SHALLOW GROUNDWATER RESPONSE TO SEA-LEVEL RISE

Alameda, Marin, San Francisco, and San Mateo Counties

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San Francisco Bay Regional Water Quality Control Board

Todd Hallenbeck
Daniel Hossfeld
San Francisco Bay Conservation and Development Commission

Makena Wong
John Allan
Kim Springer
County of San Mateo

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LEAD AUTHORS

Christine L. May, PhD PE
Abigail Mohan, MSc
Daisy Ramirez Lopez
Lindsay Luchinsky, MSc
Michael Mak, MSc PE
Pathways Climate Institute

Ellen Plane, MLA, MCP
Tony Hale, PhD
San Francisco Estuary Institute

Kristina Hill, PhD
University of California, Berkeley

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King Tide in Mill Valley, December 2021.
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E. Adaptation Workshop Summary

ABBREVIATIONS

Adapting to Rising Tides	ART
Bay Area Aquatic Resources Inventory	BAARI
Bay Area Rapid Transit	BART
California Department of Toxic Substances Control	DTSC
California Department of Transportation	Caltrans
California Department of Water Resources	DWR
California State Water Resources Control Board	SWRCB
Federal Emergency Management Agency	FEMA
Geographic Information Systems	GIS
Pathways Climate Institute	Pathways
San Francisco Bay	Bay
San Francisco Bay Area	Bay Area
San Francisco Bay Regional Water Quality Control Board	SFBRWQCB
San Francisco Estuary Institute	SFEI
United States Geologic Survey	USGS

2.1. Introduction

The response of shallow groundwater to sea-level rise is a relatively new field of study. For low-lying coastal communities, sea-level rise adaptation efforts must consider the potential for groundwater rise to avoid maladaptation. The need to better understand this slow and chronic threat was identified as a critical data gap in the San Francisco Bay Area's (Bay Area's) adaptation efforts during the Bay Area Groundwater and Sea-Level Rise Workshop in 2019.[1] The consensus in 2019 was that a better understanding of groundwater rise can inform the development of more effective and comprehensive sea-level rise adaptation strategies, especially in low-lying vulnerable communities subject to flooding from multiple sources.

> ***Low-lying inland areas could flood from below by emergent groundwater long before coastal floodwaters overtop the shoreline.***

Pathways Climate Institute LLC (Pathways) and the San Francisco Estuary Institute (SFEI) gathered and analyzed multiple data sets and collaborated with city and county partners to analyze and map the existing "highest annual" shallow groundwater table and its likely response to future sea-level rise. This effort covers four counties (Alameda, Marin, San Francisco, San Mateo)[2] and was funded by the Bay Area Council's California Resilience Challenge. The study focused on the San Francisco Bay side of each county and does not include the Pacific coastline of Marin, San Francisco, nor San Mateo Counties. An advisory committee composed of city and county representatives provided essential support by gathering data and reviewing depth-to-groundwater maps. Additional academic and agency advisors participated in project team meetings and informed project direction. This effort produced the following publicly available data and online tools to support adaptation efforts:

- Existing and future condition depth to groundwater GIS data available for download (geodatabase format).
- A StoryMap providing background information and graphical representations of the processes and impacts of groundwater rise.
- Web maps showing: (1) existing depth to groundwater; and (2) a comparison of the extent of emergent groundwater to the extent of coastal flooding under various sea-level rise scenarios.

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[1] Bay Area Groundwater and Sea-level rise Workshop Summary: adaptingtorisingtides.org/wp-content/uploads/2020/04/GW_WkshpSummary_Nov2019_FINAL_ADA.pdf

[2] The counties of Alameda, Marin, San Francisco, and San Mateo were selected because they volunteered to participate in the grant development process and committed in-kind staff time to support the project.

An interpolation-based Geographic Information Systems (GIS) model was used to create mapping approximating the existing highest annual shallow groundwater surface. The model used represents an advancement to the methods described in Plane et al. (2019). The model relies on observed depth-to-groundwater measurements, tidal water levels in San Francisco Bay (Bay) and tidally influenced tributaries, and measured, modeled, or estimated water levels in upstream tributary reaches and managed lagoons and water bodies. Future condition modeling assumes a one-to-one relationship between sea-level rise and groundwater rise, a best estimate in the absence of more advanced modeling accounting for differences in subsurface geology and groundwater flow. The value of such modeling may be limited by the ability to adequately characterize the complex subsurface geology.

Although a one-to-one relationship is reasonable for planning purposes, it may produce a higher than anticipated future groundwater surface in some areas due to limitations in capturing groundwater flow directions (Befus et al., 2020). The one-to-one model may also produce a lower than anticipated future groundwater surface as it does not consider future increases in extreme precipitation which are likely to drive even larger increases to the highest annual groundwater table (Patricola et al., 2022). The resultant mapping is not intended to replace the need for site-specific analyses where groundwater flow directions, flow rates, and the interactions with subsurface infrastructure may be important considerations.

This report explains why understanding the elevation of the future groundwater table is important for coastal communities and provides a description of the methods and data used to develop both the existing conditions groundwater mapping and the future condition projections. This report also provides data availability and download information, suggestions on how to use this dataset for planning purposes, recommendations for additional modeling and assessments, and potential next steps.

Methods considerations and maps specific to the groundwater mapping and ground truthing process for each county are provided in Appendices A to D. In support of this effort, a Groundwater Rise Adaptation Workshop was held with local government representatives. A summary of the workshop outcomes is provided in Appendix E.

2. Understanding the Challenge

Groundwater rise will contribute to inland flooding in low-lying coastal communities, with impacts often occurring earlier, and farther inland, than coastal flooding from overtopping of the Bay shoreline (Befus et al., 2020; Bosserelle et al., 2022; Plane et al., 2019; Rahimi et al., 2020). In addition, rising groundwater has the potential to impact coastal communities long before the groundwater rises aboveground and creates a new flood hazard (May et al., 2020; Michael et al., 2017; Plane et al., 2019; Rotzoll & Fletcher, 2013). Rising groundwater can degrade underground infrastructure, mobilize contaminants, and increase liquefaction hazards.

The significance of rising groundwater and groundwater inundation may create the need to re-evaluate sea-level rise driven flooding in some communities to develop effective flood risk reduction strategies (Habel et al., 2020). Failing to account for groundwater rise on the landward side of some flood risk reduction structures (e.g., levees and seawalls) could result in maladaptation if the community continues to flood from below. Strategies that break the connection between the Bay and the inland areas (e.g., cutoff walls), could limit inland groundwater rise due to sea level rise, while exacerbating inland groundwater rise due to extreme precipitation and preventing the natural outmigration of groundwater toward the Bay. Scientific advances and an understanding of hydrogeology should be integral to coastal zone management and adaptation. Addressing the compounding challenges in low-lying coastal areas will require interdisciplinary collaboration, open communication among scientists, decision makers, and the public, and strong partnerships with policymakers (Michael et al., 2017).

2.1 Infrastructure

Communities throughout the world have built complex networks of infrastructure underground (Zaini et al., 2015). Utility networks (e.g., storm sewer, wastewater, and water supply) supply our homes and businesses with essential services, and electrical lines are increasingly being placed underground. In many areas, placing utilities underground enhances a community's resilience because belowground infrastructure is not exposed to the same hazards as aboveground infrastructure (e.g., extreme storms that bring floods, high winds, and lightning). Placing infrastructure underground can also "free up" aboveground space for uses with greater social value. For example, placing transportation corridors and parking garages underground can free up space for parks, green infrastructure, and occupied living and working space aboveground (e.g. Ohlone Park in Berkeley, which is built above Bay Area Rapid Transit (BART)).

A large proportion of underground infrastructure is built within 6 feet of the ground surface (Bobylev et al., 2012), including most essential utilities and residential basements. For example, Pacific Gas & Electric's design manual for underground electrical lines states that 60 inches is the preferred maximum trench depth for electrical cables (PG&E, 2022). Commercial and industrial buildings, stormwater and wastewater pump stations, parking garages, and transportation tunnels can extend 150 feet or more below the ground surface (Bobylev et al., 2012). Underground infrastructure is typically designed relative to the highest annual groundwater table, which fluctuates throughout the year based primarily on rainfall (Armstrong et al., 2019; Caltrans, 2020; Christine May et al., 2020; Othman et al., 2014; Pathways, 2022). In most areas, the highest annual groundwater table occurs sometime after the rainy season depending on the size of the watershed and the hydraulic conductivity of the soil (i.e., how fast the groundwater can flow through the pore spaces within the soil) (May et al., 2020; Pathways, 2022; Seneviratne et al., 2021; Smail et al., 2019).

Figure 2-1 presents the seasonal fluctuations in the shallow groundwater table at one monitoring well located in the City of Alameda (SWRCB, 2020). Other monitoring wells around the Bay Area exhibit similar characteristics, although the total fluctuation (in feet) from the highest to lowest measurement varies based on location in the watershed, subsurface characteristics, and other local factors.

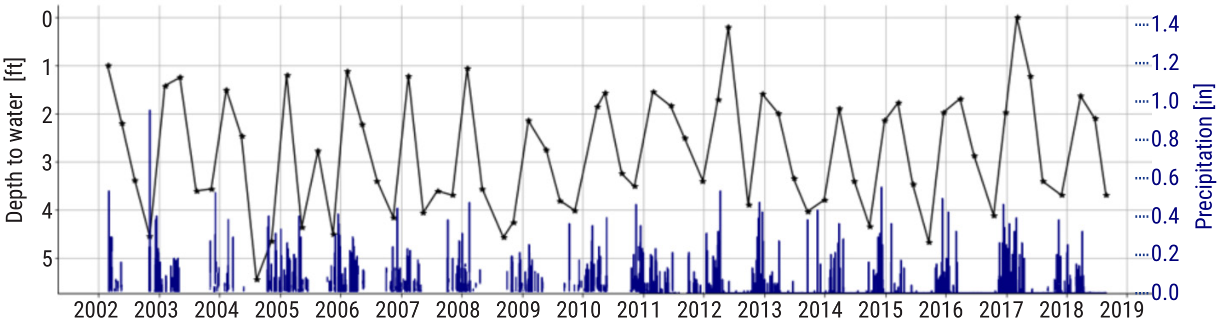

Figure 2-1 Shallow Groundwater Response to Precipitation. Source: (SWRCB, 2020). Long-term observations at a monitoring well near High Street and Gibbons Drive in the City of Alameda highlight the response of the groundwater table to precipitation. The black dots illustrate when the depth-to-groundwater measurements were observed, and the blue lines present the daily (24-hour) precipitation intensity measured at the Oakland International Airport. The highest groundwater measurements generally occur between January and March within this small watershed. The smallest recorded depth-to-water measurement during this period occurred in early 2017 when the depth-to-groundwater was zero, or at the ground surface.

During king tides in January 2022, groundwater infiltrated into the City of San Leandro storm sewers along Marina Boulevard, percolating out of manholes and flooding roadways. *Photo Credit: Kristina Hill*

If the highest annual groundwater table is below the infrastructure, groundwater may not need to be considered in infrastructure design. However, if the highest groundwater table is within ~3 feet (1 meter) of the lowest elevation of the infrastructure, the soils above the groundwater table may be effectively saturated by capillary action and groundwater may require consideration. If the highest annual groundwater table intersects the infrastructure, then the buoyancy forces pushing up on the infrastructure by the groundwater must be considered. The bearing capacity of the soils underneath or around the infrastructure must also be accounted for. Seasonal variations in the groundwater table can cause the soils to alternately swell and shrink, destabilizing the soil and causing undesired ground (and infrastructure) movement.

Although underground infrastructure has been designed and constructed to account for the historical highest annual groundwater table, what happens when the groundwater table rises above that historical level? When the groundwater table elevation exceeds the design conditions, infrastructure is at risk of damage; rising groundwater can destabilize and corrode foundations, flood basements and other underground structures, and increase infiltration into sewers (Abdelhafez et al., 2022; Caltrans, 2020; Huang et al., 2022; Jiang & Tan, 2022; McHugh et al., 2017). According to participants in the workshop conducted as a part of this study, basement flooding, foundation damage, and increased

Veterans Court in the City of Alameda during King Tides. Groundwater intrusion into the sewer system provides a pathway for inland flooding when Bay tides are high. A high groundwater table and emergent groundwater flooding have caused pavement failures.

> ***When the groundwater table elevation exceeds the design conditions, infrastructure is at risk of damage; rising groundwater can destabilize foundations, flood basements and other underground structure, and increase infiltration into sewers.***

sewer infiltration have been observed in many low-lying areas around the Bay (Appendix E). Increased groundwater infiltration into wastewater sewers could reduce capacity at wastewater treatment plants (Su et al., 2019). The San Francisco Public Utilities Commission has been implementing improvements to its combined stormwater and wastewater system for over a decade, including working to reduce sewer infiltration (Fracassa, 2017). For combined stormwater and wastewater sewers with aging infrastructure, increased groundwater infiltration could increase the frequency of combined sewer overflows (i.e., the discharge of untreated sewage into the receiving water body) after minor precipitation or even in dry weather conditions (Su et al., 2019). When wastewater treatment ponds, septic systems, and leachate fields are located near the shoreline, rising groundwater tables can impact treatment effectiveness and transport contaminants to the surrounding area and receiving waterbodies (Habel et al., 2017; Threndyle et al., 2022).

Photo credit: Kristina Hill.

Most large underground transportation corridors and tunnels, such as those used by Bay Area Rapid Transit and the San Francisco Metropolitan Transportation Commission, were constructed in areas already below the groundwater table. As sea levels rise and the groundwater table rises, the rate of groundwater pumping to keep these underground tunnels dry will increase. Although the New York subway monitors for groundwater seepage within its subway network daily to identify and plug leaks, it also pumps 13 million of gallons of water out of the subway system each day in its battle against groundwater (Kahn & Noor, 2021). BART also monitors for groundwater seepage and pumps groundwater out of the belowground infrastructure, particularly in the Powell Street station which sits the farthest below ground (CBS News, 2016); however, recent BART waterproofing improvements have helped repair extensive leaks at the station that have plagued BART for decades (Butt, 2019).

Aboveground highways, roadways, and railways are also at risk; a higher than anticipated groundwater table can exert detrimental effects on roadway and railway bases and subgrades (Knott et al., 2018; Rojali et al., 2022; C. Zhang, 2004). When roadway deterioration begins to occur due to a higher-than-expected groundwater table, the degradation of other types of infrastructure located farther belowground is likely well underway.

2.2 Contaminated Sites

The interaction of rising groundwater and contaminated sites could pose challenges for public health and the environment. Previous studies have reviewed the risks of surface inundation causing contaminants to be released (UCS, 2020; USGAO, 2019). The Toxic Tides study[1] highlighted the numerous hazardous facilities that could be inundated by sea-level rise in California by the end of this century (Morello-Frosch, 2021). However, the California Toxic Tides study significantly underestimates the number of sites located in low-lying coastal communities that contain legacy contamination from past military, industrial, manufacturing, or other purposes and does not consider sites that will be impacted by groundwater rise.

The California State Water Resources Control Board (SWRCB) and the regional San Francisco Bay Regional Water Quality Control Board (SFBRWQCB) have a mission to preserve, enhance, and restore the quality of California's water resources and drinking water for the protection of the environment and public health. In the Bay Area, their jurisdiction includes San Francisco Bay, its tributaries, and all groundwater resources, including shallow groundwater. The SWRCB and SFBRWQCB regulate discharges into these waters, as well as the cleanup of unplanned, unauthorized, or illegal discharges that impact these waters.

The California Department of Toxic Substances Control (DTSC), part of the California Environmental Protection Agency, also has a mission of protecting public health and the environment from toxic harm. DTSC regulates hazardous waste treatment and storage facilities and the cleanup of unplanned hazardous waste spills and legacy contamination. Additional contaminated sites, such as leaks from small underground storage tanks (e.g., residential oil tanks), often fall under the jurisdiction of local enforcement agencies, although the SFBRWQCB has recently taken over jurisdiction for many of these sites.

Although contaminated sites around the Bay are in various stages of cleanup, current remediation regulations consider a static climate, meaning they do not consider a rising groundwater table. Some sites have been closed despite residual soil and/or groundwater contamination, without additional institutional controls. Other sites are closed and have institutional controls in place due to the presence of remaining contamination underground: generally capped, covered with clean soil, or covered with a vapor intrusion barrier if the chemicals are volatile (i.e., if they become a gas under certain conditions of inundation or exposure). Institutional controls are legal controls that help minimize the potential for human exposure to contamination. Such controls may restrict land use on the site (e.g., limit potential uses to industrial or commercial use as opposed to residential use), require a vapor barrier to block volatile chemicals from entering buildings, required a raise in grade prior to development to maintain a buffer of unimpacted soil over any residual contamination, limit intrusive activities such as digging, and/or require regular maintenance and inspections of concrete caps, vapor barriers or other engineered features. In some places contaminated groundwater is continuously pumped and treated to manage the migration of contaminant plumes.

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1. Toxic Tides: https://sites.google.com/berkeley.edu/toxictides/home

> ***Current remediation regulations consider a static climate, meaning they do not consider a rising groundwater table. Regulations, remediation methods, and institutional controls need to consider a changing climate to protect the environment and public health.***

If the groundwater table rises above the highest annual groundwater table considered in the remediation methods and plans, will contaminants that remain underground be affected? Although this is an area of great interest among decision makers, regulators, and the public, it is still an area of active scientific research. Only one thing is certain: regulations, remediation methods, and institutional controls will need to be revised to consider a nonstationary climate to allow the SWRCB, SFBRWQCB, and DTSC to continue serve their respective missions of protecting the environment and public health. SFBRWQCB recently made one key move in revising waste discharge requirements by requiring bayfront landfills to identify strategies for landfill protection from both sea level and groundwater rise in their long-term flood protection plans (Order No. R2-2022-0031).

2.3 Liquefaction

The Bay Area is riddled with fault lines, and movement along these faults can trigger an earthquake at any moment. In 2007, scientists estimated a 63 percent probability of a magnitude 6.7 or greater earthquake occurring in the Bay Area within the next 30 years (Field et al., 2008). An earthquake of that magnitude can cause significant damage to the built environment, particularly in areas subject to liquefaction (Detweiler & Wein, 2018; Grant et al., 2021). Liquefaction occurs when loose and saturated soils behave like a liquid during an earthquake.

The areas most at risk of liquefaction are generally located along the Bay shoreline and Bay tributaries in former floodplains, marshplains, wetlands, mudflats, and open water areas that were filled for development (Witter et al., 2006). These same areas are at risk of rising groundwater, and as the groundwater table rises, the liquefaction risk is likely to increase (Grant et al., 2021; Quilter et al., 2015; Risken et al., 2015). The United States Geologic Survey (USGS) developed online story maps to help Bay Area communities better understand sea-level rise related liquefaction hazards (Poitras et al., 2022).[2]

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[2] Liquefaction and sea-level rise: geonarrative.usgs.gov/liquefactionandsealevelrise/

2.4 Emergent Groundwater

Emergent groundwater is not a new phenomenon, but for at least the last 50 years, communities have built around areas of emergent groundwater instead of on top of them. Why? Because areas of emergent groundwater are simply known as wetlands. Coastal wetlands, including saltwater and freshwater wetlands that are permanently or seasonally wet, are protected under California's Coastal Act of 1976, and additional wetlands protections are included under federal, state, and local regulations, policies, and programs.

Wetlands and ponds occur in areas where the groundwater table is at or above the ground surface, providing suitable conditions for vegetation growth, with the type of vegetation dependent on location, soil conditions, and water depth. In freshwater wetlands, presence of groundwater above the ground surface is determined by rates of precipitation, groundwater flow, and evapotranspiration (movement of water from the land surface to the atmosphere, via evaporation and transpiration by plants). Wetlands may be perennial, with groundwater at or above the surface all year, or they may be seasonal in nature. Natural areas with emergent groundwater are also referred to as marshes, wet meadows, ponds, and lakes.

The existing conditions mapping produced for this report depicts the highest annual groundwater table, based on historical depth to groundwater measurements. This represents a temporary condition, generally occurring in the spring after a winter season with significant rainfall. Many of the areas with emergent groundwater under existing conditions are wetland habitats today (e.g., tidal and muted tidal marshes, seasonal wetlands, managed ponds, lagoons, stormwater basins). As sea levels rise, the extent of areas with emergent groundwater will increase. Initially, more areas will be subjected to temporary emergent groundwater, but with sea-level rise, more low-lying inland areas could have emergent groundwater year-round (Su et al., 2022). As the groundwater rises, the extent of potential wetland and open water habitat could increase – if land owners in developed areas choose to migrate further inland and allow natural processes to progress (Siders et al., 2019). Wetland protections and legislation may need to change to continue to protect these resources as sea levels and groundwater tables rise to maintain the myriad flood risk reduction and ecosystem benefits these habitats provide (Wake et al 2019).

As the groundwater table rises, the soils below the groundwater surface will become saturated, reducing the ability of rainwater to infiltrate below the ground surface in permeable areas and creating more surface ponding after rain events. This condition already exists today in many low-lying cities, such as Marin City and Sausalito in Marin County. The rising groundwater table could also reduce the effectiveness of green infrastructure and reduce the conveyance capacity in tributaries and stormwater drainage channels in low-lying coastal areas.

November 25, 2022 near Bothin Marsh in Mill Valley with a peak Bay tide of 6.7 feet. Elevated Bay water levels and saturated soils led to flooding in low-lying coastal areas in Marin County. *Photo Credit: Juliette Hart*

What is the "highest annual" groundwater table?

Groundwater tables in the Bay Area are highest after wet winter seasons with high precipitation. In December 2022 - January 2023, a series of atmospheric river and bomb cyclone events hit the Bay Area. Daily precipitation totals for these storms exceeded a 100-year rainfall event in many Bay Area communities, and the back-to-back nature of the storms left soils saturated—in other words, with a high groundwater table. The elevated groundwater table after this series of storms is a good example of what the "highest annual" groundwater table mapped for this report looks like; however, the data used to create the maps does not include measurements from the 2022-2023 season. This series of storms have brought high rainfall totals, and a high groundwater table, that exceed the period of analysis used to create the maps. For example, in San Francisco, the two-week rainfall totals between December 28, 2022 and January 2023 were the wettest period since 1867. These storm systems will continue to increase in intensity and duration due to climate change (Patricola et al, 2022), leading to higher groundwater tables in some years than were mapped in this study, even before considering the impacts of sea-level rise.

3. Methods

This study assessed and mapped the response of the shallow groundwater table to seasonal rainfall conditions and projected the rise of the groundwater table in relation to sea-level rise in Alameda, Marin, San Francisco, and San Mateo Counties along the Bay shoreline. The methods build upon previous efforts to map the shallow groundwater table, including the rapid assessment of potential shallow and emergent groundwater hotspots in the Bay Area (Plane et al., 2017, 2019) and the subsequent efforts for the Cities of Alameda and Palo Alto (May et al., 2020; Pathways, 2022).

The existing shallow groundwater table was characterized using the following data sources:

- SWRCB monitoring well observations
- Geotechnical reports with soil boring logs
- San Francisco Bay tidal datums
- Tributaries and managed ponds and lagoons

3.1 Monitoring Wells

As in Plane et al. (2019), monitoring well data from the SWRCB GeoTracker data management system provided the primary source of depth to groundwater measurements (SWRCB, 2022). The monitoring well observations include the depth to the groundwater table, as well as concentrations of contaminants and chloride from seawater, which can inform future efforts.

Similar to Plane et al. (2019), the well data were filtered to retain only measurements collected between 2000 and 2020 (i.e., focusing on the most recent time period) for wells with depths to water less than 50 feet (i.e., to capture unconfined shallow groundwater near the ground surface as opposed to deeper aquifers). Wells with negative depths to water were removed from the data set (wells with a depth to water above the ground surface are usually associated with artesian wells).

Further refinement of the well data was provided beyond Plane et al. (2019). The well data were subsampled to select measurements collected during or shortly after wet winters (December through May). Although this subsampling reduces the number of wells available, it removes potential bias from wells with measurements limited to dry summer seasons. Between 2000 and 2020, California experienced more drought years than wet years, based on the National Oceanic and Atmospheric Administration's Palmer Drought Severity Index, with the four-year drought occurring between 2011 – 2015 estimated as the worst drought in over a century at the time (CADWR, 2015). All Bay Area counties, as well as the State of California, remain under severe to exceptional drought conditions (NOAA & NIDIS, 2022). The prolonged drought conditions may be responsible for the trend of a declining shallow groundwater table elevation observed in many well records. However, the groundwater table still shows fluctuations related to precipitation events when comparing spring to fall observations collected at individual wells.

Some depth to water measurements were reported relative to a well riser height. Most wells are flush with the ground surface, as most monitoring wells are in developed (and paved) areas; for example, near existing or former gas stations. However, some wells are placed in grassy fields, wetlands, and undeveloped areas to characterize the potential migration of contaminants away from the original source. These wells often have an elevated riser to aid in finding the well in tall, unmaintained vegetation, and to prevent inadvertent damage to the well riser from lawn mowers and other equipment and vehicles. The riser height was accounted for in the analysis so that the depth to water measurements used were all relative to the ground surface.

Monitoring well riser. *Photo by Sonoran Desert NPS, courtesy Creative Commons.*

In areas with well clusters (i.e., areas with five or more wells closely spaced together), the data were analyzed relative to elevation consistency and the observation period. In areas with multiple wells and a lengthy remediation history, wells are often closed, and new wells added to improve the accuracy of the measurements and/or to expand the area monitored. In these locations, the recent measurements from active wells were selected.

From this filtered data set, the minimum depth to water measurement for each well was extracted from the GeoTracker database. Selecting the minimum depth to water measurement is a reasonable proxy for the highest annual groundwater table. The depth to water measurements were translated to the NAVD88 topographic datum using a digital elevation model developed by the USGS and refined for the Adapting to Rising Tides (ART) program, using LiDAR data collected in 2010 and 2011 (OPC, 2010; Vandever et al., 2017).

The location of all wells with depth to water measurements collected during or after a wet winter were mapped to identify "data gap areas," or areas with limited to no wells to support an assessment of the existing groundwater table elevation (Figure 3-1). Each county provided recent geotechnical reports, if available, to fill the data gap areas (Appendix A-D).

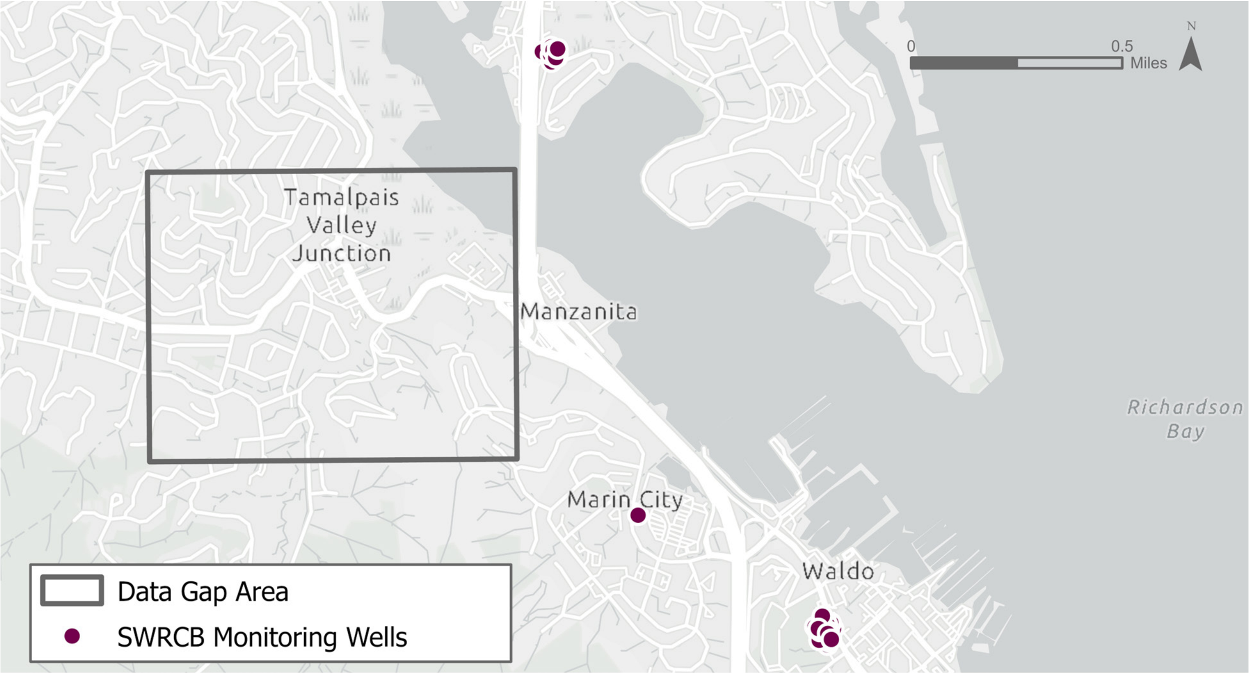


Figure 3-1. Example Data Gap Area in Marin County

3.2 Geotechnical Reports

Geotechnical reports were collected in areas with limited monitoring wells to better characterize the existing groundwater table (Figure 3-2). The soil boring logs include information on soil characteristics and the depth to water at the time the soil boring was extracted from the ground. Soil borings collected in late winter and early spring, between 2000 and 2020, were preferred to support the assessment of the highest annual groundwater table that could occur in response to precipitation.

In total, the cities and counties provided 46 geotechnical reports for review. The reports provided over 180 additional boring log locations across the four counties, of which 91 boring log records were used to fill the data gaps. Each location was hand digitized in a GIS record, along with its original data source, date of collection or sampling, depth to water, relevant soil characteristics, and other notes of interest from each respective report and soil boring log.

Additional geotechnical information from California Department of Water Resources (DWR) Well Completion Reports and California Department of Transportation (Caltrans) boring logs was collected to support the analysis. These data sets were recommended by regional stakeholders. Over 1,800 DWR sites were identified in the study area, providing boring logs for 290 locations across the four counties. Boring logs at about 40 Caltrans sites were collected; however, these boring logs did not inform the effort. Most of the boring logs collected by DWR, and all the boring logs collected by Caltrans, were collected long before the year 2000, and in some areas, significant grade changes and development had occurred between the time the soil borings were collected and the more recent period of interest. However, these datasets may provide value in the future relative to better understanding subsurface soil characteristics.

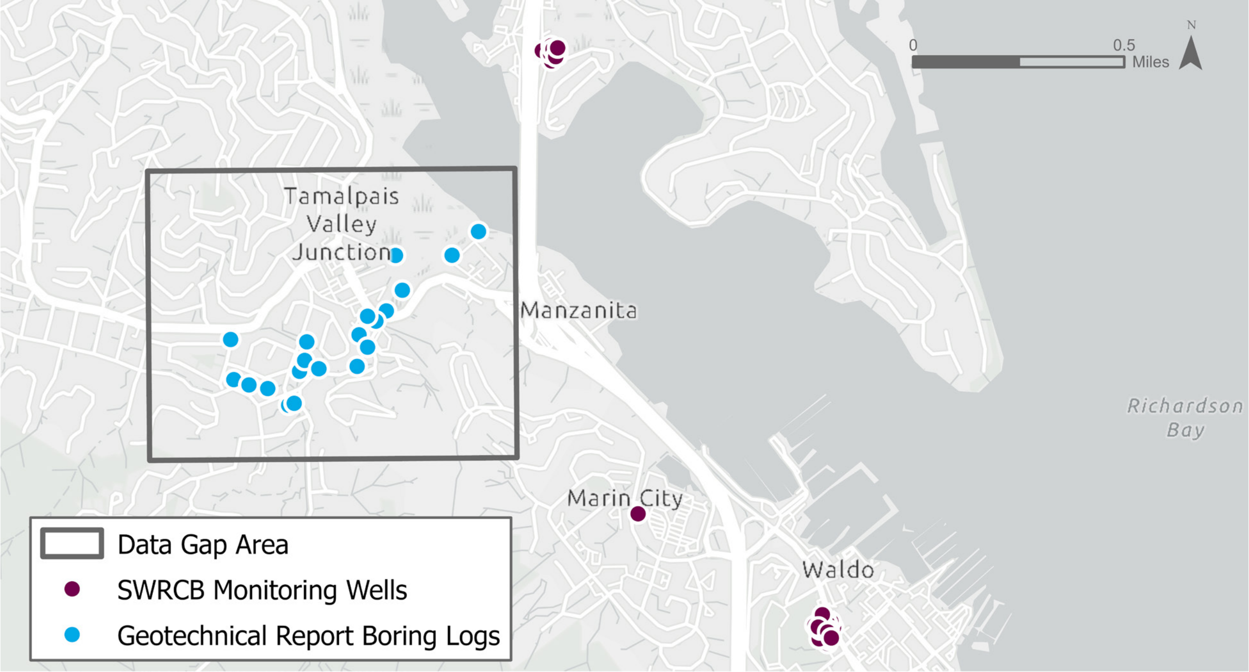


Figure 3-2. Example Filled Data Gap Area in Marin County

3.3 San Francisco Bay Tidal Datums

As in Plane et al. (2019), the shallow groundwater surface was connected to the Bay using the tidal water elevations from the San Francisco Bay Extreme Tide and Tidal Datum Study prepared by the Federal Emergency Management Agency (FEMA) (May et al., 2016). The FEMA study provides tidal datum information at over 900 points along the complex Bay shoreline. In areas with limited monitoring well information near the shoreline, this data helped approximate the natural slope of the shallow groundwater surface towards the Bay. The tides within the Bay rise and fall twice per day in a semi-diurnal cycle, and a Bay water level elevation approximately one foot above mean tide level was selected because fresh groundwater is usually found just above the mean tide line inland of coastal embayments (Moss, 2016). In the far South Bay, many of the FEMA points did not include an estimate of the mean tide level, because the points were located on vast mudflats that are exposed at mean tide. For these points, an elevation of two feet below mean high water was selected to inform the assessment.

3.4 Tributaries and Lagoons

Befus et al (2020) highlighted the importance of the connection between groundwater and the Bay's large and small tributaries and drainage systems. Groundwater generally flows from the upper watersheds toward the Bay, and groundwater also flows toward the tributaries (Fronzi et al., 2022). There are also local deviations driven by pumping, soil and subsurface geology heterogeneity, infiltration into sewers, etc. The tributaries are an important drainage mechanism for lowering the groundwater table. To approximate this drainage mechanism, stream layers from the Bay Area Aquatic Resource Inventory (BAARI) were used to supplement the data set (Figure 3-3). BAARI is a detailed base map of the Bay Area's aquatic features (SFEI, 2017).

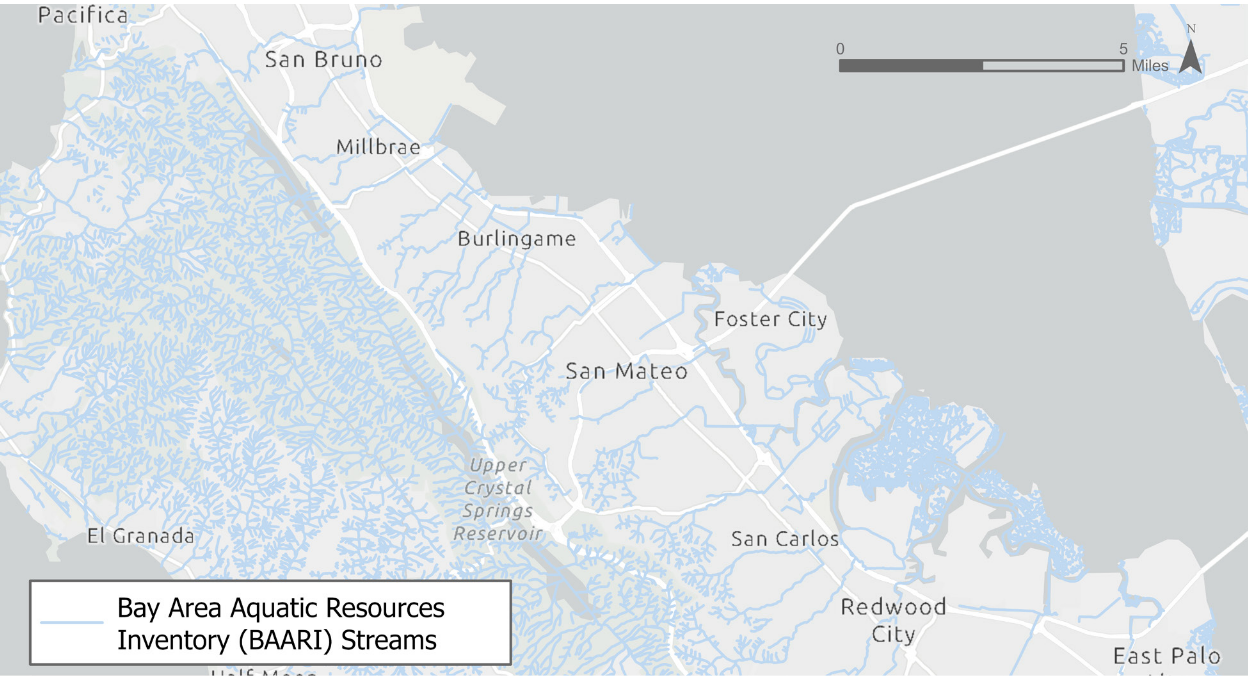


Figure 3-3. Example Bay Area Aquatic Resource Inventory Streams, San Mateo County.

In the downstream (i.e., tidally influenced) portions of the tributaries, the water levels were correlated with the San Francisco Bay Tidal Datums. Upstream of the tidal influence, the water levels were set to about one foot above the stream bed elevation to approximate the flow of groundwater seeping into the channel and flowing downstream. During extreme precipitation events, the water level in the tributaries may run bank full (i.e., carrying the maximum possible flows without overflowing the banks and flooding adjacent areas). However, the flow of groundwater through the soil towards the tributaries and towards the Bay is significantly slower than the flows within the tributaries that discharge into the Bay. Depending on the soil characteristics and subsurface geology, groundwater flow rates can vary from inches per year to hundreds of feet per year. The highest annual groundwater table in low-lying coastal areas occurs after the winter rainy season; therefore, the high streamflows associated with the precipitation events will have subsided. A review of aerial imagery revealed that most Bay tributaries have little to no stream flow in the absence of relatively recent precipitation, and generally only the areas that are tidally influenced remain wet year-round.

Alameda, Marin, and San Mateo Counties also have managed water bodies, such as lagoons, where the level of the lagoon is managed with pump stations and tide gates, such as those found in the cities of Alameda, Berkeley, Marin City, Foster City, Redwood City, and Belvedere. The water levels in the lagoons are generally drawn down in advance of an extreme precipitation event, or managed at a winter operation level, to provide stormwater storage capacity for the surrounding community and reduce the risk of stormwater flooding. Winter water levels in managed ponds at Eden Landing Ecological Reserve were also included. The managed water level elevations in ponds and lagoons were derived from personal communications and FEMA Flood Insurance Rate Maps (Appendix A – D).

3.5 Existing Conditions

Using a multi-quadratic radial basis interpolation technique in ArcGIS, the data sets described above were transformed into an approximation of the highest annual groundwater table using optimized parameters reported in Plane et al. (2019). The initial interpolations were completed by splitting each county into multiple subsections to enhance the iterative review process. The groundwater surface was reviewed for irregularities and inconsistencies due to potential data errors, and areas of emergent groundwater were compared with known wetland areas and areas of open water using visual inspections and comparisons with aerial imagery.

Areas with emergent groundwater in developed areas were flagged for review with each respective county. In most instances, city and county staff validated the presence of emergent groundwater during wet years, known urban stormwater flood issues, or areas where groundwater pumping is actively used to depress the groundwater table, such as in a roadway underpass. City and county staff provided photos, reports, and anecdotal evidence to support the validation. In select areas, city and county staff identified additional data sources, such as older geotechnical reports (pre-2000) to help improve the groundwater interpolation if evidence of emergent groundwater or a very high groundwater table could not be substantiated.

The final existing conditions interpolations were run on a full county basis, with sufficient overlap into the adjacent counties to avoid interpolation errors across jurisdictional boundaries. The groundwater mapping completed for the City of Alameda in 2020 used the same methods, with a high density of boring logs that informed the mapping both within the City of Alameda and the Oakland International Airport (May et al., 2020). The completed 2020 mapping for the City of Alameda was therefore integrated into the completed groundwater surface for Alameda County (Appendix A).

3.6 Future Conditions

Sea-level rise causes landward migration of saline groundwater, otherwise known as saltwater intrusion (Chesnaux, 2016; Werner & Simmons, 2009). This saltwater intrusion causes the overlying fresher groundwater to rise (Chang et al., 2011). Therefore, sea-level rise causes an increase in the height of the shallow groundwater table, or a decrease in the measured or modeled depth to water (Nuttle and Portnoy 1992, Masterson and Garabedian 2007, Chang et al. 2011, Rotzoll and Fletcher 2013, Wehner 2013, Chesnaux 2016, Befus et al. 2017).

The response of the shallow groundwater table to sea-level rise can vary based on the geology and topography of the area and the number of tributaries and drainage canals that help convey stormwater runoff in the watershed towards the Bay. The groundwater flows in multiple directions, both towards the tributaries and drainage canals and towards the Bay. In areas with more uniform topography and soils and few tributaries and drainage channels, the primary groundwater flow direction is towards the Bay. With more heterogeneous soil conditions, flow directions are more variable.

In areas with tributaries and drainage canals that can aid the conveyance of stormwater runoff towards the Bay, the relationship between sea-level rise and water table rise is unlikely to be exactly uniform, especially near the tributaries and drainage canals (Befus et al., 2020; Masterson & Garabedian, 2007; Nuttle & Portnoy, 1992). As the groundwater table rises, the rate of groundwater flow toward tributaries and drainage canals may increase, and the groundwater discharged into these streams and tributaries can be conveyed more swiftly towards the Bay. This mechanism can help mitigate (i.e., reduce) the rise in the groundwater table in response to sea-level rise. Drainage canals that are lined with concrete are less effective at mitigating the rise in the groundwater table, as the concrete reduces the ability of groundwater flows to discharge into the canal.

During the wet season when tributaries and drainage canals are actively conveying stormwater runoff towards the Bay, the discharge of groundwater into the tributaries may be minimal. For groundwater to discharge into a tributary, the adjacent water table must be higher than the water surface in the tributary. However, as the wet seasons ends and the water level in the tributaries and drainage canals falls below the groundwater table elevation, the flow of groundwater into the tributaries and drainage canals will slowly decrease the groundwater table elevation.

The rate of rise in the groundwater surface is also affected by many other factors, including tidal range, salinity, aquifer geology, soil characteristics, coastline change, shore slope, and surface permeability (Chesnaux, 2016; Hoover et al., 2017; Rotzoll & Fletcher, 2013). For the purposes of this study, and as a reasonable approximation in regard to flooding, a one-to-one correlation between sea-level rise and groundwater table rise is assumed within the study area (Nuttle & Portnoy, 1992). This approximation is most applicable in the zone where sea level and tidal fluctuations have an influence on the shallow groundwater aquifer; therefore, this study focuses on the nearshore areas where the saline groundwater wedge delineated by Befus et al (2020) could elevate the fresher shallow groundwater. Befus et al (2020) used groundwater salinity observations between 1968 to 2015 to inform groundwater modeling that estimated the potential change in the saline wedge with sea-level rise. The inland extent of the future condition mapping was approximately defined by the linear response saline wedge produced by Befus et al (2020) with five meters of sea-level rise, soil hydraulic conductivity (the ability of saturated soil to convey water) of 10.0 meters per day, and a Bay water level condition set at mean higher high water. In areas of Marin and San Mateo Counties the inland mapping extent was adjusted to exclude areas where the steep topography would cause extreme grade changes in the interpolation, or the data (digital elevation model or point data) was limited.

3.7 Caveats

Groundwater flow is complex, and the approaches used in this assessment are considered approximate but reasonable for planning level of estimates of infrastructure impacts and flooding. The approach used is not sufficient for assessing contaminant plume migration or potential contaminant mobilization, as this would require further examination of groundwater flow paths. Flow dynamics vary with soil characteristics such as soil porosity (soil volume relative to pore space, meaning how much space there is between the soil particles for water to flow through) and hydraulic conductivity (the ease with which water can move through saturated soil). Flow dynamics can also be driven by connections to surface water bodies, tributaries, marshes, and the Bay. Although the model uses best available information and data sources, it relies on a set of assumptions, and the mapping is therefore accompanied by a set of caveats. To account for these caveats, a more sophisticated hydrogeological modeling effort accompanied by additional monitoring and soil characterization is required. The cost and data requirements to develop and calibrate such a model would both be high, and this more sophisticated modeling effort may not necessarily provide more accurate results (Habel et al., 2019).

- The existing condition mapping uses the highest measured groundwater elevations at each SWRCB well and interpolates between them to create a map approximating the highest measured groundwater table. However, the measurements used at each well are not necessarily from the same date and do not reflect the highest measured surface at any one time period. Although measurements are recorded during late winter / early spring when the highest groundwater surface is expected to occur in response to winter precipitation, it cannot be assured that the highest groundwater surface elevation was captured. A more detailed monitoring effort would be required, such as recording hourly depth to water measurements over an entire season across multiple wells, during a very wet year.
- Some shallow groundwater in the study area may be under some degree of confining pressure due to the local subsurface geology (e.g., overlying fine-grained soils). This confining pressure may result in measurement of a potentiometric surface rather than the water table, which could contribute to inaccuracies in the mapped depiction of the shallow, unconfined groundwater surface.

- Precipitation is often the primary driver of seasonal fluctuations in groundwater table elevation (Figure 2-1). However, near the Bay shoreline, the rise and fall of the Bay tides can affect the elevation of the groundwater table on a daily (tidal) and monthly (spring-neap) cycle. The fluctuations in the groundwater table are generally muted compared to the tidal variations (i.e., the tidal range in the Bay can exceed six to eight feet from mean lower low water to mean higher high water, and this range may translate to fluctuations in the groundwater table of less than one foot depending on the soil characteristics and distance from the Bay). A more detailed monitoring effort would be required to capture the influence of the Bay tides on the elevation of the groundwater table, such as recording sub-hourly depth to water measurements for a minimum of 14 days, and preferably a minimum of 28 days to evaluate spring-neap tidal variations. Long-term groundwater table elevations are dominated by sea-level rise, climate change effects on recharge, and human interventions such as groundwater pumping, placing streamflows in underground pipes and culverts, and the use of concrete-lined drainage channels.

- The methodology is empirical and GIS-based and does not consider the complex physics of groundwater flow, nor does it consider the considerable heterogeneity in soil conditions that could result in a higher, or lower, groundwater surface in between monitoring well or geotechnical soil boring log observations. Detailed local studies are needed to determine risks of contaminant mobility.

- The depth to water measurements from the geotechnical soil borings are approximate. Depending on the soil boring collection method and the geotechnical contractor, the notation of the depth to water location for the soil boring may vary. If the geotechnical reports included information or a citation relative to a higher annual groundwater surface (i.e., a smaller depth to water) that differs from the boring log estimate(s), the higher annual groundwater surface elevation was used in place of the boring log. In general, the depth to water locations reviewed for this study were reasonable when compared with the SWRCB monitoring well measurements.

- This assessment does not consider the influence of future green stormwater infrastructure that may be installed by Bay Area communities. Green stormwater infrastructure can be designed to either increase precipitation infiltration into the soil or retain runoff in the upper watershed during storm events to reduce or mitigate the potential for downstream flooding.

- This assessment does not consider localized groundwater pumping for basement drainage, or the temporary construction-related dewatering which occurs where the groundwater is shallow. Larger-scale pumping efforts (e.g., to manage contaminant plumes or flooding) may be reflected in the mapping where measured groundwater levels in nearby wells are lowered by pumping.

- The assessment does not consider potential increases in future extreme precipitation that are likely to occur as the climate changes. Bay Area precipitation is likely to remain extremely variable, with periods of prolonged droughts and periods with extreme wet winters. Future condition atmospheric river events coupled with extratropical cyclones, which generally bring the bulk of California's rainfall, are likely to become more extreme (Lamjiri et al., 2018; Patricola et al., 2022; Polade et al., 2017; Ralph et al., 2012; Z. Zhang et al., 2019), and would therefore result in a higher wet season groundwater table elevation than projected in this assessment.

During the December 2017 king tides, emergent groundwater along Interstate 880 near the Coliseum Swap Meet in Oakland.
Photo Credit: Kristina Hill

4. Planning Guidance

Several data layers were developed to support communities as they consider existing and future groundwater table elevations in their sea-level rise vulnerability and risk assessments and climate adaptation planning. This section provides initial guidance on how the different layers could be used, although there are undoubtedly additional applications for the data layers as well. These data sets are not intended to inform detailed design, and they are not a substitute for site-specific investigations. When using these data sets, please refer to the caveats presented in Section 3.6.

See Section 4.6 for information about data access, including web maps and GIS data downloads.

4.1 High Groundwater (within Six Feet of the Ground Surface)

For existing conditions, and each future sea-level rise scenario, GIS-based polygons are available that depict the areas within each county that have a high groundwater table in response to precipitation events. A high groundwater table can occur in response to an extreme precipitation event, or multiple smaller, but consecutive, precipitation events. For this assessment, a high groundwater table is defined as being within six feet of the ground surface. This threshold was selected because most (but not all) underground infrastructure is built within 6 feet of the ground surface (Bobylev et al., 2012; PG&E, 2022), including most essential utilities and residential basements (conversations with representatives from local Bay Area agencies have confirmed this approximate depth threshold). However, the location and depth of underground utilities is generally not well known and/or documented, creating uncertainties for local communities (ASCE, 2022a, 2022b). Roadway subgrades are also located within a few feet of the ground surface, and coastal areas with a depth to groundwater of 5 feet or less are at risk of premature failure (Caltrans, 2020; Knott et al., 2018).

Under existing conditions, any infrastructure that is in an area of high groundwater may have been designed to accommodate a high groundwater table, although older infrastructure may not be consistent with modern design standards. Most likely, this infrastructure has interacted with the highest annual groundwater table at least once between the years 2000 and 2020. However, infrastructure outside this area may not be designed to accommodate a high groundwater table. The future high groundwater polygons can help a community understand how much sea-level rise would place underground infrastructure at risk of damage due to a groundwater table that exceeds design conditions.

These assumptions are gross planning-level assumptions, and do not consider the actual depth below ground where the infrastructure is located, the infrastructure's design groundwater table elevation, or the type, age, or condition of the infrastructure.

4.2 Emergent Groundwater (above the Ground Surface)

For existing conditions, and each future sea-level rise scenario, GIS-based polygons are available that depict areas in each county that may experience intermittent emergent groundwater, particularly after the winter rainy season.

As noted in Section 2.4, existing wetlands and open water areas were referenced to validate areas of emergent groundwater under the existing conditions scenario. Other areas with emergent groundwater, such as along roadways and in developed areas, were discussed with city and county staff. In most instances, the areas of emergent groundwater occurred in areas of known urban stormwater flooding. In some instances, the areas of emergent groundwater were located in roadway underpasses or other depressed areas, and city and county staff confirmed the presence of groundwater pump stations that operate seasonally or year-round to depress the groundwater table and reduce the likelihood of flooding.

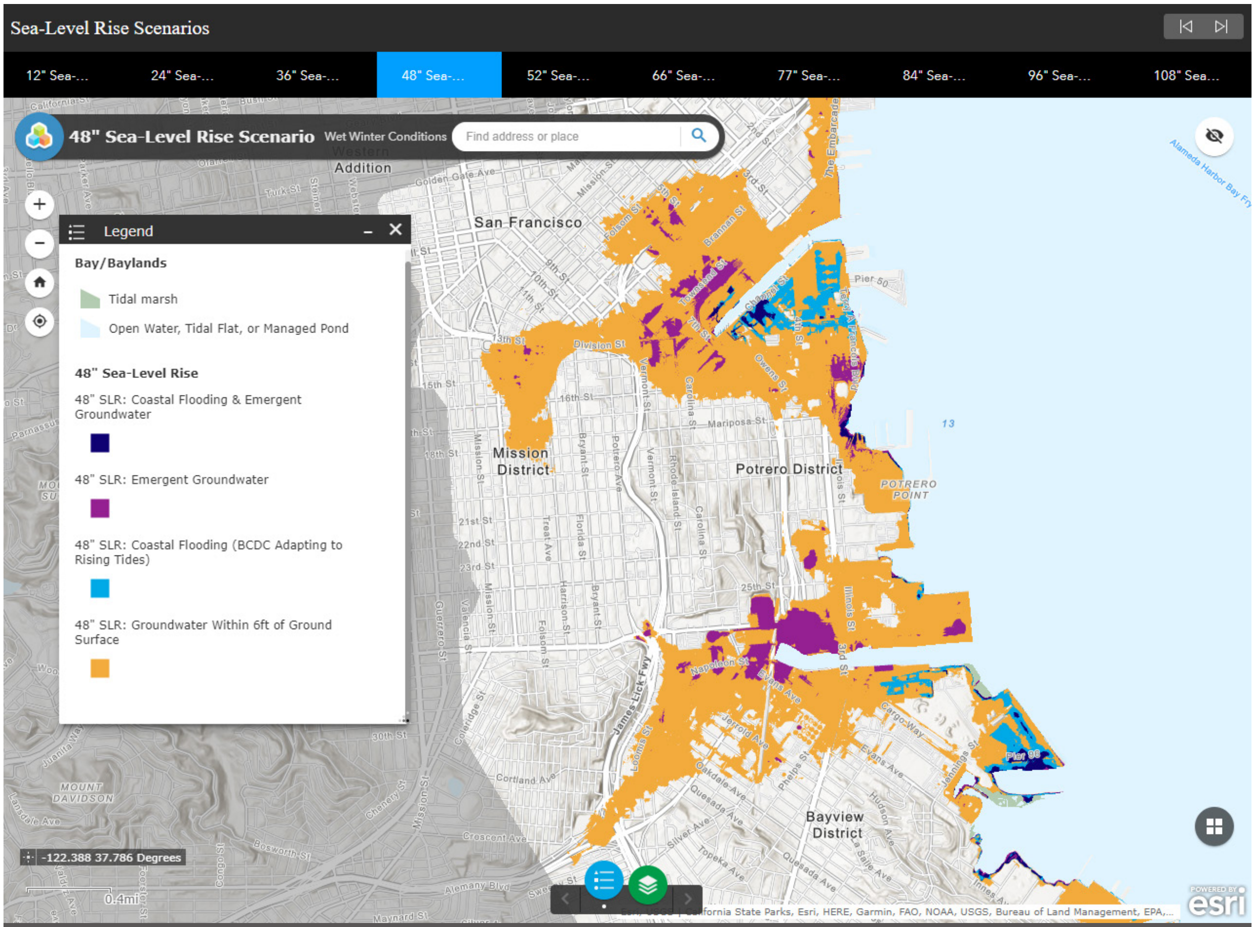
Although underground and subgrade impacts are likely to occur before the groundwater table emerges above ground (Section 2), the progression of increasing emergent groundwater, paired with sea-level rise inundation, provides a powerful visual to communicate the scale of the potential flooding challenge. The layers provided indicate only extent of emergent groundwater and do not describe water depth or how the emergent groundwater may flow along roadways, enter storm sewer infrastructure, or flow towards tributaries, drainage canals, or other surface water bodies.

4.3 Overlay Analysis

Sea-level rise inundation occurs when coastal waters (e.g., Bay water levels) overtop the shoreline and flood inland areas, whereas groundwater flooding occurs when the groundwater table emerges above the surface. To compare the extent of sea-level rise inundation with emergent groundwater flooding for each sea-level rise scenario, the ART sea-level rise inundation maps were overlaid with the corresponding flood extents from emergent groundwater flooding. For most communities, emergent groundwater flooding occurs further inland. Areas with emergent groundwater can extend three to four times farther inland than direct sea-level rise inundation, exposing additional properties and communities at risk to sea-level rise related flooding (Knott et al., 2018). The results of the overlay analysis are available in an online web viewer (Section 4.6).

Flooding from emergent groundwater and direct sea-level rise inundation will manifest in different ways. At first, emergent groundwater will occur seasonally during (or after) winters with high precipitation. Though it is beyond the scope of this study to identify, it is important to note that even a few inches of groundwater rise can affect contaminants in soil and cause corrosion of underground pipes and foundations. As sea levels rise higher, emergent groundwater may become a year-round issue in some places if adaptation strategies are not implemented. Coastal flooding will occur first during king tides and coastal storms that elevate Bay water levels, resulting in temporary flooding. As sea levels rise higher, inland areas could be inundated daily by high tides.

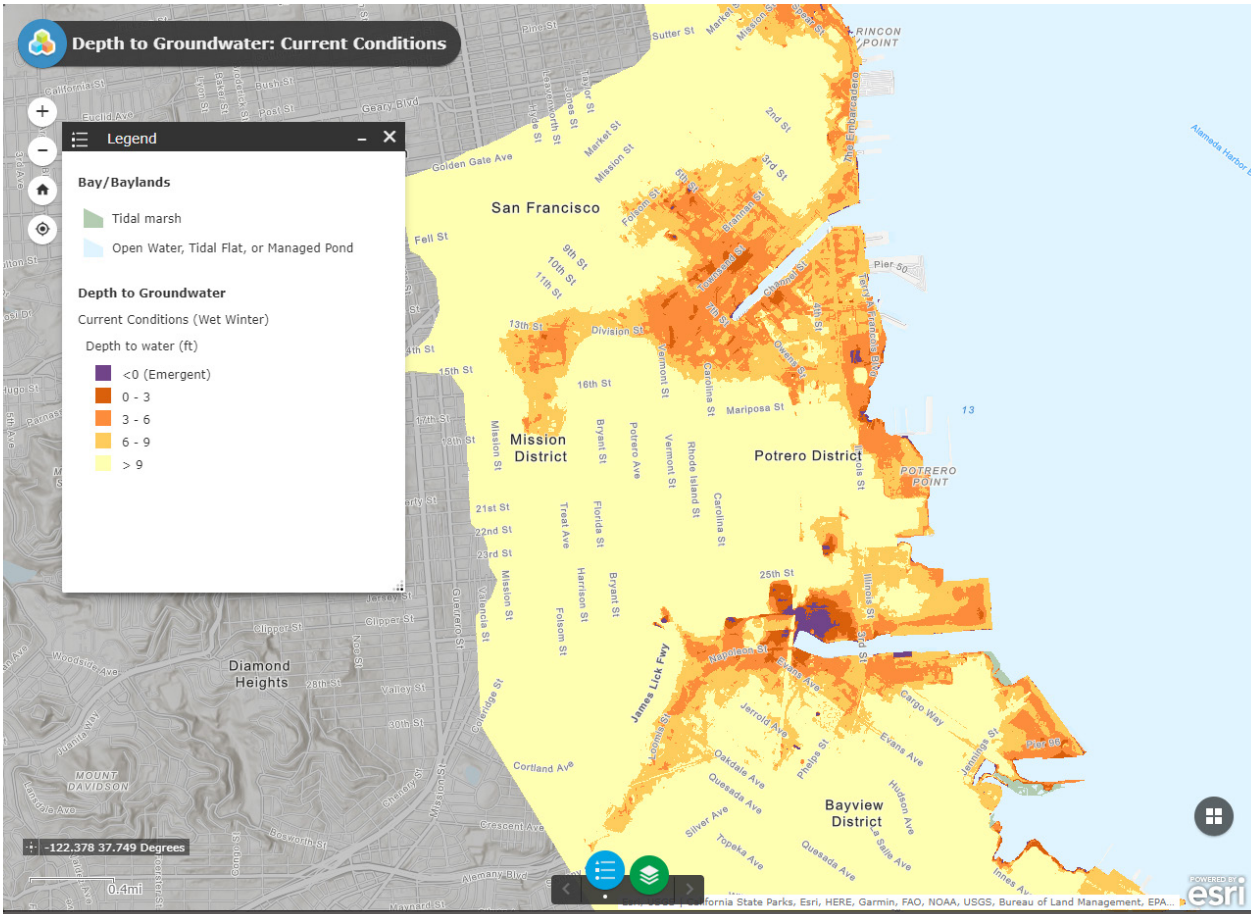
Developing effective adaptation strategies that address both types of sea-level rise driven flooding may require dynamic modeling. The inclusion of precipitation-driven flooding, such as urban stormwater and riverine flooding, should also be considered.



The overlay analysis comparing the extent of emergent groundwater to the extent of coastal flooding under various sea-level rise scenarios is available via web map (Section 4.6).

4.4 Depth to Groundwater Raster Files

For existing conditions, and each future condition scenario, raster files of the complete groundwater table for each county are available for download. The raster files are presented as depth-to-water (below the ground surface or "bgs") for consistency with common groundwater nomenclature. The raster files can be overlaid with other GIS data sets, such as utilities, roadways, open space, and contaminated lands to inform vulnerability and risk assessments, as in the assessment completed for the City of Palo Alto (AECOM and Pathways, 2022).



The existing conditions depth to groundwater raster is available to view via web map, along with a range of overlay options (Section 4.6).

4.5 Areas of Low Confidence or Not Assessed

In a few areas, inadequate information about current ground elevations meant that an accurate depth to groundwater map could not be prepared. Lack of up-to-date ground surface elevation data precluded our ability to accurately determine groundwater table elevations, despite having adequate depth-to-water information. This was the case in three locations: an area in the east side of South San Francisco at the Genentech Campus that was recently redeveloped and regraded, at the Kaiser Permanente facility in San Leandro, which was under construction when elevation data was collected, and at the Dumbarton Quarry in Newark, which has been steadily filled with available material since its closure in 2007 (EBRPD, 2021). There are likely additional areas where construction, regrading, and development projects have changed ground surface elevations since the elevation data used in the modeling were collected; however, these three areas are flagged as known issues. Data layers are included in the download package to highlight these areas of low confidence as well as another area of uncertainty at the Peacock Gap Golf Course in San Rafael, where there were insufficient depth-to-groundwater data available to use as model inputs. Data layers are also included in the download package to describe the areas in each county that are not covered by the mapping effort.

4.6 Web Maps and Data Download

Select data layers are available to view in online web maps. The current conditions web map[1] includes the existing conditions depth-to-water raster layer, and a future conditions map portfolio[2] includes the results of the sea-level rise overlay analysis (Section 4.3). Both web maps include a variety of additional layers relevant to planning for sea-level rise and groundwater rise adaptation. These overlay layers include jurisdictional boundaries, transportation infrastructure, special designations (SB 535 Disadvantaged Communities and Plan Bay Area 2050 Priority Development Areas), as well as historical and geological considerations relevant to liquefaction risk (historical baylands, artificial fill). The web maps will be available until December 2025. Pending additional funding, the data layers will be incorporated into the ART Bay Shoreline Flood Explorer.

Links to the web maps and the GIS data for download are available on the SFEI project page.[3] Downloadable geodatabases include all the layers described in this chapter:

- Polygon layers of groundwater within 6 feet of the ground surface for current conditions and under 10 future sea-level rise scenarios: 12”, 24”, 36”, 48”, 52”, 66”, 77”, 84”, 96”, 108”. These align with the scenarios used in BCDC’s mapping for the ART Bay Shoreline Flood Explorer (Section 4.1).
- Polygon layers of emergent groundwater for current conditions and under the same 10 future sea-level rise scenarios (Section 4.2)
- Raster layers of depth to groundwater for current conditions and under the same 10 future sea-level rise scenarios (Section 4.4).
- Polygon layer showing areas of low confidence (Section 4.5)
- Polygon layer showing inland areas in each county not mapped for this analysis (Section 4.5)

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1. Current conditions web map: sfei.maps.arcgis.com/apps/webappviewer/index.html?id=1f9f94366b3b491886f08acf080d01df

2. Future conditions map portfolio: sfei.maps.arcgis.com/apps/instant/portfolio/index.html?appid=2ab0c998497f4f7398aa54f176a6fb26

3. Shallow Groundwater Response to Sea-Level Rise:

2. sfei.org/projects/shallow-groundwater-response-sea-level-rise

5. Adaptation

As communities adapt to sea-level rise, adaptation plans must also consider rising groundwater tables (May et al., 2020). Most local governments in the Bay Area have not yet incorporated groundwater rise into their vulnerability assessments and adaptation plans, though participants in the workshop hosted as a part of this study indicated that they are planning to do so as better data become available. However, strategies that address coastal flooding, sea-level rise, and groundwater rise together are still in conceptual stages (Habel et al., 2020). A literature search of groundwater adaptation strategies returns numerous efforts focused on groundwater from a water supply perspective, where increasing pressures from climate change, land-use change, population growth, and salinity intrusion are impacting potable groundwater supplies (Aslam et al., 2022; Mourot et al., 2022; Walker et al., 2021).

Traditional levees and floodwalls designed to keep coastal floodwaters out may not provide protection from rising groundwater, leaving communities at risk of flooding from below. Cut-off walls, or vertical impermeable barriers, have been suggested as a strategy to physically separate the connection of the inland groundwater to the Bay. Cut-off walls are used in coastal environments to prevent groundwater flow into or out of contaminated sites (Daniel & Koerner, 1996) and to prevent saltwater intrusion into fresh groundwater aquifers used for water supplies (Abdoulhalik et al., 2022; Kaleris & Ziogas, 2013). Although the cutoff walls could prevent or minimize the rise of the groundwater table in response to sea-level rise, the walls could prevent or reduce the natural outmigration of groundwater flow to the Bay after precipitation events. This, in turn, could increase the groundwater table and result in maladaptation by increasing the inland flood risk, particularly after extreme precipitation events.

As effective shoreline flood risk reduction strategies are developed through research and innovation, there are still measures communities can take reduce their risk to rising groundwater tables. Foundations and other belowground structures that could be subject to corrosion, infiltration, and increased buoyancy should be monitored much more frequently to ensure building safety as groundwater rises. Design standards and building codes already exist for infrastructure, roadways, foundations, and structures constructed in areas with a high groundwater table. However, all new infrastructure and/or rehabilitation projects in at risk areas should design for a groundwater table that is *higher* than the highest annual groundwater table. How much higher may depend on local site conditions, the remaining functional lifespan of the infrastructure, the overall risk tolerance of the project, and any future insights yielded by more site-specific groundwater hydrogeologic models. Strategies exist today to extend the design life of new or replacement roadways in the face of a rising groundwater table with relatively simple structural modifications (Knott et al., 2018).

Inflow and infiltration are common problems in sewer systems, with continued advances in techniques to assess the volume of groundwater infiltration during both wet and dry weather (Enfinger & Stevens, 2020). Both homeowners and cities can take measures to reduce inflow and infiltration. Strategies to reduce inflow and infiltration can be costly, but they can reap significant rewards including reduced localized flooding and sewer overflows, improved operational efficiencies, and reduced maintenance costs (Bashir, 2019; Moisio & Caldwell, 2012). In areas with groundwater contaminated by volatile organic compounds, these strategies may reduce intrusion of volatile organic compounds into sewer lines, a known vapor intrusion pathway into residential homes and buildings (Beckley & McHugh, 2020; McHugh et al., 2017). Although reducing inflow and infiltration will not address all issues associated with rising groundwater and sewer systems, it can extend the functional lifespan of the infrastructure, reducing flooding, and protect public health and the environment.

Additional strategies may include a networked groundwater pumping system to reduce the groundwater surface, raising structures, filling low-lying areas, and managed retreat. Stormwater management systems, including green infrastructure solutions, may be reimagined to create more space for water, including stormwater and emergent groundwater, in the urban landscape. Existing green infrastructure planning tools (e.g., SFEI's Green Plan-IT toolkit[1]) have not yet considered groundwater rise as a factor in the siting and design process. Green infrastructure in the upper watershed may be more effective in mitigating the rising groundwater table than strategies implemented in low-lying areas where the groundwater table is high (Nakamura, 2022; Shifflett et al., 2019).

Bolder strategies, such as creating floating neighborhoods that can adapt to rising sea level and fluctuating conditions while providing wildlife habitat and ecosystem services can also be explored (All Bay Collective, 2018; Gemeente Rotterdam et al., 2007; Hill & Henderson, 2022). Transformative adaptation that pairs updated land use, policies, building codes, infrastructure investments, better monitoring systems, nature-based solutions, and managed retreat through inclusive, transparent sustained engagement with impacted communities may have the greatest chance of a successful outcome (Fuentes, 2020; Guerry et al., 2022; Kuhl et al., 2021; Zhao & Liu, 2020).

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1. Green Plan-IT Toolkit: greenplanit.sfei.org/

6. Next Steps

The completion of this effort provides a wealth of groundwater information for Alameda, Marin, San Francisco, and San Mateo Counties that can inform climate resilience and adaptation efforts. However, additional work is needed to complete the mapping in Contra Costa, Napa, Santa Clara, Solano, and Sonoma Counties. Pathways and SFEI are actively collaborating with regional agencies to identify funding to complete the mapping for the remaining counties; conduct additional studies that advance the science of sea-level rise, tidal, and groundwater interactions; enhance and promote regional adaptation; and support further communication regarding the potential risks associated with rising groundwater.

6.1 Efforts Identified But Not Funded

The study team maintains an updated list of efforts that have been identified as needs across the region, but that have not yet been funded.

- Existing and future condition groundwater mapping in the remaining five Bay Area counties: Contra Costa, Napa, Santa Clara, Solano, and Sonoma.
- Incorporating groundwater mapping into the ART Shoreline Flood Explorer (all nine counties).
- Analysis of known contaminated sites within the study area under the regulatory authority of the Regional Water Quality Control Board and/or the California Environmental Protection Agency Department of Toxic Substances Control (all nine counties)
- Analysis of the potential for rising groundwater to mobilize contaminants (all nine counties).
- Outreach and messaging to support communities at highest risk of impacts related to rising groundwater, including vulnerable communities already facing other environmental and climate impacts (all nine counties).

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2. Appendix A: Alameda County

Alameda County is a large county with a long and highly urbanized shoreline fronting wetlands, managed ponds, and open water. Figure A-1 shows the completed depth to groundwater mapping for Alameda County.

The City of Alameda (not to be confused with Alameda County) performed a study in 2019 that looked at the response of the shallow groundwater layer and contaminants to sea level rise (May et al., 2020).[1] This study was the precursor to the present effort (California Resilience Challenge-funded study covering four Bay Area counties). The City of Alameda study included extensive ground truthing sessions with many City departments. The GIS layers created for Alameda Island and Bay Farm Island as part of the 2019 City of Alameda effort were integrated with new mapping created for the California Resilience Challenge project to create complete countywide layers.

Data sources used to fill gaps in the SWRCB dataset included well completion reports from the state Department of Water Resources,[2] geotechnical reports provided by the cities of Emeryville and Oakland, and winter water levels in managed ponds at the Eden Landing Ecological Reserve (J. Krause, personal communication with Ellen Plane, May 2, 2022).

A ground truthing session was held on August 23, 2022 to review the initial depth to groundwater maps produced as part of the California Resilience Challenge effort with representatives familiar with groundwater and flooding in Alameda County. The ground truthing session was attended by representatives of Alameda County Water District, the City of Oakland, the City of Albany, the City of Berkeley and the City of Alameda. To get feedback on specific areas identified for further review, we also followed up with representatives from the Port of Oakland and the City of San Leandro. This ground truthing session covered several areas identified for further review; these areas were often places where emergent groundwater was mapped under existing conditions, and local input was needed to assess the validity of these results. Review areas included the highway underpass at 1-880, which was confirmed to be an area where emergent groundwater is an issue and is managed by pumping. Other review areas were identified as areas with low confidence. In these areas, local partners confirmed that there were construction projects with grade changes that occurred after the LiDar used to create the digital elevation model used as an input to the groundwater mapping was flown (in 2010). The Kaiser Permanente San Leandro Medical Center and the Dumbarton Quarry are thus identified as areas of low confidence in the groundwater mapping.

The cities of Emeryville and Oakland provided the following geotechnical reports, which contained information used in the interpolation:

City of Emeryville. (2019). *South Bayfront Pedestrian Bicycle Bridge - Log of Test Borings* (p. 9). City of Emeryville.

City of Oakland. (2001). *Oakland Army Base Utility Study Geotechnical Review*.

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[2] California Department of Water Resources. 2021. "Well Completion Reports, Alameda County." 2021. https://cadwr.app.box.com/v/WellCompletionReports/folder/77325813284.

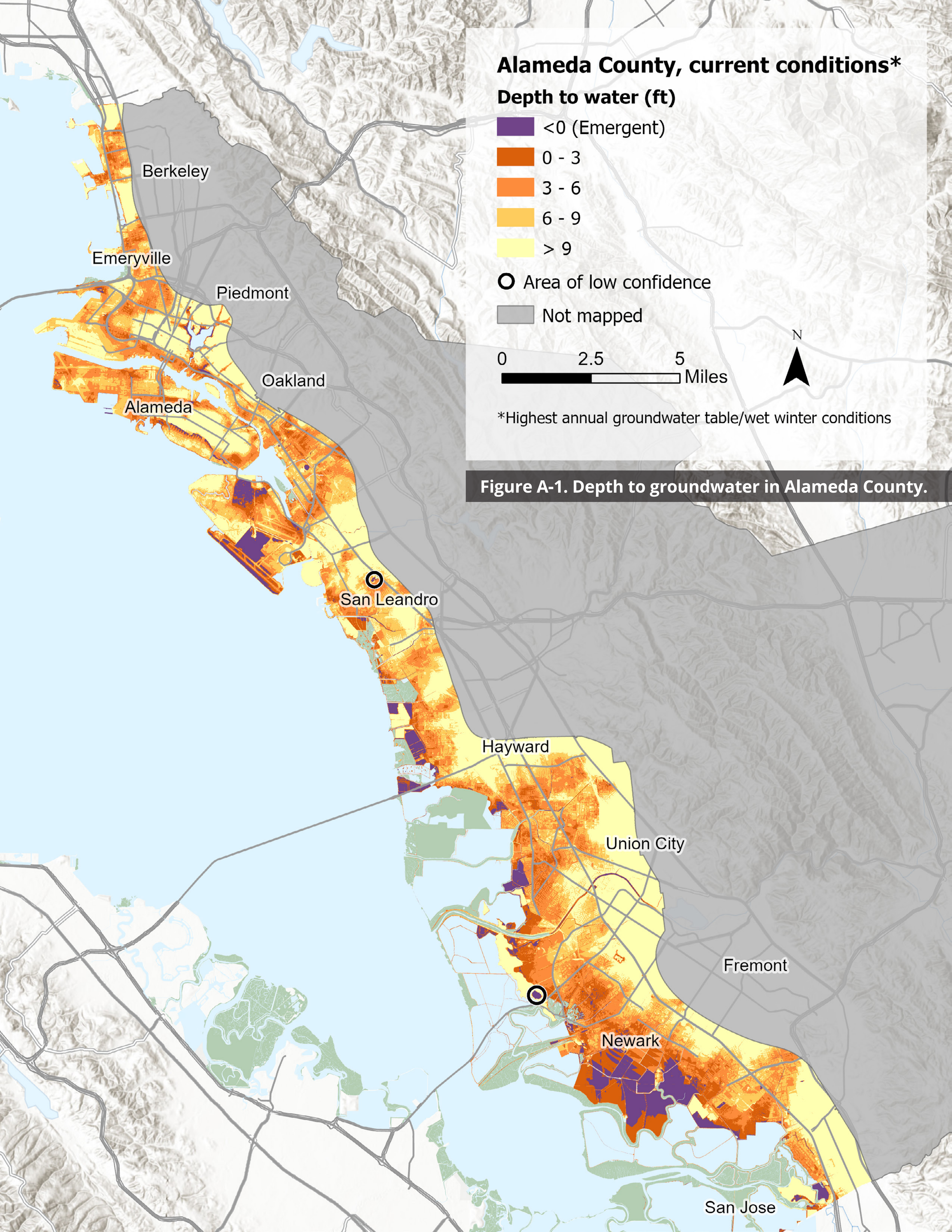

Figure A-1. Depth to groundwater in Alameda County.

2. Appendix B: Marin County

The County of Marin has steep headlands and valleys, low-lying urban areas built on fill over historical baylands, and complex drainage networks. Due to steep topography the inland extent of the shallow groundwater saline wedge used as the geographic extent for the groundwater mapping is often less than two kilometers from the shoreline. Figure B-1 shows the completed depth to groundwater mapping for Marin County.

Data sources used to fill gaps in the SWRCB dataset included well completion reports from the state Department of Water Resources,[1] geotechnical reports from a Caltrans database[2], geotechnical reports provided by the cities of Corte Madera, San Rafael, Mill Valley, and Marin County and winter water levels in lagoons accessed through FEMA Firm Mapping.

A ground truthing session was held on June 2, 2022, to review the initial depth to groundwater maps with representatives familiar with groundwater and flooding in Marin County. Representatives from Marin County and the City of San Rafael attended. Areas identified for further review were largely areas where there were few well points available to use as inputs to the interpolation. For example, the Peacock Gap golf course was an area without any well data that was mapped as having very shallow groundwater. Attendees were not aware of any known flooding issues at the golf course, so it was identified as an area of low confidence in the mapping.

The cities of Corte Madera, San Rafael, and Mill Valley and Marin County provided the following geotechnical reports with information used in the interpolation:

A-N West Inc. 2012. “Geotechnical Investigation Harbor Drive Pump Station.” Corte Madera, CA.

LCA Architects. 2019. “Fire Station 55 Upgrade Geotechnical Engineering Report.” San Rafael, CA.

Marin County Flood Control. 2006. “Geotechnical Investigation Report Crest-Marin Creek Box Culvert.” Mill Valley, CA.

Marin County Flood Control and Water Conservation District. 2013. “Santa Venetia Geotechnical Data Report.” San Rafael, CA.

Marin County Flood Control and Water Conservation District. 2015. “Coyote Creek Levee Evaluation Project Geotechnical Data Report.”

Marin County Flood Control and Water Conservation District. 2020. “Geotechnical Data Report Novato Creek Levee Evaluation.” Novato, CA.

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[1] California Department of Water Resources. 2021. “Well Completion Reports, Marin County.” 2021. https://cadwr.app.box.com/v/WellCompletionReports/folder/77325813284.

[2] Caltrans. 2021. “GeoDOG - Digital Archive of Geotechnical Data - Marin County.” 2021. https://geodog.dot.ca.gov/.

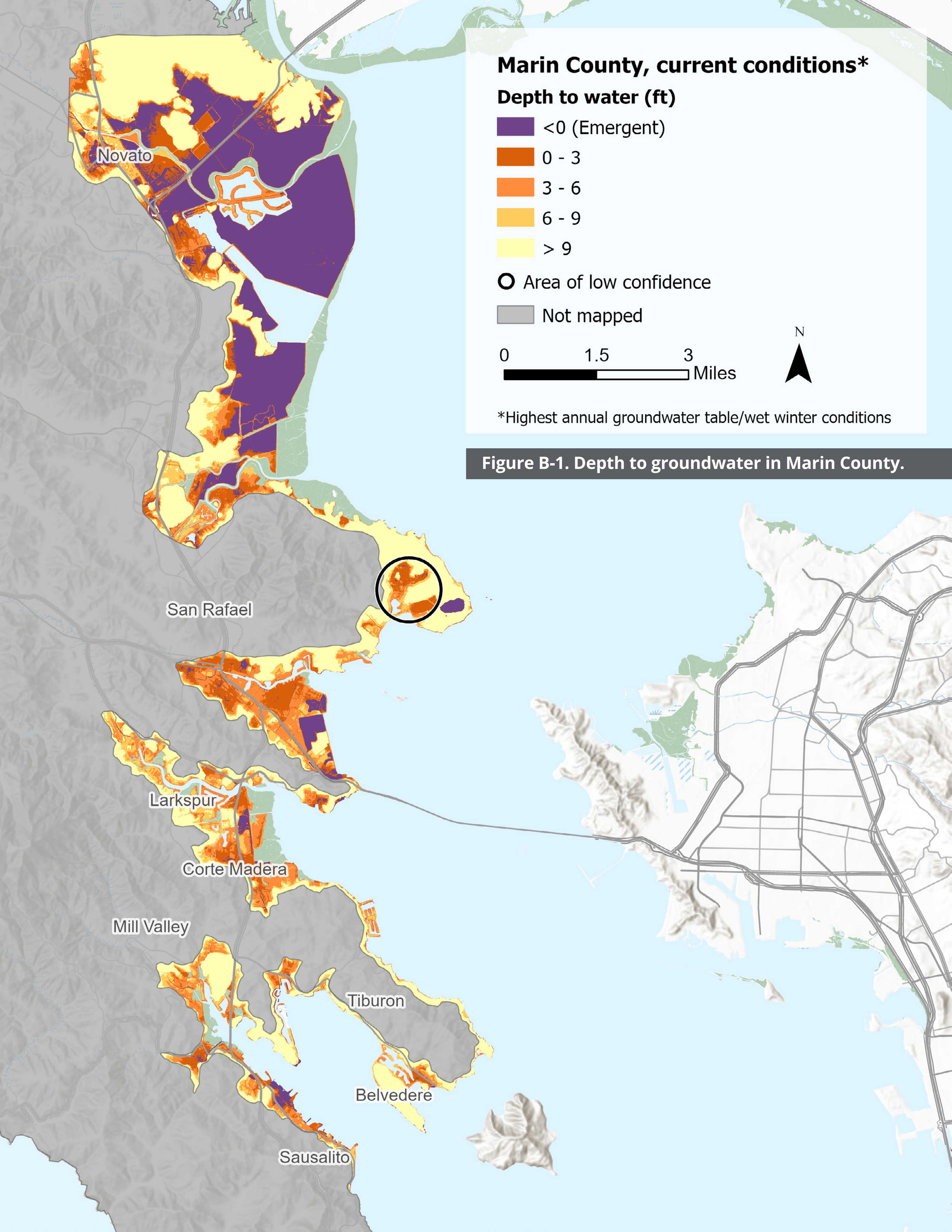

Figure B-1. Depth to groundwater in Marin County.

2. Appendix C: San Francisco County

The San Francisco shoreline has been heavily modified over the past two centuries, with former tidal wetlands filled to create the heavily urbanized areas that exist today. Mission Creek and Islais Creek are examples of former wetlands that are now home to office parks and industrial uses Figure C-1 shows the completed depth to groundwater mapping for San Francisco County.

The Port of San Francisco (Port) updated the County digital elevation model in 2021 from Vandever et al. 2017 to better refine the areas along the Embarcadero and Mission Creek, areas with active development and grade changes. This file was created for the Embarcadero Seawall Program, a component of the Port of San Francisco Waterfront Resilience Program.

Data sources used to fill gaps in the SWRCB dataset included well completion reports from the state Department of Water Resources[3], geotechnical reports provided by the Port of San Francisco, San Francisco Planning, The San Francisco Bay Conservation and Development Commission, and the Office of Resilience and Capital Planning.

A ground truthing session was held on December 16, 2021, to review the initial depth to groundwater maps with representatives familiar with groundwater and flooding in San Francisco. The ground-truthing session was attended by representatives from the San Francisco Public Utilities Commission, the Port of San Francisco, and the Office of Resilience and Capital Planning. The areas reviewed were along the Embarcadero and Mission Creek and were areas with significant recent development. Local representatives confirmed that there were known grade changes in these areas since the collection of the data used to create the digital elevation model used for the mapping. They also confirmed that these were not known areas of flooding or pumping. Mapping in the review areas was based primarily on boring logs from geotechnical reports, and it was determined that water levels had likely not reached equilibrium in the borings. Therefore, these data points were set in favor of the SWRCB data points, which were more in line with the expected depth to water in the review areas based on the expert opinion of the local representatives.

The City and County of San Francisco provided the following geotechnical reports with information used in the interpolation:

City and County of San Francisco Department of Public Works. 2010. Geotechnical Report Addendum San Francisco Public Safety Building. San Francisco, CA

Port of San Francisco. 2018. Geotechnical Data Report Geotechnical Site Investigation Seawall Earthquake Safety Program. San Francisco, CA

San Francisco Public Utilities Commission. 2020. Geotechnical Data Report Southeast Bay Outfall Islais Creek Crossing Replacement Project. San Francisco, CA

Water Emergency Transportation Authority. 2016. Geotechnical Investigation San Francisco Ferry Terminal - Phase 2. San Francisco, CA.

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[3] California Department of Water Resources. 2021. Well Completion Reports, San Francisco County. https://cadwr.app.box.com/v/wellcompletionreports/folder/77346379695 Date Accessed: February 1, 2021

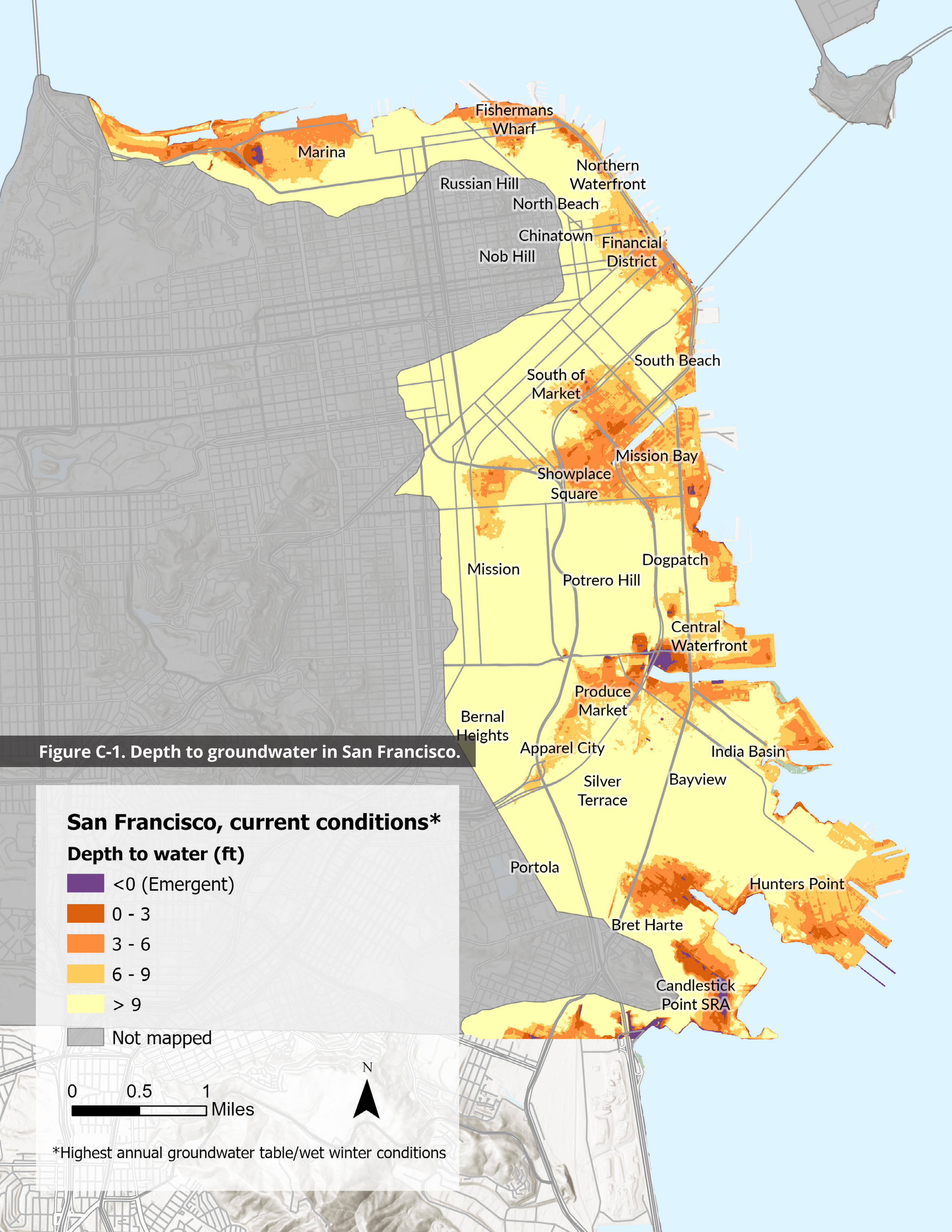

Figure C-1. Depth to groundwater in San Francisco.

*Highest annual groundwater table/wet winter conditions

2. Appendix D: San Mateo County

San Mateo County has extensive stream systems and drainage networks along with significant infrastructure and development along the shoreline in former wetland areas (e.g. SFO, Foster City). Many areas are protected by levees and are actively managed with lagoons and drainage networks. Figure D-1 shows the completed depth to groundwater mapping for San Mateo County.

Data sources used to fill gaps in the SWRCB dataset included San Mateo County shallow groundwater monitoring well data collected as part of the San Mateo Plain Groundwater Basin Assessment,[1] well completion reports from the state Department of Water Resources[2], geotechnical reports from a Caltrans database,[3] geotechnical reports provided by San Mateo County and winter water levels in lagoons accessed through FEMA Firm Mapping.

A ground-truthing meeting was held on March 24, 2022 to review the initial depth to groundwater maps with representatives familiar with groundwater and flooding in San Mateo County. The ground-truthing session was attended by representatives from San Mateo County, who then followed up with representatives from city governments to get more detailed local input. Review was provided by representatives from the City of Brisbane, the City of South San Francisco, the City of San Bruno, and the City of San Mateo. Several areas of emergent groundwater in the mapping that were identified for local review were along the inland edge of the saline wedge footprint used as a geographic extent for the analysis. Due to uncertainty and lack of data in these areas, these edges were excluded from the depth to water mapping. Another area identified for review was an area of emergent groundwater in South San Francisco. Local representatives indicated that there has extensive redevelopment in this area, including at the nearby Genentech campus, so grade changes may have occurred since the LiDAR used to create the digital elevation model used in the mapping was collected (in 2010). Therefore, this area is marked as an area low confidence in the groundwater mapping.

San Mateo County representatives provided the following geotechnical reports:

Genentech, Inc. 2005. "Geotechnical Consultation Proposed Building 3B Expansion -SSCM Genentech's Lower Campus." South San Francisco, CA.

Genentech. 2017. "Geotechnical Engineering Investigation Proposed B40 Connector Building Between Buildings 44 and 45." South San Francisco, CA.

Genentech. 2018. "Geotechnical Engineering Investigation B42 Cafeteria Expansion." South San Francisco, CA.

Oyster Point Development LLC. 2017. "Geotechnical Investigation Oyster Point Development Phase IC Infrastructure." South San Francisco, CA.

San Francisco International Airport. 2011. "Geotechnical Report Proposed Data Center Addition." South San Francisco, CA.

San Francisco International Airport. 2017a. "Combined Geotechnical Investigation Report SFO Hotel Project." South San Francisco, CA.

San Francisco International Airport. 2017b. "Geotechnical Report SFO AirTrain Extension and Improvements Project." South San Francisco, CA.

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[1] San Mateo Plain Groundwater Basin Assessment database: https://data-smcmaps.opendata.arcgis.com/search?q=Groundwater

[2] California Department of Water Resources. 2021. "Well Completion Reports, San Mateo County." 2021. https://cadwr.app.box.com/v/WellCompletionReports/folder/77346011894.

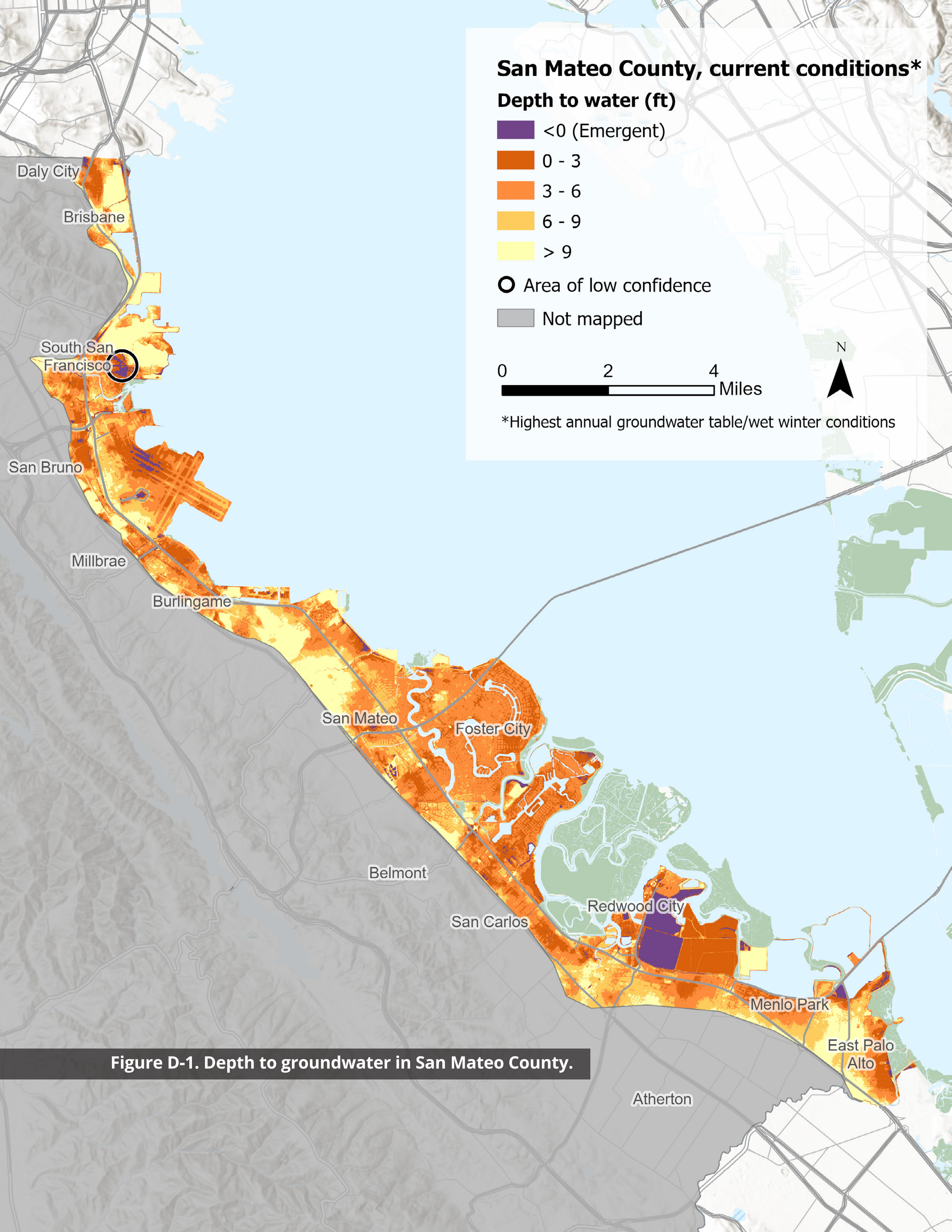


Figure D-1. Depth to groundwater in San Mateo County.

2.Appendix E: Workshop Summary

An online workshop was hosted with representatives from Bay Area local and regional governments on August 11, 2022. The goal of the workshop was to present the completed groundwater mapping (mapping for Marin, San Mateo, San Francisco Counties was complete, and mapping for Alameda County was in the final stages of review with city and county staff), discuss how rising groundwater will affect existing infrastructure, and brainstorm potential adaptation strategies (or further research needs) to address compound flooding from coastal flooding, urban stormwater flooding, and groundwater rise in low-lying coastal communities.

About 100 attendees participated in the workshop. The workshop structure included an introductory presentation to frame the science and the challenges associated with groundwater rise, a presentation on mapping results to date, and two guest presentations.

- Ellen Plane (San Francisco Estuary Institute) facilitated the workshop
- Professor Kristina Hill (University of California, Berkeley) described what groundwater is, how it can rise with sea level rise in low-lying coastal areas, and some of the challenges this can present in built environments.
- Abby Mohan (Pathways Climate Institute) presented study methods and provided an overview of the groundwater mapping completed to date.
- Dr. Shellie Habel and Professor Wendy Meguro (Sea Grant College Program, University of Hawaii) provided an overview of the rising groundwater research completed to date in Honolulu, Hawaii, and presented conceptual adaptation strategies to address rising groundwater in a densely developed coastal community (Waikiki, Hawaii) in an adaptive manner.
- Dr. Alex Grant and Dr. Anne Wein (U.S. Geological Survey) presented recent research on rising groundwater and liquefaction risk.

Following the presentation, attendees could self-select to attend one of the four breakout sessions. Attendees could also move between breakout sessions if desired. Each breakout session used an online padlet board with pre-populated question prompts. Attendees could join in verbal discussions while also adding answers to the prompts, providing information, and/or asking additional questions on the padlet boards. The padlet boards are attached following the brief summaries below.

- Room 1: Liquefaction
- Room 2: Underground Infrastructure
- Room 3: Policies and Building Codes
- Room 4: Green Infrastructure

Room 1: Liquefaction

High water tables can increase risk of soil liquefaction during earthquakes.

The following question prompts were used to start and guide the discussion:

- What do you want to know more about? What are critical gaps in knowledge that need to be addressed and who can help to fill them?
- What communication is needed to ensure cities and communities understand where liquefaction could increase in severity?
- How do earthquake response and recovery plans need to change to incorporate future increases in liquefaction hazards? How do you make sure that relevant planners and operators have all the necessary information to manage increased liquefaction risk?
- Is increased liquefaction risk being sufficiently incorporated into adaptation planning strategies? When could increased liquefaction risk undermine adaptation planning strategies (i.e. a seawall built on liquefiable material) such that you increase flood risk to a community during an earthquake?

The conversations in Room 1 were centered on closing critical knowledge and data gaps to better address liquefaction hazards and inform future planning efforts in areas at risk. Participants suggested a need for better education and increased awareness of this hazard for planners, engineers, and the public. Examples of data gaps include soil type and density, areas of intersecting risks, and basic outreach and communication tools that are appropriate for a lay audience.

Concern was raised about potential inconsistences in how adjacent structures, roadways, and utilities are designed and built. If a structure was designed to account for liquefaction risks associated with a high groundwater table, but adjacent roadways, structures, and utilities were not, does this create a residual risk on the well-designed structure? Questions also arose related to buoyancy and the uplift forces groundwater can place on foundations. Will the higher groundwater table increase the uplift forces? And will this in turn increase the liquefaction risk?

Participants discussed potential solutions to reduce liquefaction risk, such as densifying soil and deep soil mixing. However, they also expressed a need for updated guidelines for new construction that consider a higher groundwater table, including better visuals, interactive tools, infographics, and reports written in accessible language. Most hazard maps depict only a single hazard; therefore, understanding the complexity of the compounding and intersecting hazards is becoming more challenging.

Several open questions and suggestions for further discussion and investigation were raised:

- Updating building codes and design guidance should be a priority for new construction.
- What strategies and policies can encourage upgrades for existing buildings?
- Can model policies/standards be developed for local governments to use?
- Will updated regulations become too onerous and discourage new development?

Room 1: Liquefaction

High water tables can increase risk of soil liquefaction during earthquakes.

PATHWAYS CLIMATE INSTITUTE AUG 11, 2022

What do you want to know more about? What are critical gaps in knowledge that need to be addressed and who can help to fill them?

Soil needs to be loose enough to collapse, so dense soils would take shaking so strong you have other problems so knowing soil types is important

DSM is not used consistently, i.e. densified under development but not under sidewalk so you can get differential settlement, will increased water table elevation put some of those areas at higher risk of liquefaction. Places less engineered. less well mixed will have issues

Total water levels vs meters of sea level rise

Sea level rise and increasing storm intensity will both be impacting groundwater rise so having materials discussing total water levels versus just meters of sea level rise would be helpful. Being able to think about a worst case scenario- if an earthquake occurs during a storm with storm surge and heavy precipitation vs thinking of just sea level rise. Mostly a communication thing.

Do we need to separate sources of groundwater.... coastal/fresh/precipitation. I.e. SF seawall adaptation along the waterfront

How is buoyancy in foundations impacting the risk of liquefaction in foundations?

Landfill liquefaction risks?

Groundwater uncertainty dominates outcomes. Large earthquakes/ close to max out liquefaction. Effects of groundwater on the liquefaction sensitivity to SLR is greater for moderate sized earthquakes .

What communication is needed to ensure cities and communities understand where liquefaction could increase in severity?

Visual & interactive webtools (maps!), infographics, accessibly written reports

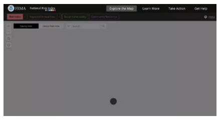
integrated hazard maps that have ALL the hazards

Fema's 'all the risks' map is a very low resolution attempt at this. (I would like to see us doing a whole lot better)

Map | National Risk Index

Explore the National Risk Index dataset with the interactive map and data exploration tools. Discover your community's natural hazard risk, compare it to other communities, and create reports.

FEMA



What agency will be charged with making a liquefaction-groundwater risk mapping available, similar to the FEMA flooding risk mapping?

USGS is talking about this, but there is no mandate per-say to do this yet — ANONYMOUS

timeline

lay out if the risk is now, soon or longer term

How do earthquake response and recovery plans need to change to incorporate future increases in liquefaction hazards? How do you make sure that relevant planners and operators have all the necessary information to manage increased liquefaction risk?

Education and awareness- I learned that many residents of East Palo Alto were not aware of evacuation routes or even that SMC has a plan.

Risks facing airports definitely important to communicate for response

What site guidelines and building standards need to be adapted to account for the mitigation of future liquefaction hazards?

There are methods to densify soil that can improve liquefaction risk

Buildings with neutral or buoyant weight

Landfills- depends on saturation of material and how much they are capped and if the soil cap is low permeability and if it has a liner below... Older ones might have less as more compacted and settled with time, newer ones are less compacted and more gas and space for waste to move around

Serious consideration if new construction should be occurring in certain high risk areas

Is increased liquefaction risk being sufficiently incorporated into adaptation planning strategies? When could increased liquefaction risk undermine adaptation planning strategies (i.e. a seawall built on liquefiable material) such that you increase flood risk to a community during an earthquake?

To my knowledge, increased liquefactoin due to SLR is not being considered.

City in washington is building seawall- but flooding is riverine (i.e. bathtub) could be increasing flood risk

Are cutoff walls a viable solution- deeper than permeability of young bay mud. Would have to build a very deep wall and potentially prohibitively expensive

Yes in San Francisco! Lots of analysis looking at this issue in even the early stages of planning. Liquefaction and lateral spreading

Room 2: Underground Infrastructure

High water tables can increase infiltration and corrosion of underground infrastructure.

The following question prompts were used to start and guide the discussion:

- Are you already seeing infiltration and corrosion in your pipes or other underground structures, and if so, where?
- What local policies and plans need to be updated to consider (a) increased infiltration rates and (b) higher corrosion rates that could require faster replacement cycles?
- Are there any creative solutions you'd like to propose for infiltration if it's going to increase with groundwater rise?
- Are there any creative solutions you'd like to share to limit corrosion impacts on pipes, conduits, and foundations?
- Who else should we be talking to in your local government or in utilities or other agencies?

The conversations in Room 2 centered on the challenges of maintaining underground infrastructure, due to impacts from both groundwater and surface water. Participants noted that corrosion and infiltration are already challenges in some communities, including the City of Alameda, the Redwood Shores neighborhood, and some areas of Oakland and San Francisco. Residences in the City of Alameda are already experiencing groundwater seepage into basements in some neighborhoods.

Stormwater and groundwater can infiltrate into wastewater pipes and overwhelm wastewater treatment plants during storm events. If the volume of infiltration increases as the groundwater tables rise, this could create a large-scale problem for many wastewater treatment plants. It was also noted that the infiltrating groundwater could have salt concentrations that could negatively affect current recycled water projects in the Bay Area.

Addressing these issues requires understanding the location, condition, material, age, and elevation of underground utilities. Many cities do not have an asset management system that includes this level of information. Addressing infiltration into pipelines will also require funding for capital improvements; however, most cities have limited funding and multiple priorities.

Discussions considered using alternate, less corrodible, and more flexible pipe materials to reduce infiltration as utility systems are upgraded, repaired, or replaced. However, concerns were also raised around potential health and environmental impacts of using PVC or Polypropylene pipes.

The participants noted that multiple agencies should come together to discuss these issues and include the public and property owners in the discussion.

Several open questions and suggestions for further discussion and investigation were raised by the group:

- Does it still make sense to continue placing overhead powerlines underground?
- Are microgrids a better option for electrical power?
- Could phytoremediation be incorporated into green infrastructure to reduce salinities near vulnerable pipelines?
- At some point, does it make more sense to move to managed retreat?

Room 2: Infiltration and Corrosion of Underground Infrastructure

PATHWAYS CLIMATE INSTITUTE AUG, 11 2022

Question 1

Are you already seeing infiltration and corrosion in your pipes or other underground structures, and if so, where?

Our CMP storm drain corrosion is typically from surface water. For now. — ANONYMOUS

Sewage pump stations along the California coast — PATRICK BARNARD

Yes, during storm events currently — ANONYMOUS

have heard from ppl in Alameda and SF of GW infiltration — ANONYMOUS

Stormwater infiltrates into cracks in piping, which gets sent to treatment centers, overwhelming them during storm events. — ANONYMOUS

I've seen it at a home in Redwood Shores, I think build on landfill. — ANONYMOUS

Infiltration is definitely a problem in wastewater infrastructure, but — ANONYMOUS

I don't have evidence of this issue at the moment but we are very vulnerable (West/East Oakland). — ANONYMOUS

Salinization of ag lands and wells in Salinas/Pajaro Valleys (CA Central Coast) — PATRICK BARNARD

Regarding infiltration into things like peoples home basements - we are already experiencing this in certain neighborhoods in Alameda, CA.

Question 2

What local policies and plans need to be updated to consider (a) increased infiltration rates and (b) higher corrosion rates that could require faster replacement cycles?

seems like in SF the conversation is just starting about rising GW impacts — ANONYMOUS

moving the pump station so they are not under water — ANONYMOUS

Seems like general plan elements or building codes, all have an some role in addressing this issue — ANONYMOUS

Not there yet, but mainly scoping allowable parcels for laundry to landscape program participation, issue of contaminants in laundry water getting into receiving water bodies. — ANONYMOUS

shallower more widely distributed pumping systems to limit subsidence. — ANONYMOUS

seems like in bay area, we have a very limited set of comprehensive information on the location, quality, elevation of underground stormwater pipes - mapping this, sharing this information, using it in analysis could be useful to prioritize areas. — ANONYMOUS

The infiltrated groundwater will be salty near the bay, which will negatively affect the numerous recycled water projects now operating in the Bay Area — ANONYMOUS

Critical need for good asset management practices (knowing where infrastructure is, what material it is made from, etc.) — ANONYMOUS

Funding for capital improvement

Question 3

Are there any creative solutions you'd like to propose for infiltration if it's going to increase with groundwater rise?

At some point, does it make more sense to move to managed retreat? — ANONYMOUS

New developments should incorporate this to designs

Observations, then solutions

New networks of observations, through time, seem to be needed to track how infiltration occurs today with tides and storms

Question 4

Are there any creative solutions you'd like to share to limit corrosion impacts on pipes, conduits and foundations?

Site-specific considerations for utility construction to protect pipes that may become in contact with contaminated groundwater (e.g., VOCs) — ANONYMOUS

anti-corrosion techniques in SF water system now with sacrificial metal. — ANONYMOUS

does switching to plastics/other materials limit/prevent the corrosion? — ANONYMOUS

Check with Marin Municipal/Water for pipeline replacement materials considered (PVC?) — ANONYMOUS

Consider PVC vs Polypropelyne and health impacts — ANONYMOUS

Microgrid for electrical?

Could phtyoremediation (halophytes) be incoroporated into green infrastrucutre adjacent to vulnerable pipes to help reduce/mitigate salinity?

Question 5

Who else should we be talking to in your local government or in utilities or other agencies? (include email address)

EBMUD, PGE — ANONYMOUS

Cal EPA/DTSC (Dep. of Toxic Substances Control) — PATRICK BARNARD

East Bay Dischargers Authority — ANONYMOUS

Planning departments — ANONYMOUS

Maintenance people who look at pipe breaks and conditions, corrosion, settlement — ANONYMOUS

Regional Water Quality Control Board and DTSC — ANONYMOUS

Publics Works — ANONYMOUS

Department of Transportation coordination — ANONYMOUS

Property Owners — ANONYMOUS

geochemist for re-mobilization of existing contaminants

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Room 3: Policies and Building Codes

High water tables may require governance structures, policies, and building codes to change.

- The following question prompts were used to start and guide the discussion: What local plans and policies need to be updated to account for groundwater rise? How should they be updated?
- Who needs to be engaged in the conversation about updating these plans/policies?
- How can design standards and building codes be adjusted to take consider the latest science on groundwater rise?
- What does a neighborhood that is resilient to rising groundwater look like? How do we get there?

The conversation in Room 3 were centered on governance changes that are required to address a changing climate, and several participants had examples of changes that have already occurred or are in process. Participants agreed that local plans and policies across the board should be updated to account for groundwater rise (and sea level rise), including climate action plans, general plans, capital infrastructure plans, local hazard mitigation plans, long range facility plans, and building codes. Underground structures (basements, parking garages) are the most immediate concern in terms of building damage from rising groundwater. Many basements and parking garages have sump pumps and/or groundwater pumps today.

Participants suggested that new underground structures should be banned in some places and/or that new design criteria should be developed. For example, the design groundwater level can be set several feet above the historical maximum to account for future groundwater rise. Participants also discussed including sea level rise, groundwater rise, and liquefaction potential in real estate disclosures to improve public awareness of these hazards.

The City and County of San Francisco has design guidelines for the foundations of tall buildings that include the effects of sea-level rise across the building's design life, including flooding, increasing hydrostatic pressure, increasing liquefaction potential, saltwater intrusion, and decreased bearing capacity (2019 SF Building Code AB-111, Section 10.4). San Francisco is also actively exploring new design guidance for buildings and rights-of-way to address combined flooding. This design guidance would be required in certain planning code overlay zones.

The group also discussed ecological and environmental justice concerns. Remediation strategies for capped contaminated sites need to be reconsidered in the context of groundwater rise to determine whether capping is still adequate to protect public and ecosystem health or if removal of material is a safer alternative prior to any redevelopment. In addition to updating policies to protect people, buildings and infrastructure, strategies may also need to be implemented to protect habitat and address impacts to urban forests.

Several stakeholders were identified that need to be engaged in conversations about updating these plans and policies. These stakeholders include local government departments (building inspection, planning, public works), community members (residents, building and business owners, environmental justice communities), and state and regional agencies (Department of Toxic Substances Control, State and Regional Water Quality Control Board, Department of Water Resources). Representatives from park districts, public and private utilities, and wastewater, stormwater, and transportation agencies should also be engaged.

One question asked participants to describe what a neighborhood resilient to rising groundwater looks like. The group’s discussion painted a picture of an urban landscape with floodable parks, raised homes, ponds, and green infrastructure. Adaptation strategies are used as an opportunity to enhance the public realm and quality of life for residents. Access to transportation corridors and essential services is maintained during flood events. Planning departments use regularly updated modeling and monitoring data to inform the building permit approval process and suggest adaptation strategies. In this future, residents in hazard areas are well-educated on risks, adaptation strategies, and funding opportunities for retrofits, including financial assistance programs that allow equitable access to building improvements.

Several open questions and suggestions for further discussion and investigation were raised by the group:

- Updating building codes and design guidance can improve resilience of new buildings. What strategies and policies can encourage upgrades for existing buildings?
- Can model policies/standards be developed for local governments to work from?
- How can we ensure that new regulations are not too onerous for new development?
- What are best practices for communicating risk of flooding and exposure to contaminant remobilization to the public?
- What beneficial uses could shallow groundwater be directed toward?
- Are there barriers to implementing adaptation strategies embedded in existing codes, plans, and policies? If so, how can these barriers be removed?

Room 3: Policies and Building Codes

PATHWAYS CLIMATE INSTITUTE AUG 11, 2022

What local plans and policies need to be updated to account for groundwater rise? How should they be updated?

Sustainability/climate action plan

We need to ban underground parking/basements in these risk areas.

Can this be addressed with adequate engineering design criteria?
— ANONYMOUS

Comp/general plans

Capital infrastructure plans

In San Francisco, we are exploring developing Design Guidance that incorporates combined flooding hazards in addition to heat and air quality impacts. We would then create a planning code overlay zone that would require buildings and the right-of-ways comply with the guidance.

Local haz mitigation plans, facility long-term plans,

New buildings would comply with the FEMA requirements but existing buildings will remain as is. Are there any good local strategies or policies that would encourage existing (especially nonresidential) buildings to upgrade?

Building plan checks

Local hazard mitigation plans

Need to reassess remediation strategies, require removal of toxic fill in risk areas, consider groundwater before employing capping for remediation purposes

Hazard Mitigation Plan, General Plan

real estate disclosures about the range of hazards including SLR, groundwater, liquefaction (holistic geotechnical assessment)

Need to consider renters as well - who would not receive disclosures
— ELLEN PLANE

Who needs to be engaged in the conversation about updating these plans/policies?

The Department of Building Inspection, the Planning Department, residents, and building owners.

Communities impacted by flooding, underground toxic materials, environmental justice communities

Dept of Toxic Substance Control (in CA), agencies responsible for remediation

Public and private utilities, Development centers, Planning and Public Works-Engineering, landfill and wastewater treatment plants and regional partners (BACWA). Stormwater co-permittees should consider stormwater planning measures

railroad, park districts, industry, ports and marinas

airports — ANONYMOUS

Seems like habitat protection and urban forest considerations should be included in these conversations

SWRCB, DWR, RWQCB

How can design standards and building codes be adjusted to take into account the latest science on groundwater rise?

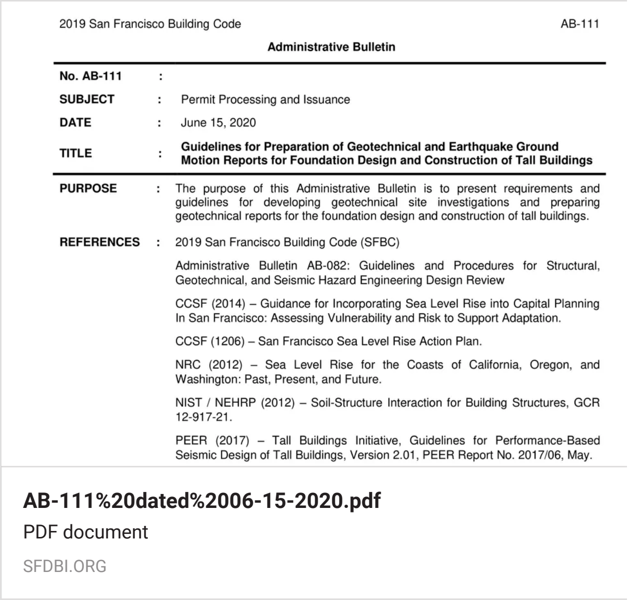
Equitable implementation and suppport is a must, esp for vulnerable communities in fill areas who may have limited resources/bandwidth to conform to new requirements and/or proactively implement retrofits

The policies should be written to include the best available science. Mapping/modeling should then be updated on a regular basis so that the policies can reflect any changes.

Would be helpful to have model policies/building standards

Need different strategies for new vs existing development. Need to be sure that regulations arent too onerous for new development

San Francisco guidelines for geotechnical reports and foundation design of tall buildings (sec 10.4 on sea level rise)



2019 San Francisco Building Code AB-111

Administrative Bulletin

No. AB-111 :
SUBJECT : Permit Processing and Issuance
DATE : June 15, 2020
TITLE : **Guidelines for Preparation of Geotechnical and Earthquake Ground Motion Reports for Foundation Design and Construction of Tall Buildings**

PURPOSE : The purpose of this Administrative Bulletin is to present requirements and guidelines for developing geotechnical site investigations and preparing geotechnical reports for the foundation design and construction of tall buildings.

REFERENCES : 2019 San Francisco Building Code (SFBC)

Administrative Bulletin AB-082: Guidelines and Procedures for Structural, Geotechnical, and Seismic Hazard Engineering Design Review

CCSF (2014) – Guidance for Incorporating Sea Level Rise into Capital Planning In San Francisco: Assessing Vulnerability and Risk to Support Adaptation.

CCSF (1206) – San Francisco Sea Level Rise Action Plan.

NRC (2012) – Sea Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future.

NIST / NEHRP (2012) – Soil-Structure Interaction for Building Structures, GCR 12-917-21.

PEER (2017) – Tall Buildings Initiative, Guidelines for Performance-Based Seismic Design of Tall Buildings, Version 2.01, PEER Report No. 2017/06, May.

AB-111%20dated%2006-15-2020.pdf

PDF document

SFDBI.ORG

What does a neighborhood that is resilient to rising groundwater look like? How do we get there?

Floodable infrastructure (e.g. basketball courts/parks), raised homes, green infrastructure

temporary ponds, fountains, parks designed to accommodate temporary flooding

Access to transportation corridors and essential services even during flood events

Residents are well-educated on the risks, solutions, funding for retrofits, and especially those at risk of flooding and exposure to underground toxic materials

I am not seeing this! would be helpful to also have model public outreach on this topic — ANONYMOUS

Planning Departments have enough information to inform community members who are doing work on their homes/buildings to inform approvals/work to be done and incorporate adaptation measures.

Is there beneficial use for shallow groundwater?

Palo Alto has looked at this and it's interesting but thorny and complicated. I'm happy to share more offline — ANONYMOUS

A combination of different tactics to create redundancy in the right-of-way and buildings in terms of wet and dry flood-proofing with a preference of tactics that increase nature-based solutions and enhance the public realm.

I heard Dr. Kris May suggest that networked groundwater pumping may something to learn about

Are any of these things we CAN'T do now, such as they are being limited by existing codes, policies, land uses? How can we consider solutions that reduce barriers to these new resilient solutions if they are standing in the way.

******

Room 4: Green Infrastructure

How will higher water tables and green infrastructure work together?

The following question prompts were used to start and guide the discussion:

- Are you implementing green infrastructure projects? What type and where in the watershed are they (upper/mid/lower)?
- How do you think rising groundwater will impact green infrastructure?
- What resources do you need to make your green infrastructure projects more resilient to rising groundwater?
- How can green infrastructure be reimagined to function as a dual adaptation strategy for stormwater and rising groundwater?

The conversation in Room 4 centered on the intersection of green infrastructure and rising groundwater. Several participants were engaged at some level in green infrastructure projects within their city. The San Francisco Public Utility Commission used modeling of their combined sewer system to identify specific areas where green infrastructure would provide the most benefits and noted that these areas tend to be in the upper to mid watershed.

Concern was raised that rising groundwater could reduce the function of some green infrastructure efforts. In general, green infrastructure installations should be at least 4 feet above the seasonal high groundwater table. Designing green infrastructure projects that account for a high groundwater table and higher salinities could require more hybrid green-gray solutions. Pumping could become an important component in green infrastructure. Buoyancy issues could also become a challenge.

The group expressed a desire for additional resources that go beyond traditional green infrastructure. For example, strategies that incorporate water reuse in the dry season, multifunctional designs that could include floodways, habitat, and bioremediation, the inclusion of coastal habitat, and a greater focus on native species. There was also discussion of green infrastructure projects with less of a focus on vegetation. It may be hard to design green infrastructure projects that can sustain infrequent extreme rainfall as well as severe and prolonged droughts.

The biggest challenge for green infrastructure is finding the space needed to construct a project. Many areas around the Bay Area that have urban flood issues are densely developed and have limited space for creativity and innovation.

Several open questions and suggestions for further discussion and investigation were raised by the group:

- How can green infrastructure fit into managed retreat and the potential conversion into coastal wetlands over time?
- Can rising groundwater be treated and used as a non-potable water source?
- Will rising groundwater create new contaminant pathways for exposure?
- Can green infrastructure help with remediation from the ground up, instead of just increasing infiltration? This would create dual purpose benefits.

Room 4: Green Infrastructure and Groundwater Rise

PATHWAYS CLIMATE INSTITUTE AUG 11, 2022

Are you implementing green infrastructure projects? What type and where in the watershed are they (upper/mid/lower)?

Ora Loma as an example for native species and upper habitat

SFPUC GI

Yes, SFPUC is implementing green infrastructure in our combined sewer system using grants, capital projects, and regulation of private development. There are also some smaller MS4 areas, mainly redevelopment along the shoreline where green infrastructure is a requirement as part of the development. Based on modeling of our combined system, we have identified specific sub-watersheds with higher hydraulic performance for green infrastructure for annual volume and flood volume reduction. These areas tend to be in the upper to mid watershed. That said, removing stormwater from our sewer system is generally a good thing everywhere in the watershed - every drop counts!

How do you think rising groundwater will impact green infrastructure?

It will make GI less functional

Salt water intrusion that may impact plants

It'll make a combination of green & grey infrastructure more necessary. Maybe making things more complex in the process?

Effects may include: facility siting; choice of facility type and whether it should be lined and underdrained; plant palette.

challenging to design GI that has the ability to sustain extreme wet and dry periods

can rising groundwater create new contaminant pathways for exposure

buoyancy could become a challenge

SFPUC GI & Groundwater

SFPUC has guidance for evaluating the feasibility of infiltrating stormwater based on various geophysical factors, including high water tables. We have thresholds for water table elevation that we use to determine whether infiltrating is feasible or not (*see below).

The areas with high groundwater table could shift overtime, reducing feasibility for infiltration. I would anticipate that the areas subject to rising groundwater are also areas of existing bay-fill, liquefaction hazards, existing high groundwater, etc. and would already generally not be feasible for infiltration. Instead of infiltration in these locations, we would turn to other types of green infrastructure solutions that detain stormwater, such as lined storage facilities or planters, or rainwater harvesting systems.

*"4-foot minimum vertical separation from base of BMP to seasonal high groundwater in all Bayside groundwater basins; 10-foot minimum vertical separation from base of BMP to seasonal high groundwater in the Lobos and Westside groundwater basins, with the potential for reduction to 4-foot separation with SFPUC approval."

What resources do you need to make your green infrastructure projects more resilient to rising groundwater?

New strategies for reuse that do not involve traditional GI

increased available space to place GI that would increase overall capacity to treat runoff/flooding/etc

Revised design guidance, multifunctional design (floodway, habitat, bioremediation)

Incorporation of other coastal habitats, not just wetlands

More focus on native species

widen it from vegetation only

resource- NY Waterfront Edge Design Guidance- not sure how much info in relation to GW

SFPUC Adapting Existing Projects

Better understanding of how rising groundwater would impact the operations and maintenance of existing GI in low lying areas. Also would be helpful to know how this will impact existing GI performance. Any tools/framework to help adapt these existing facilities would be helpful.

How can green infrastructure be reimagined to function as a dual adaptation strategy for stormwater and rising groundwater?

How GI fits into managed retreat and potential conversion into coastal wetlands over time.

Multi-disciplinary pursuit. Scientists and landscape architects are central to plant selection, habitat type creation, and recreational function with engineers looking at hydrology & hydraulics.
— ANONYMOUS

more studies on potential remediation from the ground up, instead of just the potential for infiltration. couple benefits for dual purpose

Is there a potential to treat rising GW and use it for non-potable water source.

pumping is going to be an important component in green infrastructure

can be expensive, high carbon footprint
— PATHWAYS CLIMATE INSTITUTE

Adaptation Strategy

It seems like there is opportunity to broaden the toolkit for shoreline adaptation to include nature-based adaptation measures that create room for rising groundwater as surface expressions / natural wetland areas that also serve as stormwater detention features. This could be a helpful tool in the flood resilience toolbox in some of the low-lying areas that also experience surface flooding from stormwater. Tanner Springs Park in Portland comes to mind - surface expression of the water table with extra storage volume. One thing to consider is the pre-treatment of stormwater/combined flows and the regulation of groundwater / pathways of pollutants to groundwater.

These approaches should also take an equity lens - geotechnical constraints for green infrastructure (including high groundwater table and presence of soil/groundwater contamination) overlap with EJ areas. Solutions should also consider intersecting environmental burdens and community-centered solutions.