis was a useful tool for evaluating whether or not specific levee reaches and/or levee systems were resolved. If the inundated water surface elevation was below a levee crest (i.e., the levee was not overtopped), yet the area behind the levee was not removed from the inundated surface as part of the hydraulic connectivity assessment, the levees (or other topographic features) were investigated in more detail to determine which section(s) were not represented well in the DEM. This type of assessment required an in-depth understanding of the Alameda County shoreline and the shoreline protection assets.

B4.4.3 SHORELINE OVERTOPPING POTENTIAL

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

B4.4.3.1 METHODOLOGY

The process and objectives for this analysis was as follows:

- Subdivide the study area into a series of shoreline “systems” – contiguous reaches of shoreline that act together to prevent inundation of inland areas.
- Determine at what locations in the study area shoreline assets are overtopped, causing inundation of low-lying areas landward of the shoreline.
- Determine the length (and percent) of shoreline affected by overtopping.
- For each transportation asset, determine its proximity (i.e., distance) to a segment of overtopped shoreline.
- For each transportation asset, determine which shoreline “system” is responsible for providing protection from inundation.
- Assess the potential for overtopping for each shoreline “system.”

The depth of inundation was extracted along the shoreline asset delineation described in Chapter 2. Although the delineation in Chapter 2 defines wetlands and beaches as shoreline asset categories, the delineation for the assessment of overtopping potential was moved inland in select areas to the topographic feature that could control inundation, such as levees, berms, or road embankment crests, which act as barriers to inland inundation.

The shoreline delineation was also subdivided into “systems” that act together to prevent or influence inland inundation. This approach was taken to develop meaningful metrics for assessing the vulnerability of the transportation assets and identifying potential adaptation strategies. A system could be defined as a reach of levee along the shoreline between two adjacent tributaries. Alternatively, a system could be defined as the combination of several asset types (e.g., levees, nonengineered berms, roadway embankments) that act together to influence the inundation of an inland area with similar topographic elevation. Although smaller systems could technically be defined within any given system, the size of the systems were selected to be small enough to provide meaningful metrics relating to the transportation assets, yet large enough to be manageable within the context of this high-level assessment.

The system delineation is shown on the shoreline overtopping potential maps presented in Chapter 6. In total, 28 systems were delineated within the study area ranging in length from approximately 1 to 18 miles. On average, the systems were 4.5 miles in length. The shoreline system delineation was overlain on each of the six inundation depth rasters (i.e., one raster for each of the six inundation scenarios described in Section B4.4), and depth values along the shoreline were extracted from the rasters. Contiguous reaches of overtopped shoreline were grouped together and aggregated as shoreline segments. Overtopping statistics, or metrics, were then calculated for shoreline segments and shoreline systems for each inundation scenario. 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 metrics. The following primary metrics were used to evaluate shoreline overtopping potential:

- *Potential overtopped length of each system*. The length of shoreline that is overtopped within each system can be an indication of the overall vulnerability of the system. For example, a system could have an overtopped length of 0 feet, 100 feet, or 1,000 feet. A system with an overtopped length of 1,000 feet may require more extensive adaptation strategies to reduce inland inundation.
- *Percent of shoreline overtopped for each system*. Although the size of each system may vary, the percent of shoreline overtopped is a useful metric for comparing the performance of the systems under the six storm/tide conditions. For example, a system may have less than 5 percent of its length overtopped under 16 inches (41 centimeters) of SLR and 100-yr SWEL, while 50 percent of its length is overtopped with the addition of waves.
- *Average depth of inundation along a segment*. 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 indentifying 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.
- *Distance of each transportation asset from the nearest overtopped segment along the shoreline assets*. This metric was evaluated to differentiate between transportation assets that may be protected by the same system. Transportation assets closer to the shoreline could have a more limited range of potential adaptation strategies, such as building larger engineered flood protection levees along the shoreline or relocating the transportation asset.

B4.4.3.2 DISCUSSION

Chapter 6 presents the resulting shoreline overtopping potential maps with the average depth of overtopping presented by segment for each SLR scenario and storm/tide condition, including a detailed look at five focus areas within the pilot region. The results of the analysis by system are also presented in Chapter 6 for the 16-inch and 55-inch (41- and 140-centimeter) SLR scenarios. Each figure shows three panels, representing the MHHW, 100-yr SWEL, and 100-yr SWEL + wind waves scenarios, to highlight the progression of overtopping along the shoreline under the three storm/tide conditions.

It is important to note that the shoreline overtopping potential metrics were developed to allow for comparison between the SLR scenarios and the three storm/tide conditions. If a system or segment of shoreline is overtopped, regardless of the overall length or depth of overtopping, it could result in the inundation of potentially large low-lying area, especially if the initial overtopping leads to a larger or complete failure of the flood protection infrastructure through scour, undermining, or breach expansion. Therefore, any amount of shoreline overtopping potential should be considered potentially significant.

B4.4.4 UNDERLYING 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. Most notably, the new maps include:

- The depth and extent of inundation.
- The maps rely on topographic information from the 2010 USGS LIDAR data. The flood protection levees and other features that could impede flood conveyance are captured in this latest set.
- Wave dynamics along the Alameda County shoreline are considered. Wave heights along the shoreline can exceed 4 feet (1.2 meters) in height; therefore, wave dynamics are important processes to consider when evaluating the potential for shoreline overtopping and inundation in nearshore coastal areas.
- The new mapping effort also benefited from an assessment of hydraulic connectivity, using inundation mapping methodologies developed by the NOAA Coastal Services Center to exclude low-lying areas that are below the inundated water surface elevation, but are not hydraulically connected to the inundated areas.

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

- The bathymetry of San Francisco Bay and the topography of the landward areas, including levees and other flood and shore protection features, would not change in response to SLR and increased inundation (e.g., the morphology of the region is constant over time).
- The maps do not account for the accumulation of organic matter in wetlands, or potential sediment deposition and/or resuspension that could alter San Francisco Bay hydrodynamics and/or bathymetry.
- The maps do not account for erosion, subsidence, future construction, or levee upgrades.
- The maps do not account for the existing condition or age of the shore protection assets. No degradation or levee failure modes have been analyzed as part of the inundation mapping effort.
- The levee heights and the heights of roadways and/or other topographic features that may affect floodwater conveyance are derived from the USGS 2010 LIDAR data, downsampled from a 1-meter to a 2-meter horizontal grid resolution. Although this data set represents the best available topographic data, and 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 highest high tides, in an attempt to approximate the maximum extent of future daily tidal inundation. This level of inundation can also be referred to as “permanent inundation,” as it represents the area that would be inundated regularly. Tides in San Francisco Bay exhibit two highs and two lows in any given day, and the daily high tide on any given day may be less than the calculated MHHW tidal elevation.
- The inundation depth and extent shown on the 100-yr SWEL maps is associated with a 100-year extreme water level condition—in other words, an extreme tide level with a 1-percent chance of occurring in any given year. This inundation is considered “episodic inundation” because the newly inundated areas (the areas not inundated under the MHHW scenario) would be inundated only during extreme high tides. It should be noted that extreme tide levels with greater return intervals (i.e., 500-yr SWEL with a 0.2-percent chance of occurring in a given year) can also occur, and would result in greater inundation depths and a larger inundated area.
- The depth of inundation is not shown for the extreme coastal storm event conditions (i.e., 100 yr SWEL + waves) because the physics associated with overland wave propagation and wave

dissipation are not included in this study. These processes would have a significant effect on the ultimate depth of inundation associated with the large coastal wave events, resulting in a potential reduction in the depth of inundation in most areas. Alternatively, the wave heights used in this analysis are associated with existing 10-year wave heights, and as sea level rises and bay water depths increase, the potential for larger waves to develop in the nearshore environment increases. This dynamic could result in increases in the depth of inundation, particularly directly adjacent to the shoreline assets.

- The inundation maps do not take into account inundation due to rainfall or riverine flooding. The maps do not account for inundation associated with changing rainfall patterns, frequency or intensity as a result of climate change.

B4.5 References

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