Amtrak train along the Martinez Shoreline in Contra Costa County. Photo by Cadet Wilson licensed under CC BY 2.0.

Chapter 2.5

TRANSPORTATION NETWORKS

Our region's transportation network moves us throughout the region and connects us to community facilities, jobs, family and friends, recreation and the many services we depend upon to thrive. Across the region's nine counties, 101 cities and numerous regional, state and national parks, there is a complex multimodal transportation network linking people, good and services to one another both within and outside the Bay Area. A dependable and resilient transportation system in the Bay Area is important for the region, state, and nation.

The ART Bay Area transportation assessment explores a variety of the region's transportation systems that may be at risk due to flooding from sea level rise. In the Bay Area, many of our critical transportation assets are often clustered around the shoreline. Ensuring our region's transportation networks are resilient in the face of flooding is critical to the future of the region.

The Key Takeaways listed highlight significant findings from the regional analysis of potential impacts from flooding for several of the Bay Area's regional transportation systems. More detailed findings from both the qualitative and quantitative analyses follow.

Ensuring our region's transportation networks are resilient in the face of flooding is critical to the future of the region.

IN THIS SECTION

**Methodologies and Limitations described for each Transportation Network after respective sections.*

2.5.1 Key Takeaways

- Many of the ground transportation assets in the Bay Area are vulnerable to sea level rise and storm events because many are located near the shoreline. In many cases, transportation infrastructure along the shoreline also serves as ad-hoc shoreline protection for communities located behind it.

- Bridge touchdowns are especially vulnerable since they are typically placed on bay fill and have experienced considerable subsidence.

- Tubes, tunnels, and roads with below-grade sections are particularly vulnerable because these are largely below current sea level and their openings are generally unprotected and at grade. Although much of the BART system in the Bay Area is elevated, assets critical to operations are located at grade or underground and are highly sensitive to even small amounts of water. The disruption or damage of these assets could shut down the entire BART system or a large portion of it.

Traffic on the I-80 heading towards San Francisco Bay Bridge. Photo by BCDC.

- Temporary flooding of vulnerable sections of interstate and state highways may not cause permanent asset damage but will have potentially significant consequences on both goods and commuter movement. This may also impact access for emergency responders as there is a lack of alternate routes with adequate capacity to serve all of the traffic needs.

- Rail lines are highly sensitive to even small amounts of water on the tracks, if a portion of track is damaged it often results in the closure of many miles of connected track, and there is a lack of redundant or alternative rail lines in the region. Flooding of the rail network has high consequences due to the reliance of the region's seaports on rail connections as well as the commuter role that much of the regional rail network serves. Disruption of the rail system would lead to an increase in the number of trucks needed to transport cargo, having negative and widespread effects on road congestion, air quality, community noise and quality of life.

- The Bay Trail is highly vulnerable to sea level rise and storm event flooding due to its construction and location along the shoreline. Erosion, poor drainage, and surface damage can all result in lengthy closures. Adaptive measures can be taken, such as building with different types of materials, improving drainage, and using boardwalks and bridges, but at some point, these will become ineffective.

- Both the San Francisco and Oakland International airports are vulnerable due to their low elevation and location along the shoreline, but their primary vulnerabilities may be due to the disruption of assets outside of the airport, such as flooded access roads. Disruption to the region's airports would have regional economic consequences on jobs and cargo movement, as well as local economic activities that are supported by the proximity of the airport, such as businesses that rely on frequent travel or ready access to cargo. There would also be broad national and international impacts on passenger and goods movement from flooding.

2.5.2 Regional Analysis of Transportation Network Systems

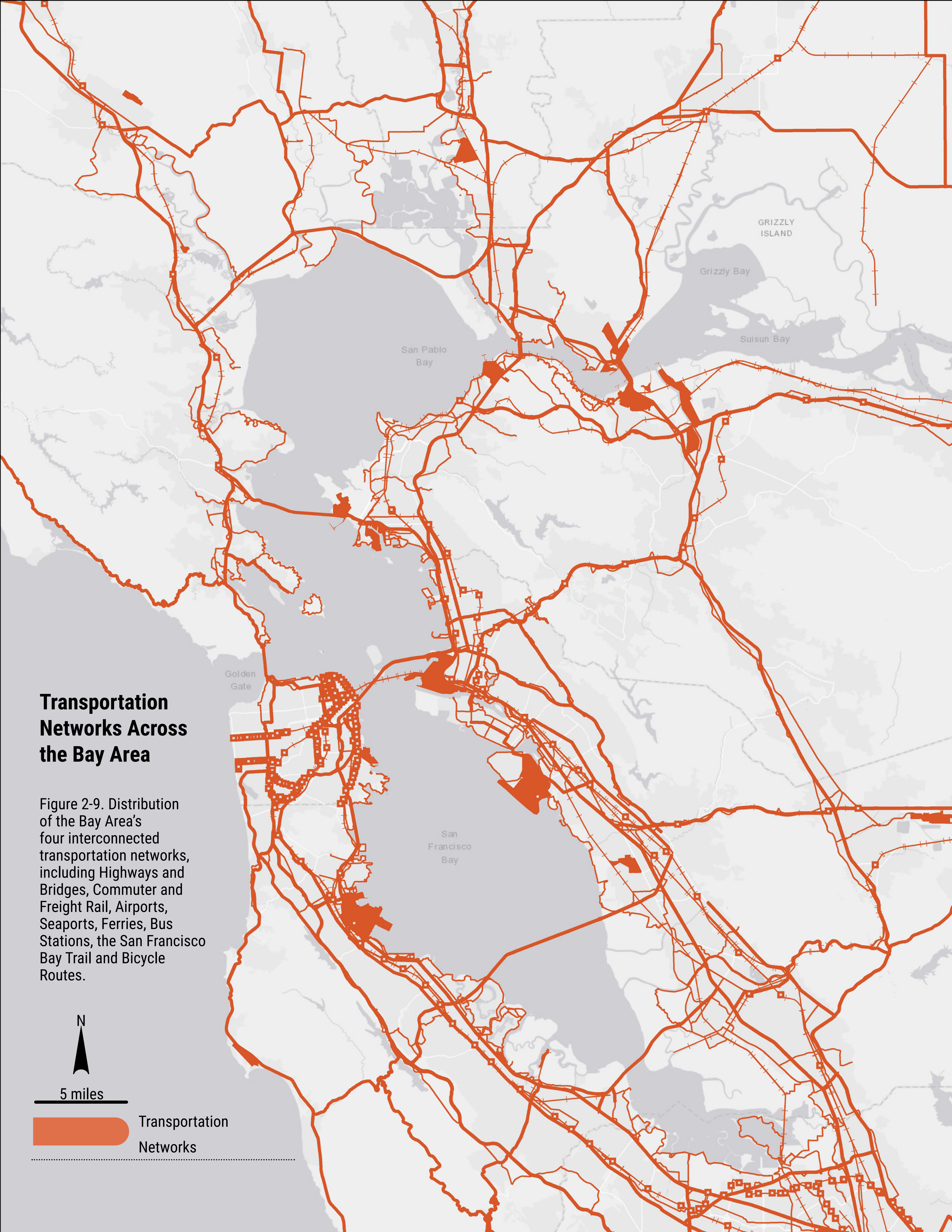
OVERVIEW

A dependable and resilient transportation system in the Bay Area is important for the region, state, and nation. This network of assets moves people, goods, and services throughout the region and links them with community facilities, jobs, family and friends, recreation, and services. Transportation is critical for the economic and social well-being of the Bay Area (Figure 2-9). Analysis of the region's transportation systems explores the vulnerabilities and consequences to current and future flooding from sea level rise and storm events. This analysis includes multiple components of the transportation system, including:

- Highways and Bridges
- Commuter Rail
- Freight Rail
- Airports
- Seaports
- Ferries
- Busses
- Active Transportation

In this analysis, we used two different methodologies to assess regional transportation system. The first is a data-driven quantitative assessment of regional exposure and consequences of flooding for transportation systems. The second methodology and approach to evaluating the transportation systems included a detailed qualitative assessment on a subset of transportation assets to understand and describe the characteristics and nuances of vulnerability. Vulnerability statements are described in this section that resulted from then detailed qualitative assessment. Methodologies can be found in the Appendix.

This chapter will discuss the details of the regional system assessed, results of the two analysis, and a discussion on what this means for the region moving forward.



Transportation Networks Across the Bay Area

Figure 2-9. Distribution of the Bay Area's four interconnected transportation networks, including Highways and Bridges, Commuter and Freight Rail, Airports, Seaports, Ferries, Bus Stations, the San Francisco Bay Trail and Bicycle Routes.

REGIONAL ASSESSMENT APPROACHES

Regional Data-Driven Consequence Results

This portion of the quantitative assessment is based on data-driven results from analysis of the region-wide consequence indicators. First, flood exposure of the transportation systems were analyzed to understand the extent and timing of exposure at ten different total water levels (TWLs). Thirteen consequence indicators were then identified and analyzed to measure the magnitude of flooding impacts to the transportation systems. This section outlines the results of the system-wide impacts within the eight transportation systems outlined above as total water levels rise. Table 2-2 indicates transportation indicators of consequence analyzed.

Individual Qualitative Assessment Results

The second portion of the assessment is based on a subset of assets identified to be regionally significant and were assessed using assessment questionnaires, desktop research, and stakeholder interviews to identify the nuances of vulnerability of individual assets. These results culminated in vulnerability statements that are described at the end of the transportation section. Additional details of the qualitative vulnerability assessments can be found in Chapter 3.0 Local Assessments that include information on shared vulnerabilities and consequences of flooding in specific locations around the Bay Area. This regional section focuses only on the regional scale results, while local results are in Chapter 3.0. Details on the different methodologies for selection can be found in the Appendix.

Freeways near San Francisco International Airport. Map data ©2019 by Google Earth Pro.

Structure of the Transportation Network Analyses

Each asset type and its exposure and consequence indicators are discussed separately in the following sub-sections. Following these exposure and consequence sections is the regional vulnerability statements resulting from the local assessments. Lastly, conclusions are drawn on transportation networks for the region.

Indicators of Consequence for Transportation Networks

Regional System	Asset Type	Consequence Indicator	Unit of Measurement
Transportation Network	**Highways and Bridges**	AADT	Annual average daily traffic (all vehicles)
		Truck AADT	Annual average daily truck traffic
		Lifeline Route	Binary (yes or no)
	Commuter Rail	Passenger Flow (Rail Lines)	Passengers per average weekday
		Ridership (Rail Stations)	Passengers per average weekday
	Freight Rail	Freight Train Flow	Freight trains per day
	Airports	Passengers	Boardings per year
		Cargo Volume	Pounds of freight per year (millions)
	Seaports	Cargo Volume	Dollar value of exports and imports
	Ferry Terminals	Ridership (by terminal)	Passengers per average weekday
	High Quality (HQ) Bus Routes	Miles of Impacted HQ Bus Routes	HQ Bus Routes (miles)
	San Francisco Bay Trail	Miles of Impacted Trail	Bay Trail (miles)
	Regional Bicycle Network	Miles of Impacted Bicycle Infrastructure	Bicycle routes (miles)

Table 2-2. Indicators used to measure consequence for Transportation assets in ART Bay Area.

2.5.3 Regional Transportation Network Results

HIGHWAYS AND BRIDGES

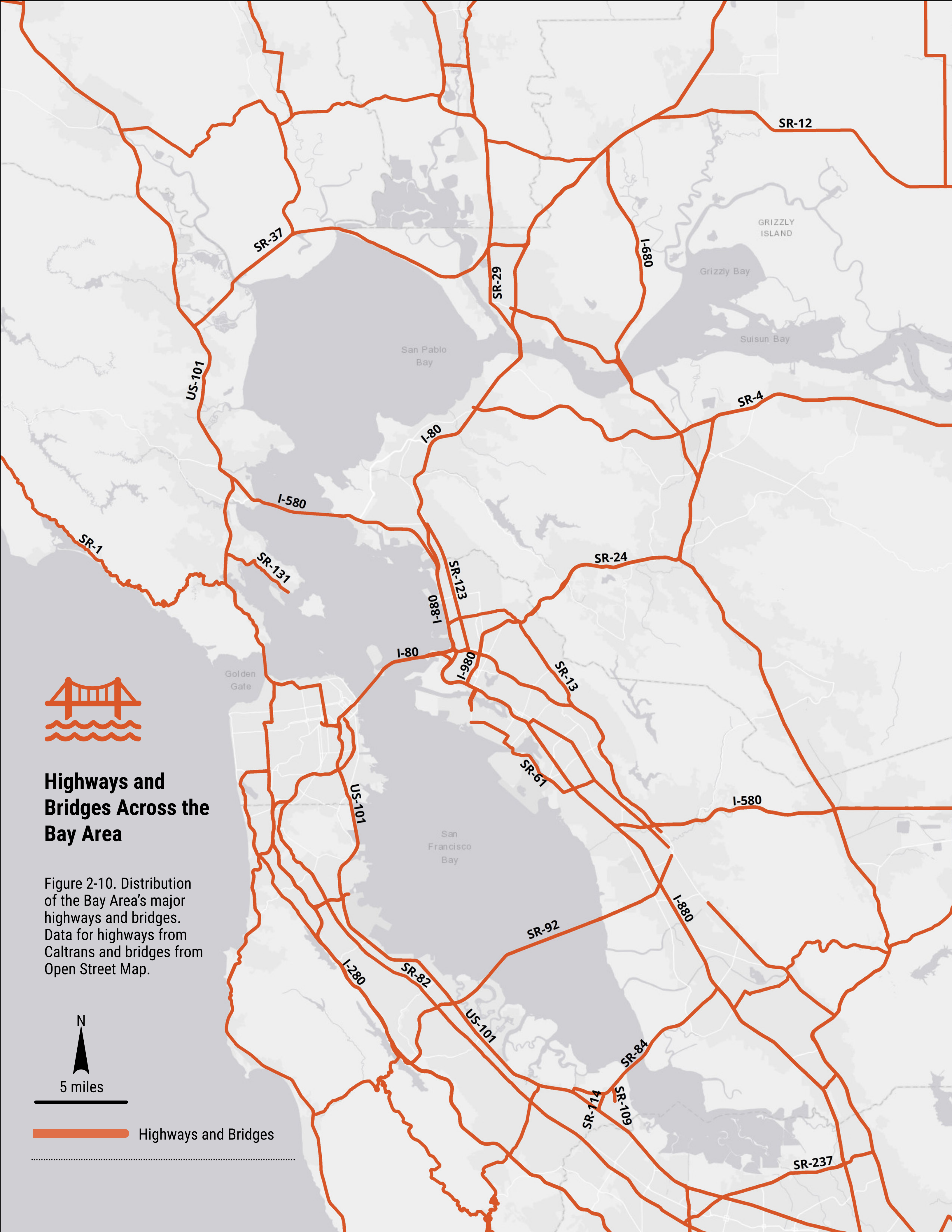
State and federal interstate highways serve to move people and goods through the region and provide a critical emergency response function. In the Bay Area, Caltrans District 4 manages seven major toll bridges as well as 1,440 miles of the State Highway System, which includes ten interstate highways, 38 state highways, and one U.S. highway (Figure 2-10). These assets provide critical transportation connections that support the region. As home prices have risen in the Bay Area, commuters move further away from jobs and are forced to travel further distances on our highway network, increasing the duration and intensity of congestion on Bay Area roadways, which are at or beyond capacity.

Many of the highway assets in the Bay Area are vulnerable to sea level rise and storm events because many are located near the shoreline. In many cases, highway infrastructure along the shoreline also serves as de facto or ad-hoc shoreline protection for communities located behind it. Additionally, the Bay Area is home to seven major bridges and numerous smaller bridges over tidal creeks and channels[1].

The touchdowns for these bridges are vulnerable to flooding because they have experienced substantial subsistence. Caltrans has begun developing spatial data to better reflect vulnerabilities (for example, for culverts or pumps). However, understanding the underlying causes of all vulnerabilities is challenging because some planning data (e.g., location of electrical facilities, pavement condition) are not readily available to the public, and design and survey data (e.g., structure elevation information) are not easily accessible to asset managers, such as through searchable, system-wide, centralized databases.

Temporary flooding of vulnerable sections of interstate and state highways may not cause permanent asset damage, but due to the lack of alternate routes with adequate capacity to serve all of the traffic needs flooding may have potentially significant consequences on both goods or commuter movement and access for emergency responders.

Impacts to the highway system are measured through three metrics: average annual daily vehicle traffic (AADT) along highway segments, average annual daily truck traffic (AADTT) along highway segments, and whether a certain segment of highway is a designated lifeline route, meaning that it is especially critical for emergency response operations.



Highways and Bridges Across the Bay Area

Figure 2-10. Distribution of the Bay Area's major highways and bridges. Data for highways from Caltrans and bridges from Open Street Map.

Regional Exposure of Highways and Bridges

The bar graph below shows the total length of highway flooded at each total water level both in total miles and as a percent of the regional total miles within the nine county Bay Area (Figure 2-11). This figure illustrates the relative magnitude of exposure throughout the Bay Area as compared to the system as a whole. Illustrating the data in this way shows that the length of highway miles exposed to flooding is relatively low compared to the total miles in the region, but because this relatively small percentage represents thousands of daily vehicle and truck traffic in the region, the impacts will still be significant. Figure 2-12 identifies which highway segments have the highest percent of highway miles exposed to flooding by county segment.

Flood exposure affects the degree of impacts and consequences. More widespread exposure amplifies impacts and consequences, and early exposure provides much less time to prepare, which may also amplify impacts and consequences. These nuances are important to bear in mind throughout the following sections describing regional consequence results.

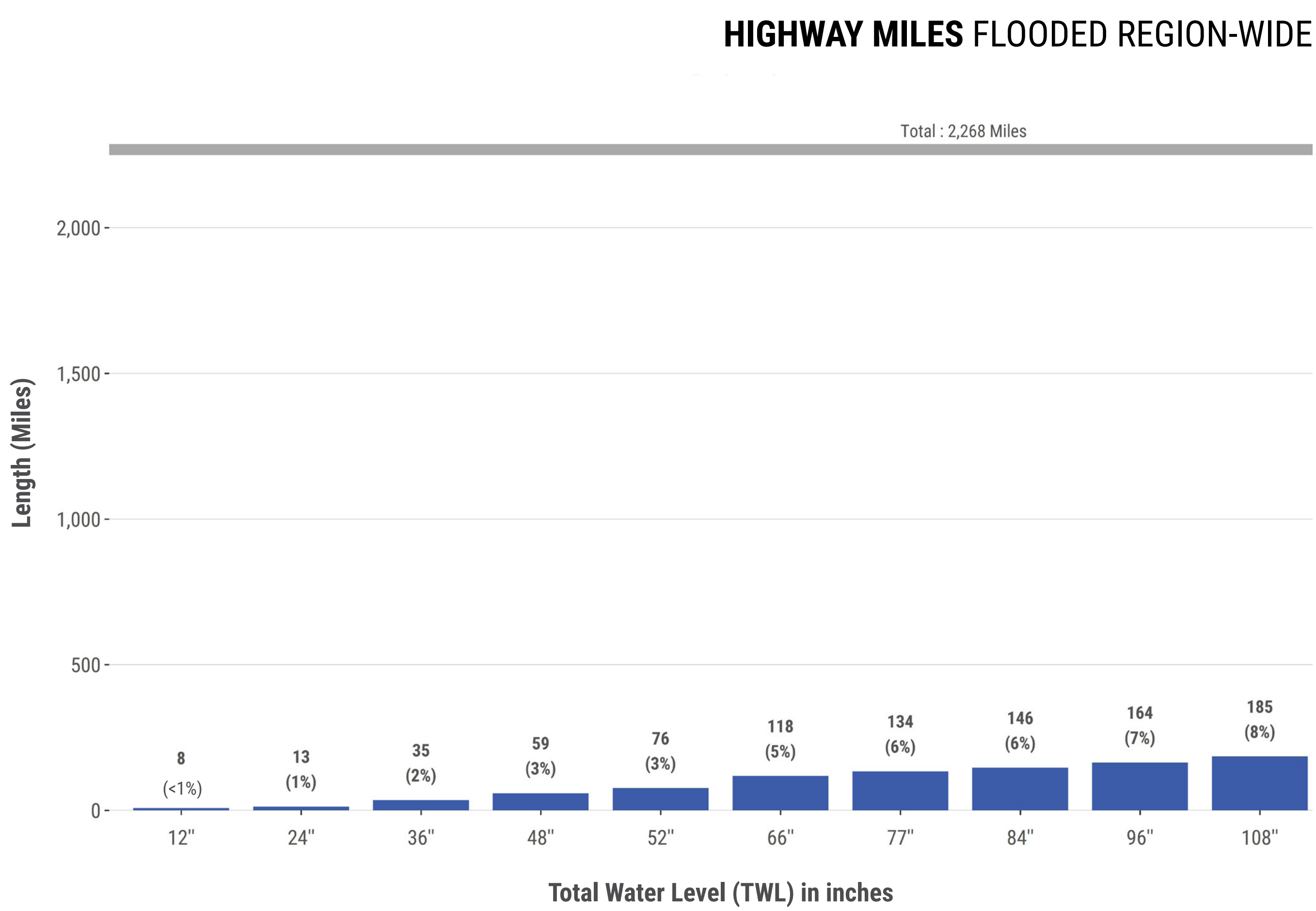


Figure 2-11. Regional exposure of highway miles by flooding. Values in parenthesis reflect the percent of miles exposed to flooding at each TWL compared to total miles of highway in the nine-county region.

Flooding on SR-37 in Novato, CA. Photo by Caltrans D4/Twitter.

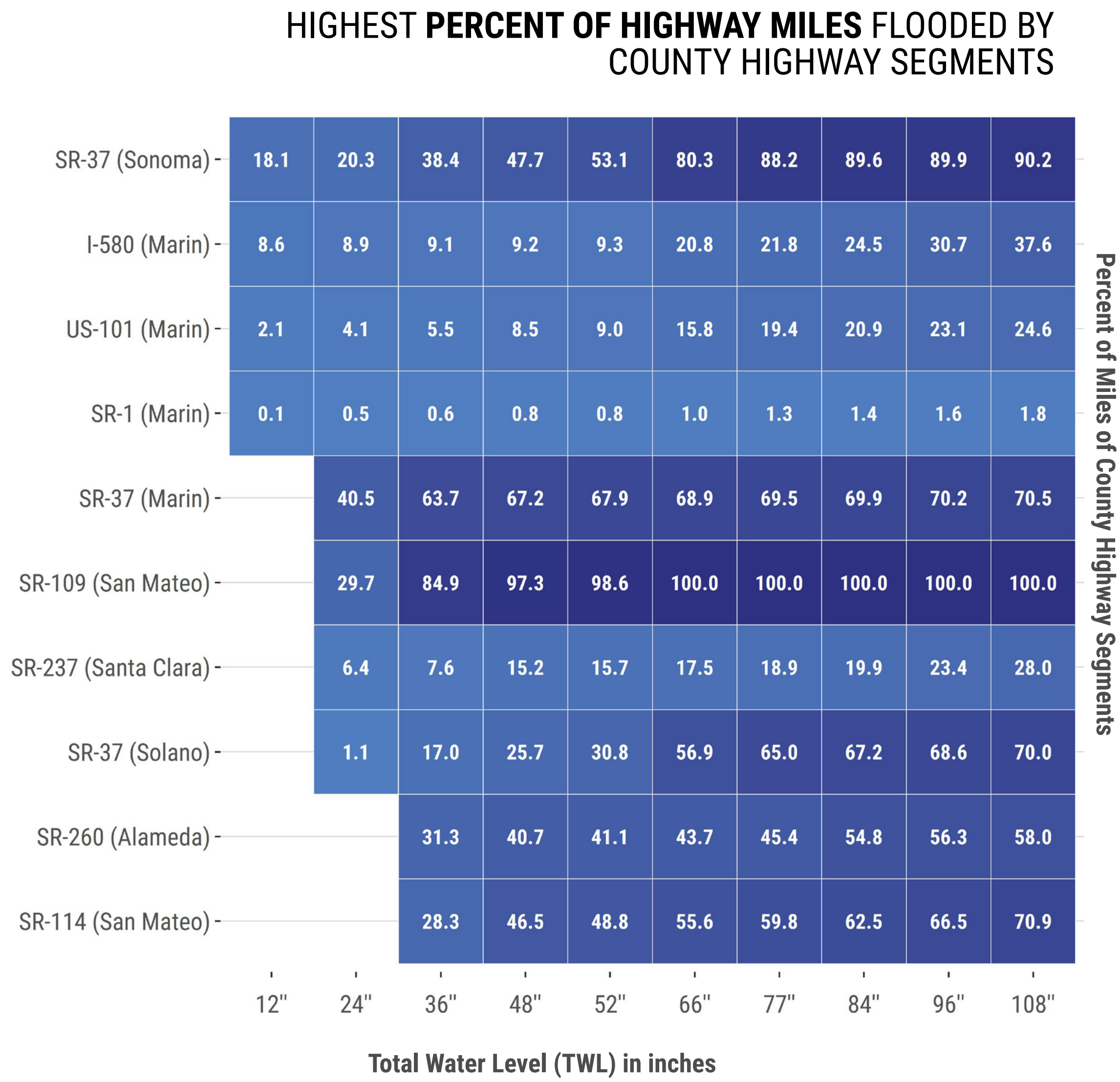


Figure 2-12. County highway segments with highest percent of highway miles exposed to flooding at ten TWLs. "Highest" exposure refers to segments ranking in the top five for highest exposure at one or more TWL. Darker colors reflect greater consequences from flooding.

Regional Consequences of Highways and Bridges

Region-wide, at 12" TWL, nearly 700,000 daily vehicle trips are impacted by flooding (Figure 2-13). These impacts grow fairly rapidly until 108" TWL, with the biggest jump between 48" and 52" TWL, going from just over 5 million daily trips to just over 7 million. By 108" TWL, over 12.3 million daily vehicle trips are potentially impacted by flooding. Early impacts are focused primarily in the North Bay but remain steady in this area over increasing water levels. However, the East Bay is not impacted until 48" TWL, but impacts become significantly worse over time. County highway segments with the highest consequences are discussed in the next section (shown in Figure 2-14) and depicted spatially in maps of consequence in Figure 2-17.

Truck traffic follows a similar trend over time and around the region but on a smaller scale, with nearly 24,000 daily truck trips impacted at 12" TWL, and a jump from 226,000 to 323,000 daily trips between 48" and 52" TWL (Figure 2-15). By 108" TWL, nearly 600,000 daily truck trips are impacted due to flooding. County highway segments with the highest consequences are discussed in the next section (shown in Figure 2-16), and depicted spatially in maps of consequence in Figure 2-17.

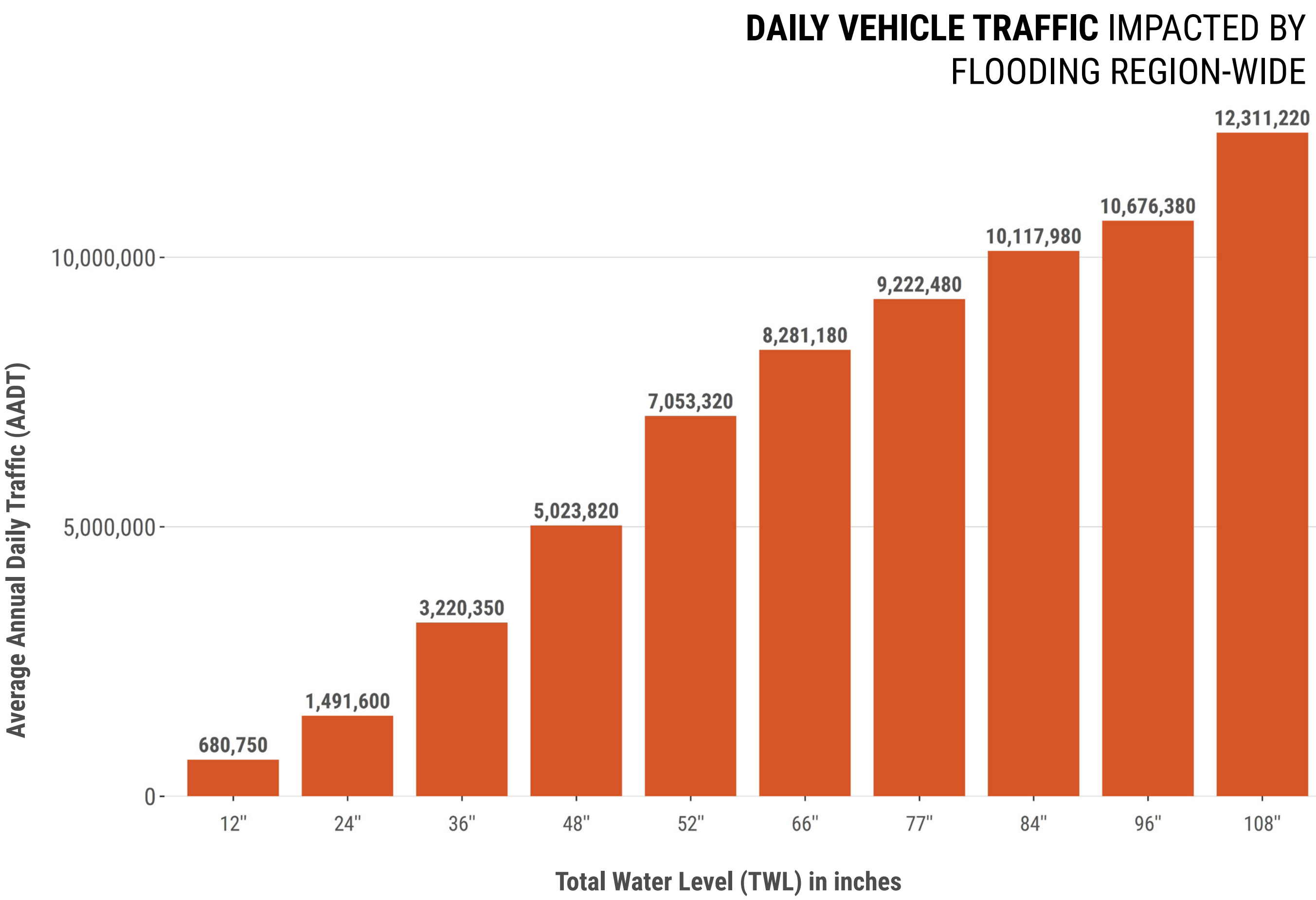


Figure 2-13. Regional impacts to highway vehicle traffic from flooding at ten TWLs as measured by impacts to annual average daily traffic (AADT). Results are aggregated across the nine-county region.

HIGHEST **DAILY VEHICLE TRAFFIC** IMPACTED BY FLOODING BY COUNTY HIGHWAY SEGMENTS

Average Annual Daily Traffic (AADT) (Thousands)

	12"	24"	36"	48"	52"	66"	77"	84"	96"	108"
US-101 (Marin)	520	520	520	1,080	1,080	1,380	1,380	1,380	1,580	1,580
I-580 (Marin)	80	80	80	80	80	80	80	80	80	170
SR-37 (Sonoma)	40	40	80	80	80	80	80	80	80	80
US-101 (San Mateo)		240	980	1,210	1,910	1,910	2,150	2,150	2,150	2,150
I-880 (Alameda)		220	220	670	1,110	1,110	1,330	1,800	2,010	2,460
SR-37 (Solano)		110	150	150	150	150	150	150	150	150
SR-37 (Marin)		80	80	80	80	80	80	80	80	80
US-101 (Santa Clara)			400	400	400	400	400	400	400	400
I-80 (Alameda)			220	430	640	640	860	860	860	1,690
I-580 (Alameda)						260	340	590	590	590
I-580 (Contra Costa)						80	80	80	80	80
US-101 (San Francisco)						60	60	60	60	60
I-80 (Contra Costa)							230	370	370	370
SR-37 (Napa)								40	40	40
I-880 (Santa Clara)									220	220
US-101 (Sonoma)									130	130

Total Water Level (TWL) in inches

Figure 2-14. County highway segments with highest impacts to highway vehicles by flooding at ten TWLs as measured by impacts to annual average daily traffic (AADT). "Highest" impacts refer to segments ranking in the top five for highest consequences at one or more TWL. Darker colors reflect greater consequences.

Trends and Drivers Around the Region

Passenger and Truck Vehicles

Early Impacts • All the early exposure of highways occurs in Marin County on SR-1, US-101, SR-37, and I-580 with segments of US-101 in San Rafael and Corte Madera representing the largest consequence for vehicle volume (Figures 2-14 and 2-17). All of these highway segments see early consequences for truck traffic, with US-101 and I-580 representing the largest number of impacted truck trips (Figures 2-16 and 2-17). All of these segments (with the exception of SR-1) are designated Lifeline Routes. At 24" TWL, exposure of highways expands to include segments of US-101 and SR-109 in San Mateo County, SR-237 and I-880 in Santa Clara County, SR-131 (Tiburon Boulevard) in Marin County, and SR-37 in Napa County. Exposure of US-101 in both Marin and San Mateo Counties represents the highest impacts to vehicle volume, followed by exposure of I-880 in Santa Clara County. These rankings change slightly with respect to truck trips, as I-880 has a higher volume of truck trips impacted than US-101 in San Mateo County. With the exception of SR-237, SR-109, and SR-131, these highways are all designated as Lifeline Routes.

Worsening Impacts • Regionally, impacts to vehicle traffic significantly worsens between 48" and 52" TWL. However, truck traffic consequences significantly worsen between 36" and 48" TWL, 48" and 52" TWL, and 96" and 108" TWL. The first two consequence jumps are due primarily to exposure of I-880 and US-101 in Alameda and San Mateo Counties, respectively, and the final jump is a result of increased exposure of I-80 in Contra Costa and Alameda Counties, I-880 at multiple locations in Alameda County, and SR-237 in Santa Clara County.

Worsening Impacts • Significant outliers in terms of large jumps in consequences to both vehicle and truck volume at higher water levels occur on exposed segments of I-880 in Alameda county at 48" TWL, US-101 in San Mateo county at 52" TWL, and I-80 in Alameda and Contra Costa Counties at 108" TWL.

Short Case Study

LINKING REGIONAL CONSEQUENCE RESULTS TO LOCAL ASSESSMENTS

Highways in Marin County are already experiencing the impacts of flooding during King Tide events and storms. These impacts will only increase with sea level rise. Regionally, these are some of the earliest highway impacts we anticipate seeing in the Bay Area (e.g. SR-37, US-101, I-580, and SR-1).

These impacts are further complicated by a general lack of redundancy of routes and public transit in the county. To address these existing and future impacts, Marin County and Caltrans are conducting adaptation planning work.

In addition to the regional assessment, ART Bay Areas assessed individual assets in each of the four region systems and the results are communicated in local assessments of shared vulnerabilities and consequences.

These can be found in Chapter 3.0 Local Assessments of the ART Bay Area report, with local assessments available for individual download.

King Tides lead to flooding at a Highway 1 off-ramp, Marin County. Photo by Brant Ward, Associated Press obtained from the SF Chronicle.

Dumbarton Bridge SR-84 west touchdown during King Tides in December 2019. Photo by SF Baykeeper, Robb Most, and LightHawk.

DAILY TRUCK TRAFFIC IMPACTED BY FLOODING REGION-WIDE

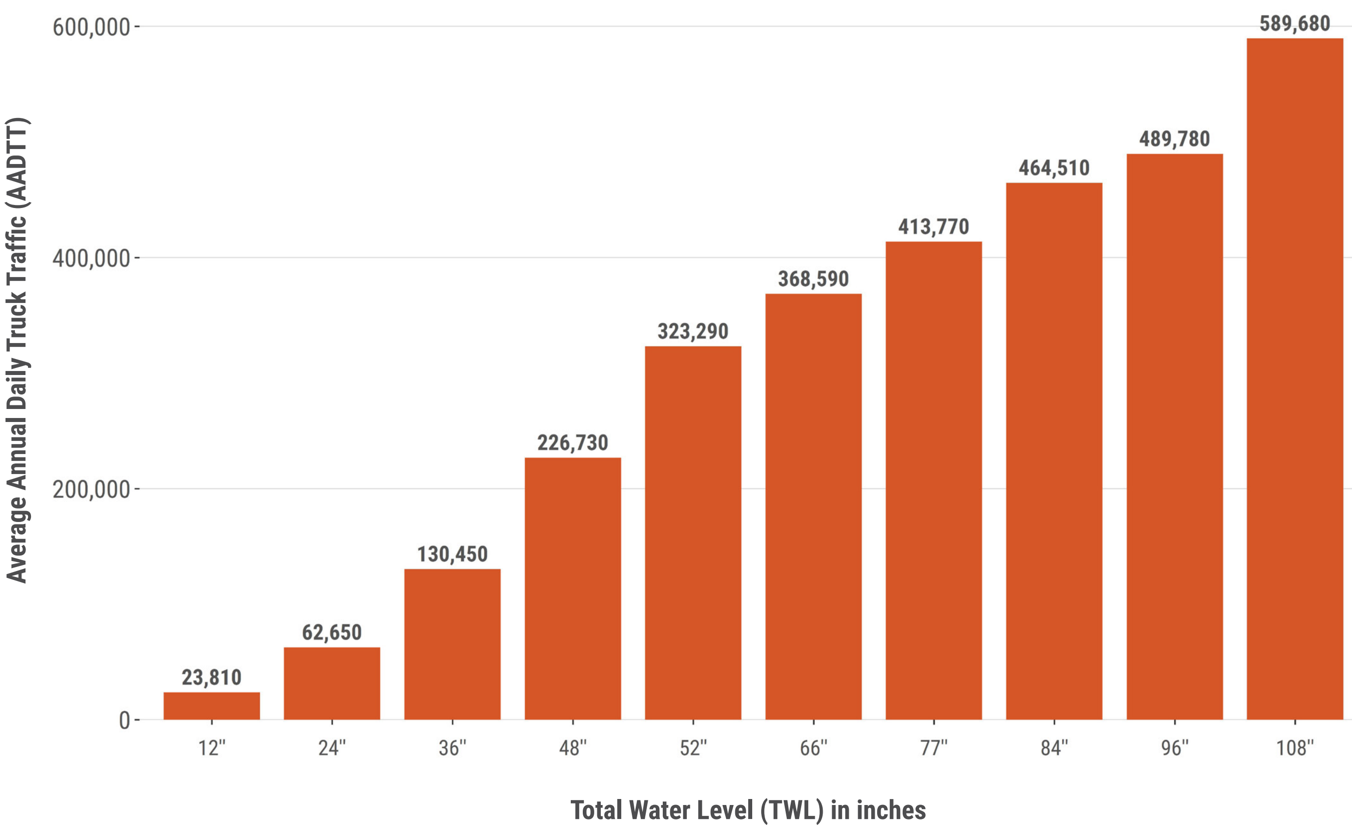


Figure 2-15. Regional impacts to highway truck traffic from flooding at ten TWLs as measured by impacts to annual average daily truck traffic (AADTT). Results are aggregated across the nine-county region.

HIGHEST **DAILY TRUCK TRAFFIC** IMPACTED BY FLOODING BY COUNTY HIGHWAY SEGMENTS

Average Annual Daily Truck Traffic (AADTT) (Thousands)

Segment	12"	24"	36"	48"	52"	66"	77"	84"	96"	108"
US-101 (Marin)	16.0	16.0	16.0	36.9	36.9	46.9	46.9	46.9	54.4	54.4
I-580 (Marin)	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	10.9
SR-37 (Sonoma)	1.7	1.7	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1
I-880 (Alameda)		11.1	11.1	55.2	90.9	90.9	102.8	142.2	153.2	192.3
US-101 (San Mateo)		10.6	40.4	49.8	78.4	78.4	89.0	89.0	89.0	89.0
SR-37 (Solano)		7.4	12.3	12.3	12.3	12.3	12.3	12.3	12.3	12.3
SR-237 (Santa Clara)		5.9	5.9	5.9	5.9	11.8	11.8	11.8	11.8	20.1
SR-37 (Marin)		3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2
US-101 (Santa Clara)			17.5	17.5	17.5	17.5	17.5	17.5	17.5	17.5
I-580 (Contra Costa)						5.5	5.5	5.5	5.5	5.5
I-580 (Alameda)						1.5	7.0	10.8	10.8	10.8
US-101 (San Francisco)						0.9	0.9	0.9	0.9	0.9
SR-37 (Napa)								3.4	3.4	3.4
I-880 (Santa Clara)									11.1	11.1
US-101 (Sonoma)									5.5	5.5

Total Water Level (TWL) in inches

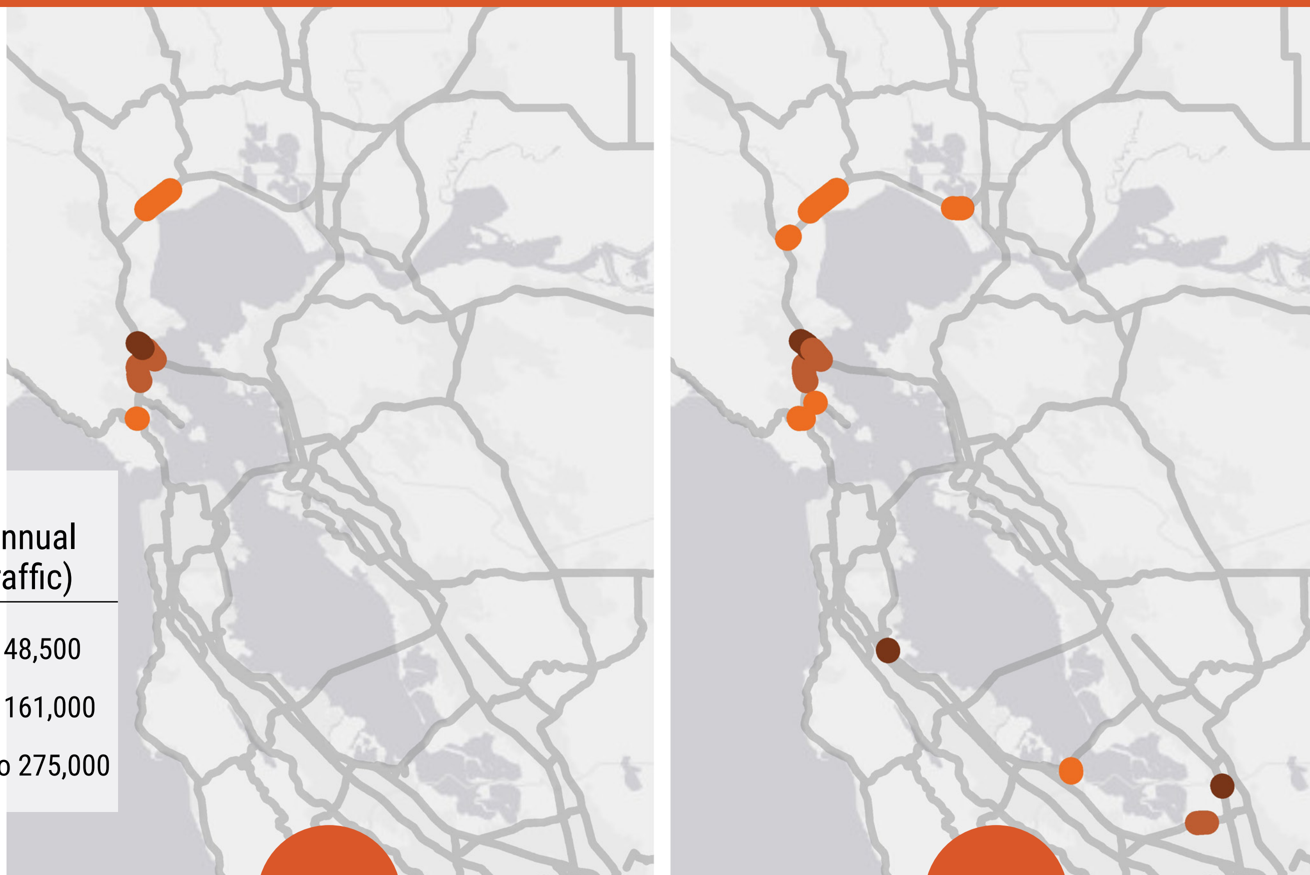
Figure 2-16. County highway segments with highest impacts to highway trucks by flooding at ten TWLs as measured by impacts to annual average daily truck traffic (AADTT). "Highest" impacts refer to segments ranking in the top five for highest consequences at one or more TWL. Darker colors reflect greater consequences.

CONSEQUENCES OF FLOODING

Transportation

Highways and Bridges

Daily Vehicle Traffic Impacted by Flooding



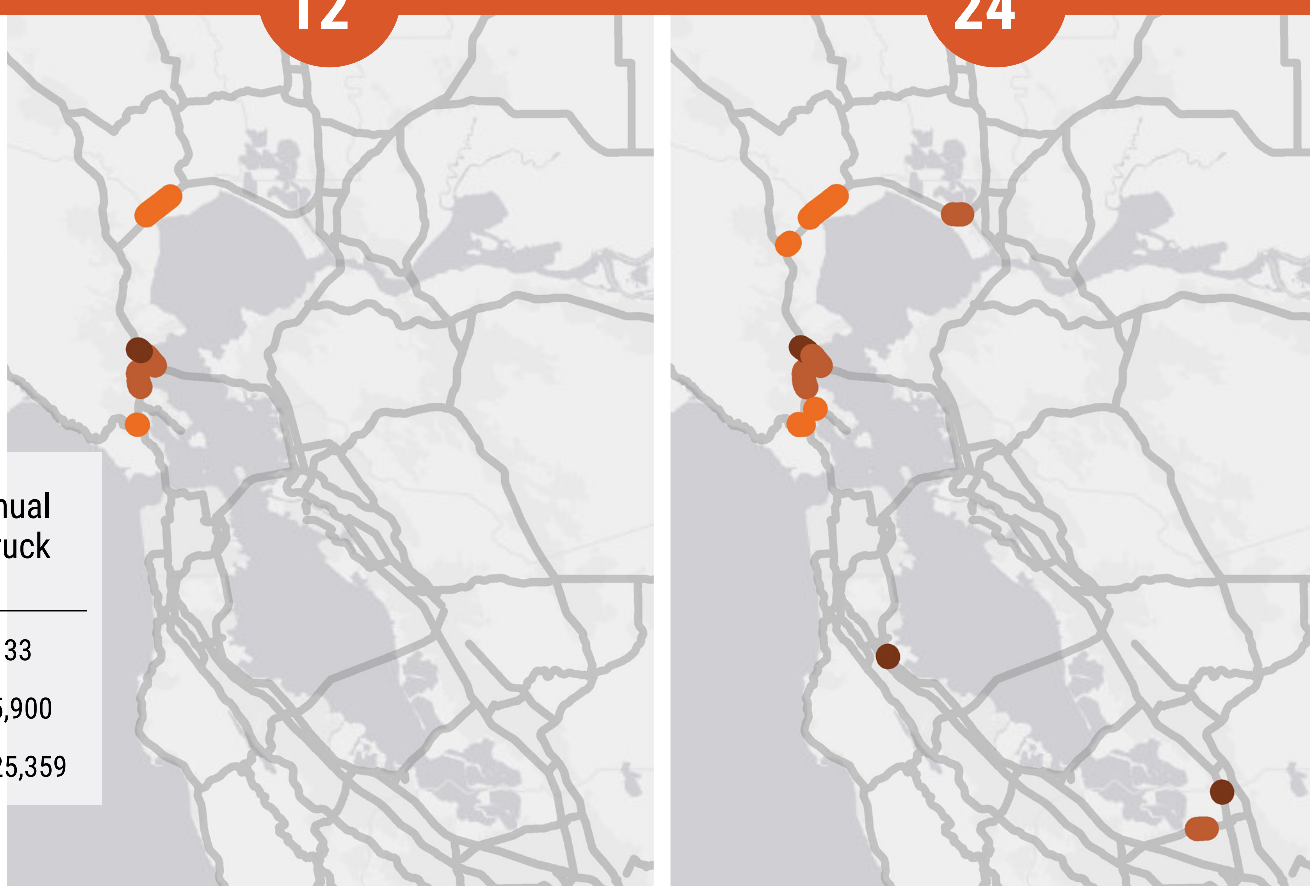
# of Vehicles (Annual Average Daily Traffic)

- 18,475 to 48,500
- 48,501 to 161,000
- 161,001 to 275,000

12"

24"

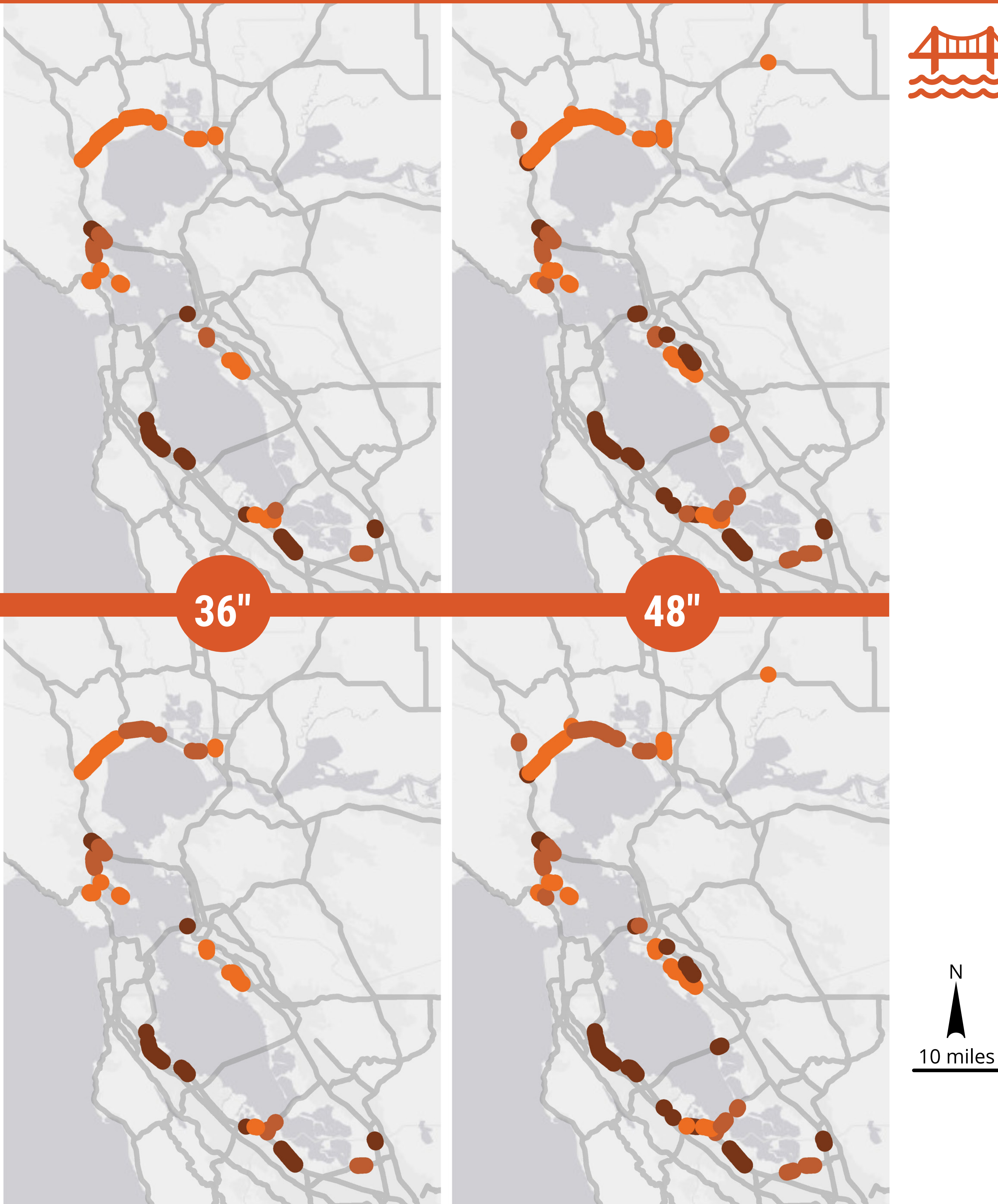
Daily Truck Traffic Impacted by Flooding



# of Trucks (Annual Average Daily Truck Traffic)

- 623 to 2,133
- 2,134 to 5,900
- 5,901 to 25,359

Figure 2-17. Maps depicting the consequences of flooding for two Highways and Bridge indicators: *Annual Average Daily Traffic* and *Annual Average Daily Truck Traffic* at 12", 24" 36" and 48" TWL. Maps below show consequences and extent of exposure.



Methodology and Limitations for Highways and Bridges

Methodology

The consequence of flooding to highways was measured using three different indicators: traffic volume, truck traffic volume, and Lifeline Routes. AADT is the total volume of all vehicle traffic on a highway for a year divided by 365 days. AADTT is the total volume of truck traffic on a highway for a year divided by 365 days. AADT represents the importance of the highway to the general population, including commuters. AADTT represents the importance of the highway to cargo and freight transport. These indicators were chosen because they are standard measures of traffic flow used in transportation planning and are regionally available for the entire Bay Area. Both AADT and AADTT volumes were provided by Caltrans at discreet points along the highway system. Lifeline Routes are designated by MTC and represent routes that are of critical importance to regional mobility.

Limitations

This approach has significant limitations in comprehensively reflecting highway and bridge vulnerability in the region. In addition to the consequence of flooding on roadways, the regional highway system is vulnerable due to numerous other factors. These include:

Drainage Channels • Across Caltrans assets, maintenance of drainage systems is a top concern when it comes to current and future flood risk. Some highway drainage channels are not being sufficiently maintained because the channel or ditch leads directly to land held by neighboring property owners/managers who do not maintain the drainage for a variety of reasons (e.g. cost, regulations, sensitive ecological habitat). As drainage channels become silted in or vegetated, they lose capacity to conduct water away from the roadway. This leads to a backup and pooling of water which may flood the roadway or increase erosion along the road margin. In the North Bay, Caltrans must work to collaborate with a large number of property owners on this issue (e.g. private landowners, land trusts, U.S. Dept. Fish and Wildlife, etc.). In the East Bay, the number of the property owners is more limited, primarily Alameda Flood Control District. While Caltrans can work to cooperate with these stakeholders, it has no power to enforce the maintenance of drainage channels needed to keep highways (and surrounding assets) dry.

Culverts • Caltrans drainage is also operating below design capacity because maintenance of culverts (where drainage channels flow under roadways and railways) has been neglected. Many of the culvert conveyance pipes and caps have corroded and are leaking or have collapsed entirely—this has prompted Caltrans District 4 to start a system-wide culvert health assessment. The assessment measures the condition of the conveyance pipes as well as the end caps for critical or poor conditions and recommends restorative action. Poor culvert health is an

Pumps in Emeryville are used to reduce local flooding impacts. Photo by BCDC.

indicator of potential flood risk because it indicates where water will backup and flood the roadway. For example, under the current assessment of culvert health there are a number of end caps in critical condition along the SR-37 corridor.

Pumps • Pumps are another crucial part of Caltrans' drainage assets which will need be improved as they are taxed by increasing storms and groundwater. The location of the groundwater pumps (which are running constantly) are a clear indication of sites that are highly vulnerable to rising groundwater, such as Bird Avenue in Santa Clara. Sea level rise may increase the groundwater table and flood conditions may make it difficult to identify spots where flood waters can be pumped/received. For example, the intersection of Cutting Boulevard and I-580 in Richmond is the location of existing pumps and is also flood prone to sea level rise and storms. Back up pumps and back up electricity are important for pumps around the Bay, particularly at groundwater pumps.

Subsidence • Subsidence is also of concern across Caltrans highways, particularly at bridge approaches which are often built on fill. Examples of extreme subsidence can be seen at the Manzanita Park and Ride in Marin which is now 3 ft. lower than its original grade and the shoulder of SR-37. Evidence of subsidence is seen at bridge approaches as potholes and uneven roadways create dangerous driving conditions—Caltrans deals with this by regularly repaving, adding to the weight of the roadway and ultimately accelerating subsidence. Despite these roadway and bridge approach subsidence issues, Caltrans Bridge Maintenance is confident in the safety of all of the bridges it manages. The bridge pilings are designed such that they are not impacted by subsidence or water that may flow around them in storm events (regardless of whether those pilings are located in creeks beds or highway over-passes).

Bridge Touchdowns • Many bridge touchdowns are built on fill and therefore vulnerable to subsidence and liquefaction. For the major bridges in the Bay Area, the touchdowns are typically the location of toll plazas, which rely on other utilities such as power, access, and oftentimes include Caltrans fueling facilities (e.g. SR-92). In general, these major bridges lack redundancy and disruption of parts of the touchdown can have major regional impacts to commuter and goods movement. Often, these are also classified as lifeline routes and support the movement of public bus transit (e.g. San Francisco – Oakland Bay Bridge). Furthermore, some bridge touchdowns (San Francisco – Bay Bridge eastbound, San Mateo – Hayward eastbound) in the region are located adjacent to sensitive tidal marsh habitat and/or habitat for listed species, complicating permitting and construction of restoration projects.

Bridge Scour • Caltrans has conducted a bridge health survey throughout District 4 and has examined scour condition for a number of bridges. This survey found that the bridge scour condition was poor for two bridges within the 108” TWL, including crossings at San Antonio Creek (Sonoma County, US-101), and Sarco Creek (Napa County, SR-121). Caltrans engineers have indicated that the predicted increase in scour of bridge supports with higher water levels associated with sea level rise is not a concern.

Pavement • Pavement type and condition is an important factor in understanding highway and interstate vulnerability. Frequent saturation of roadbed can lead to structural failures and increased maintenance of roadways. Once flooding does occur, there are certain distinguishing characteristics of Caltrans assets that make it harder for them to recover. Those highways built with Portland Cement Concrete (PCC) slabs are more likely be damaged by the effect of traffic driving through floodwaters on those slabs. Caltrans is trying to work to remove and replace these PCC slabs but some of them still exist in District 4.

Electrical • Electrical components play an important role in the day to day operation of Caltrans assets. At sites where electrical components run under roadways that routinely face salt-water exposure, those electrical components may be damaged. This impacts function of traffic signals, loop detectors, and traffic detectors. For example, the traffic signal at the Manzanita Park and Ride does not operate correctly as the Manzanita junction box is below ground and has corroded wiring that shorts out when flooded, causing outages of pedestrian signals at cross walks. Caltrans is currently investigating possible fixes to raise the junction box above the water line.

Co-location of Utilities • Utilities located under or along roadways may mean there are additional impacts of a flooded roadway. This is especially true where those utilities have not been insulated against saltwater exposure or that were constructed long ago. For example, SR-12 in Solano County has both a jet fuel pipeline and a PG&E natural gas pipeline co-located within it. The condition of these pipelines is unknown but repeated saltwater exposure may damage the pipes leading to toxic contamination and environmental damage.

Dumbarton Bridge SR-84 east touchdown surrounded by PG&E electrical substation. Map data ©2019 by Google Earth Pro.

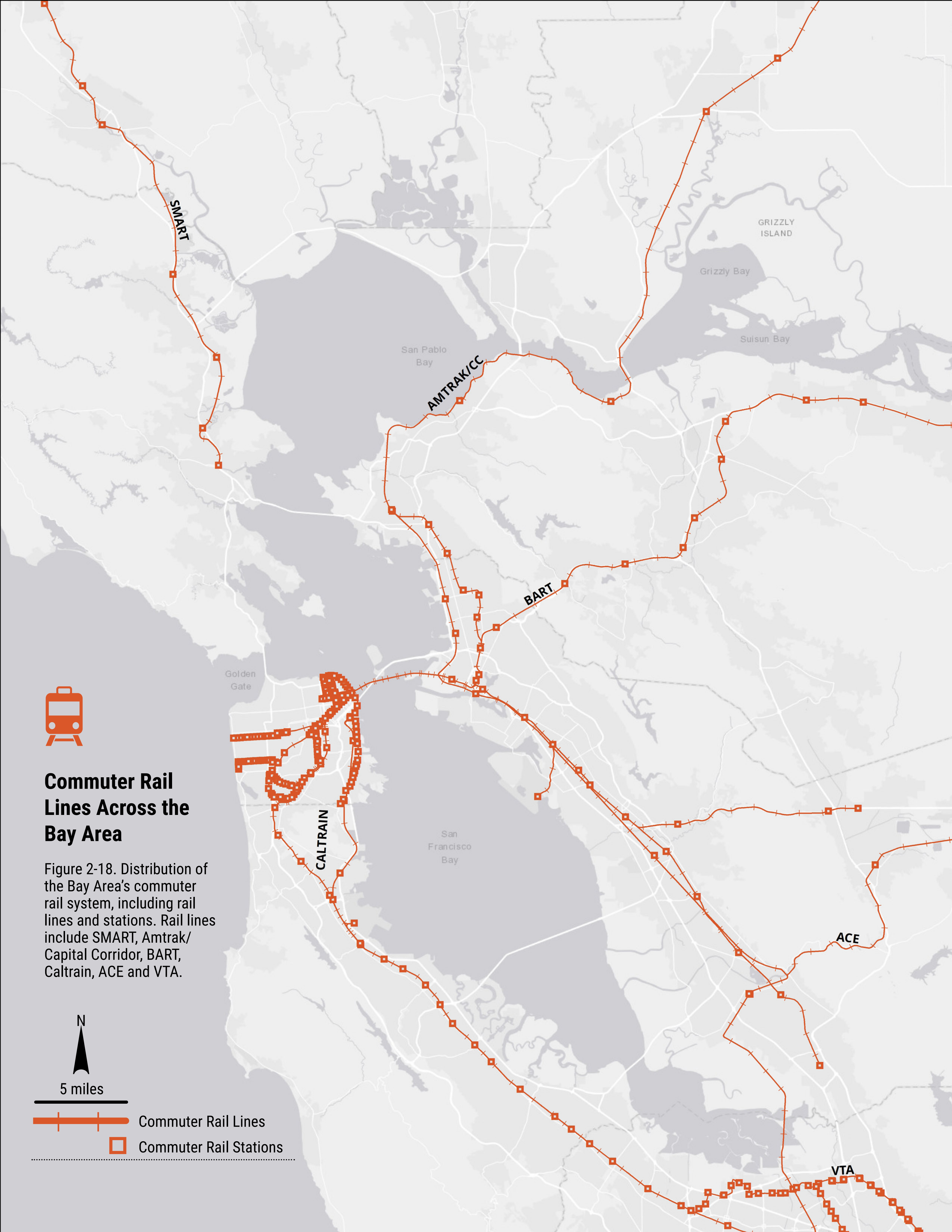
COMMUTER RAIL

The Bay Area is home to four regional and two intracity commuter rail operators linking seven of the nine Bay Area counties. On an average weekday, approximately 325,000 people take some form of commuter rail service to work, school, or tourist destinations[2].

In the Bay Area, commuter rail operates as a network with other local transit services and regional airports (Figure 2-18). The critical components of the commuter rail are the tracks, stations, power and signaling system, maintenance facilities, storm drain facilities, parking lots, and local road access. Commuter rail service can be on dedicated tracks used solely for that service (e.g. San Francisco Municipal Railway (Muni), Santa Clara Valley Transportation Authority (VTA), Bay Area Rapid Transit (BART) or may share the rail right-of-way with freight or other commuter services (e.g. Caltrain, Sonoma Marin Area Rapid Transit (SMART), Capitol Corridor (CC)/Amtrak/Altamont Corridor Express (ACE)). Most commuter rail service is already electrified and other operators (e.g. Caltrain) are in the process of electrifying the majority of their track[3].

Impacts to commuter rail are measured through two indicators: the number of passengers impacted as measured by passenger flow along rail lines, and the number of passengers impacted as measured by passenger ridership at rail stations.

Commuters taking the Santa Clara Valley Light Rail in San Jose.
Photo by Richard Masoner / Cyclelicious licensed under CC BY 2.0.



Commuter Rail Lines Across the Bay Area

Figure 2-18. Distribution of the Bay Area's commuter rail system, including rail lines and stations. Rail lines include SMART, Amtrak/Capital Corridor, BART, Caltrain, ACE and VTA.

Regional Exposure of Commuter Rail System

Commuter Rail Lines Exposure

The bar graph below shows the total length of commuter rail flooded at each total water level both in total miles and as a percent of the total miles within the nine county Bay Area (Figure 2-19). This figure illustrates the relative magnitude of exposure throughout the Bay Area as compared to the system as a whole. Illustrating the data in this way shows that the length of commuter rail miles exposed represents a substantial amount of the region's commuter rail line capacity, and subsequently significant impacts to passenger flows. This graph also illustrates how exposure increases over time. Figure 2-20 identifies which commuter rail segments have the highest percent of rail miles exposed to flooding by county segment.

Exposure affects the degree of impacts and consequences. More widespread exposure amplifies impacts and consequences, and early exposure provides much less time to prepare, which may also amplify impacts and consequences. These nuances are important to bear in mind throughout the following sections describing regional consequence results.

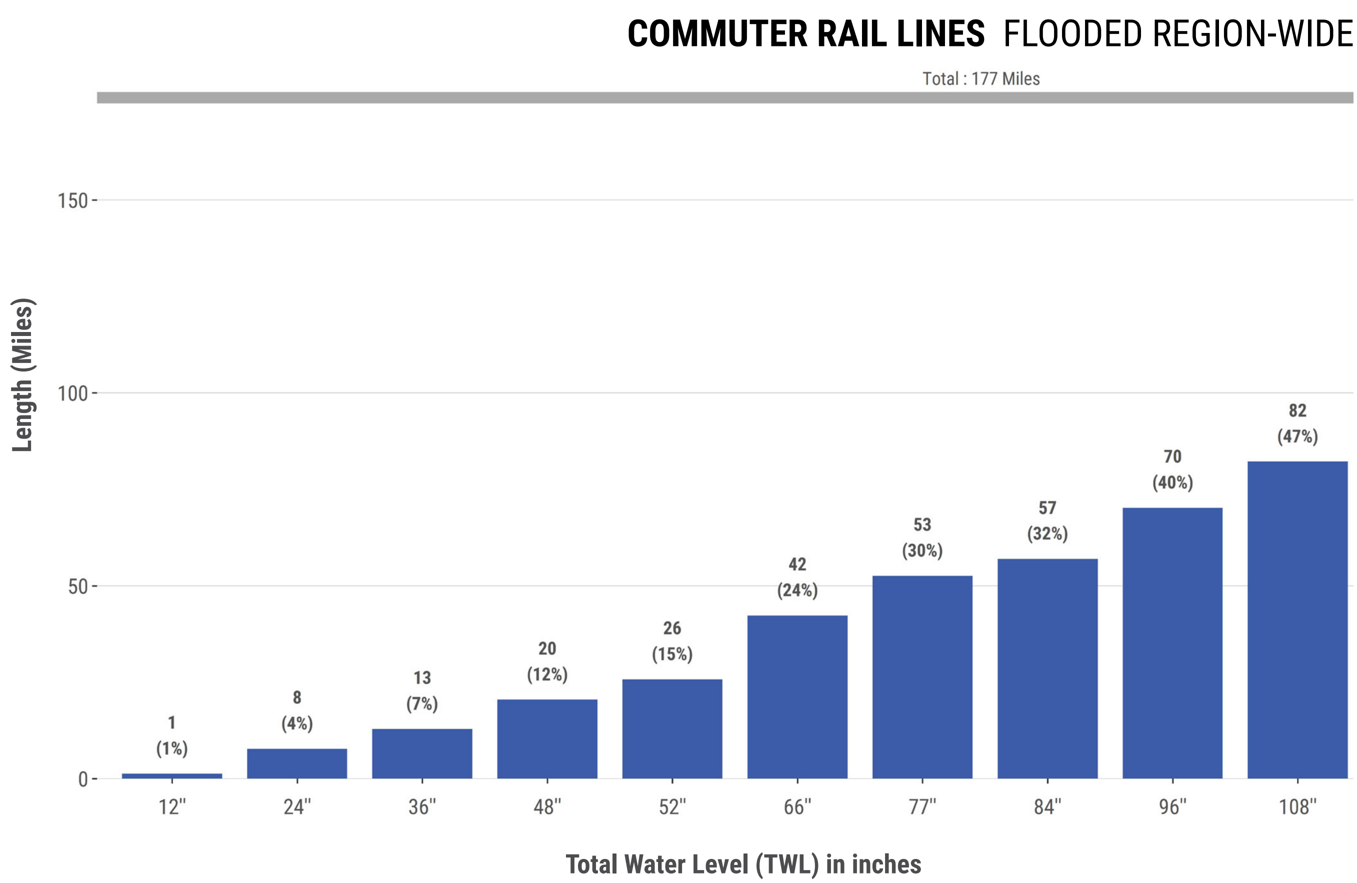


Figure 2-19. Regional exposure of commuter rail lines by flooding. Values in parenthesis reflect the percent of miles exposed to flooding at each TWL compared to total miles of commuter rail lines in the nine-county region.

SMART trains near Petaluma, CA. Photo by Don Barrett licensed under CC BY 2.0.

HIGHEST PERCENT OF **COMMUTER RAIL LINES** FLOODED BY COUNTY SEGMENTS

Percent of Total Miles by Commuter Rail Line

Segment	12"	24"	36"	48"	52"	66"	77"	84"	96"	108"
Martinez - Suisun-Fairfield (Amtrak-CC-ACE)	5.6	20.8	35.0	45.4	49.6	71.0	79.2	82.4	82.7	82.9
Santa Clara - Great America - Fremont (Amtrak-CC-ACE)	3.2	23.8	29.5	40.4	43.8	54.1	59.1	59.9	62.7	63.8
Lick Mill - Champion (VTA)		54.2	55.0	55.8	55.9	56.7	57.1	57.4	57.9	58.4
Lockheed Martin - Borregas (VTA)		32.6	43.6	78.1	80.5	87.6	95.5	96.9	100.0	100.0
Novato North-San Marin - Downtown Petaluma (SMART)		13.1	21.6	26.2	28.7	40.7	44.0	46.2	47.5	48.3
Champion - Tasman (VTA)		13.0	46.3	82.1	93.1	100.0	100.0	100.0	100.0	100.0
Downtown Petaluma - Cotati (SMART)		2.5	5.9	22.5	31.0	72.9	89.4	92.8	98.1	100.0
Borregas - Crossman (VTA)			91.4	96.2	99.5	100.0	100.0	100.0	100.0	100.0
Baypointe - Tasman (VTA)				99.8	100.0	100.0	100.0	100.0	100.0	100.0
mbarcadero & Folsom St - Metro Embarcadero Station (Muni)				43.4	90.4	100.0	100.0	100.0	100.0	100.0

Total Water Level (TWL) in inches

Figure 2-20. County commuter rail segments with highest percent of rail miles exposed to flooding at ten TWLs. "Highest" exposure refers to segments ranking in the top five for highest exposure at one or more TWL. Darker colors reflect greater consequences from flooding.

Commuter Rail Stations Exposure

The bar graph below shows the total number of commuter rail stations flooded at each total water level both in total number and as a percent of the total number within the nine county Bay Area (Figure 2-21). This figure illustrates the relative magnitude of exposure throughout the Bay Area as compared to the system as a whole.

Illustrating the data in this way shows that the number of commuter rail stations exposed represents a substantial amount of the region's commuter rail station capacity, and subsequently significant impacts to passenger ridership. Figure 2-22 identifies which commuter rail stations have the highest percent of stations exposed to flooding by county.

Exposure affects the degree of impacts and consequences. More widespread exposure amplifies impacts and consequences, and early exposure provides much less time to prepare, which may also amplify impacts and consequences. These nuances are important to bear in mind throughout the following sections describing regional consequence results.

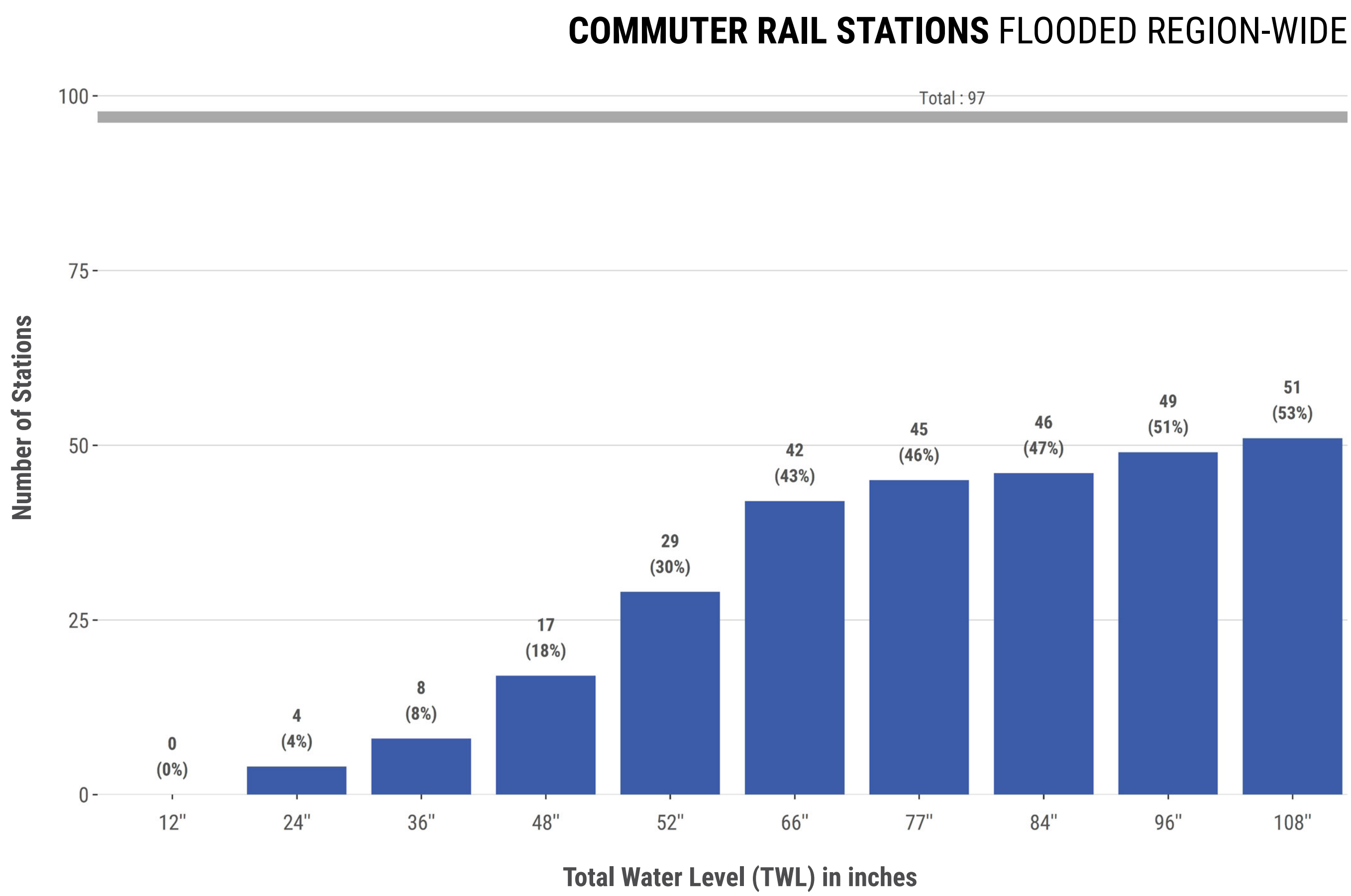


Figure 2-21. Regional exposure of commuter rail stations by flooding. Values in parenthesis reflect the percent of rail stations exposed to flooding at each TWL compared to total commuter rail stations in the nine-county region.

Amtrak train approaching the Emeryville Station. Photo by BCDC.

HIGHEST PERCENT OF **COMMUTER RAIL STATIONS** FLOODED BY COUNTY

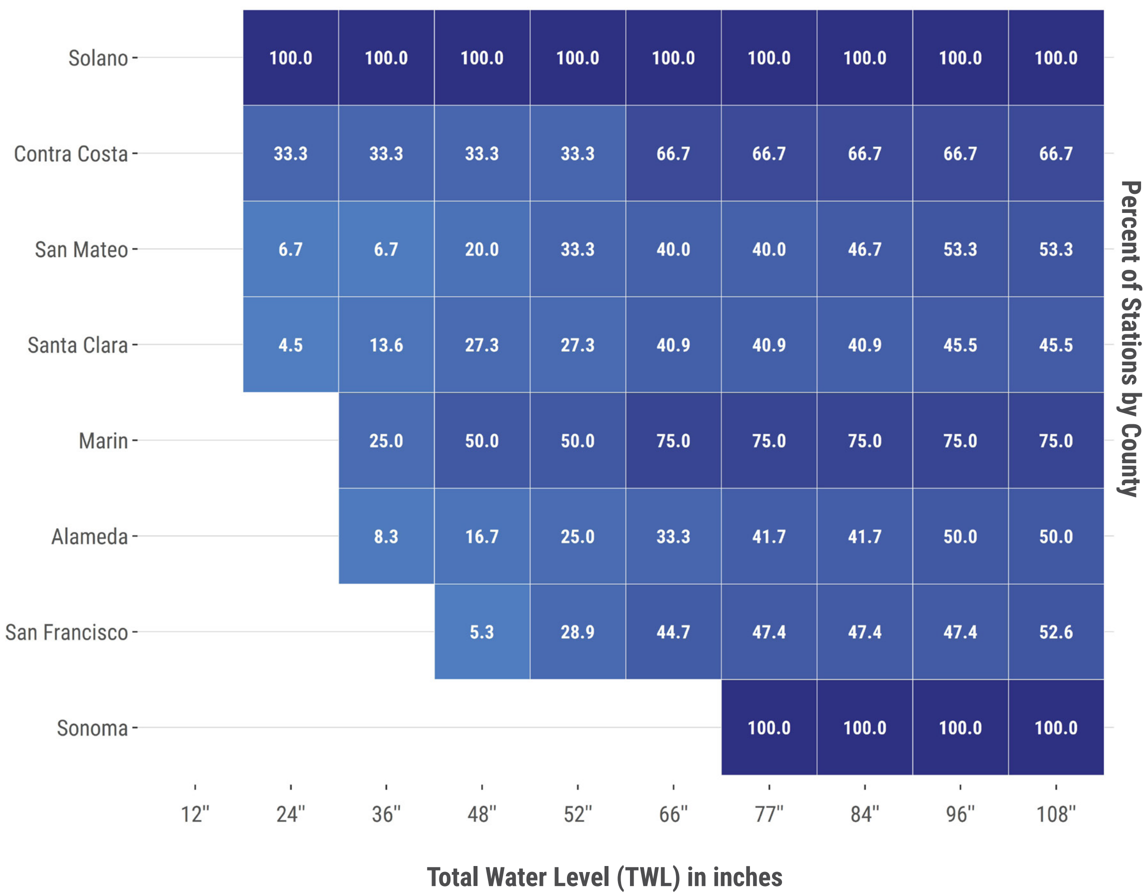


Figure 2-22. Commuter rail stations by county with highest percent of rail miles exposed to flooding at ten TWLs. Darker colors reflect greater consequences from flooding.

Regional Consequences of Commuter Rail System

Impacts to commuter rail ridership start out minimally at 12” TWL, then make significant jumps at 48” TWL, jumping from 29,000 riders impacted at 36” TWL to 84,000 at 48” TWL, and again at 77” TWL, jumping to nearly 630,000 riders impacted (from 311,000 at 66” TWL). By 108” TWL, nearly 1.1 million commuter rail riders are impacted by flooding (Figure 2-23). Commuter rail segments with the highest consequences are discussed in the next section (shown in Figure 2-24) and depicted spatially in maps of consequence in Figure 2-27.

Regionally, passenger impacts at stations also experience significant jumps in impacts at 52” and 66” TWL (Figure 2-25). Early flooding is minimal, impacting under 15,000 passengers due to flooding at stations, but jumps from 74,000 at 48” TWL to 383,000 at 52” TWL, and then to 535,000 at 66” TWL. By 108” TWL, just over 550,000 passengers are impacted by flooding at rail stations. Commuter rail stations with the highest consequences are discussed in the next section (shown in Figure 2-26) and depicted spatially in maps of consequence in Figure 2-27.

COMMUTER RAIL PASSENGER FLOW IMPACTED BY FLOODING REGION-WIDE

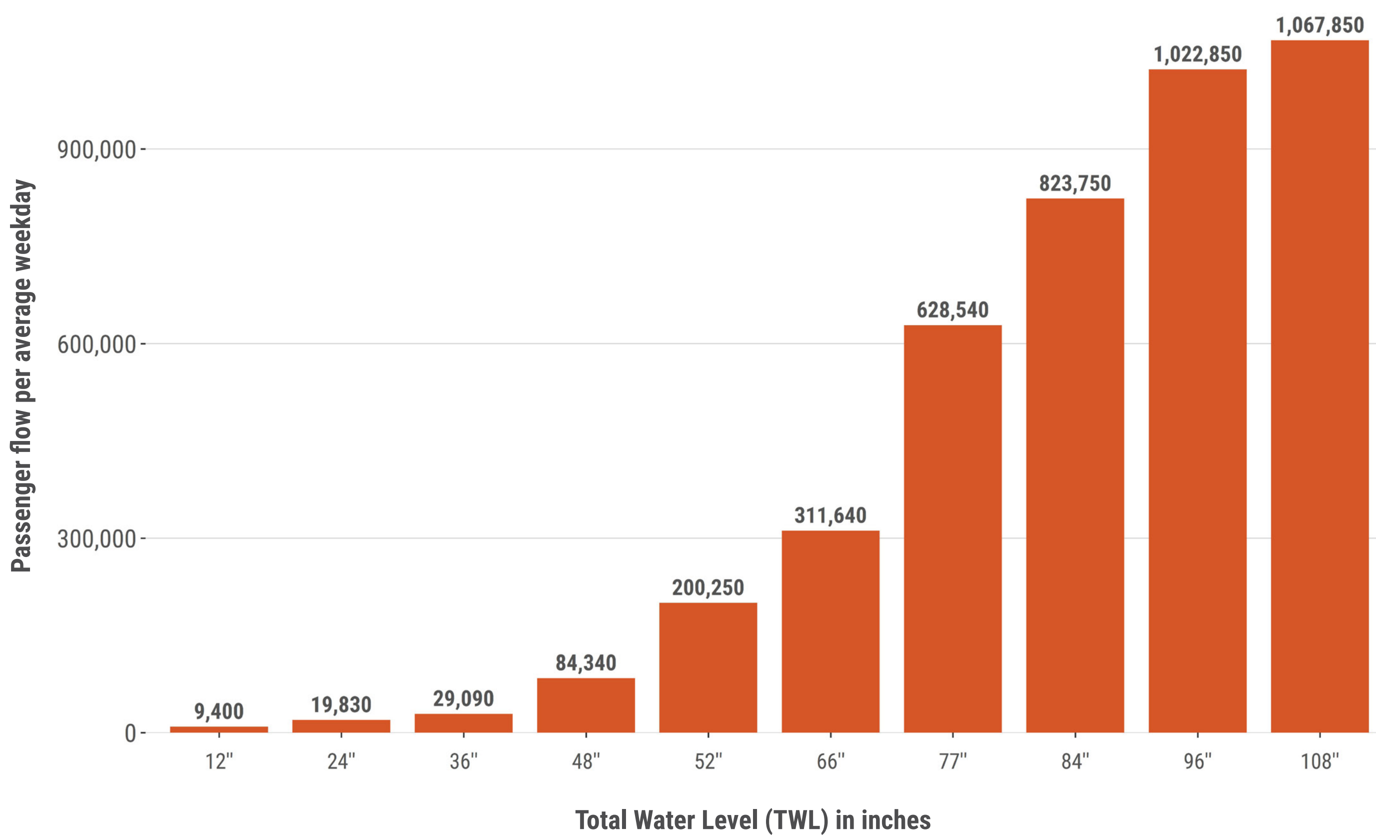


Figure 2-23. Total regional impacts to commuter rail lines from flooding at ten TWLs as measured by impacts to passengers per average weekday. Results are aggregated across the nine-county region.

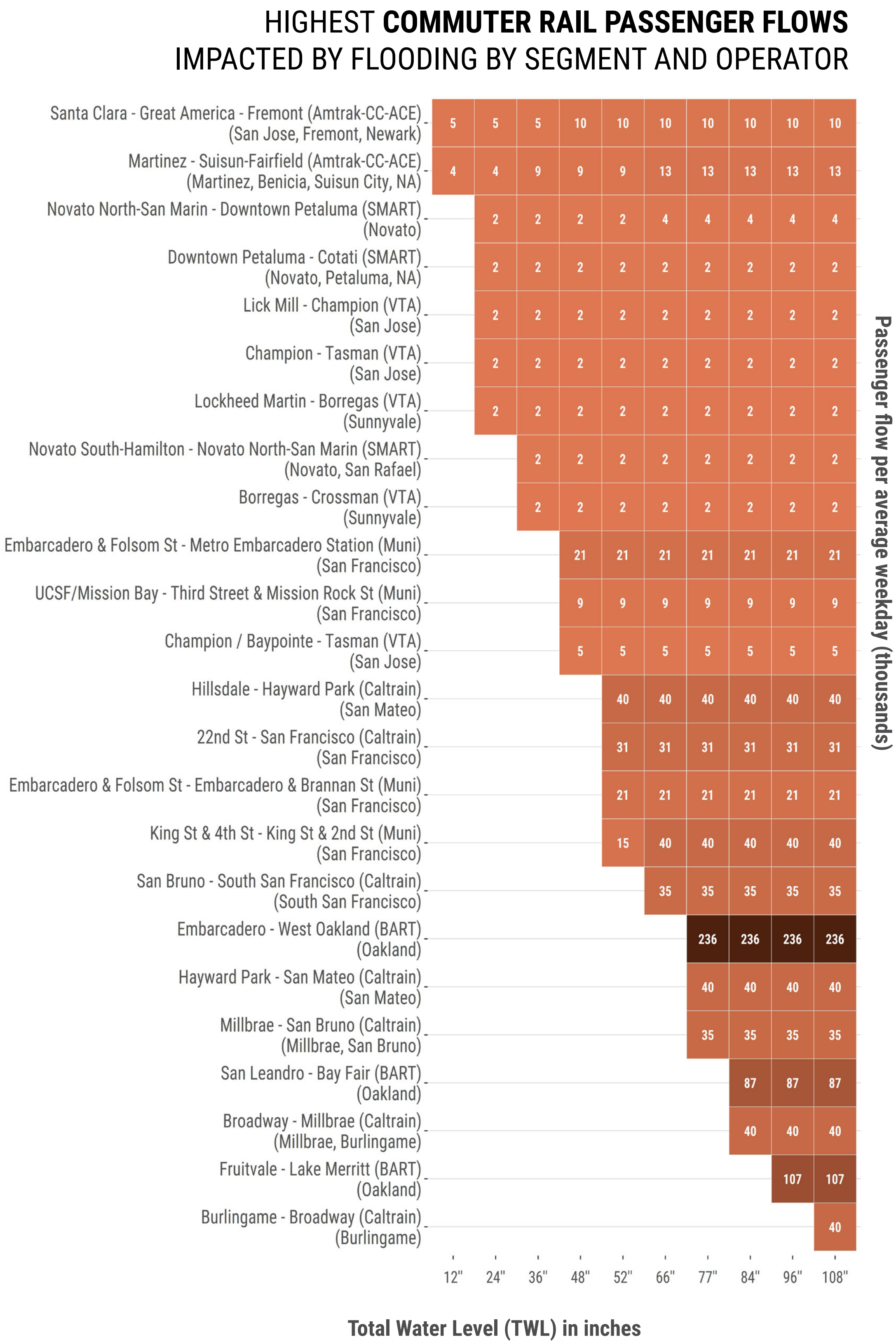


Figure 2-24. Commuter rail segments with highest impacts to passenger flows by flooding at ten TWLs as measured by impacts to passenger flows per average weekday. “Highest” impacts refer to segments ranking in the top five for highest consequences at one or more TWL. Darker colors reflect greater consequences.

Trends and Drivers Around the Region

Commuter Rail Lines and Stations

Early Impacts • All the exposed segments of commuter rail line at 12” TWL are Amtrak/CC/ACE. Amtrak/CC/ACE exposure occurs in Solano, Contra Costa, and Santa Clara Counties including service between Martinez-Suisun, Richmond-Martinez, and Santa Clara-Great America-Fremont (Figure 2-27). No stations are directly impacted at 12” TWL. At 24” TWL, exposure expands to impact SMART service between Novato San Marin-Downtown Petaluma, additional segments of the Amtrak/CC/ACE service corridor (including Martinez and Suisun-Fairfield stations), and VTA service between Lick Mill and Tasman and between Lockheed Martin and Borregas (including the Champion station). At 24” TWL, the SFO BART Station is also impacted.

Worsening Impacts • Regionally, the consequence to commuter rail ridership from exposed rail line significantly worsens between 66” and 77” TWL. This is primarily driven by the consequence of exposure to the BART rail between Emeryville and West Oakland. Additionally, exposure of Caltrain rail segments between Bayshore and San Mateo contribute to these consequences. Regional commuter rail station ridership consequences worsen between 48” and 52” as well as 52” and 66” TWL. These are largely due to the exposure of the Embarcadero station, impacting both Muni and BART trains.

Worsening Impacts • Significant outliers in ridership consequence occur when the Embarcadero station is exposed at 52” TWL, representing the highest ridership of any individual station in the Bay Area. Similarly, other significant outliers in ridership consequence occurs when BART rail segments between Embarcadero and West Oakland are exposed at 77” TWL, between San Leandro and Coliseum at 84” TWL, and between Fruitvale and Lake Merritt at 96” TWL.

Short Case Study

LINKING REGIONAL CONSEQUENCE RESULTS TO LOCAL ASSESSMENTS

In terms of passenger volume, the BART system moves the most people around the region. When these stations flood, there are significant regional impacts. The Embarcadero Station is one of the busiest in the system, connects to other regional transportation systems, and is vulnerable to flooding. BART, The Port of San Francisco, and the City and County of San Francisco are working to address these issues at the Embarcadero stations.

In addition to the regional assessment, ART Bay Areas assessed individual assets in each of the four region systems and the results are communicated in local assessments of shared vulnerabilities and consequences.

These can be found in Chapter 3.0 Local Assessments of the ART Bay Area report, with local assessments available for individual download.

BART train to Oakland International Airport. Photo by Airbus777 licensed under CC BY 2.0.

San Francisco Airport BART station is critical to the region. Photo by A. Davey licensed under CC BY 2.0.

COMMUTER RAIL STATION RIDERSHIP IMPACTED BY FLOODING REGION-WIDE

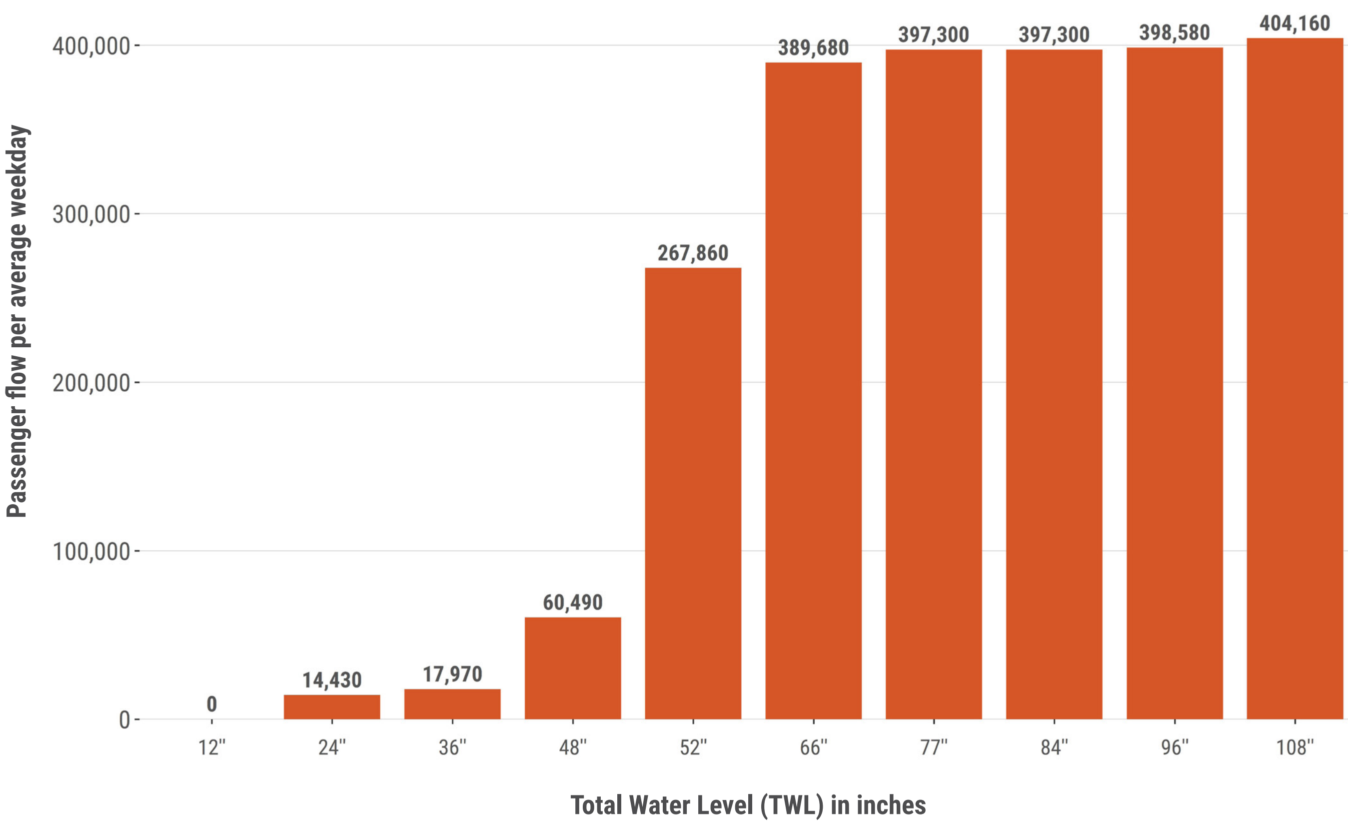


Figure 2-25. Total regional impacts to commuter rail station ridership from flooding at ten TWLs as measured by impacts to passengers per average weekday and results aggregated across the nine-county region.

HIGHEST **COMMUTER RAIL STATION RIDERSHIP** IMPACTED BY FLOODING BY STATION AND OPERATOR

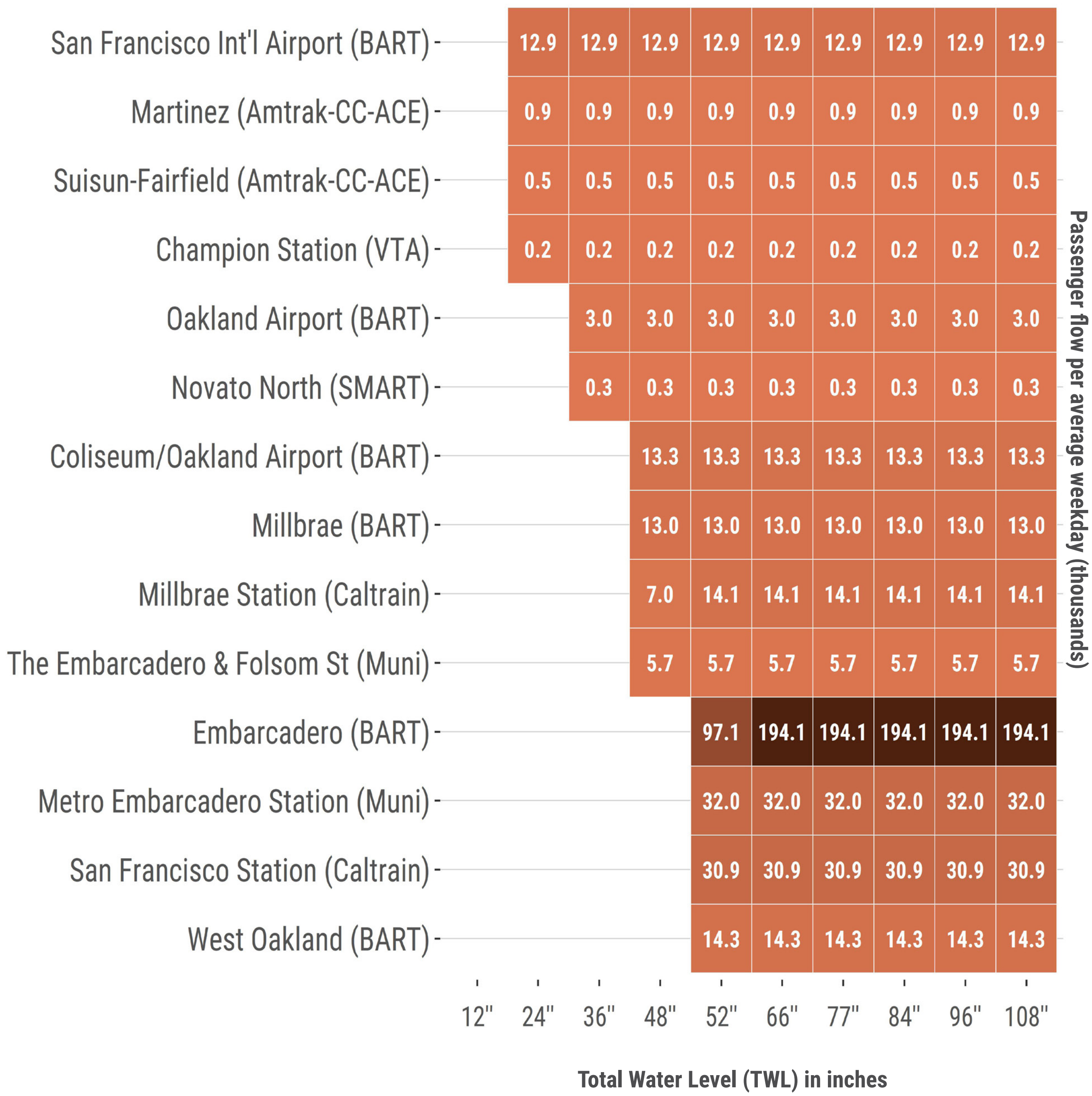


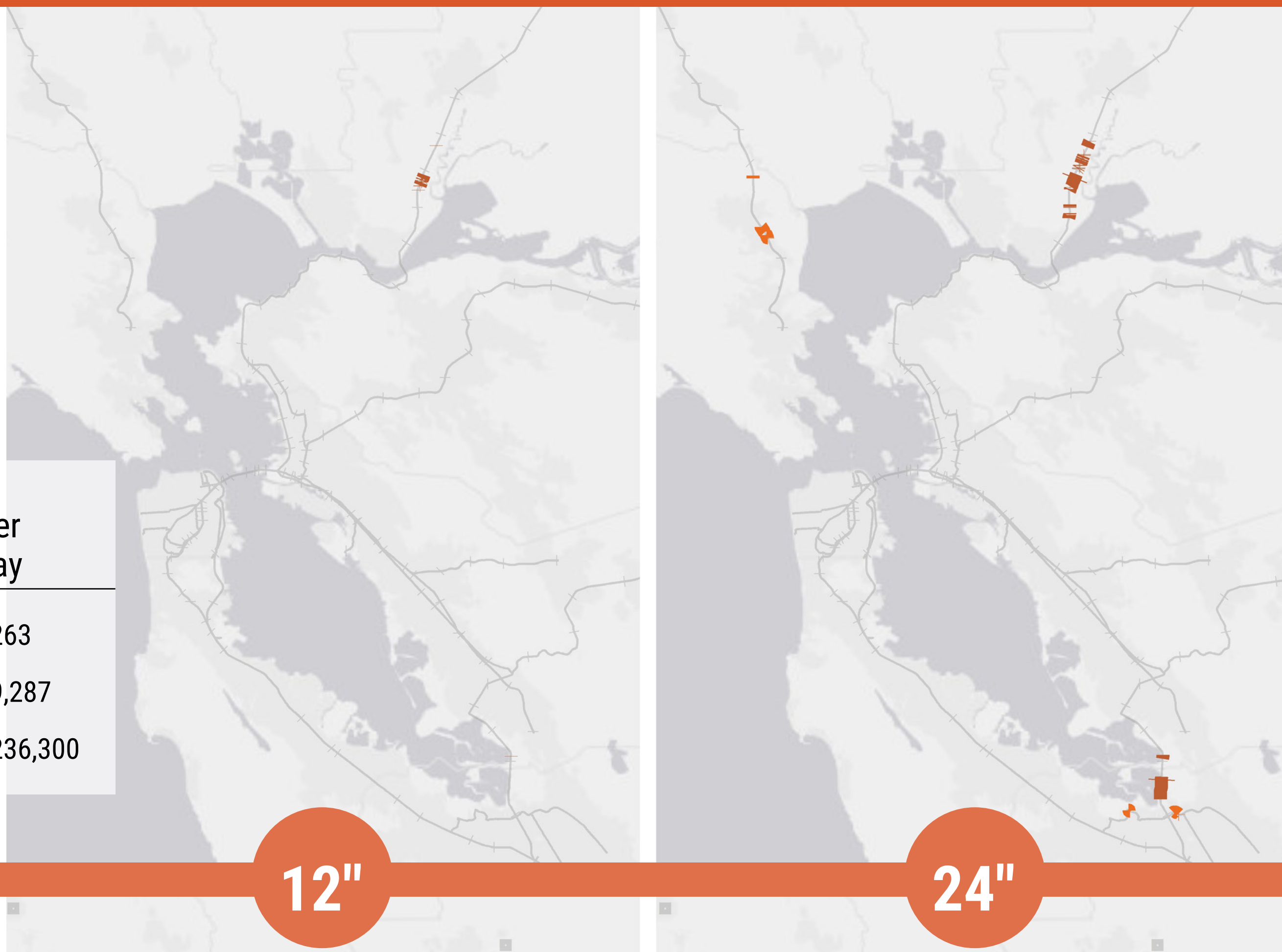
Figure 2-26. Commuter rail stations with highest impacts to ridership by flooding at ten TWLs as measured by impacts to passenger flows per average weekday. “Highest” impacts refer to stations ranking in the top five for highest consequences at one or more TWL. Darker colors reflect greater consequences.

CONSEQUENCES OF FLOODING

Transportation

Commuter Rail Consequences

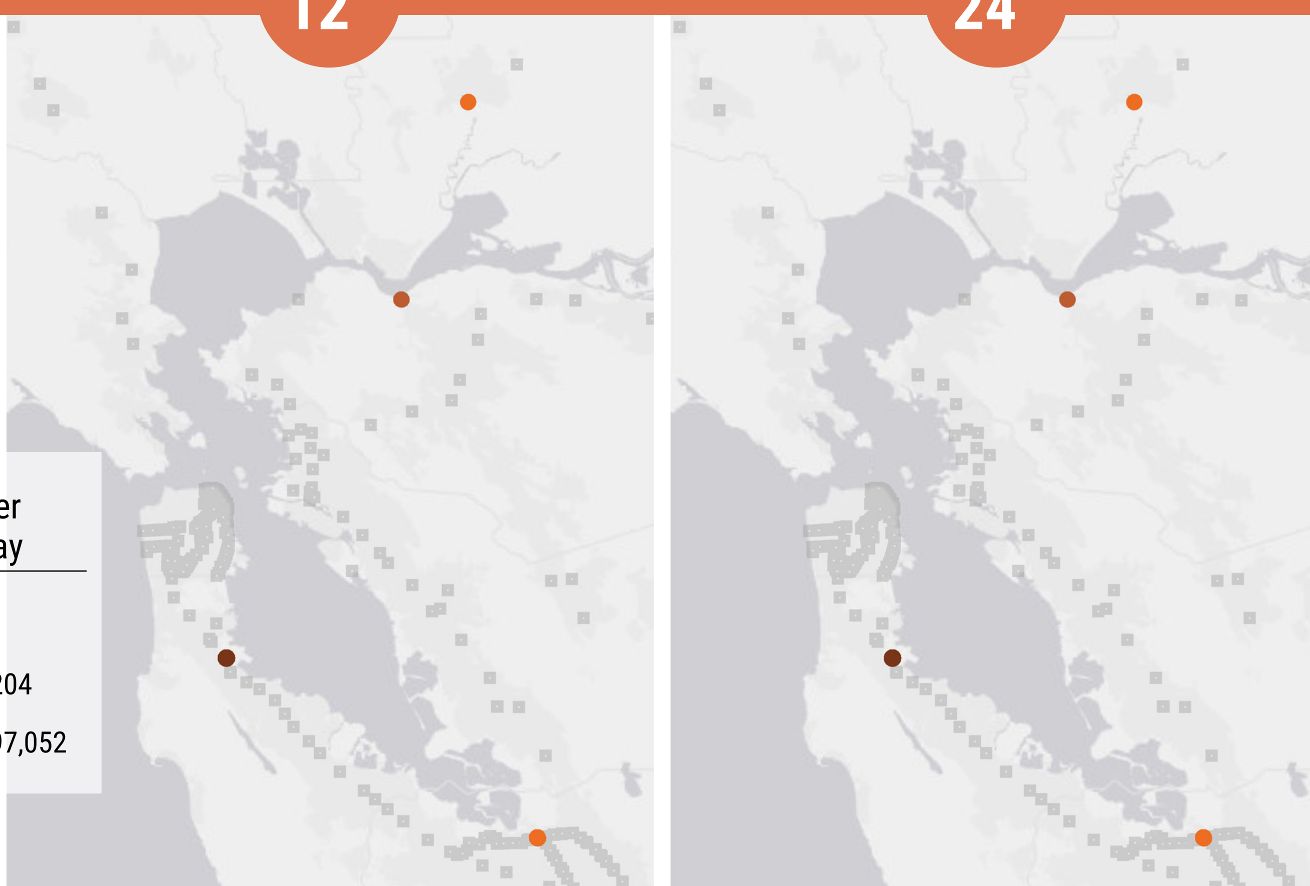
Passenger Flows Impacted by Flooding



Passengers per Average Weekday

- 471 to 2,263
- 2,264 to 9,287
- 9,288 to 236,300

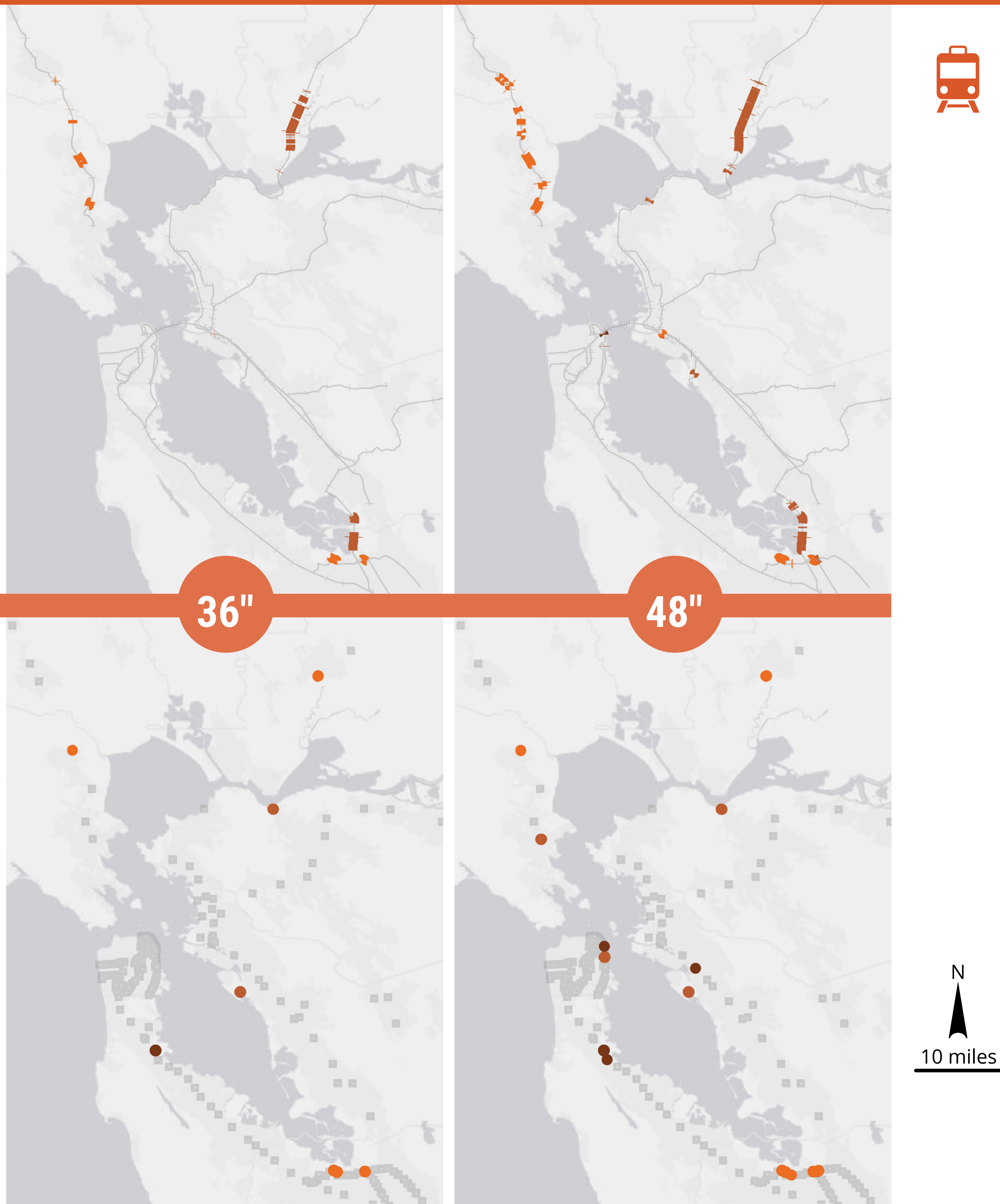
Station Ridership Impacted by Flooding



Passengers per Average Weekday

- 0 to 679
- 680 to 4,204
- 4,205 to 97,052

Figure 2-27. Maps depicting the consequences of flooding for two commuter rail indicators: *Passenger Flows* and *Station Ridership* at 12", 24" 36" and 48" TWL. Maps below show consequences and extent of exposure.



Methodology and Limitations for Commuter Rail

Methodology

Consequence of inundation to commuter rail lines was measured as average weekday ridership flow—the total number of people who travel along a given stretch between two stations on an average weekday. This indicator was chosen because the primary users of the Bay Area's rail transit are commuters, and interruptions to this system would have major impacts on both the economy and residents of the region. Although no single dataset of commuter flows exists for the Bay Area, the project team was able to make use of transit ridership data available from each operator to calculate or approximate ridership flows. A limitation of this indicator is that ridership data available for each operator were not always available for the same year or at the same level of quality.

Consequence of inundation to commuter rail stations was measured as average weekday exits from each station. This indicator represents the amount each station is used compared to others in the system. Like Commuter Rail Lines, ridership data available for each operator were not always available for the same year or at the same level of quality. Please Appendix for a discussion of the methods used for each operator's data.

Rail lines and stations were assessed separately because they have different physical properties and locations, but also because the consequence of inundation is different. If a station is impacted, this will only affect the transit riders who use that station. However, if a line is impacted, this will affect all transit riders whose trip would take them on that stretch of track. For example, a neighborhood station with comparatively few exits may exist on a busy line. If both the station and line are impacted, the consequence of the station being inundated is less than the consequence of the line being inundated. While both commuter flows and station exits are measures of ridership, they present different consequences. In the analysis, this nuance is captured by assessing lines and stations as separate asset types with different consequence indicators.

Limitations

This approach has limitations in comprehensively reflecting commuter rail vulnerability in the region. In addition to the consequence of flooding on tracks and stations, the regional commuter rail system is vulnerable due to numerous other factors. These include:

Track • Commuter rail is sensitive to even small amounts of water on the tracks, and if a portion of track is damaged it often results in the closure of routes that use that portion of the track. The linear and fixed character of the rail system inherently lacks redundancy and disruptions to one section or component of the system can disrupt the entire system. While some segments of track and stations are elevated (e.g. BART, VTA), the majority of track and stations are located at or below grade.

Stations and Platforms • Stations are less vulnerable to flooding if their height is above grade, but flooding can limit local road access, parking, and transit connections. For example, the Coliseum BART Station is elevated, but entrances and exits are vulnerable to flooding at grade.

Power and Signal Systems • Commuter rail service depends upon the functionality of the power and signal system; these electrical systems are extremely sensitive to saltwater corrosion and have limited redundancy. While some power substations are raised (e.g. VTA), other systems are located at-grade (e.g. along the BART alignment). Disruptions to the power and signal system can range from delays to entire shutdown of the route, depending on the number of disruptions to the signal and power system at one time. These concerns will increase as other commuter rail operators make the transition from diesel powered trains to electrification (e.g. Caltrain).

Maintenance and Operations Facilities • Most commuter rail services rely on centralized maintenance and operations facilities. These often support the entire fleet of trains for a given operator, lack redundancy, and are sensitive to flooding due to electrical infrastructure. For example, the Muni Metro East facility serving all the Muni Metro trains is vulnerable to flooding.

Governance and Cost • Relocating or adding new rail infrastructure is costly and significant time and money are needed for planning, financing and implementing changes to the region's rail network. There is often complex ownership and management structure for commuter rail assets, particularly for tracks that service both commuter and freight movement (e.g. Union Pacific and Capitol Corridor/Amtrak/ACE). Commuter rail operators do not own or control the shoreline where flooding occurs, which will likely complicate planning processes for future adaptation or resilience projects.

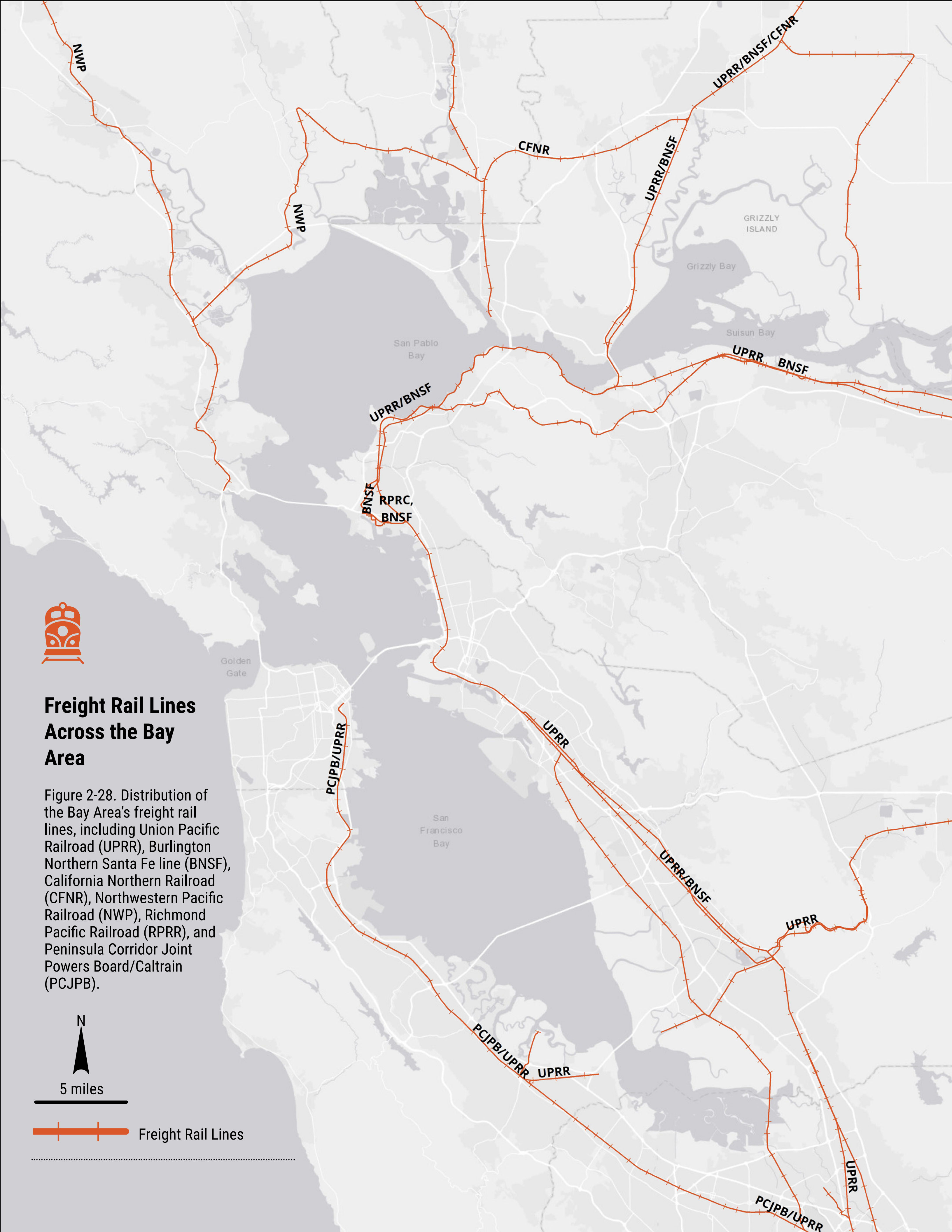
FREIGHT RAIL

Since the late 1800s rail has supported goods and commuter movement locally, regionally, across the state and nationally. In the San Francisco Bay Area goods and commuters both move by rail, on a shared track, along the shorelines of Santa Clara, Alameda, Contra Costa, and Solano Counties (Figure 2-28). The rail lines that cross the project area are critically important and support inter- and intra-regional goods and commuter movement. The Union Pacific Railroad (UPRR) Martinez Subdivision between the Port of Oakland and Martinez is the busiest rail segment in Northern California, carrying both goods and commuters. Freight volumes on the Union Pacific Martinez Subdivision are the highest in the region, and overall freight rail demand is anticipated to grow throughout the Subdivision, making it the largest bottleneck on the freight rail system in the Bay Area.[4]

Goods moved by rail typically consists of high value manufactured products, as well as agricultural and food products transported from the region's ports to Northern and Southern California and throughout the country. Goods movement-dependent industries in the Bay Area account for $490 billion (51 percent of total regional output) and provide over 1.1 million jobs (32 percent of total regional employment).[5] Rail provides a vital service in the region, supporting economic growth and connecting commuters to regional jobs.

Freight rail connects regionally with all major Bay Area ports, has limited redundancy in the network to reroute goods if sections of rail are inoperable, and serves as de facto shoreline protection along much of the Bay Area's shoreline. Track embankments are sometimes the only shoreline protection for inland communities yet are not designed as flood barriers. Due to the quasi-federal status of most national rail operators, they tend to be based outside the Bay area and participation in adaptation planning has been limited. Additionally, several commuter rail operators have track rights on rail owned by freight rail operators such as UPRR. Goods movement rely on a network of fixed, connected railroad assets including the railroad track, signal system, and bridges.

Freight rail lines within and beyond the Bay Area are vulnerable to sea level rise and storm events. In general, rail is highly sensitive to even small amounts of water on the tracks, and if a portion of track is damaged it often results in the closure of many miles of connected track. The region's capacity to withstand impacts to rail infrastructure is further hampered by the lack of redundant or alternative rail lines in the region. Relocating or adding new rail infrastructure is costly and significant time and money are needed for planning, financing and implementing changes to the region's rail network. Disruption of the rail system would lead to an increase in the number of trucks needed to transport cargo, having negative and widespread effects on road congestion, air quality, accidents, and community noise and quality of life. Finally, lack of adequate coordination between rail line owners and local jurisdictions complicates planning and information sharing. The consequence indicator for freight rail is measured by the number of freight trains per day that pass along a segment of rail.



Freight Rail Lines Across the Bay Area

Figure 2-28. Distribution of the Bay Area's freight rail lines, including Union Pacific Railroad (UPRR), Burlington Northern Santa Fe line (BNSF), California Northern Railroad (CFNR), Northwestern Pacific Railroad (NWP), Richmond Pacific Railroad (RPRR), and Peninsula Corridor Joint Powers Board/Caltrain (PCJPB).

Regional Exposure of Freight Rail

The bar graph below shows the total length of freight rail flooded at each total water level both in total miles and as a percent of the total freight rail miles within the nine county Bay Area (Figure 2-29). This figure illustrates the relative magnitude of exposure throughout the Bay Area as compared to the system as a whole. Illustrating the data in this way shows that the length of freight rail miles exposed represents a substantial amount of the region's freight rail line capacity, and subsequently significant impacts to the movement of freight trains per day. This graph also illustrates how gradual the increase in exposure is over time. Figure 2-30 identifies which operators have the highest percent of freight rail line miles exposed to flooding.

Exposure affects the degree of impacts and consequences. More widespread exposure amplifies impacts and consequences, and early exposure provides much less time to prepare, which may also amplify impacts and consequences. These nuances are important to bear in mind throughout the following sections describing regional consequence results.

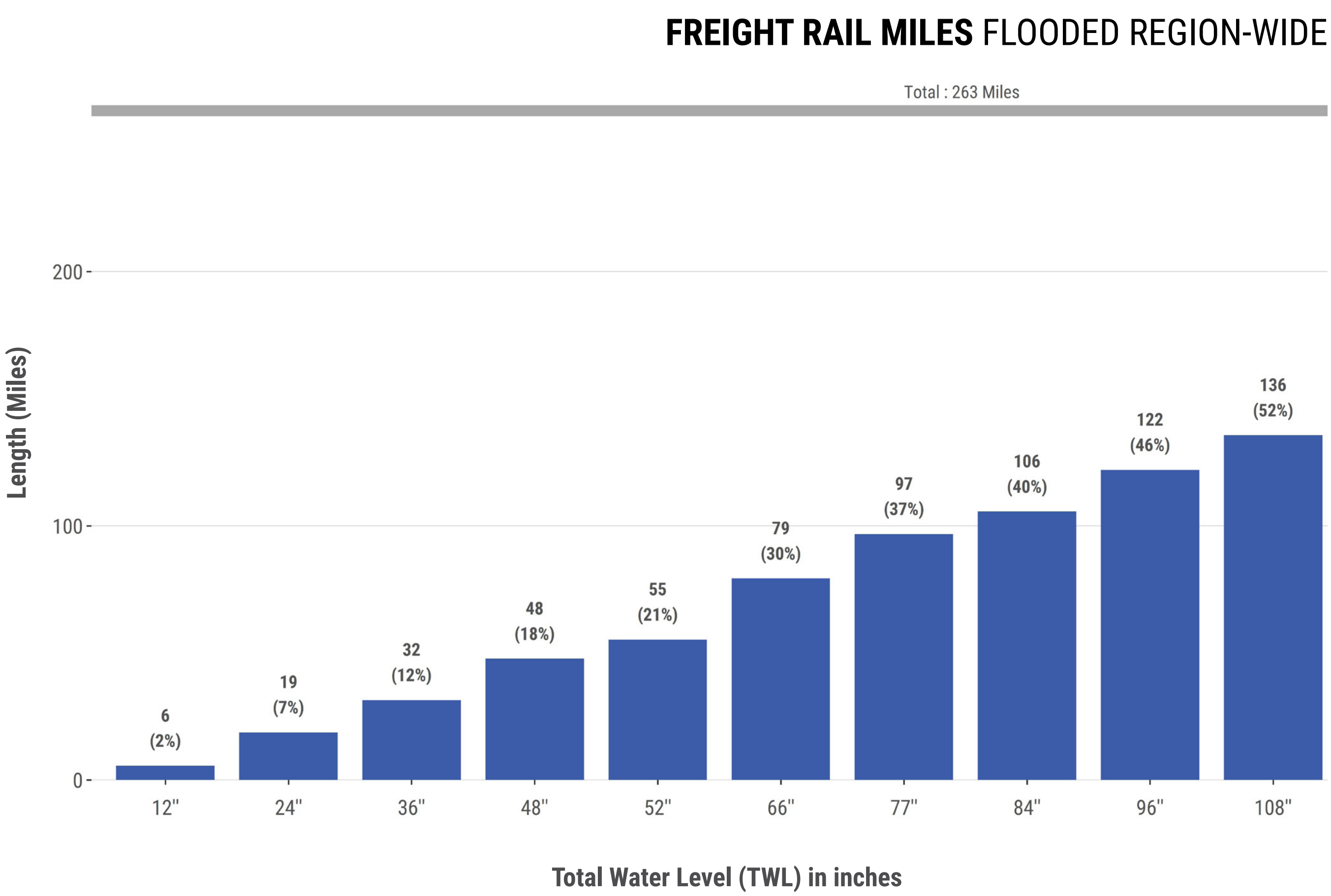


Figure 2-29. Regional exposure of freight rail line miles by flooding. Values in parenthesis reflect the percent of miles exposed to flooding at each TWL compared to total miles of freight rail lines in the nine-county region.

A freight trail along the Carquinez Straight at Eckley. Photo by Patrick Dirden licensed under CC BY-NC-ND 2.0.

HIGHEST **PERCENT OF FREIGHT RAIL MILES** FLOODED BY OPERATOR

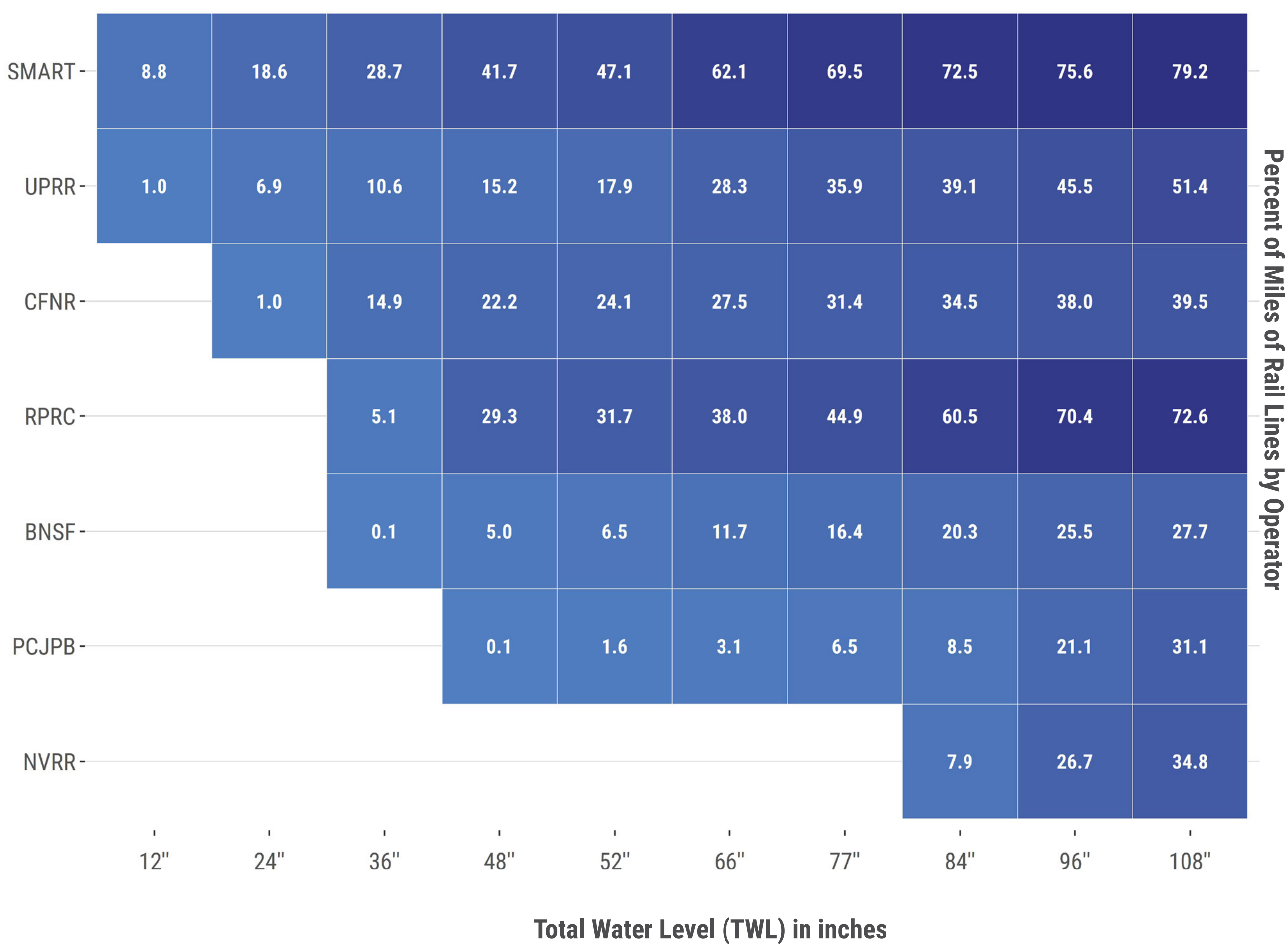


Figure 2-30. Freight rail operators with highest percent of freight rail line miles exposed to flooding at ten TWLs. “Highest” exposure refers to operators ranking in the top five for highest exposure at one or more TWL. Darker colors reflect greater consequences from flooding.

Regional Consequences of Freight Rail

Region-wide, impacts to freight rail is minimal at early total water levels, impacting 47 daily freight trains at 12” TWL and slowly climbing from there. However, significant jumps occur between 24” and 36” TWL (from 52 to 112 daily freight trains impacted), 36” to 48” TWL (112 to 216 trains impacted), and 48” to 52” TWL (from 216å to 317 trains impacted). After 52” TWL, impacts increase steadily until they reach 401 trains impacted at 108” TWL (Figure 2-31).

Freight rail operators with the highest consequences are discussed in the next section (shown in Figure 2-32) and depicted spatially in maps of consequence in Figure 2-33.

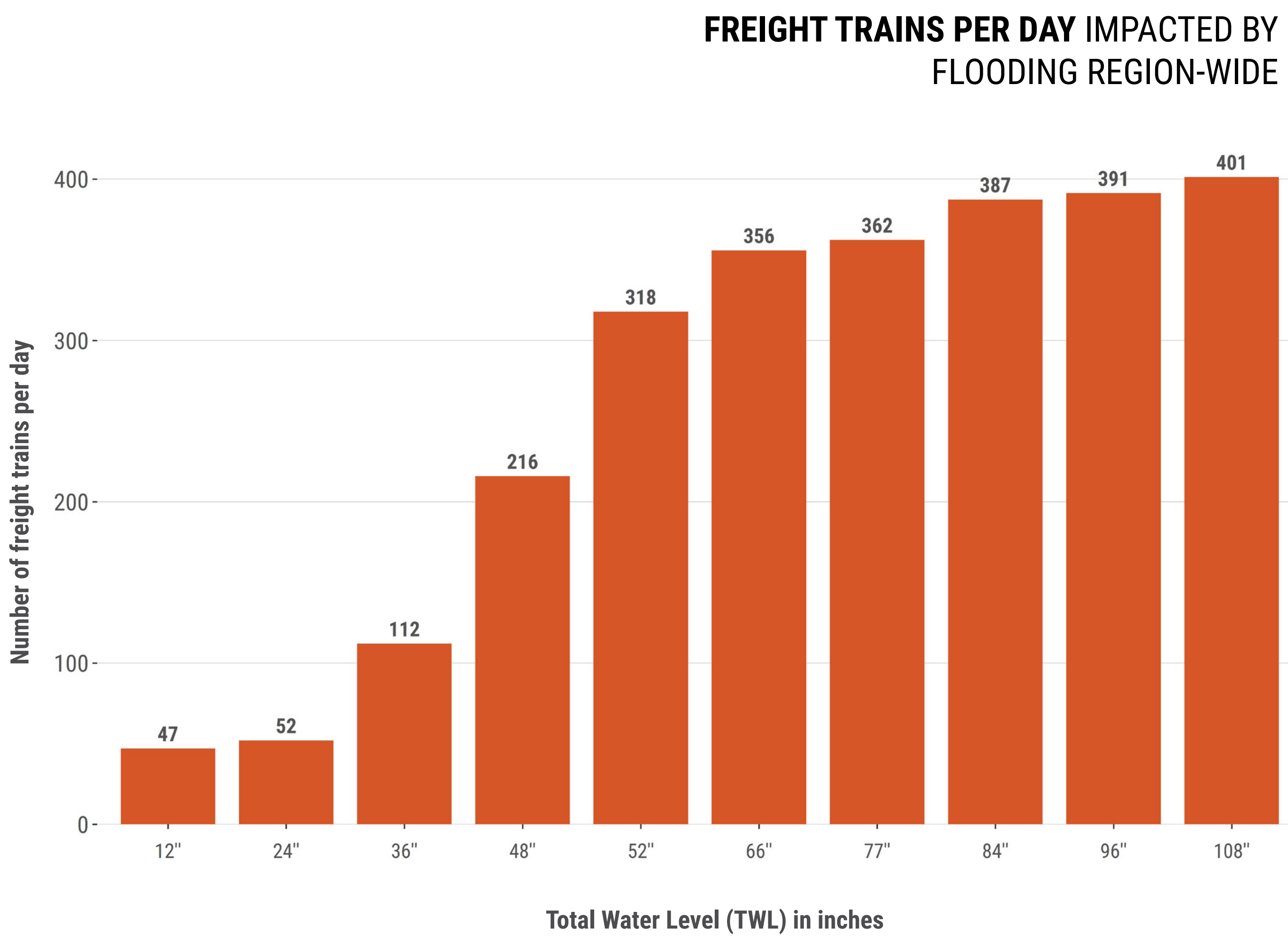


Figure 2-31 Regional impacts to freight rail from flooding at ten TWLs as measured by impacts to freight rail trains per day. Results are aggregated across the nine-county region.

Short Case Study

LINKING REGIONAL CONSEQUENCE RESULTS TO LOCAL ASSESSMENTS

Union Pacific Railroad track are vulnerable to flooding at early water levels. This vulnerability is due to the low elevation of the track as it passes through Suisun Marsh and the South Bay Salt Ponds. This rail line also supports commuter rail service by Amtrak/Capital Corridor. Disruption of the rail at these segments would have consequences for the ability of freight trains to access the Port of Oakland and Port of Richmond or transport commuters through and beyond the region. Furthermore, rail segment throughout the region are located on the shoreline and serve as de facto shoreline protection for inland communities.

Difficulties coordination and sharing information with railroad owners has complicated adaptation planning.

In addition to the regional assessment, ART Bay Areas assessed individual assets in each of the four region systems and the results are communicated in local assessments of shared vulnerabilities and consequences.

These can be found in Chapter 3.0 Local Assessments of the ART Bay Area report, with local assessments available for individual download.

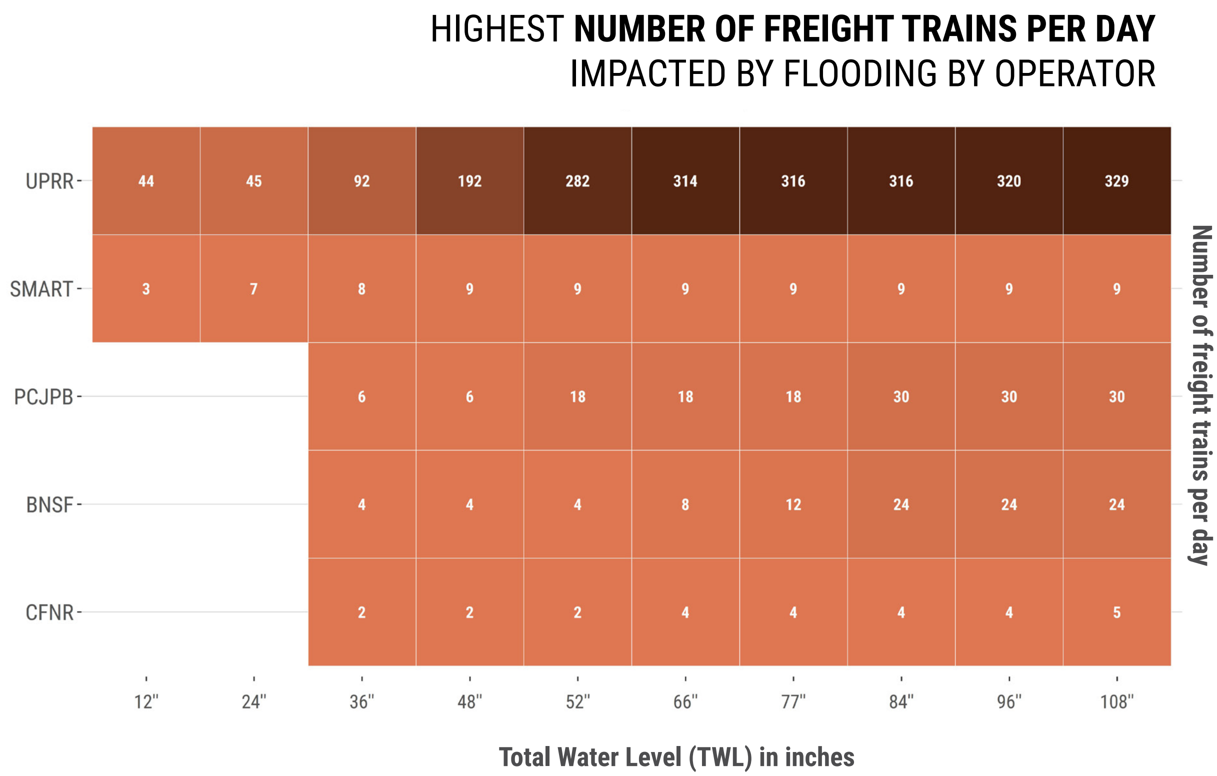


Figure 2-32. Freight rail operators with highest impacts by flooding at ten TWLs as measured by impacts to freight rail trains per day. "Highest" impacts refer to segments ranking in the top five for highest consequences at one or more TWL. Darker colors reflect greater consequences.

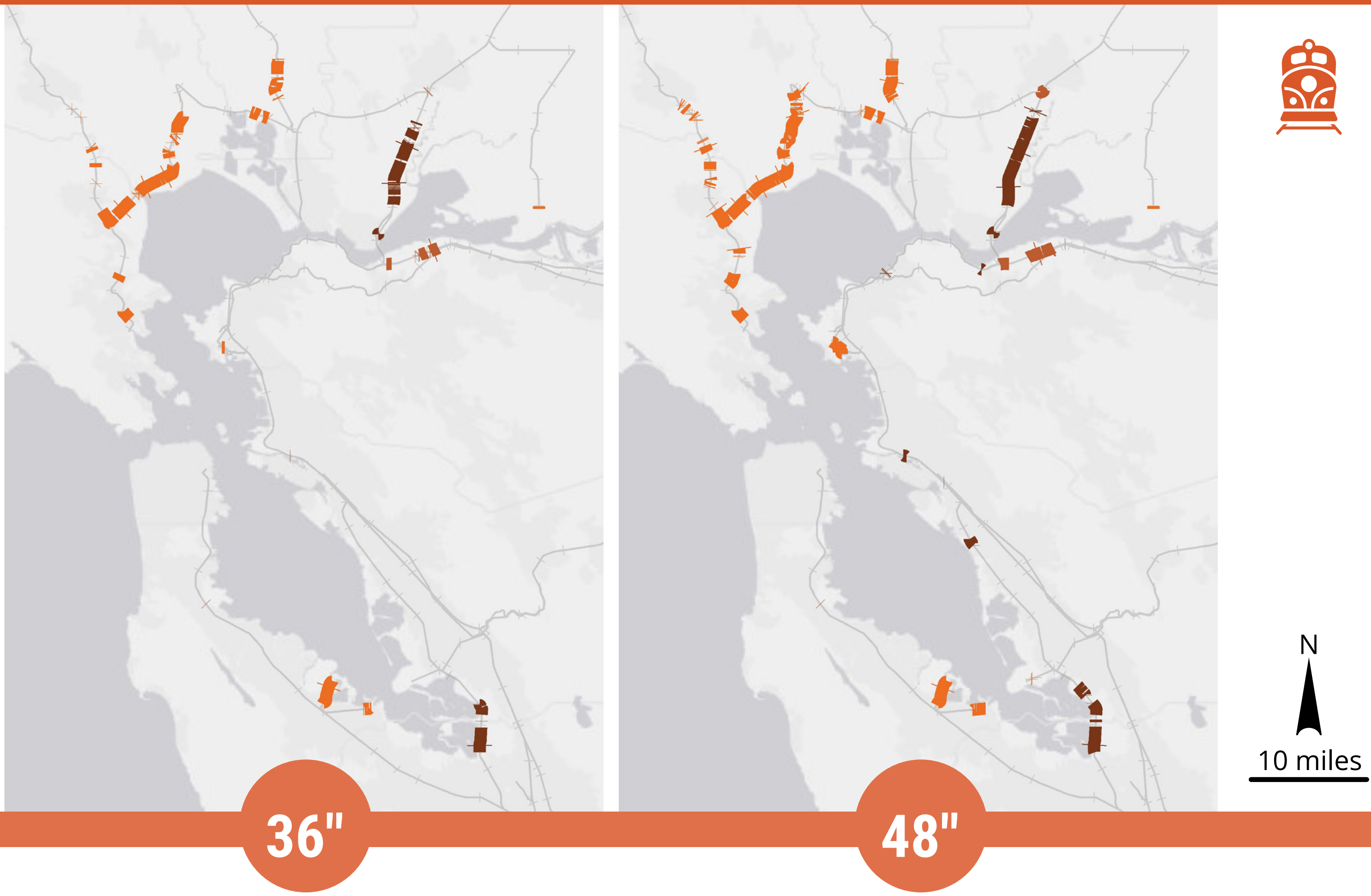
Freight Trains Impacted by Flooding

Trends and Drivers Around the Region

Freight Trains

Early Impacts • Freight rail impacts at 12” TWL includes segments owned and operated by UPRR (Solano, Contra Costa, and Santa Clara counties) and SMART (Napa and Marin counties). The UPRR segments in Suisun Marsh have the highest consequence for the daily average number of freight trains impacted. At 24” TWL, the impacts remain roughly the same, with no new freight rail operators experiencing consequences, but exposure expands into the SMART line in Novato (Figure 2-33).

Figure 2-33. Maps depicting the consequences of flooding for one freight rail indicator: *Freight Trains per Day* at 12", 24" 36" and 48" TWL. Maps below show consequences and extent of exposure.



Worsening Impacts • Regionally, freight rail consequences worsen significantly between 36" and 48" TWL and between 48" and 52" TWL. Initially, these are largely driven by exposure of multiple UPRR rail segments in Santa Clara, Alameda, Contra Costa, and Solano counties. Eventually, these consequences are driven by the exposure to UPRR rail in Suisun Marsh as well as exposure of segments near the Port of Oakland and Port of Richmond.

Outliers • Significant outliers for high consequence of freight rail both occur on UPRR owned and operated rail in Oakland and the Suisun Marsh at 52" TWL.

Freight railyards at the Port of Oakland. Photo by BCDC.

Methodology and Limitations for Freight Rail System

Methodology

The primary consequence of freight rail lines becoming inundated is disruption to regional goods movement. The amount of cargo transported on each line was measured in freight trains per day. This unit is not particularly granular, but it was the best data available for the entire region. Although data on cargo weight or cargo value would have been preferred, the project team found that the differences in freight trains per day between stretches of track were different enough to convey the relative consequence that the analysis is based on.

Limitations

This approach has limitations in comprehensively reflecting freight rail vulnerability in the region. In addition to the consequence of flooding on tracks, the regional freight rail system is vulnerable due to numerous other factors. These include:

Track • Freight rail is sensitive to even small amounts of water on the tracks, and if a portion of track is damaged it often results in the closure of many miles of connected track due to its linear nature and lack of redundancy. The linear and fixed character of the rail system inherently lacks redundancy and disruptions to one section or component of the system can disrupt the entire system or lead to lengthy rerouting.

Bridges • Fright rail passes over numerous tidal creeks and channels, which makes them very vulnerable to extreme storm events that cause high creek flow and potential overbank flooding. Scour at bridge footings is anticipated to occur as tidal energy and wave heights increase with sea level rise and should be monitored by railroad operators.

Co-location of Utilities • Freight rail is often co-located with fuel pipelines and other utilities. Erosion of the track bed could expose pipelines to corrosion and failure, disrupting facilities that rely on those utilities, and potentially spilling toxic contaminants. This also complicates planning for maintenance and adaptation.

Ad-Hoc Shoreline Protection • In large stretches of the shoreline, freight rail alignment serves as either the first or second line of protection from flooding. This is especially true in Contra Costa, Solano, and Santa Clara counties. The ballast and earth embankment under the steel railroad are sensitive to wave action, not designed for flood protection, and easily eroded during extreme storm events with strong waves.

Railyards • Railyards in the region serve to store, sort and load/unload trains. Numerous railyards in the region are vulnerable to flooding which may increase the number of cars on the mainline and cause additional freight bottlenecks. For example, freight railyards at the Port of Richmond and Port of Oakland are vulnerable to flooding.

Power and Signal Systems • Freight rail service depends upon the functionality of the power and signal system; these electrical systems are extremely sensitive to saltwater corrosion and have limited redundancy. Disruptions to the power and signal system can range from delays to entire shutdown of the route, depending on the number of disruptions to the signal and power system at one time.

Coordination and Governance • Planning for sea level rise and storm event impacts is challenging given that freight rail lines are owned and maintained by private national entities that have not been willing in the past to coordinate and share information and resources or work directly with local decision makers to find shared solutions for past or current issues.

Cost • Relocating or adding new rail infrastructure is costly and significant time and money are needed for planning, financing, and implementing changes to the region's rail network. There is often complex ownership and management structure commuter rail assets, particularly for tracks that service both commuter and freight movement. Commuter rail operators do not own or control the shoreline where flooding occurs, which will likely complicate planning processes for future adaptation or resilience projects.

AIRPORTS

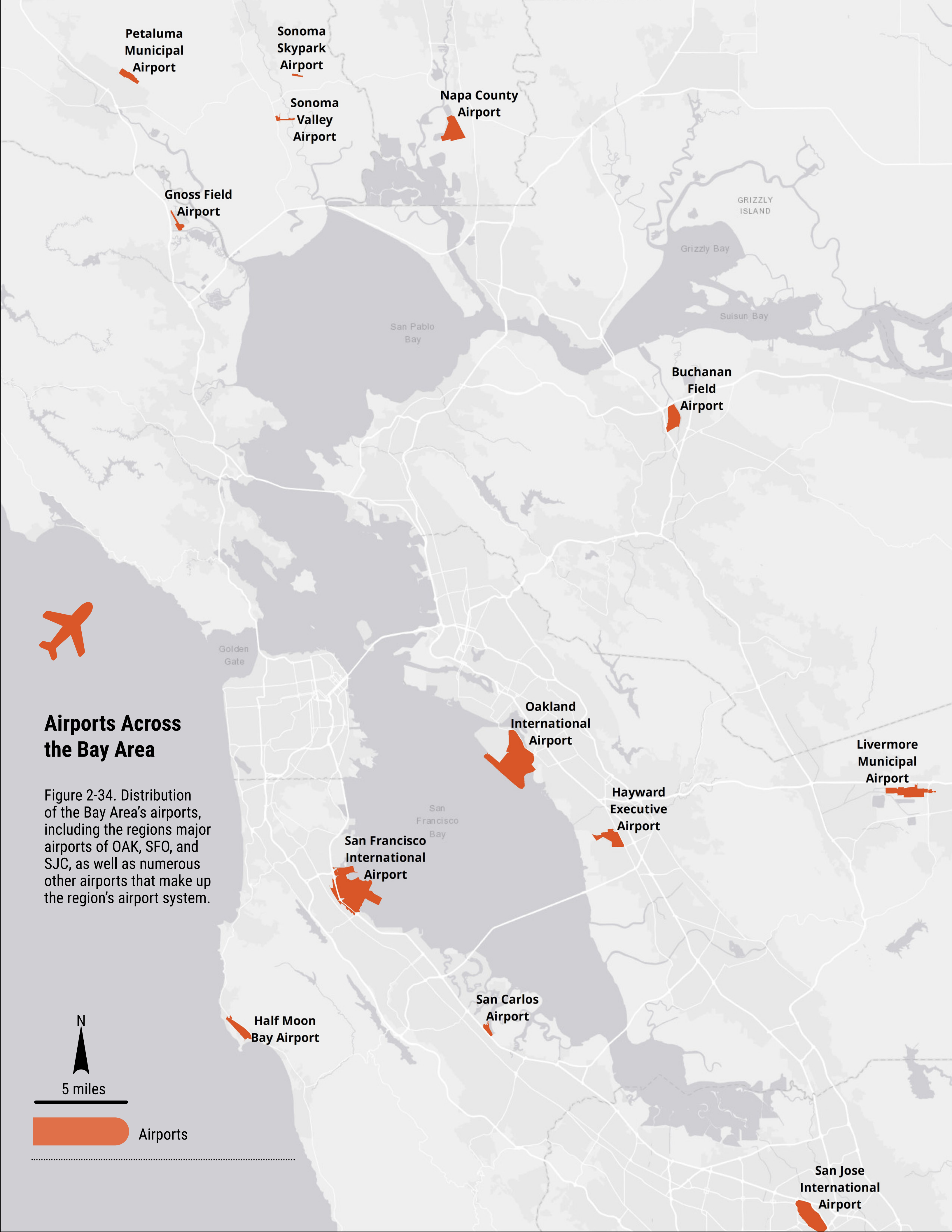
Three major commercial airports serve the Bay Area—Oakland International Airport (OAK), San Francisco International Airport (SFO), and Mineta San Jose International Airport (SJC) as well as numerous smaller airports (Figure 2-34). Both OAK and SFO are currently at risk from storm events and face significant vulnerabilities from sea level rise. These airports support hundreds of thousands of jobs and contribute billions of dollars to the Bay Area economy in addition to serving as essential transportation links for passenger and freight to the rest of the country and the world.

Airport operations are vulnerable to sea level rise and storm event impacts due to the disruption or damage that these may cause for shoreline and transportation assets owned and managed by others. For example, at the Oakland Airport the general aviation runway is at risk from flooding from Doolittle Drive, a state-owned roadway that sits between the Bay shoreline and the airport. This flooding, if left unaddressed, could eventually reach the commercial runway. Roads and the BART Oakland Airport Connector that provide access to the airport are vulnerable to storm flooding that is equivalent to today's 50-year extreme Bay tide level, in particular where this infrastructure is below-grade.

The temporary or permanent disruption of airport operations at OAK or SFO would have regional economic consequences on jobs and cargo movement because there is no additional runway capacity in the region to accommodate this loss. There would also be impacts on local economic activities that are supported by the proximity of the airport, such as businesses that rely on frequent travel or ready access to cargo shipment and receiving.

Financing strategies available to airports are currently inadequate to fund the necessary planning and implementation of adaptation actions, or to quickly make repairs when damage does occur. In addition, airports do not control or manage all of the surrounding shoreline, or the roads and transit that serve the airport, meaning that responsibility for ensuring airports remain operational and accessible rests with other entities. It will be critical for airports to coordinate and collaborate with adjacent landowners, agencies, and organizations to find shared, multi-objective adaptation solutions that can be planned and implemented together.

Impacts to airports are measured in passenger boardings per year as well as cargo volume measured in million pounds of freight per year.



Airports Across the Bay Area

Figure 2-34. Distribution of the Bay Area's airports, including the regions major airports of OAK, SFO, and SJC, as well as numerous other airports that make up the region's airport system.

Regional Exposure of Airports

The bar graph below shows the total area of airports flooded at each total water level both in total acres and as a percent of the regional total of acres for all the regional airports (Figure 2-35). This figure illustrates the relative magnitude of exposure throughout the Bay Area as compared to the system as a whole. Illustrating the data in this way shows that the area of airports exposed represents a substantial amount of the region's airport capacity, and subsequently significant impacts to passenger boardings and movement of cargo volumes. The following analysis of the impacts from this flooding illustrates early impacts of San Francisco International Airport and Oakland International Airport are large drivers of the total exposure of the system. Figure 2-36 identifies which airports have the highest percent of area exposed to flooding.

Exposure affects the degree of impacts and consequences. More widespread exposure amplifies impacts and consequences, and early exposure provides much less time to prepare, which may also amplify impacts and consequences. These nuances are important to bear in mind throughout the following sections describing regional consequence results.

AREA OF AIRPORTS FLOODED REGION-WIDE

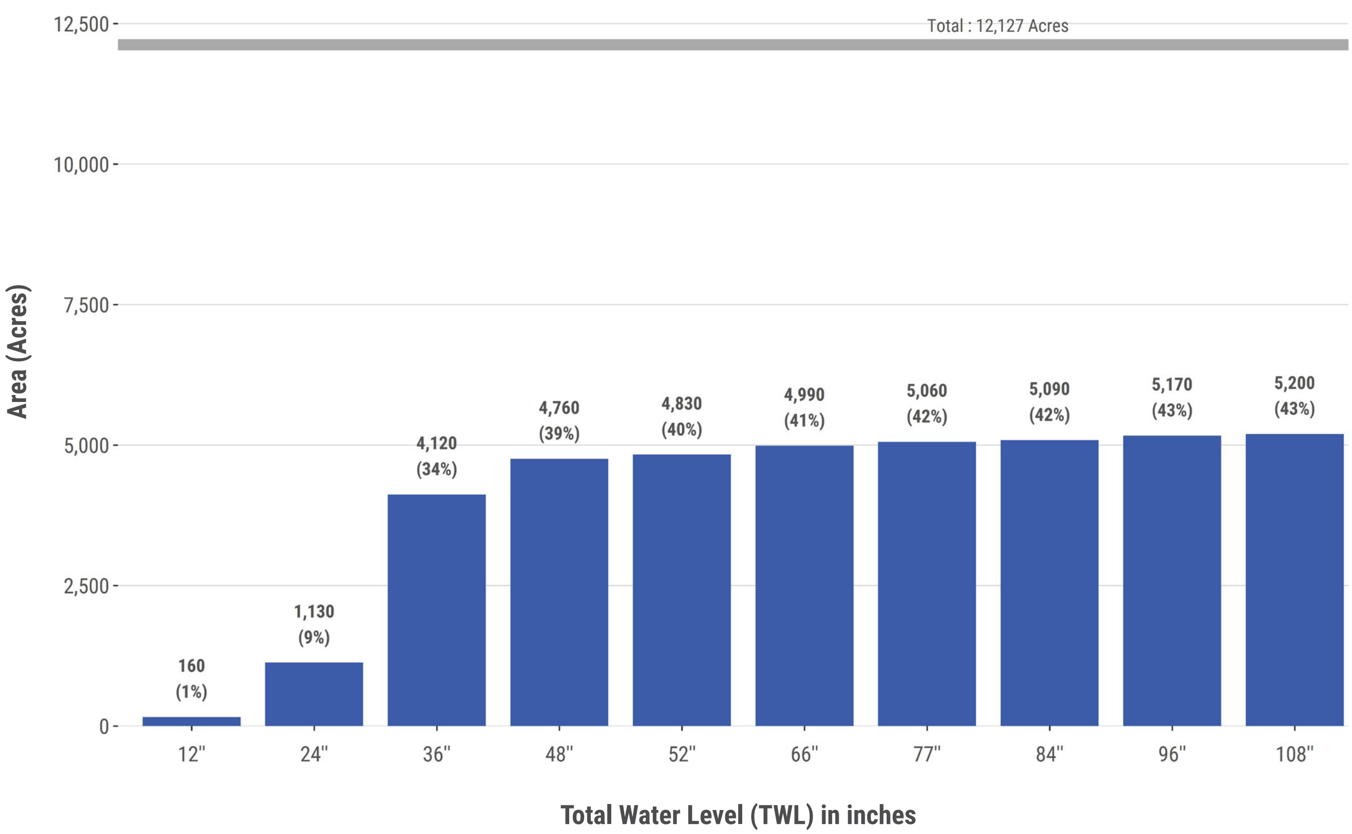


Figure 2-35. Regional exposure of airport area by flooding. Values in parenthesis reflect the percent of area in acres exposed to flooding at each TWL compared to total area of airports in the nine-county region.

San Carlos Airport in San Mateo County is located near the Bay. Photo by Nelson Minar licensed under CC BY 2.0.

HIGHEST **PERCENT OF AIRPORT AREA** FLOODED BY AIRPORT

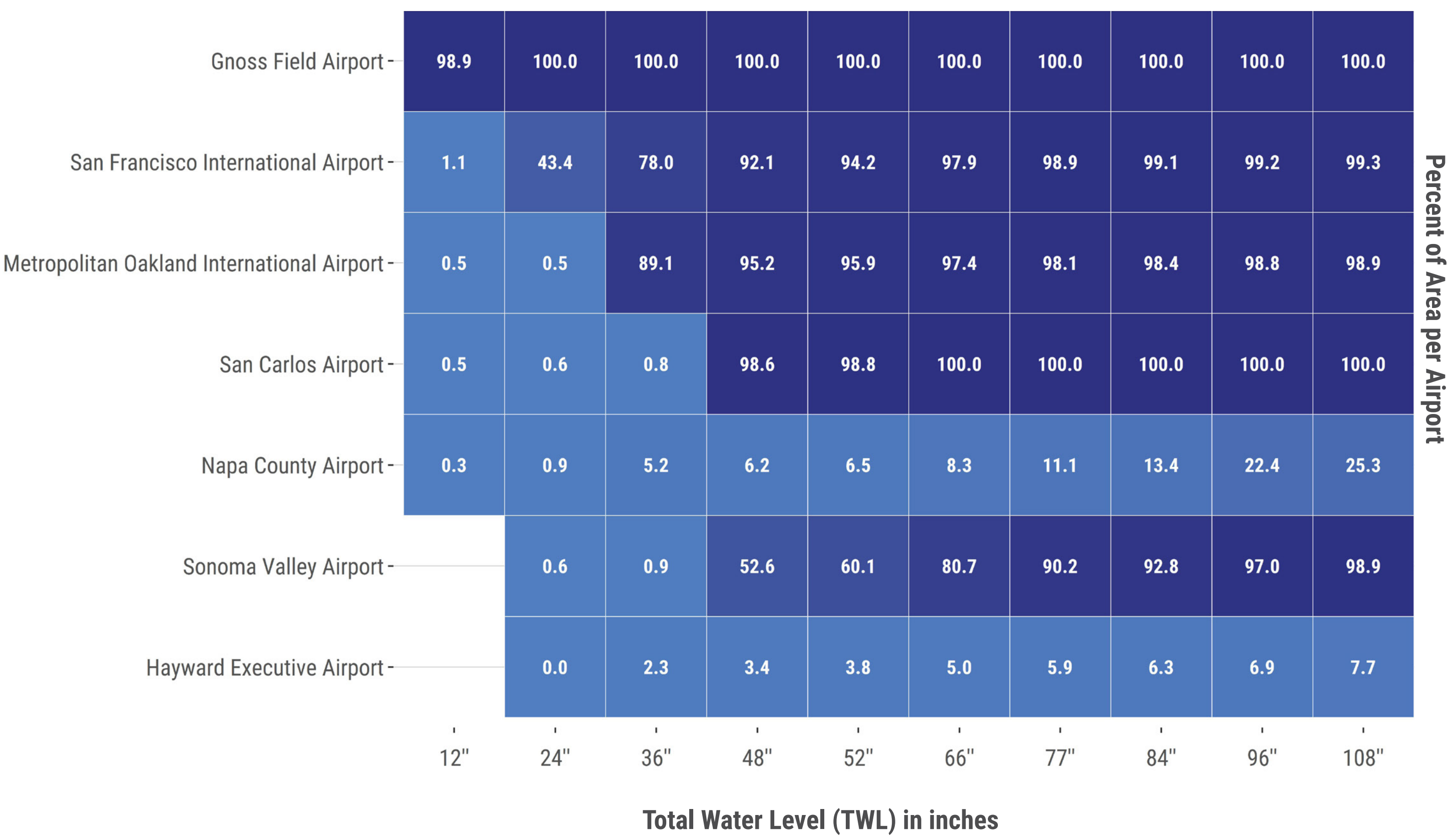


Figure 2-36. Airports with highest percent of area exposed to flooding at ten TWLs. “Highest” consequence refers to airports ranking in the top five for highest exposure at one or more TWL. Darker colors reflect greater consequences from flooding.

Regional Consequences of Airports

Impacts to passengers doesn't occur until 24" TWL, when nearly 27 million annual boardings are impacted due to flooding. This number jumps to over 33 million at 36" TWL, remaining steady until 108" TWL (Figure 2-37). Airports with the highest consequences to passenger boardings are described in the next section (shown in Figure 2-38) and depicted spatially in maps of consequences in Figure 2-41.

Similarly, airport cargo impacts don't occur until 24" TWL, when 440 million pounds of cargo are impacted. This jumps to 1.5 billion at 36" TWL, which remains steady until 108" TWL (Figure 2-39). Airports with the highest consequences to cargo volume are described in the next section (shown in Figure 2-40) and depicted spatially in maps of consequences in Figure 2-41).

AIRPORT PASSENGER BOARDINGS
IMPACTED BY FLOODING REGION-WIDE

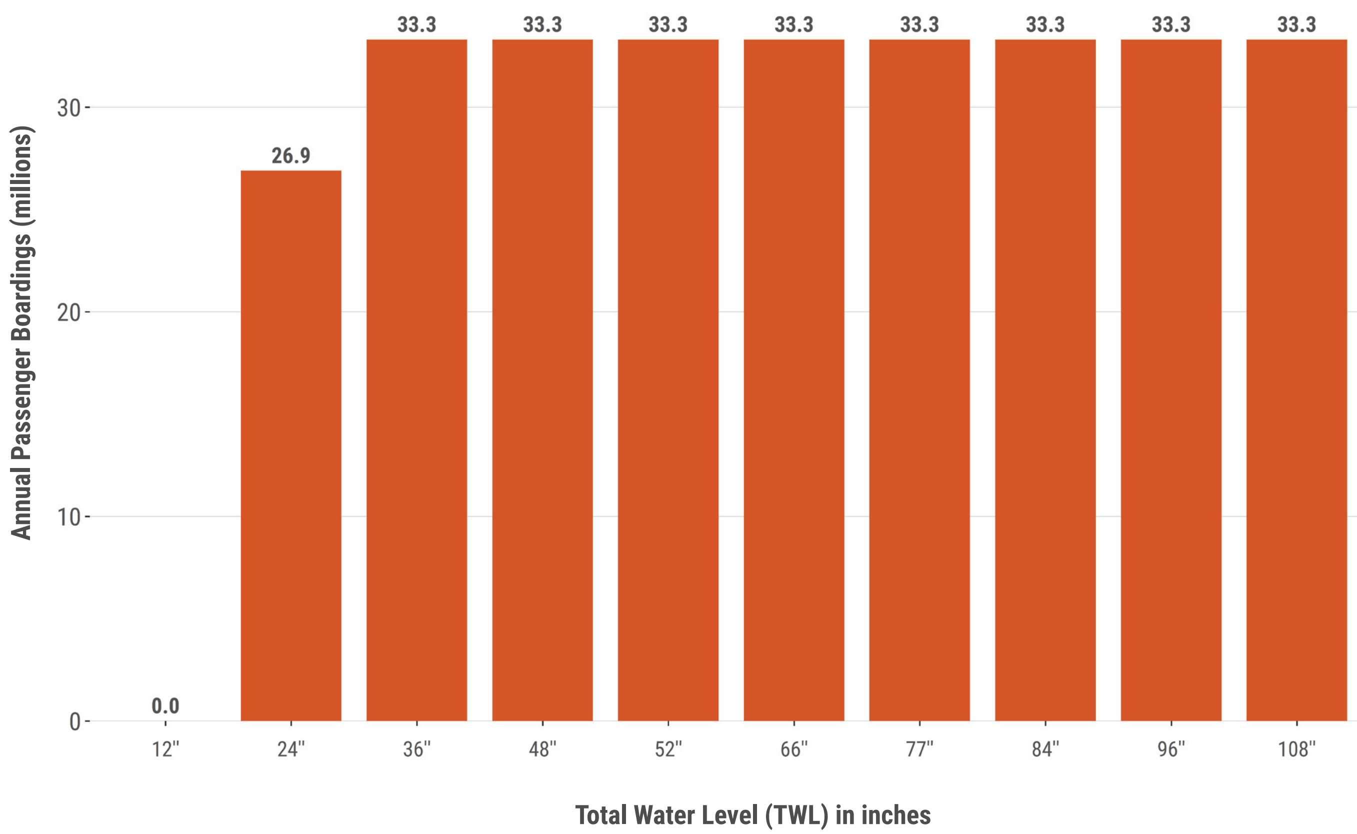


Figure 2-37 Regional impacts to airport passenger boardings from flooding at ten TWLs as measured by impacts to annual passenger boardings in millions. Results are aggregated across the nine-county region.

Short Case Study

LINKING REGIONAL CONSEQUENCE RESULTS TO LOCAL ASSESSMENTS

To address FEMA certification requirements, OAK is in the process of improving its perimeter dike to address flood risk and future sea level rise. These improvements are important for addressing vulnerabilities due to OAK's low elevation at the bay margin. However, there is additional flood risk from behind these levees along Doolittle Drive and San Leandro Bay. Addressing flood risk here is complicated by multiple assets owners and parties.

In addition to the regional assessment, ART Bay Areas assessed individual assets in each of the four region systems and the results are communicated in local assessments of shared vulnerabilities and consequences.

These can be found in Chapter 3.0 Local Assessments of the ART Bay Area report, with local assessments available for individual download.

View of Oakland International Airport runway from the San Leandro Marina. Photo by Udo S. licensed under CC BY 2.0.

HIGHEST **AIRPORT PASSENGER BOARDINGS** IMPACTED BY FLOODING BY AIRPORT

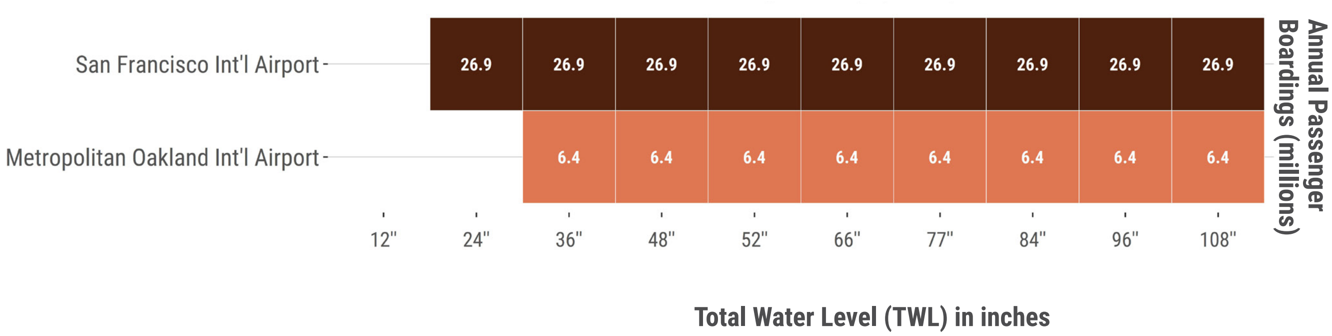


Figure 2-38. Airports with highest impacts to passenger boardings by flooding at ten TWLs as measured by impacts to annual passenger boardings in millions. "Highest" impacts refer to airports ranking in the top five for highest consequences at one or more TWL. Darker colors reflect greater consequences.

Trends and Drivers Around the Region

Airport Passengers and Cargo Volume

Early Impacts • Neither of the two Bay Airports included in this analysis (SFO and OAK), have passenger or cargo consequences at 12" TWL. However, at 24" TWL, SFO runways are impacted, disrupting operations for the Bay Area's most significant passenger airport. At 36" TWL, most of the OAK airport is flooded, significantly impacting the region's most important airport for cargo (Figure 2-41).

Worsening Impacts • Significant thresholds occur between 12" and 24" TWL as well as 24" and 36" TWL, as both SFO and OAK are inundated respectively.

Outliers • SFO reflects a significant outlier for passenger enplanements and OAK represents a significant outlier for cargo volume.

AIRPORT CARGO VOLUME IMPACTED BY FLOODING REGION-WIDE

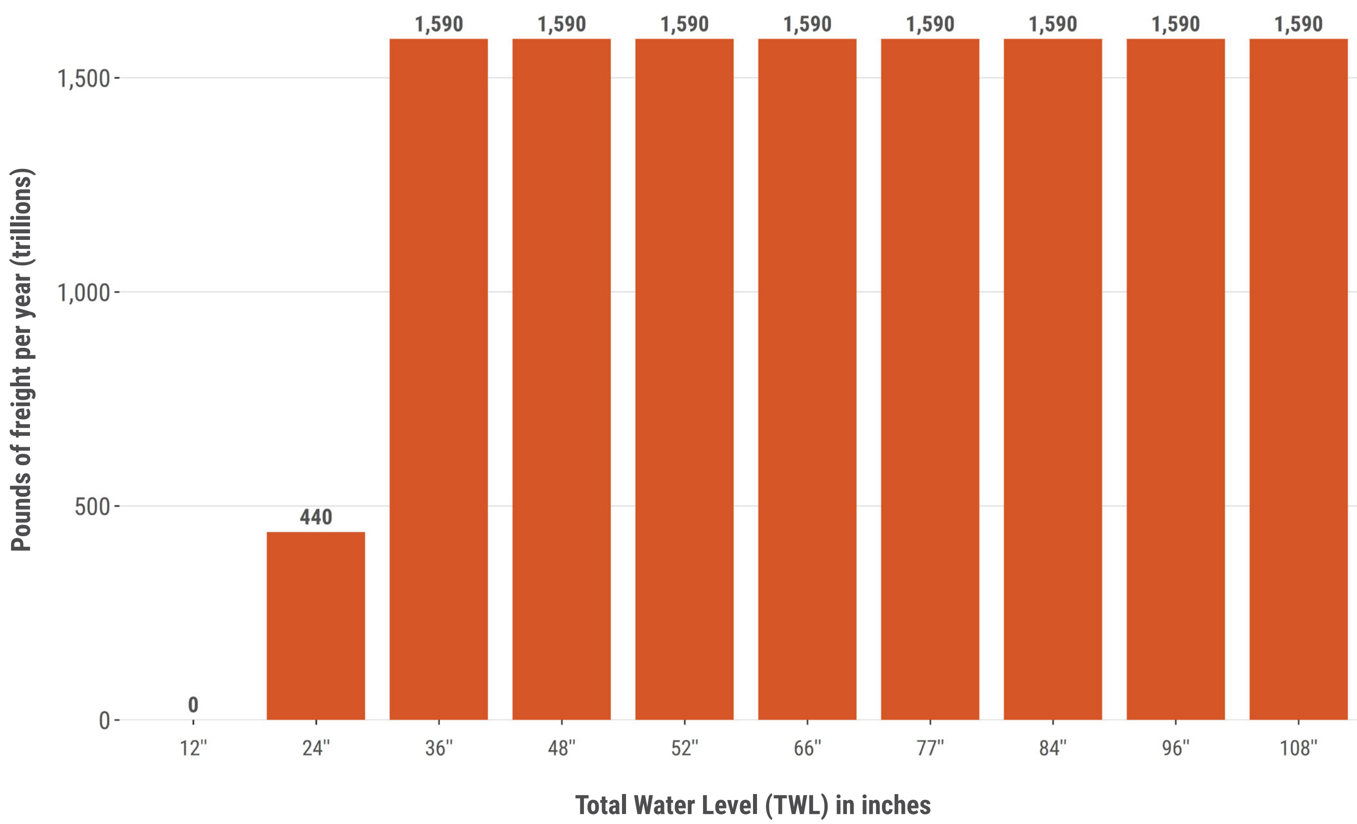


Figure 2-39 Regional impacts to airport cargo volumes from flooding at ten TWLs as measured by impacts to pounds of freight per year in the trillions. Results are aggregated across the nine-county region.

San Francisco International Airport near the Bay. Photo by Nathan Rupert licensed under CC BY 2.0.

HIGHEST **AIRPORT CARGO VOLUMES** IMPACTED BY FLOODING BY AIRPORT

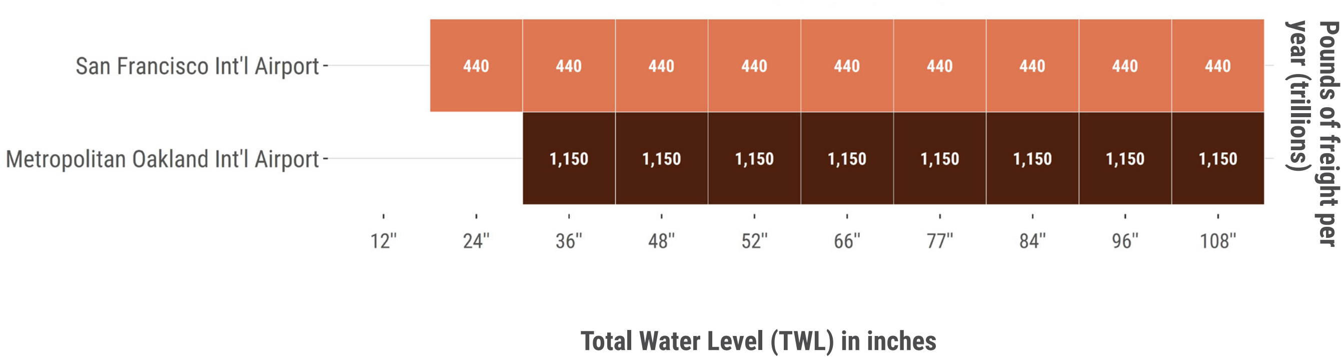


Figure 2-40. Airports with highest impacts to airport cargo volumes by flooding at ten TWLs as measured by pounds of freight per year in trillions. “Highest” impacts refer to segments ranking in the top five for highest consequences at one or more TWL. Darker colors reflect greater consequences.

Transportation

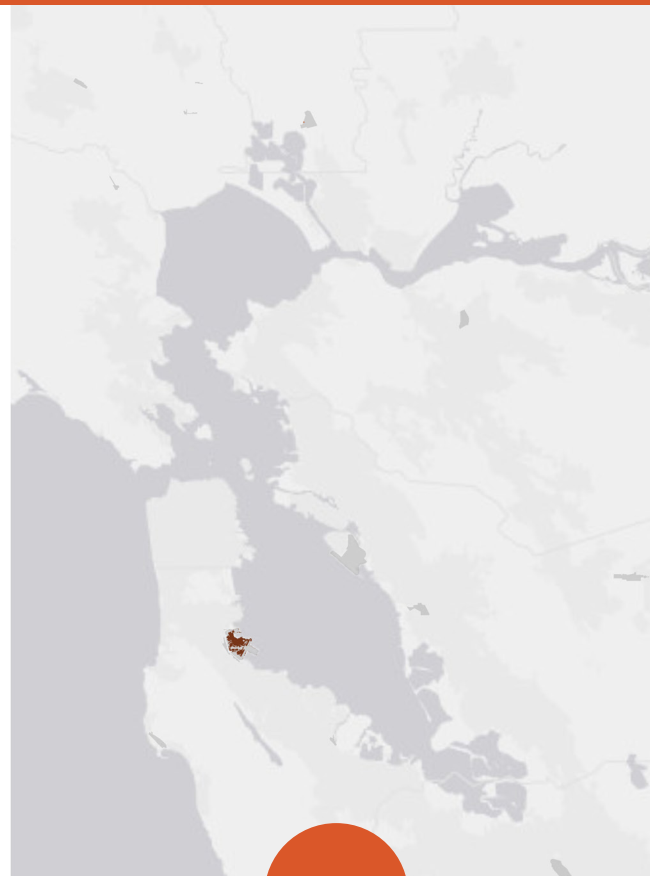
Airport Consequences

Airport Passenger Boardings Impacted by Flooding

People (Annual Passenger Boardings)

- 0 to 6.4 million
- 6.41 to 26.9 million

12"

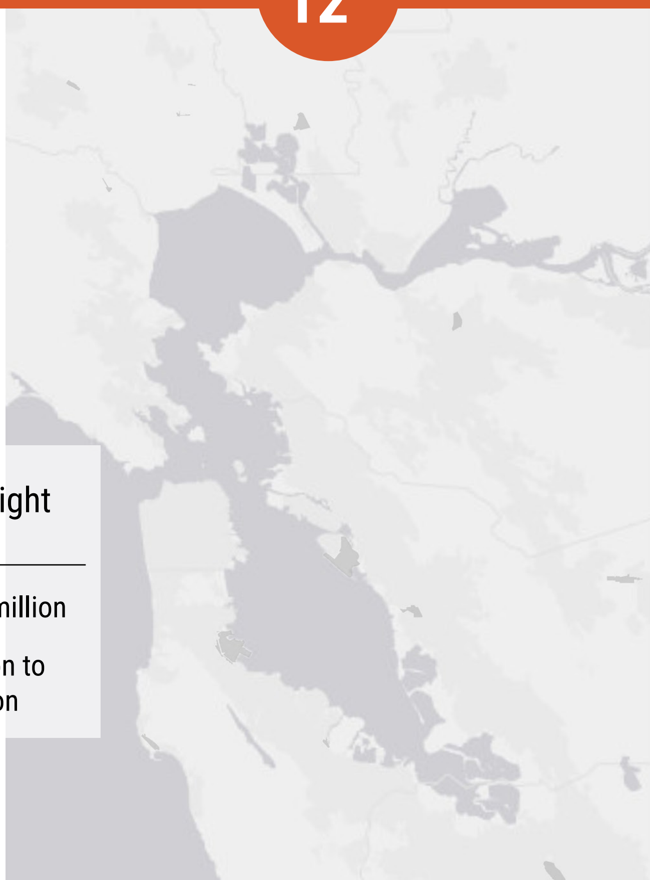


24"

Airport Cargo Volume Impacted by Flooding

Pounds of Freight Cargo per Year

- 0 to 500 million
- 500 million to 1.15 trillion



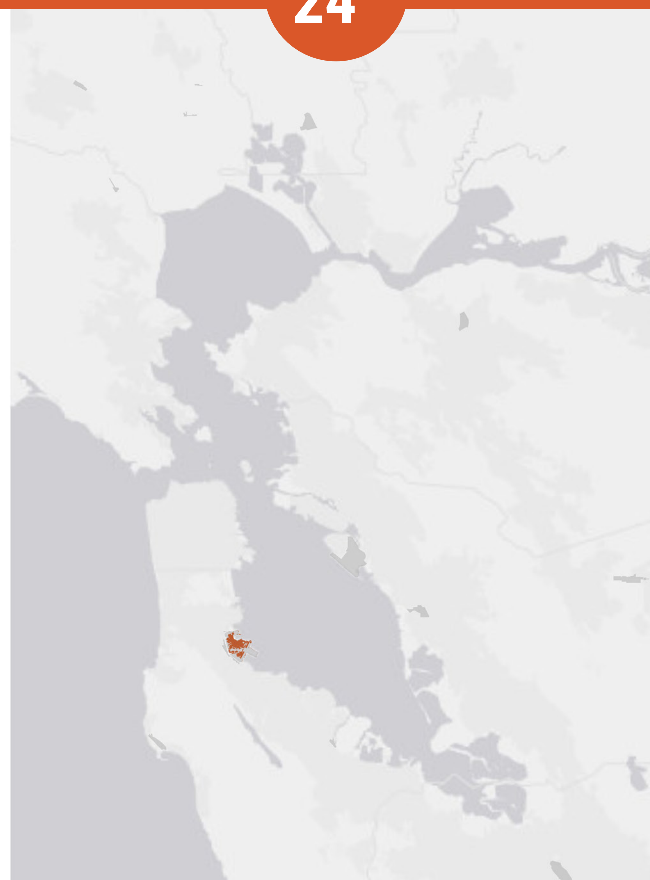


Figure 2-41 Maps depicting the consequences of flooding for two airport indicators: *Airport Passenger Boardings* and *Airport Cargo Volume* at 12", 24" 36" and 48" TWL. Maps below show consequences and extent of exposure for only two airports (SFO and OAK).

Runway at Oakland International Airport along the Bay. Map data ©2019 by Google Earth Pro.

Methodology and Limitations for Airports

Methodology

It is already widely accepted by decision-makers in the Bay Area that major airports are critical regional assets that are threatened by sea level rise. Consequences of inundation to airports were measured using two indicators: total annual enplanements (boardings) and total annual cargo weight by airport. Note that airfields not classified as Primary Commercial Service Airports by the FAA were excluded from this analysis. Reliable cargo data for these airports does not exist and the project team found that the values available for annual passengers were so low (mostly corporate flights or hobby pilots) that these airfields could not be considered critical regional assets.

For the major airports, if any of the operations area was impacted under a given total water level, all enplanements and cargo in that airport were considered impacted. This reflects the strong emphasis on operational safety at airports, as well as the fact that airports have a variety of complex below ground mechanical and electrical infrastructure that, if inundated, would have cascading impacts beyond just the flooded area. Note that although San Jose International Airport is certainly a critical regional asset, it is not vulnerable to sea level rise, even under 108” TWL.

Limitations

This approach has limitations in comprehensively reflecting airport vulnerability in the region. In addition to the consequence of flooding of terminals and runways, regional airports are vulnerable due to numerous other factors. These include:

Runways • Much of the airport runways are low-lying, below the height of today's current king tide events, and protected by a single dike or levee. Runways that are flooded or that have significant earthquake damage, such as sand boils and cracks, cannot operate. The Bay Area does not have sufficient commercial airport runway capacity to serve as a short- or long-term alternative to either OAK or SFO it they were damaged or disrupted due to sea level rise, storm events, or an earthquake.

Ground Transportation Access + Parking • The airport relies on ground transportation for passenger and cargo access to the airport. This includes highways, commuter rail, local roads, and the San Francisco Bay Trail. If these transportation networks are disrupted, access to airports may be impacted. Additionally, onsite and offsite parking for passengers and employees is critical for operations.

Fuel Tanks and Pipelines • Airports depend on the fuel system, including the tank farms and pipelines, being operational in order to provide jet fuel to aircraft. Fuel systems are generally at grade and vulnerable to flooding and ground shaking. If these facilities are disrupted, they can have consequences for environmental and public health.

Lifeline Facility • The major airports serve as lifeline facilities and need to be operable in the event of an emergency (e.g., bringing in supplies, personnel, etc.). If the runways or control tower aren't functioning, the airport won't be able to perform this service limiting emergency response in the region.

Governance and Coordination • Some facilities (e.g. control tower) are owned and operated by the FAA and located within the footprint of the airport, which is owned and operated by a different entity. Changes to these facilities would require the cooperation of all entities as well as the private airline operators. It would also have to meet all standards and regulations – including federal and local regulations – which could mean that a long lead time will be required for structural or operational changes to increase resilience. Multiple (and sometimes competing) regulations complicate permitting for resilience projects at the airport including FAA, State Fire Marshall, BCDC, US Army Corps of Engineers, regional water quality control boards, and local jurisdictions.

SEAPORTS

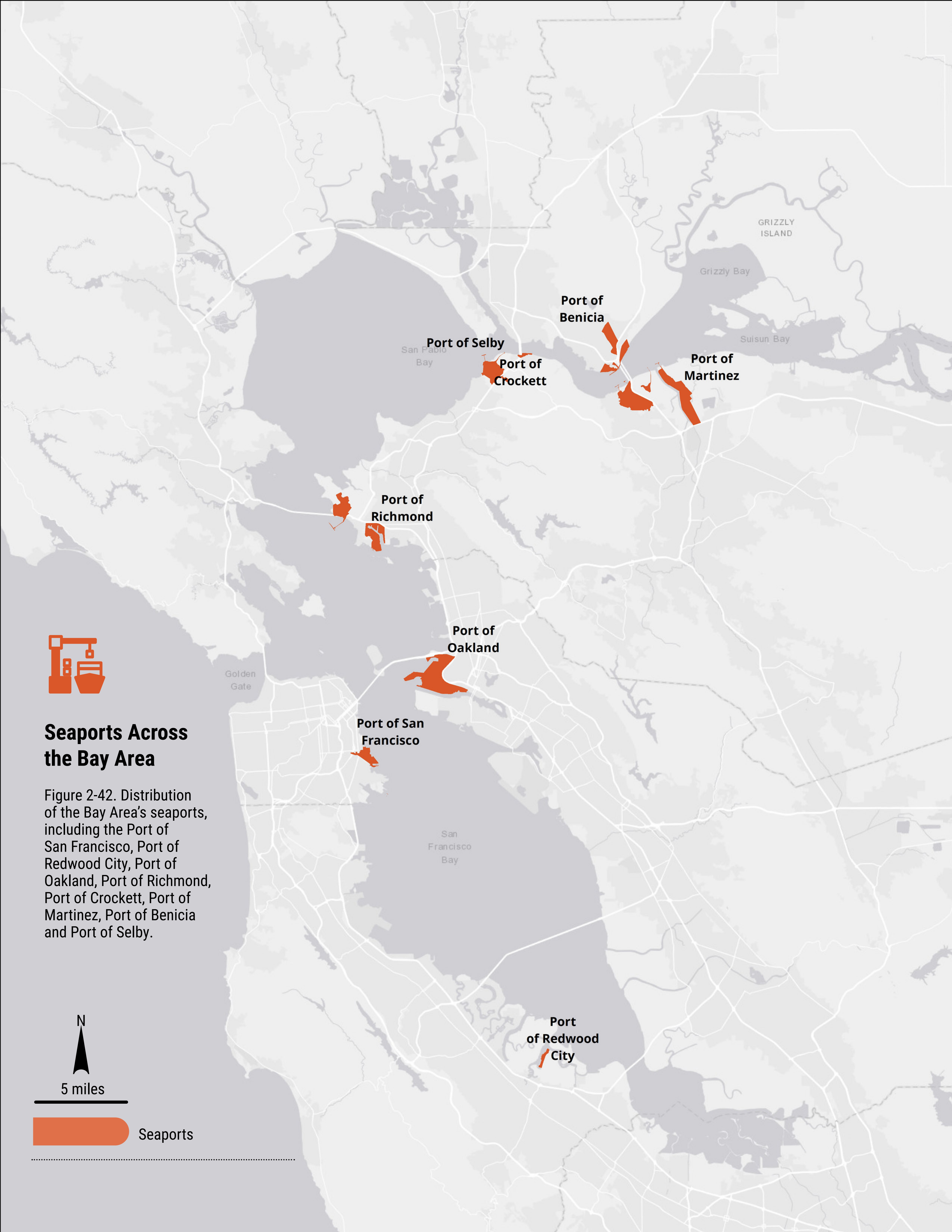
The Bay Area is home to five major seaports include the ports of Benicia, Oakland, Redwood City, Richmond, and San Francisco, as well as several smaller ports. These seaports provide for critical economic activities and logistical connections to the Bay region and Northern and Central California at large, as well as with international markets. Each port plays a unique role in the region's shipping industry (Figure 2-42).

For example, the Port of Oakland serves as the Bay Area's primary container shipping port, handling 99 percent of containerized goods moving through Northern California.[6] The Port of Oakland specializes in both the import of high-value consumer goods and the export of agricultural products from the Central, Napa, and Salinas valleys. The Port of Benicia handles cars and petroleum coke, the Port of Redwood City handles construction materials, the Port of Richmond handles liquid bulk and cars, and the Port of San Francisco handles dry bulk as well as other maritime activities such as cruise ship calls. Additionally, several smaller private ports support industrial uses along the Contra Costa County shoreline.

The Bay Area's ports are critical to the economic systems of the region, the state, and the nation, connecting imported goods to domestic markets, providing a gateway for exports, and playing a key part in the shipping and logistics industry, which provides employment and services beyond the ports themselves. Additionally, given their waterfront locations, the ports also play a role in the regional emergency response system.

The ports require ground transportation networks, shoreline access, and infrastructure in order to function. Due to the size and specialized role of each port, there is little redundancy within the port system; a disruption at any one of the ports could have significant negative impacts on the region's economy. While many seaport facilities may not be directly exposed to near-term flood hazards, the on- and off-site facilities and services on which the ports rely—including utilities, pipelines, and transportation systems—can be damaged by temporary or permanent flooding as sea levels rise. In addition, infrastructure located under wharves could be vulnerable to damage from increased tidal and wave energy connected to sea level rise.

Impacts to seaports are measured in the dollar value of exports and imports.



Seaports Across the Bay Area

Figure 2-42. Distribution of the Bay Area's seaports, including the Port of San Francisco, Port of Redwood City, Port of Oakland, Port of Richmond, Port of Crockett, Port of Martinez, Port of Benicia and Port of Selby.

Regional Exposure of Seaports

The bar graph below shows the total area of seaports flooded at each total water level both in total acres and as a percent of the regional total acres within all the seaports in the nine county Bay Area (Figure 2-43). This figure illustrates the relative magnitude of exposure throughout the Bay Area as compared to the system as a whole. Illustrating the data in this way shows that the area of seaports exposed represents a substantial amount of the region's seaport capacity, and subsequently significant impacts to dollar values of exports and imports. Figure 2-44 identifies which seaports have the highest percent of area in acres exposed to flooding.

Exposure affects the degree of impacts and consequences. More widespread exposure amplifies impacts and consequences, and early exposure provides much less time to prepare, which may also amplify impacts and consequences. These nuances are important to bear in mind throughout the following sections describing regional consequence results.

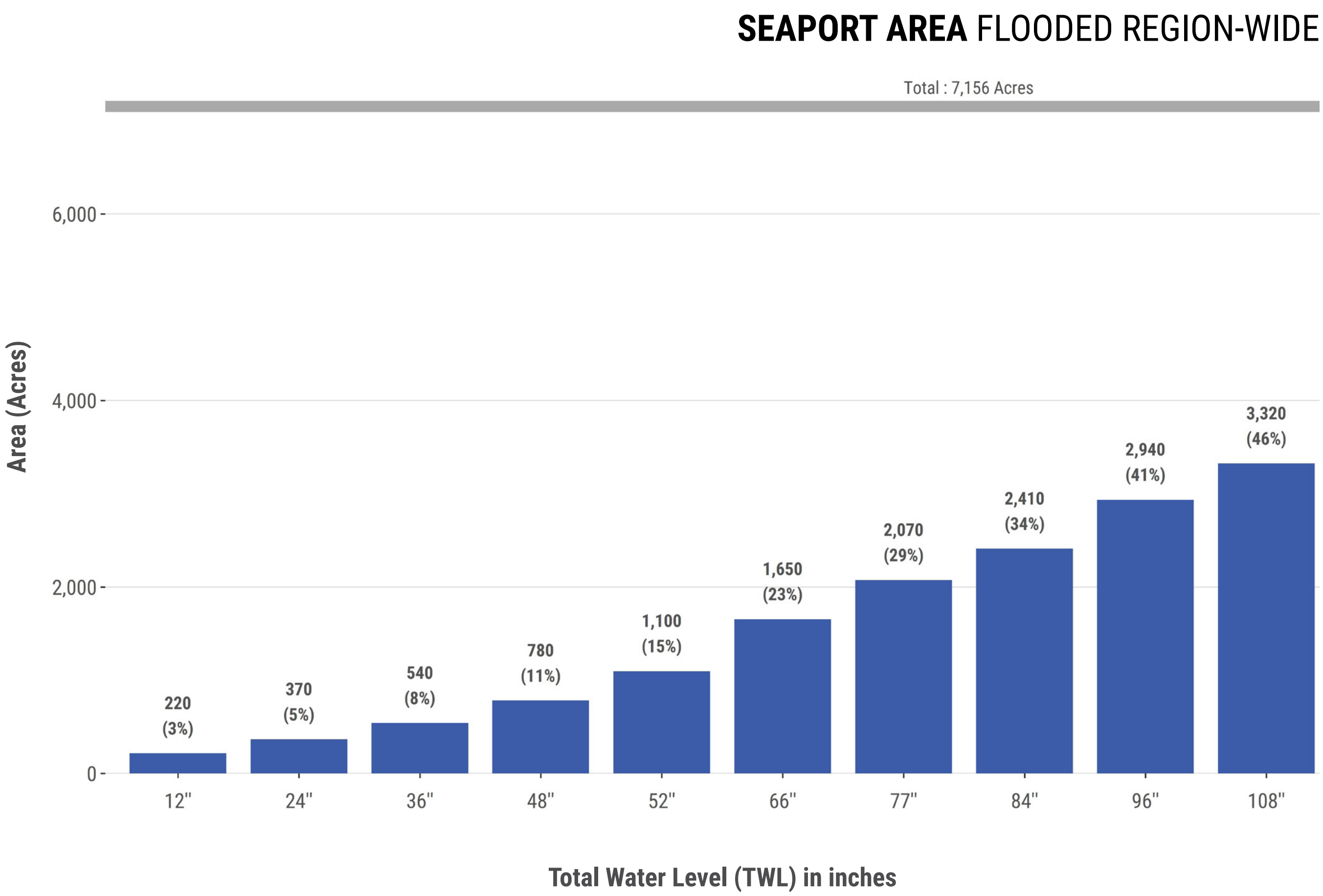


Figure 2-43. Regional exposure of seaport area by flooding. Values in parenthesis reflect the percent of area as measured by acres exposed to flooding at each TWL compared to total area of seaports in the nine-county region.

Cranes and ships at the Port of Oakland. Photo by Travis Leech licensed under CC BY 2.0.

HIGHEST **PERCENT OF SEAPORT AREA** FLOODED BY SEAPORT

Percent of Area by Seaport

Seaport	12"	24"	36"	48"	52"	66"	77"	84"	96"	108"
Port of Crockett	10.3	12.0	13.7	15.5	16.4	28.1	40.8	66.6	80.9	87.7
Port of Benicia	9.9	17.4	21.1	30.3	31.2	34.4	35.7	36.4	37.7	38.9
Port of Redwood City	6.5	46.3	66.5	83.4	85.5	89.7	91.1	91.5	92.0	92.6
Port of San Francisco	5.3	7.8	10.4	18.2	36.1	49.2	56.5	60.3	64.8	69.5
Port of Martinez	3.3	4.8	9.5	11.6	12.6	21.8	25.1	27.3	30.4	32.4
Port of Richmond	1.8	1.9	2.5	7.4	9.1	13.4	16.6	20.9	29.1	34.4
Port of Selby	0.4	0.7	1.3	1.6	1.7	2.5	3.9	7.4	11.2	15.1
Port of Oakland	0.4	0.5	0.6	1.2	12.0	23.9	37.8	47.8	64.2	76.5

Total Water Level (TWL) in inches

Figure 2-44. Seaports with highest percent of area in acres exposed to flooding at ten TWLs. "Highest" exposure refers to seaports ranking in the top five for highest exposure at one or more TWL. Darker colors reflect greater consequences from flooding.

Regional Consequences of Seaports

In general, regional impacts of flooding on seaport operations remains fairly low until significant flooding occurs at the Port of Oakland at 52" TWL. Consequences to the dollar value of exports and imports at seaport in the region reaches 13.6 billion at 52" TWL. Above 52" TWL, the regional consequence increases roughly linearly as water levels increase, up to 47.2 billion at 108" TWL (Figure 2-45).

Individual seaports with the highest consequences are discussed in the next section (shown in Figure 2-46) and depicted spatially in maps of consequence in Figure 2-47.

DOLLAR VALUE OF EXPORTS AND IMPORTS OF SEAPORTS IMPACTED BY FLOODING REGION-WIDE

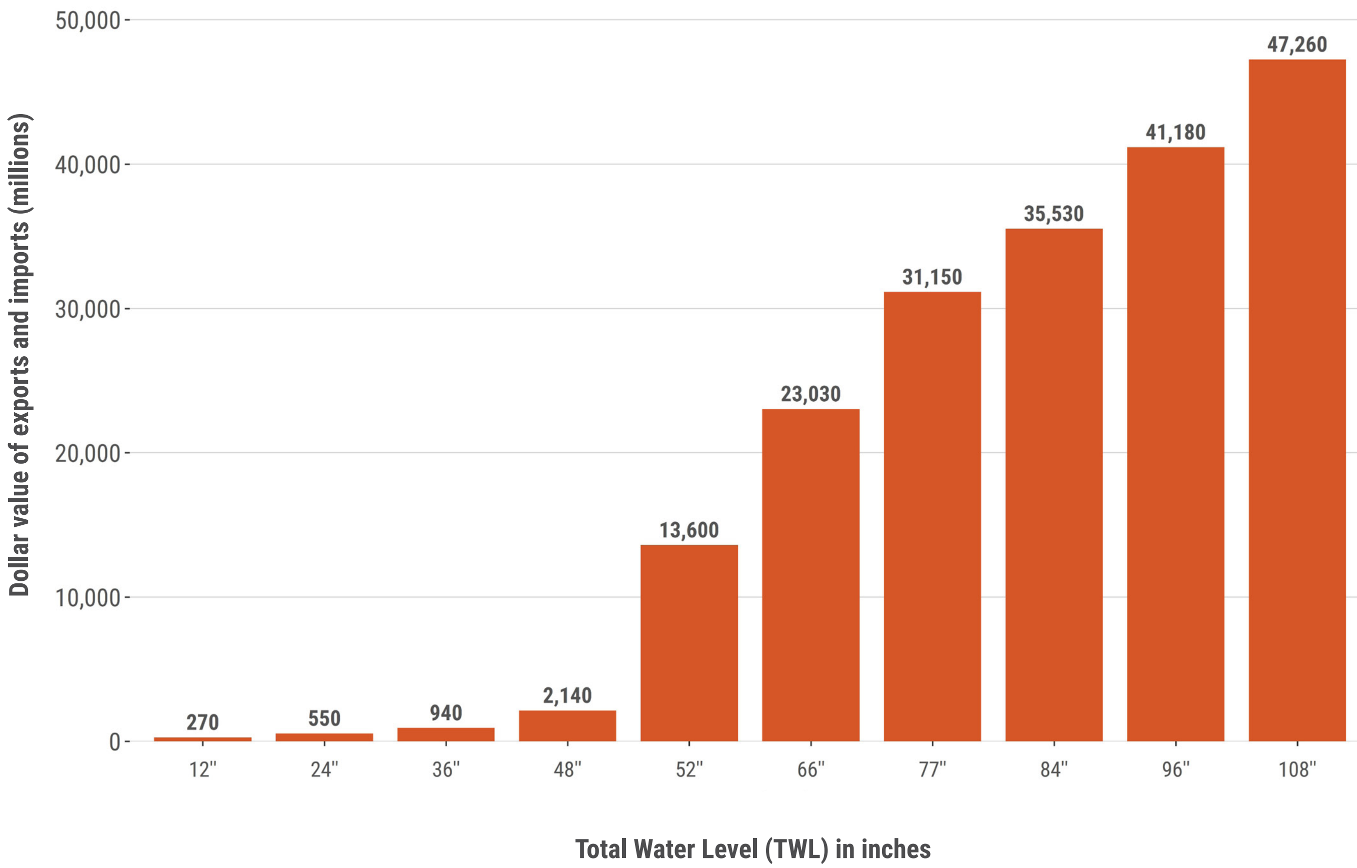


Figure 2-45 Regional impacts to seaports from flooding at ten TWLs as measured by impacts to dollar value of exports and imports in million. Results are aggregated across the nine-county region.

Short Case Study

LINKING REGIONAL CONSEQUENCE RESULTS TO LOCAL ASSESSMENTS

At the Port of Oakland, goods are transferred from ships to the Union Pacific Railroad (UPRR) and I-880, which are both at risk of future flooding. This area of shoreline is also located on bay fill, which makes rising groundwater an added risk.[9] At the Port of Richmond, some access roads and the UPRR and BNSF rail lines are located within the 100-year floodplain and may be exposed to more frequent or extensive flooding with sea level rise. The Port of Redwood City is sensitive to flood risk at Seaport Boulevard and the UPRR rail line.[10] Clearly, efforts to address seaport vulnerability must also include strategies to ensure the resilience of goods movement systems more broadly.

In addition to the regional assessment, ART Bay Areas assessed individual assets in each of the four region systems and the results are communicated in local assessments of shared vulnerabilities and consequences.

These can be found in Chapter 3.0 Local Assessments of the ART Bay Area report, with local assessments available for individual download.

HIGHEST **DOLLAR VALUE OF EXPORTS AND IMPORTS**
IMPACTED BY FLOODING BY SEAPORT

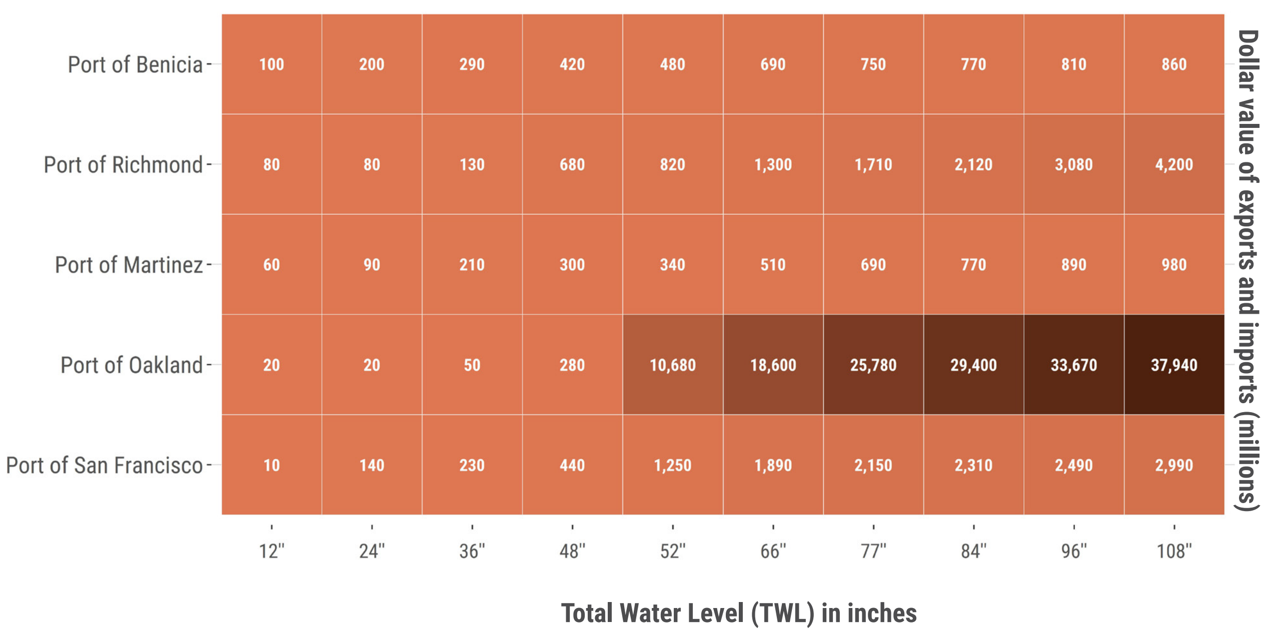
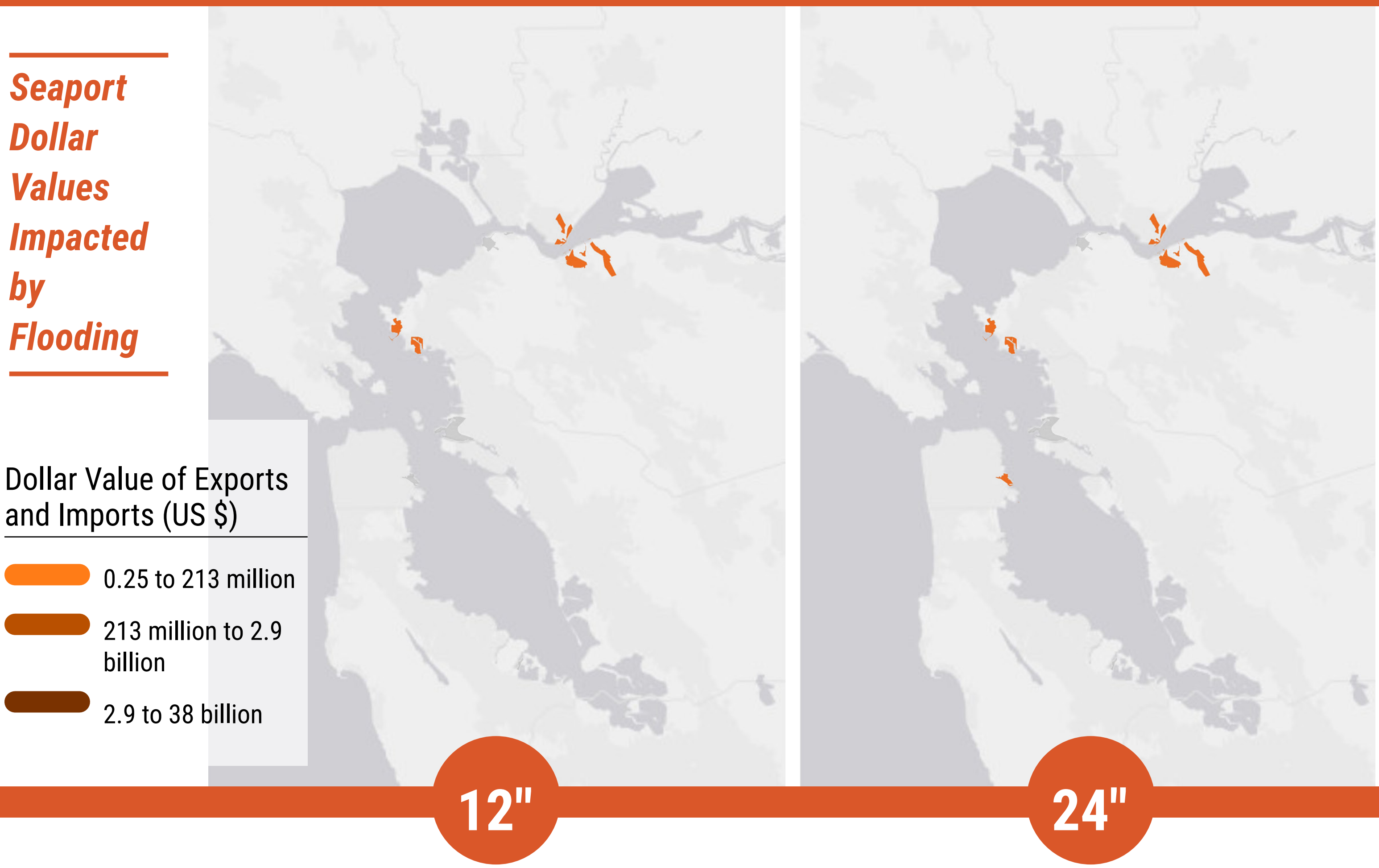


Figure 2-46. Seaports with highest impacts by flooding at ten TWLs as measured by impacts to dollar value of exports and imports in millions. "Highest" impacts refer to seaports ranking in the top five for highest consequences at one or more TWL. Darker colors reflect greater consequences.

Seaport Dollar Values Impacted by Flooding

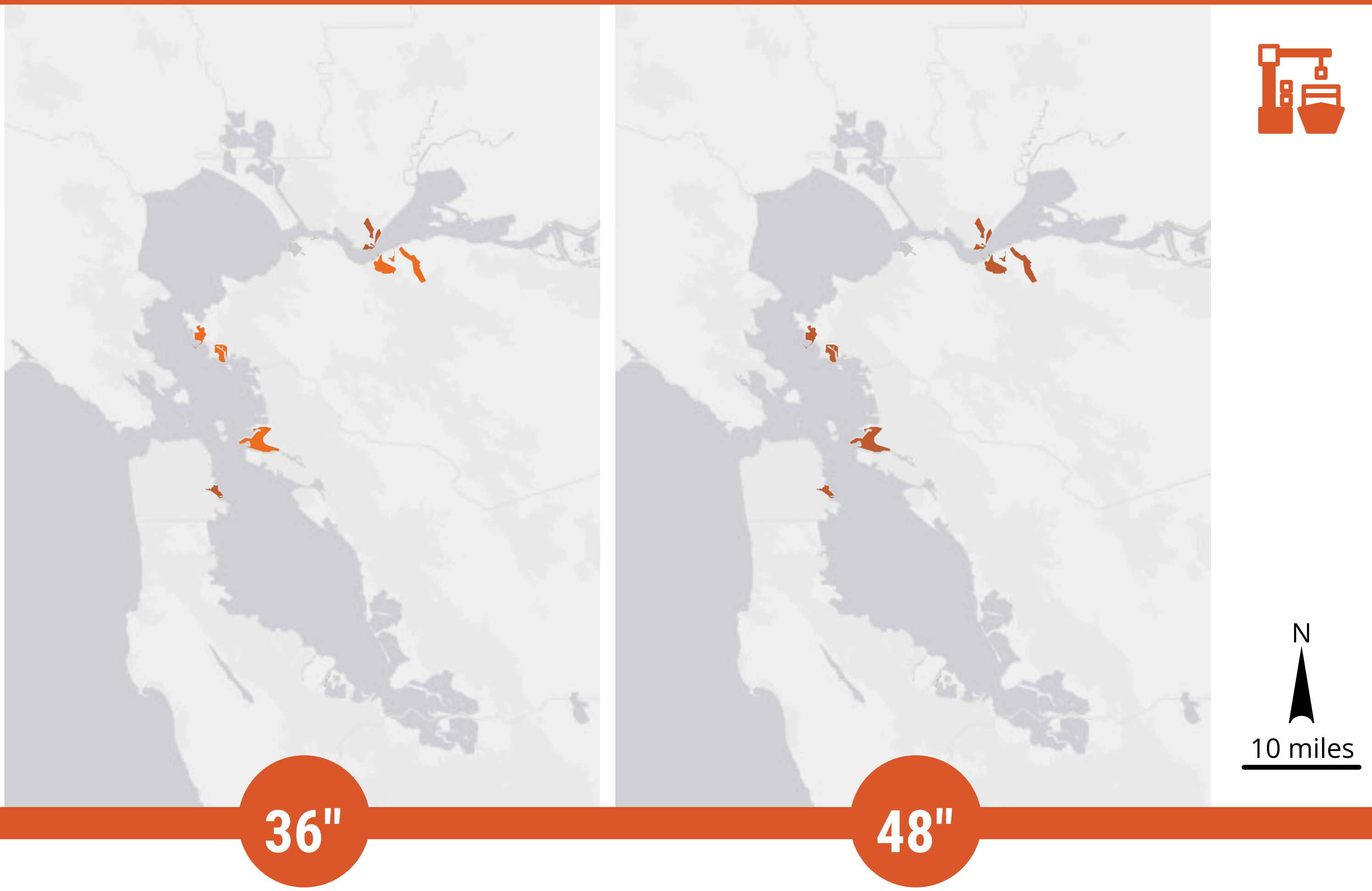


Trends and Drivers Around the Region

Seaport Dollar Values

Early Impacts • At 12" TWL, several ports in the Bay Area (except Port of Crockett) experience impacts from flooding of road and rail infrastructure. This consequence is very small (<1 percent of roads and rail) for all ports except the Port of Benicia (6 percent), Port of Redwood City (14 percent), and the Port of Martinez (2 percent). At 24" TWL, these consequences expand modestly at the Port of Benicia (11 percent), Port of Martinez (3 percent), and include impacts at Port of San Francisco. The Port of Redwood City experiences a substantial jump in consequence, with 75 percent of its road and rail infrastructure being impacted at 24" TWL (Figure 2-47).

Figure 2-47. Maps depicting the consequences of flooding for one seaport indicator: *Seaport Dollar Value of Exports and Imports* at 12", 24" 36" and 48" TWL. Assets with any portion exposed to flooding are considered impacted. Maps below show entirety of seaports impacted, not extent of exposure.



Worsening Impacts • Regionally, impacts to seaport operations worsen between 48" and 52" TWL and between 52" and 66" TWL. These are both largely driven by increases in flooding at the Port of Oakland and Port of San Francisco.

Outliers • Significant outliers of high impacts to seaports include the dramatic consequence of flooding at the Port of Oakland, which is the main contributor for the most significant threshold change among the seaports.

Methodology and Limitations for Seaports

Methodology

Seaports are very large assets with a variety of components that have varying levels of sensitivity to flooding, and that inundation of some portions of a port will likely not completely impact the port's ability to move goods. Thus, the consequence of inundation of seaports was determined based on the impact to the total annual value of exports and imports by port. This indicator was chosen over cargo volume because cargo volume would overemphasize goods with low value but high weight, such as concrete, gravel, or recyclables. Because roads and railways are critical to moving goods in or out of the ports and linework data for both are regionally available, the project team used these features to estimate the economic impacts for each port. Using geospatial analysis, the project team calculated the percentage of roads and railways within each port that would not be inundated and multiplied that percentage with the annual import/export value of each respective port so that the weighting of flooded roads was reflected in the annual import/export value. Further explanation of the methodology can be found in the Appendix.

Limitations

This method does not consider network impacts on redundancy or the vulnerability of other port components; however, it does allow for a more nuanced analysis than simply considering an entire port impacted if only a portion of the area is inundated, given the resources and data available. This approach has limitations in its ability to comprehensively reflect seaport vulnerability in the region as, in addition to the consequence of flooding of roadways and railways, regional seaport vulnerability is tied to numerous other factors, including:

Networked Transportation • Seaports rely on connections to ground transportation, including highways and rail lines, and these connections are at risk of inundation or periodic flooding as sea levels rise. Past ART projects in Alameda and Contra Costa counties have identified railroads and highways that directly serve the ports of Oakland and Richmond as areas of vulnerability. Similarly, the other ports included in this study all connect to rail and/or highway networks with the potential to flood under various sea level rise scenarios. Rail lines are often located along the shoreline and cross many tidal creeks and channels throughout the region. Damage from flooding at any point in the rail system can result in system-wide disruptions. Loss of rail service to seaports could result in increased truck traffic, affecting congestion and air quality in surrounding neighborhoods and on local roadways and interstates, and could negatively impact port operations by decreasing cargo throughput and increasing dwell time of cargo and ships.

Utilities and Shore Power • Seaports rely on various utility systems, including water, wastewater, and stormwater systems; pipelines; and power infrastructure to support operations. For example, as more seaports move to reduce greenhouse gas and air pollutant emissions, they will depend more on shore power to decrease ship exhaust while berthing. Depending on its location and how well it is maintained or protected, this infrastructure could be vulnerable to disruption from flooding or wave action associated with sea level rise, thus impacting port operations.

Lifeline Facility • As elements of the Bay Area's transportation network, the seaports would be critical facilities in the case of a natural disaster or other emergency. This is partially because the ports are entry points for goods and supplies for the region; any disruption to port operations in an emergency could delay the delivery of supplies to communities in need. Additionally, the ports are uniquely positioned to provide an alternative to regional ground transportation for both people and supplies following an emergency, in the case that roadways or rail lines are damaged or congested. For example, the Port of Redwood City has been designated by FEMA as a Federal Staging Area following an emergency and is also designated a Bulk Fuel Distribution Point and commodity staging for regional federal disaster response following a catastrophic earthquake.[7] Ensuring that the seaports are operational following an emergency will be important to maintaining the integrity of the region's supply chains and transportation infrastructure in order to serve emergency response and recovery efforts.

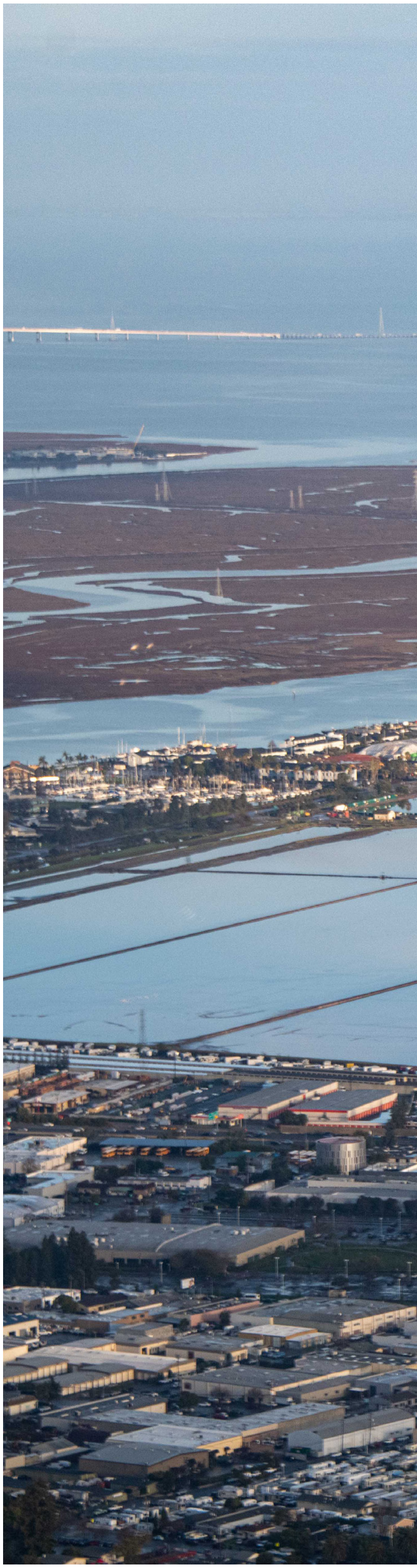
Liquefaction • Due to the nature of their operations, seaports in the Bay Area have traditionally been developed on Bay fill.[8] This increases their vulnerability to seismic liquefaction and threatens their operations and function as a lifeline facility in emergencies.

Ad-Hoc Shoreline Protection • Given the nature of their location along the shoreline, seaports serve as either the first or second line of flood protection for infrastructure and communities inland. This is especially true in West Oakland, Richmond, and San Francisco. Because the seaports may, in some cases, act as physical buffers or barriers between the shoreline and upland areas, any failure in an individual seaport's flood protection could have flood risk implications for those areas. In addition, because ports are industrial operations with heavy traffic, flood waters moving across seaport properties could carry contaminants and debris into neighboring communities, ecosystems, and/or the Bay itself. Therefore, the resilience of the seaports to sea level rise-related flood hazards is a component of floodplain planning not just for the seaports themselves, but adjacent communities as well.

Governance • Decision-making at the individual seaports may involve the participation of multiple entities with different duties, priorities, and interests, which can vary based on the management structures, ownership and lease arrangements, and other relationships at each seaport. Port governance may involve a port commission (as at the ports of Oakland, Redwood City, and San Francisco) or director (as at the Port of Richmond) appointed by the city's mayor and authorized to make determinations on port uses, operations, leases, and capital allocation; in the case of Benicia, the port is privately operated by the Benicia Port Terminal Company.

Certain matters may require review and approval by a city council or county board of supervisors. Property in the port areas are often owned and/or leased by the ports; however, some sites within the port areas may be privately owned. Facilities and services in port areas add more layers – for example, transportation facilities such as on-dock rail services are managed by operators like the UPRR, and cargo and logistics may be handled by port tenants and their contractors.

Moreover, port lands can also fall under the jurisdictions of other agencies, including the State Lands Commission and BCDC. Thus, long term planning conducted by the ports may require the cooperation of a range of stakeholders, including other city and/or county departments, businesses, tenants, members of the community, and State agencies like BCDC. Close collaboration between a variety of actors and jurisdictions will be required to develop and implement effective adaptation strategies.



Port of Redwood City during King Tides in December 2019. Photo by SF Baykeeper, Robb Most, and LightHawk.

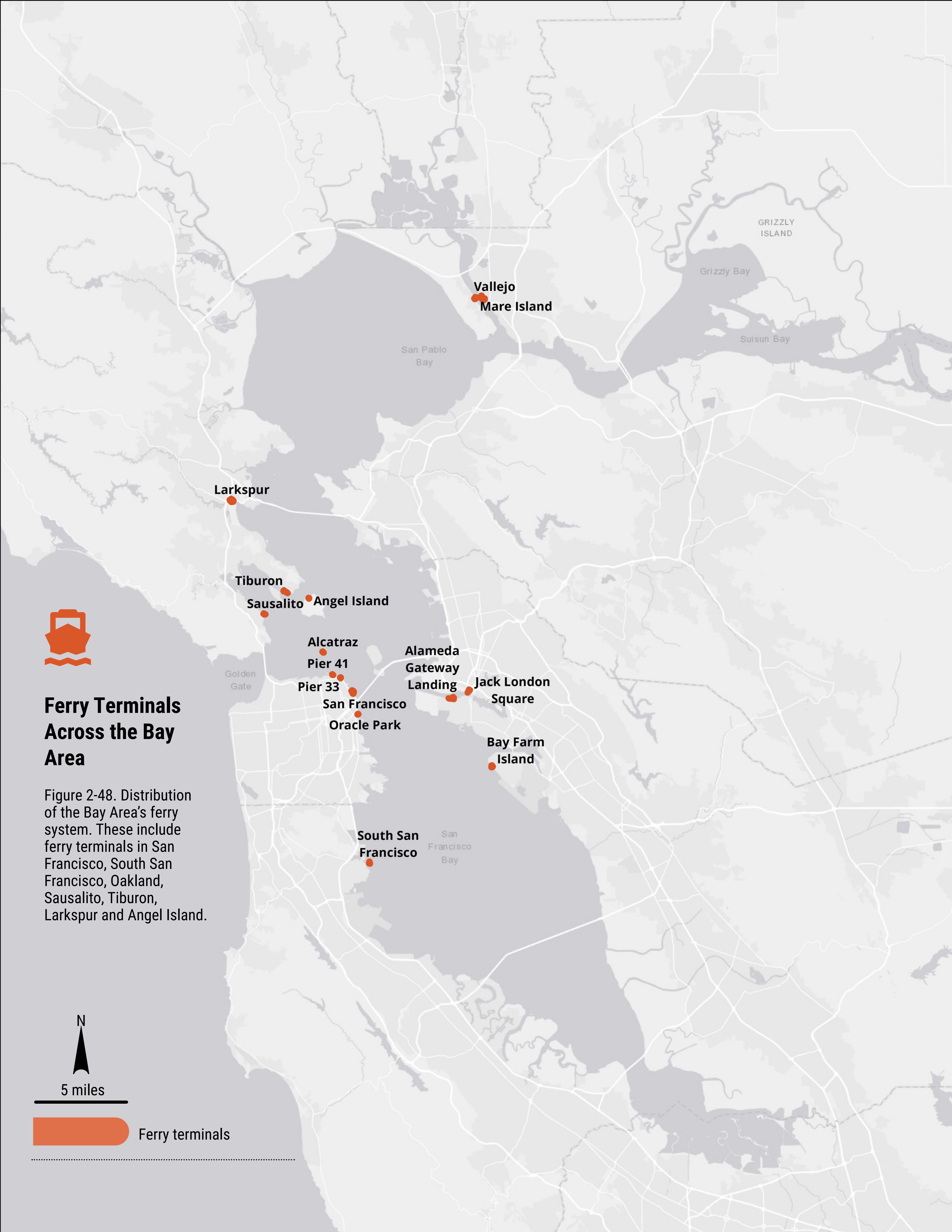
FERRY SYSTEM

The Bay Area is home to two primary public ferry vessel operators, and several smaller private water taxi services (Figure 2-48). On an average weekday, approximately 17,000 people take some form of ferry service to work, school, or tourist destinations.[11] Ridership on ferries has increased considerably in the last several years as new routes have been offered and commuters are finding alternatives to mass transit.[12]

In the Bay Area, the ferry system operates as a network with bus service, BART (e.g. Embarcadero), San Francisco Bay Trail, and rideshares providing service for the first/last mile to work or home. Ferries are utilized by disconnected communities that often lack access to other adequate transit networks (e.g. Marin County, Alameda, Vallejo/Mare Island) that travel to job centers in San Francisco or the peninsula. The critical components of the ferry system are the terminals and associated facilities (gangways, power, parking), maintenance facilities, and local road access.

Due to the water-based nature of the facilities, they typically have some resilience to exposure of saltwater, but flooding can still damage these facilities or make them inaccessible. However, ferry service is susceptible to disruption during large storm events and an increase in frequency and magnitude of these events in the future may interrupt service for commuters who rely on them. In addition to transportation, the ferry fleet is also intended to be deployed to evacuate stranded people and mobilize first responders in the event of an earthquake or major catastrophe which disables Bay Area bridges or roads. The ferry service was deployed in this manner after the Loma Prieta earthquake and Bay Bridge collapse. There is often a complex structure of terminal ownership and maintenance, vessel ownership and maintenance, and ferry operation from different entities, which makes coordination a key to adaptation.

Impacts to the ferry system are measured by average weekday boardings that may be impacted by flooding. This analysis utilized the elevation of the *land* that the ferry terminal sits on and does not account for the fact that the actual terminal or docking areas may be at a higher elevation, and thus not exposed at the same total water levels. However, ridership is still considered *impacted* due to potential impacts to ferry access, which may limit the ability of users to onboard, offboard, access entry points such as ticket booths, or access parking.



Ferry Terminals Across the Bay Area

Figure 2-48. Distribution of the Bay Area's ferry system. These include ferry terminals in San Francisco, South San Francisco, Oakland, Sausalito, Tiburon, Larkspur and Angel Island.

Regional Exposure of Ferry Terminals

The bar graph below shows the total area of ferry terminals flooded at each total water level both in total acres and as a percent of the regional total of acres within all the regional ferry terminals (Figure 2-49). This figure illustrates the relative magnitude of exposure throughout the Bay Area as compared to the system as a whole. Illustrating the data in this way shows that the area of the Bay Area's ferries exposed represents a substantial amount of the region's ferry line capacity, and subsequently significant impacts to passenger ridership. This graph also illustrates how exposure increases over time. Figure 2-50 identifies which operators have the highest percent of freight rail line miles exposed to flooding.

Exposure affects the degree of impacts and consequences. More widespread exposure amplifies impacts and consequences, and early exposure provides much less time to prepare, which may also amplify impacts and consequences. These nuances are important to bear in mind throughout the following sections describing regional consequence results.

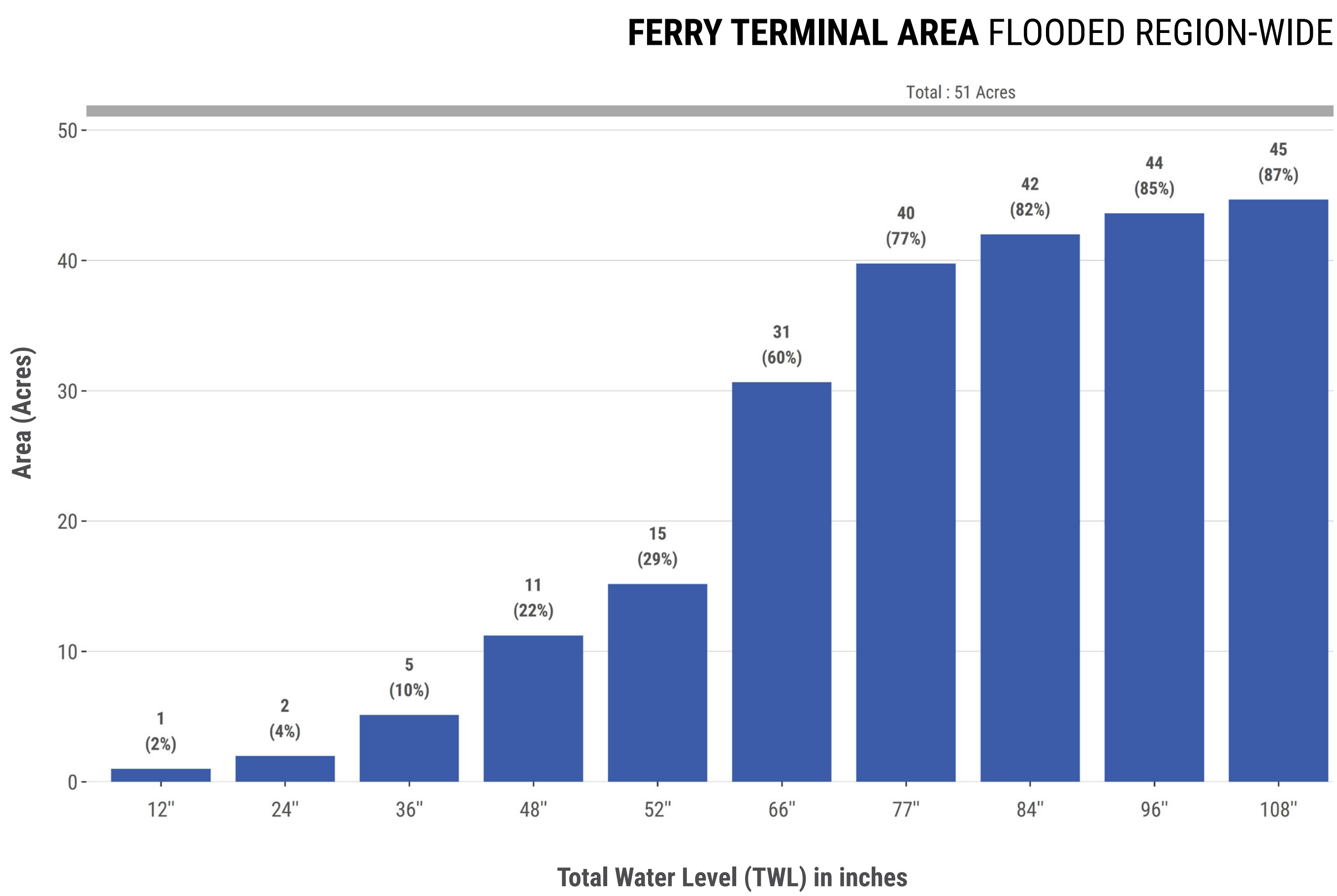
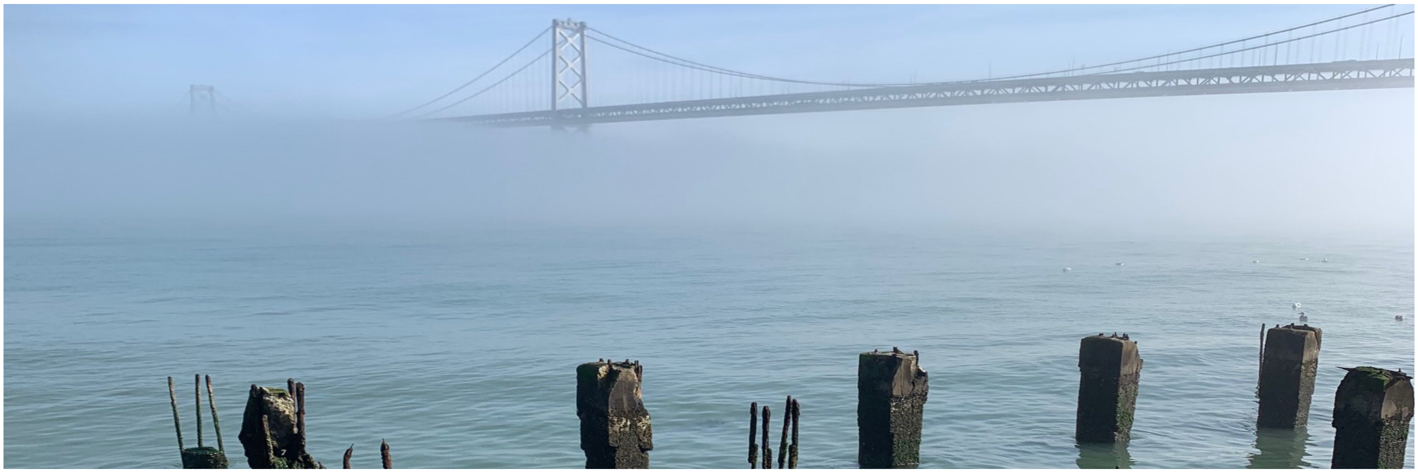


Figure 2-49. Regional exposure of ferry terminal area by flooding. Values in parenthesis reflect the percent of area as measured by acres exposed to flooding at each TWL compared to total area of ferry terminals in the nine-county region.



View of the Bay Bridge on a cloudy day from the ferry. Photo by Brad McCrea, BCDC.

HIGHEST **PERCENT OF FERRY TERMINAL AREA** FLOODED BY TERMINAL

Percent of Ferry Area by Terminal

Terminal	12"	24"	36"	48"	52"	66"	77"	84"	96"	108"
South San Francisco	9.5	15.7	30.3	47.1	53.6	70.6	78.4	81.9	83.9	84.0
Mare Island	9.0	9.0	9.0	9.1	9.1	9.4	28.6	34.8	42.8	55.9
Angel Island	5.2	5.7	6.0	6.8	7.4	68.4	78.7	79.6	80.3	80.6
Tiburon	3.3	3.3	42.0	60.6	68.1	80.6	87.0	92.1	93.8	95.0
Giants Stadium	1.8	2.0	2.4	2.7	2.9	3.5	82.6	82.6	82.6	82.6
Sausalito	1.7	1.8	1.8	1.9	7.3	33.2	70.5	88.5	91.8	92.5
Vallejo	1.3	1.3	1.3	1.3	2.8	37.8	56.2	64.6	74.7	79.1
San Francisco	1.2	1.3	1.5	2.6	10.2	85.2	85.2	85.2	85.2	85.2
Larkspur	1.1	1.2	2.5	28.0	39.3	77.3	91.6	94.2	96.1	97.2
Pier 33	0.7	0.9	1.0	1.2	1.2	1.8	92.7	95.3	95.3	95.3
Jack London Square	0.6	0.6	0.8	1.5	2.2	20.3	84.7	94.4	95.1	95.1
Bay Farm Island	0.2	0.2	0.3	0.3	35.2	67.1	84.4	91.8	95.3	96.9
Alameda Gateway Landing	0.1	16.6	38.3	65.2	73.2	96.1	97.8	97.8	97.8	97.8
Pier 41			0.3	0.9	1.0	1.3	91.3	91.4	91.4	91.4

Total Water Level (TWL) in inches

Figure 2-50. Ferry terminals with highest percent of ferry terminal area exposed to flooding at ten TWLs. “Highest” exposure refers to segments ranking in the top five for highest exposure at one or more TWL. Darker colors reflect greater consequences from flooding.

Regional Consequences of the Ferry Terminals

Impacts to the ferry system remain relatively steady across TWLs, as the majority of impacts already occur at 12" TWL. At 12" TWL, approximately 14,500 average weekday boardings may be impacted across the region, increasing to 14,745 boardings at 24" TWL. This number remains constant across all increasing TWLs (Figure 2-51). Individual ferry terminals with the highest consequences are discussed in the next section (shown in Figure 2-52) and depicted spatially in maps of consequence in Figure 2-53.

It is important to note that a limitation of this analysis is that without data on the height of terminal structures above the land they are built on, elevated terminals with inundated land beneath them may be identified as impacted, when in reality they are not. The result of this limitation is that almost all ferry terminals are shown as exposed at 12" TWL and beyond. To remedy this, site visits to each ferry terminal would be necessary.

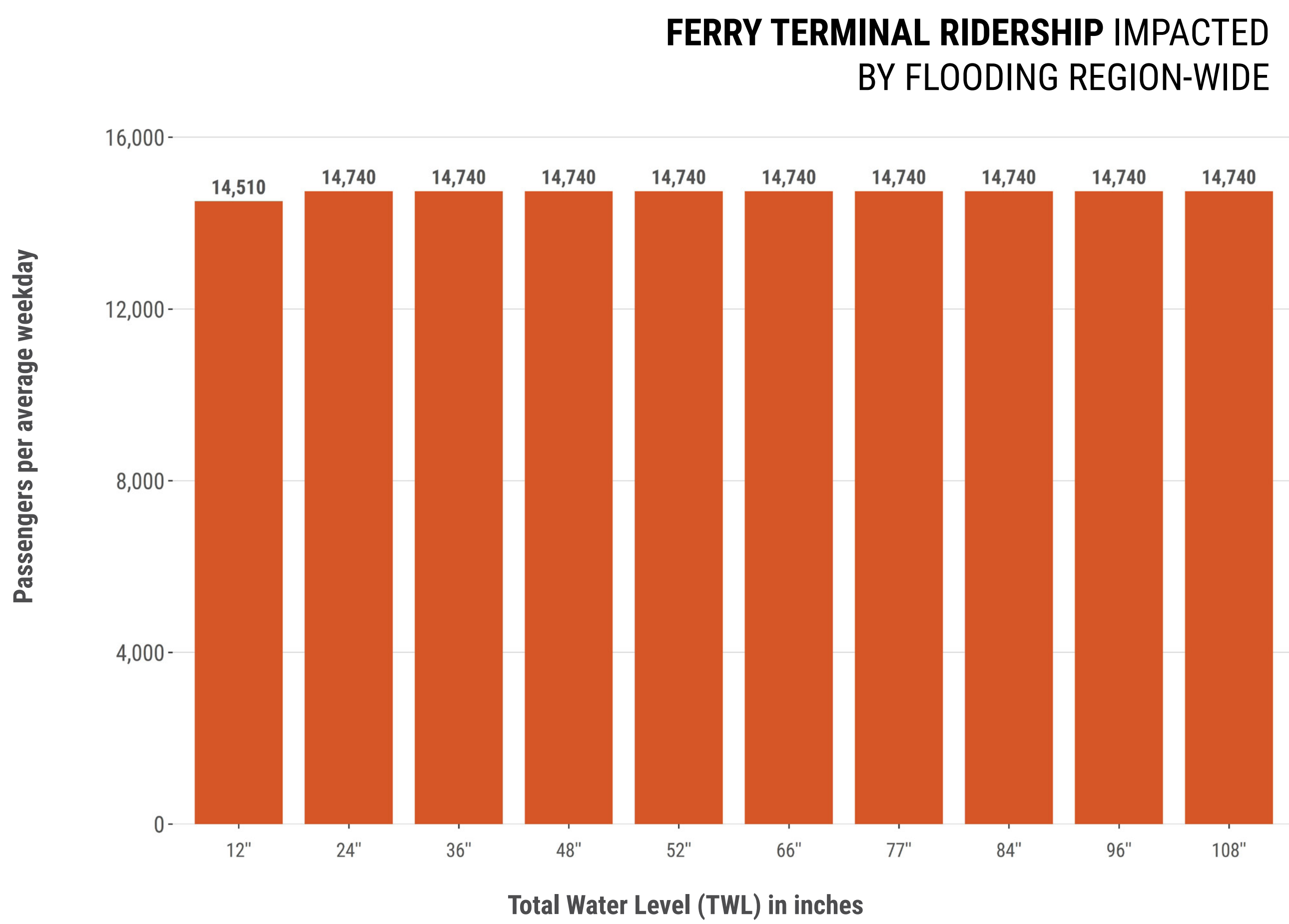


Figure 2-51 Regional impacts to ferry ridership by flooding at ten TWLs as measured by impacts to passengers per average weekday. Results are aggregated across the nine-county region.

Short Case Study

LINKING REGIONAL CONSEQUENCE RESULTS TO LOCAL ASSESSMENTS

While ferry terminals are generally adaptable to rising sea levels due to the nature of floating docks, the busiest ferry terminal operated by the Golden Gate Ferry in Larkspur is a hydraulic system. This system has limits on how high it can be raised and is already disrupted during king tide events today. The Golden Gate Ferry is currently working on a project to improve these facilities and comply with ADA requirements.

While ferry terminals are generally adaptable to rising sea level due to the nature of floating docks, access to the terminals can be disrupted by flooding. As part of the new San Francisco Ferry Terminal project under construction now, the height of queuing platforms was raised over 6 feet above grade to accommodate future sea levels.

In addition to the regional assessment, ART Bay Areas assessed individual assets in each of the four region systems and the results are communicated in local assessments of shared vulnerabilities and consequences.

These can be found in Chapter 3.0 Local Assessments of the ART Bay Area report, with local assessments available for individual download.

HIGHEST **FERRY TERMINAL RIDERSHIP** IMPACTED BY FLOODING BY FERRY TERMINAL

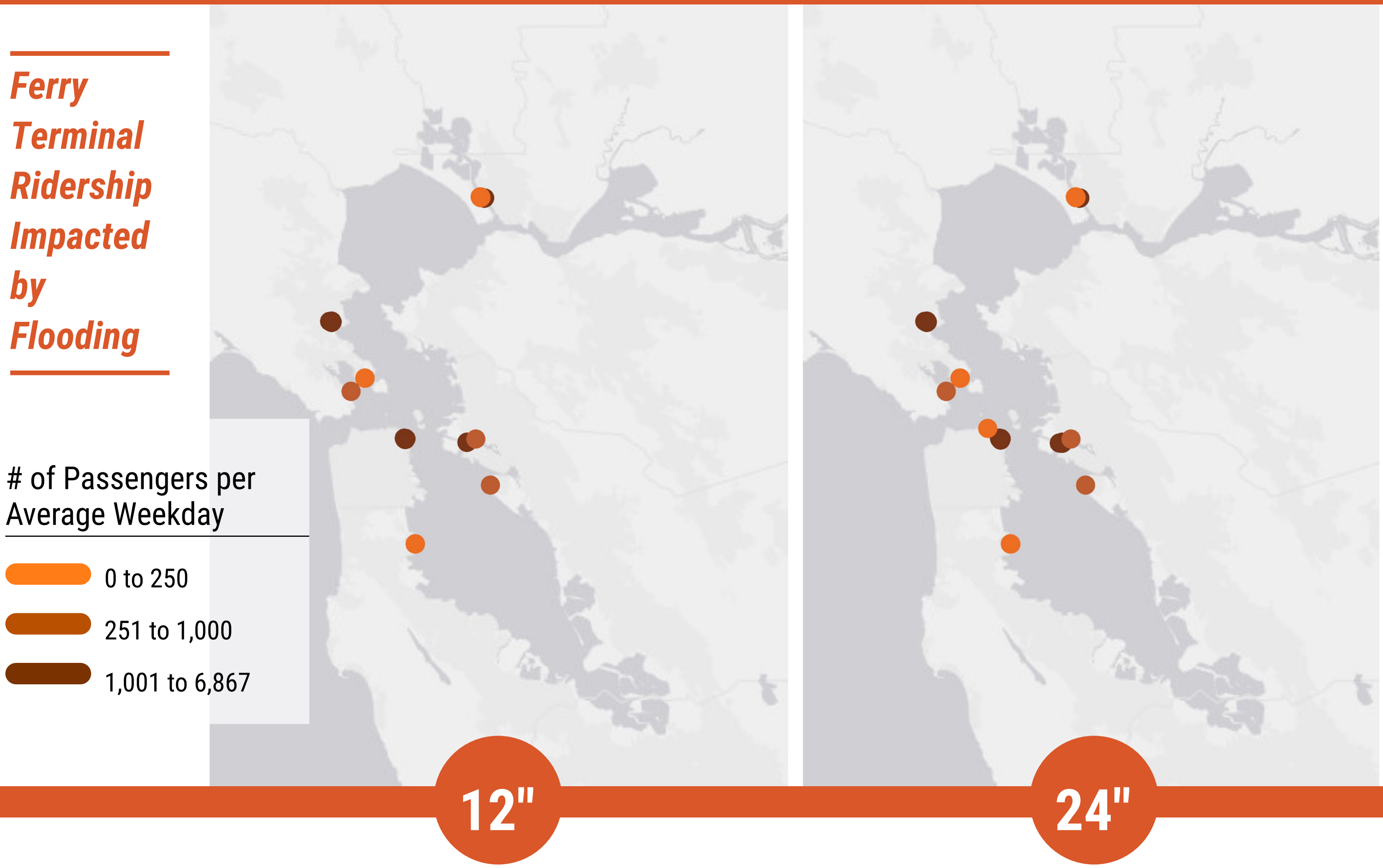
Figure 2-52. Ferry terminals with highest impacts by flooding at ten TWLs as measured by impacts to passengers per average weekday. "Highest" impacts refer to terminals ranking in the top five for highest consequences at one or more TWL. Darker colors reflect greater consequences.

CONSEQUENCES OF FLOODING

Transportation

Ferry Terminal Consequences

Ferry Terminal Ridership Impacted by Flooding

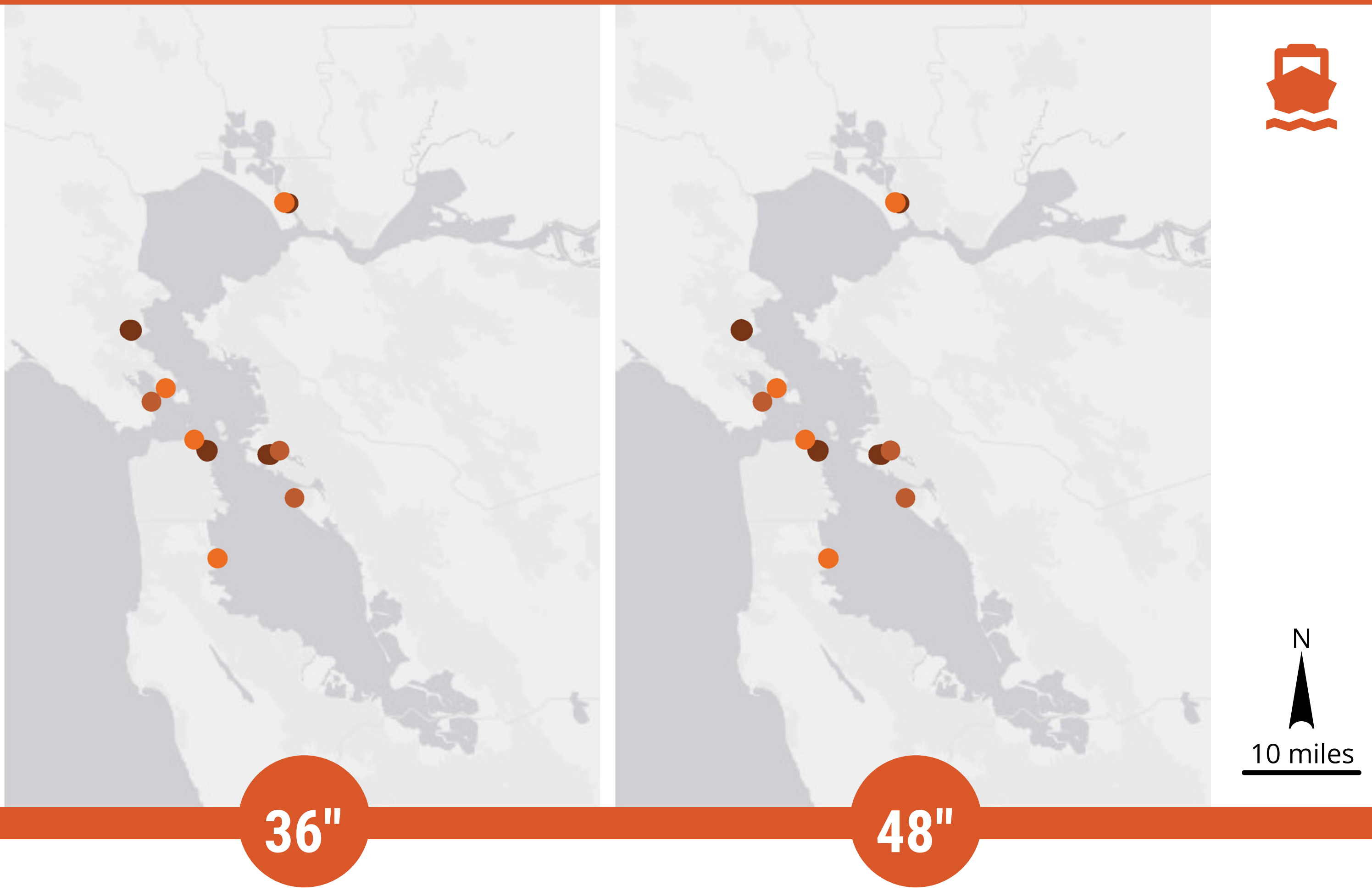


Trends and Drivers Across the Region

Ferry Terminal Ridership

Early Impacts • Given limitations to our exposure analysis (described on the following page), consequence analysis shows that nearly all ferry terminals have impacts starting at 12" TWL. This analysis overestimates early exposure consequences, since many terminals operate with floating docks, and may not have impacts this early (Figure 2-53).

Figure 2-53. Maps depicting the consequences of flooding for one ferry terminal indicator: *Ferry Terminal Ridership* for 12", 24" 36" and 48" TWL. Ferry terminals with any portion exposed to flooding are considered impacted. Maps below show entirety of impacted ferry terminals, not extent of exposure.



Worsening Impacts • Regionally, consequence for ferry ridership significantly worsen between 12" and 24" TWL reflecting the additional impact to the Pier 41 ferry terminal on the San Francisco waterfront.

Outliers • Eventual impacts to the San Francisco Ferry terminal are significant outliers in terms of regional consequence since this is the destination for nearly all the ferry routes operated by WETA and Golden Gate Transit District.

Methodology and Limitations for Ferry Terminals

Methodology

The consequence of flooding to the Bay Area's ferry terminals was measured in average weekday ridership by terminal. Weekday ridership was chosen because it is substantially higher than weekend or average ridership and represents the primary purpose of the ferry system, which is commuting. Ridership data was obtained from major ferry operators. Terminals that do not serve commuters on weekdays as well as non-commuter ferry operators were excluded from this analysis as the project team agreed that they are not critical to the region's transportation system.

As mentioned previously, an important limitation of this analysis is that without data on the height of terminal structures above the land they are built on, elevated terminals with inundated land beneath them may be identified as impacted, when in reality they are not. The result of this limitation is that almost all ferry terminals are shown as exposed at 12" TWL and beyond. To remedy this, site visits to each ferry terminal would be necessary.

Limitations

This approach has limitations in comprehensively reflecting ferry vulnerability in the region. In addition to the consequence of flooding of terminals, the regional ferry system is vulnerable due to numerous other factors. These include:

Gangways • Most ferry terminals utilize a floating gangway system. While floating gangway systems are resilient to higher water levels, at extreme tides gangways can already exceed ADA requirements for slope, limiting accessibility for disabled passengers. Higher water levels will increase the frequency of these events.

Terminal Access and Parking • Terminals rely on a ground transportation network to get passengers to/from the ferry terminals. This includes vehicles, bus, bicyclist, and pedestrian travel on local roads and the San Francisco Bay Trail. If local roads, sidewalks or parking areas are flooded, passengers may not be able to access the terminal and vessels.

Maintenance and Operations Facilities • Ferry vessels require routine maintenance for continued safe operation. Ferry operators rely on centralized maintenance and operations facilities to perform this function. These often support the entire fleet of vessels for a given operator, lack redundancy, and are sensitive to flooding due to electrical infrastructure and location near the shoreline.

Governance • Complex ownership, management, and operations structure of the ferry service may complicate coordination and decision-making around flood protection improvements. For example, gangways and vessels may be owned by one entity, but terminal facilities and parking may be owned by another.

Ferry ridership in the Bay has been increasing. Photo by BCDC.

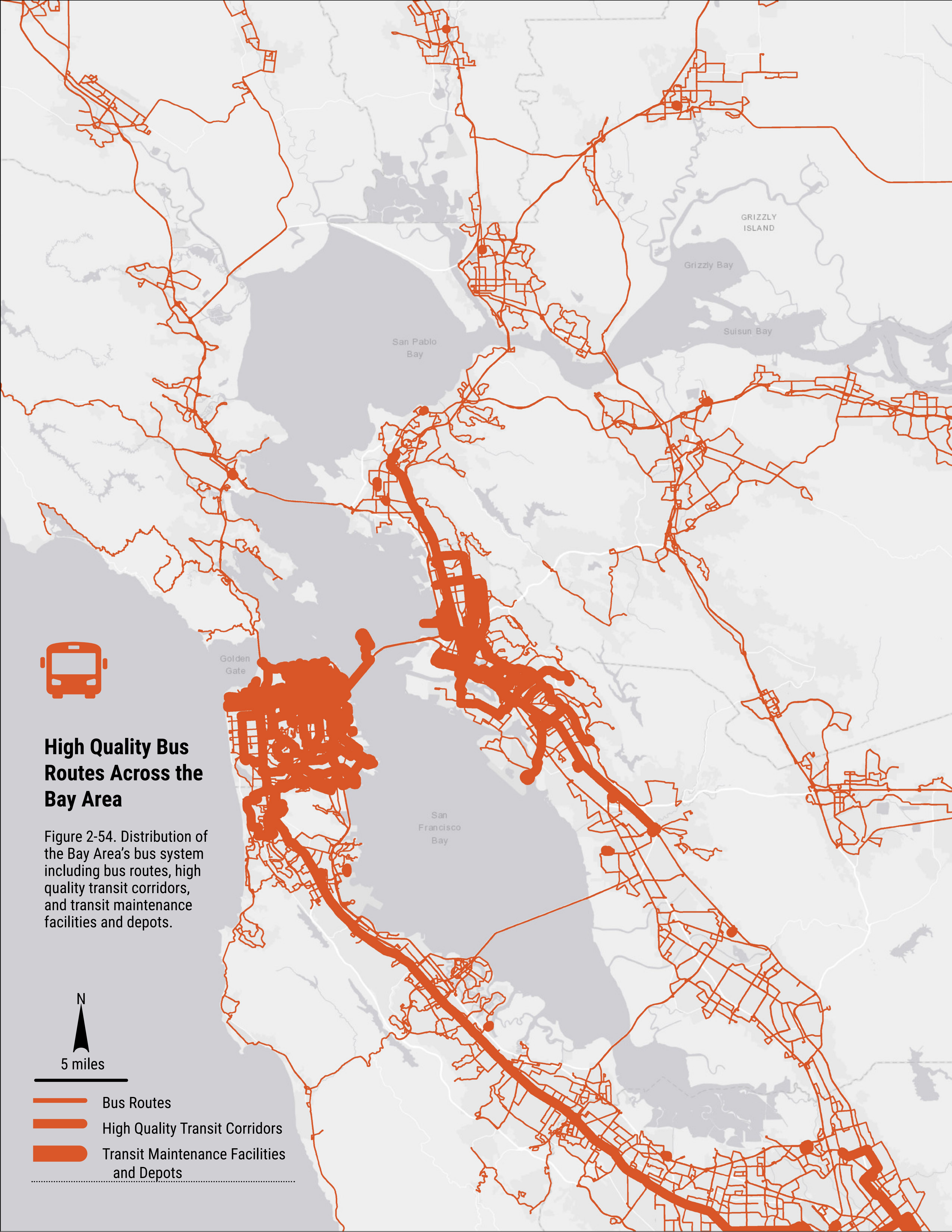
HIGH QUALITY BUS ROUTES

Buses provide important public transit services for communities that may not have access to vehicles or a rapid transit system and connect people to jobs and housing. While most buses provide intracity service, several routes cross county lines and connect far reaches of the Bay Area (Figure 2-54). Bus transit service has the highest daily transit ridership by mode within the region and in 2016 approximately 960,000 riders boarded buses every day.[13] Bus also may be the only transit option for areas of the Bay that are not served by high capacity train service such as Sonoma and Solano counties.

There are numerous bus service providers in the Bay Area including AC Transit, VTA, Muni, SamTrans, County Connection, Dumbarton Express, Emery Go Round, Fairfield and Suisun Transit, Golden Gate Transit, Marin Transit, SolTrans, Union City Transit, VINE, Sonoma County Transit, Tri Delta Transit, WestCAT, and WHEELS. Buses are also networked to other transit services providing local connections from regional transit networks like BART and ferries. Buses are also often utilized as temporary 'bridges' if segments of train networks are disrupted due to flooding or other reasons. Buses primarily operate on local roads and surface streets and disruption of these roads will mean that buses will have to reroute, miss stops altogether, or be unable to operate.

The bus network could be impacted if access to bus stops or local roads are flooded. While the bus system has some flexibility to reroute to avoid flooded areas, this may still impact certain riders who would have to get on or off at stops further away from their destination. Aspects of the bus system that are most vulnerable to flooding would be the bus electrical facilities and service facilities that provide storage, operations, and maintenance for entire fleets of buses and have limited redundancy.

Impacts to the bus system are measured by the miles of impacted high-quality bus routes.



High Quality Bus Routes Across the Bay Area

Figure 2-54. Distribution of the Bay Area's bus system including bus routes, high quality transit corridors, and transit maintenance facilities and depots.

Regional Exposure of Bus Routes

The bar graph below shows the total length of high-quality bus routes flooded at each total water level both in total miles and as a percent of the regional total miles within the nine county Bay Area (Figure 2-55). This figure illustrates the relative magnitude of exposure throughout the Bay Area as compared to the system as a whole. Illustrating the data in this way shows that the length of high-quality bus route miles exposed is relatively low compared to the total miles in the region. Figure 2-56 identifies which high quality bus routes have the highest percent of miles exposed to flooding by bus line.

Exposure affects the degree of impacts and consequences. More widespread exposure amplifies impacts and consequences, and early exposure provides much less time to prepare, which may also amplify impacts and consequences. These nuances are important to bear in mind throughout the following sections describing regional consequence results.

MILES OF HIGH QUALITY BUS ROUTES FLOODED REGION-WIDE

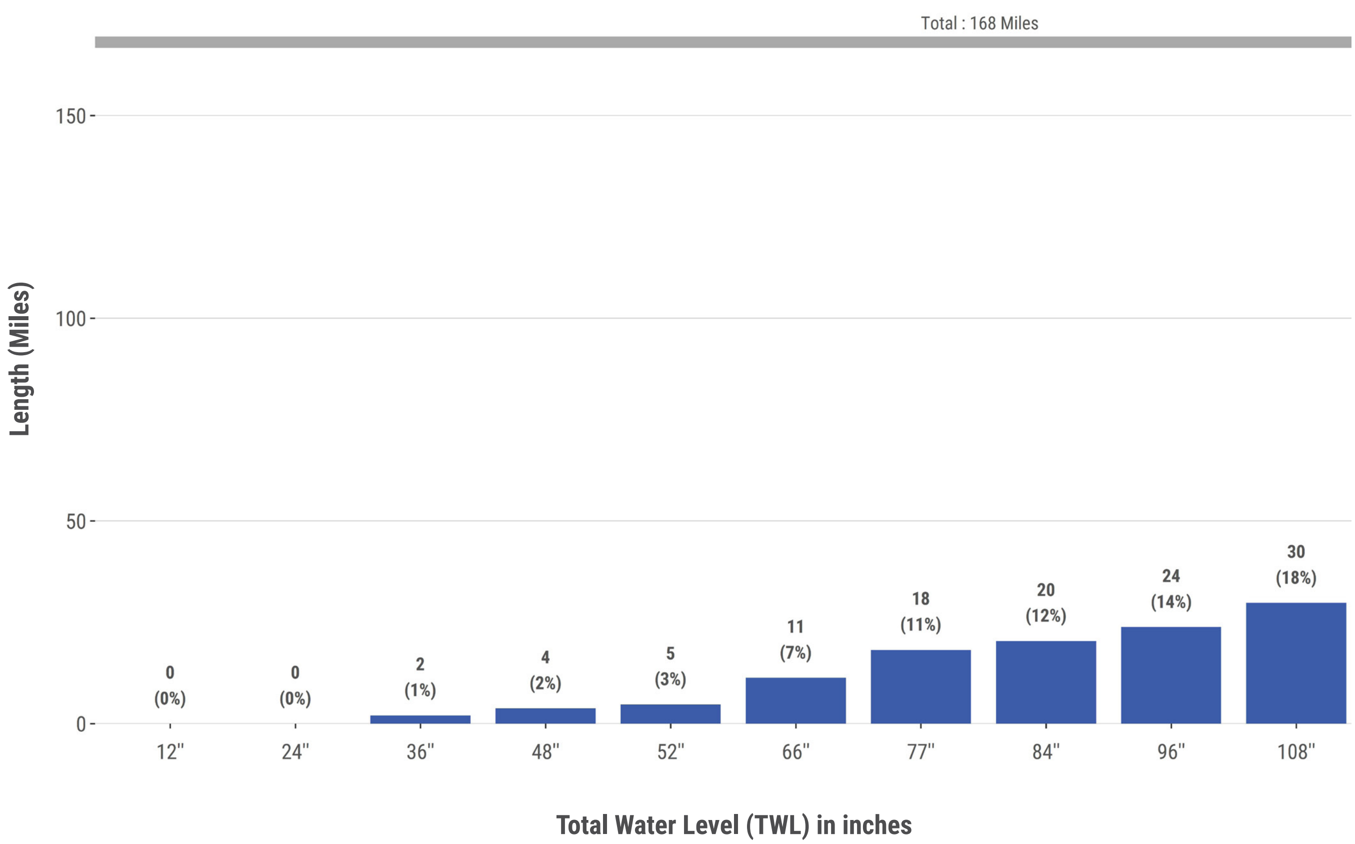


Figure 2-55. Regional exposure of high quality bus route miles by flooding. Values in parenthesis reflect the percent of miles exposed to flooding at each TWL compared to total miles of high quality bus routes in the nine-county region.

Bus routes bring people to places around the Bay. Photo by Paul Sullivan licensed under CC BY 2.0.

HIGHEST **PERCENT OF HIGH QUALITY BUS ROUTES** FLOODED BY BUS LINE

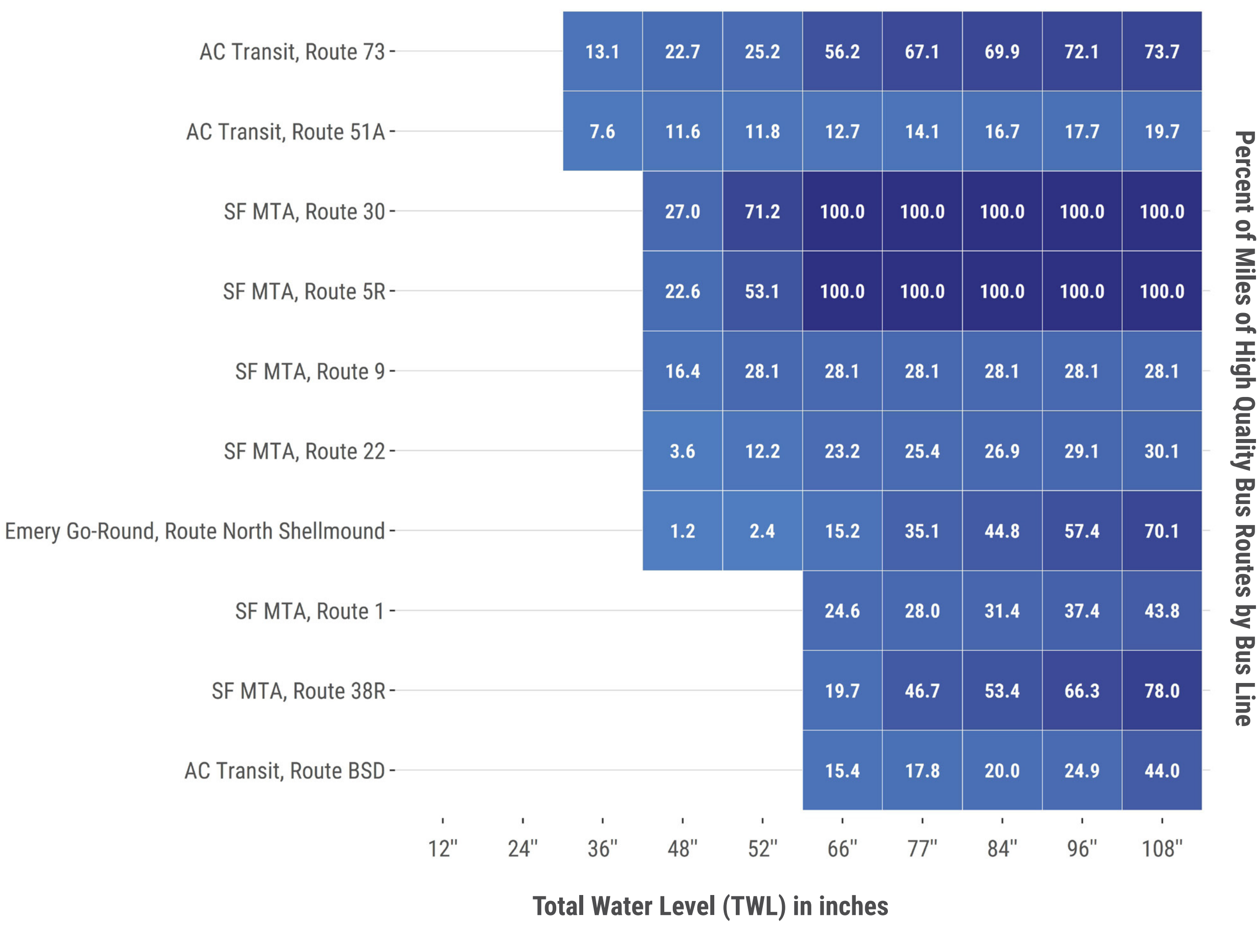


Figure 2-56. High quality bus routes with highest percent of miles exposed to flooding at ten TWLs. “Highest” exposure refer to segments ranking in the top five for highest exposure at one or more TWL. Darker colors reflect greater consequences from flooding.

Regional Consequences of Bus Routes

At early total water levels, region-wide impacts are minimal. From 36" to 48" TWL, however, impacts across the region jump from 2 to 20 high quality bus lines impacted (Figure 2-57). Another major jump occurs between 48" and 52" TWL, jumping from 40 to 90 lines impacted. From here, impacts increase steadily at each TWL, maxing out at 125 impacted high-quality bus lines at 108" TWL.

Individual bus routes with the highest consequences are discussed in the next section (shown in Figure 2-58) and depicted spatially in maps of consequence in Figure 2-59.

HIGH QUALITY BUS ROUTES IMPACTED BY FLOODING REGION-WIDE

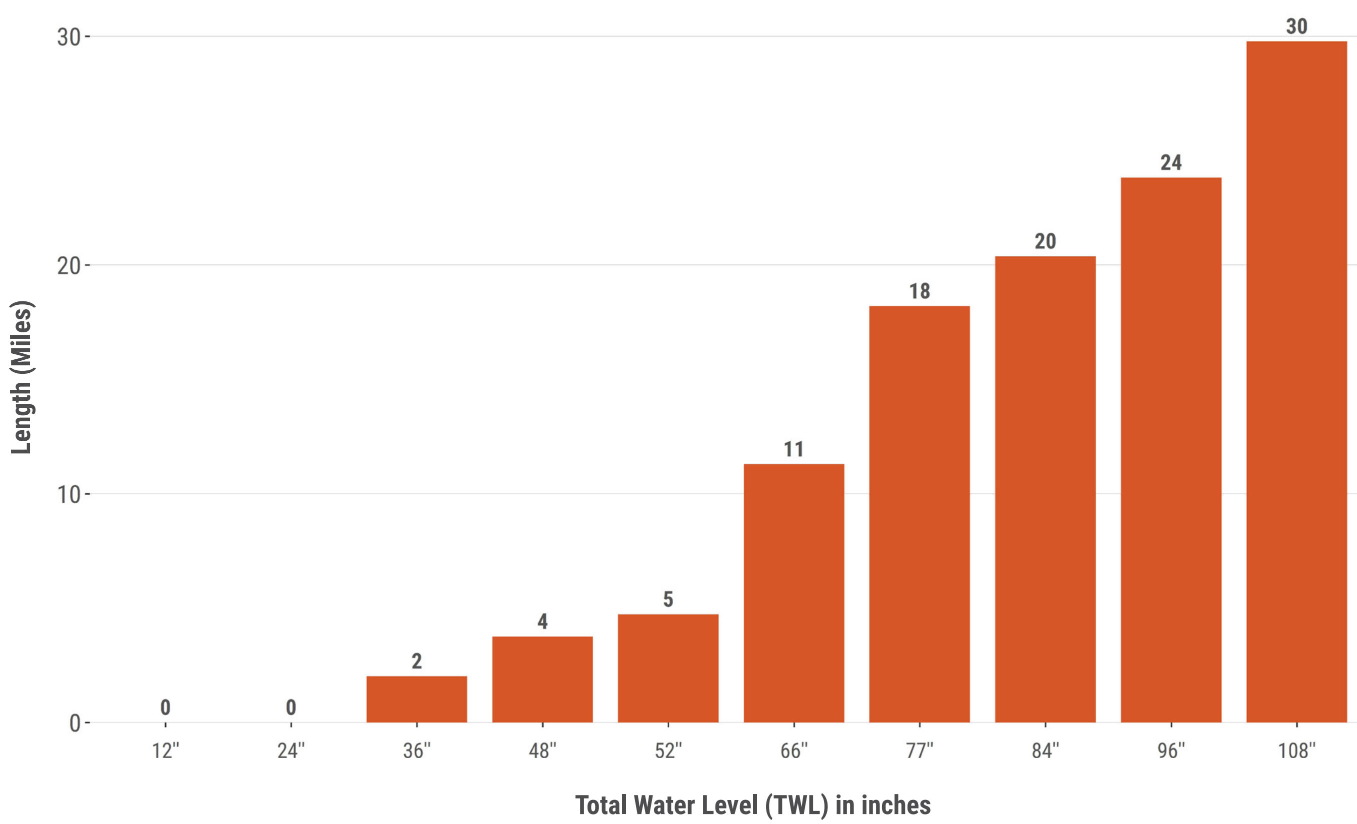


Figure 2-57 Regional impacts to high quality bus routes from flooding at ten TWLs as measured by miles of high quality bus routes impacted. Results are aggregated across the nine-county region.

Short Case Study

LINKING REGIONAL CONSEQUENCE RESULTS TO LOCAL ASSESSMENTS

SamTrans operates two bus divisions to garage and maintain its bus fleet—the North Base and the South Base. These facilities are both vulnerable to flooding and have limited redundancy. SamTrans is currently working on an adaptation plan for these facilities.

In addition to the regional assessment, ART Bay Areas assessed individual assets in each of the four region systems and the results are communicated in local assessments of shared vulnerabilities and consequences.

These can be found in Chapter 3.0 Local Assessments of the ART Bay Area report, with local assessments available for individual download.

HIGHEST **HIGH QUALITY BUS ROUTES** IMPACTED BY FLOODING BY BUS ROUTE

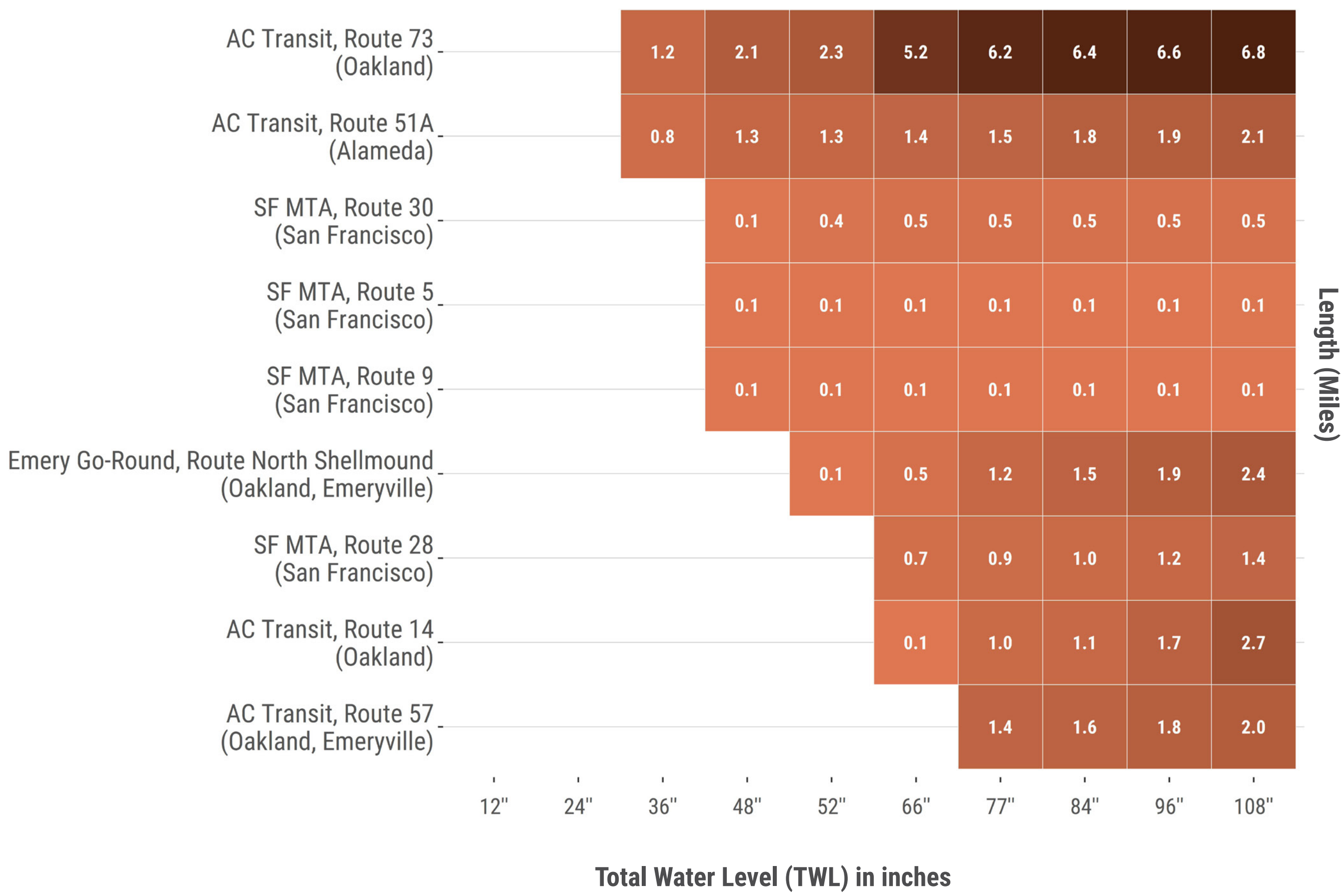


Figure 2-58. High quality bus routes with highest impacts by flooding at ten TWLs as measured by length in miles impacted. "Highest" impacts refer to segments ranking in the top five for highest consequences at one or more TWL. Darker colors reflect greater consequences.

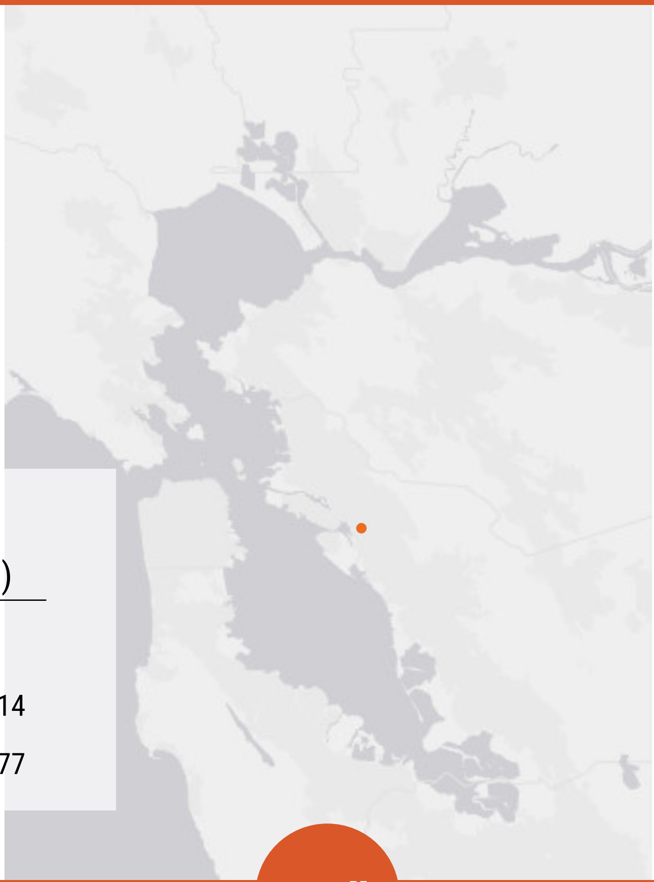
Transportation

High Quality Bus Route Consequences

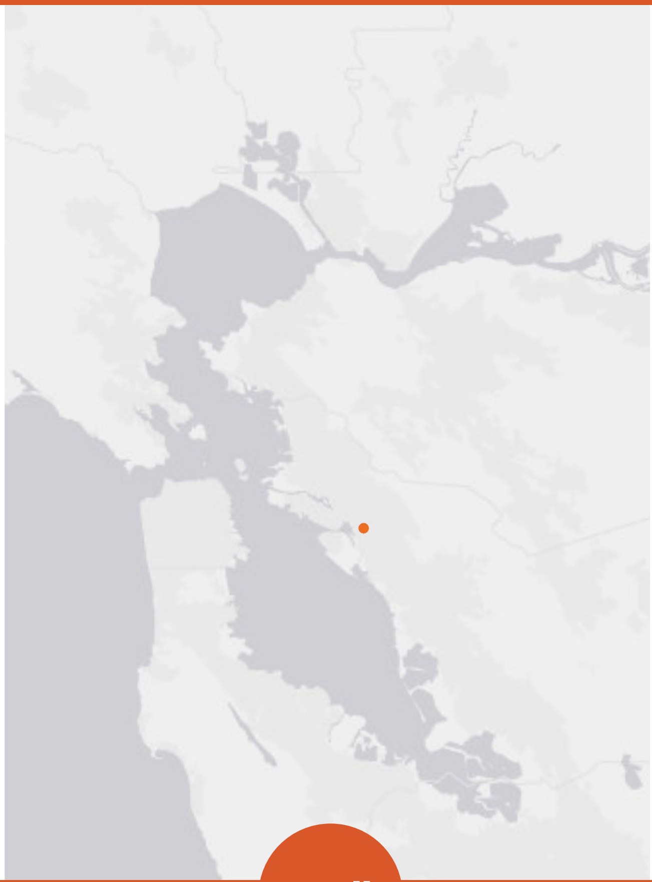
High Quality Bus Routes Impacted by Flooding

Length of Route Impacted (Miles)

- 0 to 0.59
- 0.59 to 2.14
- 2.14 to 6.77



12"



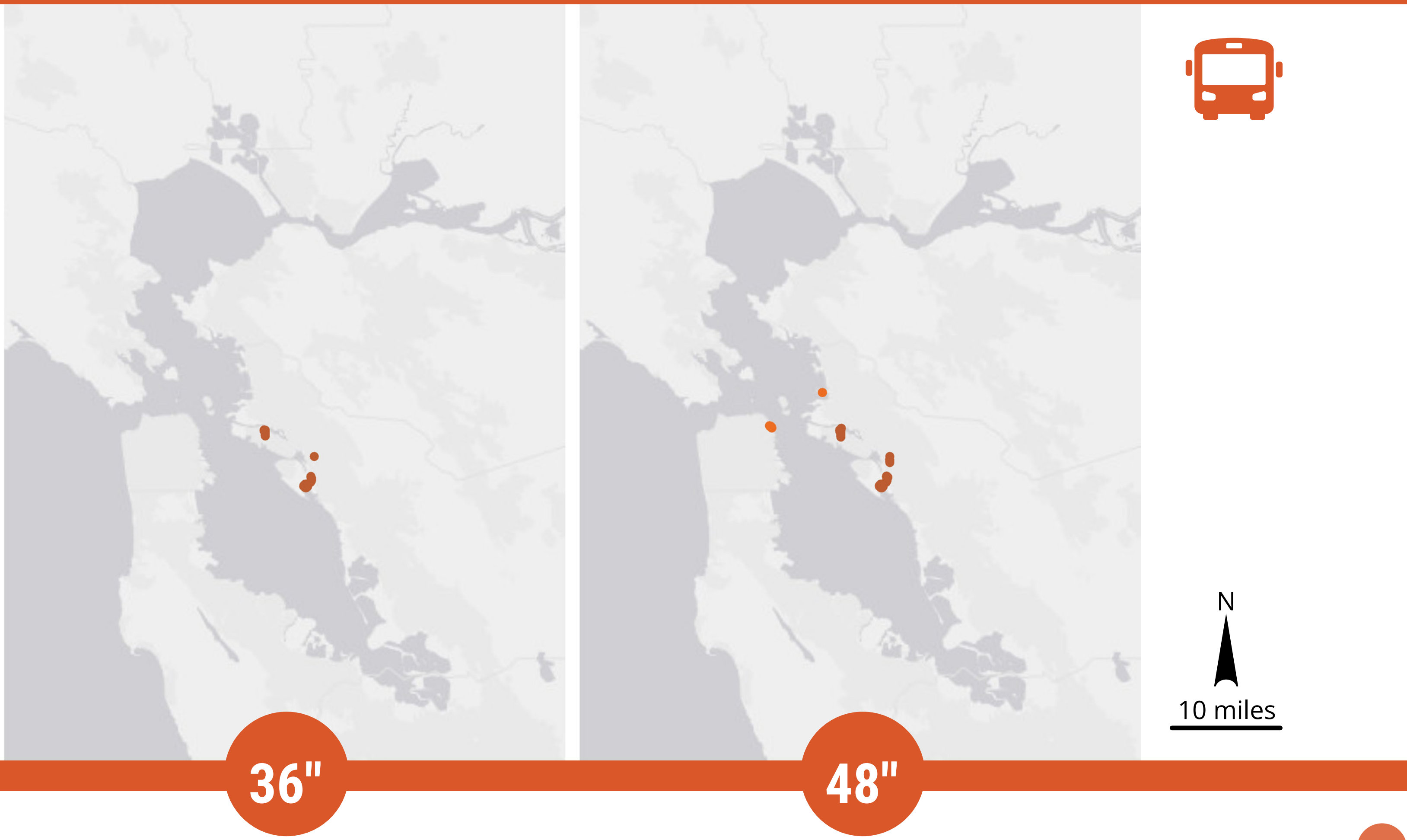
24"

Trends and Drivers Around the Region

High Quality Bus Routes

Early Impacts • Early impacts to high quality (HQ) bus routes in Alameda County occur at 12" TWL. HQ bus routes are not impacted anywhere else until 48" TWL, when HQ bus routes in San Francisco and Contra Costa counties are also impacted (Figure 2-59).

Figure 2-59. Maps depicting the consequences of flooding for one bus system indicator: *Miles of High Quality Bus Routes Impacted* at 12", 24" 36" and 48" TWL. Maps below show consequences and extent of exposure.



Worsening Impacts • Regionally, the miles of HQ bus routes impacted worsens between 52" and 66" TWL reflecting the consequences from exposure of multiple bus routes in San Francisco.

Outliers • The large concentration of HQ bus routes along the Embarcadero and Market corridors in San Francisco mean that exposure of this area has a significantly higher consequence.

Methodology and Limitations for Bus Routes

Methodology

The consequence of inundation to the Bay Area's bus systems was measured by the number of high-quality transit corridors impacted under each total water level. Ideally, our analysis would have developed rider flow data similar to the Commuter Rail Lines consequence indicator. However, regional data on bus ridership was unavailable, and few operators have reliable data for their systems.

High-Quality Transit Corridors could be used as a proxy for ridership. High Quality Transit Corridors are defined by the California Public Resources Code as a fixed-route bus corridor with headway of 15 minutes or better during the morning and evening peak periods, or a fixed-route bus corridor with headway of 15 minutes during both the morning and evening peak periods in an adopted Regional Transportation Plan.

A limitation of this consequence indicator is that in the High-Quality Transit Corridors dataset available from MTC there are no bus lines in the North Bay counties that fit the definition described above. While the fact that no bus lines in the North Bay meet the High-Quality Transit Corridor criteria means that the consequence of inundation to these systems is comparatively low, it also means that impacts to bus systems in the North Bay, however minimal, were omitted despite providing service to communities with limited access to public transit.

Limitations

This approach has limitations in comprehensively reflecting bus vulnerability in the region. In addition to the consequence of flooding on roads, the regional bus system is vulnerable due to numerous other factors. These include:

Transbay Bus Routes • Bus routes operating between rural areas and urban city centers are sometimes the only public transit available to certain communities. Flooding highways or local roads will disrupt this service or cause lengthy delays. For example, bus lanes on the Westbound approach to the Bay Bridge are flooded at early water levels and would impact Transbay buses coming from the East Bay.

Local Roads • Buses rely on local road access to operate routes. While some bus lines have a certain degree of flexibility for rerouting, electrified buses that operate on fixed catenary lines (e.g. Muni) have limited flexibility to reroute due to flooding of local roads.

Muni bus in San Francisco's Financial District. Photo by Paul Sullivan licensed under CC BY 2.0.

Bus Bridges • Buses often serve as emergency backup for delivering passengers short distances when commuter rail service is disrupted due to flooding or other emergencies. For example, BART has agreements with local bus operators (e.g. MTA, AC Transit) to provide bus bridges in the event BART service is disrupted.

Bus Stops • Bus stops are not particularly vulnerable to flooding due to few amenities located at bus stops, but flooding can limit local road access for pedestrians, vehicles, and buses.

Transit Maintenance and Operations Facilities • Most bus operators rely on centralized maintenance and operations facilities. These often support the entire fleet of trains for a given operator, lack redundancy, and are sensitive to flooding due to electrical infrastructure on site. For example, the Golden Gate Transit (GGT) Andersen maintenance yard may flood at 12” TWL. It serves as the primary bus depot for GGT and houses administrative offices and a heavy maintenance center.

Power Facilities • Bus service increasingly depends upon the functionality of the local power grid to power electrified bus or power maintenance and operations facilities; these electrical systems are extremely sensitive to saltwater corrosion and have limited redundancy.

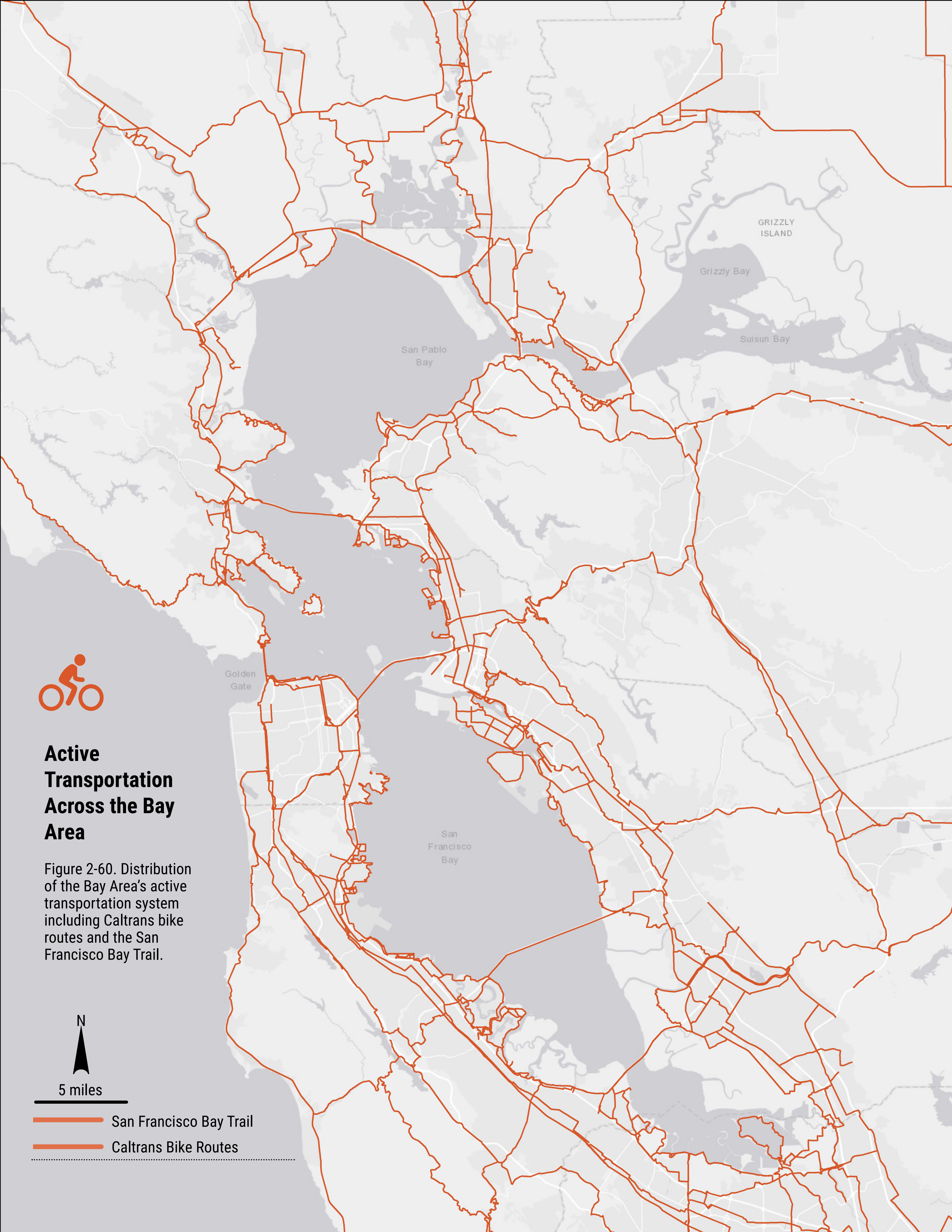
ACTIVE TRANSPORTATION

The San Francisco Bay Trail (Bay Trail) is a planned 500-mile trail network around the Bay Area (Figure 53). The Bay Trail provides easily accessible recreational opportunities for outdoor enthusiasts, including hikers, joggers, bicyclists and skaters. It also offers a setting for wildlife viewing and environmental education, and it increases public respect and appreciation for the Bay.[14] It also has important transportation benefits, providing a commute alternative for cyclists, and connects to numerous public transportation facilities (including ferry terminals, light-rail lines, bus stops and Caltrain, Amtrak, and BART stations); also, the Bay Trail will eventually cross all the major toll bridges in the Bay Area.

Within the subregion, the Bay Trail consists of off-street paved or gravel paths; on-street bike lanes and sidewalks; off-street unimproved paths (of varying width and surfaces). Other paved or gravel paths connect to the Bay Trail. In addition to the Bay Trail, there is a network of bike and pedestrian paths associated with Caltrans assets. These form critical junctures with many Bay Area communities and link up with the Bay Trail.

The Bay Trail is highly vulnerable to sea level rise and storm event flooding due to its construction and location along the shoreline. Erosion, poor drainage, and surface damage can all result in lengthy closures. Consequences of temporary or permanent closures along portions of the trail can be significant because it functions as a system of interlinked pathways for recreation and non-motorized commuting. Adaptive measures can be taken, such as building with different types of materials, improving drainage, and using boardwalks and bridges, but at some point, these will become ineffective. Loss of connected Bay Trail segments could result in more people driving rather than walking or bicycling to their destinations and reduced shoreline access opportunities, in particular for people with disabilities or reduced mobility.

Impacts to active transportation are measured in miles of Bay Trail impacted as well as miles of impacted bicycle routes within the Regional Bicycle Network.



Active Transportation Across the Bay Area

Figure 2-60. Distribution of the Bay Area's active transportation system including Caltrans bike routes and the San Francisco Bay Trail.

Regional Exposure of Active Transportation

San Francisco Bay Trail Exposure

The bar graph below shows the total length of Bay Trail flooded at each total water level both in total miles and as a percent of the regional total miles within the nine county Bay Area (Figure 2-61). This figure illustrates the relative magnitude of exposure throughout the Bay Area as compared to the system as a whole. Illustrating the data in this way shows that the length of Bay Trail exposed represents a substantial amount of the region's Bay Trail system. Figure 2-62 identifies which counties have the highest percent of San Francisco Bay Trail miles exposed to flooding.

Exposure affects the degree of impacts and consequences. More widespread exposure amplifies impacts and consequences, and early exposure provides much less time to prepare, which may also amplify impacts and consequences. These nuances are important to bear in mind throughout the following sections describing regional consequence results.

SAN FRANCISCO BAY TRAIL
MILES FLOODED REGION-WIDE

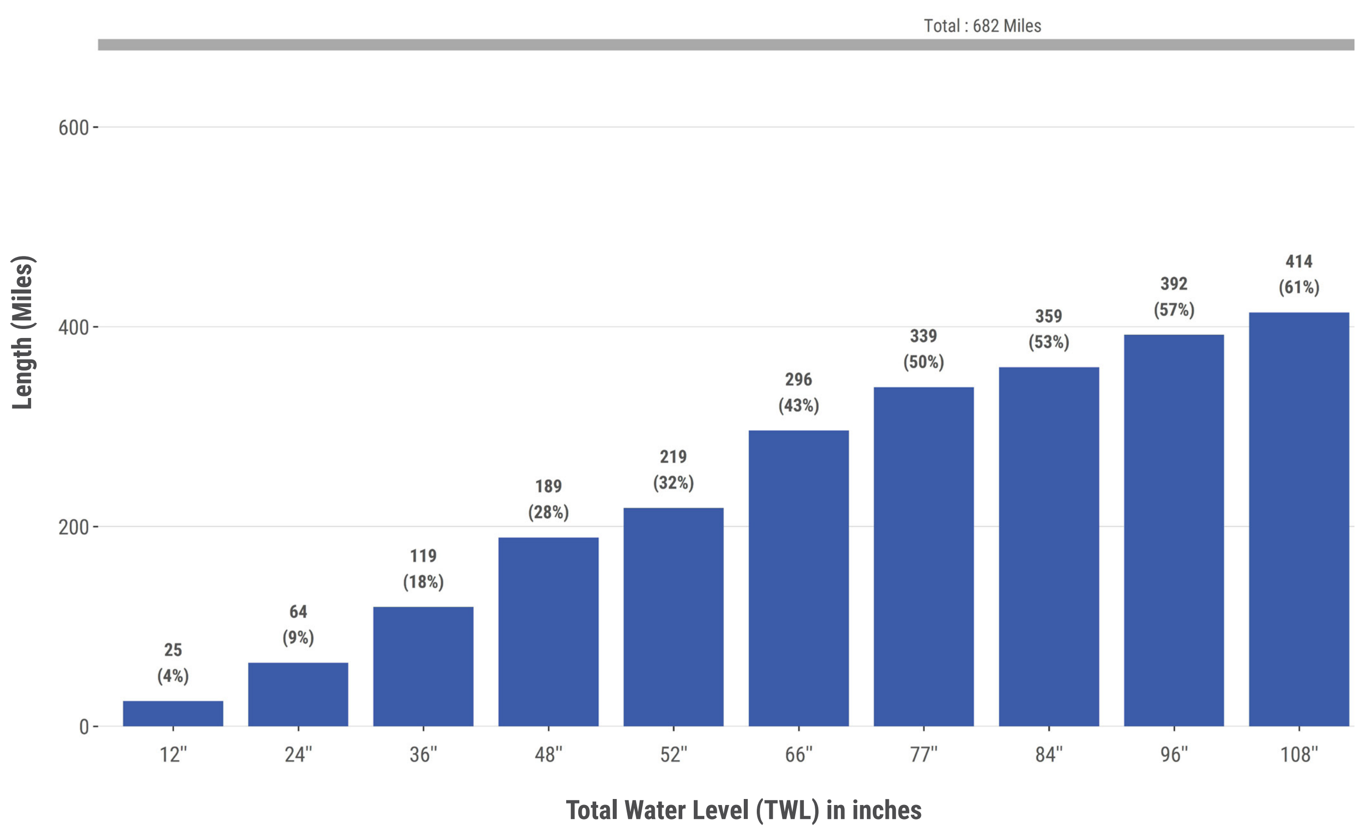


Figure 2-61. Regional exposure of San Francisco Bay Trail by flooding. Values in parenthesis reflect the percent of mile exposed to flooding at each TWL compared to total San Francisco Bay Trail miles in the nine-county region.

San Francisco Bay Trail in Oakland Shoreline Park.
Photo by Melinda * Young licensed under CC BY 2.0.

HIGHEST PERCENT OF **SAN FRANCISCO BAY TRAIL MILES** FLOODED BY COUNTY

Percent of Bay Trail by County

County	12"	24"	36"	48"	52"	66"	77"	84"	96"	108"
Sonoma	22.6	33.6	50.3	60.5	63.0	68.9	73.0	74.0	76.4	79.0
Marin	7.9	13.9	23.2	32.5	35.4	43.4	48.2	50.5	53.2	55.3
San Mateo	2.6	9.5	20.0	38.4	49.3	64.6	70.5	73.8	77.8	79.4
Napa	2.1	11.4	21.9	34.3	37.6	45.6	49.5	51.9	55.7	58.8
Solano	1.1	3.3	20.4	29.3	32.8	40.6	45.5	47.2	49.3	51.7
Alameda	1.1	3.6	10.5	20.9	25.4	39.5	49.7	53.8	60.9	65.3
San Francisco	0.7	2.0	5.6	12.5	16.4	51.3	61.0	63.4	66.6	69.8
Santa Clara	0.4	19.9	32.7	43.5	46.7	56.5	58.6	59.7	64.7	66.7
Contra Costa	0.2	0.5	1.9	4.5	5.6	10.8	14.3	17.5	24.0	28.7

Total Water Level (TWL) in inches

Figure 2-62 Counties with the highest percent of San Francisco Bay Trail miles exposed to flooding at ten TWLs. Darker colors reflect greater consequences from flooding.

Bicycle Network Exposure

The bar graph below shows the total length of Caltrans bike routes flooded at each total water level both in total miles and as a percent of the regional total miles within the nine county Bay Area (Figure 2-63). This figure illustrates the relative magnitude of exposure throughout the Bay Area as compared to the system as a whole. Illustrating the data in this way shows that the length of bike routes exposed represents a substantial amount of the region's bicycle route network. Figure 2-64 identifies which counties have the highest percent of bicycle network miles exposed to flooding.

Exposure affects the degree of impacts and consequences. More widespread exposure amplifies impacts and consequences, and early exposure provides much less time to prepare, which may also amplify impacts and consequences. These nuances are important to bear in mind throughout the following sections describing regional consequence results.

BICYCLE ROUTE MILES
FLOODED REGION-WIDE

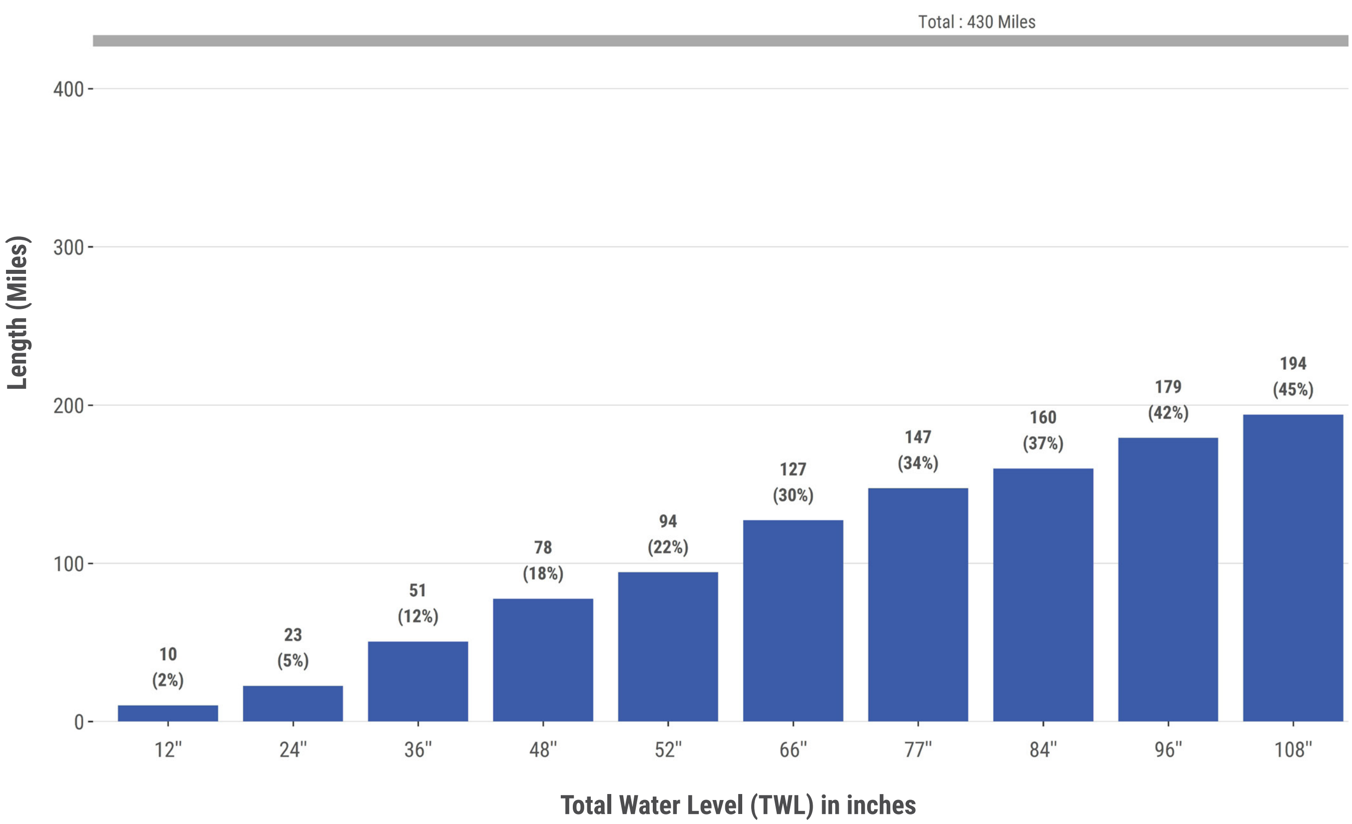


Figure 2-63. Regional exposure of bicycle networks by flooding. Values in parenthesis reflect the percent of miles exposed to flooding at each TWL compared to total miles of bicycle networks in the nine-county region.

Biker enjoying the San Francisco Bay Trail. Photo by Richard Masoner / Cyclelicious licensed under CC b BY 2.0.

HIGHEST PERCENT OF **BICYCLE ROUTES MILES** FLOODED BY COUNTY SEGMENTS

Percent of Miles by County

County	12"	24"	36"	48"	52"	66"	77"	84"	96"	108"
Sonoma	7.3	8.2	12.0	18.2	19.8	27.5	32.8	34.6	38.2	41.5
Marin	5.8	15.7	22.0	25.8	26.4	31.4	35.0	36.4	39.4	42.2
Napa	4.5	5.2	10.0	17.6	19.6	28.2	33.3	35.4	39.4	42.6
Solano	2.4	3.0	5.9	10.3	11.6	19.4	23.0	26.7	31.1	34.6
Contra Costa	0.2	0.2	0.2	1.4	4.4	10.2	15.8	20.7	32.0	37.4
San Mateo	0.0	3.0	15.5	24.6	33.6	38.8	41.6	44.0	47.8	50.4
Santa Clara	0.0	10.3	26.5	37.0	39.0	45.7	49.7	51.9	54.7	58.7
San Francisco	0.0	0.0	0.2	1.2	2.1	5.9	8.2	8.7	9.6	10.2
Alameda		0.2	3.9	11.3	15.3	25.6	33.7	37.5	44.3	49.5

Total Water Level (TWL) in inches

Figure 2-64. Counties with highest percent of bicycle network miles exposed to flooding at ten TWLs. Darker colors reflect greater consequences from flooding.

Regional Consequences of Active Transportation

Region-wide, just over 10 miles of bicycle infrastructure and 25 miles of the Bay Trail are impacted at 12" TWL (Figure 2-65). Impacts to both types of active transportation increase steadily over higher TWLs, with the Bay Trail experiencing a significant jump between 52" and 66" TWL, going from 219 to 296 miles impacted. At 66" TWL, 127 miles of bicycle infrastructure are impacted. By 108" TWL, 194 miles of bicycle infrastructure and 414 miles of Bay Trail are impacted across the region.

Locations with the highest consequences are discussed in the next section (shown in Figure 2-66 and Figure 2-67 for the San Francisco Bay Trail and Bicycle Routes, respectively) and depicted spatially in maps of consequence in Figure 2-68.

ACTIVE TRANSPORTATION IMPACTED BY FLOODING REGION-WIDE

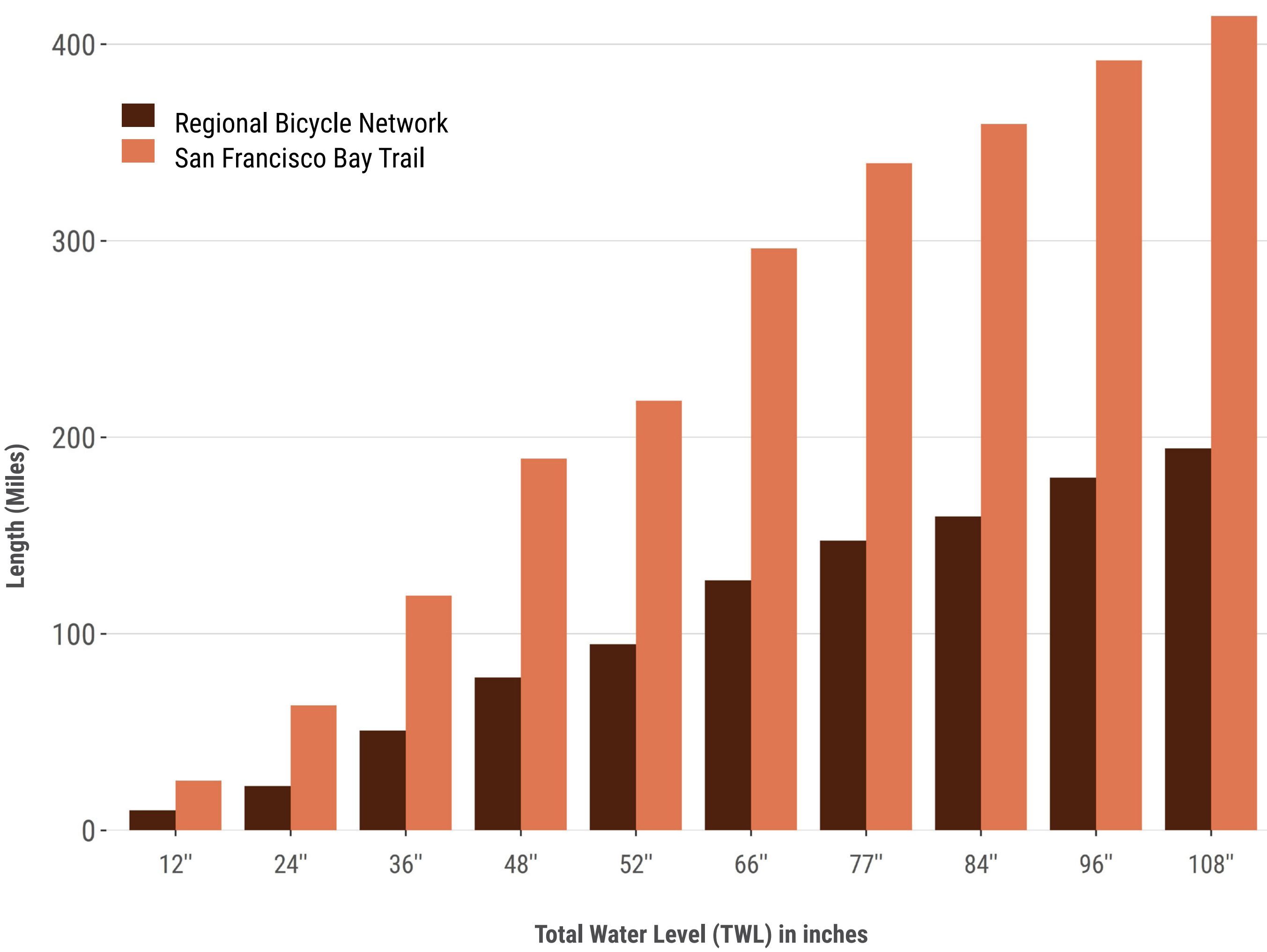


Figure 2-65. Total regional impacts to bicycle and pedestrian routes from flooding at ten TWLs as measured by impacts to miles of route. Results are aggregated across the nine-county region.

San Francisco Bay Trail along the Richmond Shoreline. Photo by BCDC.

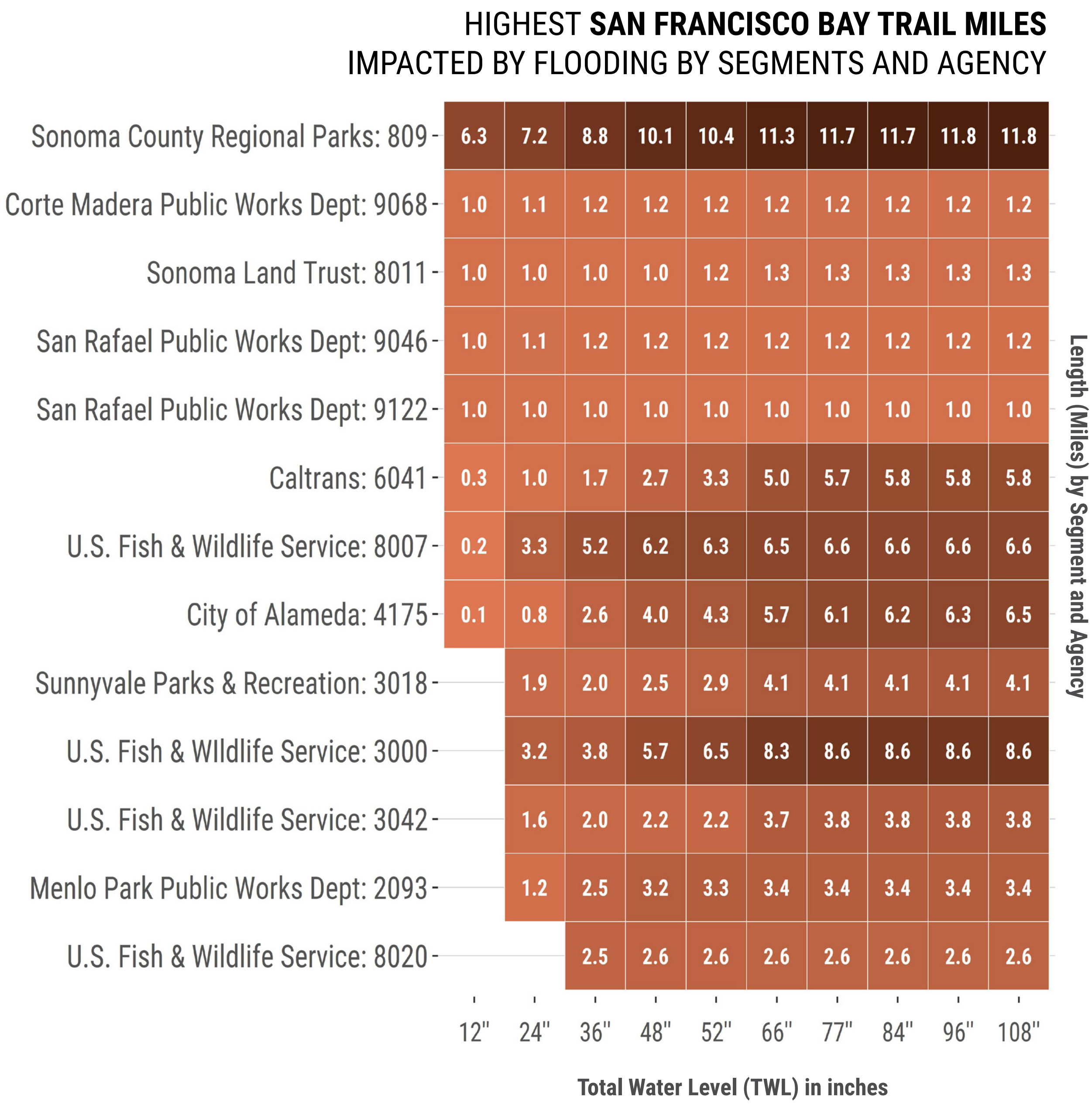


Figure 2-66. Agencies with highest impacts to the San Francisco Bay Trail length from flooding at ten TWLs as measured by impacts to San Francisco Bay Trail segments and agency. “Highest” impacts refer to counties ranking in the top five for highest consequences at one or more TWL. Darker colors reflect greater consequences.

Bikers riding in downtown San Jose. Photo by Richard Masoner / Cyclelicious licensed under CC BY 2.0.

HIGHEST **BICYCLE ROUTES** IMPACTED BY FLOODING BY COUNTY

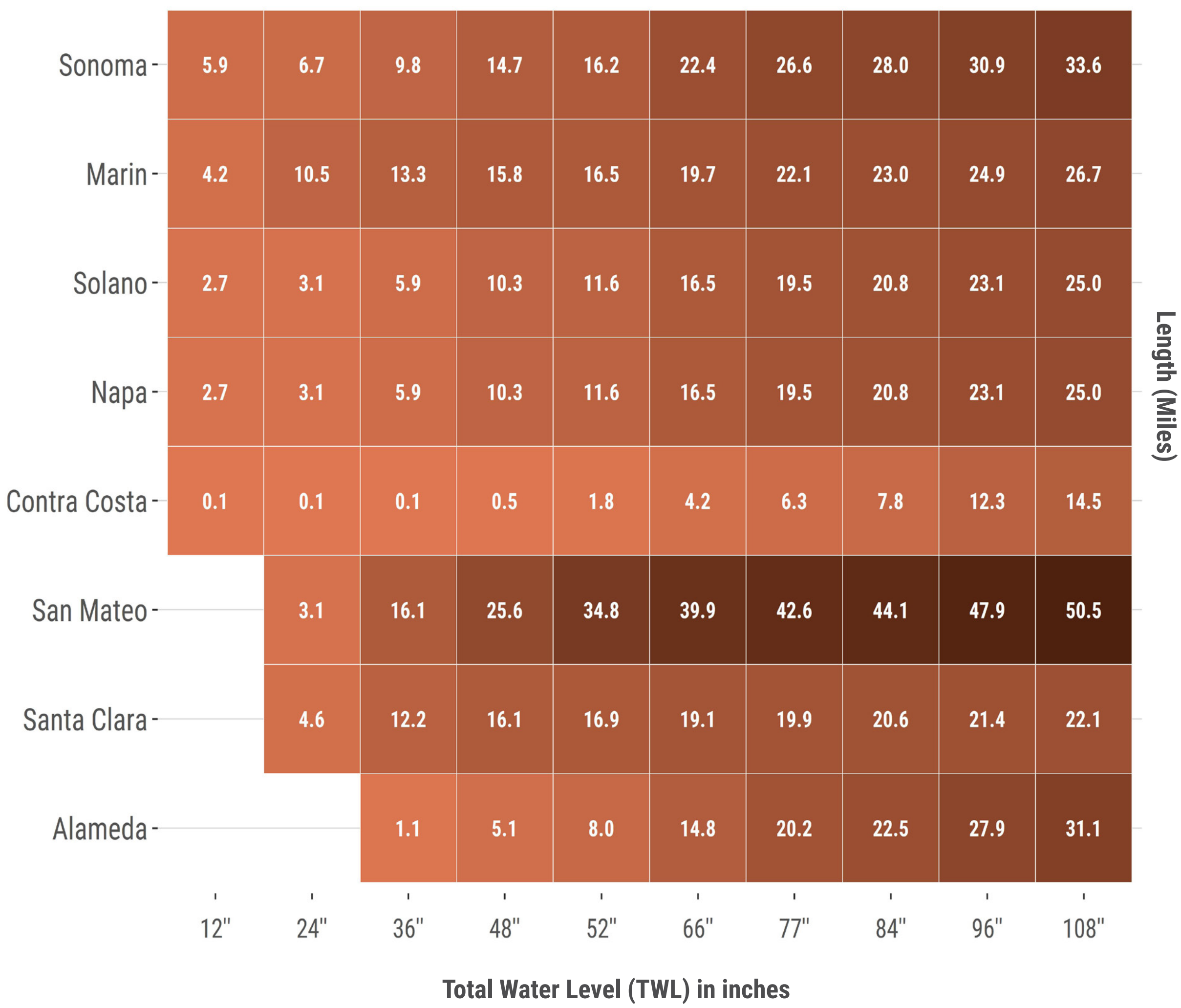


Figure 2-67. Counties with highest impacts to bicycle routes by flooding at ten TWLs as measured by impacts to Caltrans Bike Routes. Darker colors reflect greater consequences.

Top: San Francisco Bay Trail provides public access to the Bay. Photo by TJ Gehling licensed under CC BY 2.0. Bottom:Bike rider on the San Francisco Bay trail during King Tides. Photo by Schyler Olsson courtesy of California King Tides Project.

Trends and Drivers Around the Region

San Francisco Bay Trail and Bicycle Routes and

Early Impacts • Given its shoreline location, the Bay Trail is vulnerable to flooding nearly everywhere in the Bay Area. This exposure follows a generally linear trend at higher water levels. Caltrans Bike Routes are less vulnerable around the entire Bay Area, but still see early flooding in the North Bay, East Bay, and along the Peninsula. This exposure continues linearly (Figure 2-68).

Worsening Impacts • Regionally, the length of Bay Trail miles exposed significantly worsens between 52” and 66” TWL. This is largely due to increases in exposure in the East Bay. At this water level, there are nearly 300 miles of exposed Bay Trail.

Worsening Impacts • Shoreline segments with significant length of Bay Trail exposure occur in Napa County, Sonoma County, Redwood City, Santa Clara County, and Alameda County. These are similar outliers for Caltrans Bike Routes.

The San Francisco Bay Trail provides beautiful views of the Bay Area. Photo by Danny Howard licensed under CC BY 2.0.

Short Case Study

LINKING REGIONAL CONSEQUENCE RESULTS TO LOCAL ASSESSMENTS

While the majority of the Bay Trail is complete, there are proposed sections of Bay Trail that are critical linkages in our regional trail system. Some of these proposed alignments are at risk of flooding. For example, a proposed alignment in the Bayview/Hunter's Point neighborhood is currently vulnerable to flooding, yet represents an important Bay Trail connection, valuable recreational opportunities, and provides routes for commuters traveling from that neighborhood. Care should be given to establishing new Bay Trail segments in areas at risk of current and future flooding.

In addition to the regional assessment, ART Bay Areas assessed individual assets in each of the four region systems and the results are communicated in local assessments of shared vulnerabilities and consequences.

These can be found in Chapter 3.0 Local Assessments of the ART Bay Area report, with local assessments available for individual download.

The San Francisco Bay Trail provides beautiful views of the Bay Area. Photo by Danny Howard licensed under CC BY 2.0.

CONSEQUENCES OF FLOODING

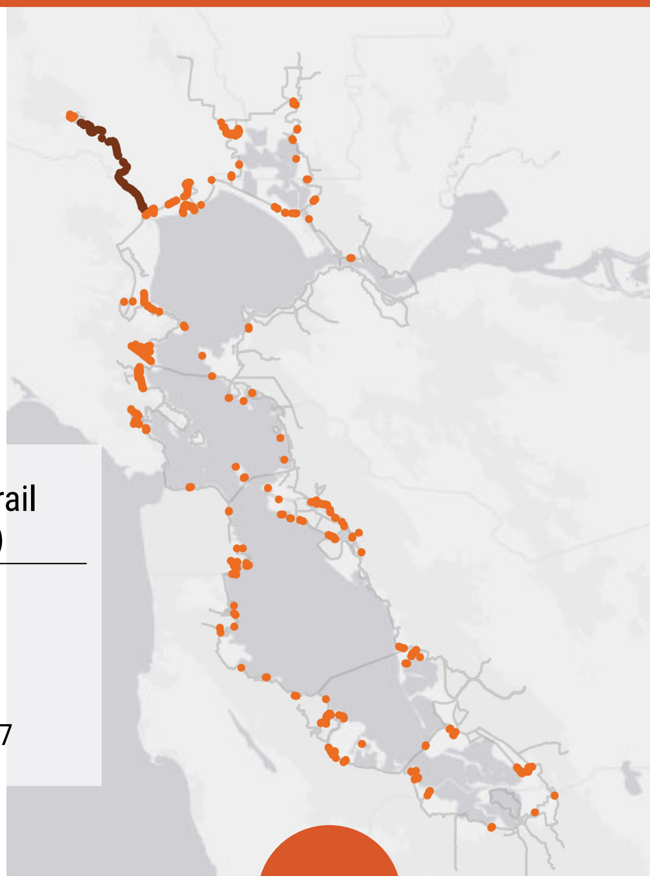
Transportation

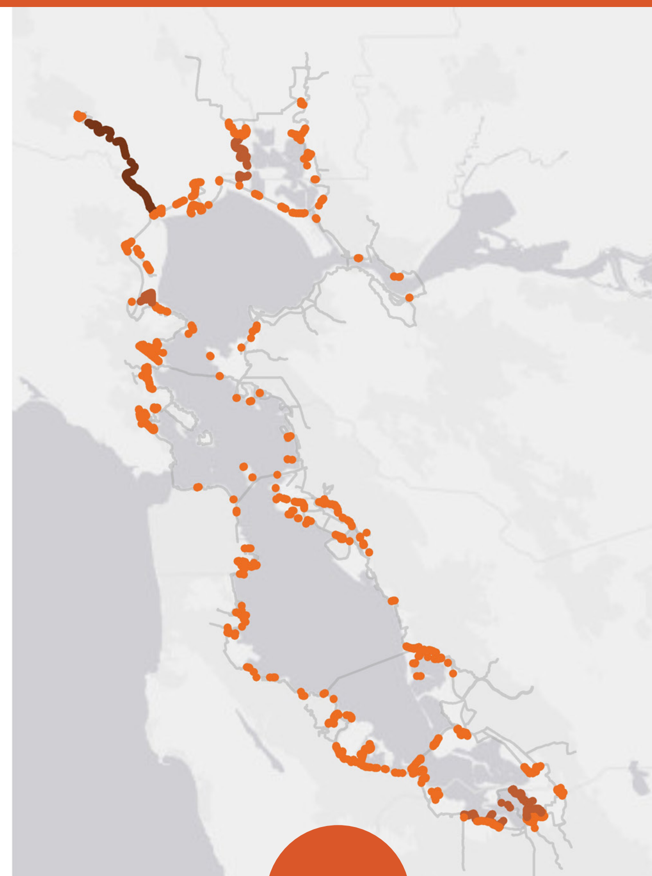
Active Transportation Consequences

San Francisco Bay Trail Impacted by Flooding

Length of Bay Trail segment (miles)

- 0 to 1.3
- 1.3 to 4.2
- 4.2 to 11.7





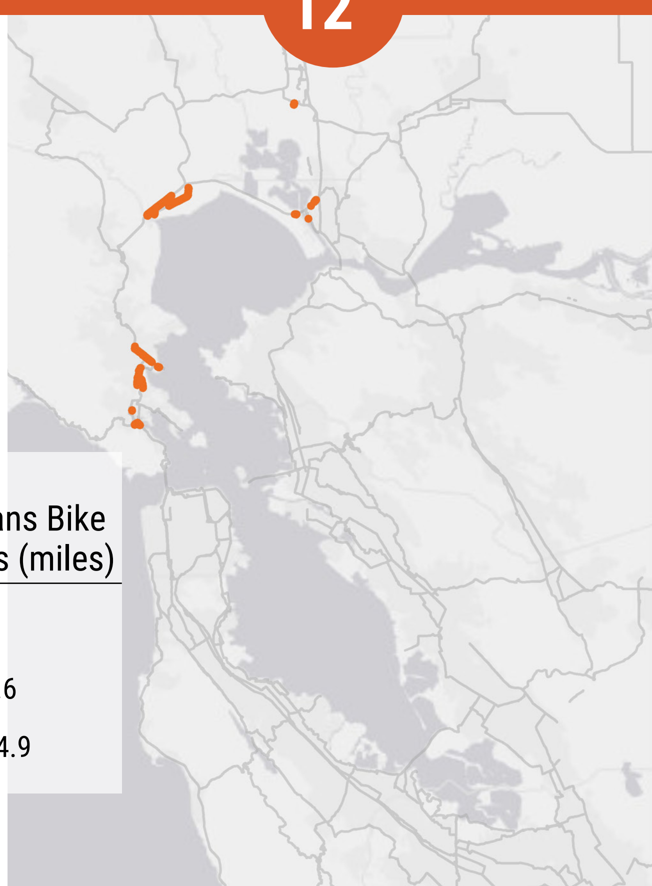
12"

24"

Bicycle Routes Impacted by Flooding

Length of Caltrans Bike Route Segments (miles)

- 0 to 5.8
- 5.8 to 12.6
- 12.6 to 24.9



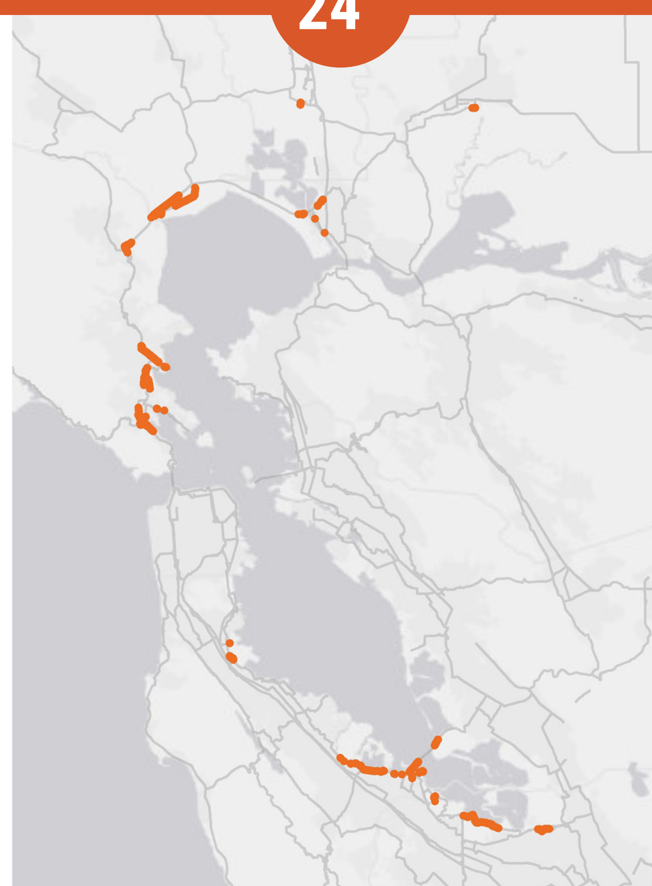
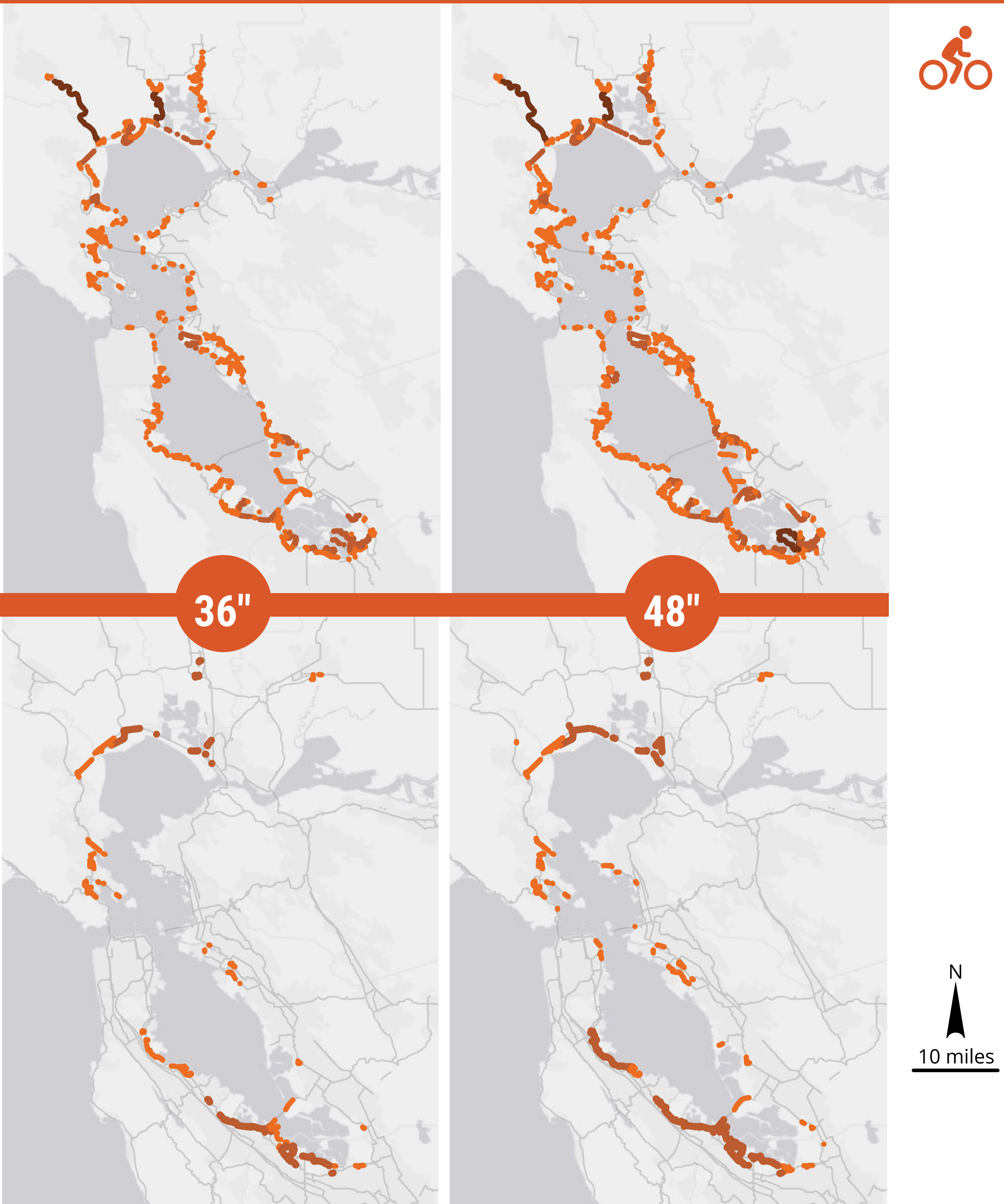


Figure 2-68. Maps depicting the consequences of flooding for two active transportation indicators: *San Francisco* and *Bay Trail Bicycle Routes* at 12”, 24” 36” and 48” TWL. Maps below show consequences and extent of exposure.



Methodology and Limitations for Active Transportation

Methodology

The consequences of inundation to the Bay Area's active transportation system was measured using two indicators – miles of Bay Trail impacted, and miles of Caltrans bike routes impacted. Although miles impacted is technically a measure of exposure, no data on ridership is currently available at the regional level for active transportation assets.

High quality linework for the Bay Trail was readily available, but linework for regional bicycle routes was not. While some Bay Area cities have extensive GIS data on their bicycle infrastructure, data was not available for the entire region. The project team considered using crowdsourced data from OpenStreetMap, but this linework has many gaps, does not differentiate between local and regional routes, and was found to mostly represent streets where bicycles are permitted, rather than streets with physical bicycle infrastructure. In lieu of a perfect dataset, the project team used data from Caltrans on bicycle access on the state highway system and alternate routes. This dataset was found to be a reasonable representation of regional bicycle routes, although important routes that are not on an alternate route for state highways are omitted.

Bikers use the San Francisco Bay Trail for commuting. Photo by Jaclyn Mandoske, BCDC.

Limitations

This approach has limitations in comprehensively reflecting active transportation vulnerability in the region. In addition to the consequence of flooding segments of Bay Trail and bike trails, regional active transportation networks are vulnerable due to numerous other factors. These include:

Information and Governance • There is a lack of regional understanding of Bay Trail use regarding demographics, frequency of use, purpose of use, etc. Individual segments of Bay Trail may be managed by multiple and different entities. Relationships between landowners, managers, and neighbors mean that future adaptation will require expanded coordination and cost-sharing between agencies.

Transportation Networks • Bike and pedestrian paths in the Bay Area provide critical connections between other transportation modes for commuting or recreation. Disruption of these active transportation paths could impact people's abilities to connect with other transportation networks.

Recreation • The Bay Trail provides low cost and healthy recreation opportunities for communities around the Bay Area. As segments are flooded or rerouted, this function is lost to vulnerable communities who may not be able to travel further or pay more for similar opportunities. This may result in disproportionate recreation and transportation challenges to vulnerable community members.

First Line of Defense • The Bay Trail is co-located as the first line of defense on shoreline protection structures, berms, and natural shorelines throughout the Bay Area making it highly vulnerable to erosion and overtopping. The trails are likely to be damaged as sea level rises and the trail and shoreline are overtopped or eroded.

2.5.4 Transportation Vulnerability Statements

This portion of the assessment is based on results from the in-depth vulnerability assessments conducted on a subset of transportation assets in the region. Qualitative vulnerability assessments were conducted to gain a more nuanced understanding of specific vulnerabilities for the transportation asset classes identified. These individual assessments were then compiled into a series of "Local Assessments" that dive into specific localities around the region. For details on this section, please see Section 3.0 Local Assessments – Local Vulnerability, Regional Impacts.

The vulnerability statements described below were derived from the results of the detailed vulnerability assessments. They provide a different level of nuanced detail than the data-driven consequence data. Because of the wide array of transportation assets that exist in the region, the functions they serve, and the multiple components within each system (linear assets like rail lines vs. point assets like stations) there are a variety of vulnerabilities that the transportation system faces in terms of flooding due to the nature of its structure.

While the vulnerabilities listed do not necessarily apply to every transportation asset in the entire region, they represent consistent themes and findings from the local vulnerability assessments conducted on a subset of the transportation assets.

Bridge touchdowns, including SR-84 Dumbarton Bridge, are often near the water. Photo by SF Baykeeper Robb Most and LightHawk.

Transportation Assets are Located Near the Shoreline

Many of the ground transportation assets in the Bay Area are vulnerable to sea level rise and storm events because many are located near the shoreline. Bridge touchdowns are especially vulnerable since they are typically placed on bay fill and have experienced considerable subsidence.

Transportation Assets Serve as Ad-hoc Shoreline Flood Protection

In many cases, transportation infrastructure along the shoreline also serves as ad-hoc shoreline protection for communities located behind it yet were not designed for flood control.

Transportation Assets are Networked

Given the interconnected nature of transportation, if one component of the network is impacted, there can be cascading consequences across the region. Limited redundancy of the transportation network reduces the ability of the system to respond to impacts. Temporary flooding of vulnerable sections of interstate and state highways may not cause permanent asset damage but will have potentially significant consequences on both goods or commuter movement and access for emergency responders as there is a lack of alternate routes with adequate capacity to serve all of the traffic needs.

Limited redundancy of the transportation network reduces the ability of the system to respond to impacts.

The Transportation Network is Critical for Emergency Response

Vulnerable transportation assets including our highways, airports, seaports, and ferry terminals serve important emergency response functions in the event of a disaster. Flooding of these systems will reduce the Bay Area's ability to respond to disasters.

Lack of Information Limits Planning

Understanding the underlying causes and components of these vulnerabilities is challenging because most planning data (e.g., storm drain and bridge crossing locations) are not readily available to the public, and design and survey data (e.g., structure elevation information) are not easily accessible to asset managers, for example through searchable, system-wide, centralized databases.

King Tides raise water levels in the Bay that show us what permanent sea level rise will look like. Photo by SF Baykeeper, Robb Most, and LightHawk.

Elevated Transportation Assets Are Also Vulnerable

Elevated and at grade roadways are vulnerable to flooding, higher groundwater and exposure to saltwater that can corrode the reinforcing materials in concrete structures, damage pavement, structural sections and landscaping, and cause major dewatering problems during future construction. Although much of the BART system in the Bay Area is elevated, assets critical to operations are located at grade or underground and have mechanical or electrical components that are highly sensitive to even small amounts of water. The disruption or damage of these assets could shut down the entire BART system or a large portion of it. This would have significant consequences, including increased roadway congestion, emissions and air and water quality issues caused by more people driving, and number of riders on other modes of transportation where capacity may already be strained.

Transportation Infrastructure is Located Below-Grade

Tubes, tunnels, and roads with below-grade sections are particularly vulnerable because these are largely below current sea level and their openings are generally unprotected and at grade. This includes some local roads and segments of the transit system (e.g. BART, SMART, SR-61).

The Rail Network Is Especially Vulnerable

Rail lines within and beyond the Bay Area are vulnerable to sea level rise and storm events. In general, rail is highly sensitive to even small amounts of water on the tracks, and if a portion of track is damaged it often results in the closure of many miles of connected track. The region's capacity to withstand impacts to rail infrastructure is further hampered by the lack of redundant or alternative rail lines in the region. Relocating or adding new rail infrastructure is costly and significant time and money are needed for planning, financing and implementing changes to the region's rail network. Disruption of the rail system would lead to an increase in the number of trucks needed to transport cargo, having negative and widespread effects on road congestion, air quality, and community noise and quality of life.

The Active Transport Network is Most Vulnerable Given Its Shoreline Location

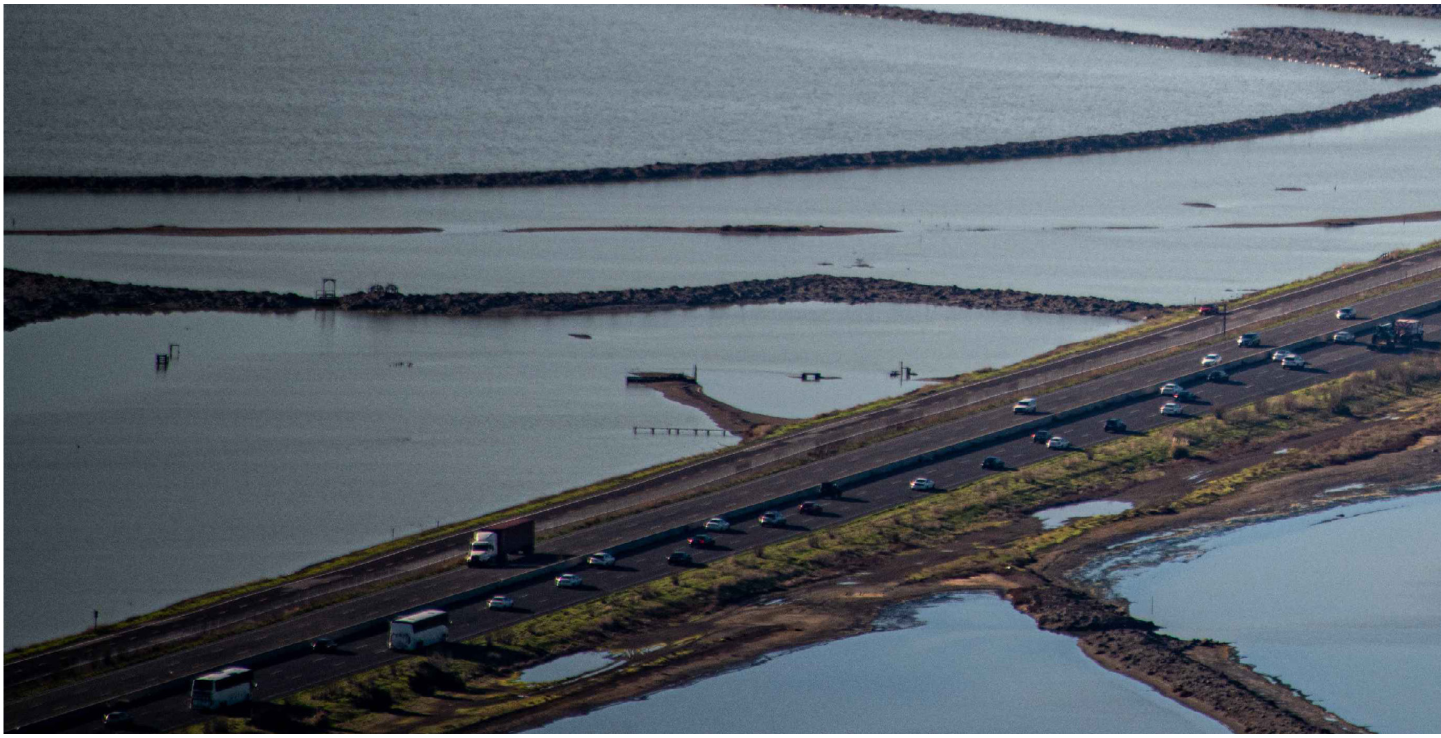
The Bay Trail is highly vulnerable to sea level rise and storm event flooding due to its construction and location along the shoreline. Erosion, poor drainage, and surface damage can all result in lengthy closures. Consequences of temporary or permanent closures along portions of the trail can be significant because it functions as a system of interlinked pathways for recreation and non-motorized commuting. Adaptive measures can be taken, such as building with different types of materials, improving drainage, and using boardwalks and bridges, but at some point, these will become ineffective. Loss of connected Bay Trail segments could result in more people driving rather than walking or bicycling to their destinations and reduced shoreline access opportunities, in particular for people with disabilities or reduced mobility.

Loss of connected Bay Trail segments could result in more people driving rather than walking or bicycling to their destinations and reduced shoreline access opportunities, in particular for people with disabilities or reduced mobility.

2.5.5 Transportation Conclusions

The analysis presented here highlights the vulnerability of our region's transportation system. Essentially, all transportation sectors will experience some degree of impact from rising seas and flooding. Given the nature of our transportation network, if critical nodes in the region's transportation infrastructure are lost or compromised, there will be cascading impacts for the region and beyond. This analysis identifies where in the region the most significant impacts from flooding may occur and the magnitude of those consequences on the movement of people, goods, and services throughout the region. The Bay Area has built its transportation system on or near the shoreline and developed limited redundancy to ensure the network can operate if segments are impacted. Building and maintaining transportation infrastructure is costly and takes decades, making adaptation difficult. Furthermore, many communities rely on the ad-hoc flood protection that many of these railways and highways provide, protection they were never designed for. As the region grows, and our transportation system grows in turn to meet the changing needs of the Bay Area, we will need to change the way we design and build our transportation infrastructure.

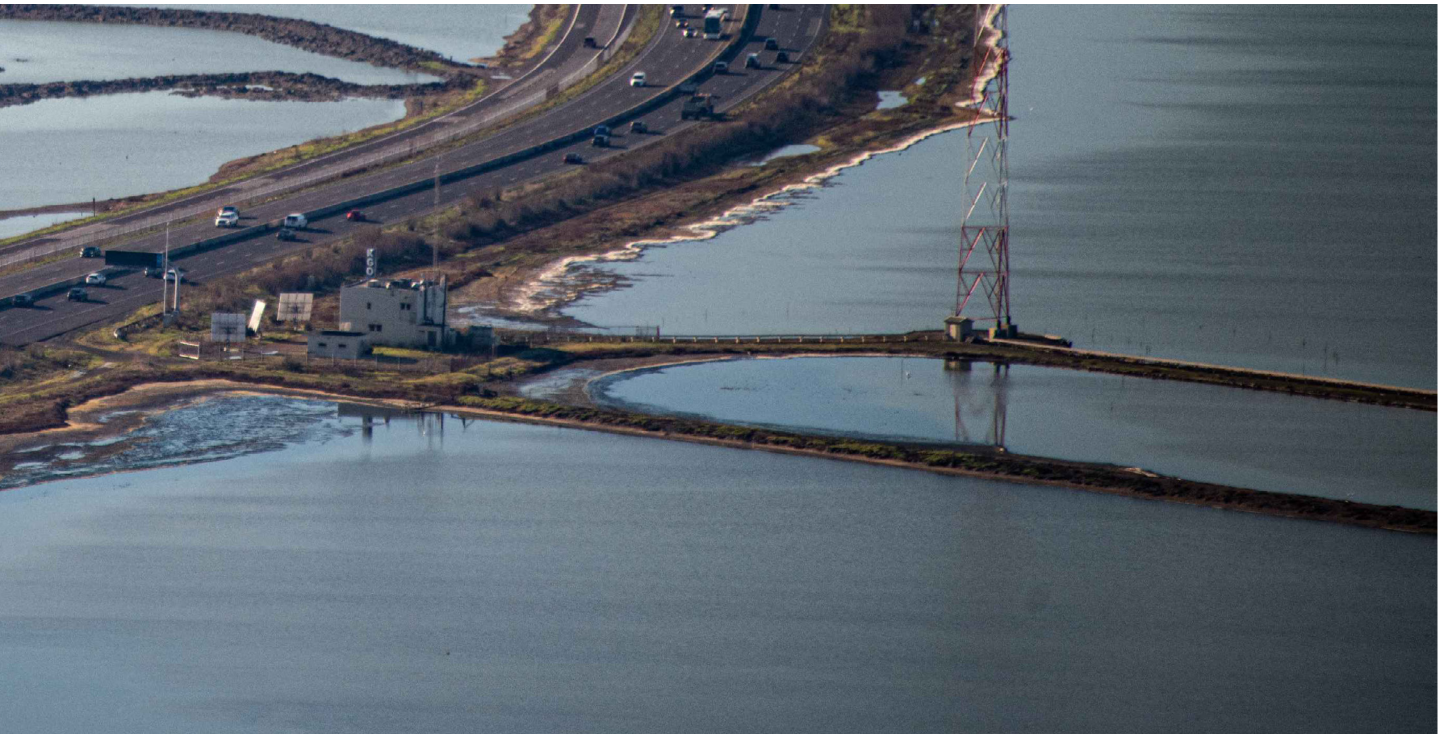
The main finding of this analysis is that transportation networks are a critical component of the overall vulnerability of the region, primarily because so many other aspects of our regional growth are tied to the transportation networks that move people, goods, and services around and through the region. As patterns



of travel change from single vehicle commuters to mass transit and bike and pedestrian modes, understanding the specific vulnerabilities of these systems will be particularly important. Adaptation will be difficult, costly, and time consuming due to the physical vulnerability of the transportation infrastructure, the cost of replacing assets, and their complex governance structures. However, the cost of inaction will be dramatic as our analyses show that possibly millions of dollars of goods won't reach our seaports and airports and that hundreds of thousands of commuters won't be able to get to their places of work or homes.

The Bay Area gains much of its regional identity from the ability of people to move easily from one part of the Bay to another. What happens in one part of the region can have serious consequences for other parts of the region, precisely because of the way our transportation system is set up. This is due to the transportation planning decisions made at the regional level. Rapid mobility of people and goods has allowed for a boom in interconnectivity, productivity, and growth in the region. While there is inherent vulnerability in the interconnectedness of our transportation network, the system has the potential for resilience through redundant networks and the potential for adaptation financing across diverse partners and long distances.

Waters rise during king tides near the SR-84 Dumbarton Bridge touchdown. Photo by SF Baykeeper, Robb Most, and LightHawk.



Endnotes

1 District 4 | Caltrans," 2019, https://dot.ca.gov/caltrans-near-me/district-4.

2 "Transit Ridership | Vital Signs," September 2017, http://www.vitalsigns.mtc.ca.gov/transit-ridership.

3 Caltrain- CalMod Program Overview," Overviews and Factsheets, accessed November 14, 2019, https://calmod.org/.

4 Andrew Cook et al., "2018 California State Rail Plan: Connecting California" (Caltrans, n.d.), http://libraryarchives.metro.net/DPGTL/harvested/2018-California-state-rail-plan.pdf.

5 Adapting to Rising Tides, "Adapting to Rising Tides Contra Costa" (San Francisco Bay Conservation and Development Commission, 2017), http://www.adaptingtorisingtides.org/contra-costa-county-art-project-report/.

6 "Port of Oakland Facts & Figures," Oakland Seaport, accessed September 3, 2019, https://www.oaklandseaport.com/performance/facts-figures/.

7 "Port of Redwood City FAQ," Fact Sheet (Port of Redwood City, n.d.), https://www.redwoodcityport.com/faq.

8 "Bay Area Earthquake Plan" (California Governor's Office of Emergency Services, Federal Emergency Management Administration, July 2016), https://www.caloes.ca.gov/PlanningPreparednessSite/Documents/BayAreaEQConops(Pub_Version)_2016.pdf.

9 Adapting To Rising Tides, "Adapting to Rising Tides: Alameda County Shoreline Vulnerability Assessment," 2015, http://www.adaptingtorisingtides.org/wp-content/uploads/2015/09/ALA-Report_FINAL_2015.05.26sm_REPORT.pdf.

10 Hilary Papendick, Jasneet Sharma, and Kelly Malinowski, "County of San Mateo Sea Level Rise Vulnerability Assessment," Vulnerability Assessment (Sea Change San Mateo County, March 2018), https://seachangesmc.org/wp-content/uploads/2018/03/2018-03-12_SLR_VA_Report_2.2018_WEB_FINAL.pdf.

11 "Transit Ridership | Vital Signs."

12 Rachel Raskin-Zrihen, "Bay Area Ferry Ridership Exploding, Especially in Vallejo," East Bay Times, March 16, 2018, https://www.eastbaytimes.com/2018/03/16/bay-area-ferry-ridership-exploding-especially-in-vallejo/.

13 "Transit Ridership | Vital Signs."

14 "San Francisco Bay Trail – A 500-Mile Trail Around the Bay," The San Francisco Bay Trail, 2019, https://baytrail.org/.