

Climate and Health Understanding the Risk:

An Assessment of San Francisco's Vulnerability to Flooding & Extreme Storms



San Francisco Department of Public Health
City and County of San Francisco
Population Health Division

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Table of Contents

Introduction	5
San Francisco Current Conditions	6
Geography: San Francisco's Waterfront	
Built Environment	
San Francisco Climate and Weather	9
Current Weather and Climate	
Climate Change Impact Projections	
Health Impacts	14
Vulnerable Populations	16
Vulnerability Assessment	16
Data Standardization	
Discussion	20
Next Steps	21
Conclusion	22
Appendix A	i
Health Impacts Literature Review	
Appendix B	ix
Vulnerable Populations Literature Review	

Table of Figures and Tables

Figure 1.	<i>San Francisco's Neighborhoods</i>	6
Figure 2.	<i>San Francisco's Waterfront</i>	6
Figure 3.	<i>San Francisco's Natural Watershed</i>	7
Figure 4.	<i>December 11 Power Outage</i>	8
Figure 5.	<i>Sea Level Rise and Storm Surge</i>	9
Figure 6.	<i>San Francisco Annual Precipitation</i>	10
Figure 7.	<i>Pineapple Express Circulation</i>	10
Figure 8.	<i>Public Perception of Precipitation-Related Inundation</i>	11
Figure 9.	<i>Co2 Emission Projections</i>	12
Figure 10.	<i>Sea Level Rise Projections, San Francisco Sea Level Rise Committee</i>	12
Figure 11.	<i>Sea Level Rise Projections 2, San Francisco Sea Level Rise Committee</i>	12
Figure 12.	<i>Most likely Precipitation-related Inundation During Extreme Storm Events</i>	12
Figure 13.	<i>Flood Inundation Comparison</i>	13
Figure 14.	<i>Flooding During Pineapple Express Circulations</i>	13
Figure 15.	<i>Flood Inundation and Extreme Storm Health Pathways</i>	14
Figure 16.	<i>Vulnerability Indicator Correlation Matrix</i>	18
Figure 17.	<i>Composition of Final Flood Health Vulnerability Index</i>	18
Figure 18.	<i>Socioeconomic and Demographic Vulnerability Index</i>	19
Figure 19.	<i>Flood Exposure Vulnerability Index</i>	19
Figure 20.	<i>Health Vulnerability Index</i>	19
Figure 21.	<i>Housing Vulnerability Index</i>	19
Figure 22.	<i>Final Flood Health Vulnerability Index</i>	20
Figure 23.	<i>Final Flood Health Vulnerability Index by Neighborhood</i>	20
Table 1.	<i>Storm Surge Projections</i>	13
Table 2.	<i>Vulnerable Populations</i>	17



Introduction

Climate change is happening now and faster than expected. For the last decade, cities and states have invested in developing climate action plans to reduce greenhouse gas emissions. Yet lesser attention has been dedicated to developing adaptive measures to protect the public's health in the event of climate change-related extreme weather events, or expand the capacity of public health departments to plan and prepare for such events.

This assessment represents just one of many concurrent citywide planning processes to prepare San Francisco for climate change-related extreme weather events. While many of these efforts focus on reducing exposure to flood inundation by expanding stormwater collection capacity, developing protective infrastructure, and incorporating sea level rise in capital planning, the purpose of this assessment is to prepare the San Francisco Department of Public Health and the City for both the direct and indirect health impacts of flood inundation. This assessment will summarize how flood inundation and extreme storms may impact public health and identify communities most vulnerable to these impacts. This assessment will provide governmental agencies, non-profit, community based organizations, businesses, and citizens information about preventative measures and interventions to mitigate health impacts of flood inundation.

This report will first examine current conditions that may modify the impact of sea level rise, storm surge, and precipitation. These current conditions include geography, the built environment, and current weather and climate patterns. Once these baseline conditions are established, this report will summarize climate projections for how climate change is most likely to impact sea level rise and extreme storms. These climate impacts will be associated with both indirect and direct health impacts, and this report will identify the most salient health impacts of flood inundation and extreme storms. Special focus will be made in detailing how these impacts effect vulnerable populations. This information will be used to create a flood vulnerability index that identifies which communities are most at risk. The index will illustrate the relative vulnerability to the health impacts of flood inundation and extreme storms by San Francisco census block groups and planning neighborhoods.

Because this report's primary interest is in the health impacts of flood inundation, and flood inundation is most pronounced during extreme storm events, SFDPH does not want to disassociate flood inundation from other extreme storm impacts (e.g. wind, power outages). This report will refer to flood inundation and extreme storms separately in this report.

San Francisco Current Conditions

In order to understand how climate change will impact San Francisco, it is important to first establish a baseline understanding of City geography, infrastructure, and weather and climate patterns that may modify this impact. Figure 1 shows San Francisco’s planning neighborhoods.

Geography: San Francisco’s Waterfront

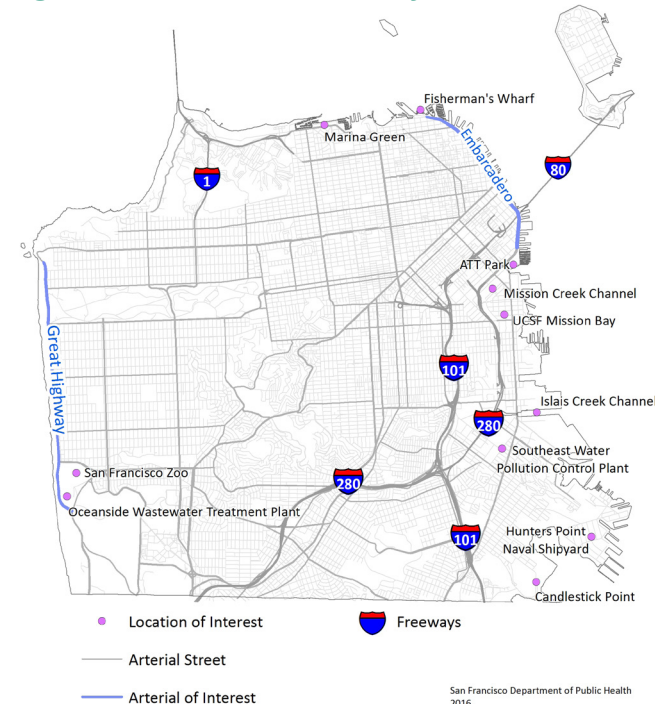
As a peninsula, the future of San Francisco is intimately intertwined with that of its waterfront. Figure 2 highlights some infrastructure that may be vulnerable to coastal flooding.

- The Pacific Ocean borders San Francisco to the west. Along this nearly seven-mile-long coastline, Ocean Beach and the Great Highway separate the Pacific Ocean from the residential Outer Richmond and Outer Sunset communities.
- Just east of the Golden Gate Bridge, the Presidio, Marina, North Beach, and Financial District border the San Francisco Bay along the northern edge of the city. Major areas of tourism are concentrated along the Embarcadero¹ and the majority of San Francisco’s business and financial sectors are centered in the Financial District and South of Market (SOMA) neighborhoods.
- SOMA, Mission Bay, and Bayview Hunters Point comprise the eastern shoreline and border the San Francisco Bay. Historically the industrial center of San Francisco, this shoreline is now dotted with Port of San Francisco facilities, high-density residential development, sports facilities, industrial warehousing and factories and large corporate, medical, and educational campuses.

Figure 1.
San Francisco’s Planning Neighborhoods



Figure 2. San Francisco’s Waterfront



San Francisco Department of Public Health
2016

Much of the land that now comprises San Francisco's Bay waterfront is not natural. As the City developed, the Bay was filled in with landfill for additional housing, commerce, and infrastructure. This landfill consists of dredged mud and sand from the bottom of the Bay, wood from discarded merchant vessels, and even rubble from the 1906 earthquake.² The neighborhoods built on landfill are at increased risk for flood inundation during extreme storms because they are often at low elevation, and located at the bottom of a watershed in a natural drainage basin. In addition to many neighborhoods being partly built on landfill, development now covers most of San Francisco's natural streams and creeks. Figure 3 shows San Francisco's historical shoreline and creeks.

Figure 3. San Francisco's Natural Watershed



Historically, San Francisco was home to Mission Creek, Islais Creek, Yosemite Creek, and other waterways that transported rainfall from the hills to the Pacific Ocean or San Francisco Bay.³ These creeks are still active, but have been diverted underground through sewer pipes. During heavy precipitation events, stormwater runoff from impervious surfaces will pool along these natural drainage channels and may flood the roads, homes, and businesses above the diverted creeks.^{4,5}

Built Environment

San Francisco's built environment affects both exposure to flood inundation and extreme storms, and the health impacts of that exposure. For the purpose of this report, built environment refers to any manmade structure or system. This report focuses most closely on San Francisco's built environment that directly affects flood inundation and its health impacts, including the stormwater and wastewater transport and management system, the power and electrical system, the transportation network, housing, and development in flood plains. The purpose of this section is to establish how these mechanisms work in concert to mitigate exposure to flood inundation and extreme storms.

Stormwater and Wastewater Management

San Francisco's stormwater management system is the first line of defense against flood inundation during extreme storm events. San Francisco is one of the few West Coast cities with a combined stormwater-wastewater sewer system.^{6,7} This system treats both stormwater and wastewater at the same time instead of separating their transport and disposal into two different piping systems. The stormwater and wastewater are transported to one of three treatment facilities to be cleaned before being released into the Pacific Ocean or San Francisco Bay.⁷ During heavy storm events, up to 200 million gallons of stormwater and wastewater can be stored in large transport/storage structure around the city perimeter. However, during the heaviest rainfall, when all storage and treatment is at capacity, stormwater and wastewater are discharged into the San Francisco Bay after removal of solids and trash.⁷ Currently, the San Francisco Public Utilities Commission (SFPUC) has a ten year, \$2.7 billion capital improvement plan to make improvements to this system.⁸ This plan includes grey infrastructure improvements to water treatment facilities and collection systems, and green infrastructure development such as daylighting creeks, and green corridors to aid stormwater biofiltration.⁷

Power and Electricity

Power outages can cause especially harmful health impacts of extreme storms and flood inundation. San Francisco power and electric infrastructure is managed by both the SFPUC and Pacific Gas and Electric Company (PG&E).⁹ While the PUC is responsible for providing power to municipal facilities and public transportation, PG&E provides most of the power to residents and businesses. The utility poles are managed by the Joint Pole Association (JPA), which is comprised of electric utilities, telephone and wireless companies and municipalities.¹⁰

Figure 4. December 11 Power Outage¹²



Transportation

The transportation network connects residents and visitors to schools and jobs, private businesses and municipal services, and to recreation and exercise. San Francisco is serviced by a complicated multi-modal transportation system tasked with not only moving San Francisco's nearly 850,000 residents throughout the city, but facilitating the commute of countless more employees and visitors. Any disruption to the transportation system will have cascading impacts. A heavy precipitation event on December 11, 2014 shut down Bay Area Rapid Transit (BART) service to the financial district, impacted San Francisco Municipal Railway (MUNI), and flooded portions of the 280 freeway in eastern and southern San Francisco.¹² Active transportation can also be impacted by heavy precipitation. Slick pavement, large puddles and reduced visibility may make conditions difficult for bicyclists and pedestrians.¹³

Housing and Building Quality

Housing quality can affect both one's exposure to flood inundation and extreme storms, and poor housing quality is associated with health impacts that can exacerbated by flood inundation and extreme storms. Building dampness and mold exposure impacts an average of 18% - 50% of buildings globally.¹⁴ Leaky roofs and windows, or broken plumbing may expose residents to molds or other harmful waterborne pathogens which can either cause or aggravate respiratory and allergic conditions, or other illnesses. During Hurricane Sandy, many residents were exposed to either cold or hot temperatures without adequate climate controls, damp conditions, or prolonged power outages which rendered elevators inoperable and spoiled food.¹⁵ Housing age, rental status, both overcrowding and isolation, and rent burden may modify the impact of health effects from flood inundation and extreme storms.

The San Francisco Department of Public Health (SFDPH) has used housing violations as a proxy to measure housing quality. Combining violation data from SFDPH, San Francisco Department of Building Inspections, and San Francisco Fire Department, the neighborhoods with the highest concentration of health and safety violations are SOMA, Chinatown, Tenderloin, and the Mission.

Development

Much of the proposed development in San Francisco is planned for San Francisco's eastern shoreline which is vulnerable to flooding due to sea level rise.¹⁶ Because many developments are planned for current or future flood inundation risk areas, the City is preparing by examining possible design elements and adaptation strategies to protect infrastructure from future coastal flooding scenarios. This preparation aims to ensure the longevity of these developments. Additionally, development in neighborhoods with high exposure to sea level rise and flood inundation will inevitably result in more San Franciscans living in flood plains. San Francisco's public health and emergency management infrastructure must add capacity and identify vulnerable public health infrastructure in order to prepare for flood events that impact a large population of San Franciscans.

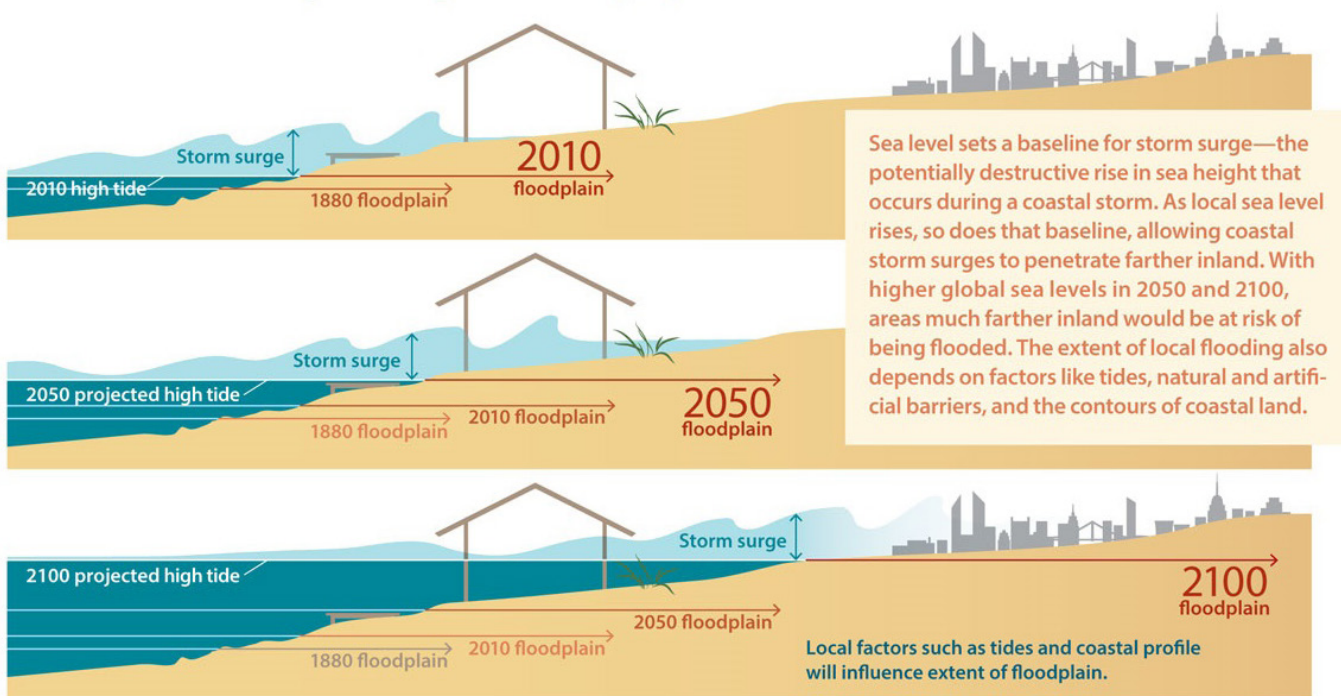
San Francisco Climate and Weather

There are three causes of flood inundation in San Francisco: 1) sea level rise caused by climate change; 2) temporary storm surge; and 3) precipitation from extreme storms¹⁷. The three causes of flood inundation are intrinsically interrelated: both precipitation and temporary storm surge are impacts of extreme storms. As climate change increases the frequency and intensity of these extreme storms, impacts to public health will be exacerbated by sea level rise and storm surge. This section will summarize current San Francisco weather and climate patterns with regard to flood inundation and extreme storms. Once these patterns are established, the report will outline climate projections to identify how climate change will impact these patterns.

Figure 5 visually shows the interplay between sea level rise and storm surge to increase flood inundation.¹⁸

The sea level rise and storm surge projections used in this report were developed the San Francisco Sea Level Rise Committee, and are based on projections developed by the National Research Council in 2012.²⁰ More information on the projections can be found in the technical guidance document, “Guidance for Incorporating Sea Level Rise into Capital Planning in San Francisco: Assessing Vulnerability, Risk, and Adaptation”.¹⁹

Figure 5. Sea Level Rise and Storm Surge



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Current Weather and Climate

Storm Surge

The vulnerability of San Francisco’s Pacific Ocean and Bay waterfronts will be determined by the extent of temporary storm surge. A 100-year storm is a storm with a 1% chance of occurring in a given year. The mean higher high water (MHHW) level is the average daily high tide. A 100-year extreme tide based on year-2000 conditions is estimated to be roughly 41 inches above current MHHW levels.¹⁹

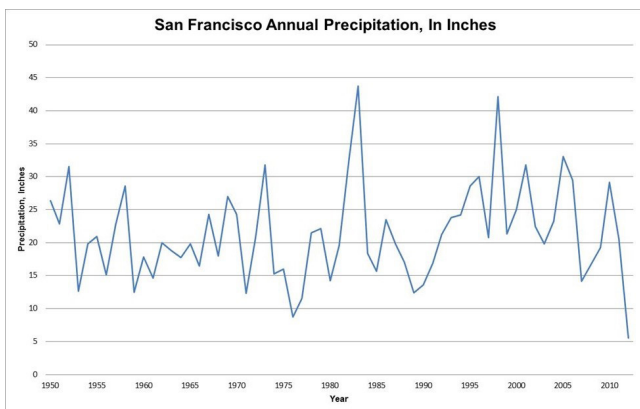
A 100-year extreme tide based on year-2000 conditions is estimated to be roughly 41 inches above current mean high high water (MHHW) levels.¹⁹

Precipitation

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.²¹ In 1983, San Francisco received 43.75 inches of precipitation while in 1977, San Francisco received just 8.73 inches.²¹ Because of the variation between wet and dry years, California is prone to both extremes: floods and droughts.

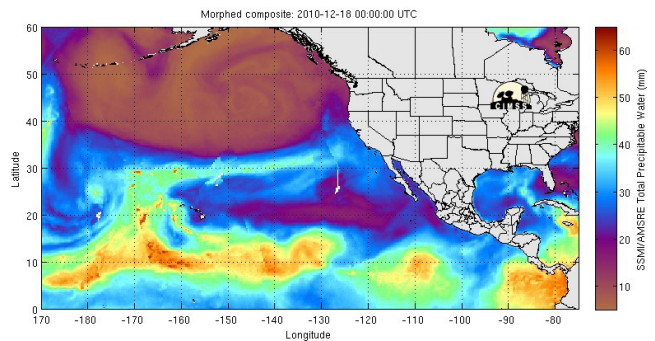
Figure 6 shows how San Francisco rainfall totals have fluctuated.

Figure 6. San Francisco Annual Precipitation



Much of California’s yearly precipitation (35% - 45%) comes in the form of atmospheric rivers or ‘Pineapple Express’ extreme storms.²² While most storm systems in Northern California originate in Alaska to the north, Pineapple Express storms occur when warm, moist air from Hawaii travels along an atmospheric river across the Pacific Ocean. Figure 6 shows a Pineapple Express atmospheric river circulation. Rainy days with Pineapple Express circulations have historically resulted in double the rainfall of rainy days without Pineapple Express circulations. Over the last half century, only about ten days per year have accounted for an average of 30% to 50% of annual California’s precipitation.²³ These extreme storms are more likely to be responsible for rainfall-related inundation in San Francisco than any other weather event and are responsible for 80% of California’s flooding.²⁴

Figure 7. Pineapple Express Circulation



On December 11, 2014, an atmospheric river event in San Francisco resulted in high winds, 18 inches of storm surge, and about 3.4 inches of rain.¹¹ The storm downed trees and power lines, sent waves crashing over the Embarcadero, and flooded sewers, roadways, and storefronts. The December 11th storm resulted in:¹¹

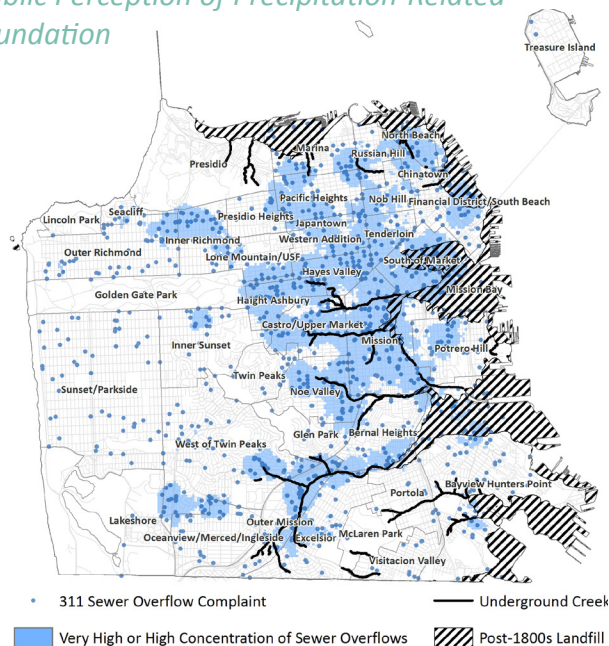
- 80,000 homes and businesses without power
- All San Francisco Unified School District schools being closed for the day
- BART and MUNI delays and closures
- Nearly 300 flood inundation-related 311 calls²⁵
- Great Highway closed and traffic diverted.

To determine locations with the highest propensity to have precipitation-related flood inundation 311 records for the 10 rainiest days in between 2009 and 2014 were analyzed and all sewer overflow-related calls are mapped in Figure 8.^{11,25}

311 records were derived from San Francisco’s Open Data Portal (DataSf). 311 is a service that connects San Francisco residents, businesses, and visitors to city information and services. Because all calls are recorded and classified by department and topic, 311 calls represent a way to geographically map areas where flood inundation was reported.

Because 311 records are based on user-reported data (largely residents who phone-in complaints), limitations and biases are inherent to the data. User-reported flooding data may over-represent neighborhoods with an especially high population density or underrepresent neighborhoods with low density populations. Additionally, 311 calls can be duplicative or be misclassified and 311 records do not validate caller’s complaints. While research should be conducted to better understand this tool’s validity in detailing the frequency and location of flooding, it can be useful in understanding where the public perceives flooding occurs.

Figure 8.
Public Perception of Precipitation-Related Inundation



According to the 311 sewer-overflows map, the neighborhoods with the highest concentration of 311 calls related to inundation during extreme storms include SOMA, Hayes Valley, Haight Ashbury, the Mission, and the Outer Mission. Figure 8 also shows that 311 calls, especially in the east and southeast sections of San Francisco, tend to occur in close proximity to underground creeks.

El Niño

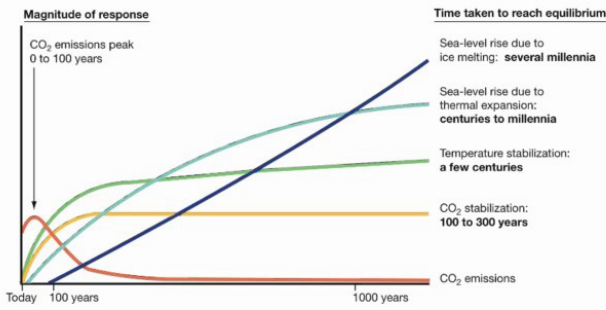
El Niño and La Niña are the two phases of the El Niño Southern Oscillation cycle (ENSO). During El Niño, an increase in Pacific Ocean equatorial surface temperatures leads to cascading weather and climate effects including unseasonably warm water temperatures and increased precipitation for California.²⁶ The last El Niño was during the winter of 1997-1998. That season was the rainiest in the last 100 years, and caused flooding throughout California. Current research suggests that, as the climate changes and weather warms, differences in water temperature near the equator may trigger a greater frequency and increased severity of El Niño events.²⁷

Climate Impact Projections

Our historical and current dependence on carbon producing activities has solidified some level of sea level rise even if all carbon-producing activities are immediately halted. Figure 9 demonstrates how long it will take the climate to normalize even in a scenario that projects no future emissions.²⁸

Although the greenhouse gasses in the atmosphere already ensures some climate change, programs and policies to limit greenhouse gasses may slow the acceleration of climate change processes. Additionally, the development of largescale adaptation infrastructure, such as sea walls, could be considered. Because the purpose of this report is to determine the health impact of flood inundation and extreme storms on San Francisco, this assessment assumes no major greenhouse gas limitations or infrastructure improvements when projecting health impacts.

Figure 9. Co2 Emission Projections



Sea Level Rise

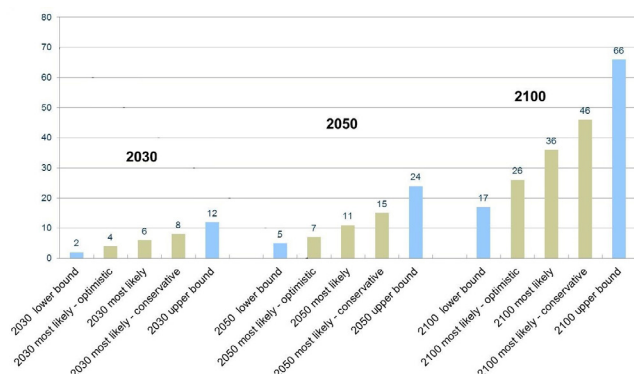
As the atmosphere warms, both the melting of the ice caps and the thermal expansion of the oceans will cause global sea levels to rise. If no mitigation measures are taken to reduce greenhouse gas emissions, based on 2010 conditions, sea levels around the San Francisco Bay are projected to rise between 7 and 15 inches by 2050, and between 26 and 46 inches by 2100.²⁰ These projections are depicted in both Figure 10 and Figure 11.¹⁹

Figure 10. Sea Level Rise Projections, San Francisco Sea Level Rise Committee

Year	Lower End of Range	Projections	Upper End of Range
2030	2 in	6 ± 2 in	12 in
2050	5 in	11 ± 4 in	24 in
2100	17 in	36 ± 10 in	66 in

Source: NRC (2012)
 NOTES: The lower and upper end of ranges represent best and worse case relative SLR scenarios in NRC 2012. They are categorized here as “unlikely but possible” consistent with NRC. The “projections” represent mid-range estimates “most likely” to occur, indicating they are the current best estimates for SLR.

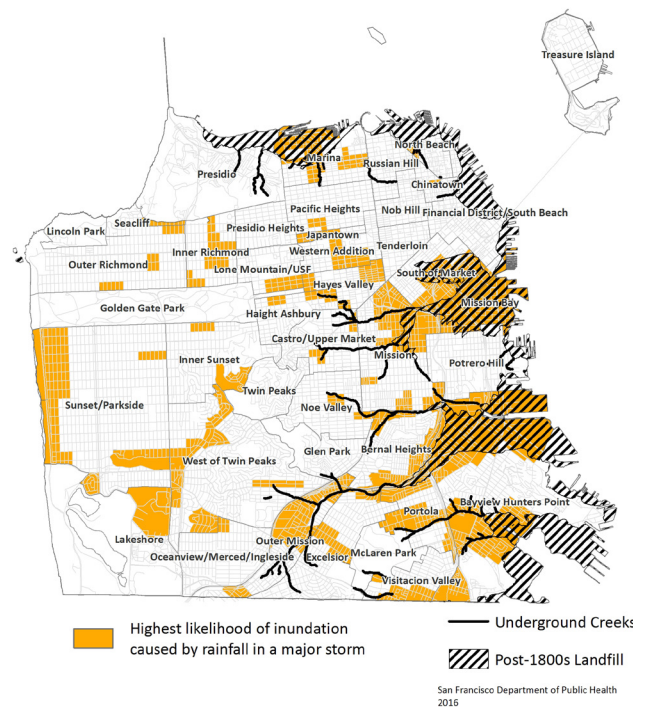
Figure 11. Sea Level Rise Projections 2, San Francisco Sea Level Rise Committee



Extreme Storms: Precipitation and Storm Surge

As sea levels rise, extreme storms will become more frequent and more intense. Extreme storms can cause flood inundation through both precipitation in the city interior and storm surge along the coastline. Most climate projections forecast the average yearly precipitation-levels to either remain stable or decrease. However, year-to-year precipitation levels are expected to cluster around the extreme dry or extreme wet years. During extreme wet years, climatologists forecast more atmospheric river events. These extreme storm events are projected to occur increasingly in the warmer spring and autumn months. Because the ground can only absorb so much water, more concentrated precipitation also translates into more stormwater runoff. Figure 12 below shows where the PUC projects flood inundation due to precipitation is most likely to occur during a major storm.²⁹ Once again, these areas tend to correspond with San Francisco’s natural watershed, as water will drain downhill and pool in natural drainage basins.

Figure 12. Most likely precipitation-related inundation during extreme storm events



Storm surge will increase with sea level rise. Sea levels are projected to rise between 26 and 46 inches by 2100.¹⁹ A 100-year storm in 2100 is projected to add an additional 36 inches on top of sea level rise. The most likely total inundation in such a scenario would be water levels 77-inches above current totals.¹⁹

Table 1. Storm Surge Projections

Sea Level Rise Scenario	Daily Tide	Extreme Tide (Storm Surge) Levels						
	Water Level above MHHW	1-yr	2-yr	5-yr	10-yr	25-yr	50-yr	100-yr
Existing Conditions	0	12	19	23	27	32	36	41
MHHW + 6-inch	6	18	25	29	33	38	42	47
MHHW + 12-inch	12	24	31	35	39	44	48	53
MHHW + 18-inch	18	30	37	41	45	50	54	59
MHHW + 24-inch	24	36	43	47	51	56	60	65
MHHW + 30-inch	30	42	49	53	57	62	66	71
MHHW + 36-inch	36	48	55	59	63	68	72	77
MHHW + 42-inch	42	54	61	65	69	74	78	83
MHHW + 48-inch	48	60	67	71	75	80	84	89
MHHW + 54-inch	54	66	73	77	81	86	90	95
MHHW + 60-inch	60	72	79	83	87	92	96	101
MHHW + 66-inch	66	78	83	89	93	98	102	107

Based on the San Francisco flood plains, a 77-inch increase in water levels would significantly flood portions of Treasure Island, SOMA, Mission Bay, the Marina District, the Presidio, North Beach, and Bayview Hunters Point. Figure 13 depicts the difference between 100 year storms with median flood inundation projections for 2000 and 2100.

Figure 13. Flood Inundation Comparison

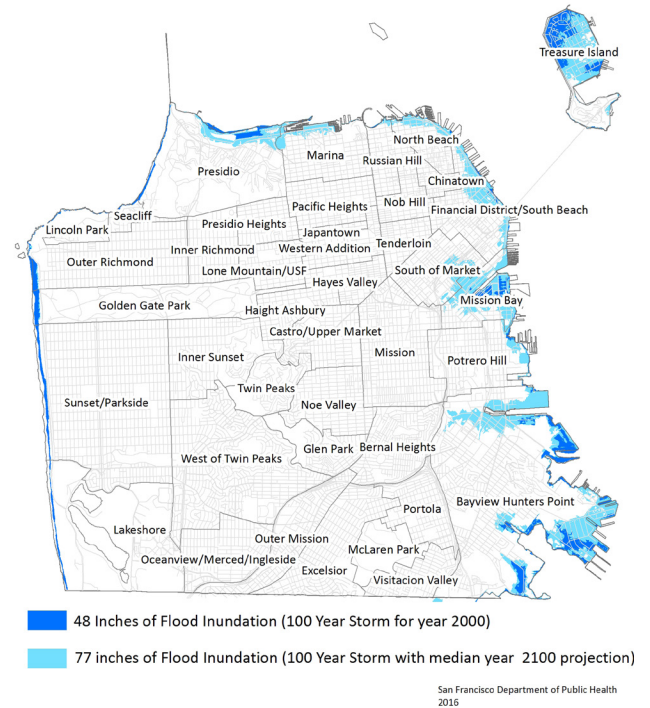


Figure 14. Flooding During Pineapple Express Circulation³⁰



Health Impacts

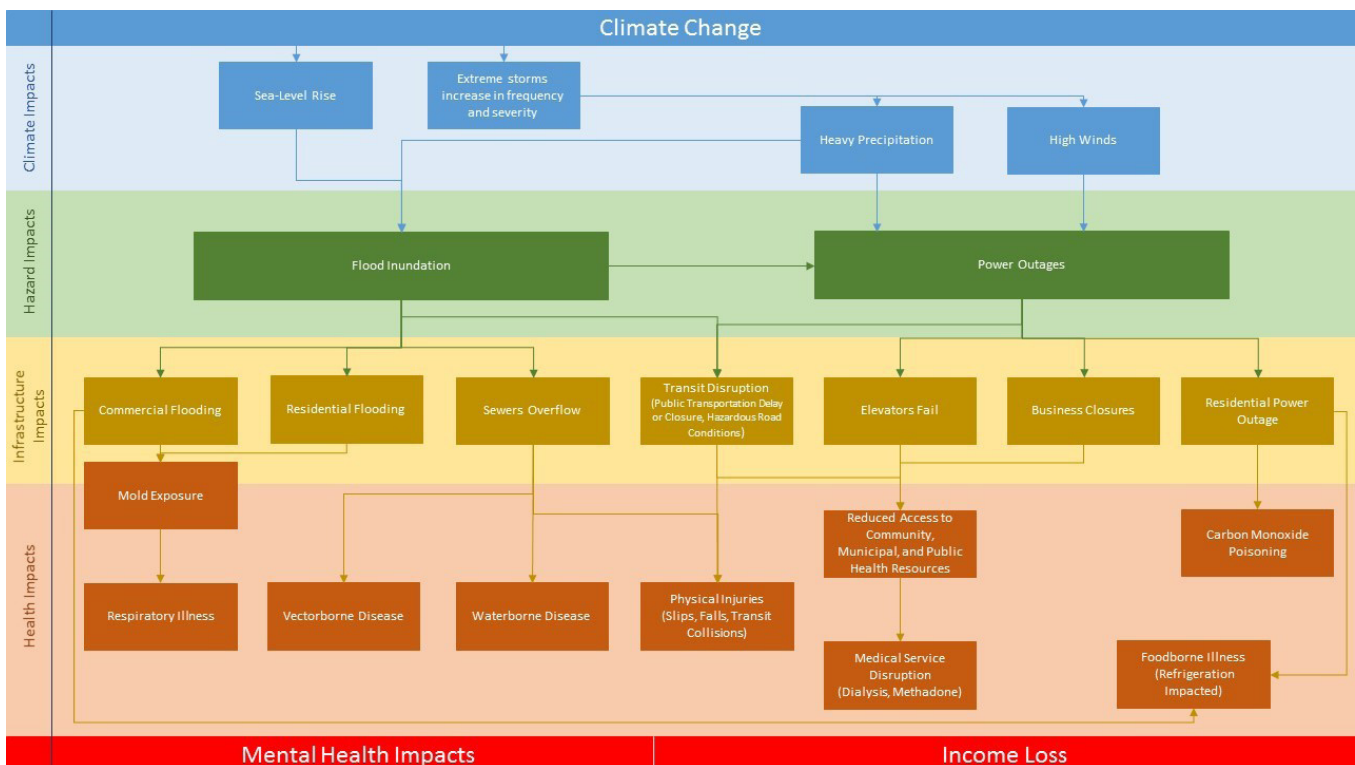
Climate change will impact all San Franciscans, though not all San Franciscans will suffer the impacts evenly. In order to determine which San Francisco communities are most vulnerable to the health impacts of flood inundation and extreme storms, it is important to first understand the pathways that connect climate impacts to health impacts.

For our health impacts literature review, we used PubMed and Google Scholar and searched with terms

including: “Flood”, “Health Impact”, “Natural Disaster”, “Climate Change” and “Illness”. We prioritized academic research, articles written for scientific, public health, and disaster management journals; and surveys and plans from local, statewide, national, and international public health agencies.

The flowchart in Figure 15 summarizes the pathways that connect flood inundation and extreme storms to potential health outcomes.

Figure 15. Flood Inundation and Extreme Storm Health Pathways



The most likely health outcomes of extreme storms and flooding include:



Physical injuries may increase due to slips and falls, automobile or bicycle collisions, or downed trees or power lines. These injuries are directly caused by flood inundation and extreme storms.



Waterborne illnesses are caused by proximity to contaminated water. San Francisco has little risk of contaminated drinking water, but because we have a combined stormwater-wastewater sewer system, stormwater overflows may result in raw sewage seepage onto streets or into the Bay. Those in contact with untreated wastewater are at increased risk for waterborne illnesses.



Respiratory illnesses that impact the lungs, throat, and airways can be spread through airborne particles. Mold growth from water intrusion or flooding in buildings, as well as water damage which may cause exposure to toxic building materials, can trigger asthma, allergies, and other respiratory illnesses.



Vector-borne disease can be exacerbated by flood events since rainy seasons, particularly after dry seasons, have been proven to be correlated with increases in rodent, which are vectors for diseases such as Hantavirus. Standing water may additionally attract mosquito vectors.



Foodborne illnesses may increase if a significant power outage impacts refrigeration in residents and food establishments, as well as if a combined sewer overflow or algal bloom impacts shellfish and other coastal seafood.



Any disruption to the city medical services, either by power outage or transportation network disruption, may cause additional health impacts. Residents dependent on methadone clinics or dialysis may need to find alternative treatments during service disruption.



Carbon monoxide poisoning is a common health impact of power outages after hazard events. Carbon monoxide poisoning is typically caused by improper usage of generators which that emit a harmful, odorless gas.



All San Franciscans are at risk of increased sensitivity to mental health impacts before, during, and after hazard events. These impacts can be caused, triggered, or exacerbated by stress, isolation, or anxiety associated with hazard events.



Any major flood inundation or extreme storm event may lead to income loss. Income loss has been correlated with many public health impacts. Income loss in a hazard event might be private losses due to missed work, household repairs, or spoiled food due to a power outage. Income loss may also be municipal, and disaster response may eat into other social programs.

A detailed synopsis of the health impacts, their causal pathways, historical examples, and vulnerable populations can be found in the Appendix A.

Vulnerable Populations

The objective of the vulnerable populations literature review was build off of the health impact literature review to identify populations particularly vulnerable to the health impacts of flood inundation and extreme storms. The identification of these populations will help the City of San Francisco to design and target interventions for the populations most in need.

We used PubMed and Google Scholar and searched with terms including “Vulnerable Populations”, “Health Impacts”, “Flood”, “Hazard” and terms associated with flood health impacts including “Asthma”, “Respiratory Disease”, “Waterborne”, “Vector-borne”, and “Mental Health”.

We prioritized academic research and established vulnerability indexes, articles written for scientific, public health, and disaster management journals, and surveys and plans from local, statewide, national, and international public health agencies. We also prioritized articles written after 2000.

A final list of vulnerable populations can be found in Table 2.

Vulnerability Assessment

In order to effectively focus adaptive resources and design interventions targeted at the vulnerable populations established by the literature review, it is important to identify the locations of these communities in San Francisco. A comparative analysis of flood health vulnerability combined to produce an overall index by both block group and neighborhood can assist the development and evaluation of programs and policies to better prepare for, respond to, and recover from, the health impacts of flood inundation and extreme storms.

The final indicators used in the flood vulnerability assessment fall into four general categories: 1) socioeconomic and demographic indicators, often

based on systemic inequalities, that may impact a person’s ability to prepare for or recover from hazard events; 2) exposure indicators that identify areas most likely to experience flood inundation; 3) pre-existing health conditions that may be especially impacted by a hazard events and interruption in government or community services during and after hazard events; and 4) the quality of housing and living conditions.

Table 2 shows the four indicator categories, its shorthand identifier, and data source. A more detailed synopsis of the indicators and their impact on flood health vulnerability can be found in Appendix B.

Table 2. Vulnerable Populations

	Flood Vulnerability Variable	Symbol	Data Source
Social and Demographic Vulnerability	Percentage of residents under 18	Children	American Community Survey 2009-2014
	Percentage of residents 65 and over	Elderly	American Community Survey 2009-2014
	Percentage of residents that do not identify as white (not Hispanic or Latino)	NonWhite	American Community Survey 2009-2014
	Percentage of all individuals below 200% of the federal poverty rate	Poverty	American Community Survey 2009-2014
	Percentage of individuals over 25 with at least a high school degree	Education	American Community Survey 2009-2014
	Percentage of households with no one age 14 and over who speaks English only or speaks English "very well"	English	American Community Survey 2009-2014
Exposure Vulnerability	Percent of the land area in the 100-year flood plain with 36-inches of sea-level rise	Sea level Rise	San Francisco Sea-Level Rise Committee, AECOM 77inch flood inundation layer, 2014
	Percent of land area with over 6-inches of projected precipitation-related flood inundation during an 100-year-storm	Precipitation	San Francisco Public Utilities Commission, AECOM, 2015
	Minimum Elevation in feet	Elevation	USGS, 2011
Health Vulnerability	Age-adjusted hospitalization rate due to diabetes; adults 18+	Diabetes	California Office of Statewide Health Planning and Development, 2004-2014
	Age-adjusted hospitalization rate due to asthma; adults 18+	Asthma	California Office of Statewide Health Planning and Development, 2005-2014
	Age-adjusted hospitalization rate due to schizophrenia and other psychotic disorders	Mental Health	California Office of Statewide Health Planning and Development, 2005-2014
	Percentage of residents reporting a physical disability	Disabled	American Community Survey 2009-2014
Housing Vulnerability	Homeless population, per 1000 residents	Homeless	2015 San Francisco Homeless Count
	Annual housing violations, per 1000 residents		San Francisco Police Department, San Francisco Public Health Department, San Francisco Fire Department violations 2010-2012
	Percentage of households with the householder living alone	LivAlone	American Community Survey 2009-2014

Data Analysis

All data was analyzed at the block group level. Raster data was summarized at the block group level using zonal statistics. Data unavailable at the block group level was proportionally split. For the purpose of establishing correlations between the indicators, all indicators were standardized by calculating z-scores. The z-score measures a score relative to the mean and provides a standard for comparison between indicators. The z-score is calculated by (indicator score – indicator mean) / standard deviation).

Figure 16 shows the degree to which the different indicators are correlated. According to the matrix, indicators whose R-Squared value is either darker blue or dark red have higher positive and negative correlations.

The matrix shows that socioeconomic and demographic indicators are especially highly correlated. Because these socioeconomic and demographic indicators are so highly correlated, a principal component analysis was necessary to reduce the dimensionality of the

six socioeconomic and demographic vulnerability indicators. The first two components explained 75% of the variance of the data. These two components were summed to create a final socioeconomic and demographic score.

Socioeconomic and demographic indicators, housing indicators, and health indicators each constitute 20% of the final flood health vulnerability score in the index, while exposure indicators comprise 40% of the final score. While all indicators in the index having compelling evidence on climate-health linkages, exposure indicators were emphasized because there is a high degree of confidence in the casual relationship between the exposure and health determinants and a high magnitude and severity impact. Quantiles were used to classify the data and flood vulnerability index maps as a way to show the relative distribution for the City. Figure 17 shows the composition of the final flood health vulnerability index. The higher vulnerable areas in the map depict where populations are most likely to suffer harm and have less ability to respond to stresses imposed by extreme storms and flood inundation.

Figure 16. Vulnerability Indicator Correlation Matrix

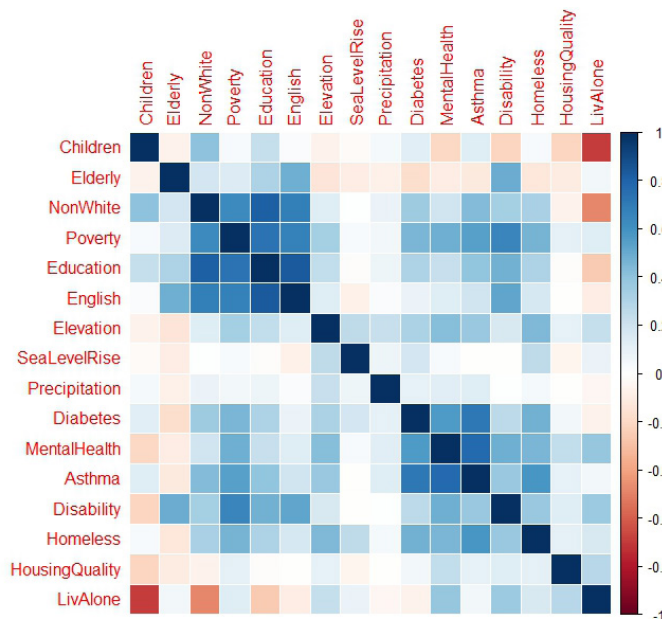
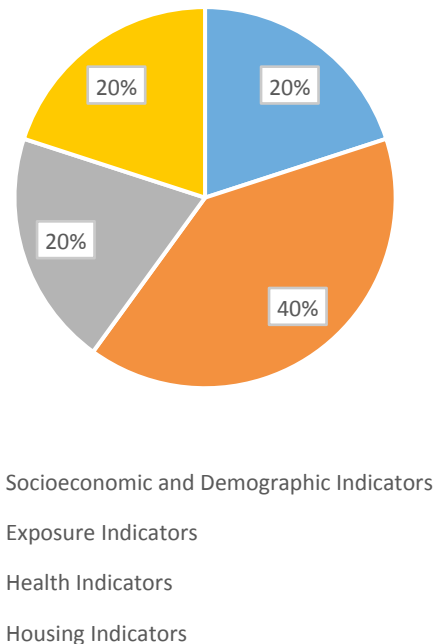


Figure 17. Composition of Final Flood Health Vulnerability Index



The following four maps (Figure 18, 19, 20, and 21) show the vulnerability indexes for the socioeconomic and demographic indicator category, exposure indicator category, health indicator category, and housing indicator category. Figure 22 shows the final combined flood health vulnerability score, and Figure 23 shows this same score by neighborhood.

Figure 18. Socioeconomic and Demographic Vulnerability Index

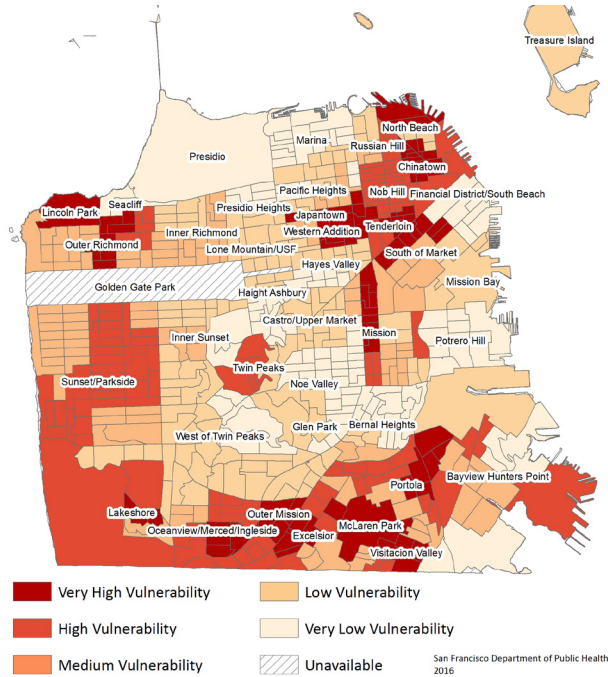


Figure 20. Health Vulnerability Index

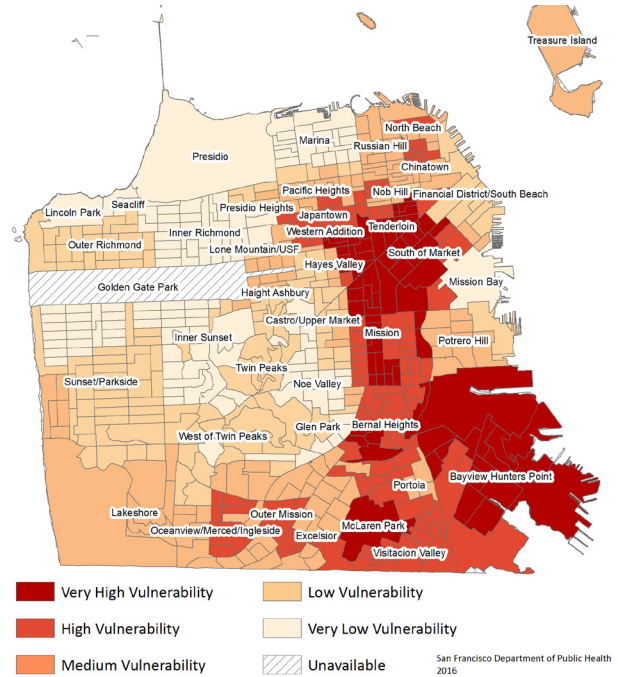


Figure 19. Flood Exposure Vulnerability Index

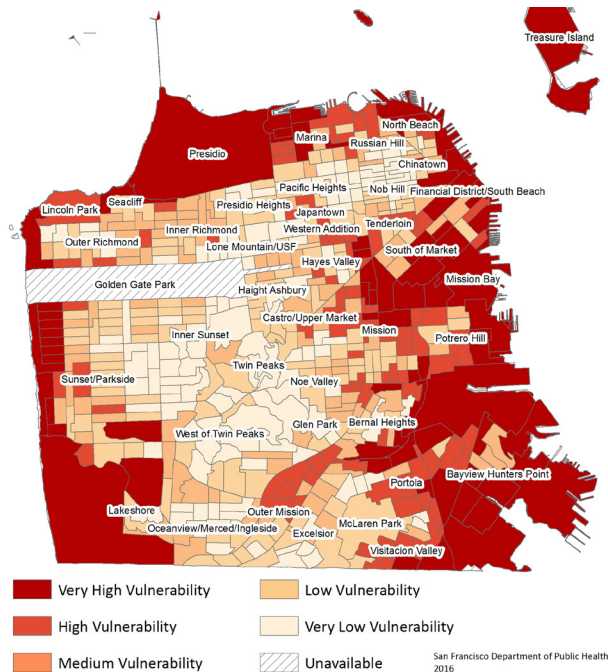


Figure 21. Housing Vulnerability Index

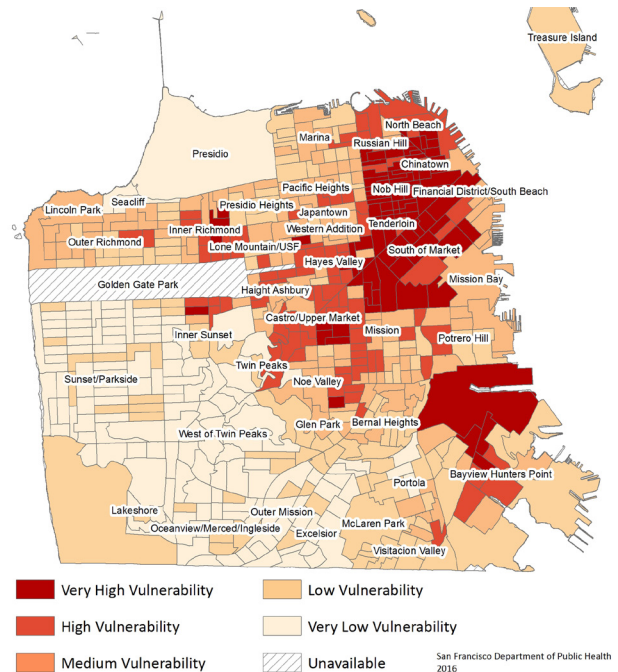
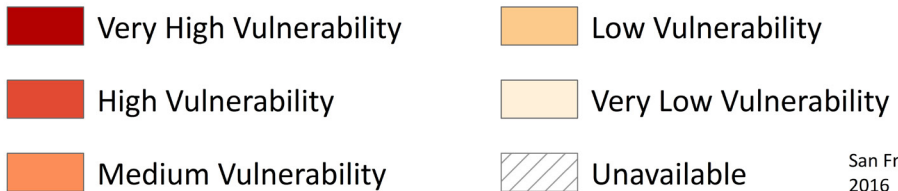
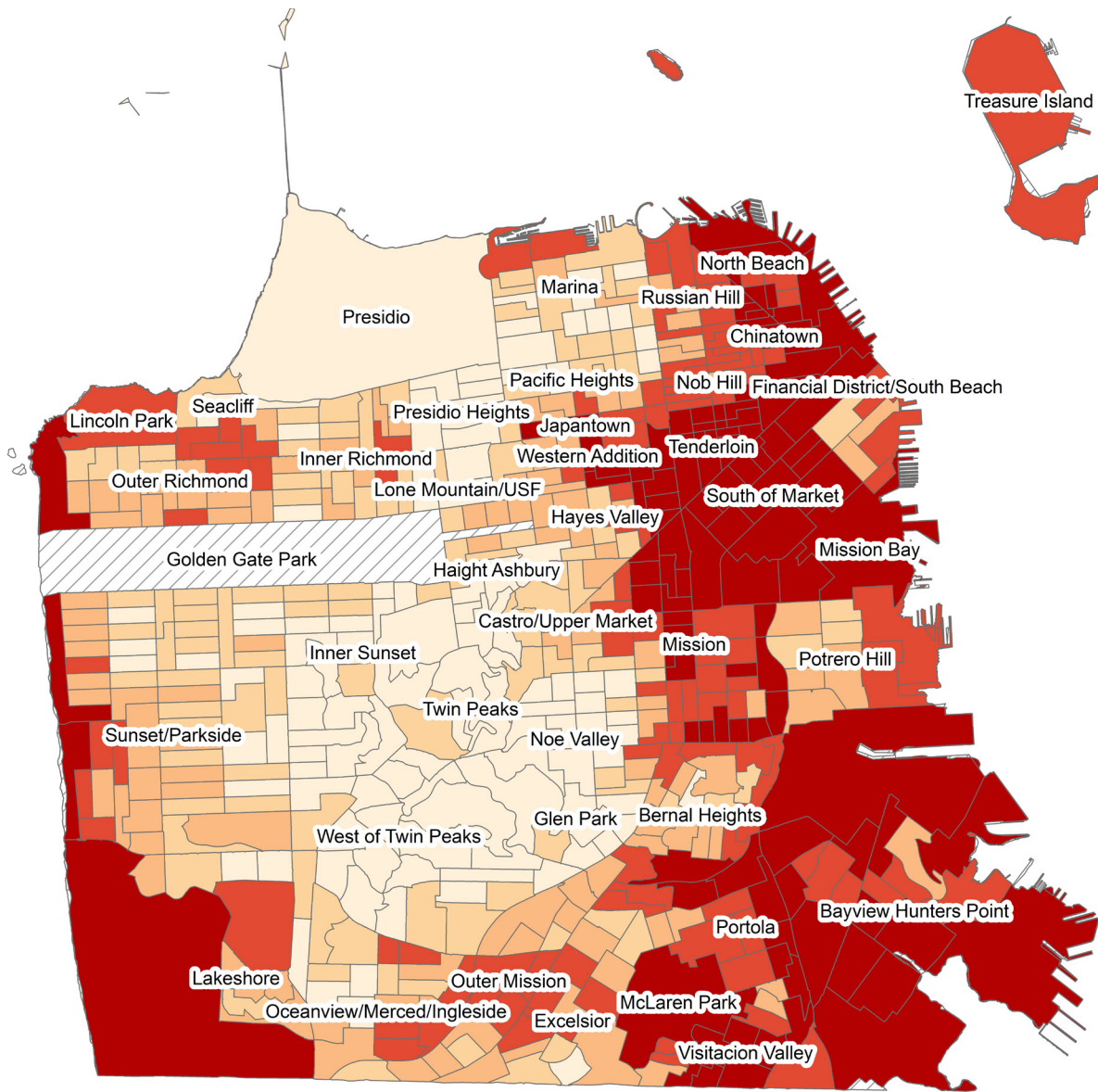
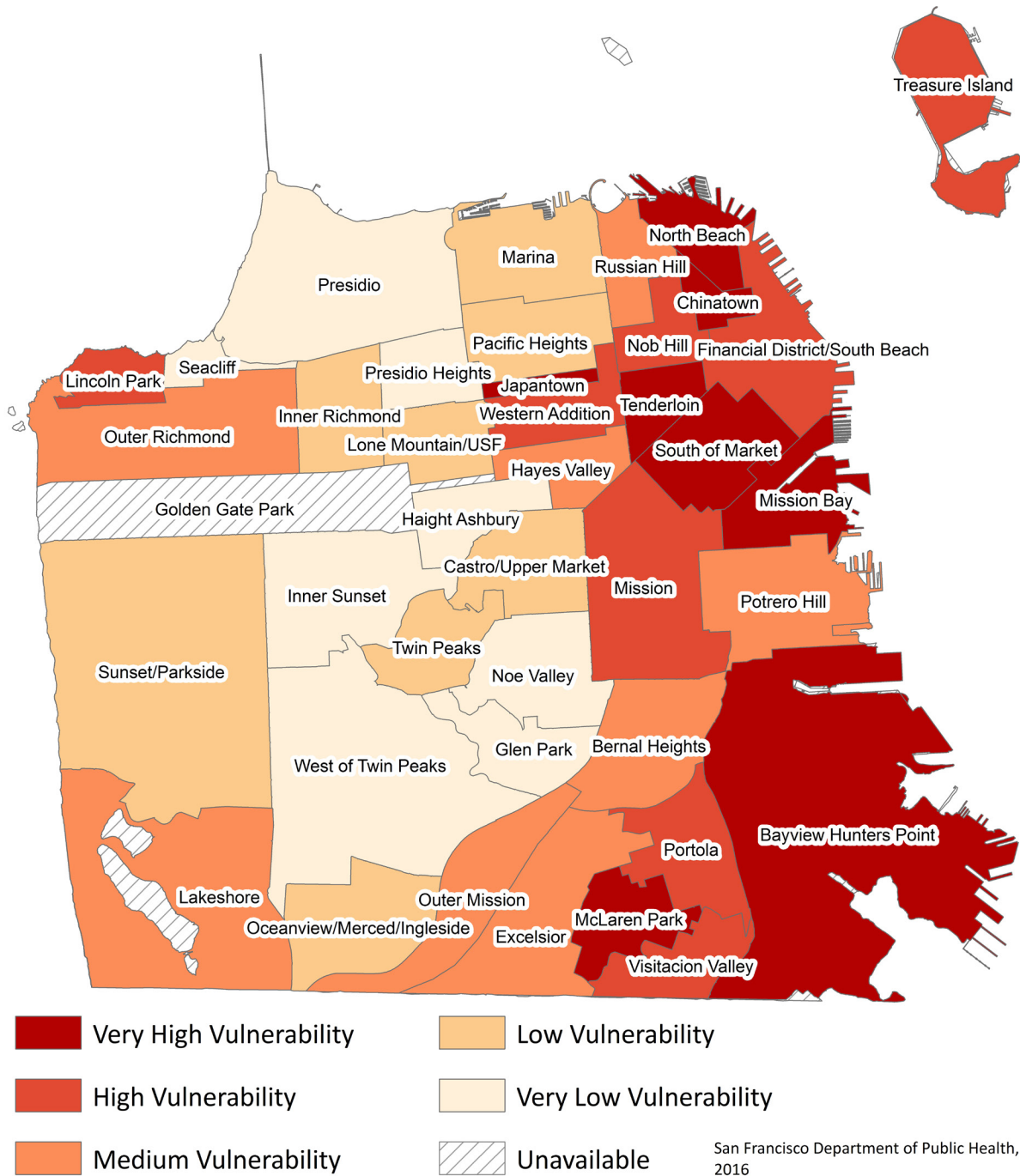


Figure 22. Final Flood Health Vulnerability Index



San Francisco Department of Public Health
2016

Figure 23. Final Flood Health Vulnerability Index, by Neighborhood



Discussion

Rather than defining flood vulnerability as just a function of exposure, the flood vulnerability index incorporates socioeconomic and demographic, health, and housing indicators into the equation. The result identifies both areas which are most likely to experience flooding, and areas are most likely to experience the health impacts of this flooding. Figure 22 shows flood vulnerability in San Francisco by block group.

Based on the flood vulnerability index, locations especially vulnerable to the health impacts of flood inundation and extreme storms include the Pacific Coastline, the Southeastern quadrant of the City, the high density SOMA, Chinatown and Tenderloin neighborhoods, and the Mission. Greater exposure to flood events renders coastal areas such as Ocean Beach and Embarcadero more vulnerable than adjacent block groups despite relatively low socioeconomic and demographic risk factors.

Figure 23 summarizes flood vulnerability index at the neighborhood level. When summarized at the

neighborhood level, vulnerability becomes increasingly concentrated along the eastern half of the City. The neighborhoods with the highest vulnerability to the health impacts of flood inundation and extreme storms are Bayview Hunters Point, Mission Bay, SOMA, Tenderloin, Chinatown, and North Beach.

Development in the San Francisco housing pipeline is overwhelmingly concentrated in very high or high flood vulnerability block groups and the total population of these communities is expected to swell. Because flood vulnerability is so intertwined with socioeconomic and demographic indicators, it is difficult to predict whether population growth will increase or decrease vulnerability. However, population turnover itself can make a community more at risk to the health impacts of flood inundation as residents may be unaware of city services, and local resilience plans may have a difficult time engaging very transient communities.

Next Steps

Although the health impacts of flood inundation and extreme storms may be severe, the City has already begun meaningful action to combat climate change, and to increase the resiliency of its residents and visitors. Some of these programs and policies include incorporating sea level rise into capital planning, the development of a San Francisco Climate Action Plan to reduce greenhouse gas emissions, establishing a clean transportation framework that incentivizes electric vehicles and active transportation, and the residential rain barrel program to capture and harvest rainwater. These measures have the opportunity to not only create a more sustainable environment, but can have beneficial health impacts and, if properly implemented, can reduce health inequities.

The Department of Environment Solar+Energy Storage for Resiliency program aims to use solar power and battery storage in disaster preparedness and emergency

response plans. The Planning Department's 2016 Sea Level Rise Action Plan is the first step towards the development on a Citywide Sea level Rise Adaptation Plan, which will identify and align sea level rise planning strategies citywide.

There are many potential next steps to advance climate adaptation. These opportunities range from increased surveillance and analysis of carbon monoxide poisoning, the development of a building health inventory to identify properties most at-risk for internal heat stress, mold, and other residential health conditions, and expansion of stormwater biofiltration, rain gardens, and other programs to reduce exposure to stormwater. The Climate and Health Program believes the data in this report can be used to increase understanding of human health vulnerability to climate change, and help the City design climate solutions that protect public health and eliminate health disparities.



Conclusion

As the changing climate raises sea levels along the Pacific Ocean and the San Francisco Bay, and as increasingly intense and more frequent extreme storm events occur, the health impacts of flood inundation and extreme storms will become more severe. Not all San Franciscans will suffer the health impacts evenly. Analysis is necessary to determine both which populations are most likely to be impacted, and where these populations are most likely to live.

Exposure to flood inundation and extreme storms not only depends on proximity to the waterfront or other water bodies, but also the built environment. Poor quality housing can increase risk of flood inundation, power outages, mold growth, rodent vectors, and other potentially harmful health impacts. The inclusion of socioeconomic, demographic, and health indicators in flood vulnerability analysis allows for greater consideration of health equity. Those most exposure to flood inundation may have strong adaptive capacity thus reducing current vulnerabilities and health impacts. Individuals and/or community may be more vulnerable to the health impacts of hazard events if they are socially, culturally or linguistically isolated, financially stressed, and/or have pre-existing health conditions.

A data-driven approach coupled with smart community engagement should be used to identify the San Francisco neighborhoods and communities most vulnerable to the health impacts of flood inundation and extreme storms. This is a necessary step toward focusing resources and developing interventions to mitigate the impact of hazard events and climate-sensitive health determinants and outcomes. The flood vulnerability index can be used to discuss climate change impacts on public health and as a starting point for planning interventions, education, and outreach, and evaluating the success of these efforts.

While San Francisco is increasingly vulnerable to climate change-related hazard events, the degree to which these events impact public health will be determined by how the City prepares. San Francisco must continue to not only reduce exposure to climate change-related hazard events, but also adapt public health infrastructure, programs, and policies to respond to climate trends and associated health impacts, work with community members to increase individual and collective capacity to identify health impacts and pursue interventions, and coordinate among City departments to ensure resources are effectively streamlined to the most vulnerable populations.

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Appendix A.

Health Impacts Literature Review

Health Impact	Definition	Pathways	Historical Example	Vulnerable Populations
Physical Injuries	Physical injuries are injuries caused directly by flood inundation. These injuries can range from moderate to severe, and usual occur immediately before, during, or immediately after a hazard event.	Wet and flooded roads are hazardous for pedestrians, bicycles and cars, and collisions could cause physical injury. The high winds, heavy rains, and sewer overflows associated with extreme storms can create dangerous roadways, knock down trees and powerlines, and increase the risk of lacerations, scrapes, broken bones, and sprains due to slippery or flooded surfaces.	During 2012’s Hurricane Sandy, the most common causes of non-fatal injuries were blunt trauma, sprains, motor vehicle crashes, animal bites, and electrocution	<ul style="list-style-type: none"> • Elderly residents. • Low-income households. • Populations living in low-quality households. • Populations in high-risk flood zones. • Populations residing in residential care facilities.

Health Impact	Definition	Pathways	Historical Example	Vulnerable Populations
Respiratory Illness	Respiratory illnesses affect the lungs, throat, and airways. These illnesses can be spread through tiny airborne particles, and include asthma, allergies, and exposure to toxins and molds.	Flood inundation around the San Francisco shoreline could increase the rate of both internal and external mold growth. Mold growth in or on damp or flooded buildings, roadways, or infrastructure will increase rates of respiratory illness associated with mold growth.	During the summer of 2006, El Paso, Texas received more than two-times its average rainfall. The ensuing floods damaged 1500 homes. In a post-disaster study of hazard-affected residents, nearly 43% of respondents reported a physical injury in the four months following the flood—with some of the most reported physical injuries included allergies and respiratory conditions.	<ul style="list-style-type: none"> • Elderly residents. • Low-income households. • Populations without English language proficiency. • Populations living in low-quality households • Populations with pre-existing respiratory conditions
Waterborne Illness	Waterborne illness is caused by recreational or drinking water contaminated by disease-causing microbes or pathogens. These illnesses include waterborne shigella, protozoal infections such as cryptosporidiosis, giardia, cyclosporiasis, and microsporidiosis, parasitic infections, bacterial infections such as e. coli, m. marinum, leptospirosis, and viral infections such as hepatitis A.	Heavy precipitation events will push combined wastewater-stormwater containment and storage tanks past capacity. Untreated wastewater may overflow sewers and stormwater runoff is released directly into the San Francisco Bay. Direct contact with contaminated water could pose a threat to vulnerable populations.	In the Spring of 2001, the Mississippi River flooded parts of Minnesota, Wisconsin, North Dakota, Iowa, and Illinois. A subsequent 19-month study revealed rates of diarrhea, gastrointestinal illness symptoms and hospitalizations for gastrointestinal conditions increased among those in direct contact with contaminated floodwaters. There was also a statistically significant increase in Legionella pneumonia during and after Hurricane Sandy. Studies show cases of Legionella pneumonia increase after heavy rainfall and exists in abundance in puddles of rainwater on roads after particularly warm storms.	<ul style="list-style-type: none"> • Children • Elderly Residents • Populations with pre-existing health conditions • Populations in high-risk sewer overflow zones

Health Impact	Definition	Pathways	Historical Example	Vulnerable Populations
Foodborne Illness	Foodborne disease and illnesses refer to bacteria, viruses and parasites spread through the food we eat.	During power outages associated with extreme storms, refrigerator failures may cause perishable food to become unhealthy to eat. Heavy rain events in agricultural regions of California may exacerbate instances of foodborne illness in produce, as irrigation systems may become contaminated.	A 1997-1998 study of Florida coastal waters found fecal indicators to be at increased levels during the El Nino season. Rising Alaskan ocean temperatures in 2004 lead to an outbreak of <i>V. parahaemolyticus</i> in oysters.	<ul style="list-style-type: none"> • Elderly Populations
Vectorborne Disease	Vectorborne and zoonotic illnesses are diseases transmitted through animal vectors, including mosquitos, ticks, fleas, and host populations like rats and mice.	Standing water can provide disease-carrying populations a place to breed. Data has additionally proven that outbreaks of mosquito-borne Saint Louis encephalitis are correlated with seasons with both excessive rainfall in winter combined with hot temperatures in summer. Although mosquito-carried West Nile Virus has historically been concentrated in other Bay Area counties, changes in precipitation, especially towards wet and dry extremes, will impact both the growth and dispersal of mosquito population. Particularly rainy seasons after dry seasons have been proven to be linked to increases in host populations such as rats. Many hantavirus outbreaks in the United States follow particularly rainy seasons.	A 1993 Hantavirus outbreak in the Southwestern United States was caused by a steep and sudden increase in the deer mice population. Researchers speculate that a rainy season after six years of drought caused an overabundance of food for the deer mice, causing their numbers to skyrocket.	<ul style="list-style-type: none"> • Homeless Populations • Populations living in high-risk flood zones • Populations living in buildings with code violations.

Health Impact	Definition	Pathways	Historical Example	Vulnerable Populations
Mental Health	Mental health effects refer to how a hazard event could affect the psychological or emotional well-being of the citizenry in the short or long-term. These effects could include anxiety, depression, post-traumatic stress disorder, and other conditions.	Experiencing a hazard event, such as a flood or an extreme storm, may either cause or exacerbate mental health or interpersonal conditions. In addition to post-traumatic stress disorder, populations for whom the storm causes long-term displacement or isolation might show an increase in chronic health problems. Income-loss associated with a hazard event could also manifest itself as a mental health stressor.	In the years after the 2010-2011 Christchurch, New Zealand earthquakes, the city’s rates of depression and bipolar disorder both increased as residents tried to recover from the disaster while simultaneously having the prepare for the next disaster. § Hurricane Katrina evacuees at a Red Cross shelter in Texas were at an increased risk of post-traumatic stress disorder, depression, anxiety, and suicide. Hurricane Katrina evacuees in Houston were found to be at increased risk for substance abuse.	<ul style="list-style-type: none"> • Non-White Populations • Low-Income Households • Socially isolated populations • Populations with pre-existing mental health conditions

Health Impact	Definition	Pathways	Historical Example	Vulnerable Populations
Income Loss	<p>Income loss refers to the economic impact of extreme storms and flood inundation. Flood inundation and other health impacts place significant financial strain on citizens, businesses, and government. Because income and poverty are connected to many poor health outcomes, income-loss can be classified as an indirect impact of flood inundation.</p>	<p>The financial burden of sea-level rise, king tides, and storm surge will affect all San Franciscans. Needed infrastructure investments may cost taxpayers billions of dollars.</p> <p>Flood inundation and extreme storms will also impact San Franciscans on an individual basis. Those along an affected waterfront might need to privately finance adaptive building improvements, replace damaged property, or fund post-hazard repairs. Transportation delays and business closures may result in lost wages. School closures will force parents to either pay for childcare or miss work. Citizens who are either hospitalized for physical or mental trauma may have to pay medical bills.</p> <p>Income loss impacts public health. Those with prolonged financial stress are more likely to exhibit mental health conditions, be food insecure, have trouble affording medical treatments, and be socially isolated.</p>	<p>New York City estimates that October 2012's Superstorm Sandy caused at least \$19 billion in private losses.</p>	<ul style="list-style-type: none"> • Low-income households • Populations in high-risk flood zones • Populations with pre-existing health conditions.

Health Impact	Definition	Pathways	Historical Example	Vulnerable Populations
<p>Health Impacts of Power Outages</p>	<p>Income loss refers to the economic impact of extreme storms and flood inundation. Flood inundation and other health impacts place significant financial strain on citizens, businesses, and government. Because income and poverty are connected to many poor health outcomes, income-loss can be classified as an indirect impact of flood inundation.</p>	<p>Sea-level rise and extreme storms commonly cause power outages. Flood inundation could damage low-lying electrical infrastructure. High winds associated with extreme storms could knock trees into electrical wires or down utility poles.</p> <p>There are many ways a power outage may indirectly impact public health. For residents dependent on electricity to operate medical equipment such as home oxygen supply, insulin storage, lifts and hoists, electric wheelchairs, and air purifiers, any power outage significantly affect a resident’s ability to manage pre-existing health conditions such as respiratory disease, diabetes or physical disabilities. In buildings without backup generators, any interruption to the power system will impact infrastructure such as water pumps, heating and cooling systems, elevators, refrigerators, and carbon monoxide detectors. These services are vital, and could exacerbate instances of foodborne illness, waterborne disease, dehydration, heat stress, asthma, communicable disease, and carbon-monoxide poisoning. A power outage would impact transportation infrastructure. Residents dependent on MUNI or BART to get to health centers or pharmacies or access healthy food would be forced to find alternative methods of transportation. A significant power outage would impact communications. Without the ability to charge cell phones, residents will be less able to contact hospitals and clinics, family-members, and service-providers. Isolation from community exacerbates stress and mental health conditions.</p>	<p>Instances of carbon monoxide poisoning peak during power outages when residents use fuel burning equipment indoors. One study reported that generator use accounted for 54% of non-fatal and 83% of fatal carbon monoxide poisoning cases. Deaths increased by 28% during the 2003 Northeast blackout. The most vulnerable population was senior citizens.</p>	<ul style="list-style-type: none"> • Elderly • Residents with pre-existing health conditions dependent on electric medical equipment such as respiratory illness, and diabetes. • Residents with pre-existing mental health conditions. • Residents living alone. • Residents with mobility disabilities.

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Appendix B.

Vulnerable Populations Literature Review

Factor	Flood Vulnerability Variable	Data Collected	Impact on Flood Vulnerability
Demographic	Children	Percentage of residents under 18	Children are vulnerable to both direct and indirect impacts of flood inundation and extreme storms. Very young children more easily develop respiratory illness, malnutrition, exhaustion, and require specialized items such as formula or diapers. Research has shown that children are particularly vulnerable to mental health stressors. Families supporting children are at additional risk for income loss, and may require public assistance or resources to recover from a hazard event.
	Elderly	Percentage of residents aged 65 and over	Elderly residents are especially vulnerable to the health impacts of flood inundation. Residents over 65-years-old comprised nearly half of the deaths during and immediately after Hurricane Sandy. Elderly populations have been identified to be at increased risk of respiratory illness, foodborne and waterborne disease, and health impacts associated with power outages.
	NonWhite	Percentage of residents that do not identify as white (not Hispanic or Latino)	Because of historic and current economic, social, and political systemic inequities, populations of color are more likely to suffer from pre-existing health conditions, live in poor quality housing in high hazard exposure zones, and lack the political access and economic resources to prepare for and recovery from flood hazard events.
	Poverty	Percentage of all individuals below 200% of the poverty level	Financially insecure households often lack the resources necessary to prepare for, mitigate, or recover from the health impacts of flood events. This population is more likely to be uncaptured by the health network and be hospitalized for preventable conditions.
	Education	Percent of individuals over 25 with at least a high school degree	Educational attainment is correlated with health, income, and resilience. Those without a high school diploma are more likely to be estranged from government services. This population is vulnerable to the health impacts of flood inundation and extreme storms.
	English	Percentage of households with no one age 14 and over who speaks English only or speaks English "very well"	Those who cannot speak English will have a more difficult time recognizing warnings and public service announcements and interacting with public health officials. This population is likely to be non-native, and is more likely to live in overcrowded households and have pre-existing health conditions. During the 2006 El Paso floods, this population had higher rates of post-flood respiratory illnesses.

Factor	Flood Vulnerability Variable	Data Collected	Impact on Flood Vulnerability
Exposure Risk	Sea Level Rise / Coastal Flood Risk	Percent of land area in the 100-year flood plain with 36-inches of sea-level rise (77inch combined flood inundation)	The 100 year flood plain is the area most susceptible to flooding due to waves, storm-surge, and high tides.
	Precipitation / Inland Flood Risk	Percent of land area with over 6-inches of projected flood inundation during an 100-year-storm	During the 2001 Midwestern Floods, the highest rates of gastrointestinal illness were among populations in direct contact with contaminated water. Because the San Francisco sewer system combines wastewater and stormwater, a heavy precipitation event could result in exposure to contaminated water.
	Elevation	Minimum elevation in feet	Exposure to both coastal and inland flood inundation increases at lower elevations. Although elevation was factored into both the inland and coastal flood risk models, it was included as a separate indicator because of its status as a best practice determinant of most likely locations for flood inundation.

Factor	Flood Vulnerability Variable	Data Collected	Impact on Flood Vulnerability
Health Risk	Diabetes	Age-Adjusted Hospitalization Rate Due to Diabetes; Adults 18+	Residents with pre-existing health conditions requiring continuing care are vulnerable to service disruptions in the case of power outage, displacement, or disruption of City services. This assessment will use those with diabetes as a proxy for this population.
	Asthma	Age-Adjusted Hospitalization Rate Due to Asthma; Adults 18+	Studies have proven that indoor dampness can exacerbate instances of respiratory illness. Extreme storms and prolonged flood inundation may cause indoor water leakage and mold growth. Residents with pre-existing respiratory conditions such as asthma will be particularly vulnerable.
	Mental Health	Age-Adjusted Hospitalization Rate Due to Schizophrenia and Other Psychotic Disorders	Hazard events may exacerbate mental health conditions. Rates of mental health conditions such as bi-polar disorder, post-traumatic stress disorder, anxiety, and depression, all have increased after earthquakes in Christchurch, New Zealand and Hurricane Katrina in New Orleans.
	Physical Disabilities	Percentage of residents reporting a physical disability	Populations with physical or mobility disabilities are particularly dependent on local resources and services and vulnerable to any disruption to those services. Analysis into health impacts of Hurricane Sandy found this population to be highly correlated with income, age, social isolation, and poor housing quality.

Factor	Flood Vulnerability Variable	Data Collected	Impact on Flood Vulnerability
Infrastructure Risk	Homeless Population	Homeless population, per 1000 residents.	Urban homeless populations are particularly exposed to all hazard events and are among the populations most vulnerable to flood inundation and extreme storms. This population is more at-risk for infectious disease, more likely to suffer from mental health stressors and at a higher risk for psychological symptoms after the hazard. Homeless populations require special outreach in preparation of a flood even to reduce their exposure to the storm, and provide mental and physical care while in emergency shelters.
	Housing Violations	Annual Housing Violations, per 1000 residents	Housing quality is an important measure of risk and vulnerability in flood and extreme storm events. Residents living in households with many health and safety violations may be exposed to mold, have trouble evacuating, or be overcrowded.
	Living Alone	Percentage of households with the householder living alone	Those that live alone are at greater risk of illness or injury. They are more likely to be socially isolated and could be especially vulnerable while sheltering in place.

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