Extreme Storms in San Francisco Bay – *Past to Present*

Final Report • April 2016

AECOM

Acknowledgments

CONSULTANT TEAM: Kris May, Michael Mak, Erica Harris, Mark Lightner, Julie Guyenet, Justin Vandever, Sarah Kassem, Laura Adleman

This report was funded by the Federal Emergency Management Agency (FEMA) using information from the FEMA San Francisco Bay Area Coastal Study.

Front Cover Photo used under Creative Commons. Provided by Flickr user TJ Gehling.

Extreme Storms in San Francisco Bay – *Past to Present*

Final Report • April 2016

CONTENTS

1.0

INTRODUCTION


LOCAL
EARTH
5374

1. INTRODUCTION

Large storm events impact the California coastline every winter; however, extreme storms and their potentially destructive effects are relatively rare occurrences. Although there is no single definition of an extreme storm, the term *extreme* is typically applied to storms with the potential to cause large-scale damage. In the San Francisco Bay (Bay) Area, flooding is one of the most severe threats to daily life. Other natural threats on par with flooding include earthquakes, landslides, and wildfires. There are more than 45 communities situated near the Bay shoreline, with a significant number of people, homes, businesses, and critical infrastructure within the low-lying areas that surround the Bay. Nearly all of the Bay Area's 8.7 million residents would be impacted in some manner during an extreme storm event.

The purpose of this study is to illustrate how the Bay responds to the complex and unique climatic forces that produce extreme storms and coastal flooding in the Bay Area. This study also illustrates how no single historic extreme storm event has produced the highest Bay water levels on record at every location along the complex Bay shoreline. One of the questions most commonly asked of the Federal Emergency Management Agency (FEMA) is what storm event can be considered the 1-percent-annual-chance event—or the 100-year event. To fully understand and characterize local flood hazards, multiple historic storms events must be analyzed. It is therefore important to understand the types of storms that impact the Bay Area, and how these storms have impacted different regions of the Bay.

To establish context, this study provides a primer on storm climatology and the processes and storm events that have contributed to some of the greatest flooding observed in the Bay Area in the past century. The three historic extreme storm events that occurred in January and December 1983 and February 1998 produced the highest water levels on record along the Bay shoreline. This study transforms these three storm events to today's climatic conditions to assess the potential extent of flooding if these storms were to occur today or in the near future.

1.1 ORGANIZATION OF REPORT

Following this introduction, this report is organized as follows:

- **Section 2** provides an overview of the large-scale oceanic and atmospheric processes that lead to large storms and elevated water levels off the California Coast and in San Francisco Bay.
- **Section 3** describes the response of San Francisco Bay to these phenomena and the local factors that govern the severity of flooding along the Bay shoreline. Section 3 also describes some of the most severe storms that have occurred in the Bay.
- **Section 4** discusses some of the changing characteristics of the Bay (e.g., sea level rise and development) that affect how storms can impact the shoreline today. Section 4 also transforms three historic extreme storm events described in Section 3 to assess the extent of flooding that might result if these storms were to occur today or in the near future.
- **Section 5** describes how the extent of flooding from the transformed historic storms relates to the preliminary and effective Flood Insurance Rate Maps (FIRM) produced by FEMA as part of the San Francisco Bay Area Coastal Study.
- **Sections 6** presents the conclusions of this study.
- **Section 7** lists the sources cited in this study.

1.2 ACRONYMS/ABBREVIATIONS

Bay	San Francisco Bay
CCMP	California Coastal Mapping Program
ENSO	El Niño Southern Oscillation
FEMA	Federal Emergency Management Agency
FIRM	Flood Insurance Rate Map
ft/century	foot (feet) per century
GCM	Global Circulation Model
mm/yr	millimeter(s) per year
mph	mile(s) per hour
NAVD88	North American Vertical Datum of 1988
NCDC	National Climatic Data Center
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
PDO	Pacific Decadal Oscillation
SFO	San Francisco International Airport
USGS	United States Geological Survey

2.0

PROCESSES AFFECTING SAN FRANCISCO BAY COASTAL STORMS

2. PROCESSES AFFECTING SAN FRANCISCO BAY COASTAL STORMS

Located on the Central California coastline, the Bay Area has a variable climate that is dominated by many large-scale atmospheric and oceanic processes. Although generally characterized by a mild Mediterranean climate with dry summers and cool, wet winters, the Bay Area is also a region that experiences volatile storms that can cause widespread flooding in low-lying coastal areas. The region is particularly vulnerable to prolonged periods of heavy rainfall, elevated tides, and strong winds. The following storm types (e.g., extra-tropical storms and atmospheric rivers) and large-scale climate patterns (e.g., the El Niño Southern Oscillation [ENSO] and the Pacific Decadal Oscillation [PDO]) may contribute to elevated water levels and coastal flooding.

2.1 EXTRA-TROPICAL STORMS (LOW-PRESSURE SYSTEMS)

The most common type of storm impacting Central California is governed by the North Pacific High, a persistent zone of high pressure located over the northeastern Pacific Ocean near the Aleutian Islands. The strength and location of this high-pressure system varies annually and seasonally. During the summer months, the high-pressure zone migrates northward, diverting most storm tracks to the north. However, during the winter months, the high-pressure system shifts to the south, allowing intense extra-tropical storms to follow a more southerly track and impact the central and southern portion of California. Because these storms possess great energy, it is not uncommon for them to generate offshore waves of 20 to 30 feet and wind speeds of 40 miles per hour (Griggs et al. 2005). Low-pressure systems allow waters to expand and temporarily increase the water surface elevation. Approximately every 1 inch decrease in atmospheric pressure results in a corresponding 1 inch increase in sea level (USGS 1999). Figure 2-1 shows the size of the low-pressure system that resulted in one of the largest tides ever recorded in the Bay. This particular storm system also carried in heavy precipitation that lasted over multiple days.

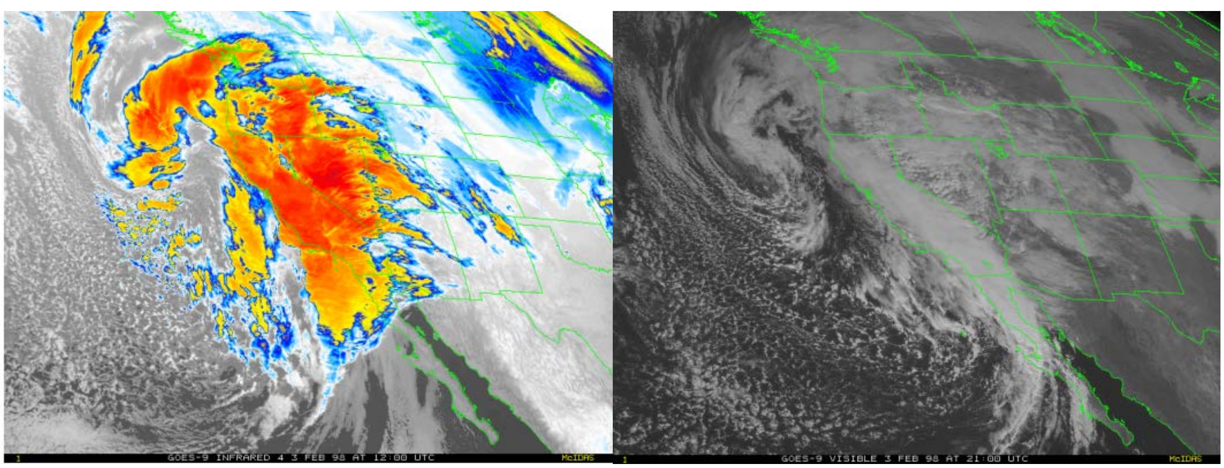

Figure 2-1. Visible satellite (right panel) and infrared image of low-pressure system on February 3, 1998. Source NCDC, 1998

2.2 ATMOSPHERIC RIVERS

Atmospheric rivers are relatively narrow, ribbon-like bands of moisture that originate from the tropics and result in substantial rainfall. Atmospheric river conditions often persist for days and can amplify storm conditions when they make landfall and stall over a region. The most familiar atmospheric river in the

California region is the so-called Pineapple Express, which brings warm, moist water vapor from the tropics near Hawaii to California and other areas along the Pacific coast. Strong atmospheric rivers contain the moisture equivalent of 7.5 to 15 times the amount of water flowing through the mouth of the Mississippi River. They are part of a broad, warm, conveyor belt that forms when strong winds draw in moisture from air masses far to the south over the subtropical and tropical Pacific Ocean and then focus this moisture into narrow regions ahead of a cold front. The impacts of atmospheric rivers are more pronounced during the winter season and can result in twice the precipitation of non-winter storms. Many of the largest storms that have occurred in the Bay Area have been due to atmospheric rivers. Figure 2-2 shows an image of the atmospheric river that dropped significant rainfall in Northern California on December 11, 2014, resulting in widespread flooding, street closures, and power outages across the Bay Area.

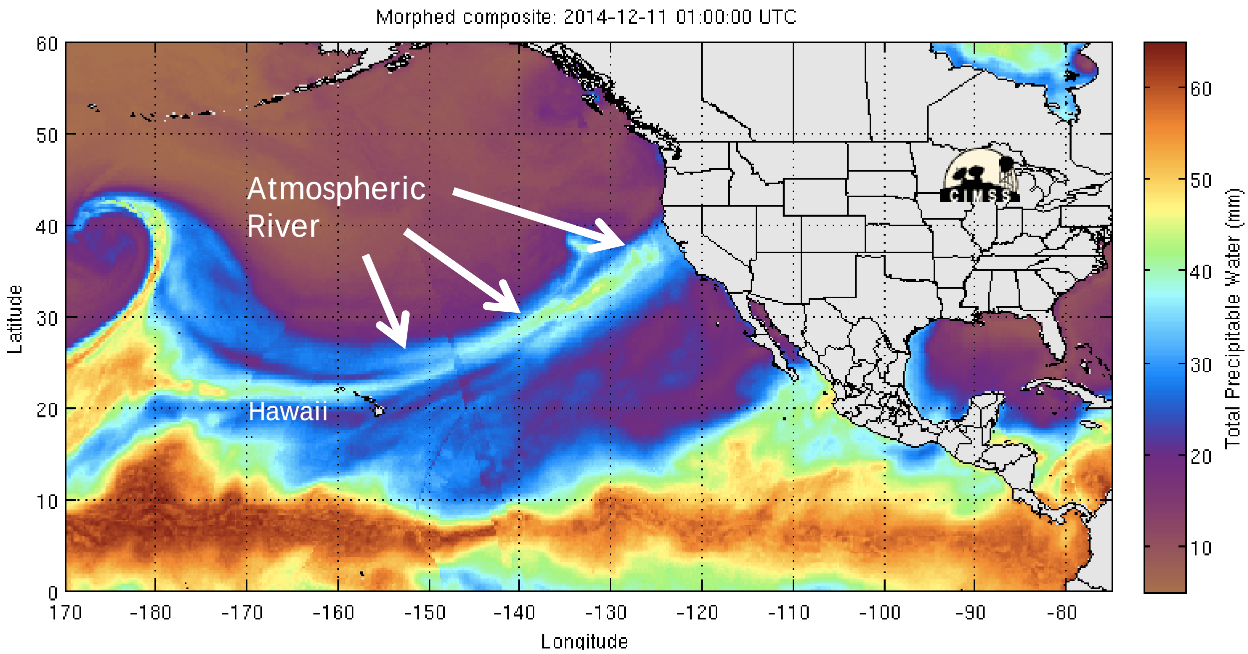

Figure 2-2. Atmospheric river resulting in heavy rains across the Bay Area on December 11, 2014. Source: Cooperative Institute for Meteorological Satellite Studies

2.3 EL NIÑO SOUTHERN OSCILLATION

Water levels in San Francisco Bay are strongly influenced by the large-scale changes in the ENSO cycle. Under normal conditions, global trade winds blow from east to west across the Pacific, moving warm surface water away from the Americas toward the western Equatorial Pacific. From there, the warm waters move up to Japan and down to Australia. Every 2 to 7 years, these winds weaken and can reverse. Warm, equatorial water flows east toward the Americas, and during strong El Niños, unusually warm waters migrate northward along the California coast. Because these warm waters are less dense, tides can become elevated for prolonged periods. During El Niño, atmospheric and oceanographic conditions in the Pacific Ocean produce severe winter storms that can result in Bay Area flooding. During this time, Pacific Ocean storms follow a more southerly route, bringing intense rainfall, high winds, and frequent low-pressure systems. Tides are often elevated 0.3 to 1.0 foot above normal, and wind waves and ocean-driven swells can elevate local water levels further. El Niño winter conditions prevailed in 1977–1978, 1982–1983, 1997–1998, 2009–2010, and, most recently, 2015–2016. Figure 2-3 shows how the sea levels off the California coast and throughout the Pacific Ocean changed in the months before the 1997–1988 winter season, one of the strongest El Niños to occur in the past century.

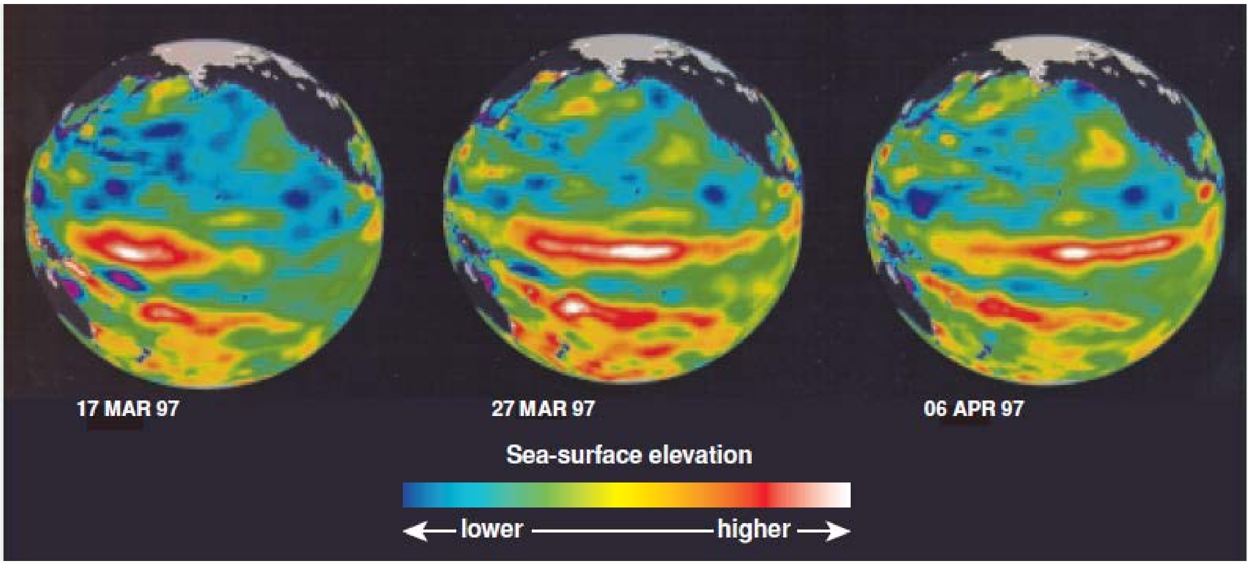

Figure 2-3. Changing sea surface temperatures resulting in elevated sea levels offshore of the California coast before the strong 1997–1998 El Niño winter season. Source: USGS, 2009

2.4 PACIFIC DECADAL OSCILLATION

This atmospheric shift is similar to ENSO, but varies over a time scale of decades rather than years. The PDO can remain in the same phase for 20 to 30 years, in contrast to the ENSO phases of 9 months to 2 years. As with ENSO, the extreme phases of the PDO are classified as either warm or cool based on ocean temperature anomalies in the northeast and tropical Pacific Ocean. Shifts in the PDO phase can intensify or diminish the impacts of ENSO events. If both ENSO and PDO are in a warm phase, El Niño impacts may be magnified. Conversely, if ENSO is in a warm phase and the PDO is in a cool phase, impacts from an El Niño may be dampened or prevented from occurring.

For the past decade, the PDO has been in a cool phase, suppressing El Niño conditions and water elevations along the U.S. West Coast. Evidence suggests that the PDO phase is currently switching to a warm phase, which may enhance local water levels and future El Niño events. Figure 2-4 shows the sea surface temperature variation from normal in the Pacific, attributed to PDO and El Niño. The departure from normal due to El Niño is more pronounced, but lasts for a shorter time compared to the PDO cycle.

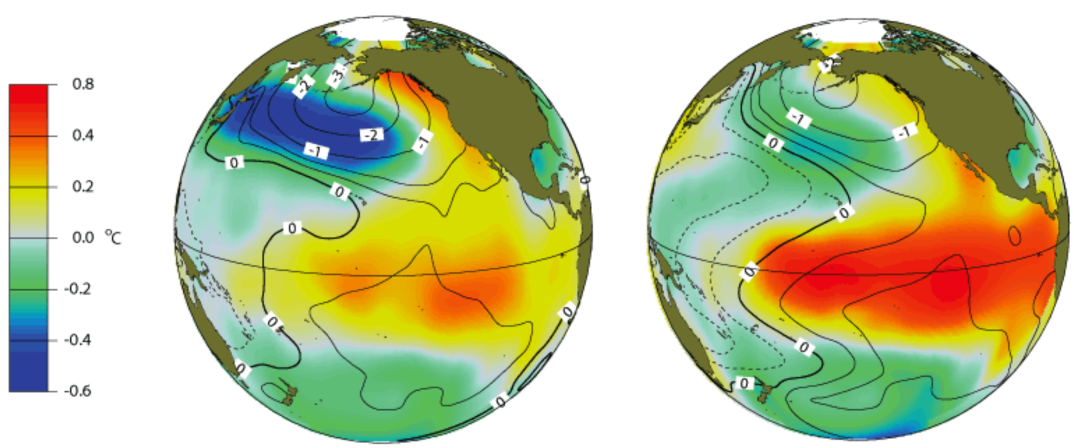

Figure 2-4. Typical PDO (left) and ENSO (right) sea surface temperature departures from normal (during positive years). Source: Climate Impacts Group, 2009

Photo Courtesy of Contra Costa Flood Control and Water Conservation District

3.0

SAN FRANCISCO BAY RESPONSE TO STORMS

3. SAN FRANCISCO BAY RESPONSE TO STORMS

The Bay shorelines and hydrodynamics are complex. In addition to the large-scale atmospheric phenomena that influence the region, storm characteristics and spatially unique local factors cause storm impacts to be felt differently throughout the Bay. In fact, no single event has produced the highest water levels along all of the Bay shorelines. This section describes some of the major factors that control how Bay dynamics are influenced by storm conditions and the storm characteristics associated with three of the largest storms that have occurred in the Bay since 1950.

3.1 INFLUENCES ON BAY WATER LEVELS

Although numerous factors can influence local and regional Bay water levels, the primary processes include storm surge, ocean-driven swell, and wind-driven waves. Each of these components is influenced by the overall characteristics of a given storm event and the bathymetry, topography, and shoreline characteristics that are unique for each community.

3.1.1 STORM SURGE

Storm surge is an increase in ocean surface elevation caused by low atmospheric pressure and wind effects. Even on clear days, storm surge can raise Bay water levels. When storms coincide with high tides, storm surge can produce extreme high tides, resulting in temporary flooding. Storm surge in the Bay due to large storms can exceed 2 to 3 feet in height, resulting in an increase in Bay water levels that is 2 to 3 feet higher than the predicted astronomical tide elevation. Examples of large historical storm surge events within the Bay include: January 27, 1983 (2.6 feet); December 3, 1983 (2.1 feet); February 2, 1998 (3.1 feet); January 8, 2005 (1.2 feet); and December 11, 2014 (1.8 feet).

3.1.2 OCEAN-DRIVEN SWELL

Storms occurring over the open ocean can generate large waves, or swells, that propagate outward from the storm, traveling thousands of miles across the ocean until impacting land. Large swells generated by Pacific storms release most of their destructive energy on the open coasts, where waves can reach heights of 20 to 30 feet. These swell waves are generally blocked by the narrow Bay entrance; however, some of these waves are able to pass through the Golden Gate. The largest presence of ocean-driven swells occurs in the Central Bay between the Bay Bridge and the Richmond-San Rafael Bridge, due to its proximity to the Golden Gate.

3.1.3 WIND-DRIVEN WAVES

Local winds blowing across the Bay generate short, disorganized choppy waves known as wind-driven waves. During high-wind conditions, the waves can grow to 4 to 5 feet in height. The height of the waves is dependent on the length of the available fetch (i.e., the distance the wind can blow across the water surface), the wind speed, the duration of the wind, and the water depth. Wind-driven waves are common in the Bay, and variations in wind direction and shoreline exposure can lead to localized differences in wave heights along the shoreline. For example, winds from the south can create waves that impact the south-facing shorelines, but with limited impact to adjacent east- and west-facing shorelines. Wind direction is typically from the west and northwest in the spring, summer, and fall, with more variable conditions in the winter.

3.1.4 OTHER LOCAL INFLUENCES

In addition to the hydrodynamic and atmospheric conditions that can amplify storms in the Bay, many other local factors influence the ultimate size of storms and the water levels and flooding at the shoreline. Figure 3-1 presents some of the other local factors that can influence localized flooding.

Figure 3-1. Local factors that influence storm conditions in the Bay

3.2 HISTORIC STORMS IN THE BAY

Large storm events impact the California coastline every winter; however, extreme storms and their potentially devastating effects are rare occurrences. There are many reports of coastal flooding, erosion, and damage resulting from extreme coastal storms in the Bay Area in the past century. Figure 3-2 presents a timeline of several extreme storm events that have occurred in the Bay Area in recent history. Many of the most damaging events occurred during El Niño winters, when storm surge, high tide, and waves coincided. Heavy rainfall also compounded the flood hazards.

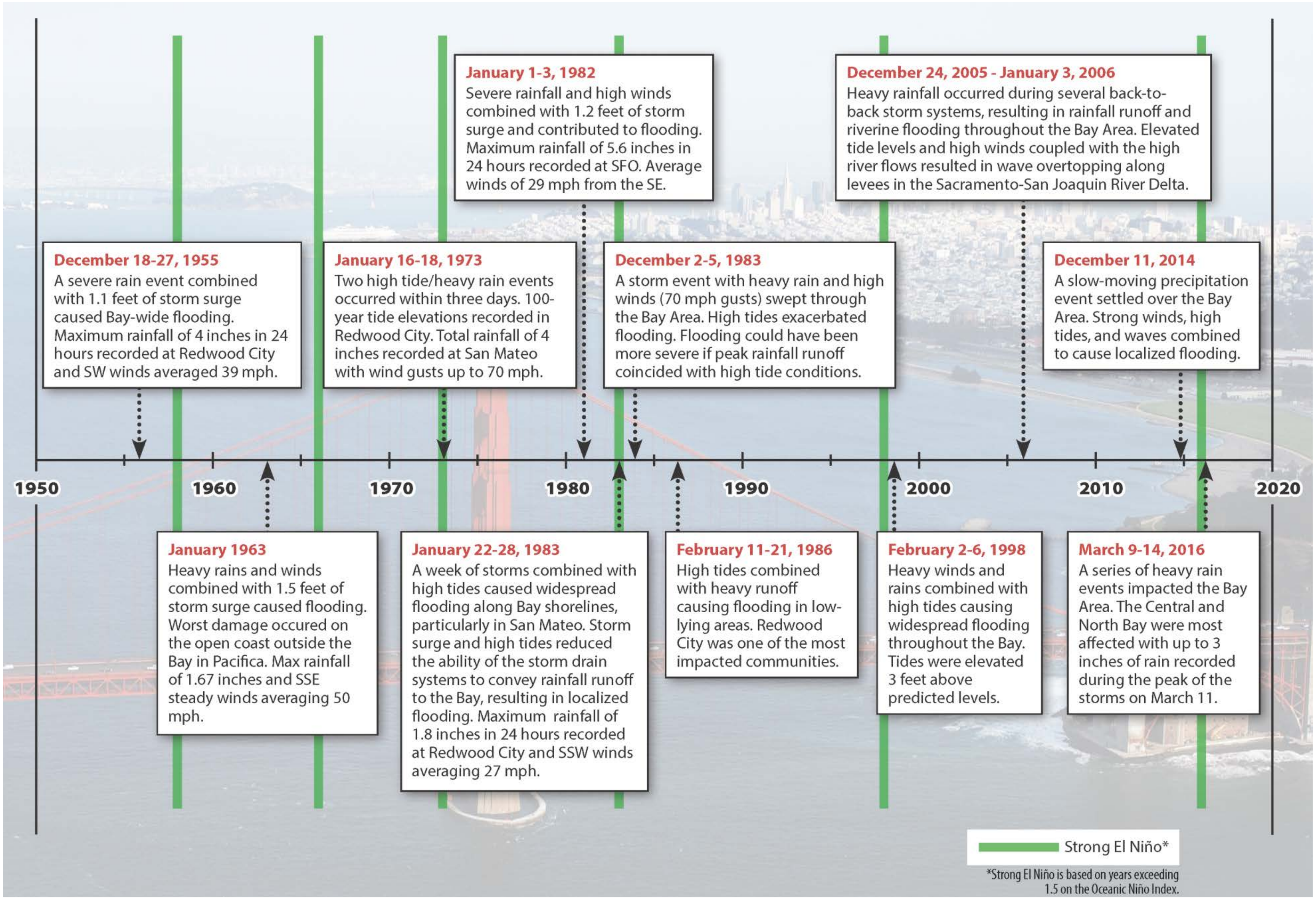

Figure 3-2. Timeline of extreme storm events in the Bay Area in recent history

The following sections summarize the details of the three storm events that resulted in the highest Bay water levels ever recorded: the January 1983 event, the December 1983 event, and the February 1998 event. Each storm system resulted in the highest water levels on record for different locations in the Bay. The January 1983 event resulted in the highest water levels in the Central Bay; the December 1983 event resulted in the highest water levels in the South Bay; and the February 1998 event resulted in the highest water levels in the North Bay upstream of the Carquinez Strait.

3.2.1 JANUARY 27, 1983

Primed by heavy rainfall in the days leading up to the event, the storm's low-pressure system and warmer-than-average ocean temperatures resulted in strong storm surge conditions. Large offshore swells slammed into the open coast and entered the sheltered Bay waters through the Golden Gate, enhancing flooding in the Central Bay. Rain-saturated hills in the Bay Area led to numerous landslides. This storm event was one of six major storms to occur in the short time frame of January 22 to 29, 1983. The 1982–1983 winter season was associated with one of the strongest El Niños on record.

On January 27, 1983, this storm produced the highest observed tide on record at the San Francisco Presidio tide station. The highest tides recorded one day before and one day after January 27 almost reached similar extreme elevations. The maximum hourly wind speed recorded at San Francisco International Airport (SFO) on January 27 was 17 miles per hour (mph) from a west-northwest direction. Figure 3-3 provides a snapshot of the January 1983 storm conditions, including the predicted tide; the observed tide; the difference (residual), which includes the storm surge; and the barometric pressure throughout the storm. The peak storm surge occurred on January 26, one day before the peak water level conditions occurred (period highlighted by the blue band in Figure 3-3). If the peak storm surge occurred just 21 hours later to coincide with the higher astronomical tide on January 27, an extreme tide with elevations just over 9 feet (North American Vertical Datum of 1988 [NAVD88]) would have occurred; this is 0.7 feet higher than the observed tide on this day. By February 9, 1983, the amount of structural damage and flooding that had occurred throughout the Bay Area led FEMA to declare a state of emergency for the State of California.

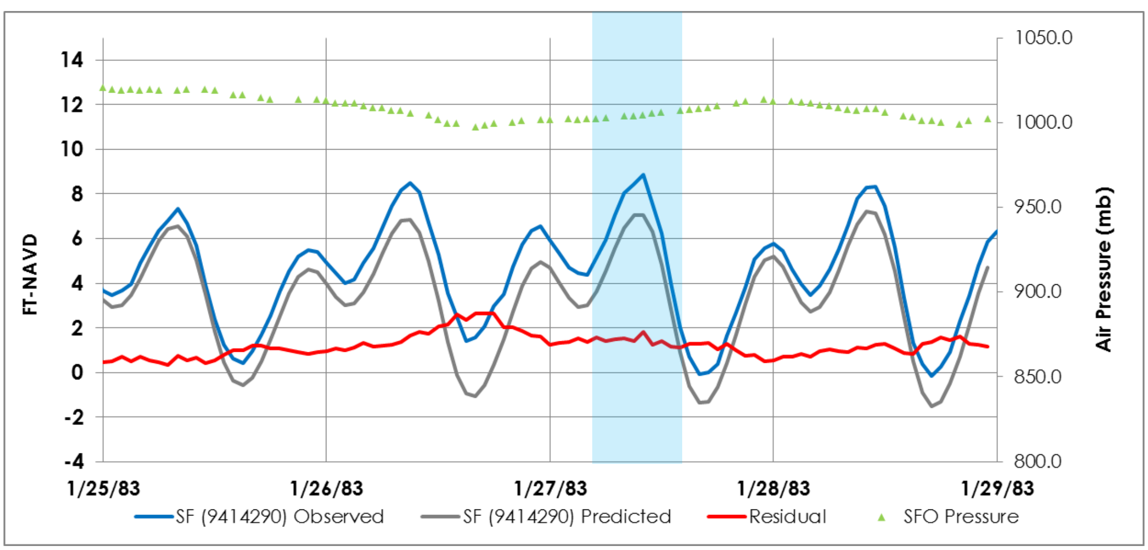

Figure 3-3. January 27, 1983, strong El Niño coastal storm

3.2.2 DECEMBER 3, 1983

This storm's strong low-pressure system and surge (over 2 feet) reached San Francisco Bay concurrently with rising high tide on December 3, 1983, bringing the observed tide levels to elevations similar to those observed during the January 27, 1983, event. However, heavy rains did not amplify the extreme tide that occurred on December 3. Figure 3-4 provides a snapshot of the December 1983 storm conditions, including the predicted tide; the observed tide; the difference (residual), which includes the storm surge; and the barometric pressure throughout the storm. The peak water level conditions occurred during the period highlighted by the blue band.

In the December 1983 storm, winds with gusts of over 75 mph ravaged the Bay Area, even closing the Golden Gate Bridge for several hours. The maximum hourly wind speed recorded at SFO was 45 mph from a west-northwest direction. The January and December 1983 storms were almost equal in peak elevation at the San Francisco Presidio tide station, but due to other storm factors (e.g., stronger local winds), the peak tides were higher in the South Bay during the December 3 storm event.

Although the December 3 storm produced slightly smaller wave conditions than observed in the January 27 event, large swells still pummeled the open Pacific coast and entered the Bay through the Golden Gate. The December 3 event was one of the last in a string of storms to impact the California coastline in 1983, causing considerable damage.

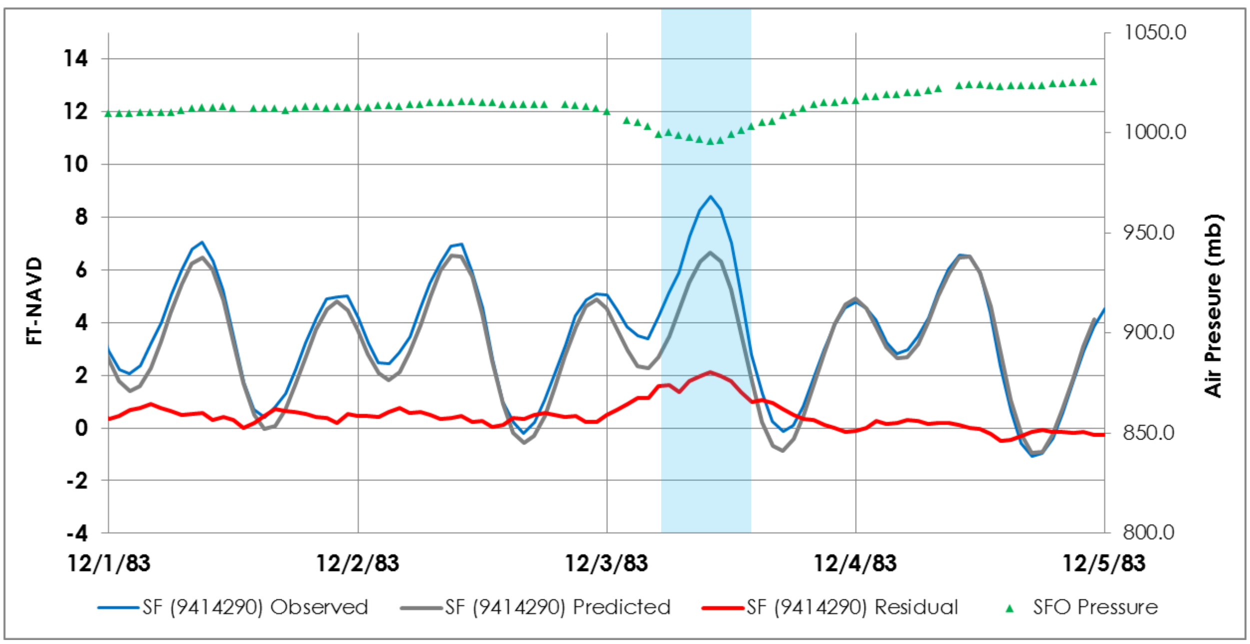

Figure 3-4. December 3, 1983, strong coastal storm

3.2.3 FEBRUARY 2–8 1998

During the strong El Niño winter season of 1997–1998, a low-pressure system caused high storm surge and strong winds that led to extreme wave conditions in early February. Figure 3-5 provides a snapshot of the February 1998 storm conditions, including the predicted tide; the observed tide; the difference (residual), which includes storm surge; and the barometric pressure throughout the storm. The peak water level conditions occurred during the period highlighted by the blue band.

Although the peak tide level from this event occurred on February 6, the highest storm surge occurred 3 days earlier, during low tide. This storm produced a larger storm surge than the two 1983 storms (3 feet), which occurred on top of elevated tides from a strong El Niño. The days leading up to the February 6 coastal storm brought large rainfall amounts, with 6 inches falling in approximately 30 hours. The maximum wind speed recorded at SFO on February 6 was 29 mph from a west-northwest direction. The heavy rainfall, coupled with the storm surge, extreme waves, and high tides elevated by El Niño conditions, caused localized flooding throughout the Bay Area. Many rivers in the Central Bay were overwhelmed by the riverine flows, causing floodwaters to crest riverbanks and inundate surrounding properties. Water levels near the Sacramento–San Joaquin River Delta were elevated to the highest levels experienced in the last four decades. In developed areas, homes were inundated and hundreds were evacuated. By February 9, 1998, FEMA had declared a state of emergency for many counties along the Central California coast.

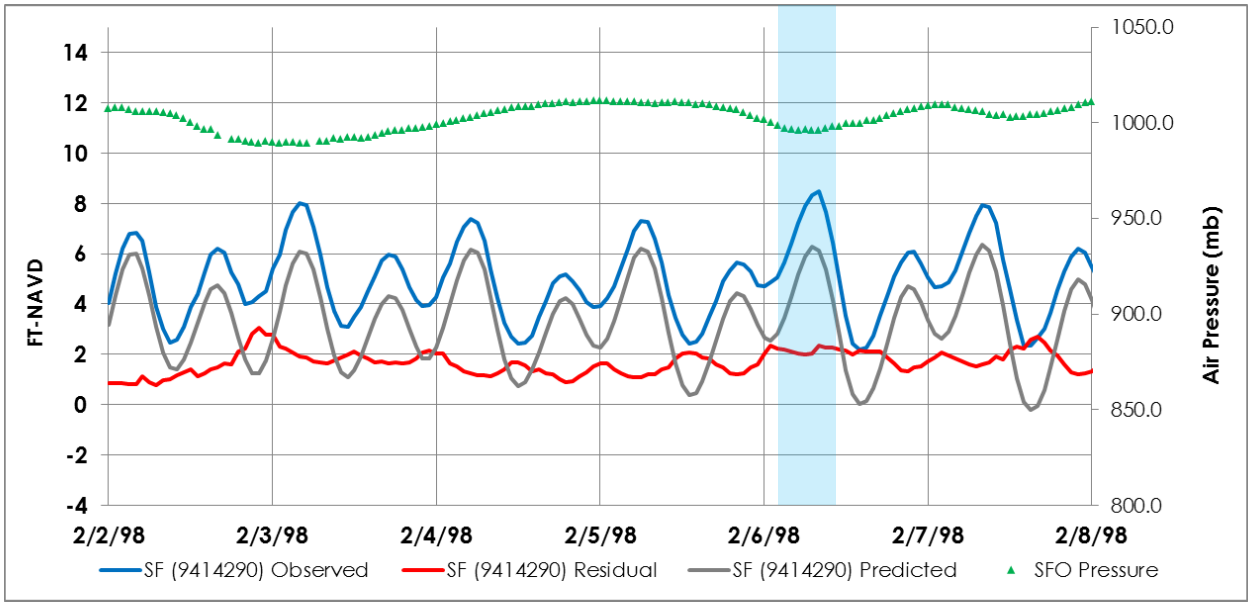

Figure 3-5. February 2-8 1998, strong El Niño coastal storm

3.2.4 HISTORICAL STORM SUMMARY

These brief narratives of three historical storms demonstrate that every storm is unique and that many factors contribute to peak Bay water levels and the extent of inland flooding. Figure 3-6 shows the spatial variation of the impacts of the three storms responsible for producing the maximum water levels along the shoreline since 1956. The largest tide observations in the Central Bay occurred during the January 27, 1983, storm. This event had a large storm surge and high incoming ocean swells that entered the Bay through the Golden Gate. In contrast, the north and south regions of the Bay exhibited the highest Bay water levels during the December 3, 1983, event, which was dominated by high winds. The area upstream of the Carquinez Strait and into the Sacramento–San Joaquin River Delta exhibited the highest water levels during the February 6, 1998, storm. Coastal water levels were elevated during this event, but this storm event was dominated by the large riverine inflows from the San Joaquin and Sacramento Rivers. Although each storm can be considered extreme, and each storm impacted the Bay Area as a whole, no single historical storm event can be considered the “most severe storm on record” for the entire region.

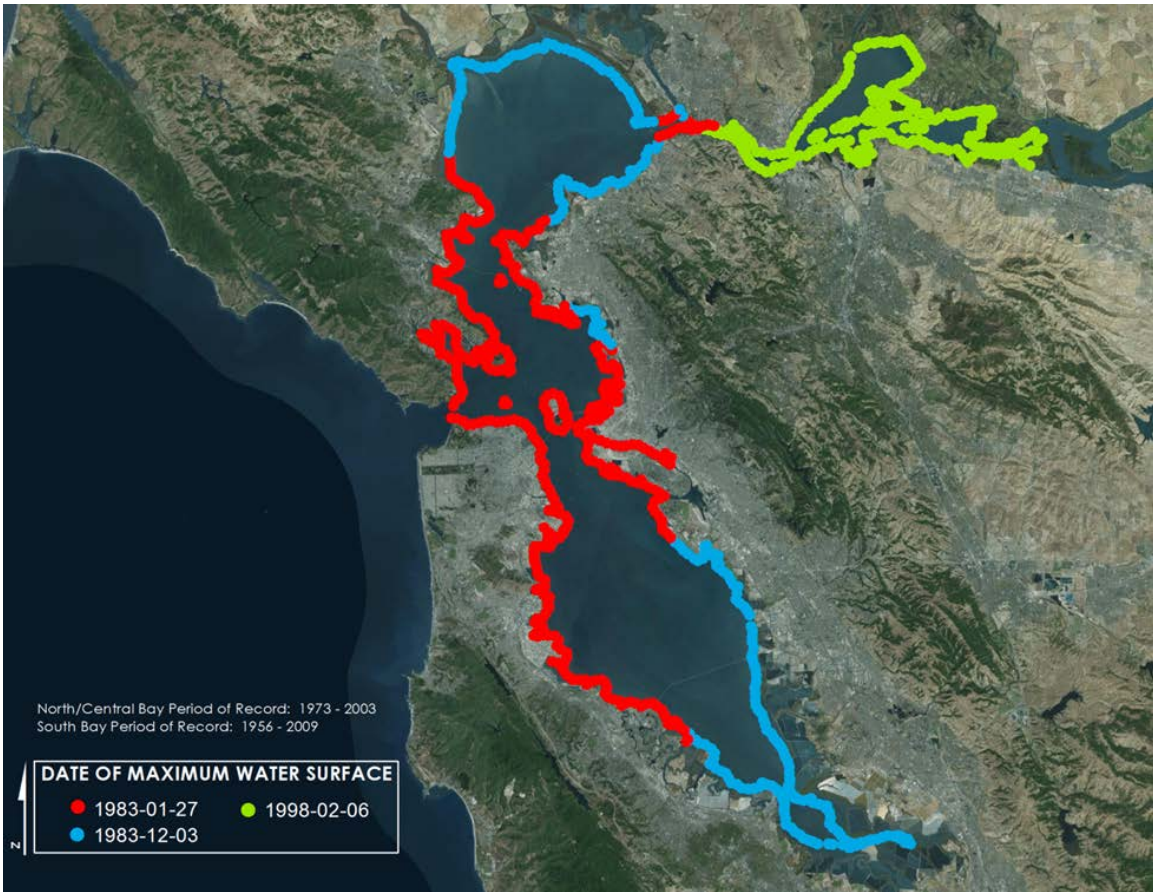

Figure 3-6. Date of maximum Bay water level (since 1956)

4.0

UNDERSTANDING FUTURE STORM IMPACTS

4. UNDERSTANDING FUTURE STORM IMPACTS

Examining historical storms and their associated impacts can inform decisions on how to better protect coastal communities from potential future storms. However, individual historical storm events are not necessarily indicative of what the future may bring. Even if a past storm event were to re-occur today, the flooding impacts would not be identical. The Bay shoreline is continually evolving as new developments are constructed, levees are built or upgraded, shorelines are eroded, and coastal areas are restored to enhance and expand natural habitats. As the shoreline changes, the inland flooding potential may also change. In addition, climate change is resulting in increased sea levels and may also be affecting the Bay Area's climatology, which will affect how the Bay responds to future storm events.

This section describes changing conditions in the Bay and summarizes how the three historical storms discussed in Section 3.2 might have different impacts if they were to occur today. This transformation of historical storm events to today's conditions can help enhance how we use historical storm information to improve decision-making related to shoreline management and provide better information to inform development and investments within areas potentially at risk of flooding.

4.1 CHANGING BAY CONDITIONS

Changing sea levels, storm intensities, and shoreline conditions should be considered when using historical storm records to estimate the potential damage from present-day and future storms.

4.1.1 CHANGING SEA LEVELS

There is no doubt that sea levels have risen and will continue to rise at an accelerated rate over the coming century (NRC 2012). Data collected by a worldwide network of tide stations, including satellite-based measurements, indicate that global mean sea level rose at an average rate of approximately +1.8 millimeters per year (mm/yr) (0.59 foot per century [ft/century]) between 1961 and 2003. This rate increased to approximately +3.1 mm/yr (1.0 ft/century) between 1993 and 2003 (IPCC 2007), and the rate of increase is projected to further accelerate over the coming century.

Local rates of sea level rise along the California open coast and within San Francisco Bay differ slightly from global rates because of local conditions such as large-scale land motions (e.g., uplift, subsidence) and local atmospheric and oceanic circulation processes, among other factors. Within San Francisco Bay, sea level rise rates may vary based on variations in local hydrodynamics. Figure 4-1 presents a map of historical local sea level rise rates within the Bay calculated using monthly tide data recorded at four National Oceanic and Atmospheric Administration (NOAA) tide stations.

The science associated with sea level rise is continually being updated, revised, and strengthened. Although it is difficult to predict with certainty how quickly the seas will rise, there is agreement that seas will rise at rates that exceed historical trends. The sea level rise projections presented in this document draw on the best available sea level rise science for California as of April 2016.

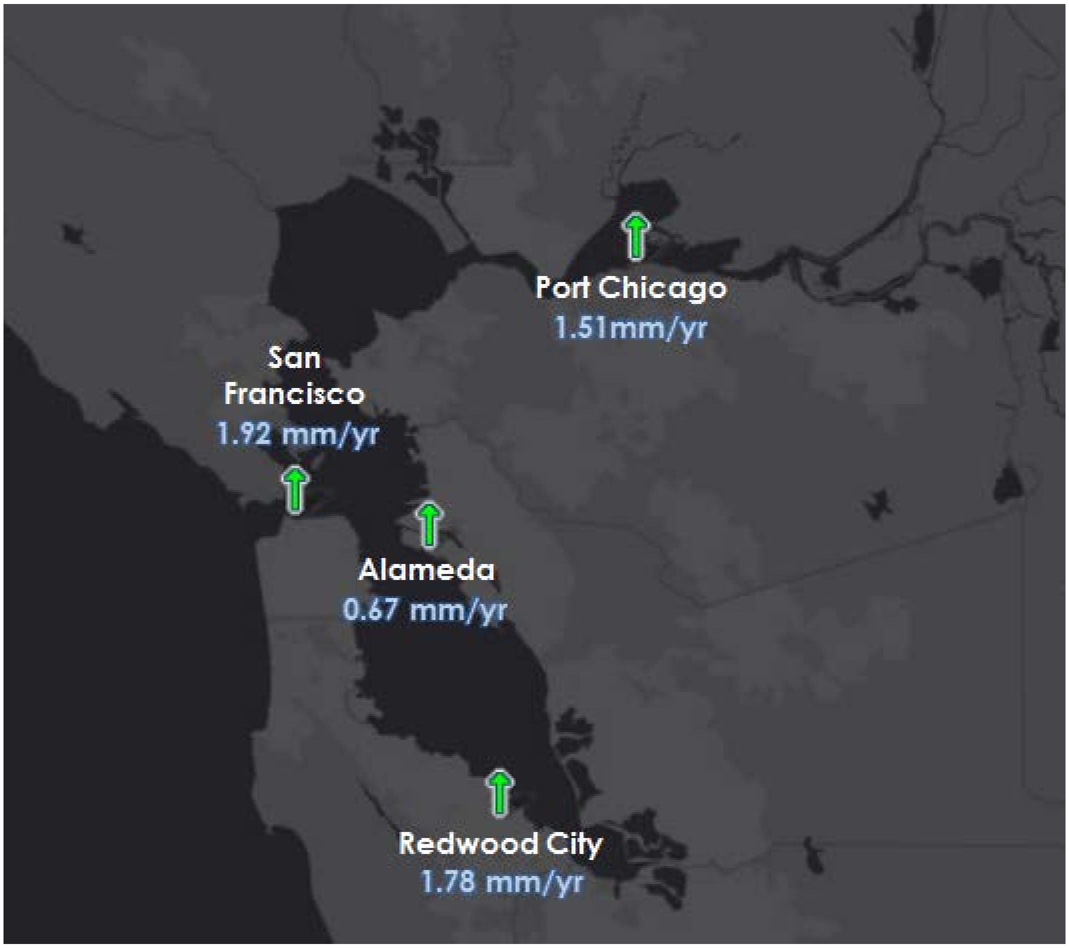

Figure 4-1. Mean sea level rise rates for NOAA tide stations

Figure 4-2 presents the National Research Council (NRC) sea level rise projections for San Francisco Bay relative to the year 2000 (NRC 2012). NRC presents several possible sea level rise scenarios, including projections and ranges up to the year 2100. The projections (for example, 11 inches in 2050) represent the likely sea level rise values based on a moderate level of greenhouse gas emissions, extrapolation from the continued acceleration of land ice melt patterns, plus or minus one standard deviation. The projections are also referred to as the “most likely” scenario. NRC also presents an upper range (for example, 24 inches in 2050), which represents unlikely but possible levels of sea level rise using very high-emissions scenarios and including potential significant land ice melt.

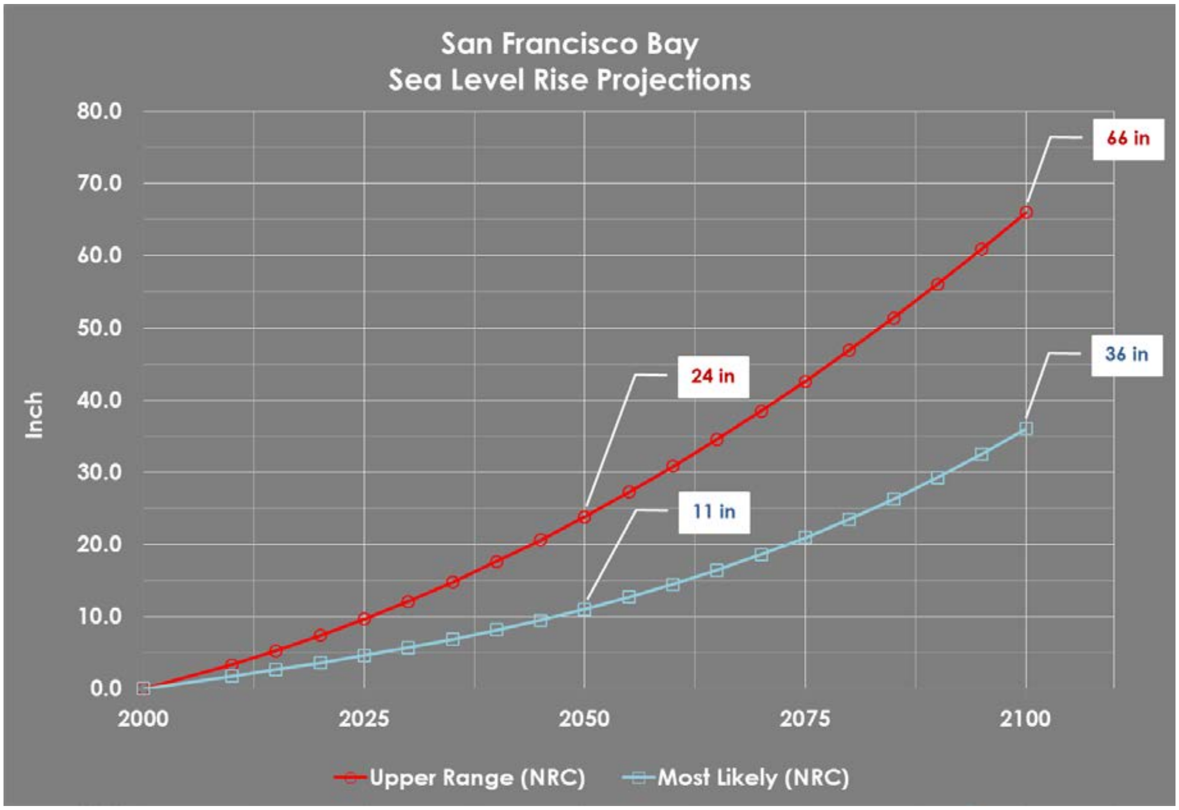

Figure 4-2. NRC sea level rise estimates (most likely and upper range) for the San Francisco Bay

As local sea levels increase, coastal flooding is expected to occur more often. Rising sea levels provide access for storms to impact infrastructure at backshore elevations that was once out of the Bay's reach. Water levels that are associated with today's 1-percent-annual-chance condition (i.e., a water level that has a 1 percent chance of being equaled or exceeded in any given year, more commonly called a 100-year water elevation) may soon occur much more often. For example, a 100-year water elevation near San Francisco Bay may occur every 5 years by 2050 (Tebaldi et al. 2012). These shifts in the frequency of extreme tide elevations will have important design implications for flood protection infrastructure and the resilience and persistence of valuable shoreline habitats.

4.1.2 CHANGING STORM INTENSITIES

There is a general consensus among scientists that climate change will affect the intensity, frequency, and paths of coastal storms and wave events. However, no clear consensus has yet emerged on the nature of these changes in the North Pacific Ocean (NRC 2012). 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. 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 waves along the Bay shoreline.

Increases in Pacific Ocean temperature (both the atmospheric temperature and the oceanic temperature) for the remainder of the century are more confidently projected by today's Global Circulation Models (GCMs). Although the direct correlation with the large-scale climatic processes that result in extreme storms in the San Francisco region is still uncertain, it is expected that the region will experience a range of storm events that are outside the range of the recent historical record. The impacts to the Bay could include a landward migration of flooding beyond current expectations. Such an impact would put additional critical infrastructure, communities, and natural resources at risk.

4.1.3 CHANGING SHORELINES

Identifying and understanding storms that can cause flooding in the Bay is a challenge, and rising sea levels and changing storm intensities are just some of the drivers that will influence the severity of the storms that will occur today and in the future. The physical orientation and characteristics (slope, shoretype, etc.) of the Bay shoreline also plays a major role in the extent of inland inundation that may occur during an extreme storm.

The Bay includes more than 1,000 miles of shoreline, ranging from natural tidal marshes and beaches to hardened engineered structures such as levees, revetments, and seawalls. In response to historical storm events, growing populations, and increasing environmental awareness, these natural and engineered shorelines have evolved. Flood protection structures have been constructed or improved to provide a higher level of flood protection. New developments and infrastructure in close proximity to the shoreline have been constructed and expanded to accommodate the rising Bay Area population. From 1990 to 2000, the local population grew by 12 percent, creating a greater need for more infrastructure to support more housing and businesses, and the local population base continues to increase (ABAG 2015). At the same time, many areas along the shoreline are actively in various stages of restoration to increase the amount of tidal wetland habitat around the Bay shoreline. For example, the California Coastal Conservancy is currently managing the restoration over 15,000 acres of former salt ponds in the South Bay, and multiple agencies are working to restore former salt ponds and agricultural areas in the North Bay.

Jurisdiction over Bayfront development in the past 30 years has also transformed the shoreline. From 1970 to 2014, the San Francisco Bay Conservation and Development Commission authorized projects resulting in alteration of 18,500 acres of Bay shoreline using artificial fill (BCDC 2015). A significant percentage of this fill was used to construct shoreline protection structures (BCDC 1988). Although large-scale filling of the Bay to support development has stopped, several existing developments are constructed on Bay fill (i.e., areas where fill has been placed in the Bay beyond the historical shoreline), and these areas may be at the greatest risk of land subsidence, which lowers the ground elevations and increases the risk of coastal flooding. Land subsidence can also be associated with groundwater withdrawals and earthquakes, which can cause large-scale land movement quickly.

4.2 TRANSFORMING HISTORIC STORMS TO THE PRESENT

This section describes how the three storms discussed in Section 3.2 can be transformed to be more representative of a storm event that could occur today or in the near future.

4.2.1 BAY WATER LEVELS

The San Francisco Bay Area Coastal Study included detailed hydrodynamic modeling of the Bay, and this effort captured the January 1983, December 1983, and February 1998 storm events (DHI 2011). The modeled Bay water levels associated with the storm events were extracted at over 900 locations along the Bay shoreline. The number and location was selected to capture the variations in water level just offshore of the existing shoreline.

4.2.2 SEA LEVEL RISE

Mean sea level in the Bay is increasing at a rate of 1.92 mm/yr (0.76 inch/year) at the San Francisco Presidio tide station. Although the rate of sea level rise may differ within the Bay, for simplicity, the historical rate of sea level rise was assumed to be constant in the Bay. At the 900 points along the shoreline, the peak water levels for each storm event were increased by the amount of sea level rise that occurred from the date of each storm to the start of 2016 (i.e., January 1, 2016). For example, to transform the January 27, 1983, peak water levels to a January 1, 2016, condition, 2.49 inches of sea level rise were added to the modeled water levels (0.76 mm/yr * 32.93 years = 2.49 inches). Similarly, the peak water level of the December 3, 1983, and the February 2–8, 1998, storm was adjusted by 2.42 inches and 1.35 inches, respectively.

4.2.3 SHORELINES

No transformation of the shoreline and inland areas was required to assess the potential inundation extent of the three storms under present-day conditions, because the topographic data set used is a representative snapshot of existing conditions as of 2010. The topographic data were collected by the United States Geological Survey (USGS) and NOAA as part of the California Coastal Mapping Program (CCMP).[1] The data include the flood protection improvements that were implemented after the 1983 storm events occurred.

4.2.4 MAPPING METHODS

The extent of potential flooding was mapped for the transformed storm events using topographic data that reflect present-day conditions. This mapping provides insight on the level of flood protection offered by the existing shoreline infrastructure and helps identify where vulnerable areas may still exist. This mapping exercise relied on the methods developed by Marcy et al. (2011) for NOAA to evaluate inundation extents over land. This method accounts for the physics of overland flow, dissipation, levee overtopping, storm duration, and potential shoreline or levee erosion that may occur during an extreme storm. The mapping is also limited to coastal flooding associated with high Bay water levels. The January 1983 and February 1998 storm events also included heavy rainfall, which would exacerbate flooding due to riverine inflows and inadequate storm drainage capacity, resulting in an increase in the extent of the flood.

4.3 THE STORMS OF TODAY

The combined extent of flooding throughout the Bay Area from the transformed January 1983, December 1983, and February 1998 storms is presented on Figure 4-3, which shows a composite flood map of the three storm events rather than presenting each mapped storm event individually. In general, the differences in flood extent between the three storms are driven more by the topography of the Bay Area than the differences in the Bay water elevations. In other words, the floodwaters often extend until an area with steep topography is reached. At the selected mapped scale of 1 inch equals 6 miles, the difference in flood extent would be nearly impossible to discern.

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

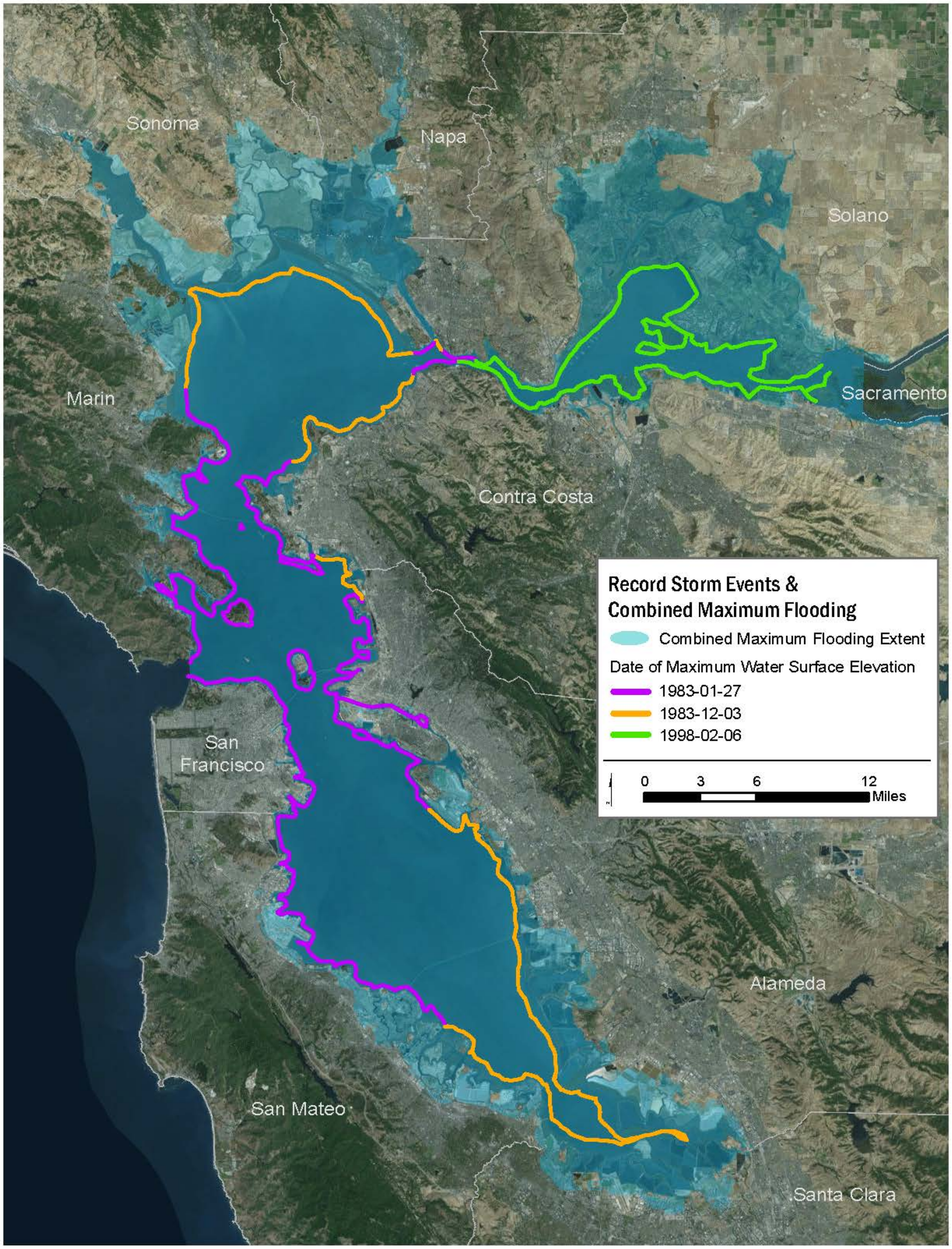

Figure 4-3. Combined extent of flooding and date of maximum water level (January 1983, December 1983, and February 1998 storms)

Figure 4-3 also highlights which storm event resulted in the highest water level along the shoreline. Similar to Figure 3-6, no one storm event would result in the highest water level along the entire Bay shoreline. The flood extent upstream of the Carquinez Strait is likely under-represented on Figure 4-3, because the February 1998 storm was associated with intense precipitation and high riverine inflows from the Sacramento–San Joaquin River Delta. The flooding associated with rainfall runoff and riverine inflows was not included in this assessment, but is an important consideration in this region.

4.4 THE STORMS OF THE FUTURE

The January 1983, December 1983, and February 1998 storm events are three of the largest coastal storm events on record. These storms were transformed to today's conditions by incorporating the amount of sea level rise that had occurred between the date of the storm and today. However, if the storm climatology differed slightly, the storms could have been even more extreme. For example, if the peak storm surge from the January 1983 storm had coincided with the highest observed tide on January 27 (a day after the highest observed surge), Bay water levels would have been nearly a foot higher. Similarly, if strong El Niño conditions had persisted during the 1983–1984 winter, or if heavy rainfall had coincided with the December 1983 event, flood impacts would have been intensified across the Bay. The largest storm surge condition observed during the three storm events occurred during the February 1998 storm event. If this storm surge amount had occurred during the highest predicted tide for this area, Bay water levels could have been nearly 0.5 foot higher than the highest observed water level on the local San Francisco record (January 27, 1983).

The "perfect storm" in the Bay could hypothetically occur if the peak high tide, peak storm surge, and peak rainfall all occurred simultaneously. Although it is *possible* that these peaks could occur concurrently, this alignment has not occurred over the historical record to date. Therefore, the perfect-storm condition was not considered as part of this effort. However, sea levels will continue to rise, so the flooding extents associated with storm events similar to the 1983 and 1998 storm events will continue to increase over time. Studies have also shown that extreme precipitation events may be increasing in intensity in the Bay Area (Russo et al. 2013), which may increase the potential for rainfall runoff and riverine flooding. When extreme precipitation is coupled with high Bay water levels, flooding will increase in both depth and extent.

4.5 ASSUMPTIONS AND CAVEATS

As described in Section 2, many layers of complexities in storm processes and local factors control the way the Bay's shoreline has responded—and will respond—to storm events. Figure 4-3 presents a simplistic snapshot of how flooding could look in the Bay today based on the three transformed storm events. The assumptions and caveats associated with this exercise are detailed below:

- This map does not consider the duration of flooding or the potential mechanism for draining the floodwaters from the inundated land after the extreme water levels recede.
- An increase in wave heights and the frequency of El Niño events was not incorporated into the climate change projections. There is general consensus among scientists that climate change will affect the intensity, frequency, and paths of coastal storms and wave events; however, no clear consensus has yet emerged on the nature of these changes in the North Pacific Ocean (NRC 2012).
- The map does 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 and NOAA 2010 LiDAR (CCMP) data set. Although this data set represents the best available topographic data, the data have not been extensively ground-truthed, and levee crests and other features impacting floodwater conveyance may be over-represented or under-represented by the LiDAR data.
- The inundation map does 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.

5.0

RELATIONSHIP TO THE FEMA FLOOD INSURANCE RATE MAPS

5. RELATIONSHIP TO THE FEMA FLOOD INSURANCE RATE MAPS

FEMA has recently completed detailed analysis to update the coastal hazards on the FIRM maps for the nine Bay Area counties. The FIRMs present the 1-percent-annual-chance coastal flood hazard, calculated using a statistical approach that analyzes multiple events that have occurred in the historical record. FEMA evaluates many combinations of the physical processes that can occur simultaneously during storm events (e.g., ocean swell, locally generated wind-driven waves, tidal variations, and elevated water levels during El Niño conditions). The January 1983, December 1983, and February 1998 events are a small subset of the historical storms that FEMA evaluated as part of the San Francisco Bay Area Coastal Study (DHI 2011, 2013).

Although the extent of the flooding shown on Figure 4-3 is different from the flood hazards shown on the updated FEMA FIRMs, the flood extent is actually remarkably similar on the FIRMs and Figure 4-3. Figure 5-1 compares the extent of flooding shown on Figure 4-3 with a composite of the flood extents from the current effective and preliminary FIRMs associated with the San Francisco Bay Area Coastal Study as of April 2016. The areas shown in red represent areas where the FEMA FIRMs depict a greater extent of flooding, and the areas in blue represent areas where the flooding shown on Figure 4-3 is greater. The areas shown in purple represent areas that are flooded both on Figure 4-3 and on the FEMA effective and preliminary FIRMs associated with the San Francisco Bay Area Coastal Study.

The largest areas shown in blue (i.e., Foster City, Redwood Shores, and the Oakland International Airport) are areas where FEMA did not update the coastal hazard information shown on the preliminary FIRMs. These communities are currently coordinating with FEMA regarding the status of their respective existing levee systems. The areas shown in red where the FEMA coastal floodplain is larger are typically associated with berms, embankments, or other structures that are not certified in compliance with Title 44 of the Code of Federal Regulations (Section 65.10) as providing protection from the 1-percent-annual-chance flood hazard. Structures that are not certified are assumed to fail or breach, allowing floodwaters to propagate behind the structure.

For the majority of the San Francisco Bay Area, the flood extents developed by transforming the three historical storm events to present day conditions match well with the coastal flood hazards shown on the recently updated preliminary and effective FIRMs.

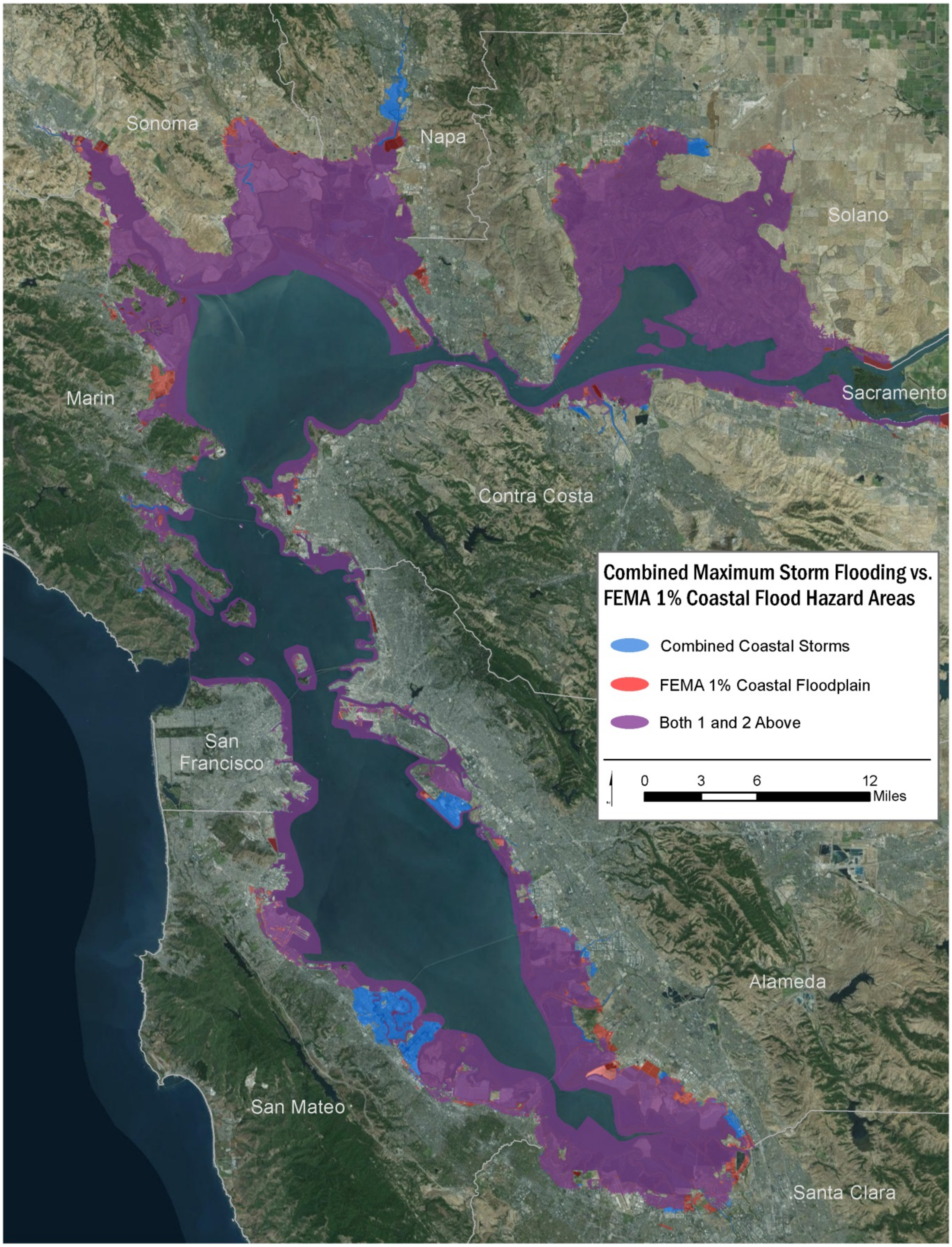

Figure 5-1. Comparison of the extent of flooding due to the combined coastal storms and the FEMA 1-percent-annual-chance coastal floodplain

6.0

CONCLUSIONS

6. CONCLUSIONS

This study provides background on extreme storm events that have occurred in the Bay Area. Specifically, it highlights three of the largest storm events that have impacted the Bay's shoreline communities with respect to coastal flooding. This study also illustrates how no single storm event has produced the highest water levels on record—and therefore potentially the worst flooding on record—for the entire Bay Area. Extreme storm events are unique, and each storm event can impact the shoreline differently, depending on the storm type and storm characteristics. Therefore, there is no simple answer to the question: What storm event can be considered the 1-percent-annual-chance event—or the 100-year event—for the Bay Area? The 1-percent-annual-chance coastal flood hazards mapped by FEMA are part of a statistical "event" that is, in simple terms, a combination of multiple storm events that have occurred in the past and transformed to current conditions.

Although it is problematic to develop a perfect-storm condition for the Bay Area, we can use historical storm event information to better understand current and future flood risks. However, because of changing Bay conditions, climate change, and ongoing shoreline change that may include flood protection infrastructure, sea level rise adaptation measures, development, erosion, and restoration of natural habitats, historic storm events must be transformed to present (or future) conditions if we want to better understand flood risk in the Bay Area.

7.0

REFERENCES

7. REFERENCES

ABAG (Association of Bay Area Governments). 2015. *San Francisco Bay Area State of the Region*. Final Report.

BCDC (San Francisco Bay Conservation and Development Commission). 1988. *Protecting Shoreline Property from Tidal Erosion: An Analysis of the Effectiveness of Administratively Authorized Protective Structures.*

———. 2015. *2014 Annual Report*. http://www.bcdc.ca.gov/cm/2015/2014Annual-Report.pdf.

Climate Impacts Group. 2009. The Washington State Climate Change Impacts Assessment. June 2009.

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

———. 2013. *Regional Coastal Hazard Modeling Study for the South San Francisco Bay*. Final Draft Report. Prepared for the Federal Emergency Management Agency as part of the FEMA Services Group (DHI, Nolte Associates, and Fugro).

Griggs, G., K.G. Patsch, and L.E. Savoy. 2005. *Living with the Changing California Coast*. 540 pp.

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

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 for Visualizing Sea Level Rise and Coastal Flooding Impacts.* In: *Proceedings of the 2011 Solutions to Coastal Disasters Conference*, American Society of Civil Engineers (ASCE), Anchorage, AK. June 2011.

NCDC (National Climatic Data Center). 1998. *The El Niño Winter of '97-'98*. Technical Report 98-02. April 1998.

NRC (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.

Russo, T. A.*,* A. T. Fisher*, and* D. M. Winslow. 2013*.* Regional and local increases in storm intensity in the San Francisco Bay Area, USA, between 1890 and 2010*,* J. Geophys. Res. Atmos.*,* 118*,* 3392–3401*, doi:*10.1002/jgrd.50225*.* Tebaldi, C., B.H. Strauss, and C.E. Zervas. 2012. *Modelling Sea Level Rise Impacts on Storm Surges along US Coasts*. Environmental Research Letters, vol. 7, no. 1.

USGS (United States Geological Survey). 1999. *El Niño Sea-Level Rise Wreaks Havoc in California's San Francisco Bay Region*. Fact Sheet 175-99. http://pubs.usgs.gov/fs/1999/fs175-99/.