Chapter 04

Hazards Analysis

The HCR characterizes 13 hazards that impact San Francisco. Each hazard has a profile capturing the impact, the history of past hazard events, the location, severity, and probability of future events. The chapter also includes an overview of climate change science and how climate change influences hazards in San Francisco.

Earthquake	Tsunami	Landslide	Dam or Reservoir Failure	Flooding	High Wind	Extreme Heat	Drought	Large Urban Fire	Wildfire	Poor Air Quality	Pandemic	Hazardous Materials

4.1 Climate Change and Implications for Hazards

This section provides an overview of climate change and how it influences hazards in San Francisco now and into the future.

What is Climate Change?

Carbon dioxide is a naturally occurring gas produced by decay, fermentation, and combustion, and absorbed by plants through photosynthesis. Carbon dioxide is one of many greenhouse gases, which are chemical compounds that allows sunlight to reach the earth's surface in one form (as visible light), but absorbs reradiated energy (in the form of heat) from the earth and inhibits it from escaping the atmosphere.[1] Beginning in the 20th century, industrial emissions, energy production, transportation, agricultural production, as well as deforestation of the plants that absorb carbon dioxide has increased the concentration of these greenhouse gases in our atmosphere. As these greenhouse gases trap heat, global temperatures increase, and weather becomes more variable and extreme.[2]

Climate change is already happening. The National Ocean and Atmospheric Administration (NOAA) identifies 2015, 2016, 2017, and 2018 as the four hottest years in recorded history.[3] These extreme temperatures have a significant and cascading impact on global weather patterns. High temperatures melt polar ice caps and contribute to the thermal expansion of the oceans which cause global sea levels to rise. Warm ocean temperatures also increase evaporation, and this increased concentration of water vapor in the atmosphere changes rainfall patterns as storms and droughts both become more extreme. Climate change results in three important changes to the global climate system:

- Increasing temperatures
- Rising sea levels
- Changing precipitation patterns

[1] https://www.ncdc.noaa.gov/monitoring-references/faq/greenhouse-gases.php
[2] San Francisco Climate and Health Adaptation Framework
[3] https://www.noaa.gov/news/2018-was-4th-hottest-year-on-record-for-globe

Representative Concentration Pathways (RCPs)[1]

Considering future climate change hazards, as determined by climate model projections, requires an understanding of the assumptions that inform the projection models. These models aren't unknowable black boxes, Global Climate Models are a math-based simplification of four primary interactions driving climate change, namely: The Atmosphere, The Oceans, The Land, and Human Influences. These systems are all interconnected but human influences in these climate models are expressed as Representative Concentration Pathways (RCPs). RCPs assume different levels of human influence on the climate based on potential cumulative anthropogenic CO_2 emissions, from the year 2000 as a baseline:

- RCP 8.5 assumes anthropogenic global greenhouse gas emissions continue to rise over the next century (i.e., there are no significant efforts to limit or reduce emissions)
- RCP 6.0 assumed anthropogenic global greenhouse gas emissions peak in 2080 and then decline
- RCP 4.5 assumes anthropogenic global greenhouse gas emissions peak in 2040 and then decline
- RCP 2.6 assumes stringent emissions reductions, with anthropogenic global emissions declining by about 70% between 2015 and 2050, to zero by 2080, and below zero thereafter (i.e., humans would absorb more greenhouse gasses from the atmosphere than they emit).

While climate change may be global in scope, its impacts are local. The following sections discuss the implications that climate change has for hazards in San Francisco today and into the future.

Increasing Temperatures

As a result of climate change, we are already experiencing an increase in temperatures. From 1950 through 2005, the Bay Area saw an average annual maximum temperature increase of 1.7° F.[4] San Francisco reached an all-time high temperature of 106° F on September 1, 2017.[5] Scientists project that temperatures will continue to increase in the decades to come. As a result, San Francisco will experience more extreme heat days. In addition, higher temperatures can worsen drought and wildfires.

Projections

Average Temperature

- Average yearly temperatures are expected to increase between 1.3°F and 3.1°F by mid-century and 3.3°F and 5.5°F by end-of-century compared to 2010.[6]

Extreme Heat

- Baseline: An extreme heat day is any day when the maximum temperature reaches the 98th percentile of all temperatures for that particular region. In San Francisco, an extreme heat day is any day that surpasses 85°F. Between 1961 and 1990, San Francisco averaged about four extreme heat days per year. [7]
- Projection: Climate scientists project 15-40 extreme heat days per year by mid-century, and upwards of 90 extreme heat days per year by end-of-century.[8] Heat waves are similarly projected to increase in both frequency and severity.

Implications for Future Hazards

Higher temperatures influence several hazards, including:

- San Francisco will experience more extreme heat days and heatwaves will be longer. San Franciscans are particularly vulnerable to extreme heat (for additional information see Extreme Heat Hazard Profile).

[4] California National Resources Agency. California's Fourth Climate Change Assessment: San Francisco Bay Area Region Report. Retrieved from: http://www.climateassessment.ca.gov/regions/docs/20180827-SanFranciscoBayArea.pdf (Accessed: 9/10/2018)
[5] http://sanfrancisco.cbslocal.com/2017/09/01/excessive-heat-warning-declared-for-entire-bay-area/
[6] Scrips Institute of Oceanography, Cal-Adapt and California Nevada Applications Program. Temperature: Extreme Heat Tool, http://cal-adapt. org/temperature/heat/
[7] Scrips Institute of Oceanography, Cal-Adapt and California Nevada Applications Program. Temperature: Extreme Heat Tool, http://cal-adapt. org/temperature/heat/
[8] ibid

- Drought and wildfires fires may become more frequent and severe. Higher temperatures increase evaporation, which dries out soils and vegetation, increasing the severity of drought and making the region more prone to wildland-urban-interface fires.[9] In addition, more wildfires can increase the occurrence of poor air quality events (For additional information see Drought Hazard Profile, Wildfire Hazard Profile, and Air Quality Hazard Profile).

Rising Sea Levels

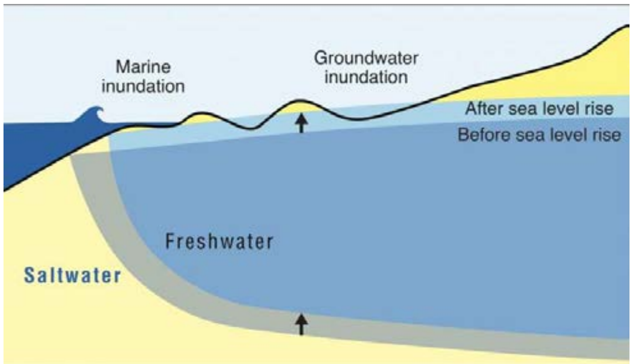
Rising sea levels will have implications for flooding and liquefaction risks. Sea levels in the bay area have already risen by as much as 8 inches in the last 100 years.[10] Low-lying areas not currently exposed to regular tides may become inundated. In addition, temporary coastal flooding events may happen more often, and the flooding may extend farther inland. Stormwater flooding may also increase as stormwater drainage capacity is reduced by higher sea levels. Higher sea levels will also elevate the groundwater table, increasing the susceptibility of soils to liquefaction during an earthquake and potentially compromising potable groundwater supplies in the future. Some areas of the city developed on bay fill zones also face the prospect of subsidence increasing the relative impact of SLR. Studies of the San Francisco waterfront found that subsidence rates of 10 to 20 mm per year can be observed as the mud and artificial fill that constitutes these areas consolidate and compact under the pressure of development.[11]

[9] Ekstrom, Julia A., and Susanne C. Moser. 2012. Climate Change Impacts, Vulnerabilities, and Adaptation in the San Francisco Bay Area: A Synthesis of PIER Program Reports and Other Relevant Research. California Energy Commission. Publication number: CEC-500-2012-071.

[10] California National Resources Agency. California's Fourth Climate Change Assessment: San Francisco Bay Area Region Report. Retrieved from: http://www.climateassessment.ca.gov/regions/docs/20180827-SanFranciscoBayArea.pdf (Accessed: 9/10/2018)

[11] California National Resources Agency. California's Fourth Climate Change Assessment: San Francisco Bay Area Region Report. Retrieved from: http://www.climateassessment.ca.gov/regions/docs/20180827-SanFranciscoBayArea.pdf (Accessed: 9/10/2018)

FIGURE 4-1
SEA LEVEL RISE DIAGRAM[12]



Projections

San Francisco relies on two primary documents to integrate sea level rise projections into adaptation and hazard mitigation planning. The first is the National Research Council's (NRC) 2012[13] report which provided the best available science on sea level rise at the time and was used to create the CPC SLR guidance[14] as well as the City's 2016 Sea Level Rise Action Plan. The second is the State of California Sea-Level Rise Guidance report (State Guidance) which is periodically updated. The 2018 update to the State Guidance integrates the latest findings from national and regional studies, uses a probabilistic projection method which differs from the NRC report, and includes an extreme, but unlikely, scenario referred to as H++. [15]

Figure 4-2 presents a rough comparison between the NRC 2012 and updated State Guidance sea level projections for 2100. The NRC 2012 values are compared to their

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[12] UHM Coastal Geology Group

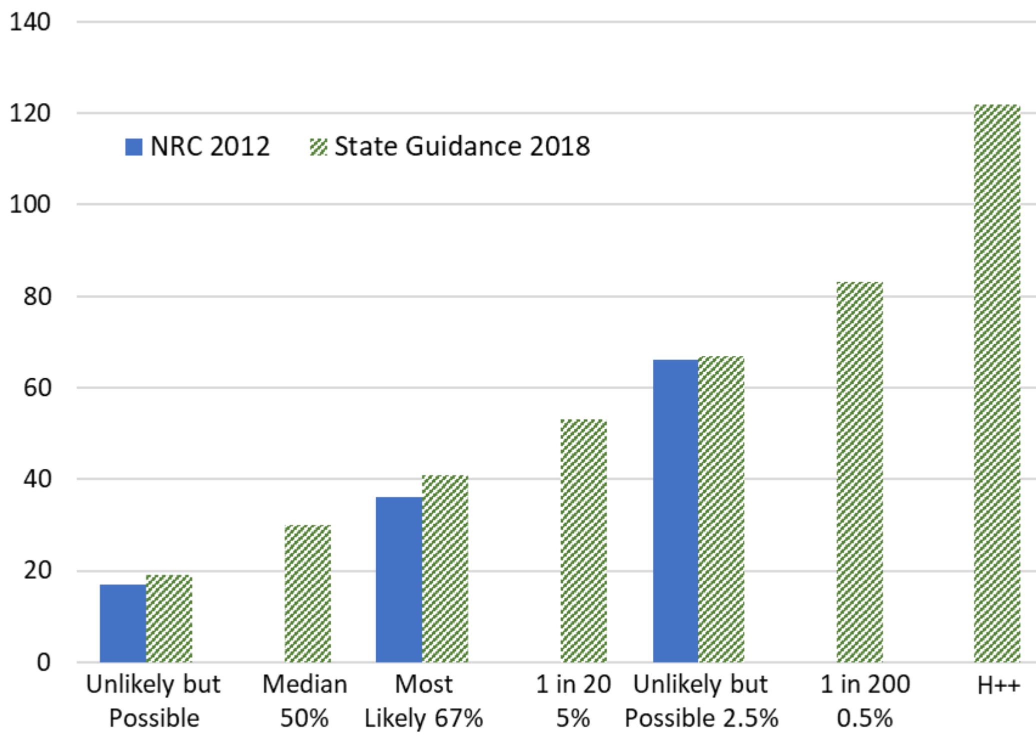
[13] National Research Council (2012). Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present and Future. Prepared by the Committee on Sea Level Rise in California, Oregon, and Washington, Board on Earth Sciences and Resources, Ocean Studies Board, and the Division on Earth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

[14] Capital Planning Commission. *Guidance for Incorporating Sea Level Rise in Capital Planning In San Francisco: Assessing Vulnerability and Risk to Support Adaptation.* Accessed 10/5/2018. http://onesanfrancisco.org/sites/default/files/inline-files/Guidance-for-Incorporating-Sea-Level-Rise-into-Capital-Planning1.pdf. 2019 SLR checklist update: Adopted 07/22/2019 by the Capital Planning Commission (CPC)

[15] California Ocean Protection Council. *State of California Seal-Level Rise Guidance*. Accessed 10/5/2018. http://www.opc.ca.gov/webmaster/ftp/pdf/agenda_items/20180314/Item3_Exhibit-A_OPC_SLR_Guidance-rd3.pdf

most similar proxy in the State Guidance. For example, the unlikely but possible values represent the lower bound of the 2100 projection range for NRC 2012 (17 inches) and the State Guidance median projection for RCP 2.6 at 2100 (19 inches). These represent the lowest values presented in both documents for the end of the century. The most likely values include the most likely value recommended in NRC 2012 (36 inches) and the upper bound of the likely range recommended in the State Guidance (41 inches). The upper bound values include the upper bound of the projection range presented in NRC 2012 (66 inches), compared with the State Guidance projection that has a 2.5% probability of occurrence (67 inches). This probability value was selected for comparison because the projection range presented in NRC 2012 used a calculation based on two standard deviations (i.e., two standard deviations captures 95 percent of the data, or the values between the 2.5-percentile and the 97.5-percentile).

FIGURE 4-2
COMPARISON OF SEA LEVEL RISE PROJECTIONS BY NRC (2012) AND THE STATE GUIDANCE (2018)[16]



[16] The sea level rise projections from NRC (2012) are based on greenhouse gas emission scenarios published in 2000 for IPCC in the Special Report on Emission Scenarios (SRES). IPCC used the SRES

Although the NRC 2012 and State Guidance projections are similarly comparable, the State Guidance recommends using higher water levels. For example, the recommended upper bound number for long-range adaptation planning increases from 66 inches (NRC 2012) to 83 inches (State Guidance). In addition, the recommended most likely value of sea level rise increases from 36 inches (NRC 2012) to 41 inches (State Guidance). In addition, the latest update to the State Guidance includes a more extreme SLR scenario known as H++, which projects 122 inches of SLR at 2100 which peaks at 164 inches when coupled with a 100-year storm. This scenario is based on a future with rapid loss of the West Antarctic ice sheet, however, this scenario is highly uncertain and the subject of ongoing research. Therefore, the H++ scenarios is not used for planning or adaptation purposes at this time, but it does illustrate the inherent uncertainty in the practice of projecting SLR.

In light of the updated State Guidance and the evolving science on sea level rise[17], the CPC Guidance was updated in July 2019. The Sea Level Rise checklist has been updated to include the likely and 1-in-200 chance values for RCP 4.5 and RCP 8.5 based on the most recently updated science. Likely values for RCP4.5 are 33 inches and RCP8.5 is 41 inches which compares well with the existing NRC recommendation of 36 inches. However, NRC recommended using the upper range value of 66 inches of sea level rise by 2100 for adaptation planning. The 1-in-200 values for RCP4.5 and RCP8.5 exceed this, with 71 inches and 83 inches of sea level rise by 2100 respectively. This represents a notable increase in the amount for sea level rise recommended for use in adaptation planning.

As this update occurred far into the development of this planning effort, the updated values were unable to be used in this assessment, therefore this report relies on the CPC Guidance values derived from the NRC 2012 report.

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approach in the Third and Fourth Assessment Reports published in 2001 and 2007, respectively. The projections in the State Guidance (2018) are based on the updated Representation Concentration Pathways (RCPs) adopted by the IPCC for the fifth Assessment Report in 2014. The assumptions and science behind the SRES and RCP approaches are very different; therefore, direct comparisons are challenging and should be considered for illustrative purposes only.

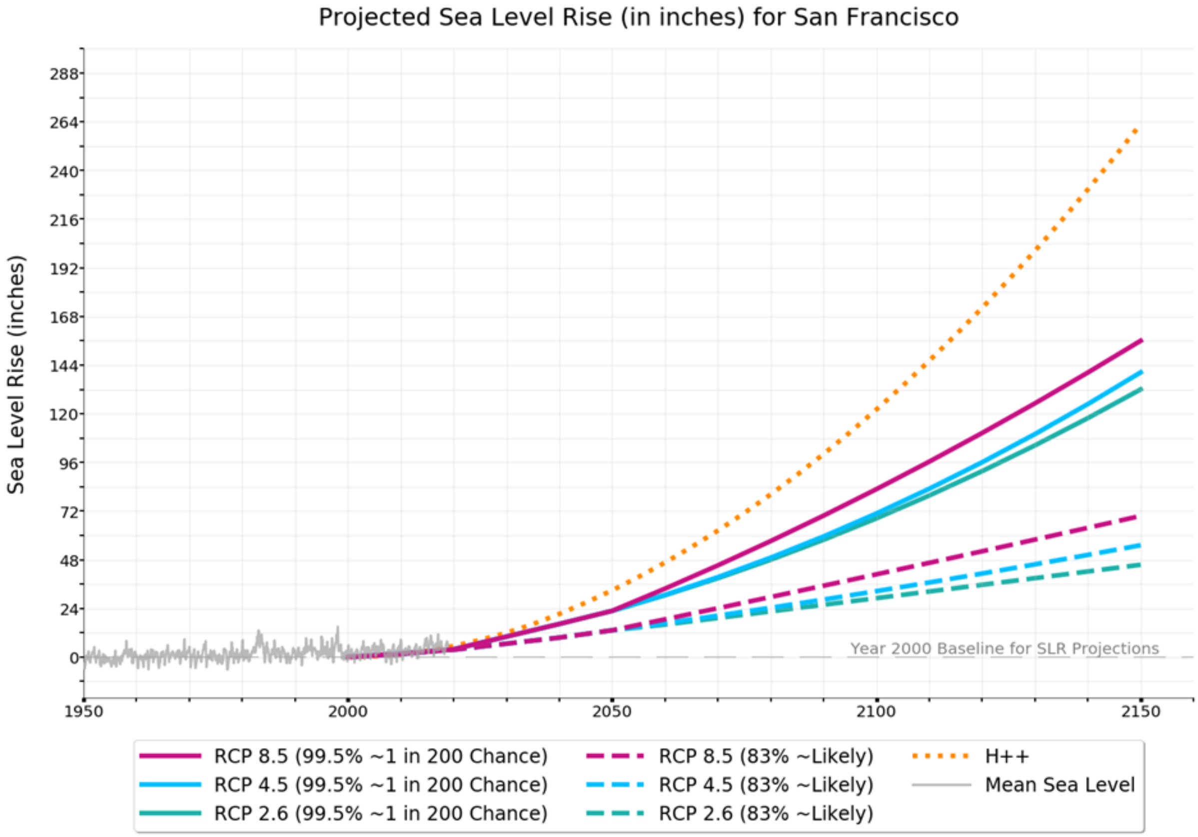
[17] Griggs, G, Árvai, J, Cayan, D, DeConto, R, Fox, J, Fricker, HA, Kopp, RE, Tebaldi, C, Whiteman, EA (California Ocean Protection Council Science Advisory Team Working Group). Rising Seas in California: An Update on Sea-Level Rise Science. California Ocean Science Trust, April 2017.

FIGURE 4-3
SEA LEVEL RISE PROJECTIONS BY NRC (2012) AND THE RISING SEAS (2017)[18]

	NRC 2012		RCP 4.5 Rising Seas 2017		RCP 8.5 Rising Seas 2017	
Year	Likely	Upper Range	Likely	1 in 200 Chance	Likely	1 in 200 Chance
2030	6	12	6	10	6	10
2050	11	24	13	23	13	23
2070	20	38	20	39	24	45
2100	36	66	33	71	41	83
2150	--	--	55	140	70	156

[18] This table demonstrated the different suggested values between the NRC report that underpinned the original CPC guidance and the values shown in the rising seas report (see previous citation) which formed the basis for the 2019 CPC guidance update.

FIGURE 4-4
RELATIVE SEA LEVEL RISE IN SAN FRANCISCO, CA[19]



For a more in-depth treatment of SLR Projections, see "Chapter 2: Sea Level Rise Climate Science and Scenarios" of the San Francisco's Sea Level Rise Vulnerability and Consequences Assessment.[20]

For the exposure and vulnerability assessment in this report, we have selected two different sea level rise scenarios:

- **66 inches above MHHW**, which represents the 2050 upper-end SLR projection plus 100-year extreme tide or the 2100 upper-range SLR projection without extreme tide (NRC 2012)

[19] City and County of San Francisco, (Publication forthcoming). "Draft Sea Level Rise Vulnerability and Consequences Assessment"

- **108 inches above MHHW**, which represents 2100 upper-end SLR projection plus 100-year extreme tide (NRC 2012)

For more detailed mapping of SLR scenarios, please see the San Francisco Sea Level Rise Vulnerability & Consequences Assessment,[21] which uses 10 scenarios that represent a range of SLR projections aligning with the NRC (2012) SLR projections and the State Guidance (2018) projections and include storm surge events.

Implications for Future Hazards

Without action, a variety of hazards will increase as seas rise, including:

- Low-lying areas that are not currently exposed to tides will experience inundation during high tides in the long-term.[22] (For additional information see Flooding Hazard Profile.)
- Coastal flooding will become more frequent as Bay and sea levels occur more often. Coastal flooding will be more extensive and longer-lasting, especially during storm events.[23] (For additional information see Flooding Hazard Profile.)
- Stormwater flooding will increase as high bay levels can impede drainage of stormwater runoff.[24] (For additional information see Flooding Hazard Profile).
- Higher sea levels will also increase the elevation of the groundwater table, increasing the susceptibility of some soils to liquefaction during an earthquake.[25] (For additional information see Earthquake Flooding Hazard Profile).

[21] City and County of San Francisco, (Publication forthcoming). "Draft Sea Level Rise Vulnerability and Consequences Assessment".
[22] City and County of San Francisco, 2016. "Sea Level Rise Action Plan."
[23] Ibid
[24] Ibid
[25] Adapting to Rising Tides, "Climate Impacts and Scenarios."
http://www.adaptingtorisingtides.org/portfolio/climate-impacts-and-scenarios/

Changing Precipitation Patterns

San Francisco precipitation levels have historically fluctuated between wet and dry extremes. Climate change will amplify this trend. As a result, San Francisco is projected to experience an increase in both flooding and drought.

Projections

Baseline: Although San Francisco has historically received on average 21 inches of rainfall annually, Bay Area precipitation levels are prone to large year-to-year variation.[26] California currently receives 35% - 45% of its annual precipitation from discrete storm events. These extreme storms events occur between November and March when atmospheric rivers transport water vapor from Hawaii across the Pacific Ocean towards the west coast of the United States.[27] Compared to other storm systems that originate in Alaska, atmospheric river storms are warm and wet and are associated with many of California's flood events. While 35% - 45% of California's annual precipitation comes from atmospheric river storms, they are responsible for nearly 80% of California's flooding because of both the quantity of precipitation these storms contain, and because these storms are less likely to result in snowfall because they have warmer water and can occur in spring or fall.[28] These storms may carry as much water as seven to fifteen Mississippi Rivers in a single event and often play a pivotal role in ending periods of drought[29].

Projection: Considering RCP4.5 mean projections, most regions of the state can expect to see at least modest increases in mean wet-season precipitation compared to historical amounts. However, the San Francisco Bay area is projected to see potential average late-century increases of up to 10.5 percent, the highest in the state, making the region most likely to see changes in future storm events.[30] This trend is also evident

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[26] NOAA National Center for Environmental Information Station ID CHCND:USW000232272

[27] Dettinger, Michael, 2011. "Climate Change, Atmospheric Rivers, and Floods in California – A Multimodel Analysis of Storm Frequency and Magnitude Changes", *Journal of the American Water Resources Association*, Vol. 47, No. 3

[28] https://www.jpl.nasa.gov/news/news.php?feature=5648

[29] California National Resources Agency. California's Fourth Climate Change Assessment: San Francisco Bay Area Region Report. Retrieved from: http://www.climateassessment.ca.gov/regions/docs/20180827-SanFranciscoBayArea.pdf (Accessed: 9/10/2018)

[30] He, Minxue, Andrew Schwarz, Elissa Lynn, Michael Anderson (California Department of Water Resources). 2018. Projected Changes in Precipitation, Temperature, and Drought across California's Hydrologic Regions. California's Fourth Climate Change Assessment.

in the RCP8.5 projections that point to average wet-season mid-century changes as much as 10.3% and as much as 18.7% by late-century. These indicators represent a general trend towards more intense/frequent storms during the wet-season in the coming decades.

FIGURE 4.5
AVERAGE WET-SEASON PRECIPITATION CHANGE ACROSS THE STATE ASSUMING A RCP4.5 SCENARIO[31]

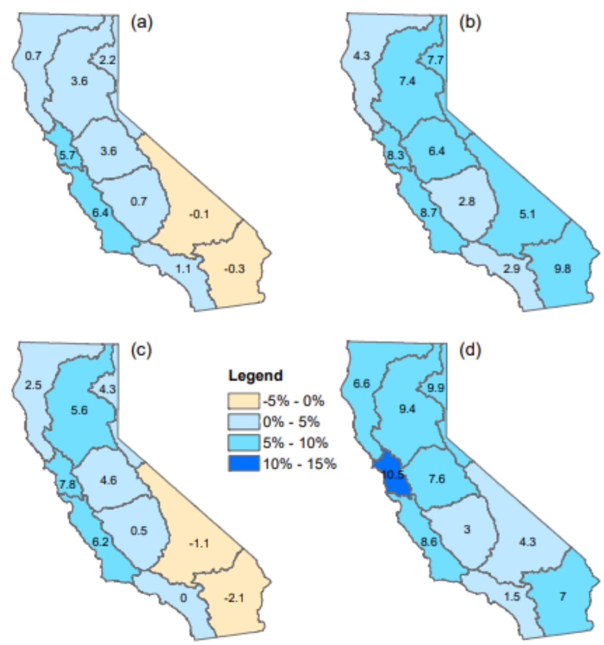

Figure 3: Percent Differences (%) between Historical and Mean RCP 4.5 Projections on (a) Annual Precipitation in Mid-Century, (b) Wet Season Precipitation in Mid-Century, (c) Annual Precipitation in Late-Century, and (d) Wet Season Precipitation in Late-Century.

Year-to-year precipitation levels are expected to increasingly cluster around wet and dry extremes.[32] Precipitation is expected to become more variable in the future, with

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Publication number: CCCA4-EXT-2018-002.

[31] He, Minxue, Andrew Schwarz, Elissa Lynn, Michael Anderson (California Department of Water Resources). 2018. Projected Changes in Precipitation, Temperature, and Drought across California's Hydrologic Regions. California's Fourth Climate Change Assessment. Publication number: CCCA4-EXT-2018-002.

[32] Dettinger, Michael, 2011. "Climate change, atmospheric rivers, and floods in California – A Multimodel Analysis of Storm Frequency and Magnitude Changes", *Journal of the American Water Resources Association*, Vol. 47, No. 3

more rainfall occurring during extreme events, as higher temperatures can result in more water held in the atmosphere that is able to fall as rain. By the end of the century, atmospheric river storms are expected to provide nearly 50% of California's annual precipitation.[33] Under the RCP8.5 high-emissions scenario, severe storms with a return frequency of once every 200 years (a storm on the magnitude of the Great California Flood of 1862) could potentially occur every 40-50 years in the Bay Area by 2100.[34]

San Francisco gets 85% of its water from the Sierra Nevada.[35] According to a study by the UCLA Center for Climate Science, the snowpack in the year 2100 is expected to be 36 percent of the snowpack in 2000, which presents a major challenge for water management.[36]

Implications for Future Hazards

Changing precipitation patterns may influence several hazards, including:

- Concentrated precipitation in extreme events may increase stormwater flooding, especially along San Francisco's underground creeks and in San Francisco's natural drainage basins. (For additional information see Flooding Hazard Profile.)
- Concentrated precipitation in extreme events may also increase the risk of landslides. An increase in wildland-urban-interface fires also increases landslide risks. (For additional information see Landslide Hazard Profile.)
- In dry years, when coastal high-pressure systems do not dissipate during winter months, California may be subject to frequent and severe droughts. In addition, a reduced snowpack in the Sierras can exacerbate drought and compromise water supply. (For additional information see Drought Hazard Profile).

[33] Dettinger, Michael, 2011. "Climate Change, Atmospheric Rivers, and Floods in California – A Multimodel Analysis of Storm Frequency and Magnitude Changes", *Journal of the American Water Resources Association*, Vol. 47, No. 3
[34] California National Resources Agency. California's Fourth Climate Change Assessment: San Francisco Bay Area Region Report. Retrieved from: http://www.climateassessment.ca.gov/regions/docs/20180827-SanFranciscoBayArea.pdf (Accessed: 9/10/2018)
[35] San Francisco Public Utilities Commission - http://www.sfwater.org/index.aspx?page=355
[36] Reich, KD, N Berg, DB Walton, M Schwartz, F Sun, X Huang, and A Hall, 2018: "Climate Change in the Sierra Nevada: California's Water Future." UCLA Center for Climate Science.

TABLE 4-5
SUMMARY OF CLIMATE CHANGE IMPLICATIONS FOR HAZARDS

Climate Change:	Increasing Temperatures	Rising Sea Levels	Changing Precipitation Patterns
Implications for Hazards:	More **extreme heat** days, making heatwaves more frequent and longer-lasting. **Drought** and **wildland-urban-interface fires** may become more frequent and severe.	More frequent, extensive and longer-lasting **coastal flooding**, especially during storm events. **Stormwater flooding** may increase as high bay levels can impede drainage of stormwater runoff. Higher groundwater table may **increase the susceptibility of some soils to liquefaction** during an earthquake.	Concentrated precipitation in discrete storm events may increase **stormwater flooding**. **Droughts** may be more frequent and severe. Reduced snowpack in the Sierras may also exacerbate **drought**.

Earthquake Hazard Profile

4.2 Earthquake

Earthquakes present one of the greatest risks to San Francisco's buildings, infrastructure and people. San Francisco has experienced several devastating earthquakes in its history, and there is a high likelihood of a large earthquake in the near future. An earthquake is a sudden slip on a fault in the earth's crust, and the resulting ground shaking and radiated seismic energy caused by the slip.[37] A fault is a fracture in the earth's crust where a block of crust on one side moves relative to the other.[38]

The energy released in earthquakes can produce different types of hazards. Groundshaking and Liquefaction are discussed in greater detail in this profile, while tsunami, earthquake-induced landslide, fire following earthquake (large urban fire), and dam failure are discussed in their own profiles. Each of which are discussed in greater detail in this section:

Ground Shaking

Impact Statement

All of San Francisco is susceptible to very strong to extreme ground shaking during a major earthquake. There is a 72 percent chance that an earthquake of moment magnitude (Mw) 6.7 or greater will strike the San Francisco Bay Region between now and 2043. A Mw 6.7 earthquake or above on one of the seven major faults in the Bay Area could result in very strong to severe shaking in the city, which in turn may result in widespread casualties and infrastructure damage. Though the impact of climate change on earthquakes has not been clearly established,[39] sea level rise may result in higher ground water tables, which may increase the areas of the city susceptible to liquefaction.[40]

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[37] United States Geological Survey (USGS) Earthquake Hazards Program, "Earthquake Glossary - Earthquake," accessed May 17, 2018, https://earthquake.usgs.gov/learn/glossary/?term=earthquake.

[38] USGS Earthquake Hazards Program, "Earthquake Glossary - Fault," accessed May 17, 2018, http://earthquake.usgs.gov/learn/glossary/?term=fault.

[39] Ilan Kelman, "Climate Change and the Sendai Framework for Disaster Risk Reduction," *International Journal of Disaster Risk Science* 6 (2015): 121, accessed May 22, 2018, https://link.springer.com/content/pdf/ 10.1007%2Fs13753-015-0046-5.pdf.

[40] Peter Quilter, Sjoerd van Ballegooy, and Marje Russ, "The Effect of Sea Level Rise on Liquefaction Vulnerability." *6th International Conference on Earthquake Geotechnical Engineering*, 1-4 November 2015, Christchurch, New Zealand.

Nature

The effects of large earthquakes can be felt far beyond the site of their occurrence. Earthquakes occur without warning and can cause significant damage and extensive casualties after just a few seconds. The most common effect of earthquakes is ground shaking. When an earthquake occurs, the energy from the quake radiates outward from the fault in all directions in the form of seismic waves. As seismic waves reach the earth's surface, they shake the ground and anything on it. Strong ground shaking may damage or destroy buildings and may injure or kill occupants. Ground shaking is the primary cause of earthquake damage to buildings and infrastructure.[41]

The severity of ground shaking in an earthquake depends on the magnitude of the quake, the distance from the fault, and local geologic conditions. We can anticipate the amount of shaking that may occur at a given location from a particular fault by knowing how long the fault is (which indicates earthquake magnitude), where the fault is (giving us the distance to any location), and the geological conditions at the site.[42] Soil type is one geological condition that may affect ground shaking. The velocity at which soil or rock transmits shear waves generated by earthquakes contributes to amplification of ground shaking. Shaking is stronger where the shear wave velocity is lower. Because soft soils have lower shear wave velocity, they amplify or increase ground shaking. As a result, earthquake damage is typically more severe in areas with soft soils.[43]

Table 4-7, below, shows soil types in the Bay Area and their shear wave velocity. San Francisco's predominant soil is Type D, but there are locations in the city with Type E soils. Both of these soil types amplify shaking. For a map showing soil types in San Francisco, see Figure 4-6 below.

[41] USGS, Earthquake Hazards Program, "Soil Type and Shaking Hazard in the San Francisco Bay Area," accessed May 17, 2018, https://earthquake.usgs.gov/hazards/urban/sfbay/soiltype/.

[42] Southern California Earthquake Center (SCEC), "Earthquake Shaking - Accounting for "Site Effects," accessed May 17, 2018, http://scecinfo.usc.edu/phase3/overview.html.

[43] USGS, Earthquake Hazards Program, "Soil Type and Shaking Hazard in the San Francisco Bay Area."

FIGURE 4-6
SOIL TYPES IN SAN FRANCISCO

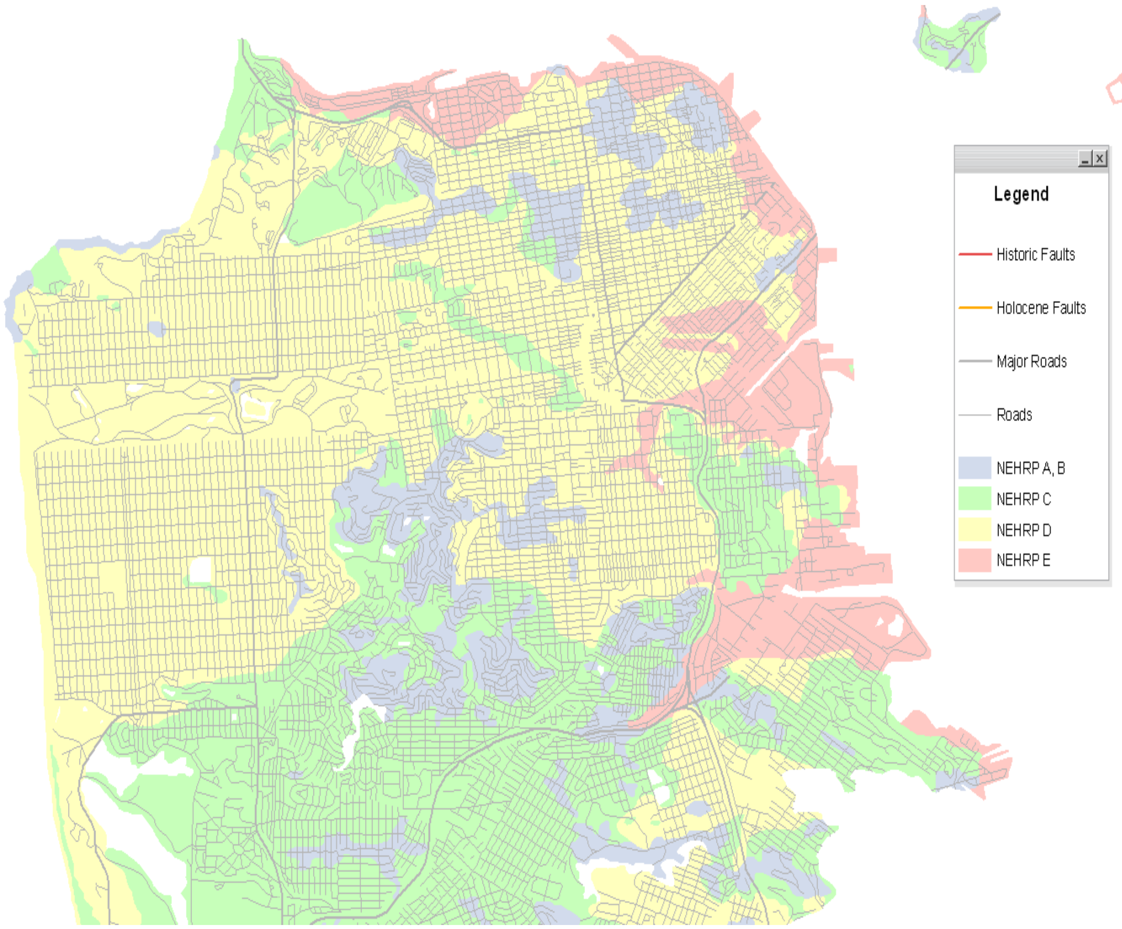

TABLE 4-7
SOIL TYPES AND SHAKING AMPLIFICATION[44]

Soil Type	Shear-Wave Velocity (Vs)	Soil Definitions
Type A	Vs > 1500 m/sec	Includes unweathered intrusive igneous rock. Occurs infrequently in the Bay Area. Soil types A and B do not contribute greatly to shaking amplification.
Type B	1500 m/sec > Vs > 750 m/sec	Includes volcanics, most Mesozoic bedrock, and some Franciscan bedrock. The Franciscan Complex is a Mesozoic unit that is common in the Bay Area.
Type C	750 m/sec > Vs > 350 m/sec	Includes some Quaternary sands, sandstones, and mudstones; Upper Tertiary sandstones, mudstones and limestone; Lower Tertiary mudstones and sandstones; and Franciscan melange and serpentinite.
Type D	350 m/sec > Vs > 200 m/sec	Includes some Quaternary muds, sands, gravels, silts and mud. Significant amplification of shaking by these soils is generally expected.
Type E	200 m/sec > Vs	Includes water-saturated mud and artificial fill. The strongest amplification of shaking is expected for this soil type.

The severity of an earthquake can be described in terms of intensity and magnitude. Intensity is the impact of an earthquake on the Earth's surface. Intensity measures the strength of shaking from an earthquake at a certain location as indicated by its effects on people, structures, and the natural environment. Intensity generally increases with the amount of energy released, which is proportional to the size of the earthquake, and decreases with distance from the quake epicenter.[45]

One scale used in the United States to measure earthquake intensity qualitatively is the Modified Mercalli Intensity (MMI) Scale. The MMI Scale consists of 10 increasing levels of intensity ranging from imperceptible shaking to building destruction.[46] MMI less than 6 does not generally damage buildings. Table 4-10 below shows the expected impacts

[44] USGS, Earthquake Hazards Program, "Soil Type and Shaking Hazard in the San Francisco Bay Area," accessed May 17, 2018, https://earthquake.usgs.gov/hazards/urban/sfbay/soiltype/
[45] USGS, "The Severity of an Earthquake," *General Interest Publication 1989-288-913*, accessed May 17, 2018, https://pubs.usgs.gov/gip/earthq4/ severitygip.html.
[46] USGS, Earthquake Hazards Program, "The Modified Mercalli Intensity Scale," accessed May 17, 2018, https://earthquake.usgs.gov/learn/topics/mercalli.php.

to building contents and common building types. For maps showing MMI for various earthquake scenarios that may impact San Francisco, see Figure 4-8 and Figure 4-9 below.

Ground shaking intensity can also be quantitatively measured in terms of acceleration, velocity, or displacement. Peak ground acceleration (PGA) is a common ground motion parameter used by engineers. PGA measures earthquake intensity by quantifying the rate of acceleration of the ground at a given location. Peak acceleration is the largest increase in velocity recorded by a particular geophysical instrument station during an earthquake.[47] PGA is expressed as a percentage of the acceleration of gravity (g): One g is an acceleration of 9.8 meters per second.[48]

Another means of measuring earthquake severity is Magnitude (M), which measures the size of an earthquake. The first magnitude scale was the Richter Scale, also known as local magnitude (M_L). Because the Richter Scale does not satisfactorily measure the size of larger earthquakes, it is no longer commonly used. The magnitude scale currently used by seismologists is the moment magnitude (Mw) scale.[49] The Mw scale, based on the concept of seismic moment, is uniformly applicable to all sizes of earthquakes.[50] Table 4-11 shows an approximate correlation between the Mw and MMI Scale for intensities typically observed at locations near the epicenter of earthquakes of different magnitudes.

47 USGS, Earthquake Hazards Program, "Earthquake Glossary - Acceleration," accessed May 17, 2018, https://earthquake.usgs.gov/learn/glossary/?term=acceleration.

48 USGS, Earthquake Hazards Program, "Earthquake Glossary – G or g," accessed May 17, 2018, https://earthquake.usgs.gov/learn/glossary/?term=G%20or%20g.

49 USGS, Earthquake Hazards Program, "Measuring the Size of an Earthquake," accessed May 17, 2018, https://earthquake.usgs.gov/learn/topics/measure.php.

50 USGS, Earthquake Hazards Program, "Earthquake Glossary – Magnitude," accessed May 17, 2018, https://earthquake.usgs.gov/learn/glossary/?term=magnitude.

FIGURE 4-8
PREDICTED GROUND SHAKING INTENSITY: 7.0 HAYWARD FAULT SCENARIO

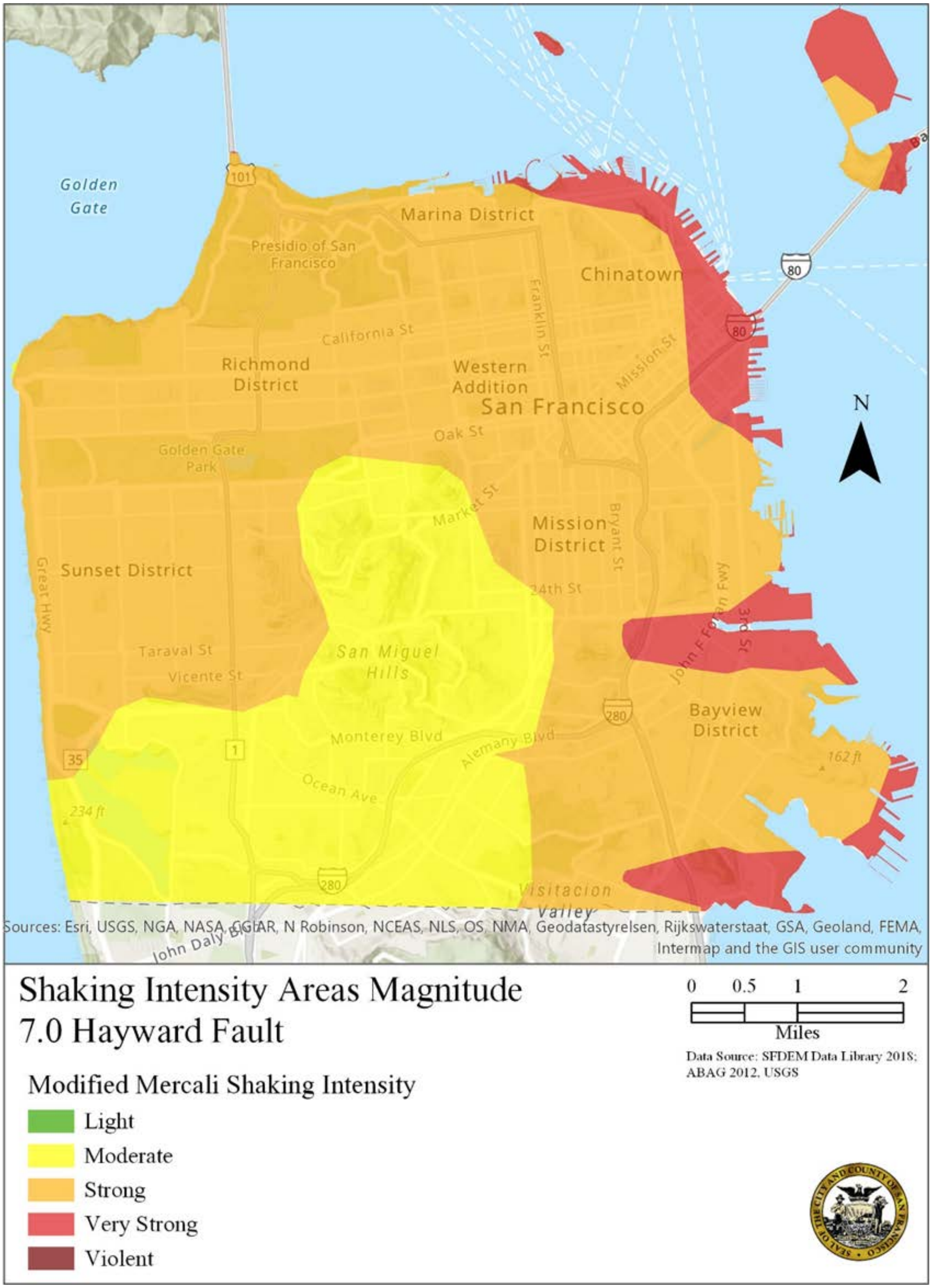

FIGURE 4-9
PREDICTED GROUND SHAKING INTENSITY: 7.8 SAN ANDREAS FAULT SCENARIO

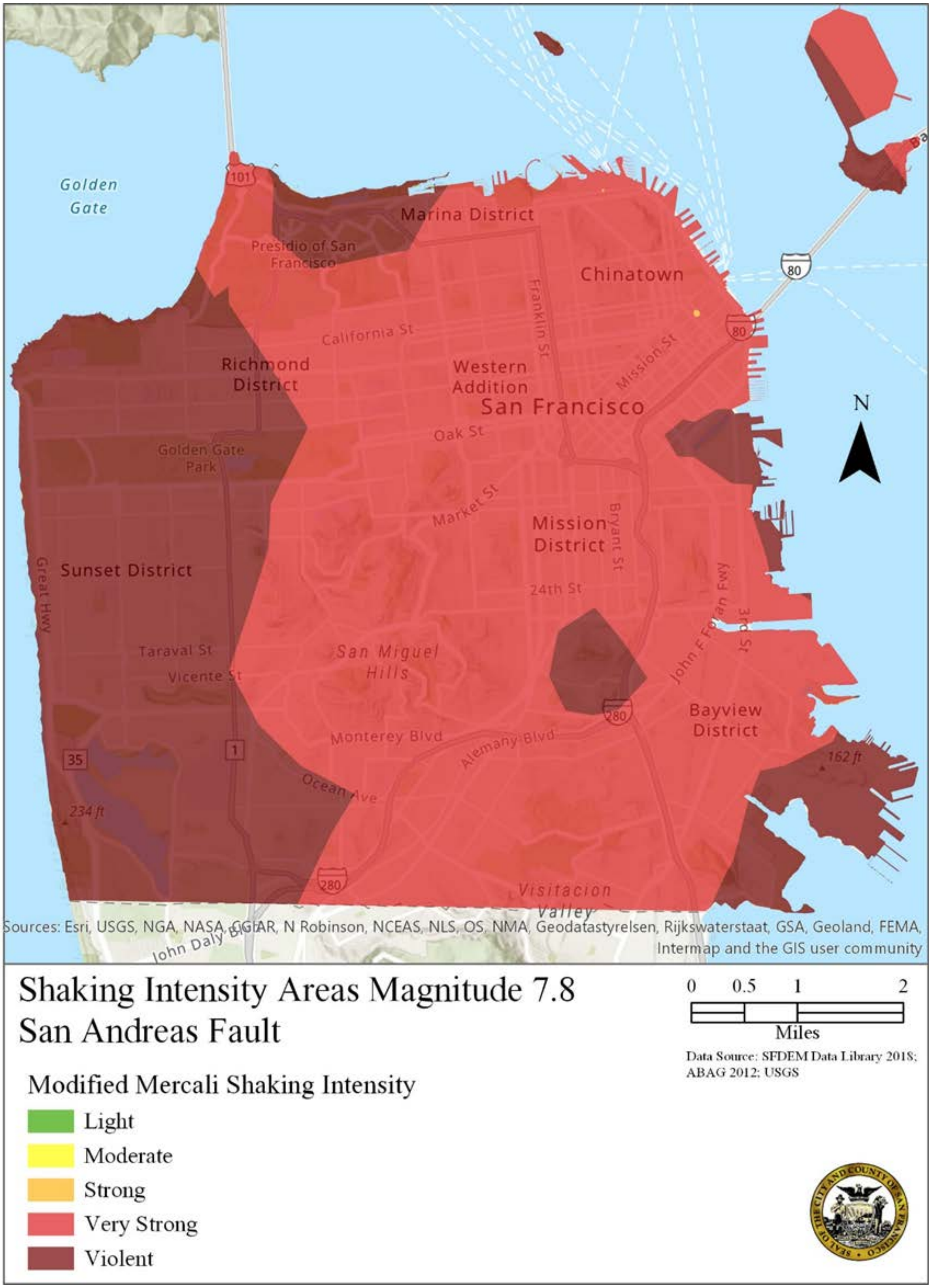

TABLE 4-10
SHAKING INTENSITY IMPACTS[51]

Intensity	Shaking	Intensity Description or Damage
I	Not Felt	Not felt except by a very few under especially favorable conditions.
II	Weak	Felt only by a few persons at rest, especially on upper floors of buildings.
III	Weak	Felt quite noticeably by persons indoors, especially on upper floors of buildings. Many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibrations similar to passing of a truck. Duration estimated.
IV	Light	Felt indoors by many, outdoors by few during the day. At night, some awaken. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.
V	Moderate	Felt by nearly everyone; many awaken. Some dishes and windows broken. Unstable objects overturned. Pendulum clocks may stop.
VI	Strong	Some things thrown from shelves, pictures shifted, water thrown from pools. Some walls and parapets of poorly constructed masonry buildings crack. Some drywall cracks. Some chimneys are damaged. Some slab foundations, patios, and garage floors slightly crack.
VII	Very Strong	Many things thrown from walls and shelves. Furniture is shifted. Poorly constructed buildings are damaged and some well- constructed buildings crack. Cornices and unbraced parapets fall. Plaster cracks, particularly at inside corners of buildings. Some unretrofitted soft-story buildings strain at the first-floor level. Some partitions deform. Many chimneys are broken and some collapse, damaging roofs, interiors, and porches. Weak foundations can be damaged.
VIII	Severe	Nearly everything thrown from shelves, cabinets, and walls. Furniture overturned. Poorly-constructed buildings suffer partial or full collapse. Some well-constructed buildings are damaged. Unreinforced walls fall. Unretrofitted soft-story buildings are displaced out of plumb and partially collapse. Loose partition walls are damaged and may fail. Some pipes break. Houses shift if they are not bolted to the foundation or are displaced and partially collapse if cripple walls are not braced. Structural elements such as beams, joists, and foundations are damaged. Some pipes break.
IX	Violent	Only very well anchored contents remain in place. Poorly constructed buildings collapse. Well- constructed buildings are heavily damaged. Retrofitted buildings damaged. Unretrofitted soft-story buildings partially or completely collapse. Some well- constructed buildings are damaged. Poorly constructed buildings are heavily damaged, some partially collapse. Some well- constructed buildings are damaged.
X	Extreme	Only very well anchored contents remain in place. Retrofitted buildings are heavily damaged, and some partially collapse. Many well- constructed buildings are damaged.

[51] US Geological Survey (USGS). https://earthquake.usgs.gov/learn/topics/mercalli.php

TABLE 4-11
MAGNITUDE AND INTENSITY COMPARISON[52]

Moment Magnitude (Mw)	Modified Mercalli Intensity (MMI) Scale
1.0-3.0	I
3.0 - 3.9	II – III
4.0 - 4.9	IV – V
5.0 - 5.9	VI – VII
6.0 - 6.9	VII – IX
7.0 and higher	VIII or higher

History

The San Francisco Bay Area is located within the boundary between the Pacific and the North American tectonic plates, where the Pacific plate is slowly and continually sliding northwest and past the North American plate.[53] Historically, the San Andreas Fault system is the most active system in the Bay Area. This fault system is capable of generating very strong earthquakes of magnitude 7.0 or greater.

The last major earthquake on the northern portion of the fault occurred in 1906. Known as the Great 1906 San Francisco Earthquake, this event was centered off San Francisco's Ocean Beach, and lasted 45 to 60 seconds. The 1906 quake has been estimated at moment magnitude 7.7 to 7.9.[54] The quake was reported at the time to have resulted in 498 deaths in San Francisco and $80 million in earthquake damage to the region.[55] Later research has produced estimates of over 3,000 deaths in San Francisco from the 1906 earthquake.[56]

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52 USGS. http://earthquake.usgs.gov/learning/topics/mag_vs_int.php

53 USGS, *Earthquake Outlook for the San Francisco Bay Region 2014—2043*, by Brad T. Aagaard, James Luke Blair, John Boatwright, Susan H. Garcia, Ruth A. Harris, Andrew J. Michael, David P. Schwartz, and Jeanne S. DiLeo, Fact Sheet 2016-3020, (Reston, Virginia, 2016), 2, accessed May 21, 2018, https://pubs.usgs.gov/fs/2016/3020/ fs20163020.pdf.

54 USGS, Earthquake Hazards Program, "1906 Earthquake: What was the magnitude?" accessed May 17, 2018, https://earthquake.usgs.gov/earthquakes/events/1906calif/18april/magnitude.php.

55 USGS, Earthquake Hazards Program, "Casualties and damage after the 1906 Earthquake," accessed May 17, 2018, https://earthquake.usgs.gov/earthquakes/events/1906calif/18april/casualties.php.

56 Gladys Hansen and Emmet Condon, *Denial of Disaster* (San Francisco: Cameron and Co., 1989), 14.

On October 17, 1989, San Francisco experienced the Mw 6.9 Loma Prieta Earthquake. The 1989 quake was centered near Loma Prieta peak in the Santa Cruz Mountains, approximately 60 miles south-southeast of San Francisco. The quake lasted only 15 seconds, but resulted in severe shaking in the San Francisco and Monterey Bay regions.[57] In San Francisco, Loma Prieta resulted in 12 deaths, 300 people injured, and $2 billion dollars in property damage.[58]

The largest earthquake since Loma Prieta was the August 24, 2014, South Napa Earthquake, a Mw 6.0 earthquake on the West Napa fault, which is part of the Calaveras Fault Zone system. The Napa quake resulted in two deaths and 300 injuries, and caused extensive damage in Napa, Solano, and Sonoma counties. It did not result in significant damage in San Francisco.[59]

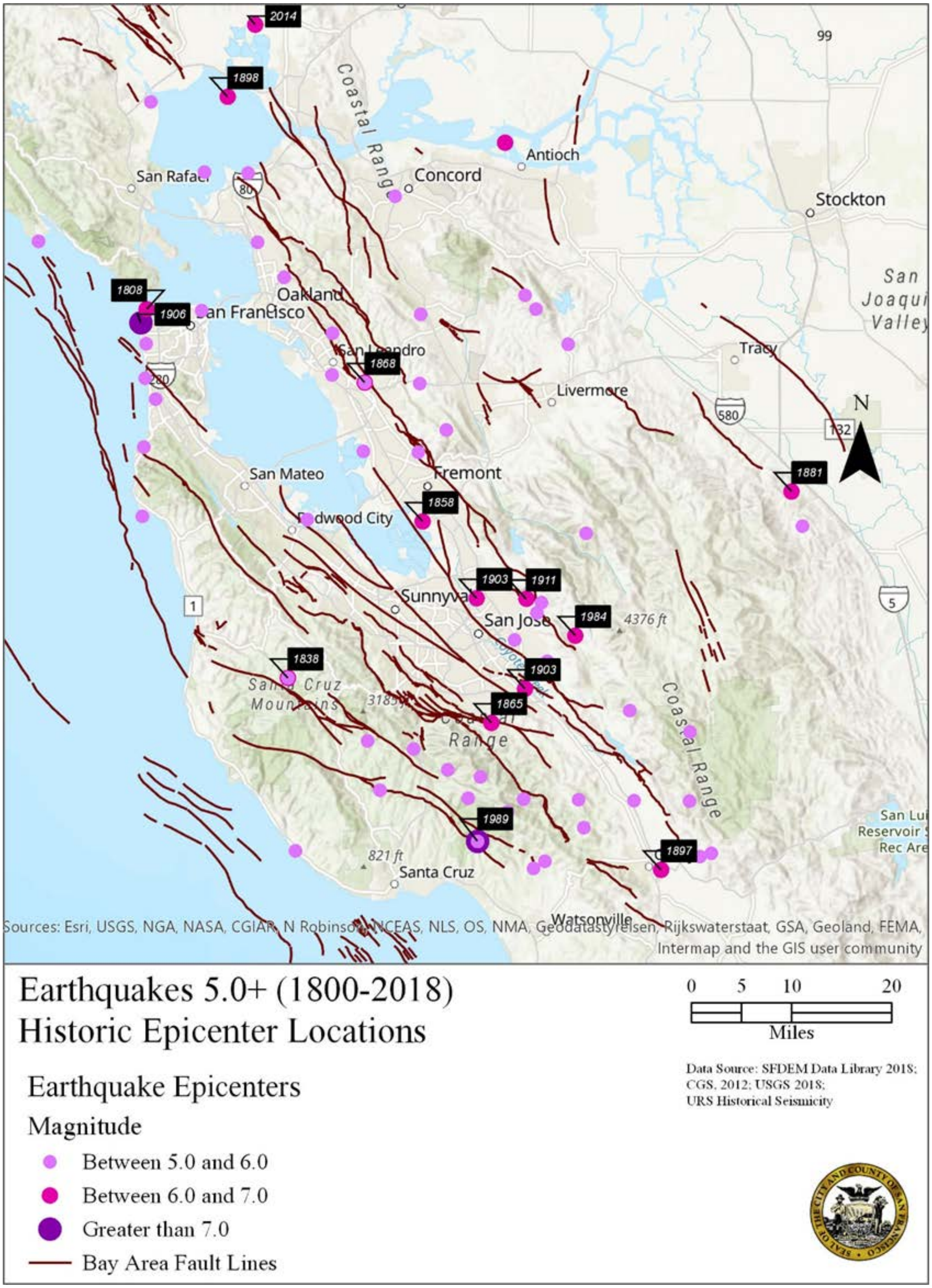
As shown in Figure 4-12 below, the San Andreas and other regional faults, including the Hayward fault, have generated 70 recorded M 5.0 or greater earthquakes since 1800. Of these recorded earthquakes, three (1838, 1906, and 1989) registered at a M_L of 6.8 or greater. For further discussion of measurement of earthquake severity, see Ground Shaking, Nature, above.

[57] USGS, Earthquake Hazards Program, “M 6.9 October 17, 1989 Loma Prieta Earthquake,” accessed May 17, 2018, https://earthquake.usgs.gov/earthquakes/events/1989lomaprieta/.

[58] California Senate Committee on Toxics and Public Management, "1989 Northern California Earthquake," California Senate Paper 228 (1989), 2, accessed May 21, 2018, https://digitalcommons.law.ggu.edu/cgi/viewcontent.cgi?referer=https://www.google.com/&httpsredir=1&article=1219&context=caldocs_senate. Dollar figures are in 1989 dollars. In 2018 dollars, this would represent over $4 billion in damage.

[59] See California Seismic Safety Commission and Pacific Earthquake Engineering Research Center, *The Mw 6.0 South Napa Earthquake of August 24, 2014: A Wake-up Call for Renewed Investment in Seismic Resilience Across California*, by Laurie A. Johnson and Stephen A. Mahin, CSSC Publication 16-03, PEER Report No. 2016/04 (2016), 1, accessed May 21, 2018, https://peer.berkeley.edu/publications/peer_reports/reports_2016/CSSC1603-PEER201604_FINAL_7.20.16.pdf.

FIGURE 4-12
EARTHQUAKES 5.0+ (1800-2018) HISTORIC EPICENTER LOCATIONS



Location

Though no known active faults are located within San Francisco County boundaries, San Francisco is susceptible to seismic hazards from numerous known faults in the Bay Area, and from potentially unmapped or undiscovered faults. Most of the known major faults in the Bay Area are strike-slip faults, which are vertical or nearly-vertical fractures where the ground generally moves horizontally.[60] The Bay Area also has several thrust or reverse faults, which are fractures where the ground generally moves vertically with a dip of 45 degrees or less.[61] The most active of the large strike-slip faults in the region are the San Andreas Fault and the Hayward Fault, which has three segments, including the Rodgers Creek Fault. Table 4-13, below, lists major Bay Area faults, their locations, and lengths within the Bay Area.

[60] USGS, Earthquake Hazards Program, "Earthquake Glossary – Strike-slip," accessed May 17, 2018, https://earthquake.usgs.gov/learn/glossary/?term=strike-slip.

[61] USGS, Earthquake Hazards Program, "Earthquake Glossary – Dip slip," accessed May 17, 2018, https://earthquake.usgs.gov/learn/glossary/?term=dip slip.

TABLE 4-13
MAJOR KNOWN FAULTS IN THE SAN FRANCISCO BAY AREA[62]

Fault Source	Location	Fault Type	Length (Miles)
Northern San Andreas	Northern California Coast	Strike-slip	294
Hayward-Rodgers Creek	Alameda, Contra Costa, Marin, Santa Clara, and Sonoma Counties	Strike-slip	118
Calaveras	Alameda, Contra Costa Counties	Strike-slip	81
Concord-Green Valley	Alameda, Contra Costa, Solano, Santa Clara Counties	Strike-slip	81
Greenville Fault	Alameda, Contra Costa, Santa Clara Counties	Strike-slip	34
San Gregorio	Marin, Monterey, San Mateo, Santa Cruz Counties	Strike-slip and reverse thrust	68
Mt. Diablo Thrust	Alameda, Contra Costa Counties	Thrust fault	20

Severity and Probability of Future Events

As noted earlier, the severity of an earthquake at a particular location can be expressed in terms of the MMI Scale. Figure 4-9 shows the shaking intensity for a Mw 7.9 earthquake on the northern segment of the San Andreas Fault, an event similar to the 1906 earthquake. Figure 4-8 shows the shaking intensity for a Mw 6.9 earthquake on the northern segment of the Hayward Fault. Figure 4-9 indicates that all of San Francisco is susceptible to very strong to extreme shaking. Figure 4-8 shows areas subject to very strong shaking in San Francisco including the Lake Merced area, Treasure Island, the Marina District, North Waterfront, Financial District North, Financial District South, South of Market (SOMA), Mission Bay, South Beach, Potrero Hill, Bayview District, and Hunters Point neighborhoods.

[62] USGS, Quaternary Fault and Fold Database of the United States; 2007 WGCEP, 2008, Uniform California Earthquake Rupture Forecast, Version 2 (UCERF 2): USGS Open-File Report 2007-1437 and California Geological Survey Special Report 203, 28, https://pubs.usgs.gov/of/2007/1437/

There is a strong likelihood that San Francisco will experience a significant earthquake from one of the known major faults in the next 30 years. In 2014, the Working Group on California Earthquake Probabilities (WGCEP) issued its Third Uniform California Earthquake Rupture Forecast (UCERF3). UCERF3 indicates there is a 72-percent chance that an earthquake of moment magnitude 6.7 or greater will strike the nine-county San Francisco region over a 30-year period (2014–2043) along one of the Bay Area fault systems identified in the forecast.[63] Figure 4-14 below, shows the earthquake outlook for major faults in the Bay Area as determined by UCERF3. The WGCEP expects to issue an updated earthquake rupture forecast in 2020 or later.[64]

[63] Edward H. Field and 2014 Working Group on California Earthquake Probabilities (WGCEP), *UCERF3: A New Earthquake Forecast for California's Complex Fault System: Fact Sheet 2015–3009 (2015)*, 4, accessed May 18, 2018, https://dx.doi.org/10.3133/fs20153009.

[64] Dr. Edward Field, e-mail message to author, May 22, 2018.

FIGURE 4-14
EARTHQUAKE OUTLOOK FOR THE SAN FRANCISCO BAY REGION 2014–2043[65]

Map of known active faults in the San Francisco Bay region. The 72 percent probability of a magnitude 6.7 or greater earthquake includes the well-known major plate-boundary faults, lesser-known faults, and unknown faults. The percentage shown within each colored circle is the probability that a magnitude 6.7 or greater earthquake will occur somewhere on that fault system by the year 2043. The probability that a magnitude 6.7 or greater earthquake will involve one of the lesser-known faults is 13 percent.

[65] USGS, Earthquake Outlook for the San Francisco Bay Region 2014-2043, https://pubs.usgs.gov/fs/2016/3020/fs20163020.pdf

Liquefaction

Impact Statement

Liquefiable soils in San Francisco are generally found in water saturated sandy or silty soils or landfill along the Pacific coast and San Francisco Bay and in inland areas of fill in the Financial District, South of Market Area, the Mission District, Civic Center areas, and on Treasure Island. The area surrounding the San Francisco International Airport (SFO) in San Mateo County is also within the State liquefaction zone. Liquefiable soils must be shaken hard enough and long enough to trigger liquefaction. Given past instances of severe liquefaction during the Great 1906 and 1989 Loma Prieta Earthquakes, it is reasonable to assume that severe liquefaction will again occur in future earthquakes with strong shaking. As groundwater levels rise due to climate change-related sea level rise, liquefaction zones can be expected to increase in size. Conversely, for earthquakes occurring during a multi-year, severe drought, a low water table and dry ground may inhibit liquefaction that might otherwise occur during large earthquakes.

Nature

Earthquake-induced soil liquefaction is a leading cause of earthquake damage worldwide.[66] Liquefaction is a process in which water-saturated soil temporarily loses strength and acts as a fluid. Liquefaction can occur during earthquake shaking,[67] when seismic waves cause water pressure to increase to the extent that sand grains in the sediment lose contact with each other, leading the sediment to lose strength. Soil that has liquefied may lose its ability to support structures, cause it to flow down even very gentle slopes or to erupt to the ground surface in the form of sand boils. The ground surface may also experience settlement as a result of liquefaction; this phenomenon typically occurs in uneven patterns that damage buildings, roads and pipelines.[68]

The effects of liquefaction on buildings and other infrastructure can be extremely damaging, and may include cracking of foundations, damage to support structures, and

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[66] National Academies of Sciences, Engineering, and Medicine, *State of the Art and Practice in the Assessment of Earthquake-Induced Soil Liquefaction and Its Consequences* (Washington, DC, 2016), 1, accessed May 23, 2018, https://doi.org/10.17226/23474.

[67] USGS, Earthquake Hazards Program, "Earthquake Glossary – Liquefaction," accessed May 22, 2018, https://earthquake.usgs.gov/learn/glossary/?term=liquefaction.

[68] USGS, San Francisco Bay Region Geology and Geologic Hazards, "About Liquefaction," accessed May 22, 2018, https://geomaps.wr.usgs.gov/sfgeo/liquefaction/aboutliq.html.

even structural collapse. Such structural damage may in turn cause injuries to people and leave structures unusable.

Three factors are required for liquefaction to occur:[69]

1. Loose, granular sediment.
2. Saturation of the sediment by ground water.
3. Strong shaking.

Many areas of San Francisco have loose, sandy soils, or have been built up over "reclaimed" areas of human-made "fill." In these areas, ground water fills the spaces between sand and silt grains, making liquefaction more probable during strong shaking. All parts of San Francisco Bay have the potential to be shaken hard enough for susceptible sediment to liquefy.[70]

In most of the San Francisco Bay region, ground water is closest to the surface, where it can saturate younger sediment, in the winter and spring, during and following what is typically San Francisco's rainy season. In 1906, the region experienced a relatively dry rainy season. The 1989 Loma Prieta earthquake occurred at the end of the dry season in October, when ground water levels were relatively deep beneath the ground surface. Nevertheless, the city experienced considerable liquefaction-related damage as a result of both these earthquakes.[71]

History

The United States Geological Survey (USGS) has mapped liquefaction occurrences in San Francisco for earthquakes occurring in 1838, 1852, 1865, 1868, 1906, 1954, and 1989.[72] Detailed liquefaction maps for the 1906 earthquake show very high liquefaction susceptibility in areas along the Pacific Ocean and San Francisco Bay, including Treasure Island and small portions of Yerba Buena Island.[73] Detailed liquefaction maps

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[69] USGS, San Francisco Bay Region Geology and Geologic Hazards, "Factors of Liquefaction," accessed May 22, 2018, https://geomaps.wr.usgs.gov/sfgeo/liquefaction/factors.html

[70] USGS, San Francisco Bay Region Geology and Geologic Hazards, "Factors of Liquefaction."

[71] Ibid

[72] USGS, San Francisco Bay Region Geology and Geologic Hazards, "Earthquakes That Have Caused Liquefaction in the San Francisco Bay Area," accessed May 22, 2018, https://geomaps.wr.usgs.gov/sfgeo/liquefaction/ eq_caused.html

[73] USGS, San Francisco Bay Region Geology and Geologic Hazards, "Earthquakes That Have Caused Liquefaction in the San Francisco Bay Area, Locations of liquefaction features produced during the 1906 San Francisco earthquake," accessed May 22, 2018, https://geomaps.wr.usgs.gov/sfgeo/liquefaction/image_pages/ liqmap_16.html

for the 1989 Loma Prieta Earthquake show very high susceptibility to liquefaction in the same areas affected by the 1906 earthquake.[74]

A significant portion of the damage resulting from the 1906 earthquake was directly or indirectly related to liquefaction. Most liquefaction-related damage in the 1906 quake occurred in reclaimed areas that were once bay or marshland.[75] Liquefaction caused great damage to buildings and structures in areas like the Mission District and the Market Street area, including settlement, lateral spreading, and damage to water mains and sewers.[76] In addition, the catastrophic fires following the earthquake, which burned for the better part of three days, were so damaging in part because liquefaction-related damage to the city's water system severely limited the city's ability to fight the fires.[77]

After the 1989 Loma Prieta earthquake, liquefaction in the Marina District caused vertical settlement, lateral displacement of buildings, buckling of sidewalks, cracking of asphalt pavement, and breaking of water pipes and gas lines. Over 70 sand boils were reported in garages and backyards. Some of the sand boils were nearly four feet in depth. Liquefaction during the Loma Prieta quake also impacted the city's Auxiliary Water Supply System (AWSS), which provides San Francisco with water for firefighting purposes.[78] AWSS is currently referred to as the Emergency Firefighting Water System (EFWS).

Location

In both the 1906 and 1989 earthquakes, most liquefaction occurred in areas where significant local amplification of ground motion was caused by underlying soft sediment.[79] As shown on the following page, in Figure 4-15, the USGS and California Geological Survey (CGS) have mapped areas of liquefaction potential. Liquefiable soils in San Francisco are generally found in areas of landfill along the bay front, former bay

[74] USGS, San Francisco Bay Region Geology and Geologic Hazards, "Earthquakes That Have Caused Liquefaction in the San Francisco Bay Area, Locations of liquefaction features produced during the 1989 San Francisco earthquake," accessed May 22, 2018, https://geomaps.wr.usgs.gov/sfgeo/liquefaction/image_pages/ liqmap_17.html

[75] USGS, San Francisco Bay Region Geology and Geologic Hazards, "Liquefaction in Past Earthquakes," accessed May 22, 2018, https://geomaps.wr.usgs.gov/sfgeo/liquefaction/effects.html

[76] USGS, *The Loma Prieta, California Earthquake of October 17, 1989—Liquefaction*, Professional Paper 1551-B (Washington, DC, 1998), B37–B39, accessed May 22, 2018, https://pubs.usgs.gov/pp/1551b/report.pdf.

[77] USGS, San Francisco Bay Region Geology and Geologic Hazards, "Liquefaction in Past Earthquakes," accessed May 22, 2018, https://geomaps.wr.usgs.gov/sfgeo/liquefaction/effects.html.

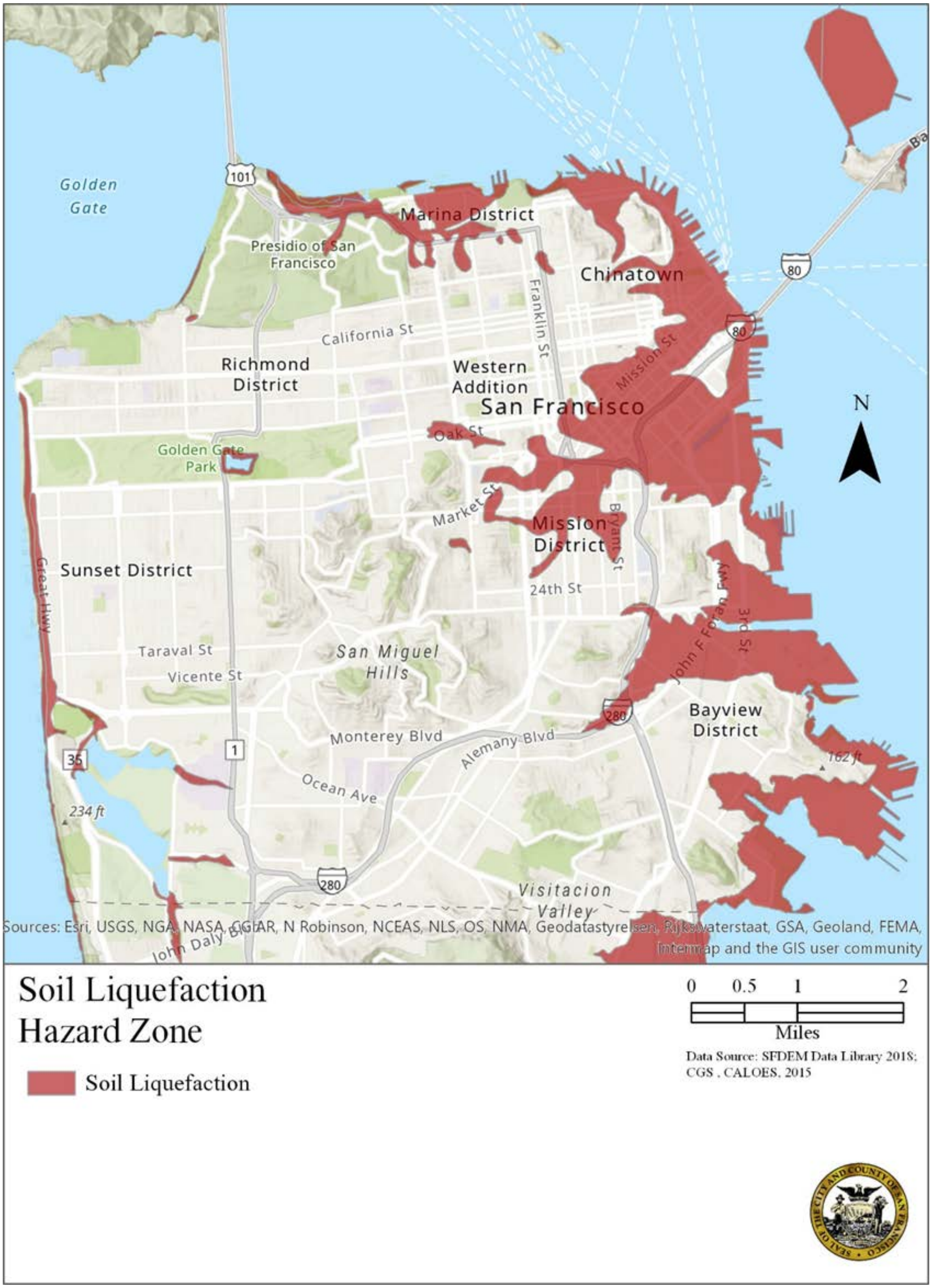
[78] USGS, *The Loma Prieta, California Earthquake of October 17, 1989—Liquefaction*.

[79] USGS, *The Loma Prieta, California Earthquake of October 17, 1989—Liquefaction*, B3.

inlets, and sandy low-lying areas along the ocean front. Locations subject to very high liquefaction susceptibility in San Francisco include areas of Ocean Beach in the Sunset and Richmond Districts and portions of the Presidio, Marina District, North Waterfront, the Financial District, South Beach, Mission Bay, the Central Waterfront (Dogpatch), Hunters Point, Candlestick Point, and Treasure Island. Inland portions of the city that also have very high liquefaction susceptibility include the South of Market Area (SOMA), the Stowe Lake area of Golden Gate Park, and Civic Center. In addition, the area surrounding the San Francisco International Airport (SFO), located in San Mateo County, is within the state's Seismic Hazards liquefaction zone, as mapped by CGS pursuant to the Seismic Hazards Mapping Act of 1990.[80]

[80] California Geological Survey, "Earthquake Zones of Required Investigation, San Mateo Quadrangle" (2015), accessed May 22, 2018, http://gmw.conservation.ca.gov/SHP/EZRIM/Maps/SAN_MATEO_EZRIM.pdf; Cal. Public Resources Code §§ 2690 et seq.

FIGURE 4-15
POTENTIAL LIQUEFACTION AREAS



Severity and Probability of Future Events

San Francisco has experienced severe liquefaction, and the attendant impact on infrastructure, in past major earthquakes in 1906 and 1989. As mentioned above, liquefaction can cause ground rupture, sand boils, ground subsidence, and lateral and vertical displacement of the ground. Given the fact that significant portions of the city are located on soft, sandy, liquefiable soils, it is reasonable to assume that severe liquefaction will occur in any future earthquake with strong shaking. SFO is located is another area that is likely to experience liquefaction in a major earthquake. As noted earlier, scientists have determined that there is a 72 percent chance of a Mw 6.7 or greater earthquake along one of the seven Bay Area fault systems in the 30-year period ending in 2043.[81] For further discussion of earthquake severity, probability, and response planning, see the City and County of San Francisco's Earthquake Annex.

Climate change can impact liquefaction from earthquakes. As groundwater levels rise due to sea level rise, liquefaction zones are expected to increase in size.[82] Conversely, for earthquakes occurring during a multi-year, severe drought, a drought-induced low water table and dry ground may inhibit landslide and liquefaction that might occur during large earthquakes, resulting in less damage than might otherwise take place.[83]

Related Hazards

Tsunami

A tsunami is a series of ocean waves caused by sudden movement of the sea floor, typically as a result of major earthquakes. Tsunamis also may be caused by undersea landslides or volcanic activity.[84] Earthquakes of Mw 7.5 or greater at plate boundaries

[81] Field and WGCEP, *UCERF3: A New Earthquake Forecast for California's Complex Fault System*, 4.

[82] Poh Poh Wong, et al, 2014: "Coastal Systems and Low-Lying Areas," in Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the *Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, by C.B. Field, et al., (eds.), (New York, NY, 2014), 383, accessed May 22, 2018, https://www.ipcc.ch/pdf/assessment-report/ar5/wg2/WGIIAR5-Chap5_FINAL.pdf; Capitol Corridor Joint Powers Authority, *Sea Level Rise Vulnerability Assessment*, Executive Summary (2014), ii, accessed May 22, 2018, http://www.adaptingtorisingtides.org/wp-content/uploads/2015/04/CCJPA-SLR-Vulnerability-Assessment_Final.pdf.

[83] USGS, "Science Features: South Napa Earthquake – One Year Later," accessed May 17, 2018, https://www2.usgs.gov/blogs/features/usgs_top_story/south-napa-earthquake-one-year-later/.

[84] National Oceanic and Atmospheric Administration (NOAA), "Tsunami," accessed May 23, 2018, https://www.tsunami.noaa.gov/.

located in subduction zones around what is known as the Pacific Ring of Fire may generate ocean-wide tsunamis. For further discussion, please see the Tsunami Hazard Profile.

Earthquake-Induced Landslide

A landslide is the downhill movement of ground typically caused by the action of gravity on weakened soil or rock. Slopes may be weakened by weathering, erosion, saturation, or the addition of weight from artificial fill, structures, or rock. Earthquake-induced landslides typically originate from steep, weakened slopes as a result of strong ground shaking. The most common earthquake-induced landslides include shallow rock falls, rock slides, and slides of earth and debris. For further discussion of landslide, see the Landslide hazard profile, below.

Reservoir Failure Following Earthquake

A reservoir failure involves structural collapse of a reservoir resulting in a release of water stored in the reservoir. Reservoir failure may occur as a result of an earthquake. For further discussion of reservoir failure following earthquake, see the Dam or Reservoir Failure hazard profile, below.

Fire Following Earthquake

While ground shaking may be the predominant agent of damage in most earthquakes, fires following earthquakes can also lead to catastrophic damage depending on the combination of building characteristics and density, meteorological conditions, and other factors. Fires following the 1906 San Francisco Earthquake led to more damage than that due to ground shaking. More recently, fires in the Marina District following the 1989 Loma Prieta Earthquake demonstrate that fires following earthquakes pose a significant hazard in San Francisco. For further discussion of fire following earthquake, see the Large Urban Fire hazard profile.

Landslide Hazard Profile

4.3 Landslide

Impact Statement

Landslides are most likely to occur on steep slopes on hills and cliffs and intermediate slopes with previous landslide deposits. In addition, weak saturated soils that are bordered by steep or unsupported embankments or slopes are prone to landslide. Given the dense urban nature of San Francisco, landslides can result in many casualties and in serious damage to homes and other infrastructure. Heavy rainfall events and wildland-urban interface fires are anticipated to become more frequent with climate change. Thus, San Francisco may experience an increase in the frequency of landslides in the future.

Nature

Landslide is a general term used to describe the downslope movement of soil, rock, and organic materials under the effects of gravity. It also is used to refer to the landform that results after such movement. Landslides can be classified into different types based on the type of material and the type of movement involved. In general, material in a landslide is either rock or soil, or both. Soil is described as earth if primarily composed of sand-sized or finer particles, and as debris if composed of coarser fragments. Type of movement refers to the actual mechanics of how the landslide is displaced. Movement categories are fall, topple, slide, spread, or flow. Thus, landslides are described using two terms that refer respectively to material and movement, such as rock fall or debris flow. Landslides may also encompass complex failures that involve more than one type of movement, such as rock slide-debris flow.[85]

Landslides are typically caused by the action of gravity on weakened soil or rock. However, most landslides have multiple causes. Slope movement occurs when forces acting down-slope exceed the strength of the materials that make up the slope. Causes include factors that increase the effects of down-slope forces and that contribute to low or reduced strength of slope materials. Landslides can be caused in slopes that are weakened because of rainfall, snowmelt, changes in ground water, erosion, earthquakes, disturbances by human activities, or a combination of these factors. Earthquake shaking

[85] U.S. Geological Survey (USGS), *The Landslide Handbook—A Guide to Understanding Landslides,* by Lynn M. Highland and Peter Bobrowsky. U.S. Geological Survey Circular 1325 (Reston, VA, 2008), 4–5, accessed May 24, 2018, https://pubs.usgs.gov/circ/1325/pdf/C1325_508.pdf.

and other factors also can induce landslides underwater called submarine landslides. Submarine landslides may trigger tsunamis that damage coastal areas.[86]

Slope saturation by water is a primary cause of landslides. This can occur in the form of intense rainfall, snowmelt, changes in ground-water levels, and water-level changes along coastlines, earth dams, and lake banks, reservoirs, canals, and rivers. Earthquakes in steep landslide-prone areas also greatly increase the chances that landslides will occur due to ground shaking or to shaking-caused expansion of soil materials, which allows rapid infiltration of water. Ground shaking due to earthquake can also cause rock falls.[87] San Francisco has experienced landslides, rockslides, and other types of ground failure due to moderate to large earthquakes and winter storms.

History

U.S. Geological Survey (USGS) records show that localized damage in the San Francisco Bay Area due to earthquake-induced landslides has been recorded since 1838 for at least 20 earthquakes. The 1906 earthquake generated more than 10,000 landslides throughout the region, killing 11 people and causing substantial damage to buildings and infrastructure.[88] The most significant landslides caused by the 1989 Loma Prieta earthquake were located in the Santa Cruz Mountains. However, landslides from the Loma Prieta earthquake were reported in in the Lake Merced area of San Francisco in the weakly-cemented sand, silt, and clay of the Merced Formation. These same materials also are believed to have produced several landslides in the 1906 earthquake and in the 1957 Daly City earthquake.[89]

Non-earthquake-induced landslides in San Francisco generally occur during or after prolonged winter rainstorms. On January 3–5, 1982, a catastrophic rainstorm over the Central California coast triggered landslides in San Francisco, which resulted in approximately $399,000 in damages in 1982 dollars ($1 million in 2018 dollars) to public

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[86] USGS, “What is a landslide and what causes one?” Accessed May 24, 2018, https://www.usgs.gov/faqs/what-a-landslide-and-what-causes-one?qt-news_science_products=7#qt-news_science_products.

[87] USGS, Landslide Types and Processes, Fact Sheet 2004-3072 (2004), accessed May 24, 2018, https://pubs.usgs.gov/fs/2004/3072/pdf/fs2004-3072.pdf.

[88] David K. Keefer, “Landslides Synopsis,” in *The Loma Prieta, California Earthquake of October 17, 1989: Strong Ground Motion and Ground Failure,* USGS Professional Paper 1551-C (Washington, DC, 1998), C1, accessed May 24, 2018, https://pubs.usgs.gov/pp/pp1551/pp1551c/pp1551c.pdf.

[89] Keefer and Manson, “Regional Distribution and Characteristics of Landslides Generated by the Earthquake,” C21.

and private property in San Francisco, predominantly to private residences. Most landslide damage was located in the Twin Peaks, Mount Davidson, and Glen Park areas.[90]

Winter rainstorms in December 1995 contributed to the collapse of a 100-year old sewer line, subsequently creating a landslide and damaging sinkhole. A couple structures were swallowed by the pit, 23 homes were evacuated, and utilities were temporarily disrupted for the entire neighborhood[91].

Landslides also occurred in February 1998, as a result of El Niño storms. El Niño is a disruption of the ocean-atmosphere system in the Tropical Pacific, which has important consequences for weather and climate around the globe. Between February 2, and February 26, 1998, landslides and minor debris flows were reported on steep slopes near Mount Sutro in Forest Knolls, Mount Davidson in the Miraloma Park neighborhood, and in the Twin Peaks, Diamond Heights, Potrero Hill, and Seacliff neighborhoods. These landslides caused an estimated $4.1 million in damages in 1998 dollars ($6.3million in 2018 dollars) to residential properties, and to the Olympic Club golf course.[92]

Nine years later, on February 28, 2007, after three days of rainfall, a 75-foot-wide mass of Telegraph Hill slid down a granite and sandstone slope above Broadway, between Montgomery and Kearny Streets. Approximately 120 people from a 45-unit condominium were evacuated until the property owner stabilized the hillside.[93] Similarly, on January 23, 2012, extensive rainfall resulted in a rockslide on Telegraph Hill, which crushed a car and required the partial evacuation of a condominium complex.[94]

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[90] Stephen D. Ellen, et al., *Landslides, Floods, and Marine Effects of the Storm of January 3-5, 1982, in the San Francisco Bay Region, California* (USGS Professional Paper 1434) (1988), 198–200, accessed May 24, 2018, http://pubs.usgs.gov/pp/1988/1434/.

[91] Carl Nolte: SFgate. (1995) "Sea Cliff Mansion Tumbles into Hole/Aged Sewer Line Collapses under Home". Retrieved from: https://www.sfgate.com/news/article/Sea-Cliff-Mansion-Tumbles-Into-Hole-Aged-sewer-3017549.php

[92] John W. Hillhouse and Jonathan W. Godt, "Map Showing Locations of Damaging Landslides in San Francisco City and County, California, Resulting from 1997-98 El Nino Rainstorms," USGS MF-2325-G (1999), accessed May 24, 2018, https://pubs.usgs.gov/mf/1999/mf-2325-g/mf2325g.pdf.

[93] Robert Selna, et al., "Telegraph Hill Landslide Forces 120 from Homes," *San Francisco Chronicle*, February 28, 2007, accessed May 24, 2018, https://www.sfgate.com/news/article/Telegraph-Hill-landslide-forces-120-from-homes-2614672.php.

[94] CBS SF Bay Area, "Residents Near SF Telegraph Hill Landslide Allowed to Return," January 24, 2013, accessed May 24, 2018, http://sanfrancisco.cbslocal.com/2012/01/24/residents-near-sf-telegraph-hill-landslide-allowed-to-return/.

In February 2016, during heavy precipitation associated with the 2015-2016 El Niño, a landslide in the Mount Davidson area of San Francisco destroyed one house, and damaged five others. However, it appears that this slide was due to human-caused changes in the area. Public Works crews subsequently discovered and repaired a rupture in an eight-inch water main under a nearby street that is believed to have led to the slide.[95]

Location

According to the California Geological Survey (CGS), steep slopes on hills and cliffs and intermediate slopes with previous landslide deposits are highly susceptible to landslides. In addition, weak saturated soils that are bordered by steep or unsupported embankments or slopes are prone to lateral spreading, which is a type of landslide.[96] Seismic Hazard Zones, seen in Figure 4-16, show areas susceptible to earthquake-induced landslide in San Francisco. These areas include hills and cliffs in the Outer Richmond, Sea Cliff, Presidio, Lake Shore, Bayview Heights, Midtown Terrace, Twin Peaks, Clarendon Heights, Golden Gate Heights, Forest Hills, Diamond Heights, the Castro, Dolores Heights, Noe Valley, and Yerba Buena Island.

CGS has also developed a landslide susceptibility map that shows the relative likelihood of deep-seated landslides based on the location of past slides and on regional estimates of rock strength and steepness of slopes.[97] Slides are considered deep-seated if the slip occurs on a surface more than 10 to 15 feet below the ground.[98] The San Francisco-portion of this map is included in Figure 4-16. The map shows areas similar to those

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[95] KTVU2, "SF Landslide That Threatened Homes Appears More Man-Made than Natural," February 1, 2016, accessed May 25, 2018, http://www.ktvu.com/news/sf-landslide-that-threatened-homes-appears-more-man-made-than-natural; CBS SF Bay Area, "PG&E Sued Over Landslide That Destroyed San Francisco Home," October 18, 2017, accessed May 25, 2018, http://sanfrancisco.cbslocal.com/2017/10/18/pge-lawsuit-landslide-casitas-miraloma/.

[96] California Department of Conservation, California Geological Survey (CGS), *Guidelines for Evaluating and Mitigating Seismic Hazards in California*, Special Publication 117 (2008), 19–21, accessed May 25, 2018, http://www.conservation.ca.gov/cgs/Documents/SHZP_Webdocs/SP117.pdf.

[97] C.J. Wills, et al., *Susceptibility to Deep-Seated Landslides in California*, California Geological Survey (CGS) Map Sheet 58 (2011), accessed May 24, 2018, http://www.conservation.ca.gov/cgs/information/publications/ms/ Documents/MS58.pdf.

[98] Helen Gibbs, et al., "USGS Monitors Huge Landslides on California's Big Sur Coast, Shares Information with California Department of Transportation," accessed May 24, 2018, https://soundwaves.usgs.gov/2017/10/ fieldwork.html.

noted in the seismic hazard zone map mentioned above as susceptible to deep-seated landslides.[99]

CGS has not prepared maps for San Francisco that identify hazards associated with non-earthquake induced landslides. However, in general, areas that are subject to landslides during earthquakes are also subject to landslides under other conditions. Thus, the earthquake-induced landslide map in Figure 4-16, seen below, is instructive as to the location of steep-sloped areas where landslides may occur due to heavy rainfall or other non-seismic conditions.

In addition, steep, recently burned areas are susceptible to debris flows within the first two years after a fire. Even modest rain storms during non-El Niño years can trigger post-wildfire debris flows.[100] Fire-related debris flows are likely to occur in steep, rural out-of-county areas where some city-owned infrastructure is located. Examples include the area surrounding Hetch Hetchy Reservoir and O'Shaughnessy Dam in Tuolumne County, California, which is part of the system that provides drinking water to city residents. For further discussion of wildland-urban interface fires, see the Wildland-Urban Interface profile.

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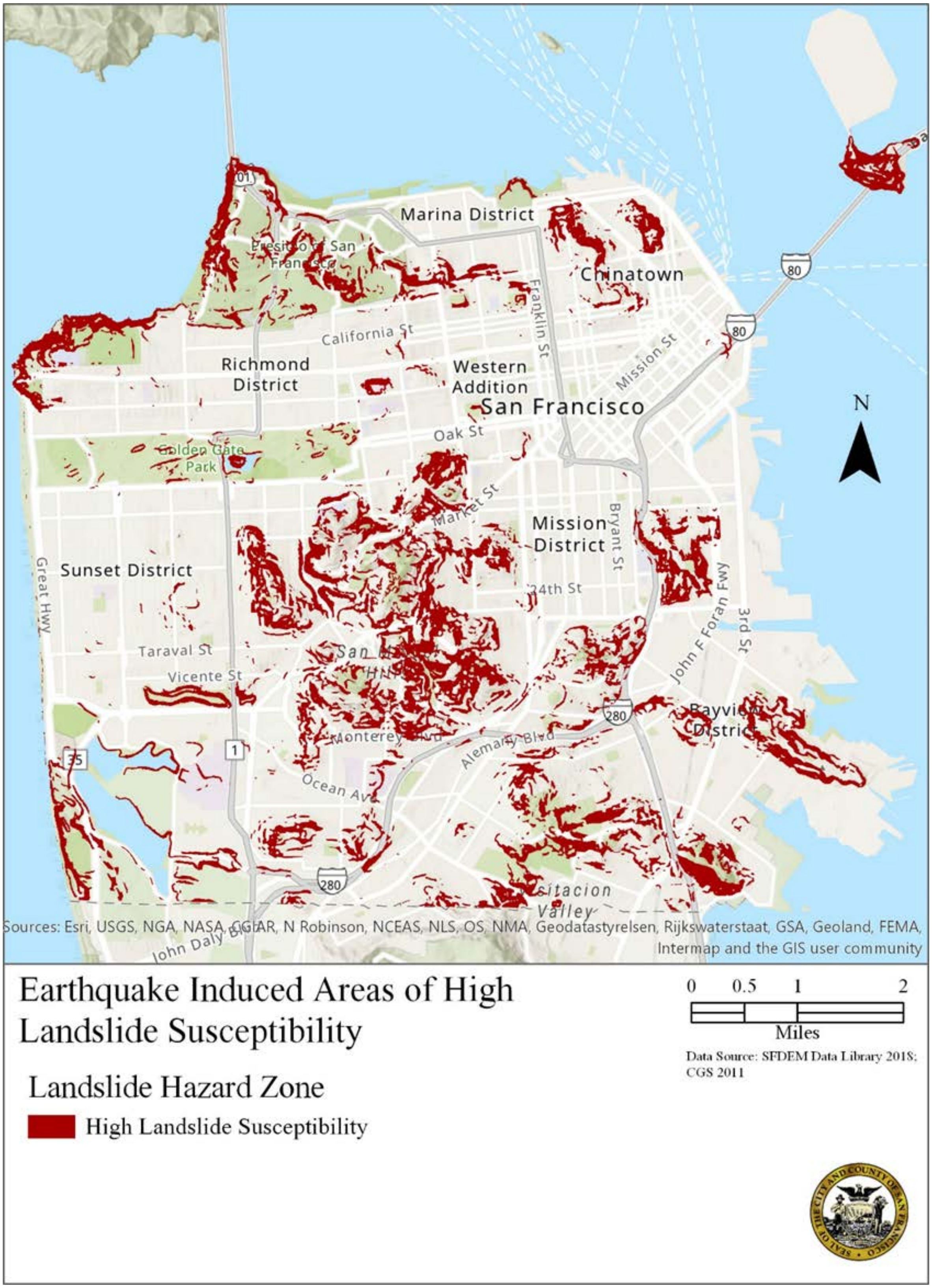
[99] Wills, *Susceptibility to Deep-Seated Landslides in California*. CGS intends this map to provide a general overview of where landslides are more likely to occur. It does not include information on landslide-triggering events such as rainstorms or earthquake shaking, nor does it address susceptibility to shallow landslides such as debris flows. It is not appropriate for evaluation of landslide potential at any specific site.

[100] See USGS, Landslide Hazard Program, "Rainfall and Landslides in Northern and Central California," accessed May 25, 2018, https://landslides.usgs.gov/research/ca-rainfall/ncal.php; USGS, California Water Science Center, "Post-Fire Debris Flow," accessed May 25, 2018, https://ca.water.usgs.gov/flooding/wildfires-debris-flow.html.

FIGURE 4-16
EARTHQUAKE INDUCED AREAS OF HIGH LANDSIDE SUSCEPTIBILITY



Severity and Probability of Future Events

The severity of an earthquake-induced landslide depends on the landslide characteristics and materials and on the settings in which the landslide occurs. Shallow rock falls disrupted rock slides, and disrupted slides of earth and debris are the most common types of earthquake-induced landslides. Earth flows, debris flows, and avalanches of rock, earth, or debris typically transport material the farthest.[101] The USGS reports that landslides in San Francisco are typically narrower than 1,500 feet, or about one quarter of a mile.[102] Given the dense urban nature of the city, slides of this size could cause many casualties and serious damage to homes and other infrastructure.

USGS studies show that earthquakes as small as magnitude 4.0 may trigger landslides on susceptible slopes.[103] Larger earthquakes may generate thousands of landslides within the area impacted by the earthquake.[104] Whether a particular earthquake produces a landslide depends on slope material strength and configuration, pore-water pressure, and the level of ground motion.[105] Given the Working Group on California Earthquake Probabilities (WGCEP) finding of a 100 percent chance that the San Francisco region will experience a Mw 5 or greater quake between 2014 and 2044, and a 72 percent chance of a Mw 6.7 or greater earthquake in the region during the same period,[106] San Francisco is extremely likely to experience one or more earthquake-induced landslides from a major earthquake event.

Non-earthquake induced landslides are most likely to occur during winter storm events that produce heavy or prolonged rainfall. Based on past occurrences of El Niño-enhanced periods of precipitation, San Francisco can expect to experience rain-induced landslide every eight to 10 years.[107] These are periods, typically during winters, when a

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[101] David K. Keefer, "Earthquake-Induced Landslides and Their Effects on Alluvial Fans," *Journal of Sedimentary Research*, Section A: Sedimentary Petrology and Processes 69(1) (1999), 84.

[102] Carl M. Wentworth, et al., Summary Distribution of Slides and Earth Flows in San Francisco County, California, USGS Open File 97-745 C, Sheet 6 of 11 (1997), accessed May 25, 2018, https://pubs.usgs.gov/of/1997/of97-745/sfdl.html.

[103] Keefer, "Landslides Caused by Earthquakes," 409; USGS, "Landslides 101, What is a landslide?" Accessed May 24, 2018, https://landslides.usgs.gov/learn/ ls101.php.

[104] Keefer, "Landslides Synopsis," C1.

[105] Keefer, "Landslides Caused by Earthquakes," 406.

[106] Edward H. Field and 2014 Working Group on California Earthquake Probabilities (WGCEP), *UCERF3: A New Earthquake Forecast for California's Complex Fault System,* Fact Sheet 2015–3009 (2015), 4, accessed May 18, 2018, https://dx.doi.org/10.3133/fs20153009.

[107] Christopher C. Burt, "California: Waiting for El Nino," Weather Underground WunderBlog Archive, December 9, 2015, accessed May 25, 2018,

strong El Niño increases the frequency and intensity of Pacific storms. In addition, areas burned as a result of wildfires are particularly susceptible to landslides depending on slope conditions and soil characteristics.

The Intergovernmental Panel on Climate Change (IPCC) has indicated with high confidence that urban climate change-related risks, including extreme precipitation, fires, and landslides, are increasingly affecting urban areas, resulting in widespread negative impacts on people and on local and national economies and ecosystems.[108] As both heavy rainfall and wildland-urban interface fires are anticipated to become more frequent with climate change, San Francisco may experience an increase in the frequency of landslides in the future.

https://www.wunderground.com/blog/weatherhistorian/california-waiting-for-el-nino.html.

[108] Aromar Revi, et al., "Urban Areas," Chapter 8 in *Climate Change 2014: Impacts, Adaptation, and Vulnerability*, Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, C.B. Field, et al. (eds.) (New York, NY, Cambridge University Press, 2014), 565, accessed May 25, 2018, https://www.ipcc.ch/pdf/assessment-report/ar5/wg2/WGIIAR5-Chap8_FINAL.pdf.

Tsunami Hazard Profile

4.4 Tsunami

Nature

A tsunami is a series of ocean waves caused by sudden movement of the sea floor, typically as a result of major earthquakes. Tsunamis also may be caused by undersea landslides or volcanic activity.[109] Earthquakes of Mw 7.5 or greater at plate boundaries located in subduction zones around what is known as the Pacific Ring of Fire may generate ocean-wide tsunamis.

San Francisco may experience tsunamis from three possible sources: (1) distant sources, such as large earthquakes near Japan, Alaska, or Chile; (2) regional sources, such as earthquakes in the Cascadia Subduction Zone, which begins off Humboldt County, California and extends north to British Columbia, Canada; and (3) near sources off the coast of Northern California, such as the Point Reyes Thrust Fault. For a list of tsunami types, their classification based on distance from San Francisco, how quickly they may arrive in San Francisco, and the likelihood of occurrence, see Table 4-17, below.

TABLE 4-17
TYPES OF TSUNAMIS THAT MAY BE EXPERIENCED IN SAN FRANCISCO

Tsunami Types	Source Event Distance from San Francisco	Time to Reach San Francisco	Likelihood of Occurrence
Distant Source	621 miles or more	4–21 hours	Moderate
Regional Source	Less than 621 miles	1–1½ hours	Moderate
Near Source	62 miles or less	10–15 minutes	Low

In the open ocean, tsunamis can travel over 500 miles per hour (mph)—the speed of a jet—and are barely perceptible to ships at sea. However, as tsunami waves reach shallow water, they slow in speed and grow in height. At the shoreline in San Francisco,

109 National Oceanic and Atmospheric Administration (NOAA), "Tsunami," accessed May 23, 2018, https://www.tsunami.noaa.gov/.

tsunami waves may range in height from a few inches to over 30 feet. The first wave is almost never the largest.[110]

Normal, wind-driven ocean waves move only the surface layer of the water. In contrast, tsunami waves are longer in length, and move the entire "column" of water from the ocean floor to the surface. As a result, tsunami waves have increased power to inundate or flood low-lying coastal areas, making tsunami waves more dangerous and destructive than normal ocean waves. In addition, unlike normal ocean waves, the wave period, or time between tsunami waves, may vary from a few minutes to up to two hours. Thus, damaging tsunami waves may last for hours or days,[111] though typically the largest, most damaging tsunami waves occur in the first five hours of a tsunami incident.[112] Tsunamis also can cause powerful, dangerous currents in harbors, ports, and other shoreline areas that may last for several days after the initial tsunami wave.

Tsunami inundation is the maximum horizontal distance reached by tsunami waves on shore. "Runup" is the maximum height and distance of tsunami-related water inundation onshore. Runup is measured vertically from a reference sea level, such as mean sea level. Inundation is measured horizontally from the mean sea level position at the water's edge.[113] For a visual representation of inundation and runup, see Figure 4-18, below.

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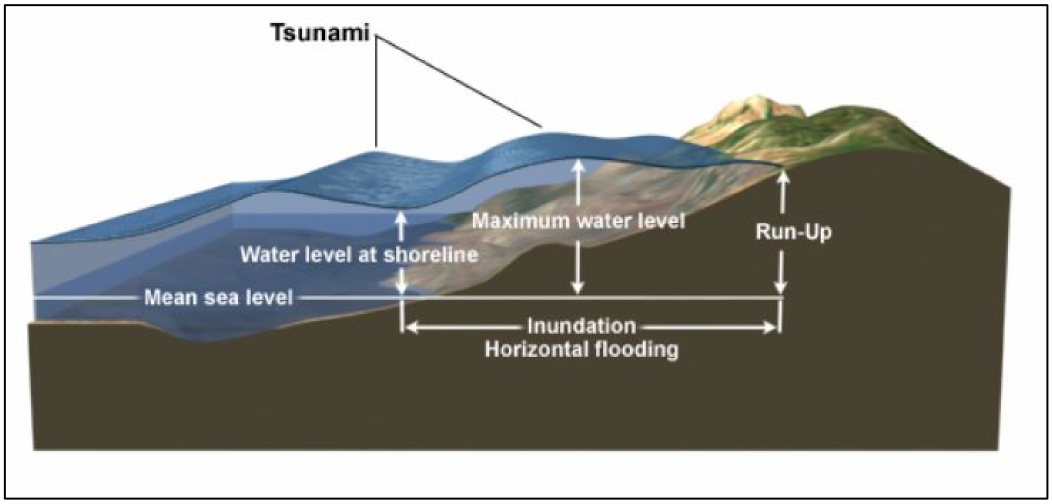
[110] U.S. Department of Commerce, NOAA/National Weather Service, U.S. Tsunami Warning System, "Tsunami Frequently Asked Questions," accessed May 18, 2018, https://www.tsunami.gov/?page=tsunamiFAQ.

[111] Pacific Tsunami Warning Center (PTWC), "Frequently Asked Questions (FAQ)," How are tsunami waves different from normal ocean waves? accessed May 23, 2018, http://ptwc.weather.gov/faq.php.

[112] California Department of Conservation, California Geological Survey, *Tsunami Emergency Response Playbooks and FASTER Tsunami Height Calculation: Background Information and Guidance for Use*, by Rick I. Wilson and Kevin M. Miller, California Geological Survey Special Report 236 (Sacramento, CA, 2014), 15.

[113] See USGS, Pacific Coastal and Marine Science Center, "Life of a Tsunami—Starting Points," accessed May 23, 2018, https://walrus.wr.usgs.gov/tsunami/basics.html; COMET Program, MetEd, *Community Tsunami Preparedness* (2d ed.) (2015), accessed May 23, 2018, http://www.meted.ucar.edu /tsunami/community/ print.htm#page_2.0.0.

FIGURE 4-18
TSUNAMI RUN-UP CROSS-SECTION[114]



Tsunamis not only affect beaches open to the ocean, but also may cause damage to bays, ports, harbors, tidal flats, and coastal inlets. Because of their long wavelengths, tsunami waves can wrap around and reflect off land masses. Thus, peninsulas, offshore islands, and human-made breakwaters may not provide protection from tsunamis.[115] In addition, it is important to note that tsunamis can cause damage even when they do not result in inundation. Because tsunamis can generate strong, powerful, currents that may last for many hours, they can result in significant damage to maritime assets, including ports, harbors, marinas, and vessels.[116]

History

Since 1850, 57 tsunamis have been recorded or observed in San Francisco Bay. None of these tsunamis resulted in inundation or in significant damage in San Francisco. Eleven of the tsunamis originated off Japan; all were generated by major earthquakes. Ten originated off Alaska; eight of these were caused by an earthquake, two were caused by

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[114] © The COMET Program, *Community Tsunami Preparedness* (2d ed.) (2015), Hazards. https://www.meted.ucar.edu/tsunami/community/print.htm

[115] PTWC, "Frequently Asked Questions (FAQ)," What is the "wrap-around effect?" accessed May 23, 2018, http://ptwc.weather.gov/faq.php.

[116] Patrick J. Lynett, et al., *Assessment of the Tsunami-Induced Current Hazard*, Geophysical Research Letters, 41 (2014), 2048, accessed May 23, 2018, doi:10.1002/2013GL058680.

earthquake and landslide. Eight tsunamis originated off Chile, all generated by earthquakes.[117]

Only one tsunami originating along the Northern California Coast has been recorded. A 4-inch wave run-up was recorded at the Presidio gauge station shortly after the 1906 earthquake.[118] The 1906 earthquake is believed to have caused down dropping of the seafloor north of Lake Merced, between overlapping segments of the San Andreas Fault, generating a small tsunami.[119]

The magnitude 6.8 Hayward Earthquake of October 21, 1868 is reported to have produced a wave at the Cliff House that was 15 to 20 feet higher than usual. The likely cause of this tsunami was an earthquake-triggered submarine landslide.[120] The magnitude 9.2 Great Alaskan Earthquake generated a distant-source tsunami that produced maximum water heights over sea level of 1.13 meters (3.7 feet) as recorded on the tide gauge at the San Francisco Presidio near Crissy Field. However, the largest waves from the Great Alaskan tsunami occurred during low tide. Had these waves arrived at high tide, the absolute water level could have reached over 12 feet above sea level at the Presidio.[121]

Little damage occurred in San Francisco as a result of the tsunami generated by the Japan Tohoku earthquake of March 11, 2011. The Tohoku tsunami produced a maximum measured amplitude of 0.62 meters (two feet) at the San Francisco Marina, and estimated maximum currents of seven knots, or approximately eight miles per hour. Currents in excess of three knots are known to cause damage to fixed piers and structures, as well as present hazards to water navigation. Two piles were broken, and

[117] NOAA, National Geophysical Data Center/World Data Service (NGDC/WDS): "Global Historical Tsunami Database," accessed May 23, 2018, doi:10.7289/V5PN93H7.

[118] NOAA, NGDC/WDS: "Global Historical Tsunami Database."

[119] USGS, Pacific Coastal and Marine Science Center, "Tsunamis and Earthquakes, "Tsunami Record from the Great 1906 San Francisco Earthquake," accessed May 23, 2018, https://walrus.wr.usgs.gov/tsunami/1906.html.

[120] U.S. Department of Commerce, National Oceanic and Atmospheric Administration, *Tsunamis Affecting the West Coast of the United States, 1806–1992*, by James F. Lander, Patricia A. Lockridge and Michael J. Kozuch (Boulder, CO, 1993), 18, 20, ftp://ftp.ngdc.noaa.gov/hazards/publications/Kgrd-29.pdf.

[121] Jose Borrero et al., *Numerical Modeling of Tsunami Effects at the Marine Oil Terminals in San Francisco Bay,* Report Prepared for California State Lands Commission, Marine Facilities Division (2006), 8, http://www.slc.ca.gov/Programs/MOTEMS/NumericalModeling.pdf.

boats keeled over in the San Francisco Marina.[122] Damage from the Tohoku tsunami was minimal in San Francisco because the largest surges occurred during low tide.[123]

Location

In 2009, the California Geologic Survey (CGS), the California Governor's Office of Emergency Services (Cal OES), and the Tsunami Research Center at the University of Southern California produced statewide tsunami inundation maps for coastal areas of California, including San Francisco and San Mateo Counties. The maps indicate coastal areas that could be flooded in an inundating tsunami. The state prepared the tsunami inundation maps to assist coastal communities in identifying tsunami hazards and in creating tsunami evacuation and response plans. The inundation lines shown on the maps represent the maximum considered tsunami runup based on several extreme but realistic tsunami scenarios.[124] Figure 4-19 shows the tsunami inundation map prepared for the City and County of San Francisco.

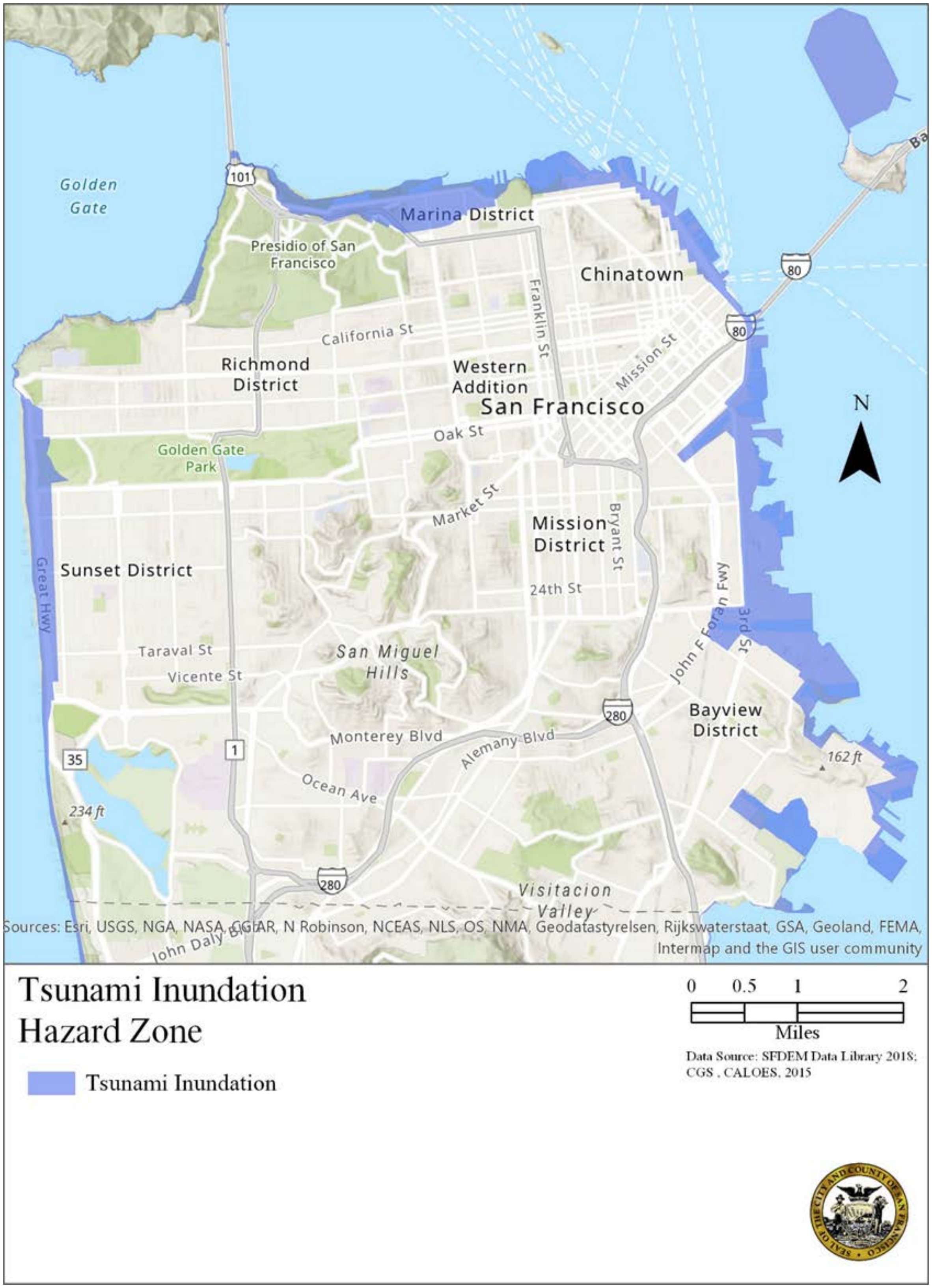
Areas within San Francisco susceptible to tsunami inundation include Pacific Coast areas of Lake Merced, the Sunset and Richmond Districts, Sea Cliff, and the Presidio. Areas adjacent to San Francisco Bay are also subject to tsunami inundation, including the Presidio, the Marina District, North Waterfront, Fisherman's Wharf, China Basin, Mission Bay, Potrero Hill, Bayview, Hunters Point, Treasure Island, and portions of Yerba Buena Island (see Figure 4-19 below).

[122] California Natural Resources Agency, California Coastal Commission, "The Tohoku Tsunami of March 11, 2011: A Preliminary Report on Effects to the California Coast and Planning Implications," Attachment 5, Summary of California Damage (San Francisco, CA, 2011), 37, http://www.coastal.ca.gov/energy/tsunami/ccc_tohoku_tsunami_report.pdf; Rick Wilson, et al., *The Effect of the 2011 Tohoku Tsunami on the California Coastline* (poster, Annual Meeting, Seismological Society of America, Memphis, TN, April 13-15, 2011), accessed May 23, 2018, http://www.conservation.ca.gov/cgs/geologic_hazards/Tsunami/Documents/ssa_2011_california_tohoku_small.pdf.

[123] Rick I. Wilson and Kevin M. Miller, *Tsunami Emergency Response Playbooks and FASTER Tsunami Height Calculation: Background Information and Guidance for Use*, California Geological Survey Special Report 236 (Sacramento, CA, 2014), 19, accessed May 23, 2018, ftp://ftp.consrv.ca.gov/pub/dmg/pubs/sr/sr_236/ CGS_Special_Report_236.pdf.

[124] Rick I. Wilson, et al., *New Maximum Tsunami Inundation Maps for Use by Local Emergency Planners in the State of California, USA* (poster, American Geophysical Union Fall Meeting, San Francisco, CA, December 15-19, 2008), accessed May 23, 2018, http://www.conservation.ca.gov/cgs/geologic_hazards/Tsunami/Inundation_Maps/Documents/AGU08_tsunami_poster.pdf.

FIGURE 4-19
CITY AND COUNTY OF SAN FRACNISCO TSUNAMI HAZARD ZONES



Severity and Probability of Future Events

Inundating tsunamis are infrequent, but high impact events that may result in widespread damage and destruction in San Francisco. Injuries and deaths are one of the primary impacts of tsunamis. Drowning is the most common cause of death associated with tsunami.[125] Widespread damage to homes and businesses, and the resulting displacement of people in coastal areas are additional concerns after a destructive tsunami.[126] Damage to infrastructure from a flooding tsunami would be extensive, and could include impacts to roads, public transportation, power systems, and sewage treatment plants.[127] In addition, tsunami waves may damage building foundations, bridges, roads, and other structures.[128] Even a non-inundating tsunami can result in strong currents and rip tides that cause damage to vessels and maritime facilities in or near coastal waters. Currents of three knots (3.5 miles per hour) or more have resulted in damage to fixed piers and structures and may present navigation hazards to vessels in the area.

The primary tsunami threat to San Francisco is a distant-source tsunami generated by an earthquake in the eastern portion of the Aleutian-Alaska Subduction Zone. Data from the California Seismic Safety Commission indicates that since 1872, Alaska earthquakes have produced tsunami run-ups in the Bay Area ten times, for a recurrence interval of 14.6 years. Historically, the runup from these events has been only a few inches. However, the modeling used to create the 2009 state tsunami inundation maps indicates that an Mw 9.2 in the Central Aleutians, San Francisco's "worst-case" tsunami scenario, produced an estimated maximum tsunami wave runup elevation of 22 feet above mean sea level at Ocean Beach. As tsunami waves from this modeled event wrapped around the city and entered the Golden Gate, wave heights diminish to 11 feet above mean sea level at Aquatic Park, 8 feet above mean sea level at Treasure Island, and 6 feet above mean sea level at Candlestick Point.[129]

San Francisco also has a moderate risk of an earthquake-generated tsunami from a regional source. Our most likely regional source is an earthquake and tsunami in the

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[125] *Community Tsunami Preparedness*, 58.

[126] Centers for Disease Control and Prevention, Emergency Preparedness and Response, "Health Effects of Tsunamis," accessed May 20, 2015, http://www.bt.cdc.gov/disasters/tsunamis/healtheff.asp.

[127] *Community Tsunami Preparedness*, 58.

[128] Matthew J. Francis, *Tsunami Inundation Scour of Roadways, Bridges and Foundations: Observations and Technical Guidance from the Great Sumatra Andaman Tsunami*, EERI/FEMA NEHRP 2006 Professional Fellowship Report (Oakland, CA, 2006), 13.

[129] CGS, et al., "Tsunami Source Scenario Model Results for the San Francisco Bay Area."

Cascadia Subduction Zone (CMZ), a 600-mile fault approximately 70 to 100 miles off the Pacific coastline that runs from Cape Mendocino in Northern California to British Columbia. There have been 41 earthquakes in the last 10,000 years within the CMZ. The last earthquake in this area was an estimated magnitude 9.0 on January 26, 1700, which resulted in an ocean-wide tsunami. Currently, scientists predict that there is a 40 percent chance of an Mw 9.0 or greater earthquake in this fault zone in the next 50 years.[130]

San Francisco has a low risk of a near-source tsunami, given that the majority of the region's faults are strike-slip faults. The nearby Point Reyes Thrust Fault, San Gregorio Fault, and Hayward-Rodgers Creek Fault are all believed capable of producing a near-source tsunami affecting San Francisco. However, to date, none of these faults have produced local tsunamis. State tsunami modeling shows worst-case inundation from a near-source tsunami generated by the Point Reyes Thrust Fault of six feet above mean sea level at Ocean Beach, 4 feet above mean sea level at Aquatic Park, 3 feet above mean sea level at Treasure Island, and 3 feet above mean sea level at Candlestick Point.[131] A strike-slip fault event could produce a potential localized tsunami threat from an earthquake-induced landslide. However, the gentle topography of near-shore areas of San Francisco Bay and the lack of history of large landslides into the bay indicate that the risk of a landslide-generated tsunami into the Bay is low.[132]

The State of California, NOAA, and FEMA are currently developing probability-based tsunami inundation maps and products that can be used for site evaluation, land-use planning, and building design and construction. Release of these products is anticipated within the next year, depending on funding.[133]

For further discussion of tsunami severity, probability, and response planning see the City and County of San Francisco Tsunami Annex.

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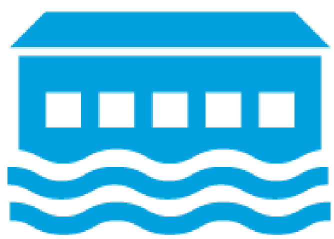
130 Oregon Military Department, Office of Emergency Management, Hazards and Preparedness, "Cascadia Subduction Zone," accessed May 23, 2018, http://www.oregon.gov/oem/hazardsprep/Pages/Cascadia-Subduction-Zone.aspx.

131 CGS, et al., "Tsunami Source Scenario Model Results for the San Francisco Bay Area."

132 Burak Uslu "Deterministic and Probabilistic Tsunami Studies in California from Near and Farfield Sources", *Phd Diss*, 57–58, accessed May, 2018

133 Kevin M. Miller, in discussion with author, May 23, 2018.

Flooding Hazard Profile



4.5 Flooding

Flooding is the accumulation of water where such accumulations do not normally occur, or the overflow of excess water from a stream, river, lake, reservoir, or coastal body of water onto adjacent floodplains. Floodplains are lowlands adjacent to water bodies that are subject to recurring floods. In most cases, floods are naturally occurring events that are only considered hazards when people and property are affected. This hazard profile focuses on the flood hazards that have the potential to occur within San Francisco county limits (coastal and stormwater) and a brief description of a flood hazard that may affect publicly-owned assets located outside county limits (riverine).

- **Coastal flooding** in San Francisco is generally caused by high tides, storm surge, and wave action associated with Pacific Ocean storms. These low-pressure storms typically occur from November through February and affect low-lying areas adjacent to the open Pacific Ocean coast and the San Francisco Bay shoreline. As sea level rises, temporary coastal flooding associated with low pressure storms will be more frequent, extensive, and longer lasting.[134] In addition, low-lying areas near the shoreline that are not currently exposed to tidal inundation could experience inundation during high tides if no adaptation strategies are implemented.[135] This hazard is described in greater detail below.

- **Stormwater flooding** occurs in San Francisco during some high precipitation storm events as rainfall runoff collects in areas that at one time were naturally-formed waterways but are now contained within the City's combined sewer and stormwater collection system. As a result, streets aligned with historic waterways and some low-lying areas are prone to collect stormwater. The stormwater accumulating on the surface and backups from the combined sewer-stormwater system may enter nearby structures, resulting in property damage. The risk of stormwater flooding may increase in the future due to more intense precipitation events and sea level rise. This hazard is described in greater detail below.

- **Riverine flooding** occurs when runoff from rainfall and snowmelt exceeds the carrying capacity of streams and rivers. San Francisco does not have significant riverine flood sources within the county limits, because few natural watercourses

[134] City and County of San Francisco, 2016. "Sea Level Rise Action Plan."
[135] Ibid

remain. However, some publicly-owned assets outside county limits are located in areas that are subject to riverine flooding. This hazard is not described in greater detail below given the focus of this report on assets within the County jurisdiction and SFO.

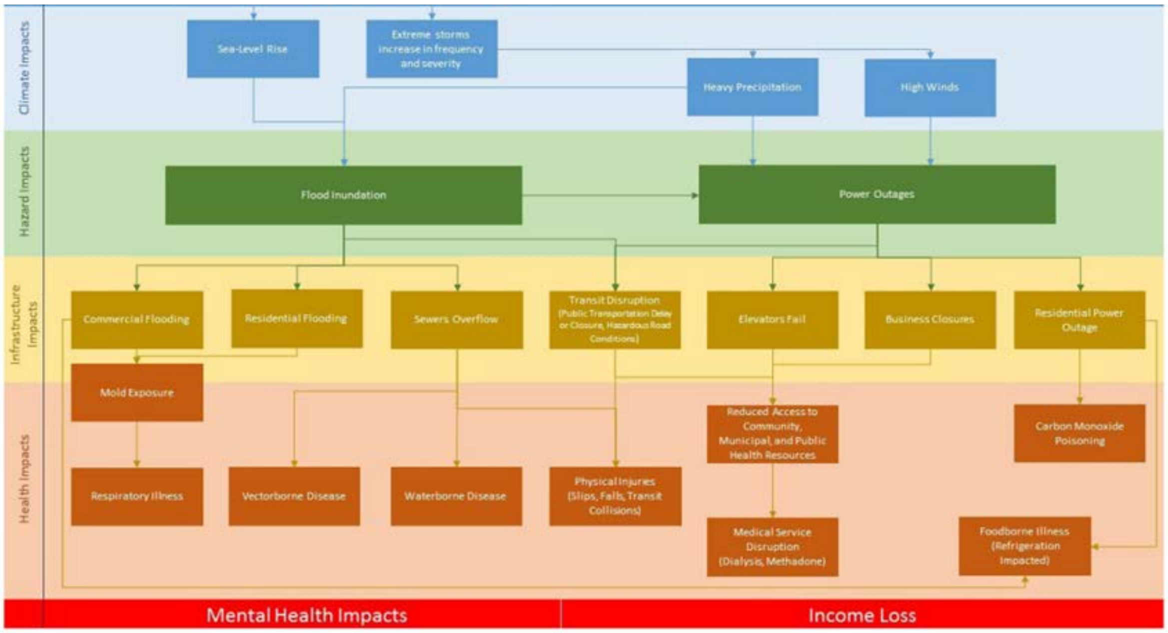
Physical damage from floods includes the following:

- Inundation of facilities, causing water damage to structures and contents.
- Impact damage to buildings, roads, bridges, culverts, and other facilities from high-velocity flow and waves, and from debris carried by floodwaters. Debris may also accumulate on bridge piers and in culverts, increasing loads on these features or causing overtopping or backwater effects.
- Erosion of stream banks and shorelines, undermining or damaging nearby facilities.
- Release of sewage and hazardous or toxic materials as wastewater treatment plants and other facilities are inundated, storage tanks are damaged, and pipelines back up or are severed.

Flooding is often associated with low pressure storms that bring high winds and power outages (more information in the Wind Hazard section). Floods pose threats to life and public safety; disrupt the normal function of a community; force people to leave their residences, sometimes permanently; cause economic losses through the closure of businesses and government facilities; damage and disrupt transportation and transit systems; and damage and disrupt communications and utilities. Floods may also result in health impacts such as respiratory illnesses, vector-borne diseases, water-borne diseases, physical injuries, and medical device interruptions (see Figure 4-20).[136] In addition, floods may result in significant expenditures for emergency response.

[136] San Francisco Department of Public Health, 2016. Climate and Health Understanding the Risk: An Assessment of San Francisco's Vulnerability to Flooding & Extreme Storms

FIGURE 4-20
CLIMATE AND HAZARD HEALTH IMPACT PATHWAYS[137]



Flooding, Extreme Storms, and Health Impacts

Coastal inundation and stormwater flooding can have profound impacts on the health of communities across San Francisco, particularly where vulnerable populations are geographically concentrated (See Vulnerable Populations Profile). To understand this risk, the San Francisco Department of Public Health created a flood vulnerability index in 2015 to determine which specific neighborhoods would likely see the largest impacts from current and future flooding. Indicators for this analysis included geographic location, living conditions, health conditions, and social vulnerability. The resulting map, seen in Figure 4-21 below, identified the following neighborhoods as particularly vulnerable to flooding events: The Pacific Coastline, the Southeastern quadrant of San Francisco, the Mission, and high-density areas such as South of Market, Chinatown, and the Tenderloin Neighborhoods.[138]

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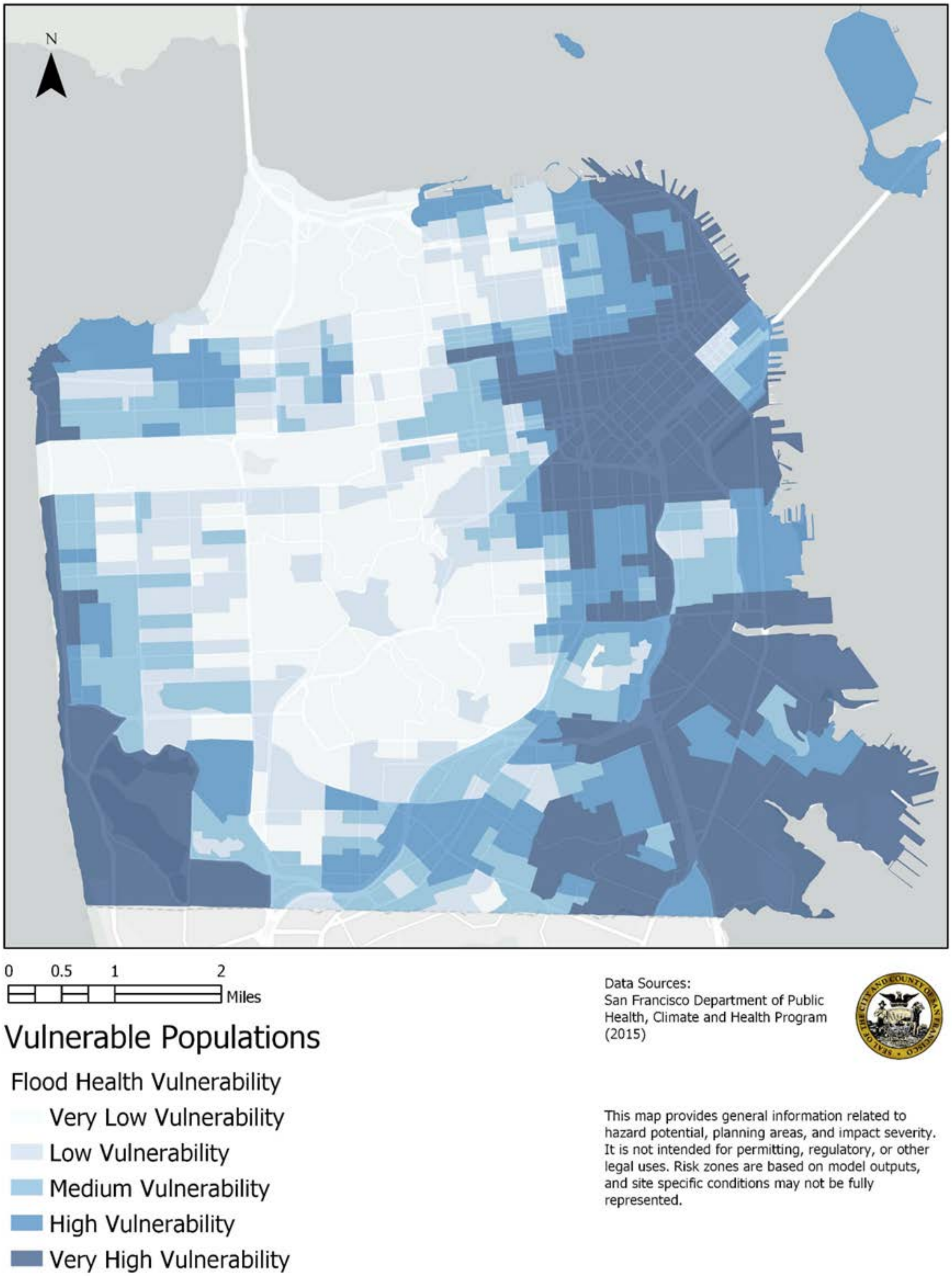
[137] Ibid

[138] San Francisco Department of Public Health. (2015). "San Francisco Flood Vulnerability: A Health Focused Assessment". Retrieved from: https://sfgov.maps.arcgis.com/apps/MapJournal/index.html?appid=69004eefbb3f4a27aa8b6c6566f8dc0b#

FIGURE 4-21
FLOOD VULNERABILITY INDEX



Coastal Flooding

Impact Statement

Currently, the shoreline of San Francisco Bay and the open Pacific Coast include areas that experience temporary flooding during extreme high tides and coastal storm events. As sea level rises, temporary coastal flooding will be more frequent and will inundate larger areas at greater depths and for longer durations. Areas that are particularly susceptible to increasing risk of coastal flooding due to sea level rise include Mission Bay, Islais Creek, Hunters Point, Candlestick Point, the Financial District, the Marina District, Treasure Island, and SFO. Coastal flooding can pose threats to life and public safety, cause physical damage to buildings and infrastructure, disrupt economic activity, and impair public health.

Nature

Coastal flooding in San Francisco is generally caused by the following phenomenon:

Annual high tide inundation (King Tides): King Tides are abnormally high but predictable astronomical tides that occur approximately twice per year. King Tides are the highest tides that occur each year when the gravitational influence of the moon and the sun on the tides are aligned, rather than opposed, and when the earth is at a point in its rotation which is particularly close to either the moon or sun. When King Tides occur during winter storms, the effects are particularly pronounced and make these events more dramatic. King Tides result in temporary flooding, often involving low- lying roads, boardwalks, and waterfront promenades. The Embarcadero waterfront (Pier 14) and the Marina area in San Francisco experience flooding under current King Tide conditions

Storm Surge: When Pacific Ocean storms coincide with high tides, storm surge due to meteorological effects can elevate Pacific Ocean and San Francisco Bay water levels, resulting in temporary flooding. Such storm surge events occurred on January 27, 1983, December 3, 1983, February 6, 1998, January 8, 2005, December 31, 2006, and December 24, 2012. Extreme high tides can cause severe flooding of low-lying roads, boardwalks, promenades, and neighborhoods; exacerbate coastal and riverine flooding and cause upstream flooding; and interfere with stormwater outfalls. The Ocean Beach area is prone to inundation and erosion associated with extreme high tides and storm surge.

El Niño winter storms: During El Niño,[139] atmospheric and oceanographic conditions in the Pacific Ocean bring warm, higher waters to the Bay Area and may produce severe winter conditions that bring intense rainfall and storm conditions to the Bay Area. Tides are often elevated 0.5 to 3.0 feet above normal along the coast for months at a time, and additional storm surge and wave setup during storm events can elevate water levels even further. El Niño conditions prevailed in 1977- 1978, 1982-1983, 1997-1998, and 2009-2010. The 2015-16 El Niño produced wave energy conditions that were 50% larger than typically seen in the San Francisco Bay Area, with a variety of consequences. Typical impacts include severe flooding of low-lying roads, boardwalks and waterfront promenades; storm drain backup; wave damage to coastal structures and erosion of natural shorelines (see Ocean Beach sidebar which highlights the power of coastal erosion).

Pacific Decadal Oscillation: Similar to the ENSO, this event references cyclical oceanic heating and cooling trends but on a longer time horizon than changes in the ENSO. These shifts occur over a 20 to 30-year period and, while typically less pronounced than the ENSO, persists for significantly longer.[140]

Ocean swell and wind-wave events (storm waves): Low pressure Pacific Ocean storms and strong thermal gradients can produce high winds that blow across the ocean and the Bay. When the wind blows over long reaches of open water, large waves are generated that impact the shoreline and cause damage. Typical impacts include wave damage along the shoreline, particularly to coastal structures such as levees, docks and piers, wharves, and revetments; backshore inundation due to wave overtopping of structures; and erosion of natural shorelines.

Physical damage from floods could include the following:

- **Inundation of facilities**, causing operational closures at critical transportation facilities such as SFO, the Port, BART, and various facilities operated by MTA.
- **Inundation and damage to various infrastructure** including buildings, roads, bridges, culverts, pump stations, support structures, parks, and open space.

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

[140] AECOM, 2016. "Extreme Storms in San Francisco Bay – Past to Present". Retrieved from: http://www.r9map.org/Documents/Extreme_Storms_SF_Bay_Past_to_Present_FINAL.pdf

- **Overland flooding may block access** to underground utilities, may damage electrical boxes and substations causing prolonged power outages, and may damage pump stations and other electrical equipment resulting in equipment failure.
- **Release of sewage and hazardous or toxic material** when wastewater treatment plants, storage tanks and other facilities are inundated and compromised.
- **Erosion of natural shorelines and stream banks,** disruption of wetlands and natural habitats, and undermining of the support foundations and structures of important facilities

As sea level rises, temporary coastal flooding will be more frequent, extensive, and longer lasting.[141] In addition, low-lying areas that are not currently exposed to tides will experience inundation during high tides in the long-term if no adaptation strategies are implemented.[142]

History

Several areas along the shoreline are already experiencing periodic flooding and erosion, including: Ocean Beach on the Pacific Coast, which is subjected to significant coastal storms and waves; the Embarcadero, which is overtopped in several areas during the annual highest high tides, or King Tides; and San Francisco International Airport (SFO), which experiences wave overtopping of flood protection structures and inundation of low-lying areas.

Location

San Francisco is susceptible to coastal flooding along three sides of the city, with the open Pacific Ocean to the west and San Francisco Bay to the north and east.

<u>Flood Hazard Mapping Within the City and County of San Francisco</u>

San Francisco participates in the National Flood Insurance Program (NFIP). Under the NFIP, which is administered by the Federal Emergency Management Agency (FEMA), the federal government makes affordable flood insurance available in communities that

[141] City and County of San Francisco, 2016. "Sea Level Rise Action Plan."
[142] Ibid

participate in the program. In exchange, participating communities agree to adopt and enforce floodplain management requirements meeting the minimum NFIP criteria. San Francisco has participated in the NFIP since 2010 and has adopted a Floodplain Management Ordinance that meets NFIP requirements.

In support of the NFIP, FEMA publishes Flood Insurance Rate Maps (FIRMs) for participating communities. The FIRMs show areas that are subject to inundation during a flood having a 1% chance of occurrence in any given year (also referred to as the base flood or 100-year flood). Unlike other Bay communities participating in the NFIP, San Francisco does not currently have a final, published FIRM. In 2015, FEMA provided San Francisco with a “preliminary” or draft FIRM that is based on the following studies:

- Bay Area Coastal Study: This study includes analyses of coastal storm surge and wave hazards for the San Francisco Bay shoreline. FEMA used the analyses to develop flood hazard mapping for San Francisco’s waterfront east of the Golden Gate Bridge, for Treasure Island, and for SFO.
- Open Pacific Coast Study: This study includes analyses of coastal storm surge and wave hazards for the open Pacific Ocean and the coastline. FEMA used the analyses to develop flood hazard mapping for the Pacific coastline of San Francisco west of the Golden Gate Bridge.

There are no natural riverine flood sources remaining within the county limits; therefore, FEMA did not complete an assessment if riverine flood hazards. Additionally, FEMA does not assess stormwater flooding, as this source of flooding is most directly related to the conveyance capacity of the City’s sewer system and not a natural water body. The preliminary FIRM does not show flood hazard data for inland areas within the county limits; the FIRM only shows coastal flood hazard data for the Bay and Pacific coast shorelines.

FEMA is currently making final adjustments to the preliminary FIRM based on comments provided by San Francisco and plans to finalize and publish the effective FIRM in late 2018 or 2019. Because the FIRM is still in production, specific data elements shown on the preliminary FIRM could change before the FIRM is effective. However, the general location and extent of the SFHAs depicted on the FIRM are likely to remain consistent.

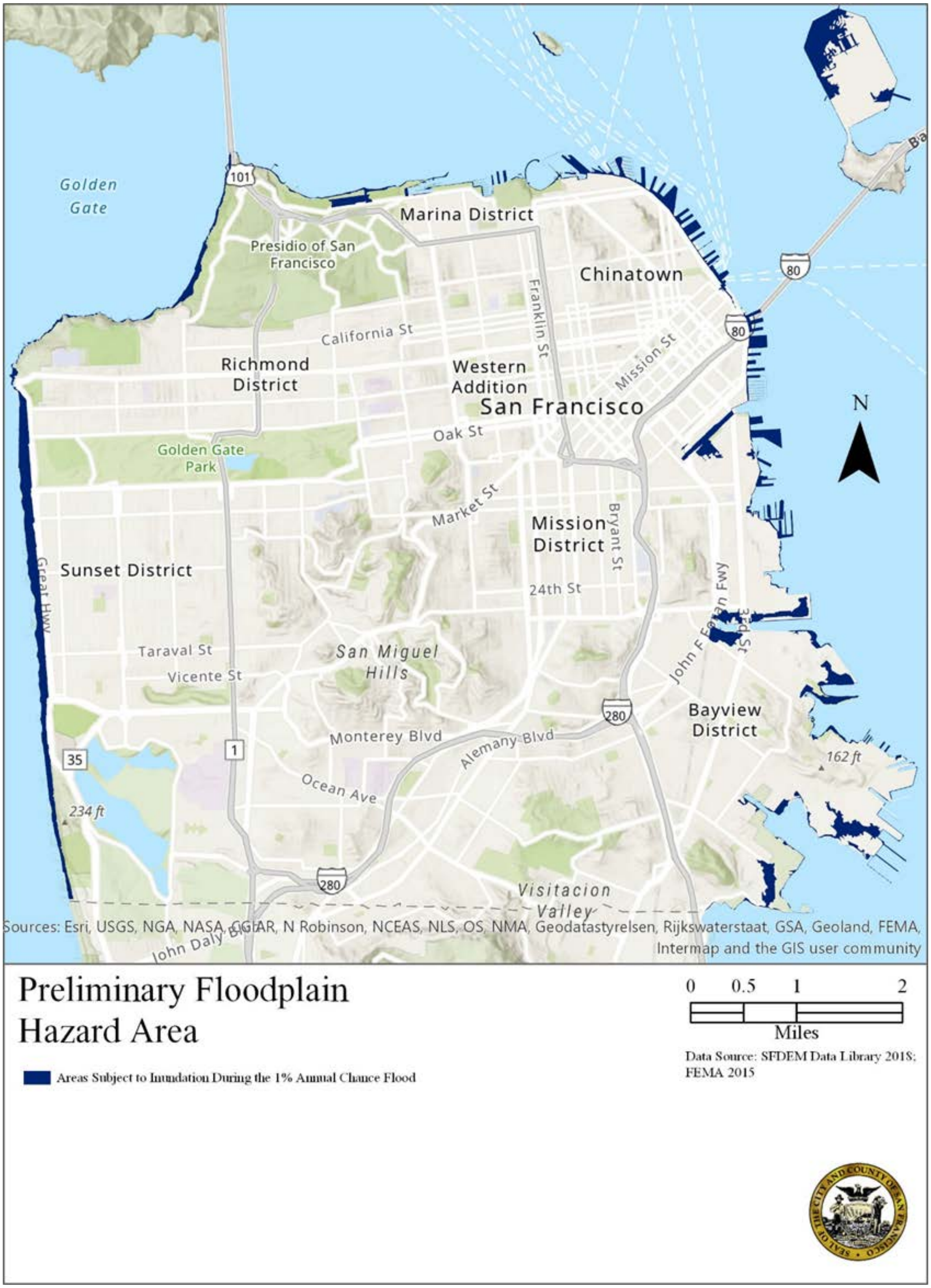
As described above, San Francisco adopted a Floodplain Management Ordinance in 2010, and uses that ordinance to regulate new construction and substantial improvement of buildings located in areas prone to flooding. Because FEMA has not yet published an effective FIRM for San Francisco, the City uses the "Interim Floodplain Map" as the basis for floodplain management. The Interim Floodplain Map is based on the preliminary FIRM data provided by FEMA.[143] Once FEMA has issued a Letter of Final Determination for the effective FIRM; the City will amend the Floodplain Management Ordinance to adopt the effective FIRM and use it for floodplain management purposes.

[143] The Interim Floodplain Map is available at https://sfgsa.org/san-francisco-floodplain-management-program.

FIRMs are organized on a countywide-basis and may include the following information:

- **Special Flood Hazard Area (SFHA)**: A SFHA is an area that is subject to flooding during the one-percent-annual-chance flood. The SFHA is the basis for the insurance and floodplain management requirements of the NFIP. A SFHA may be associated with a stream, river, lake, or other flooding source; or with a coastal flooding source, such as San Francisco Bay.
- **Base Flood Elevation (BFE)**: The BFE is the estimated flood elevation for the one-percent-annual-chance flood. The BFE is used for insurance ratings and for floodplain management.
- **SFHA zone designations**: An SFHA is defined using a zone designation that is based on the level of analysis used to establish the SFHA and the physical characteristics of the SFHA. “Zone AE” and “Zone VE” are used to represent flood hazards that were analyzed using detailed methods; whereas “Zone A” and Zone V” where determined by approximate methods. The zone designation also describes the type of risk associated with the flood hazard; it is used for insurance rating purposes and to determine the appropriate floodplain management requirements for structures located in that zone. “Zone AE” is used for inland flooding sources and for coastal flooding sources where waves are less than three feet in height. SFHAs in coastal areas where waves are three feet or greater in height are identified as “Zone VE” on the FIRM. The elevation of the flood hazard (i.e., 1-percent annual change flood elevation) is generally reported after the zone designation (e.g., Zone AE 12 represents an area with a flood hazard, with waves less than 3 feet, with a water surface elevation of 12 feet NAVD88). All flood elevations presented on the FIRM are rounded to the nearest whole foot.
- **Other flood hazard data**: The FIRM may also show other flood hazard data, such as “Shaded Zone X” floodplains associated with a flood having a 0.2 percent chance of occurrence in a given year (the 500-year flood), and “Zone X Protected by Levee” if a levee is accredited by FEMA as providing flood protection for the 1% annual flood.

FIGURE 4-22
PRELIMINARY FLOODPLAIN HAZARD AREA

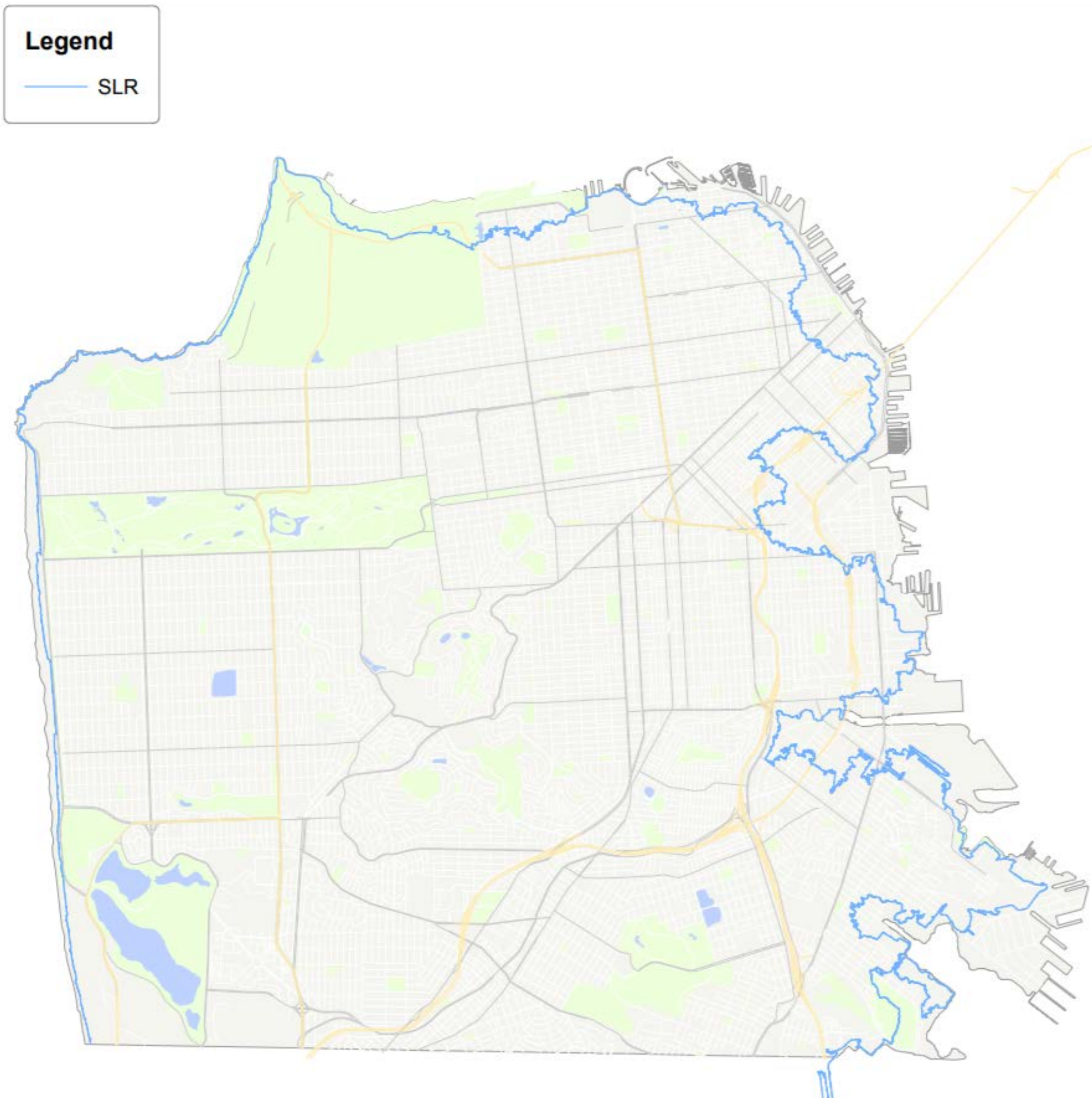


Sea Level Rise Vulnerability Zone

For long-range planning, Capital Planning Committee (CPC) Guidance defines a SLR Vulnerability Zone based on the 2012 National Research Council's (NRC) upper range (unlikely, but possible), end-of-century SLR estimate.[144] The Zone (see Figure 4-23) therefore includes shoreline areas that could be exposed to 66 inches of permanent SLR inundation combined with temporary flooding from a 100-year (1% annual chance) extreme tide if no adaptation measures or actions are taken.

[144] National Research Council, 2012. Sea-Level Rise for the Coasts of California, Oregon, and Washington. Past, Present, and Future.

FIGURE 4-23
SAN FRANCISCO SEA LEVEL RISE VULNERABILITY ZONE



Severity and Probability of Future Events

Floods are described in terms of their extent, including the horizontal area affected and the vertical depth of floodwaters, and the related probability of occurrence. Flood studies often use historical records, such as stream-flow and tide gages, to determine the probability of occurrence of floods of different magnitudes. The probability of occurrence is expressed as a percentage of the chance of a flood of a specific extent occurring in a given year. The magnitude of flood used as the standard for floodplain management in the United States is a flood having a probability of occurrence of one percent in any given year. This is known as the 100-year flood or base flood.

The most readily available source of information regarding the current one-percent-annual-chance flood hazard is the system of FIRMs prepared by FEMA (described above). FEMA has also created Increased Flooding Scenario Maps for the interior shoreline for all nine Bay Area counties, which are non-regulatory products that complement the FIRMs. These maps utilize the most up-to-date coastal floodplain mapping data based on FEMA's San Francisco Bay Area Coastal Study and provide additional information on how the 1-percent-annual-chance (i.e. 100-year) coastal floodplain may change with a 1-foot, 2-foot, and 3-foot increase in Bay water levels.

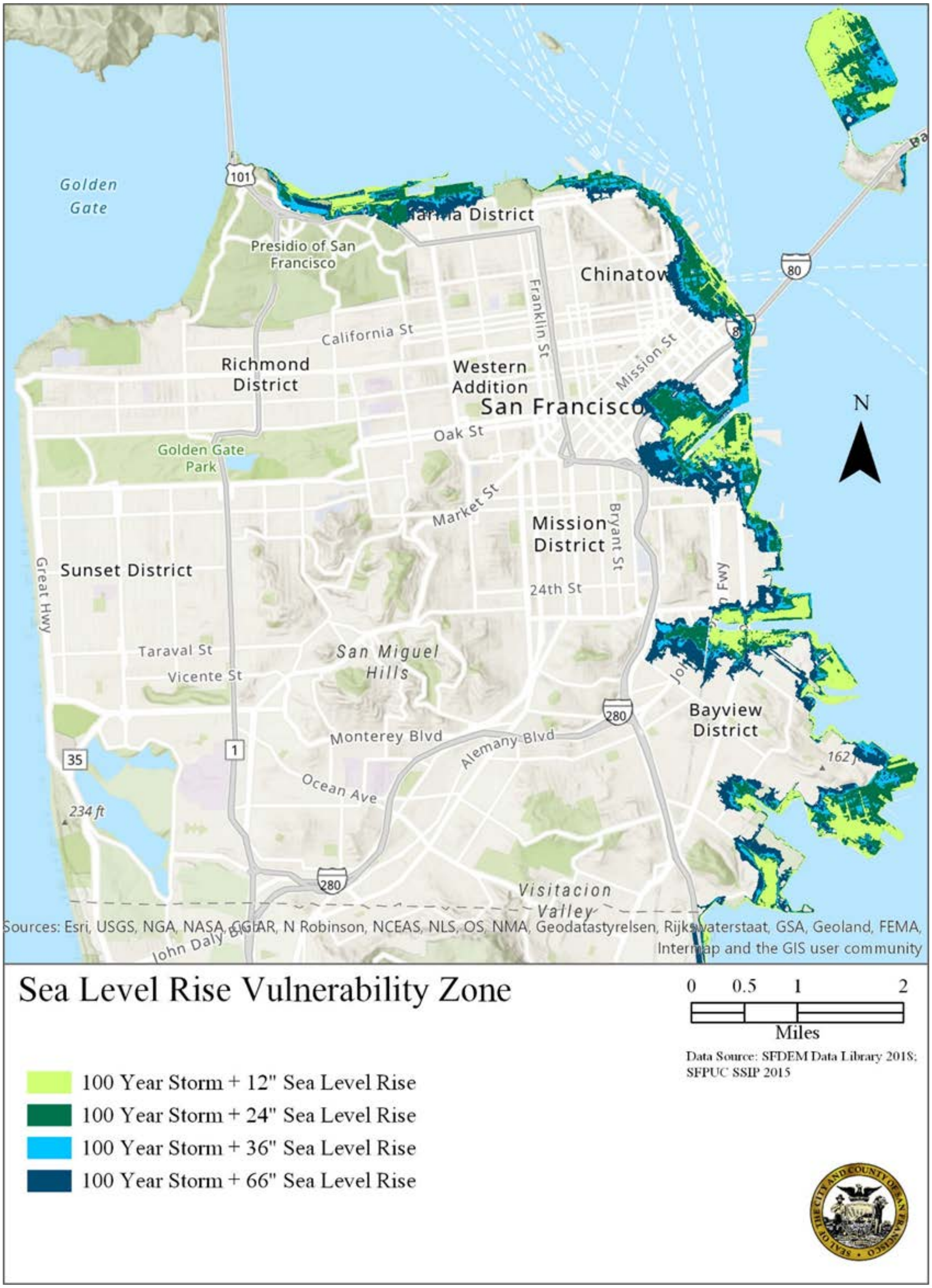
Projected sea level rise will worsen existing coastal flood hazards by increasing the elevation and frequency of flooding, extending the coastal flood hazard zone further inland, and accelerating shoreline erosion. Without action, a variety of coastal flood hazards will increase as seas rise, including:

- **Temporary coastal flooding** from extreme tides, storm surge, and large waves may increase in frequency and extent. Figure 4-24, seen below, shows the areas potentially exposed to temporary flooding during a 100-year storm with 12 to 66 inches of sea level rise.

- **Permanent inundation of areas currently not exposed to regular tides:** Sea level rise can cause areas that are not currently exposed to regular high tide inundation to be inundated regularly, resulting in the need to either protect or move people and infrastructure, and the loss of trails, beaches, vistas, and other shoreline recreation areas. Without action, up to six percent of San Francisco's current land could be permanently inundated by daily tides by the end of the century, including portions of Mission Bay, Central SOMA, and Hunters Point, and areas adjacent to Islais Creek. Parts of the San Francisco International Airport could also be exposed to permanent inundation without action.

- **Shoreline erosion:** The Pacific coastline and some Bay shoreline areas, such as Crissy Field, are susceptible to increased erosion associated with extreme tides and increased wave action. Without protective action, rising seas will increase erosion hazards.
- **Elevated groundwater and increased salinity intrusion**: As sea levels rise, groundwater and salinity levels are also predicted to rise. This will cause damage to below grade residential and commercial spaces and infrastructure.

FIGURE 4-24
TEMPORARY COASTAL FLOODING IN SEA LEVEL RISE VULNERABILITY ZONE



Stormwater Flooding

Impact Statement

Stormwater flooding occurs during storm events as rainfall runoff collects in areas that at one time were naturally-formed waterways but are now contained within the City's combined sewer and stormwater collection system. The Islais Creek area (Cayuga/Alemany), South of Market, Inner Mission, and Civic/Center Western Addition include significant areas that are at risk of stormwater flooding during a 100-year storm, as well as during rainfall events that occur more frequently. Smaller areas across the city also experience temporary flooding during precipitation events.[145] As precipitation events may become more intense and sea level rises due to climate change, the frequency and extent of stormwater flooding may increase. Stormwater flooding can cause physical damage to buildings and infrastructure, disrupt economic activity, and impair public health.

Nature

As San Francisco has developed over time, its hilly topography has been largely paved over. During storms, runoff flows along streets aligned with historic waterways and in areas that are built on landfill. The stormwater accumulating on the surface and backups from the combined sewer-stormwater system may enter nearby structures, resulting in property damage, forcing people to leave their homes, and causing disruptions to businesses. Additionally, fast-moving water on the surface is a threat to public safety, even at shallow depths. San Francisco's stormwater infrastructure is sized for the current 5-year storm, so heavier precipitation events can lead to localized flooding.

Stormwater flooding can also be exacerbated by high tides. As the sewage and stormwater system reaches maximum capacity during heavy precipitation events, the effluent may be discharged directly into the bay. High water levels in the bay can slow these discharges, causing backups in the sewage and stormwater system. These backups can increase the extent and duration of stormwater flooding. This phenomenon will be exacerbated as sea level rises. Discharges to the bay can create a

[145] San Francisco Public Utilities Commission. "Flood Maps." http://sfwater.org/index.aspx?page=1229

pollution problem when the effluent carries untreated sewage and debris, chemicals, trash, and other pollutants that have collected on streets.

History

A query of the National Oceanic and Atmospheric Administration's Storm Events Database, indicates that San Francisco has 23 flood events from 1998 to 2018, primarily resulting in flooded roadways.[146] Several large storms in recent years have caused significant flooding in certain neighborhoods of San Francisco. Recently, two very large storms in December 2014 caused property damage, loss of business revenue, and other significant impacts in some low-lying areas. Many of these areas also flooded in an extreme storm in February 2004.[147]

Location

The SFPUC has developed a Draft 100-Year Storm Flood Risk Map (Draft Map) that shows areas of San Francisco where significant flooding from storm runoff is highly likely to occur during a 100-year storm. A "100-year storm" means a storm with a 1% chance of occurring in a given year. The SFPUC used computer modeling that simulates the Citywide operation of the stormwater system during a 100-year storm to identify areas subject to flooding.

The Draft Map shows parcels that are highly likely to experience "deep and contiguous" flooding during a 100-year storm. "Deep and contiguous flooding" means flooding that is at least 6-inches deep spanning an area at least the size of half an average City block. This Draft Map shows flood risk from storm runoff only. It does not consider flood risk in San Francisco from other causes such as inundation from the San Francisco Bay or Pacific Ocean.

Areas with stormwater flooding risks include the Islais Creek area (Cayuga/Alemany), South of Market, Inner Mission, and Civic/Center Western Addition.

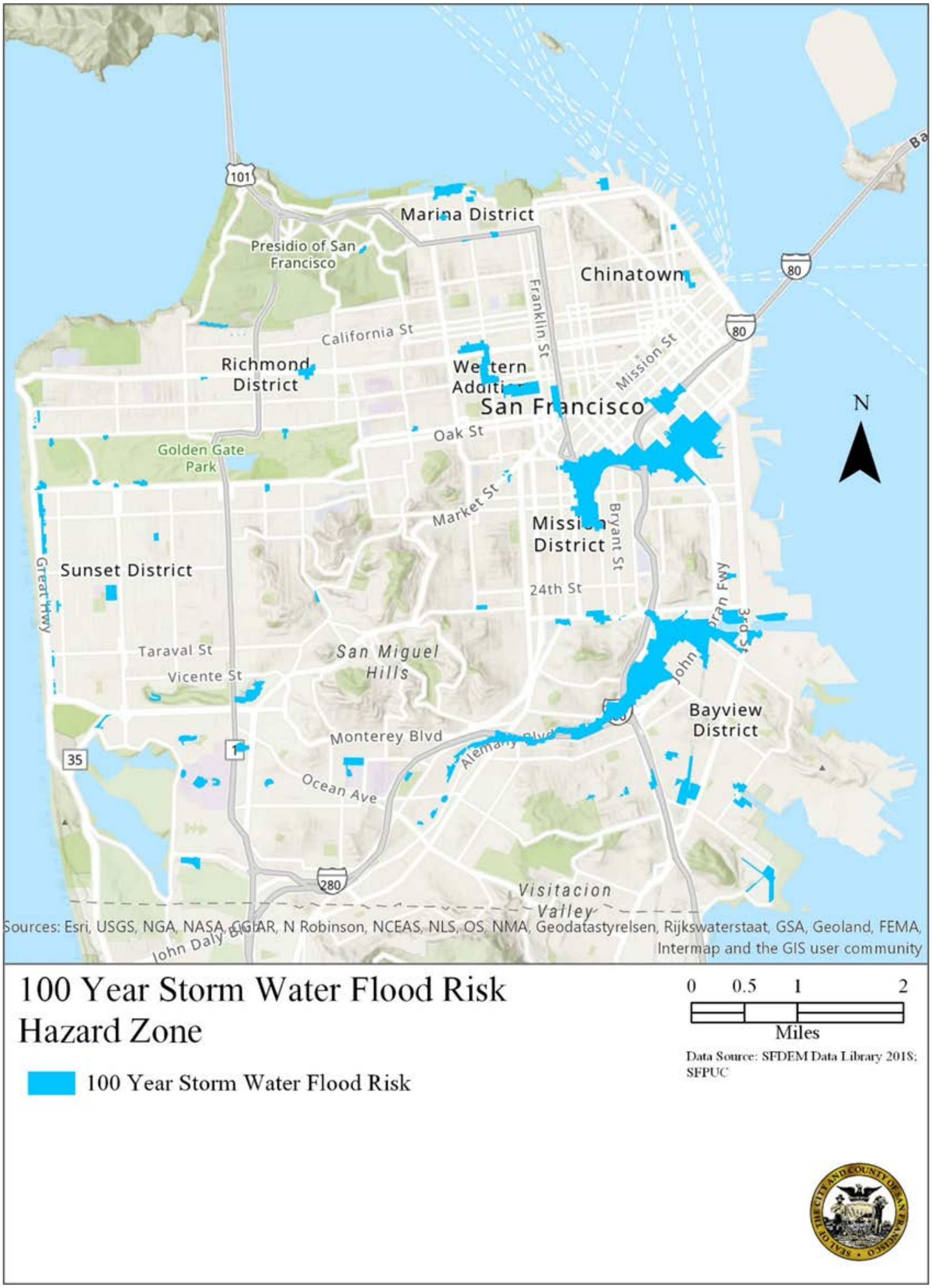
Severity and Probability of Future Events

As sea level rises and precipitation events become more intense, stormwater flooding may increase in frequency and severity. More intense precipitation may lead to localized

[146] National Oceanic and Atmospheric Administration. https://www.ncdc.noaa.gov/stormevents/
[147] San Francisco Public Utilities Commission, 2016. "Flood Resilience Report. Executive Summary." http://sfwater.org/Modules/ShowDocument.aspx?documentid=9127

flooding because stormwater infrastructure is sized for the current 5-year storm. This effect will be exacerbated as sea levels rise because higher Bay waters will further slow stormwater discharge. This effect will be particularly severe in low-lying coastal areas, but slow discharge rates could affect system-wide drainage rates and cause upstream flooding.

FIGURE 4-25
100-YEAR STORM FLOOD RISK HAZARD MAP



Dam or Reservoir Failure Profile

4.6 Dam or Reservoir Failure

Impact Statement

Dam or reservoir failure may impact the Sunset, Midtown Terrace, Twin Peaks, Clarendon Heights, and University Mound areas of San Francisco, where state-regulated reservoirs are located. Factors that increase the risk of dam or reservoir failure include the age of the structures and the likelihood of an earthquake. Climate change impacts, including changing precipitation patterns, may also increase the risk of dam or reservoir failure in and outside of the County.

Nature

A dam or reservoir failure is an unplanned release of water resulting from the structural compromise or collapse of a dam or other structural element, such as the wall of a tank. The Federal Emergency Management Agency (FEMA) classifies the causes of dam failures into five general categories:[148]

- **Hydrologic**: Dam failures caused by extreme rainfall or snowmelt events that can lead to natural floods. The main causes of hydrologic dam failure include overtopping, structural overstressing, and surface erosion due to high velocity flow and wave action. Overtopping due to inadequate spillway design, debris blockage of spillways, or settlement of the dam crest accounts for about 34 percent of all dam failures in the United States.

- **Geologic**: Includes failures due to piping and internal erosion, slope instability and hydraulic fracturing, long-term seepage of water in earthen dams, inadequate geotechnical design of the embankment and foundation, inadequate seepage controls, or increased load situations.

- **Structural**: Involves failure of a critical dam component. Structural failures may stem from inadequate initial design, poor construction, poor construction materials, inadequate maintenance and repair, or gradual degradation and

[148] Federal Emergency Management Agency (FEMA), *Federal Guidelines for Inundation Mapping of Flood Risks Associated with Dam Incidents and Failures*, FEMA P-946 (Washington, DC, 2013), 4-4–4-8, accessed June 5, 2018, https://www.fema.gov/media-library-data/96171edb98e3f51ff9684a8d1f034d97/Dam_Guidance_508.pdf; FEMA, *Living with Dams: Know Your Risks*, FEMA P-956 (Washington, DC, 2013) 9, 10, accessed June 4, 2018, https://www.fema.gov/media-library-data/20130726-1845-25045-7939/fema_p_956_living_with_dams.pdf.

weakening over time. Structural failures have caused about 30 percent of all dam failures in the United States.

- **Seismic**: In earthquake zones, seismic failures typically are related to ground movement or liquefaction. Liquefaction can cause immediate dam failure or can result in slumping that exposes the dam crest to overtopping and erosion. Seismic-induced piping can occur due to internal cracking caused by earthquake ground motion, which may cause a dam to shift, settle, or crack in a way that prevents the dam from performing as designed.

- **Human-caused**: Failures related to improper design, maintenance, or operation of a dam, or to terrorist acts.

The age of a dam or reservoir may make it more susceptible to failure. As dams get older, deterioration and repair costs increase. Common characteristics of older dams include:[149]

- Deteriorating metal pipes and structural components;

- Sediment-filled reservoirs; and

- Increased runoff from subdivisions and businesses built upstream.

The sudden release of water following a dam or reservoir failure has the potential to cause dangerous flooding, resulting in human casualties; economic loss, including property damage; and environmental damage.[150] In addition, dam or reservoir failure may result in lifeline disruption, including impacts on delivery of drinking water and electricity to areas served by the dam or reservoir.[151] Dam or reservoir failure can occur rapidly, providing little warning, thus leaving little time to evacuate people located downstream from or below the failing structure. Damage occurs as a result of the momentum of the sediment-laden water, flooding over channel banks, and the impact of the debris carried by the flow.

History

[149] FEMA, *Living with Dams*, iii.

[150] Association of Dam Safety Officials, “What are the Top Issues Facing the Dam Community?” accessed June 5, 2018, https://damsafety.org/top-issues-facing-dam-community; FEMA, *Living with Dams*, 2, 3.

[151] See FEMA, *Living with Dams*, 1–3.

To date, there is no history of a dam or reservoir failure occurring within San Francisco boundaries. Nor is there a history of failures for dams or reservoirs located outside San Francisco that are owned by the city or by the SFPUC. However, on March 22, 2018, seepage was detected on the downstream face of the SFPUC-owned 60-foot earthen Moccasin Dam in Tuolumne County after heavy rainfall sent a major surge of water and debris into the Moccasin Reservoir. The seepage triggered activation of the Moccasin Dam Emergency Action Plan, which included evacuations of a downstream campground and fish hatchery close to the dam and prompted the closure of two nearby highways. The SFPUC drained the Moccasin reservoir into the larger Don Pedro Reservoir located downstream and conducted extensive inspections of the dam and its spillways. Though the dam itself never overtopped or failed,[152] cleanup and repair efforts cost approximately $43 million.[153]

Location

There are 15 reservoirs located within San Francisco County limits. Six San Francisco reservoirs are considered dams regulated by the California Department of Water Resources, Division of Safety of Dams (DSOD). Under California law, state-regulated dams are artificial barriers that impound or divert water and are 25 feet or more in height, or that store 50 acre-feet or more of water.[154] The state also regulates artificial barriers that are more than six feet in height, regardless of storage capacity; or that hold more than 15 acre-feet of water, regardless of height.[155]

State-regulated dams within San Francisco County limits are listed in Table 4-26, below. Each of these reservoirs are owned by the City and County of San Francisco and are managed by the SFPUC. Table 4-26 includes the names of the reservoirs and dams, the year of construction, the type of construction of the main dam, the reservoir capacity in acre-feet, and the dam height and crest length in feet. It also includes the DSOD assessment of downstream hazard. DSOD's categories for downstream hazard

[152] See San Francisco Public Utilities Commission (SFPUC), News Releases, "Moccasin Reservoir Stabilized Following Threat of Dam Failure," March 22, 2018, accessed June 4, 2018, http://sfwater.org/index.aspx?recordid= 450&page=17; "Update on Status of Moccasin Dam and Reservoir," March 23, 2018, accessed June 4, 2018, https://sfwater.org/Index.aspx?page=17&recordid=452.

[153] San Francisco Chronicle, "March Storm Caused $43M in Damage at Moccasin Dam, Per SFPUC," May 2, 2018, accessed June 4, 2018, https://www.sfgate.com/news/bayarea/article/March-Storm-Caused-43M-In-Damage-At-Moccasin-12883240.php.

[154] See California Water Code § 6002.

[155] See California Water Code § 6003.

assessment are based on federal recommendations of low-, significant-, and high-hazard potential classifications. However, DSOD has included a fourth category, "Extremely High," to identify dams that may impact highly populated areas or critical infrastructure or that may have short evacuation warning times. The assessment is not related to the condition of the dam or its auxiliary structures, or an indication of probability of dam failure.[156] State-regulated reservoirs within San Francisco County are located in the Sunset District (Sunset North and South), Midtown Terrace (Sutro), Twin Peaks, Clarendon Heights, and University Mound.

TABLE 4-26
STATE-REGULATED DAMS WITHIN SAN FRANCISCO COUNTY[157]

Reservoir Name	Dam Name	Year Built	Dam Type	Reservoir Capacity (ac-ft)	Dam Height/ Crest Length (ft)	Downstream Hazard
Sunset Reservoir	Sunset North Basin	1938	Earth	275	74/2,300	Extremely High
	Sunset South Basin	1960	Earth	268	34/ 980	Extremely High
Sutro Reservoir	Sutro Reservoir	1952	Earth	96	55/850	Extremely High
Twin Peaks Reservoir	Stanford Heights	1928	Earth	37	31/1,480	Extremely High
Summit Reservoir	Summit Reservoir	1954	Earthen Embankment	43	39/120	Extremely High

[156] California Department of Water Resources, Division of Safety of Dams (DSOD), *Dams Within Jurisdiction of State of California, Dams Listed Alphabetically by County* (Sacramento, CA, 2017), ii, accessed June 5, 2018, https://www.water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/All-Programs/Division-of-safety-of-dams/Files/Publications/Dams-Within-Jurisdiction-of-the-State-of-California-Alphabetically-by-County.pdf; see FEMA, *Federal Guidelines for Inundation Mapping of Flood Risks Associated with Dam Incidents and Failures,* FEMA P-946 (Washington, DC, 2013), 6-4, accessed June 5, 2018, https://www.fema.gov/media-library-data/96171edb98e3f51ff9684a8d1f034d97/Dam_Guidance_508.pdf.

[157] California Department of Water Resources, Division of Safety of Dams, 2017

Reservoir Name	Dam Name	Year Built	Dam Type	Reservoir Capacity (ac-ft)	Dam Height/ Crest Length (ft)	Downstream Hazard
University Mound	University Mound North	1885	Earth	182	17/2,422	Extremely High
	University Mound South	1937	Earth	250	61/1,150	Extremely High

In addition, San Francisco is home to a number of smaller reservoirs that are not regulated by the state. Together with the state-regulated reservoirs shown in Table 4-26, these reservoirs are part of the SFPUC's San Francisco Retail Water System. This system includes 10 reservoirs and eight water tanks located within the city, which store water delivered by the Hetch Hetchy Regional Water System and the local Bay Area water system. The Hetch Hetchy Regional Water System provides the majority of San Francisco's drinking water.[158]

The City and County of San Francisco and the SFPUC also own a number of state-regulated dams located outside county boundaries. These dams and reservoirs are part of the Hetch Hetchy Regional Water System, which provides drinking water to other cities in the San Francisco Bay Area Region in addition to San Francisco. Dams and reservoirs in this system are located in Alameda, San Mateo, and Tuolumne Counties. Table 4-27, below, contains a list of these dams and reservoirs. For a map of the Hetch Hetchy Regional Water System see Appendix B.

[158] SFPUC, "San Francisco Groundwater Supply Project," accessed June 5, 2018, https://sfwater.org/index.aspx? page=1136.

TABLE 4-27
CITY AND SFPUC-OWNED, STATE-REGULATED DAMS OUTSIDE SAN FRANCISCO COUNTY[159]

Dam Name	County	Year Built	Dam Type	Reservoir Capacity (ac-ft)	Dam Height/ Crest Length (ft)	Downstream Hazard
Calaveras	Alameda	1925	Hydraulic Fill	100,000	210/1,200	Extremely High
James H. Turner	Alameda	1964	Earthen Embankment	50,000	193/2,160	Extremely High
Lower Crystal Springs	San Mateo	1888	Gravity	57,910	149/600	Extremely High
Pilarcitos	San Mateo	1866	Earth	3,100	103/520	High
San Andreas	San Mateo	1870	Earth Embankment	19,027	107/727	High
Cherry Valley	Tuolumne	1956	Earth and Rock	273,500	315/2,630	High
Early Intake	Tuolumne	1925	Constant Radius Arch	115	56/262	Low
Lake Eleanor	Tuolumne	1918	Multiple Arch	28,600	61/1,260	High
Moccasin Lower	Tuolumne	1930	Earth and Rock	554	60/720	High
O'Shaughnessy	Tuolumne	1923	Gravity	360,000	312/900	Extremely High
Priest	Tuolumne	1923	Hydraulic Fill	2,067	168/1,000	High

[159] California Department of Water Resources, Division of Safety of Dams, 2017

Extent and Probability of Future Events

In general, dam or reservoir failure is a low probability, high consequence event. Most of the dams and reservoirs making up the Hetch Hetchy Regional Water System are more than 85 years old. Damage to these structures could be caused by a major earthquake, by a severe storm with attendant runoff, by a slope failure, through terrorism, or by other means.

There is a 72 percent chance of magnitude 6.7 or greater earthquake occurring in the San Francisco Bay Area between 2014 and 2044.[160] In this regard, it is important to note that the SFPUC has performed, and continues to perform, extensive seismic work on its dams and reservoirs, including retrofits to the Sunset and University Mound reservoirs, upgrades to the water tanks within the city that make up the Emergency Firefighting Water System,[161] and the ongoing Calaveras dam replacement project.[162]

As required by California law,[163] the SFPUC has prepared inundation maps showing areas of potential flooding in the event of sudden or total failure of state-regulated dams or reservoirs located in and outside San Francisco. SFPUC has submitted the maps to the California Governor's Office of Emergency Services and to DSOD for approval. State-approved maps are available on the DSOD web site.[164] Figure 4-28, below, shows potential inundation areas for reservoirs within San Francisco. With a changing climate that includes an expectation of increased extreme weather events in California, including prolonged periods of drought and intense wet periods with less snowpack, dam operation becomes more difficult and the risk of dam failure from overtopping may increase.[165]

[160] Edward H. Field and 2014 Working Group on California Earthquake Probabilities (WGCEP), *UCERF3: A New Earthquake Forecast for California's Complex Fault System,* Fact Sheet 2015–3009 (2015), 4, accessed May 18, 2018, https://dx.doi.org/10.3133/fs20153009.

[161] SFPUC, *Earthquake Safety and Emergency Response Bond Program 2010 & 2014 Quarterly Status Report* (March 2016) 2, 28, accessed June 5, 2018, http://www.sfearthquakesafety.org/uploads/1/9/4/3/19432507/ quarterly_status_report_jan_-_march_2016.pdf.

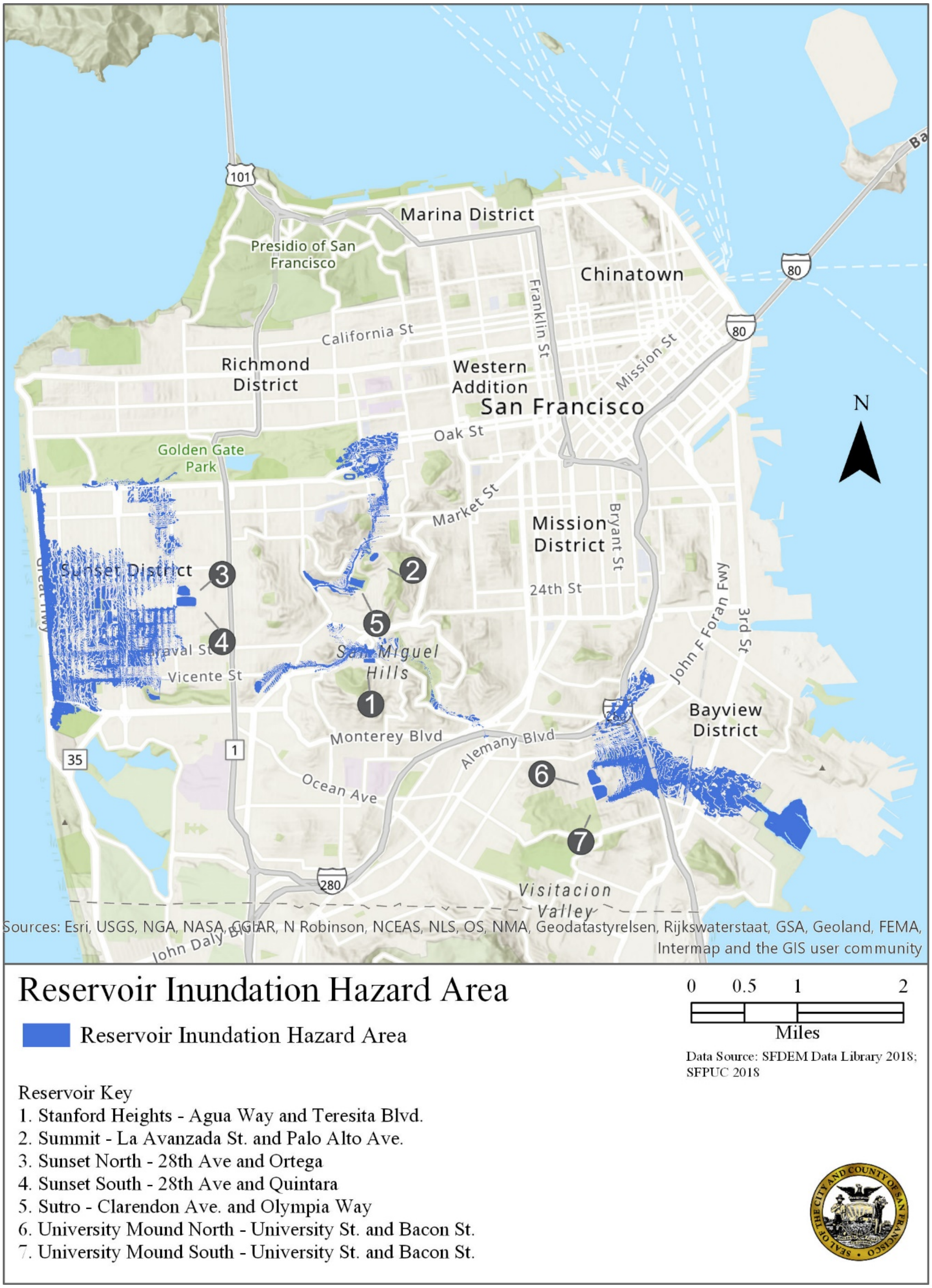
[162] SFPUC, "Calaveras Dam Replacement Project," accessed June 5, 2018, https://sfwater.org/index.aspx?page=979.

[163] See Cal. Water Code §§ 6160 et seq.; Cal. Govt. Code § 8589.5.

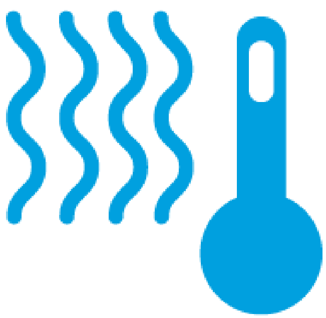
[164] See DSOD, Inundation Maps," accessed June 5, 2018, https://www.water.ca.gov/Programs/All-Programs/Division-of-Safety-of-Dams/Inundation-Maps.

[165] State of California, 2018. "2018 State Of California Multi-Hazard Mitigation Plan. Public Review Draft."

FIGURE 4-28
RESERVOIR INUNDATION HAZARD AREA



Extreme Heat Profile



4.7 Extreme Heat

Impact Statement

Historically, San Francisco has experienced extreme heat events six to seven days per year, generally between May and October. Though an excessive heat event in San Francisco impact all areas of the city, it does not affect all inhabitants equally. The elderly, the very young, and those with chronic health problems are most at risk when extreme heat occurs. Neighborhoods with the greatest risk, based on sociodemographic characteristics, include Chinatown, SOMA, Tenderloin Center, Bayview/ Hunters Point, and the Mission District. Climate change is expected to increase the frequency and severity of extreme heat events. By 2100, the number of extreme heat days is projected to increase by 1.5 orders of magnitude to 90 days per year, up from around six currently.

Nature

Located at the north end of a peninsula and surrounded on three sides by San Francisco Bay and the Pacific Ocean, San Francisco is almost perfectly positioned for moderate temperatures year-round. Cool marine air and coastal fog keep the average summertime temperatures between 60- and 70-degrees Fahrenheit. The warmest time of year is typically the late summer and early fall when the fog is less pronounced. However, occasional heat events (defined below) do occur for San Francisco. Given that San Francisco has such a relatively mild climate, a sudden spike in temperatures has a much greater impact on local residents compared with noncoastal communities. Though air conditioning is the leading protective factor against heat-related illness and death, most residential units in San Francisco lack air conditioning.

According to the National Weather Service, extreme heat occurs when the temperature reaches extremely high levels or when the combination of heat and humidity causes the air to become oppressive and stifling. In San Francisco, heat or extreme heat is generated when a massive high-pressure ridge inhibits the normal onshore breezes, resulting in temperatures in the high 80s, 90s, and possibly the 100s. Generally, extreme heat is considered to be 10 degrees above the normal temperature over an extended period of time. In San Francisco, extreme heat events have been specified as occurring when daytime temperatures are at or above 85 degrees.[166] However, extreme heat can manifest itself in several other ways, including:

- A spell of sweltering humidity, which reaches levels commonly associated with moist tropical regions. Stress on the body can be exacerbated when atmospheric conditions cause pollutants to be trapped near the ground.
- An excessively dry condition, in which strong winds and blowing dust can worsen the situation.
- A rise in the heat index, the body's perception of the "apparent" temperature based on both the air's real temperature and the amount of moisture present in the air. Humidity and mugginess make the temperature seem higher than it is. In high humidity, an 85-degree day may be perceived as 95 degrees.

During heat or extreme heat events, local National Weather Service offices may issue heat-related messages as conditions warrant. Such messages include:

- **Excessive Heat Outlook**: Issued when the potential exists for an excessive heat event in the next three to seven days. An outlook carries a minimum 30 percent confidence level that the event will occur.
- **Excessive Heat Watch**: Issued when conditions are favorable for an excessive heat event in the next 12 to 48 hours. A watch is given when the level of confidence that the event will occur reaches 50 percent or greater.
- **Excessive Heat Advisory**: Issued when an excessive heat event is expected in the next 36 hours. An advisory is used for a less severe event that is not assumed to be life-threatening, when caution is advised to mitigate the event's impact.
- **Excessive Heat Warning**: The most serious alert, issued when an excessive heat event is expected in the next 36 hours, or such an event is occurring, is imminent,

[166] According to Cal-Adapt, an Extreme Heat day is defined as a day in April through October when the Maximum Temperature exceeds the location's Extreme Heat Threshold, which is calculated as the 98th percentile of historical maximum temperatures between April 1 and October 31 based on observed daily temperature data from 1961–1990.

or has a very high probability of occurring. A warning assumes the potential for health consequences due to extreme heat.

While extreme heat events are less dramatic, they are potentially more deadly. A California Energy Commission study indicates that over the past 15 years, heat waves have claimed more lives in California than all other declared disaster events combined.[167]

History

Using data from the National Weather Service (NWS), San Francisco's daily temperature has exceeded 100 degrees only 11 times between 1921 and 2017, for a recurrence interval of approximately once every 9 years. Between 1921 and 2017, the NWS observation site in downtown San Francisco has averaged 6.6 days per year with high temperatures at or above 85 degrees. However, 1984, 1995, and 1996 was an exception to this average: There were 17, 18, and 18 days, respectively, during those years when temperatures were at or above 85 degrees.

On the rare days when the temperature reaches 100 degrees, the health impact is extreme. On June 14, 2000, San Francisco experienced a 103-degree heat wave, the highest temperature ever recorded for San Francisco at the time. This heat event resulted in reports of 102 heat-related illnesses and nine deaths in San Francisco. During the 2017 Labor Day weekend, San Francisco experienced the highest temperature ever recorded, with temperatures of 106 degrees observed. It is estimated that during this event, at least three people died, and 50 people were hospitalized due to heat-related illness in the city. The number of 911 calls overwhelmed ambulances and forced San Francisco to request mutual aid from neighboring counties.[168] These numbers likely underestimate the event's health impacts, as exposure to extreme heat can exacerbate underlying health conditions, leading to hospitalization and even premature death.

Location

As previously note, though an excessive heat event in San Francisco impacts all areas of the city, it does not affect all inhabitants equally. The elderly, the very young, and those with chronic health problems are most at risk when extreme heat occurs. In addition,

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[167] Heat waves are three sequential extreme heat days and are also expected to increase.

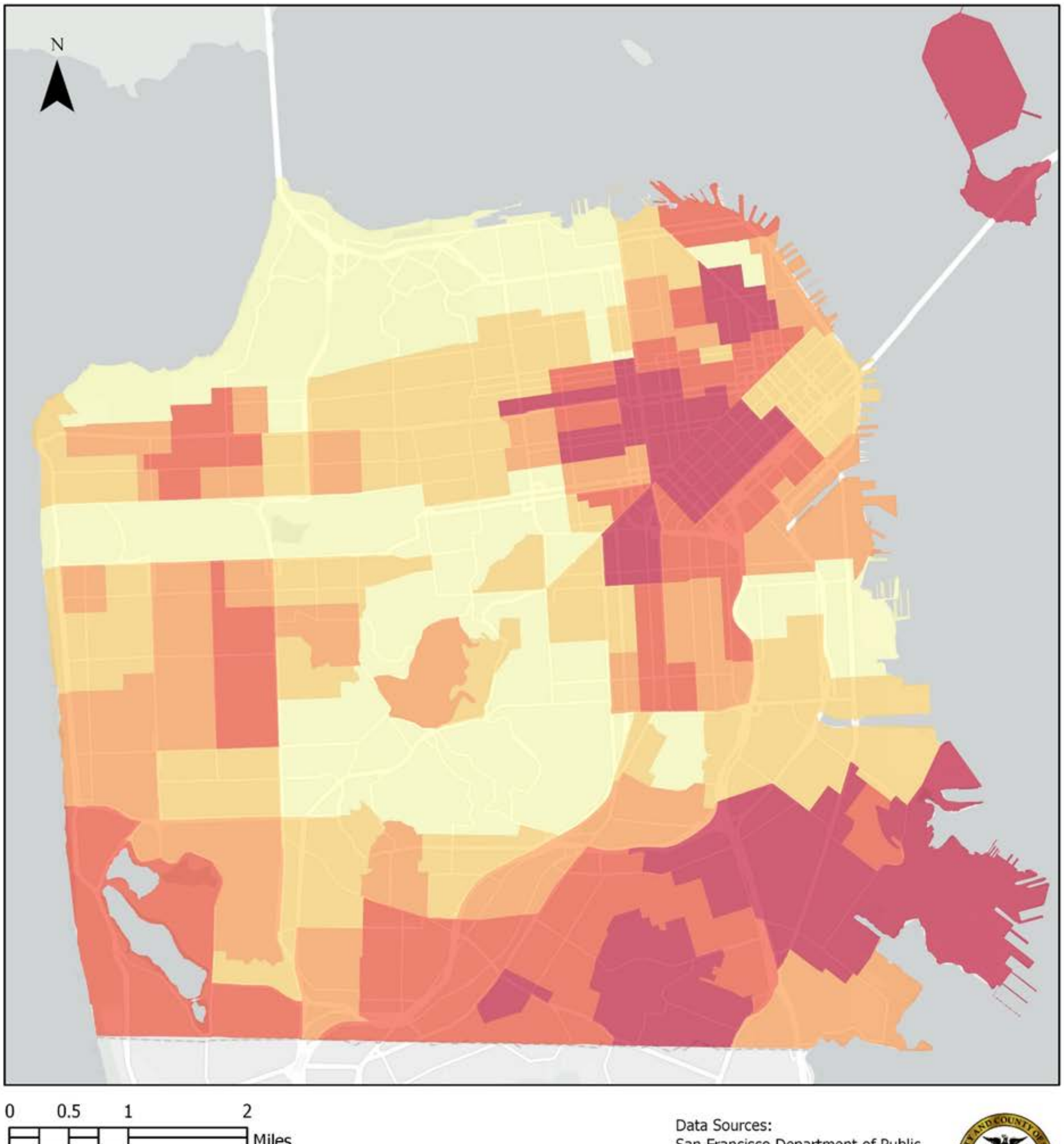
[168] There were 1,342 emergency calls on Friday, September 1, and 1,413 emergency calls on Saturday, September 2, the most since New Year's Eve 2012.

environmental exposure factors affect vulnerability to extreme heat. These factors include air quality, tree density, and proximity to parks/green space. Housing can also modify the relationship between temperature and heat-related illnesses. This is often called the Urban Heat Island (UHI) effect, which describes the temperature difference between dense urban areas and their more forested outer limits, where more intense urbanization contributes to increased relative temperatures. Due to the unique pattern of urbanization in the San Francisco bay area, temperatures can vary significantly over even small geographic scales. For example, the localized UHI in Downtown San Francisco contributes to a 1° C temperature increase relative to North Beach or Russian Hill, areas less than 1 km away[169]. This effect exacerbates extreme heat hazards by contributing to the duration and severity of individual extreme heat events in different parts of the City, posing significant health risks to the residents of various neighborhoods.

Using socioeconomic and census tract data for the entire city, the San Francisco Department of Public Health has developed a Heat Vulnerability Index to determine which neighborhoods have the highest concentration of residents at risk in excessive heat events. This index considers the following indicators: exposure to extreme heat, population sensitivity, and adaptive capacity. A map showing areas of vulnerability is shown in Figure 4-29). Neighborhoods with the greatest risk include Chinatown, SOMA, Tenderloin, Bayview/Hunters Point, and the Mission District. However, health impacts are anticipated for every neighborhood in the city.

[169] CalEPA, *Creating and Mapping an Urban Heat Island Index for California,* accessed September 21, 2018, *https://calepa.ca.gov/wp-content/uploads/sites/6/2016/10/UrbanHeat-Report-Report.pdf*

FIGURE 4-29
HEAT VULNERABILITY INDEX



Vulnerable Populations

Extreme Heat Health Vulnerability

- Some Health Impacts
- Most Health Impacts

Data Sources:
San Francisco Department of Public Health, Climate and Health Program (2019)

This map incorporates exposure, sensitivity, and adaptive capacity indicators to create a Heat Health Vulnerability Index. The index assesses which neighborhoods are most vulnerable to the health impacts of extreme heat

The purpose of the Index is to predict the distribution of health impacts in San Francisco. While this Index predicts certain neighborhoods to have a greater concentration of extreme heat health impacts, we anticipate health impacts in every neighborhood and all neighborhoods must prepare their vulnerable residents for these health impacts.

Severity and Probability of Future Events

Historically, San Francisco has experienced temperatures in excess of 85 degrees six to seven days per year, generally between May and October. Climate change is expected to increase the frequency and severity of extreme heat events. Since 1920, average annual temperatures have been increasing across California, including the San Francisco Bay Area. Average yearly temperatures are projected to increase between 1.3°F and 3.1°F by mid-century 3.3°F and 5.5°F by end-of-century compared to 2010. Annual extreme heat days are expected to increase from about six currently, to 15-40 by 2050, up to 90 per year by 2100. [170] Heat waves are similarly expected to increase in both frequency and severity.

[170] Scripps Institute of Oceanography, Cal-Adapt and California Nevada Applications Program. *Temperature: Extreme Heat Tool,* http://cal-adapt.org/temperature/heat/

Drought Hazard Profile

4.8 Drought

Impact Statement

California's Mediterranean climate is typified by dry summers followed by long, wet winters, thus making the state particularly susceptible to drought and flooding. The majority of San Francisco's water is brought to the city from the Hetch Hetchy watershed located in the Sierra Nevada Mountains through a complex series of reservoirs, tunnels, pipelines, and treatment systems.[171] As a result, changes in precipitation in the Sierra Nevada impacts the water supply in the Bay Area. Climate models project that a warming planet will lead to changes in precipitation distribution, including a reduced Sierra snowpack and earlier melting of the snowpack.[172]

Nature

The broad definition of drought is insufficient water over a prolonged time period. Drought condition indices typically consider the following factors: hydrological, meteorological, soil moisture, and applicable snowpack levels.[173] A drought occurs when there is a prolonged period of dryness in which precipitation is less than expected or needed in a given geographic location or climate over an extended period of time. In California, droughts typically occur in the winter, because winter is California's primary precipitation or wet season. During drought winters, the high-pressure belt that sits off the west coast of North America, and typically shifts southward during the season, remains stationary. As a result, Pacific storms that would normally approach the northern California coast are diverted elsewhere, depriving the Sierra Nevada mountain range of its normal winter storm activity and precipitation.

The San Francisco Bay Area and much of the state depend on spring runoff from the Sierra Nevada snowpack to replenish the water supply. Dry winters mean reduced snowpack. When dry winters occur over consecutive years, or when water demand increases beyond supply, drought is the result. Drought is a gradual phenomenon that may span multiple seasons and years.

[171] San Francisco Public Utilities Commission, "About Us: Overview", accessed September 28, 2018, https://sfwater.org/index.aspx?page=355
[172] Reich, KD, N Berg, DB Walton, M Schwartz, F Sun, X Huang, and A Hall, 2018: "Climate Change in the Sierra Nevada: California's Water Future." UCLA Center for Climate Science.
[173] California National Resources Agency. California's Fourth Climate Change Assessment: San Francisco Bay Area Region Report. Retrieved from: http://www.climateassessment.ca.gov/regions/docs/20180827-SanFranciscoBayArea.pdf (Accessed: 9/10/2018)

Drought is often measured in terms of its effect on crops, or in terms of its environmental impact, such as livestock deaths, wildfire, impaired productivity of forest land, damage to fish habitat, loss of wetlands, and air quality effects. Drought may also be measured by its social effects, including economic and physical hardship and increased stress on residents of a drought-stricken area. In San Francisco, the primary impact of drought is reduced availability of water for residential and commercial use.

History

California's Mediterranean climate is typified by dry summers followed by long, wet winters, thus making the state particularly susceptible to drought and flooding. According to the Climate Readiness Institute at UC Berkeley, 10-year droughts occurred across the west in previous millennia.[174] In modern history, droughts exceeding three years are relatively rare in northern California.[175] To date, San Francisco County has not been declared a Presidential disaster area as a result of drought. However, statewide droughts have been declared in 1976-1977, 1987-1992, 2008, and 2013-2016. In 2013, the United States Department of Agriculture declared the state a drought disaster area to provide relief for farmers and for the agriculture industry.

In the winter of 2013, California experienced record warmth and dryness with some locations in northern California experiencing 50 consecutive days with no measurable precipitation. Governor Jerry Brown issued a proclamation of emergency in January 2014 that ordered state agencies to take specific actions and called on Californians to voluntarily reduce their water usage by 20 percent[176].

In January 2014, the SFPUC called on its retail customers to reduce water use by at least 10 percent. In February 2014, Mayor Edwin M. Lee issued an executive directive requiring all City departments to develop individual water conservation plans and take immediate steps to achieve a mandatory 10 percent reduction in their water consumption. In August 2014, the SFPUC imposed a mandatory reduction of 10% on outdoor irrigation of ornamental landscapes or turf with potable water by retail

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[174] Climate Readiness Institute, *Bay Area Water Future* by William D. Collins, accessed 10 June 2015 http://climatereadinessinstitute.org/wp-content/uploads/2015/06/Collins-CRI-Water-Future.compressed.pdf
[175] California Governor's Office of Emergency Services, *2018 California State Hazard Mitigation Plan*, accessed http://www.caloes.ca.gov/for-individuals-families/hazard-mitigation-planning/state-hazard-mitigation-plan
[176] ibid

customers. Starting in July 1, 2015 the reduction was increased from 10% to 25%.[177] In response to these measures, single-family households reduced their water use by 16 percent compared to 2013.[178]

Early seasonal rain in the winter of 2014 helped alleviate some of the drought conditions, however, January 2015 was considered the driest January since meteorological records have been kept. Governor Brown signed emergency legislation to fast track more than $1 billion in funding for drought relief and critical water infrastructure projects. Despite record breaking summer heat, Californians continued to meet and surpass the Governor's 25 percent water conservation mandate, with a 31.3 percent reduction in July.[179]

Rain and snow levels in 2016 improved, but not enough to draw the state out of the drought. Moisture deficits across the state following the 2012-2016 drought had not been seen in the last 1,200 years and precipitated a 1 in 500 year low in the Sierra snowpack.[180] Fortunately, 2017 brought significant precipitation and the Governor ended the drought state of emergency on April 7, 2017 for all counties except Fresno, Kings, Tulare, and Tuolumne. Though the emergency declaration is over, water reporting requirements and prohibitions on wasteful practices such as hosing off sidewalks, and irrigating turf in public street medians remain in effect for all Californians. [181]

Although the severely dry conditions that afflicted much of the state starting in the winter of 2011-2012 are gone, damage from the drought will linger for years in many areas. The drought reduced farm production in some regions, killed an estimated 100 million trees, harmed wildlife and disrupted drinking water supplies for many rural communities.

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[177] San Francisco Public Utilities Commission, Water *Resources Division Annual Report Fiscal Year 2014-15,* accessed https://sfwater.org/modules/showdocument.aspx?documentid=8207
San Francisco Public Utilities Commission, Water *Resources Division Annual Report Fiscal Year 2015-16,* accessed https://sfwater.org/Modules/ShowDocument.aspx?documentid=9999
[179] California Governor's Office of Emergency Services, *2018 California State Hazard Mitigation Plan*, accessed http://www.caloes.ca.gov/for-individuals-families/hazard-mitigation-planning/state-hazard-mitigation-plan
[180] California National Resources Agency. California's Fourth Climate Change Assessment: San Francisco Bay Area Region Report. Retrieved from: http://www.climateassessment.ca.gov/regions/docs/20180827-SanFranciscoBayArea.pdf (Accessed: 9/10/2018)
[181] ibid

Location

Drought is not localized to San Francisco, but occurs simultaneously across the region, and may extend statewide or across a larger expanse of western states.[182] The majority of San Francisco's water is brought to the city from the Hetch Hetchy watershed located in the Sierra Nevada Mountains through a complex series of reservoirs, tunnels, pipelines, and treatment systems.[183] As a result, shortages in precipitation in the Sierra Nevada impacts the water supply in the Bay Area. Because so much of the city's water is generated from outside of the City, drought must be considered a regional hazard that is not confined to a single geographic area.

Severity and Probability of Future Events

Drought is difficult to measure due to its diverse geographical and temporal nature and its operation on many scales. Despite that difficulty, various indices for measuring and characterizing drought can be useful. The most commonly used are the Palmer Drought Indices (Palmer Z Index, Palmer Drought Severity Index, and Palmer Hydrological Drought Index) and the Standardized Precipitation Index. For example, the Palmer Index shows that San Francisco's climate division, the central coastal zone that extends south to San Luis Obispo, experienced severe drought conditions in April 2013 and had improved to near normal by April 2018 following two years of healthy precipitation. Despite the improved precipitation conditions in 2017 and 2018, it is unknown how long such a period may last or when another drought event may begin.

A significant body of climate research indicates that extended periods of drought followed by increased precipitation are more likely to occur in the future. A recent UCLA study indicates that such dry-to-wet precipitation events are projected to increase over the next century.[184] Long-term climate forecast models suggest that a warming planet will lead to changes in precipitation distribution, including a reduced Sierra snowpack and earlier melting of the snowpack.[185] With projected drier conditions and increasing

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[182] Association of Bay Area Governments, *San Francisco Bay Area Risk Profile 2017*, accessed http://resilience.abag.ca.gov/wpcontent/documents/mitigation_adaptation/RiskProfile_4_26_2017_optimized.pdf

[183] San Francisco Public Utilities Commission, "About Us: Overview", accessed September 28, 2018, https://sfwater.org/index.aspx?page=355

[184] Daniel Swain et.al, "Increasing Precipitation Volatility in Twenty-First-Century California", *Nature Climate* Change accessed September 28, 2018, https://www.nature.com/articles/s41558-018-0140-y

[185] Reich, KD, N Berg, DB Walton, M Schwartz, F Sun, X Huang, and A Hall, 2018: "Climate Change in the Sierra Nevada: California's Water Future." UCLA Center for Climate Science.

population, managing drought and water supplies in California may become more challenging.

Wildfire Hazard Profile

4.9 Wildfire

Impact Statement

Within San Francisco, a small portion of the Crocker Amazon neighborhood has been designated as a high fire hazard area. Moderate fire hazard areas in the city designated by the state include wooded areas such as Mounts Sutro and Davidson, as well as Yerba Buena Island. Significant portions of the Hetch Hetchy Regional Water System in San Mateo, Santa Clara, and Tuolumne Counties are also located in state-designated very high fire hazard areas. Though the probability of wildfires or wildland-urban interface fires within San Francisco is low, it remains high for areas outside the county where city-owned infrastructure is located. Global warming and lower precipitation rates due to climate change are expected to increase the risk of damaging fires in Northern California.

Nature

A wildfire is an unplanned, uncontrolled fire in an area of combustive vegetation or fuel.[186] Wildfires typically occur in forests or other areas with ample vegetation. Relatedly, Wildland-urban interface (WUI) fires are wildfires that spread into communities.[187] The WUI is an area where houses meet or are interspersed with undeveloped wildland vegetation.[188] In these areas, wildfires can cause significant property damage and may present an extreme threat to public health and safety.[189] Both wildfires and WUI fires can be caused by human activities, such as arson, campfires, or trees being blown into power lines, and by natural events such as lightning strikes.[190]

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[186] Judith R. Phillips, "Natural Disasters: On Wildfires and Long-Term Recovery of Community-Residing Adults," in *Traumatic Stress and Long-Term Recovery: Coping with Disasters and Other Negative Life Events*, Katie E. Cherry ed. (Switzerland: Springer International Publishing, 2015), 25.

[187] Samuel L. Manzello and Stephen L. Quarles, *Summary of Workshop on Structure Ignition in Wildland-Urban Interface (WUI) Fires*, National Institute of Standards and Technology (NIST) Special Publication 1198 (2015), 1, accessed May 30, 2018, https://nvlpubs.nist.gov/ nistpubs/SpecialPublications/NIST.SP.1198.pdf.

[188] V. C. Radeloff, et al., "The Wildland-Urban Interface in the United States," *Ecological Applications* 15, no. 3 (2005), 799, accessed May 30, 2018, https://www.nrs.fs.fed.us/pubs/jrnl/2005/nc_2005_radeloff_001.pdf.

[189] U.S. Department of Agriculture (USDA), *The 2010 Wildland-Urban Interface of the Conterminous United States*, Abstract, accessed May 31, 2018, https://www.fs.fed.us/nrs/pubs/rmap/rmap_nrs8.pdf.

[190] William M. Kramer, *Disaster Planning and Control* (Tulsa: PennWell Fire Engineering Books, 2009), 142.

The following three factors contribute significantly to wildfire behavior and can be used to identify wildfire or WUI fire hazard areas:[191]

- **Topography**: Topography is the shape of land, including its elevation or height above sea level; slope, or the steepness of the area; aspect, the direction a slope faces; and features such as canyons, valleys, and rivers. Topographical features can help or hinder the spread of fire. For example, the steeper a slope, the faster fire will travel up the slope. South-facing slopes are also subject to more solar radiation, making them drier and thus intensify wildfire behavior.
- **Fuel**: Fuels are combustible materials. The composition of vegetation or other fuel in the area, including moisture level, chemical makeup, and density, determines its degree of flammability. Dense or overgrown vegetation increases the amount of fuel for the fire. The ratio of living to dead plant matter is also important. Accelerated plant growth during rainy winter seasons can become particularly dried out during summer dry months contributing to fire risks as autumn winds fan small spot fires into potentially large firestorms[192]. The risk of fire increases significantly during periods of prolonged drought, as the moisture content of both living and dead plant matter decreases, where a disease or infestation has caused widespread damage, or where anthropogenic forest management practices have allowed fuel to build up.
- **Weather**: Weather Characteristics such as temperature, humidity, wind, and lightning impact the probability of ignition and spread of fire. Extreme weather, such as high temperatures and low humidity, can lead to extreme wildfire activity. In contrast, cooling and higher humidity often mean reduced wildfire occurrence and easier containment.

Even small fires can cause significant property damage and casualties. This is especially true in WUI areas where structures and other human development abut or intermingle with wildland vegetation and may also become fuel. The indirect effects of wildfires can

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[191] California Department of Forestry and Fire Protection (CAL FIRE) et al., *Living with Wildfire in Northwestern California*, 2nd ed. (2017), 13, accessed May 21, 2018, http://www.fire.ca.gov/HUU/downloads/Living_w-Wildfire_NW_CAL_April2017.pdf; National Park Service, "Wildland Fire - Learning In Depth: Wildland Fire Behavior," accessed May 31, 2018, https://www.nps.gov/articles/wildland-fire-behavior.htm.

[192] California National Resources Agency. California's Fourth Climate Change Assessment: San Francisco Bay Area Region Report. Retrieved from: http://www.climateassessment.ca.gov/regions/docs/20180827-SanFranciscoBayArea.pdf (Accessed: 9/10/2018)

also be disastrous. Besides stripping the land of vegetation and destroying forest resources, large, intense fires can harm the soil, waterways, and the land itself. Soil exposed to intense heat may lose its ability to absorb moisture and support life. Exposed soils erode quickly and enhance siltation of rivers and streams, which in turn enhances flood potential, harms aquatic life, and degrades water quality. In addition, because fires strip property of vegetation and root systems that normally retain soil, they increase a community's susceptibility to landslides and debris flows.[193]

History

The California Department of Forestry and Fire Protection (CAL FIRE) has no record of any wildfires or WUI fires occurring within San Francisco from 1943 through 2016, the period during which the agency has maintained statistics.[194] Given that San Francisco is a highly-urbanized area, CAL FIRE has also characterized the city as a low vegetative fuels hazard area.[195] However, wildfire and WUI fire do pose a risk for city-owned assets outside San Francisco's limits.

The Rim Fire, which began on August 17, 2013, in Tuolumne County, burned over 257,000 acres and threatened the Hetch Hetchy Regional Water System, which provides approximately 85 percent of San Francisco's total water needs. Though the Rim Fire reached the edges of the Hetch Hetchy Reservoir watershed, it did not impact water quality or water delivery operations. However, as of June 2017, the San Francisco Public Utilities Commission reported cumulative total expenses of approximately $23.8 million for facilities and infrastructure damage and costs related to emergency response due to Rim Fire damage.[196]

The City and County of San Francisco declared a local emergency due to the Rim Fire on August 22, 2013. The Governor of California issued a state emergency proclamation for

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[193] Daniel G. Neary, Kevin C. Ryan, Leonard F. DeBano, eds., *Wildland Fire in Ecosystems: Effects of Fire on Soil and Water*, General Technical Report RMRS-GTR-42, vol. 4 (Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, 2008) 51, 105, accessed May 31, 2018, https://www.fs.fed.us/rm/pubs/ rmrs_gtr042_4.pdf.

[194] See Cal FIRE, "Historical Wildfire Activity Statistics," accessed May 30, 2018, http://www.fire.ca.gov/ fire_protection/fire_protection_fire_info_redbooks.

[195] Cal FIRE Fire and Resource Assessment Program, "Characterizing the Fire Threat to Wildland-Urban Interface Areas in California," 4, accessed May 30, 2018, https://frap.fire.ca.gov/projects/wui/525_CA_wui_analysis.pdf.

[196] KPMG, "San Francisco Water Enterprise and Hetch Hetchy Water and Power: Statement of Changes in the Balancing Account, June 30, 2017," 18, accessed May 31, 2018, https://sfwater.org/modules/showdocument.aspx? documentid=12148.

the fire on the same day, and on August 23, 2013, submitted a request for a federal fire management assistance declaration. A Fire Management Assistance declaration, FEMA-5049-FM, was issued on the same day, making FEMA funding available to reimburse up to 75 percent of the eligible firefighting costs for managing, mitigating, and controlling the fire. On December 13, 2013, the President of the United States issued Major Disaster Declaration DR-4158 for the Rim Fire, making it possible to obtain federal Public Assistance for repairs or replacement of damaged public facilities, and to undertake hazard mitigation projects to reduce the long-term risk to life and property from future fires.[197] To date, approximately $23 million in Public Assistance grants have been made available to the state for the Rim Fire. Almost $18 million has been made available for emergency work; $3.6 million has been made available for permanent work.[198]

Wildfires and WUI fires need not occur within San Francisco to impact our jurisdiction. In early October 2017, smoke from wildfires and WUI fires in Napa, Sonoma, and Solano Counties in Northern California converged over San Francisco and other Bay Area counties. These fires introduced levels of particulate matter pollution that the Bay Area Air Quality Management District (BAAQMD) indicated were unprecedented for the Bay Area.[199] As a result, from October 9th through 18th, the BAAQMD issued a number of health advisories and "Spare the Air Alerts" urging residents and visitors to limit outdoor activities and reduce exposure to smoke by remaining inside with windows closed.[200] The poor air quality, coupled with high temperatures in the city, prompted San Francisco's officials to make a number of public libraries available as filtered-air sites for residents and visitors,[201] and to activate the city's Emergency Operations Center from

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[197] FEMA, Federal Aid Programs for the State of California, HQ-13-127 Factsheet (2013), accessed May 31, 2018, https://www.fema.gov/news-release/2013/12/13/federal-aid-programs-state-california-declaration.

[198] FEMA, California Rim Fire (DR-4158), accessed May 31, 2018, https://www.fema.gov/disaster/4158.

[199] Bay Area Air Quality Management District (BAAQMD), "Health Advisory, Spare the Air Alert," October 10, 2017, accessed June 4, 2018, http://www.baaqmd.gov/~/media/files/communications-and-outreach/publications/news-releases/2017/2017_092_staalert_healthadvisory_101017-pdf.pdf?la=en.

[200] See, e.g., BAAQMD, "Smoke Advisory," October 9, 2017, accessed June 4, 2018, http://www.baaqmd.gov/~/ media/files/communications-and-outreach/publications/news-releases/2017/smoke_171009-pdf.pdf?la=en; "Health Advisory, Spare the Air Alert," October 10, 2017, accessed June 4, 2018, http://www.baaqmd.gov/~/ media/files/communications-and-outreach/publications/news-releases/2017/2017_092_staalert_healthadvisory_ 101017-pdf.pdf?la=en.

[201] See San Francisco Department of Public Health, "Public Health Advisory," October 9, 2017, accessed June 4, 2018, https://sfdem.org/article/public-health-advisory.

October 9 to 14, 2017.[202] A 2018 survey of local air quality managers identified wildfires as the number one environmental event impacting air quality of districts' across the state[203]

Additionally, while voluntary, the regional mutual aid policy that the City has with surrounding counties means that even fires occurring outside of San Francisco proper has implications for our department's resource utilization. Mutual aid is intended to ensure that adequate resources, facilities, and other emergency support are provided to jurisdictions whenever their own resources prove to be inadequate to cope with a given situation at no charge to the receiving jurisdiction[204]. On July 23rd, the Carr Fire began in Shasta and Trinity County. Before being contained on August 30th it burned over 229,651 acres of wildland, caused the evacuation of 38,000 people, and required support from nearly every bay area county (including San Francisco) in the form of equipment and personal.[205]

Location

In 2007, pursuant to state law, CAL FIRE adopted Fire Hazard Severity Zone FHSZ maps for State Responsibility Areas (SRAs), the areas in California where the state is financially responsible for the prevention and suppression of wildfires. The maps use a fuel ranking assessment methodology that assigns a rank—moderate, high, or very high—based on expected fire behavior for unique combinations of topography and vegetative fuels under a given severe weather condition, including wind speed, humidity, and temperature.[206] CAL FIRE also has developed FHSZ maps for Local Responsibility Areas (LRAs) within California. LRAs include incorporated cities such as San Francisco, where fire protection is typically provided by a city fire department. The LRA fire hazard zone maps developed by CAL FIRE use an extension of the SRA FHSZ model, which

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[202] San Francisco Department of Emergency Management, *City and County of San Francisco Department of Emergency Management 2017 Annual Report*, 11, accessed June 4, 2018, https://sfdem.org/sites/default/files/ DEM_2017_Annual_Report.pdf.

[203] Julia A. Ekstrom & Louise Bedsworth (2018) Adapting air quality management for a changing climate: Survey of local districts in California, Journal of the Air & Waste Management Association, 68:9, 931-944, DOI: 10.1080/10962247.2018.1459325

[204] City and County of San Francisco Emergency Response Plan. ESF#4: Firefighting Annex. Retrieved from: https://sfdem.org/sites/default/files/FileCenter/Documents/25-ESF%204%20-%20Firefighting%20Annex.pdf

[205] San Francisco Examiner: Bay City News. "Bay Area fire departments help battle raging Carr Fire". Retrieved from: http://www.sfexaminer.com/bay-area-fire-departments-help-battle-raging-carr-fire/

[206] CAL FIRE, "Wildland Hazard and Building Codes, Fire Hazard Severity Zone Development," accessed May 31, 2018, http://www.fire.ca.gov/fire_prevention/fire_prevention_wildland_zones_development.

reflects flame and ember intrusion from adjacent wildlands and from flammable vegetation in urban areas.[207]

The current CAL FIRE hazard map indicates that San Francisco has no Very High Fire Hazard Severity Zones in its LRA. However, as shown in Figure 4-30, CAL FIRE has designated a small portion of the Crocker Amazon neighborhood as a high fire hazard area. Moderate fire hazard areas include wooded areas near Fort Funston and Lake Merced in the Stonestown District; Stern Grove in the Central Sunset District; Mount Davidson and Glen Canyon Park in the Miraloma and Diamond Heights neighborhoods; the Forrest Knolls and Midtown Terrace neighborhoods; wooded areas of Sutro Heights, Lincoln Park, the Presidio, and Fort Mason; and Bayview Park and Candlestick Point Recreation Area in the Bayview-Hunters Point Districts of San Francisco. Yerba Buena Island has also been designated by CAL FIRE as a moderate fire hazard area.[208]

City-owned infrastructure located outside San Francisco County are also located in areas that are susceptible to wildfire or to WUI fire. Among these facilities are significant portions of the Hetch Hetchy Regional Water System, including the Crystal Springs Reservoir and Watershed in San Mateo County, parts of which are located in or near a very high fire severity zone (VHFSZ); the Moccasin Powerhouse and Reservoir, Priest Reservoir, Kirkwood Powerhouse, Holm Powerhouse, and O'Shaughnessy Dam, in Tuolumne County, all of which are located in a VHFSZ; and the Calaveras Dam located in Alameda County, which is located in a high fire severity zone. For a map showing the Hetch Hetchy Regional Water System and fire severity zones, see Appendix B.

Extent and Probability of Future Events

Generally, it's difficult to attribute individual fire events to climate change but climate change can be expected to increase the susceptibility of the region to wildfires by altering vegetation growth rates and influencing the severity/length of each year's fire season. However, at the local scale, urbanization has a demonstrated influence on WUI fire hazards. As development is sited in previously uninhabited wildlands, more ignition events can be expected to occur. Conversely, as semi-dense areas increase density these areas can actually expect a reduction in the number of fire events. This implies

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[207] CAL FIRE, "Wildland Hazard and Building Codes, Fire Hazard Severity Zone Maps," accessed May 31, 2018, http://www.fire.ca.gov/fire_prevention/fire_prevention_wildland_zones.

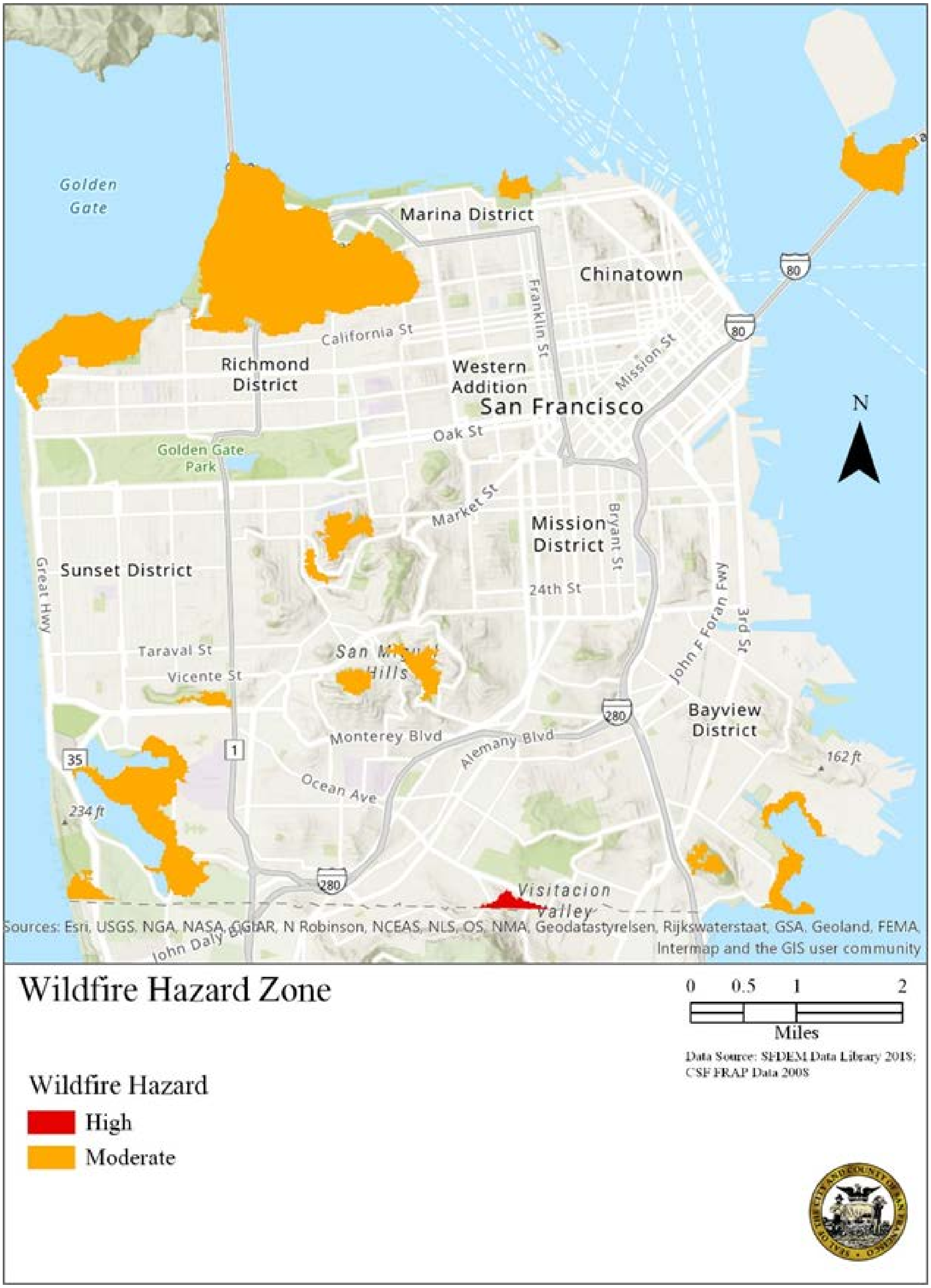
[208] CAL FIRE, "Wildland Hazard and Building Codes, San Francisco County FHSZ Map," http://www.fire.ca.gov/fire_prevention/fhsz_maps_sanfrancisco.

that land use considerations are essential for the city and region as they consider wildland/WUI fire hazards.[209] Figure 4-29, seen below, displays the extent of wildfire hazards in San Francisco. In general, the susceptibility for wildfires dramatically increases in the late summer and early autumn as vegetation dries out, decreasing plant moisture content and increasing the ratio of dead fuel to living fuel. Common causes of wildfires include arson and negligence. Though there is no historical record of a wildfire occurring in San Francisco, the impacts of climate change, including the probable increase in extreme heat days in the future, gives San Francisco a moderate risk of a future wildfire or WUI fire event. The probability of a future wildfire or WUI fire in out-of-county areas where city-owned assets are located is high.

Wildfire activity in California has increased over the past 10 years. This increase has been particularly severe in forested areas of the Sierra Nevada and Coast Ranges of Northern California. Researchers have attributed this increase to warmer spring and summer temperatures; lower precipitation rates; reduced snow pack and earlier snow melts; and longer, drier summer fire seasons in some middle and upper elevation forests. These trends are expected to continue under accepted climate change scenarios, leading to further increases in the risk of large, damaging wildfires in areas where city-owned infrastructure is located.[210]

[209] California National Resources Agency. California's Fourth Climate Change Assessment: San Francisco Bay Area Region Report. Retrieved from: http://www.climateassessment.ca.gov/regions/docs/20180827-SanFranciscoBayArea.pdf (Accessed: 9/10/2018)
[210] Anthony Westering and Benjamin Bryant, "Climate Change and Wildfire in California," *Climatic Change* 87 (2008), S231-232, accessed June 4, 2018, http://tenaya.ucsd.edu/~westerli/pdffiles/08CC_WesterlingBryant.pdf; see John T. Abatzogloua and A. Park Williams, "Impact of Anthropogenic Climate Change on Wildfire Across Western US Forests," *Proceedings of the National Academy of Sciences* 113, no. 42 (2016), 11770,11775, accessed June 4, 2018, http://www.pnas.org/content/pnas/113/42/.11770.full.pdf.

FIGURE 4-30
CITY AND COUNTY OF SAN FRANCISCO WILDFIRE HAZARD ZONE



Large Urban Fire Profile

4.10 Large Urban Fire

Impact Statement

Most of San Francisco is believed to have a moderate risk of large urban fires, but areas believed to be at greatest risk include the North Waterfront, South Beach, Mission Bay, Potrero Hill, Hunters Point, Civic Center, Downtown, Tenderloin, and Hayes Valley neighborhoods. The most likely cause of large urban fire in San Francisco is a severe earthquake (fire following earthquake), which has the potential to cause severe damage to buildings and infrastructure. When making decisions about capital projects, maintenance, operations, and investments in the City's fire fighting systems, the San Francisco Fire Department (SFFD), San Francisco Public Utilities Commission (SFPUC), and San Francisco Public Works (SFPW) utilize a model that reflects the fires that could arise after a 7.8 earthquake on the San Andres fault.

Nature

A Large Urban Fire is a large destructive fire that spreads across one or more city streets.[211] If not contained, a Large Urban Fire may expand uncontrollably beyond its original source location to engulf adjoining areas. Conflagrations can have many causes, including:[212]

- As secondary events to disasters such as earthquake (fires following earthquake), tsunami, flooding, and lightning strikes.
- Criminal acts, such as arson, acts of terrorism, or civil unrest;
- Residential accidents, including improper use of electrical and heating appliances, improper storage or handling of flammables, faulty connections, grease fires, misuse of matches and lighters, or improper disposal of charcoal and wood ashes;
- Industrial accidents, such as hazardous material incidents, explosions, and transportation accidents.

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[211] Introduction to *Fire Following Earthquake*, ed. Charles Scawthorn, John M. Eidinger, Anshel Schiff (Reston, VA: American Society of Civil Engineers, 2005), 1.

[212] William M. Kramer, *Disaster Planning and Control* (Tulsa: PennWell Fire Engineering Books, 2009), 138–140.

Fire following earthquake: The process by which an earthquake triggers fires and a community suppresses those fires consists of the following interrelated events[213]:

- Occurrence of the earthquake: earthquake shaking causes damage to buildings and contents, including knocking things over (such as candle or lamps.)
- Ignition: Ignition sources include overturned heat sources, gas-related sources, abrades and shorted electrical wiring, spilled chemicals, and friction of things rubbing together.
- Discovery: In the confusion following an earthquake, discovery may take longer than it would otherwise.
- Report: Communications system dysfunction may delay reports to the Fire Department.
- Response: In the aftermath of a damaging earthquake, the response of the Fire Department may be impeded by other emergencies the firefighters must respond to, such as building collapse.
- Suppression: Numerous factors, including water supply functionality, building construction type, building density, wind and humidity conditions, manpower and equipment deployed affect success of suppression.

History

San Francisco was devastated by six major fires during the California Gold Rush era, from 1849 to 1855.[214] These fires destroyed significant portions of the city, and thus are considered "great fires." The largest fire to affect San Francisco to date occurred as a result of the Great San Francisco Earthquake of 1906. On the morning of April 18, 1906, a Mw 7.8 earthquake shook the San Francisco Bay region. Within two hours of the quake, 52 fires had ignited within San Francisco. The fires quickly spread throughout the northeastern portion of the city, burning an area covering approximately 4.7 square miles, and destroying 80 percent of the 28,000 buildings lost due to the quake. The

[213] Applied Technology Council, 2017. “Study of Options to Reduce Post-Earthquake Fires in San Francisco.”
[214] Virtual Museum of the City of San Francisco, “Early History of the San Francisco Fire Department,” accessed May 29, http://guardiansofthecity.org/sffd/history/volunteer_department.html.

1906 earthquake severely damaged the city's water system, limiting firefighters' ability to suppress the fires.[215]

Construction of San Francisco's Auxiliary Water Supply System (AWSS), now referred to as the Emergency Firefighting Water System (EFWS), was completed in 1913 with the goal of avoiding such devastation in the aftermath of another earthquake. The city also has developed a Portable Water Supply System (PWSS) as a backup to the EFWS and the Municipal Water Supply System. The PWSS consists of a hose tender, large-diameter hose, portable hydrants, pressure reducing valves, and other fittings, allowing the Fire Department to pump water from San Francisco Bay, from underground cisterns positioned around the city, or from other bodies of water.[216] When making capital project, maintenance, and operational decisions, the SFFD, SFPUC, and SFPW utilize a model that reflects the large urban fire that could arise after a 7.9 earthquake on the San Andres fault. Over the past decade, the city has undertaken a major effort to upgrade the Emergency Firefighting Water System.[217]

Working together, the SFFD, SFPUC, and SFPW have completed the following in the past 8 years:

- 95% completion of the $4.8 billion Water System Improvement Program (WSIP), providing robust seismic upgrades to the pipelines, reservoirs, and infrastructure that supply water to San Francisco and the EFWS (the SFPUC's Regional Water System is the primary source of water for the EFWS);
- Added a larger pipe to increase the speed of re-filling the Twin Peaks EFWS reservoir from the 11-million-gallon Summit Reservoir;
- Connecting the 70-million-gallon South Basin of the University Mound Reservoir to EFWS (expected completion in 2018);
- Replaced the engines and installed remote control capabilities for Seawater pump station #1 to allow for remote operation;

[215] Charles Scawthorn, Thomas D. O'Rourke, and Frank T. Blackburn, "The 1906 San Francisco Earthquake and Fire—Enduring Lessons for Fire Protection and Water Supply," *Earthquake Spectra* 22, no. S2 (2006), S135–S139.

[216] Scawthorn, O'Rourke, and Blackburn, "The 1906 San Francisco Earthquake and Fire—Enduring Lessons for Fire Protection and Water Supply," S150–S151.

[217] San Francisco Public Utilities Commission, "Emergency Firefighting Water System," accessed May 29, 2018, https://sfwater.org/index.aspx?page=467.

- Installation of 30 new cisterns (with 15 of these cisterns installed in the Sunset and Richmond districts);
- Reliability upgrades at the three primary source supplies – Twin Peaks Reservoir, Ashbury Heights Tank, and Jones Street Tank;
- Completion of 6 pipeline and tunnel projects;
- Motorizing critical seismically-reliable valves for remote control, and improving the electronic control system of the valves; and
- Began structural and seismic upgrades of Seawater pump station #2 (expected completion in 2020);
- Began designing the installation of the Potable EFWS to provide high-pressure fire suppression for the Westside of San Francisco;
- Began designing the installation of a pump station at Lake Merced to feed into the Potable EFWS; and
- Began investigating the installation of a seawater pump station at Ocean Beach to serve as a secondary source of water for fire suppression for the Westside.

San Francisco's most recent large urban fire incident occurred as a result of the Loma Prieta earthquake on October 17, 1989. A total of 41 fires were reported in San Francisco following the Loma Prieta earthquake; 27 of the 41 fires occurred within seven hours of the quake.[218] Of the 41 fires, 14 were due to electric wiring and equipment, 11 resulted from gas or electric stoves, and four were caused by water heaters or other gas appliances.[219] The largest fires occurred in the Marina District, resulting in the destruction of four buildings. The Fire Department utilized the fire boat Phoenix and the PWSS to prevent the Marina fire from becoming a conflagration. The Fire Department also relied on the AWSS to fight the Marina District fires, but water main breaks in the system several miles from the fires impaired its functionality.[220] The

[218] Jamshid Mohammed, Sam Alyasin, D. N. Bak, *Investigation of Cause and Effects of Fires Following the Loma Prieta Earthquake*, National Science Foundation Report IIT-CE-92-01 (1992), 4, 19, accessed May 29, 2018, https://nehrpsearch.nist.gov/static/files/NSF/PB93120046.pdf

[219] Ibid.

[220] Scawthorn, Eidinger, and Schiff, eds., *Fire Following Earthquake*, 29–31.

Fire Department reported fire losses due to the earthquake of over $10 million,[221] or $19.1 million in 2018 dollars.

Table 4-30 below shows the number of actual working fires and greater alarms that the San Francisco Fire Department has responded from 2008 through 2017. During this 10-year period, there were four five-alarm fires, and 16 four-alarm fires.

TABLE 4-30:
SAN FRANCISCO WORKING FIRES AND GREATER ALARMS, 2008-2017[222]

YEAR	Alarm Level 1	Alarm Level 2	Alarm Level 3	Alarm Level 4	Alarm Level 5	TOTAL
2008	278	24	4	1		**307**
2009	213	13	8	1		**235**
2010	208	14	2	1		**225**
2011	217	20	6	2	1	**246**
2012	166	27	4	6		**231**
2013	216	21	6	1		**244**
2014	188	12	7		2	**209**
2015	164	20	4	2		**190**
2016	155	13	3	1	1	**173**
2017	157	20	1	1		**179**

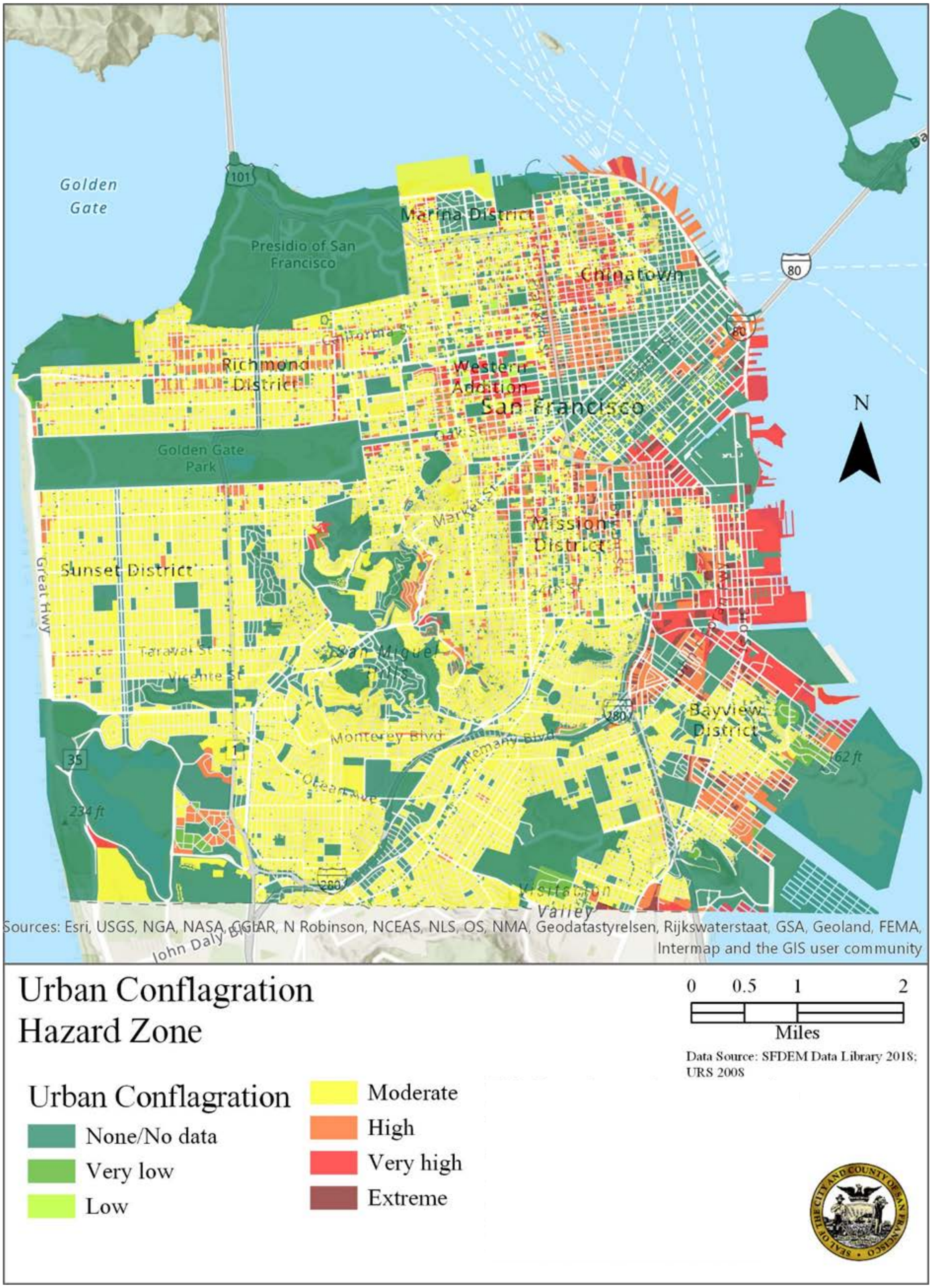
[221] Virtual Museum of the City of San Francisco, "Report on the Operations of the San Francisco Fire Department Following the Earthquake and Fire of October 17, 1989," Introduction, accessed May 29, 2018, http://www.sfmuseum.net/quake/report.html.

[222] San Francisco Fire Department 2018

Location

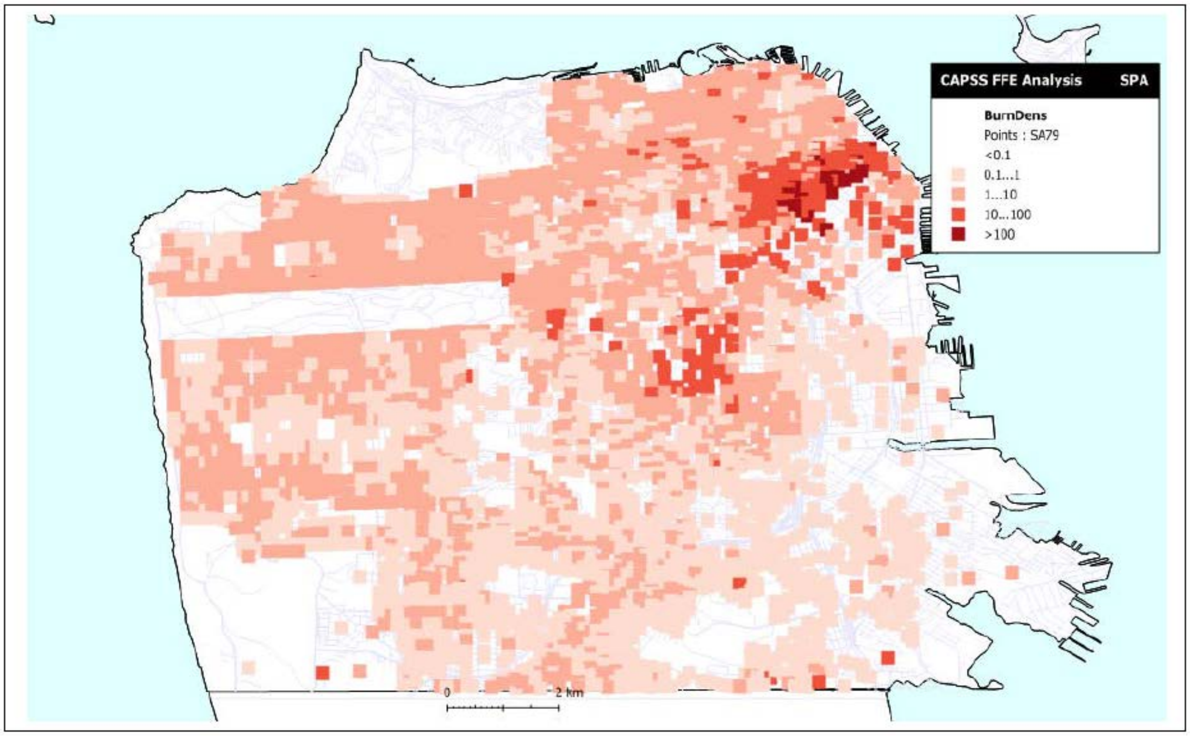
Figure 4-31, seen below, shows large urban fire hazard areas for all parts of the city for which Assessor parcel data is available. This model considers building construction material, land use, and structural age. For construction material, wood frame structures were assumed to be more vulnerable to conflagration than other structure types. Similarly, commercial and industrial land uses were calculated as a higher risk of large urban fires. Finally, older structures were assumed to have a high conflagration risk, as they pre-date modern fire codes. Areas within San Francisco believed to be at greatest risk for large urban fire include the North Waterfront, South Beach, Mission Bay, Potrero Hill, Hunters Point, Civic Center, Downtown, Tenderloin, and Hayes Valley neighborhoods.

FIGURE 4-31
LARGE URBAN FIRE HAZARD ZONES



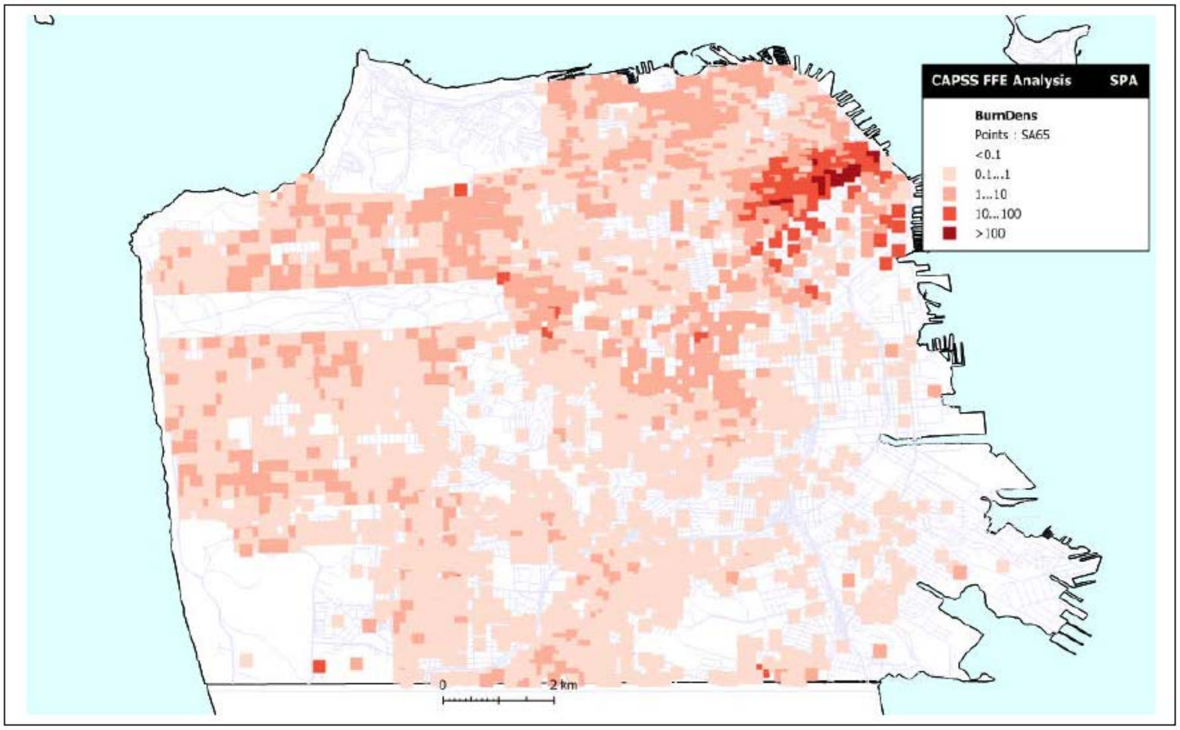
Fire following earthquake: In 2010, the Community Action Plan for Seismic Safety (CAPSS) Program produced a detailed study of the scope of the city's fire following earthquake hazard and risk. Figures 4-32 and 4-33 illustrate the geographic distribution of potential building losses (in 2010 dollars) due to fire following earthquake.

FIGURE 4-32: DISTRIBUTION OF BURN DENSITY PER BLOCK (MILLIONS $) IN 7.9 SAN ANDREAS SCENARIO[223]



[223] Scawthorn, 2010. "Analysis of Fire Following Earthquake Potential for San Francisco, California."

FIGURE 4-33: DISTRIBUTION OF BURN DENSITY PER BLOCK (MILLIONS $) IN 6.9 HAYWARD FAULT SCENARIO[224]



Severity and Probability of Future Events

Given the 72 percent chance of a magnitude 6.7 or greater earthquake in the San Francisco Bay Area between 2014 and 2044,[225] the most likely scenario leading to large urban fire in San Francisco is a severe earthquake in the Bay Area, particularly on the North San Andreas Fault zone. Because San Francisco's building stock is composed predominantly of wood, the fires resulting from such earthquakes may cause far more damage. Based on a detailed study of the scope of the city’s fire following earthquake risk, an estimated 68-120 ignitions may occur in a 7.9 earthquake on the San Andreas fault resulting in an estimated $4.1 - $10.3 billion in losses. An estimated 27-68 ignitions may occur due to a 6.9 earthquake on the Hayward fault, resulting in an estimated $1.3 - $4.0 billion in damages.[226]

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[224] Ibid

[225] Edward H. Field and 2014 Working Group on California Earthquake Probabilities (WGCEP), *UCERF3: A New Earthquake Forecast for California’s Complex Fault System,* Fact Sheet 2015–3009 (2015), 4, accessed May 18, 2018, https://dx.doi.org/10.3133/fs20153009.

[226] Applied Technology Council, 2017. “Study of Options to Reduce Post-Earthquake Fires in San Francisco.”

Based on the working fire and greater alarm statistics set forth in Table 5-9 above, during the ten-year period from 2008 through 2017, the San Francisco Fire Department responded to an average of 224 actual working fires per year. During this same period, there were approximately four single-alarm fires every week. Larger fires—two-alarms or greater—occurred an average of 25 times annually. It is also noteworthy that the total number of actual working fires has steadily fallen from 307 in 2008 to 179 in 2017, a decrease of 42 percent.

For discussion of wildfire and wildland-urban interface fires, see the Wildfire Hazard Profile.

High Wind Profile

4.11 High Wind

Impact Statement

Although San Francisco experiences winds throughout summer, especially in the afternoon and early evening, the most disruptive “high winds” occur either with strong storms in the winter or spring, or in late fall as part of the warm “Diablo winds”. Storm-related wind can down trees or power lines and contribute to electrical outages. When these storm-related winds hit 100mph along the coast or at higher elevations, they may become hazardous, especially for big rig trucks on bridges. The “Diablo winds” can stoke fires in nearby counties and transport smoke to San Francisco. Winds year-round can transport pollens and contribute to allergies.

Nature

Winds are horizontal flows of air that blow from areas of high pressure to areas of low pressure. Wind strength depends on the difference in pressure between the high- and low-pressure systems and the distance between them. A steep pressure gradient results from a large pressure difference or short distance between these systems, causing high winds.

The National Weather Service (NWS) defines “high winds” as sustained wind speeds of 40 miles per hour (mph) or greater lasting for one hour or longer, or winds of 58 mph or greater for any duration. The NWS issues a wind advisory when there are sustained winds of 25 to 39 mph, or gusts to 57 mph. A wind storm is an incident exceeding those values as measured by weather observation equipment, or as indicated by damage consistent with such wind speeds.

During the summer months in San Francisco, temperature and pressure differences between the Pacific Ocean and the interior valleys of California create strong afternoon and evening sea breezes. These westerly winds flow across the Golden Gate and through breaks in the high terrain of the Coast Range, often reaching afternoon speeds of between 20 and 30 mph. Normally, San Francisco’s hilly terrain breaks up strong winds, but occasionally strong storms with significant wind gusts halt normal activity in the city, and cause widespread power line damage and electrical outages due to toppled trees and broken limbs.

In addition, the typical summer weather pattern of cooler, more humid air flowing in an easterly direction from the ocean to inland areas reverses. These hot, dry offshore winds from the northeast, which typically occur in the Bay Area during the spring and fall, are known as “Diablo winds.” Diablo winds can be quite strong, with gusts up to 40 mph. Diablo winds are most common in the fall when the jet stream dips farther south, and alternating areas of high and low pressure affect California. Fall is also the time of year when wildlands and the urban-wildland interface are particularly dry. Dry land cover, when combined with hot dry Diablo winds, may result in high fire danger. This was the meteorological scenario leading to the Oakland Hills firestorm in October 1991 and the North Bay fires in 2017.

History

In San Francisco, high winds associated with cyclonic systems and their cold fronts occur in the winter, generally between the months of November through March (refer to Table 4-34). On average, there have been 1.2 wind storm events per year. Data from the Golden Gate Weather Service on some of the larger, more recent, high wind storm events in San Francisco is presented in Table 4-35 below. NOAA’s National Climatic Data Center has recorded 83 significant wind storm incidents in the San Francisco region from 1948 through 2017 as measured by wind gusts above 58 mph.[227] During these events winds predominantly blew from the south and west (refer to Table 4-36).

TABLE 4-34
HIGH WIND EVENTS BY MONTH, 1948-2017[228]

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
Count of Events	16	14	6	7	3	4	0	0	0	5	8	20
Pct. of Events	19%	17%	7%	8%	4%	5%	0%	0%	0%	6%	10%	24%

[227] These events were observed at NOAA’s San Francisco International Airport Station. Wind data from San Francisco proper was not available.
[228] Based on observations from San Francisco International Airport Station
Source: National Centers for Environmental Information, NOAA. 2018. Accessed June 15, 2018

TABLE 4-35
SELECT HIGH-WIND EVENTS[229]

	Dec. 22, 1955	Oct. 12, 1962	Mar. 31, 1982	Dec. 22, 1982	Dec. 12, 1995	Dec. 16, 2002	Jan. 4, 2008	Oct. 13, 2009	Jan. 8, 2017
San Francisco 24-Hour Rain Total	2.57"	3.11"	2.57"	2.00"	3.27"	2.07"	2.01"	2.48"	1.62”
SFO Maximum Sustained Wind	42 mph	43 mph	47 mph	47 mph	54 mph	43 mph	53 mph	41 mph	44 mph
Peak Bay Area Wind	90 mph	86 mph	81 mph	100 mph	103 mph	91 mph	87 mph	77 mph	77 mph

TABLE 4-36
HIGH WIND EVENTS BY WIND DIRECTION, 1948-2017[230]

Wind Direction (degrees)	Northerly-north to south (316-365, 0-45)	Easterly-east to west (46-135)	Southerly-south to north (136-225)	Westerly-west to east (226-315)
Count of Events	0	1	58	22
Percentage	0%	1%	70%	27%

Location

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229 Golden Gate Weather Services, Bay Area Storm Index [http://ggweather.com/basi_archive.htm]
230 Based on observations from San Francisco International Airport Station
Source: National Centers For Environmental Information, NOAA. 2018. Accessed June 15, 2018

San Francisco as a whole is subject to strong southeasterly winds associated with powerful winter cold fronts. However, strong sea winds from the Pacific Ocean generally have a greater impact on the west side of San Francisco. Each year, at least one winter storm typically results in closure of the Great Highway, when wind gusts deposit large amounts of sand on the roadway. The Great Highway runs along the Pacific Ocean on the western boundary of San Francisco through the Outer Sunset and Outer Richmond Districts.

Severity and Probability of Future Events

Storms combining strong winds with heavy rain have the largest impact on San Francisco during the winter months. Wind gusts of 40 mph have the potential to bring down trees and branches and to trigger power outages leaving thousands of people without electricity. Based on previous wind events, San Francisco can continue to expect to experience at least one winter wind storm annually.

Sustained winds of more than 50 mph have been recorded in San Francisco during various Pacific Storms. During isolated storm incidents, gusts may peak at more than 100 mph along the coast and at higher elevations. In such conditions, Bay Area bridges become hazardous, especially for big rig trucks that may overturn on bridges during high wind events.

Climate change is expected to modify San Francisco's wind, the extreme storms that generate the most severe winds, and the impact of wind on San Francisco. While climate scientists project climate change to generally reduce wind in the United States, the pineapple-express extreme storms that generate the most severe wind in the San Francisco Bay Area are expected to increase in both frequency and severity[231]. Similarly, there is some evidence that climate change will lengthen the "Diablo winds" fire season[232]. Additionally, drought-like conditions may impact San Francisco's urban forest and make trees more vulnerable to winds.

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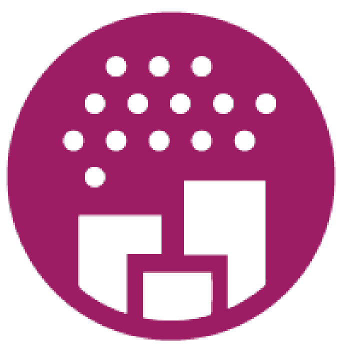
[231]Kristopher Karnauskas, Julie Lundquist, and Lei Zhang (2018) Southward shift of the global wind energy resource under high carbon dioxide emissions. *Nature Geoscience, 11,* 38-43.
[232] Henry Fountain, "California winds are fueling fires, It may be getting worse", *New York Times,* accessed October 11, 2017, https://www.nytimes.com/2017/10/11/climate/caifornia-fires-wind.html.

Poor Air Quality Profile



4.12 Poor Air Quality

Impact Statement

Air quality is closely associated with public health. Exposure to pollutants increases rates of allergies, bronchitis, asthma attacks and other respiratory illnesses, heart disease and other cardiovascular illnesses, and is an environmental risk factor connected to premature birth and low birth weight, mental health conditions, and many cancers. Although all together San Francisco enjoys clean air relative to other urban areas in the country, current air pollution is not evenly distributed. In San Francisco, air pollution is influenced by proximity to freeways and other high-density arterials, industrial activity, and maritime activity. San Francisco is also vulnerable to air quality impacts of wildfires. Although it is unlikely a wildfire occurs within San Francisco's city limits, smoke from wildfires elsewhere may be transported into the City and significantly impact San Francisco's air quality.

Nature

The Air Quality Index (AQI) measures air quality for the five pollutants regulated by the Clean Air Act: ground-level ozone, particulate matter, carbon monoxide, sulfur dioxide, and nitrogen dioxide[233].

- **Ground-level ozone** is created through a chemical reaction between sunlight, nitrogen oxide, and volatile organic compounds (VOCs), which are chemicals emitted from cleaning supplies, glues, paints, pesticides, and other household materials. Ground-level ozone is the main ingredient of smog.
- **Particulate matter (PM)** includes vehicle emissions and other fuel combustion, smoke from fireplaces or wildfires, dust, molds, and pollens. Particulate matter is organized by size, as emissions tend to be fine PM (<2.5 micrometers in diameter), while dusts, molds, and pollens tend to be coarse (<10 micrometers in diameter).
- **Carbon monoxide** is an odorless gas byproduct of combustion and is released by the burning of gasoline, kerosene, oil, propane, coal, and wood.

[233] https://airnow.gov/index.cfm?action=aqibasics.aqi

- **Sulfur dioxide** is a gas byproduct of industrial activities that involve the burning of materials that contain sulfur such as coal, oil, and gas. Sources of sulfur dioxide include power plants and other industrial activities.

- **Nitrogen dioxide** is another byproduct of the burning of fossil fuels and is largely emitted from cars, trucks, and power plants.

The AQI provides each pollutant a score 0 – 500. A score of 100 approximates the federally set EPA National Ambient Air Quality Standards (NAAQS). The AQI is presented as the highest score of the 5 pollutants. San Francisco generally enjoys good air quality as a dependable ocean breeze regularly dissipates pollution. However, when coastal high-pressure systems or inversion layers trap pollutants, San Francisco can experience short-term spikes in AQI.

History

According to data supplied by the Bay Area Air Quality Management District (BAAQMD), San Francisco enjoys good air quality a majority of the year, with AQI rarely above national standards. This data can be found in Table 4-37 below. Because there is only one air quality station in San Francisco, AQI measurements do not take into account AQI variation throughout the City, and homes adjacent to high-density arterials, industrial uses, or maritime uses may have AQIs significantly higher than those reported below.

In 2018, a wildfire in Butte County coincided with the westward “Diablo Winds” and funneled wildfire smoke south and west through the delta into the San Francisco Bay. A high-pressure system off the coast blocked San Francisco’s normal ocean breezes and trapped the wildfire smoke in the Bay Area. San Francisco’s AQI was over 150 for 12 straight days, peaking at 228. This wildfire smoke emergency caused significant disruption as schools were canceled. It is likely that the wildfire smoke emergency impacts were not evenly distributed as residents with access to air filtration were less exposed to wildfire smoke.

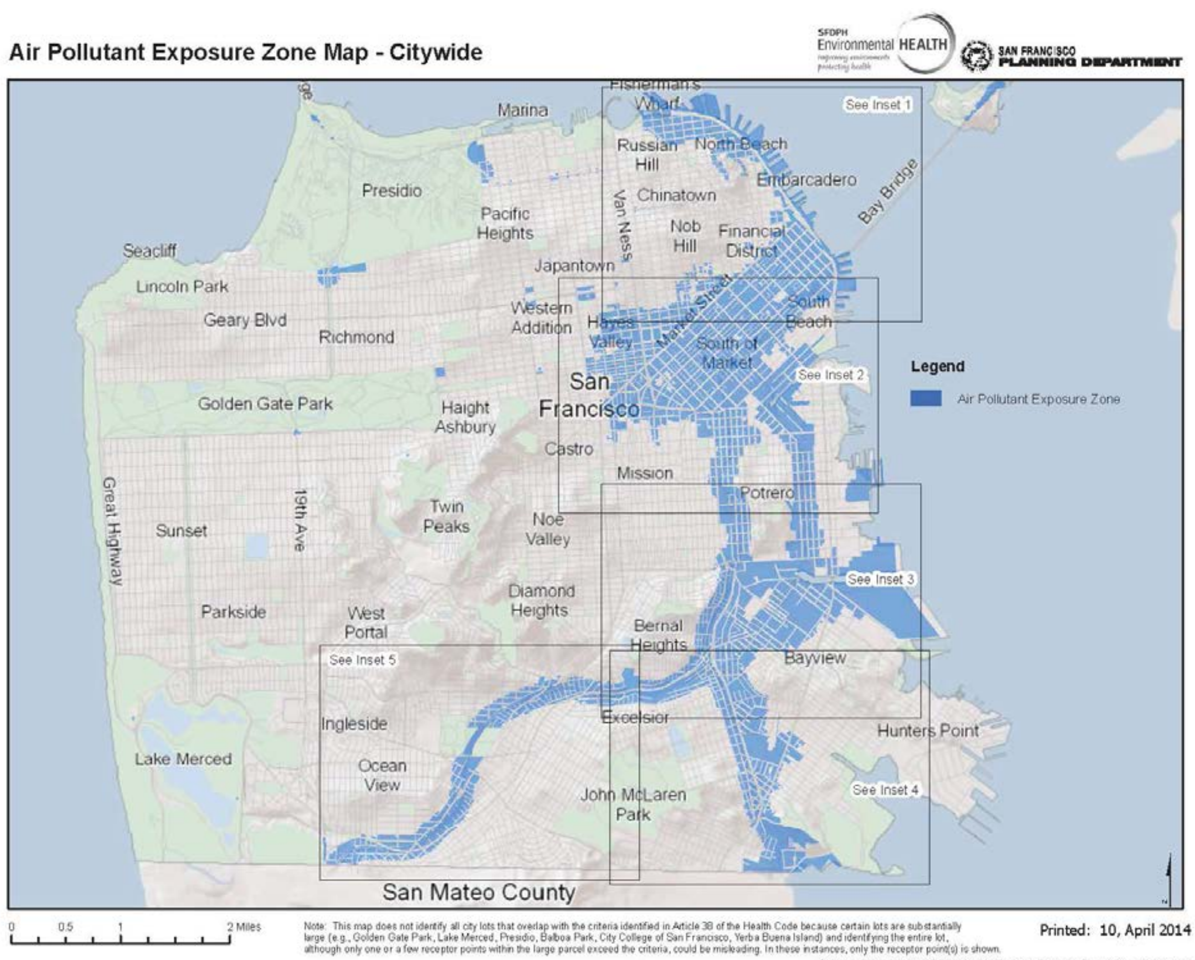
TABLE 4-37
SAN FRANCISCO AIR QUALITY INDEX (AQI)

San Francisco	Total Days	Good	Moderate	Unhealthy for Certain Groups	Unhealthy	Very Unhealthy
Year		0 - 50	51 - 100	101 - 150	151 - 200	200 - 300
2018	360	272	74	2	11	1
2017	365	276	82	7		
2016	365	310	55			
2015	365	300	65			
2014	365	309	56			
2013	364	254	109	2		
2012	361	291	68	2		
2011	365	252	111	2		
2010	365	249	113	3		
2009	365	196	164	5		
2008	366	223	140	3		
2007	365	281	79	5		
2006	363	264	95	4		
2005	365	288	70	7		
2004	366	243	116	7		
2003	365	294	66	5		
2002	365	273	71	14	7	
2001	365	291	61	10	3	
2000	366	277	83	6		

Location

In 2014, BAAQMD, the San Francisco Planning Department, and the San Francisco Department of Public Health identified neighborhoods most exposed to air pollution. The Air Pollution Exposure Zone (Figure 4-38) identifies air pollution exposure based on cancer risk, PM2.5 concentration and proximity to freeways and other high-density arterials. New construction in the air pollution exposure zone is regulated under Article 38 and is required to have adaptive infrastructure and safe construction practices to protect against the health impacts of air pollution. According to the air pollution exposure zone map, neighborhoods particularly impacted by air pollution include Bayview/Hunters Point, SOMA, Central Market/Tenderloin, and the Financial District.

FIGURE 4-38
ARTICLE 38 CITYWIDE MAP



Severity and Probability of Future Events

While San Francisco's air quality will remain above current EPA standards, climate change is likely to increase concentrations of both ground-level ozone and $PM_{2.5}$ which will increase morbidity and mortality in San Francisco.

- Climate change is expected to exacerbate yearly fluctuations in precipitation. During especially dry years, drought can impact air quality. The 2011-2016 drought contributed to the deaths of an estimated 66 million trees in the Sierra Nevada forests. Future droughts will have similar impacts and create conditions for more frequent and intense wildfires[234].

- PM is likely to be impacted by climate change. PM levels are strongly affected by local weather patterns such as precipitation, wind speed, and vertical mixing. Increased mixing height, or the height of the air layer closest to the ground, and wind speeds have been shown to significantly reduce PM concentrations. However, atmospheric stagnation, characterized by low wind speeds and little vertical mixing, has been shown to be correlated with increased PM levels in Canadian cities[235], and is predicted to increase regionally as a result of modern climate change.

- Temperature increases are also expected to alter the growing season for allergen-producing plants.

- As climate change increases temperatures, hot and dry temperatures will accelerate the creation of ground-level ozone.

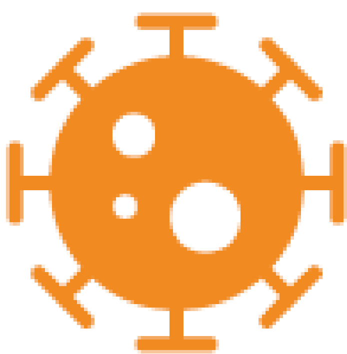
Additionally, the largest increases in ozone levels from climate change will also occur in areas where ozone is already high, meaning that those same communities that are affected most by current pollution will also suffer the worst of the changes. So, while the research suggests that average increases in ozone and PM levels will be relatively small,

[234] USDA Office of Communications *Forest Service Survey Finds Record 66 Million Dead Trees in Southern Sierra Nevada.* U.S. Forest Service. https://www.fs.fed.us/news/releases/forest-service-survey-finds-record-66-million-dead-trees-southern-sierra-nevada

[235] Cheng, C. S. (2005). *Differential and combined impacts of winter and summer weather and air pollution due to global warming on human mortality in south-central canada.* (No. 6795-15-2001/4400011). Toronto, CAN: Toronto Public Health.

it is also clear that the impact of those increases will not be evenly distributed and can have significant effects on vulnerable populations.

Pandemic Hazard Profile



4.13 Pandemic

Impact Statement

The probability for a naturally occurring moderate outbreak of pandemic influenza is considered high. Throughout the last century, there have been five influenza pandemics of varying severity, and a future pandemic is a near certainty. Daily impacts of moderate to severe flu will primarily impact human health, health services, and public health systems. It must be noted that the cumulative impact will likely be much more significant, as influenza pandemics typically last 6-12 weeks.[236] Currently, little is known about the potential impact of climate change on future pandemics.

Pandemics severely strain the healthcare system by causing prolonged patient surge. Because of their frequency, duration, and scale, pandemics are one of the greater public health threats to the City and County of San Francisco; this threat has only increased with the rise in population density and international travel.

Nature

A pandemic is an epidemic of an infectious disease occurring worldwide, or over a very wide area, which crosses international boundaries and affects a large number of people. Pandemic influenza is one of the most pressing public health planning needs today. Even with a "moderate" pandemic, the cumulative effect on health and health care would be dire. For example, the 1918 "Spanish Flu," which had a 30 percent attack rate and a 2 percent case fatality rate, was defined by the Center for Disease Control (CDC) as a moderate event.

Pandemics are hazards that have a long duration. Though daily impacts may be low, cumulative impacts are likely to be overwhelming for both the health system and the community. During a moderate pandemic, San Francisco could see a sustained increase in intensive care unit admissions, in emergency department (ED) admissions, in patients needing to be placed in respiratory isolation, and in deaths. Capacity to provide medical care, including basic emergency medical system (EMS), hospital ED services, and isolation rooms, will be reduced. At the same time, a higher than usual absenteeism rate for all employees is expected. It is estimated that there would be an 18 percent

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[236] San Francisco Department of Public Health, Public Health and Medical Hazard Risk Assessment (2013), *Internal Document*.

decrease in workers secondary to being ill with the flu, with effects compounded over time. This would have dramatic consequences both for the health care system and for the community in general.[237]

Compared to the 1918 pandemic event, an influenza pandemic today could have far-reaching, negative consequences for the health and well-being of San Francisco's residents and for the economic and social stability of the Bay Area. Our population includes more elderly than it did in the past. Our ability to respond effectively to a pandemic is also limited. Our health care system today has little surge capacity. "Just-in-time" ordering of needed supplies has replaced the warehousing of critical items onsite for most businesses and governmental organizations. In addition, unlike citizens in 1918, we are not accustomed to following government restrictions such as the rationing of goods and services.

History

There have been five pandemics since 1900; the 2009 H1N1 Pandemic is the most recent. From April 12, 2009 to April 10, 2010, CDC estimated that between 151,700 and 575,400 people worldwide died from 2009 H1N1 virus infection during the first year the virus circulated. Additionally, CDC estimated that 80 percent of (H1N1)pdm09 virus-associated global deaths were in people younger than 65 years of age, which differs from typical seasonal influenza epidemics during which about 70 percent to 90 percent of deaths are estimated to occur in people 65 years of age and older. In the United States estimates included 60.8 million cases, 274,304 hospitalizations, and 12,469 deaths due to the (H1N1)pdm09 virus. In San Francisco, 208 hospitalizations and 60 intensive care unit (ICU) or fatal cases were reported during the 2009 H1N1 Pandemic.

Because pandemics are recurring events, it is not a question of whether there will be another pandemic; the question is when the next pandemic will occur and how severe it will be. Previous pandemics occurred in 1918-1920, 1957-1958, 1968-1969, 1977-1978, and 2009-2010. The 1918-1920 Pandemic, often referred to as the Spanish Flu, was unusually severe and had a high mortality rate. It is estimated that the 1918 Pandemic killed up to one percent of the world's population, or 40,000,000 people worldwide, including more than 500,000 in the United States.

[237] San Francisco Department of Public Health, Public Health and Medical Hazard Risk Assessment (2013), Internal Document., Public Health and Medical Hazard Risk Assessment (2013), *Internal Document*.

Location

By definition, a pandemic is a global event; San Francisco as a major center for domestic and international tourism and business would expect to be significantly affected by a pandemic flu. The World Health Organization (WHO) classifies pandemics according to phases. Phase 1 starts with the virus circulation among domesticated or wild animals prior to human infection. Additional phases coincide with community level outbreaks in multiple countries in multiple WHO regions, culminating with Phase 6. A Phase 6 Pandemic involves a virus that is widespread, with human-to-human transmissibility.

Since travelers and residents are free to travel throughout the city, it is anticipated that from a hazard mitigation perspective, San Francisco will be uniformly affected geographically. However, based on the actual pandemic virus, certain populations within San Francisco may have different morbidity and mortality than the general population. In general, the following groups tend to be at higher risk for seasonal influenza complications: individuals with specific chronic medical conditions; children younger than five years old, with children younger than two at special risk; adults 65 years of age and older; pregnant women; American Indians; and Alaskan Natives.

Severity and Probability of Future Events

Based on the Bay Area Regional Risk Assessment conducted in 2013, the probability of a naturally occurring, mild to moderate pandemic affecting San Francisco is considered high. In many respects, the City and County of San Francisco is more vulnerable to a pandemic today than it was in 1918. Population density in the city is higher than in 1918, and people in the Bay Area travel more internationally and come into contact with far more people on a daily basis than did people in 1918.

The extent of a pandemic depends on the actual virus involved. The 2009 H1N1 Pandemic was generally considered mild, with a very low case fatality rate; it is estimated that 0.001 percent to 0.007 percent of the world's population died of respiratory complications associated with the (H1N1)pdm09 virus infection during the first 12 months the virus circulated. In contrast, the 1918 Pandemic had a higher case fatality rate, with a reported 1-3% mortality rate worldwide. As stated earlier, based on the CDC's scale, the 1918 Pandemic is considered a moderate pandemic influenza.

The speed of onset of a Pandemic also varies depending on the particular influenza virus, how rapidly it spreads, the availability of vaccines and antivirals, and the effectiveness of medical and non-medical containment measures. Some influenza strains remain at early phases, with no human-to-human transmission for many years, while others move through the stages to become a pandemic relatively quickly. Global travel and movement of populations speeds up the spread of disease.

Pandemics are likely to last between six and 12 weeks, and typically come in two to three waves over a three- to 18-month period. The second wave may occur several months after the first wave. The level of illness during the second wave is often more severe than that in the first wave.

Hazardous Materials Release Profile

4.14 Hazardous Materials Release

Impact Statement

According to state & local databases there are approximately 2,700[238] Hazardous Materials facilities throughout San Francisco. An accidental hazardous materials release can occur wherever hazardous materials are manufactured, stored, transported, or used. The majority of these facilities are located along the east/south east portion of the city; therefore, the risk is greatest in that part of the city.

Nature

Hazardous materials have properties that make them potentially dangerous and harmful both to human health and to the environment. An accidental hazardous material release can occur wherever hazardous materials are manufactured, stored, transported, or used. Depending on the substance involved, the release may affect nearby populations and may contaminate critical or sensitive environmental areas. The universe of hazardous materials is large and diverse. Hazardous substances can be in liquid, solid, or gas form, and can include toxic chemicals, radioactive materials, infectious substances, and wastes.

Over the past 25 years there has been heightened awareness and attention paid to the health hazards posed by toxic materials. During this period, many federal, state, and local regulations governing hazardous materials have been put into place. These regulations are continually updated and augmented. The Hazardous Materials and Waste Program at the San Francisco Department of Public Health (DPH) implements six state environmental mandates and two local mandates regulating hazardous materials activities. DPH environmental health staff inspect regulated businesses at least once every three years.

A release of hazardous materials can occur from any of the following:

- Fixed facilities such as refineries, storage facilities, manufacturing facilities, warehouses, wastewater treatment plants, swimming pools, dry cleaners, automotive sales and repair, and gas stations.

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[238] Josuwa Bernardo (SFDPH), *SF Hazardous Materials Sites*, 2018, Distributed by California State Water Resource Board (SWRCB). Email Correspondence regarding compiled data.

- Highway and rail transportation, such as tanker trucks and railcars transporting hazardous materials.
- Commercial maritime transportation, including transportation of petroleum products by barges and ocean-going tankers and spills associated with petroleum terminals.
- Air transportation involving cargo packages.
- Pipeline transportation of substances such as petroleum products, natural gas, and other chemicals.

Though large petroleum storage or manufacturing facilities are typically located outside of residential areas, pipelines are ubiquitous in our communities. Virtually all natural gas, which accounts for about 28 percent of energy consumed annually in the United States, is transported by transmission pipelines.

History

Hazardous materials incidents impacting the San Francisco Bay Area have occurred as a result of spills from commercial and recreational vessels in the San Francisco Bay; from transportation accidents that resulted in petroleum spills; from sewer breaks and overflows; and from various accidents or incidents related to the manufacture, use, and storage of hazardous materials by industrial and commercial facilities. One of the most publicized incidents occurred on November 7, 2007, when the container ship Cosco Busan struck the Delta Tower of the San Francisco - Oakland Bay Bridge during a thick fog. Over 53,569 gallons of heavy fuel oil, often referred to as "bunker fuel," spilled into San Francisco Bay, soiling San Francisco’s western, northern, and northeastern coastline, as well as other shorelines throughout the Bay Area. The spill impacted birds, marine mammals, fish, and humans, and required clean-up and response efforts from local, state, and federal authorities.

More recently, October 30, 2009, another tanker vessel, the Dubai Star, spilled over 400 gallons of intermediate fuel oil during a refueling incident just south of the Bay Bridge. The spill affected more than 10 miles of shoreline, from just north of the east approach to the Bay Bridge to San Leandro Bay along the Alameda County coastline. The impact included bird mortalities, as well as beach and fisheries closures.

The National Response Center (NRC), which serves as the sole national point of contact for reporting all oil, chemical, radiological, biological, and etiological discharges into the environment in the United States, shows that from 2002 through 2012, a total of 806 hazardous material incidents were reported in the study area. Of this number, 586 were water-related incidents including bilge oil, gasoline, hydraulic oil, jet fuel, and diesel oil spills. Common causes of these incidents included operator error and equipment failure. During this same 10-year period, NRC data also indicates that there were 45 rail-related incidents, and 49 land-based, non-rail spill incidents. According to NRC, for the year 2017, there were at least 30 reported material incidents in San Francisco that received federal notice[239]

Location

An accidental hazardous material release can occur wherever hazardous materials are manufactured, stored, transported, or used. In San Francisco, a hazardous material event is most likely to occur within the City's industrial area, which is concentrated in the southeast part of the city. The primary PG&E gas transmission pipeline also runs through the southeast part of the city.

In addition, a variety of transportation corridors traverse the city. Though federal regulations impose restrictions on the use of certain routes to transport hazardous materials within the city, vehicles using San Francisco's transportation corridors commonly carry a variety of hazardous and highly flammable materials, such as gasoline, petroleum products, and other chemicals known to cause human health problems. Similarly, container ships, car carriers, tankers, and other types of vessels constantly move through the shipping channels of San Francisco Bay, presenting a risk to the local marine environment in the event of a spill. Hazardous materials also are transported to and from, are used, and are stored at the San Francisco International Airport (SFO) and at adjacent airport facilities just south of San Francisco.

Severity and Probability of Future Events

The geographic and economic characteristics of San Francisco make it likely that hazardous materials releases will continue to occur. Based on statistics maintained by DPH, from 2007 through 2017, there were 413[2] hazardous materials incidents requiring a response in San Francisco. San Francisco's commercial sector and transportation

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[239] United States Coast Guard, "2017 Report" accessed September 25, 2018. (*National Response Center*, http://www.nrc.uscg.mil/)

routes share space with several bodies of water, wetlands, environmentally sensitive areas, and a densely-populated urban environment, creating areas of great potential risk for a hazardous materials release. Moreover, SFO, a large international airport, is just a few miles from downtown San Francisco. Thus, the threat to San Francisco of a hazardous material incident impacting land, sea, or air remains high.

Hazardous material releases are notable among the hazard profiles this plan addresses because of the degree to which it can be expected to occur in combination with other hazards. For example, as flooding increases in occurrence there will likely be an increased number of hazardous material incidents due to the compromise of coastal/floodplain storage infrastructure

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