SAN FRANCISCO WATERFRONT COASTAL FLOOD STUDY, CA

APPENDIX B.1.5 – QUALITATIVE SHALLOW GROUNDWATER ASSESSMENT [DRAFT]

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USACE TULSA DISTRICT | THE PORT OF SAN FRANCISCO

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PORT OF SAN FRANCISCO

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Acronyms and Abbreviations

Acronym	Definition
Bay	San Francisco Bay
CFRM	Coastal Flood Risk Management
DTSC	Department of Toxic Substance Control
FWOP	Future Without Project
FWP	Future With Project
K	Hydraulic Conductivity
SFEI	San Francisco Estuary Institute
SWRCB	State Water Resources Control Board

B.1.5-1 Introduction

Coastal flood hazards within the study area are directly linked to the current and future presence of shallow unconfined groundwater below the ground along the San Francisco shoreline. As sea levels rise within San Francisco Bay (Bay), the shallow groundwater table is expected to rise, first impacting buried and below-grade infrastructure with eventual emergence impacting surficial drainage. In the absence of groundwater-specific flood risk reduction measures, rising groundwater can impact the ability of the coastal flood protection alternatives in protecting landward areas from flooding and can exacerbate stormwater drainage challenges.

This shallow groundwater assessment leverages recently completed reports that estimate the depth and extent of the existing shallow groundwater table, the response the shallow groundwater table to sea level rise, and qualitative future groundwater challenges associated with proposed coastal flood protection alternatives. Descriptions and assumptions on the existing and future groundwater conditions are presented, and shoreline cross sections illustrate the expected connectivity between rising groundwater, potential flood risk reduction measures, and typical inland conditions in areas with subsurface Bay fill. This information qualitatively informed the formulation and evaluation of alternatives (*Appendix A: Plan Formulation*). However, groundwater impacts in the Future Without Project (FWOP), and Future With Project (FWP), conditions were not qualitatively evaluated nor monetized for the purposes of plan selection.

The FWP alternatives developed for the San Francisco Waterfront Coastal Flood Study were formulated to a feasibility level for the purpose of cost, benefit, and impact analyses, but these alternatives were not evaluated relative to their influence on the inland groundwater table.

The State Water Resources Control Board (SWRCB) and California Environmental Protection Agency Department of Toxic Substance Control (DTSC) both maintain monitoring well networks at sites with ongoing cleanup or long-term monitoring requirements. However, well observations (including depth to water) are generally only collected twice per year in the spring and fall.

B.1.5-2 Coastal Groundwater Behavior

Coastal groundwater conditions, responsiveness, and overall behavior are determined by inter-related effects of geology and hydrology, in addition to infrastructure and water management actions.

B.1.5-2.1 Geologic Controls

The geology of coastal groundwater flow systems determines the physical environment and important flow parameters, including the topography, rock and/or sediment types, and the thickness of the deposits. Topography creates the potential energy for groundwater flow, where recharge at higher elevations will have more energy and drive flow toward lower energy areas at lower elevations. Rock and sediment types set several important parameters for groundwater conditions, including the intrinsic permeability and porosity, that are variable in space. With a focus on shallow groundwater that is most directly connected to Bay water levels, the thickness and properties of the shallowest water-bearing unit (e.g., aquifer if useful for human needs) matter most in setting the water table position and dynamics. This shallowest unit is considered unconfined if its maximum pressure is equal to atmospheric pressure and can have unsaturated material overlies it, called a water table or unconfined aquifer. The lower boundary of the unconfined water-bearing unit is geologically defined by a lower-permeability unit that allows little to no water flow through it, such as a clay or bedrock (i.e., lower confining unit). Additional confining units and aquifers could exist below this confining unit. Confined aquifers are most commonly used for domestic and other water resource needs, are most sensitive to pumping and thus saline groundwater intrusion and are more hydraulically disconnected from surficial hydrology than unconfined units. For coastal hazards of groundwater emergence and shoaling, unconfined units are the main groundwater focus.

Like surficial watersheds, the boundaries of groundwater systems, or groundwater basins, can be mapped based on topographic divides with the addition of geologic controls in the subsurface. Of the seven groundwater subbasins in San Francisco, three underlie the San Francisco east side waterfront: the Marina, Downtown, and Islais Valley groundwater basins (California Department of Water Resources, 2003), which align with the surficial watersheds shown in the Inland Drainage *Sub-Appendix B.1.4*. These groundwater basins are mainly comprised of unconsolidated sediments and include alluvial fan deposits, beach and dune sands, undifferentiated alluvium, and artificial fill. The greatest depths to bedrock are less than 300 feet with an overall trend of shallower bedrock inland and thicker sediment toward the Bay, comprising a sedimentary wedge that thickens from inland to the Bay. Bay mud within this sedimentary wedge can act as a confining unit, although in some areas its thickness and extent may lead it to act more as a semi-confining unit. Geologic variability and history interact to set the topography, which is the uppermost limit for groundwater tables to rise before creating seepage or springs. Water tables are generally a damped representation of the topography, such that higher topographic areas likely have higher elevation water tables. For the purposes of understanding groundwater table responses, only the portion of these units that are hydraulically connected to Bay levels will determine future water levels, where the deeper confined units may respond but have minimal influence on the water table position.

Differing geologic materials also range in their values of intrinsic permeability and porosity. Intrinsic permeability (units of length squared) is the ease of flow of any fluid through the geologic material, whereas hydraulic conductivity (units of length per time) includes both the properties of the rock (i.e., permeability) and the fluid (i.e., density and viscosity). Permeability and hydraulic conductivity of geologic materials can vary by over 12 orders of magnitude, making it a highly variable physical property. Geologic changes in space as well as in flow direction also contribute to the challenge of assigning these parameters to a given location, although most rock and sediment types have primary ranges of about four orders of magnitude. Porosity is correlated with permeability, but porosity itself does not determine the ease of groundwater flow (i.e., is not in

Darcy's Law). Instead, porosity represents the storage capacity for groundwater related to pumping or other hydrologic forcings, and it also is important in quantifying how pressure waves propagate through porous media. For unconfined aquifers, the storativity, or volume of groundwater that is released per unit area of aquifer per unit drop in head, is dominated by the drainable portion of the porosity, also called the specific yield.

Two higher order groundwater parameters consider the combined effects of (1) aquifer thickness on the ease of flow, or transmissivity, by integrating hydraulic conductivity across the aquifer thickness, and (2) porosity and permeability through the ratio named the hydraulic diffusivity, which is transmissivity divided by storativity. Transmissivity is a major control for setting the water table elevation in unconfined systems with larger transmissivity allowing more rapid drainage and lower water tables relative to a lower transmissivity system. The hydraulic diffusivity sets how responsive water tables are to tides in coastal groundwater systems, where high hydraulic diffusivity systems will have more responsive water tables to tides and other hydrologic forcings. Materials with either higher hydraulic conductivity or lower porosity could increase the hydraulic diffusivity and result in more water table responsiveness.

Extensive geotechnical borings have been used to construct idealized stratigraphic profiles of the shallow sediment underlying the Bay waterfront and extending approximately 1,000 feet perpendicular to the shoreline (Fugro, 2020; Parsons & RJSD, 2022). The thickness and hydrogeologic properties of artificial fill are likely most important for the existing and future positions of the coastal water table, described as mainly composed of dune sands but with significant clay (Fugro, 2020). Underlying the artificial fill are thick deposits of Young Bay Mud, which are interrupted by silt and sand layers. The Young Bay Mud could act as a confining unit that focuses Bay water level effects into the artificial fill only, but the sand and silt layers may allow some hydraulic connection with deeper sediment – most likely the Upper Layered Sediments (Fugro, 2020). The rock dikes underlying the seawalls introduce additional hydrogeologic complexity in how the Bay levels would influence the coastal water table. The borings indicate the rock dikes are highly permeable and porous and may enhance groundwater connectivity to the Bay, depending on the hydraulic influence of other seawall materials. While the borings provide dense information on the location of these units and variations in sediment types, the important hydraulic parameters of porosity and permeability can only be roughly estimated without additional tests (e.g., permeameter, pump, or slug tests).

B.1.5-2.2 Hydrologic Controls

Groundwater systems conserve mass and energy, such that any inputs to an unconfined unit must be balanced by other water losses elsewhere or an increase in storage. For unconfined systems, an increase in water storage occurs primarily through raising the water table and filling additional unsaturated pores above the water table with water. Groundwater recharge is the portion of water that infiltrates the soil and reaches the water table to add water to the unconfined unit. For the eastern half of San Francisco, the groundwater recharge rate has been simulated to be approximately 0.57 foot per year considering both precipitation and water/sewer line losses

(Phillips et al., 1993). Recharge changes through time seasonally and with climate change through the interaction of changing precipitation amounts and intensity in addition to changing evapotranspiration losses influenced by both temperature and humidity (Taylor et al., 2013). Areas with high proportions of impervious surfaces would direct more water toward the storm sewer system rather than allowing infiltration to recharge a water table. Conversely, transitions from impervious to more pervious surfaces could increase recharge rates and lead to water table rise.

Groundwater exiting the subsurface balances the inflows as a combination of direct discharge into the Bay, discharge as baseflow to the creek network, evapotranspiration from evaporative losses from shallow water tables or plant roots accessing the water table, and infrastructure-related pumping and drainage (e.g., leakage into storm sewers). Net losses of groundwater from these processes would lead to a net lowering of the water table, but the location and timing of losses are important for predicting where and how the water table would lower. With pumping specifically, the pumping rate is a key factor, and the amount of drawdown (i.e., water table decline) caused by pumping increases with lower hydraulic conductivity and storativity materials. For such dewatering applications, lower hydraulic conductivity materials, rich in clays and silts, would require less pumping than higher conductivity sands and gravels. In coastal areas, pumping can eventually lead to saline groundwater intrusion because higher salinity water is intruded buoyantly either from nearby waterbodies or the subsurface toward the well even if only fresh groundwater is pumped.

Combining both influences of hydrology and geology, the “water table ratio” has been defined such that values greater than one indicate a “full” groundwater system with a large-scale water table shape set by drainage to topographic lows, termed a topography-limited system (Haitjema & Mitchell-Bruker, 2005). Conversely, a groundwater system with a water table that is deep and generally disconnected from topography is termed flux-controlled or recharge-limited, implying sufficient losses relative to recharge to maintain a relatively low water table. These terms are useful for understanding coastal water tables under present conditions as well as with sea level rise because topography-limited systems have little room to respond to sea level rise and flux-controlled systems generally rise linearly with sea level (Befus et al. 2020; Michael et al. 2013). The San Francisco waterfront likely has a groundwater table that is topography-limited meaning there is little topography and unsaturated thickness to accommodate a rise in the water table.

B.1.5-2.3 Compounding Effects with Tides and Storms

Groundwater levels are also affected over short and long timescales by coastal hydrodynamics and seasonal climatology, such that a static representation or infrequent measurement would not be sufficient to understand the existing present-day or future groundwater conditions. Tides and their seasonal variability induce head and flow fluctuations in coastal groundwater with water level response magnitude decaying exponentially with distance and linearly in time controlled by tidal amplitude and hydraulic diffusivity (Housego et al., 2023). Therefore, the maximum groundwater level change caused by tides would be correlated to San Francisco Bay tidal amplitude, and the exponential decay of this signal inland in the coastal aquifer would depend on its spatially changing thickness and hydraulic properties (e.g., storativity and hydraulic conductivity).

Storms and storm surges can create a larger and longer lasting influence on inland groundwater levels. With a short-lived but large storm surge, groundwater levels can be elevated more and farther inland than would be expected for a similar size tide (Li et al., 2004), representing a groundwater emergence response.

Further investigation is required to characterize the existing dynamic water level conditions for the coastal groundwater systems along the San Francisco waterfront. Geotechnical borings provide static groundwater levels at the time of drilling, but the tidal and seasonal variability would require additional observations and measurements for a more complete understanding of the current groundwater conditions. SWRCB is actively monitoring groundwater levels at 15 sites with leaking underground storage tanks and 55 cleanup program sites, with many cleanup sites having multiple active observation wells (SWRCB, 2022). DTSC is also overseeing sites with ongoing monitoring, such as Hunters Point which is outside of the study area and has over 100 monitoring wells. Each well is monitored at least twice per year for regulatory requirements. Observations are collected in the late spring when groundwater levels are usually higher, especially after a wet winter season, and in the early fall when groundwater levels are often low. Although this seasonal fluctuation is often observed in the groundwater measurements, there is no certainty that the highest or lowest depth to water measurement was collected due to the limited number of annual observations. In regions were rising groundwater tables due to sea level rise are already impacting communities, such as Miami-Dade County, groundwater monitoring networks are being established to better characterize both short-term and long-term variability in the groundwater table (Nicoletti, 2023).

B.1.5-3 Groundwater Response to Sea Level Rise

It is expected that the existing topography-limited groundwater system along the San Francisco waterfront will rise in response to sea level rise in both the FWOP and FWP conditions. The following sections include descriptions of the groundwater issues and challenges that are expected to occur coincident with sea level rise.

B.1.5-3.1 Groundwater Shoaling and Emergence

Groundwater shoaling occurs when a water table gains elevation and becomes shallower relative to the land surface. Groundwater emergence occurs when the water table intersects the land surface, resulting in either the formation of a new spring, seep, ponding, or evaporative deposit, depending on the nearby climate and topography. With sea level rise, the water table at the shoreline will rise to meet the new sea level. This is because the lowest elevation of the coastal water table is on average near or above mean sea level in most coastal areas, unless losses other than discharge to the coast reverse flow such that saline water flows inland and causes intrusion (e.g., pumping or evaporation). Shallow and emergent groundwater represent hazards for surficial flooding, water quality, transportation, and shallow buried infrastructure (Habel et al., 2017; Hill et al., 2023; Knott et al., 2017, 2018; May, 2020; Rotzoll & Fletcher, 2013; Su et al., 2020). Tides create additional complexity, where the amount of porewater exchange and water level responses caused by the tide is dependent upon the local hydrologic and geologic setting and hydraulic parameters discussed earlier (e.g., Abarca et al., 2013). Over seasons, groundwater tables both near the shore and more inland fluctuate based on the seasonality in recharge set by infiltrating rainfall amounts and seasonal Bay water levels, with seasonal water level changes of about 3 feet observed in Alameda (May et al. 2022) that suggests similar seasonality could exist in the shallow groundwater along the San Francisco waterfront due to it having similar hydroclimatic and hydrogeologic conditions, including areas of Bay fill.

B.1.5-3.2 Saltwater Intrusion

Saltwater intrusion, which is more technically termed saline groundwater intrusion for subsurface pathways, is caused by the infiltration of groundwater with higher salinities into water-bearing units with previously lower salinities. Causes of intrusion are primarily from hydrologic changes, including pumping, less recharge, and/or sea level rise. Pumping from the unconfined system is expected to cause more intrusion than century-scale sea level rise (Ferguson & Gleeson, 2012), although local hydrologic and geologic variability may lower the importance of pumping. Sea level rise has little effect on saltwater intrusion in flux-controlled groundwater systems and causes much more intrusion in topography-limited systems (Befus et al. 2020; Werner et al. 2012; Michael et al. 2013). As most of the San Francisco waterfront is topography-limited (Michael et al. 2013; Befus et al. 2020), there is high potential for additional saltwater intrusion with sea level rise.

Saltwater intrusion is typically a water quality concern, threatening the ability to use groundwater as a freshwater resource and altering the chemical setting in areas with historic contamination within the soils. Shallow groundwater basins along the eastern San Francisco waterfront are not utilized as a potable water source, therefore saltwater intrusion is not considered to be a FWOP concern. However, saltwater intrusion may lead to potential ecosystem degradation and accelerated corrosion rates to buried infrastructure (May 2020).

B.1.5-3.3 Compounding Effects with Tides and Storms

As discussed in the existing conditions section, groundwater levels are affected over short and long timescales by coastal hydrodynamics and seasonal climatology. If tidal range (i.e., the difference between mean higher high water and mean lower low water) is assumed to remain unchanged as sea levels rise, the tidal range will rise at the same rate. Near the shoreline, in areas where hydraulic properties (e.g., storativity and hydraulic conductivity) allow the groundwater levels to respond on short timescales comparable to the tidal cycles, the groundwater table could become emergent during extreme tide events and annual king tides before the groundwater table exceeds the surface elevation over larger areas along the shoreline.

Little research has been performed on how shoreline infrastructure such as the existing bulkheads, seawalls, and the other hydrogeologic changes involved in their construction influence the connections between coastal waterbodies and coastal groundwater systems. Most of such work has focused on how partially penetrating cutoff walls and subsurface dams may defend against saline groundwater intrusion (Abd-Elaty et al., 2019; Anwar, 1983; Chang et al., 2019; Gao et al., 2021; Kaleris & Ziogas, 2013; Sugio et al., 1987; Zheng et al., 2020). As noted in Section B.1.5-3.2, saltwater intrusion is not a primary concern within the study area.

There is engineering interest in using cutoff walls to limit the connection between coastal water bodies and inland developed areas, thereby limiting the increase in the inland groundwater table in response to sea level rise. However, research currently in review demonstrates that all impermeable cutoff walls that intersect the water table can lead to groundwater emergence on the inland side of the cutoff walls (Su et al., in review). This occurs because the partial blocking of the aquifer thickness by the cutoff wall reduces the transmissivity of the aquifer, causing a combination of either a steepening of the hydraulic gradient to maintain flow under the cutoff wall by raising the groundwater level on the inland side or by having groundwater discharge to the land surface inland of the cutoff wall.

Su et al. (in review) conclusions assume an infinitely long barrier in the horizontal plane; however, a short (in the horizontal plane) cutoff wall parallel to the shoreline may lead to less potential for groundwater emergence if sufficient flow can be maintained both under and around the sides of the barrier. Such a wall would not inhibit the connection between the inland shallow groundwater and the coastal water body. Ultimately, subsurface barriers are limited in length along the shoreline, and three-dimensional groundwater flowpaths could change the tradeoff between intrusion protection and groundwater emergence (Liu et al., 2023; Wu et al., 2020). Additionally, the nuances of the construction materials and designs in combination with the hydrogeologic setting make the analysis of groundwater responses in areas with hydrologically influential infrastructure specific to each site.

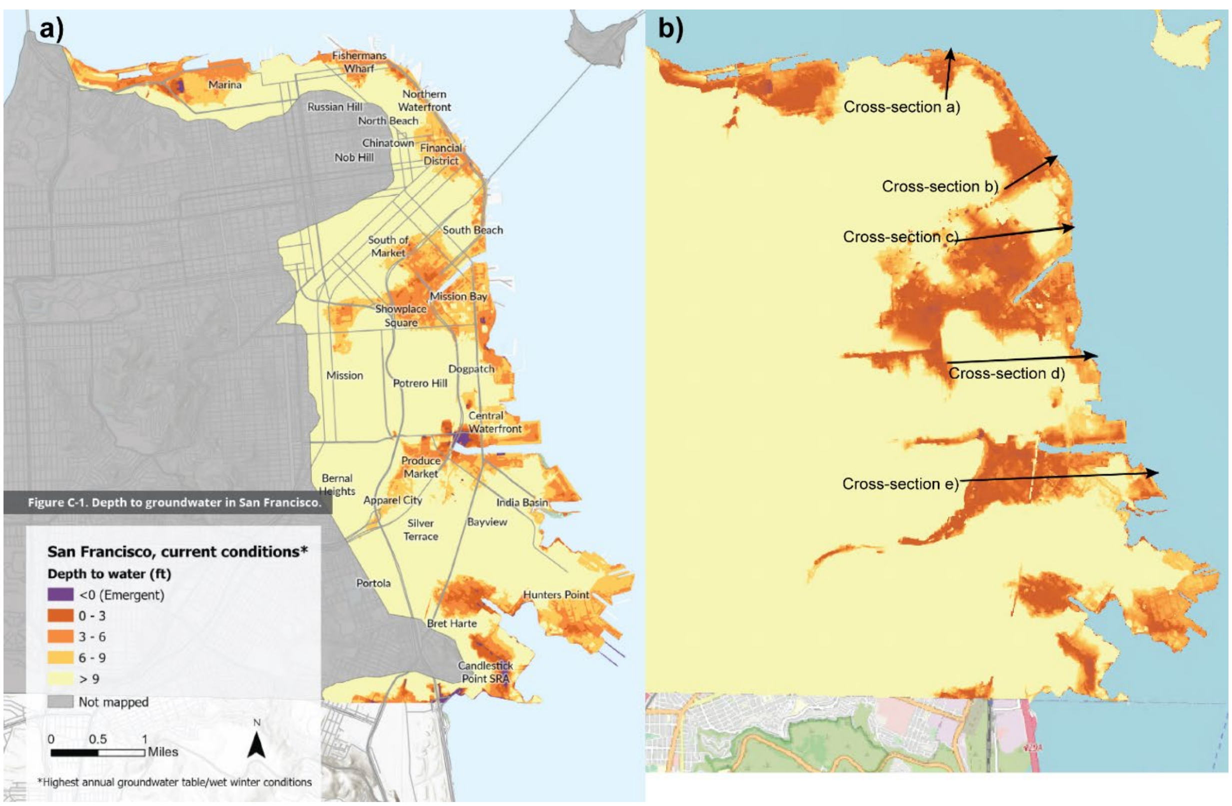
B.1.5-4 Existing and Future Groundwater Depth Analyses for the San Francisco Waterfront

Two assessment techniques have been applied to understand how and where groundwater levels may change with sea level rise over the study area within larger regional analyses (e.g., Befus et al. 2019). The empirical modeling technique interpolates maximum well water level observations[1] to produce maps of the shallowest historic groundwater levels that are raised by the amount of sea level rise (May et al. 2019; Plane et al. 2019; May et al. 2022). This study draws on the network of

[1] SWRCB well observations were filtered to use only maximum well water level observations collected in the winter to spring (Dec – May) after wet winters when groundwater levels are generally at their highest. The filtering process eliminated observations collected during drought years, and eliminated wells that did not have winter to spring measurements within the observational record. 175 wells in the low-lying areas of San Francisco had depth to water measurements that met the project criteria. Many wells have observations extending back to the year 2000 when the SWRCB GAMA program began centrally collecting monitoring well observational data.

over 290,000 observation wells throughout the State of California with monitoring information reported to the SWRCB Groundwater Ambient Monitoring and Assessment Program and made publicly available through GeoTracker (SWRCB, 2022). The numerical modeling technique solves the mathematical equation of groundwater flow to produce maps of forecasted groundwater levels based on hydrologic and geologic inputs to the model (Befus et al. 2020; May et al. 2019). The Befus et al. (2020) study also used the SWRCB and U.S. Geological Survey networks of observation wells to validate the numerical model. Additional details comparing the empirical and numerical modeling methods can be found in May et al. (2019).

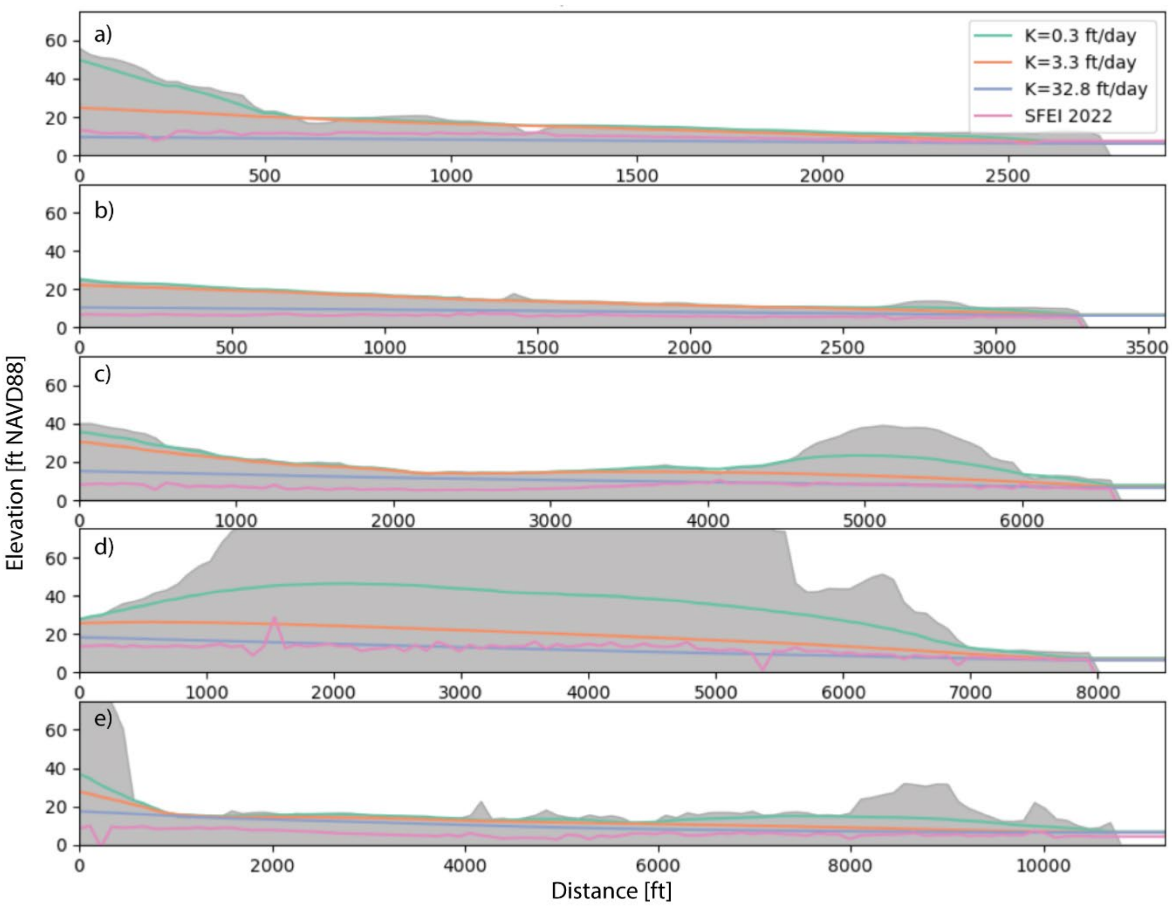
Both techniques indicate the presence of emergent (purple) and/or very shallow groundwater (dark orange, indicating less than 3 feet deep) for existing conditions within the study area as shown in both plan view (**Figure B.1.5-1**) and cross-section (**Figure B.1.5-2**). Sea level rise is expected to expand these areas over time as indicated by orange and light orange shading on **Figure B.1.5-1**. Additional discussion on the existing and future groundwater table is available in *Appendix J: Climate* and Section 4 of *Appendix A: Plan Formulation*.



Source: May et al. 2022; K M Befus et al. 2020

Figure B.1.5-1: Existing Depth to Groundwater Maps for the San Francisco Study Area

Map views of (a) the empirical mapping technique results for the present-day depth to the water table using highest observed water table levels (May et al. 2022), and (b) the numerical modeling technique results for the present-day depth to the water *table with a homogeneous hydraulic conductivity of 3.3 feet per day (1 meter per day), which was the middle value used by (Befus et al. 2020).*



Source: (May et al. 2022; Befus et al. 2020)

Figure B.1.5-2: Cross-section Views of the Present-Day Water Table Elevation

Cross-section views of the present-day water table elevation for both the empirical mapping technique (May et al. 2022) and the numerical modeling technique with three values of hydraulic conductivity (K) (Befus et al. 2020). The locations of these profiles are indicated on Figure B.1.5-1. SFEI stands for the San Francisco Estuary Institute, the host institution for the (May et al. 2022) report.

B.1.5-5 Future Without Project Conditions

Currently, the mean sea level at Presidio gage is approximately 3.2 feet (NAVD 88) as shown in Appendix B.1.1. The ground water table near the shore is roughly at or above mean sea level and with sea level change the groundwater is expected to rise at the same or rate. The average shoreline elevation is approximately 10.5-11 feet, with low points in each reach at approximately 9 feet for Reaches 1 and 3, 8.5 feet for Reach 2, and 7 feet for Reach 4. **Figure B.1.5-3** shows the increase to mean sea level based on the three sea level rise curves when compared to the two shoreline elevations, 8.5 feet representing the approximate low points in the study area and 11 feet representing the average elevation in the study area.

Projected and Observed Sea Level Change

All figures are measured with respect to the North American Vertical Datum of 1988

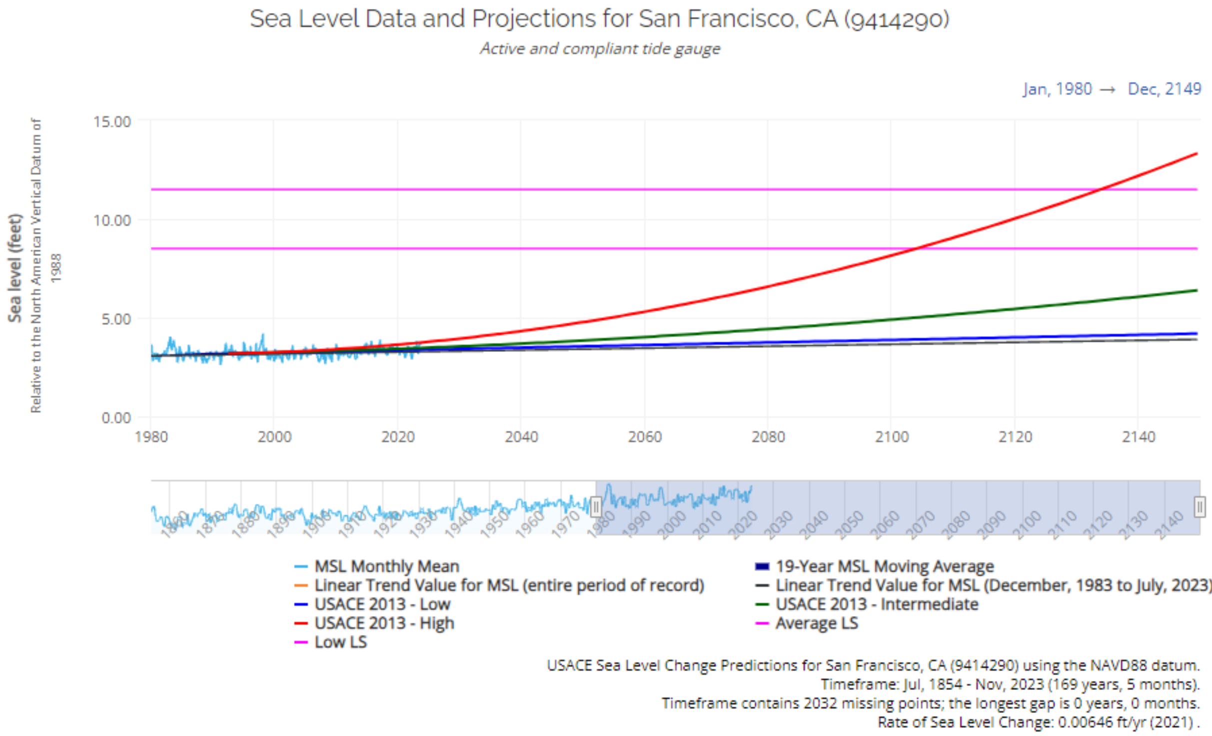


Figure B.1.5-3: Projected and Observed Sea Level Change for Mean Sea Level

The previous section introduced several challenges associated with the groundwater response to sea level rise. The relationship between inflows (e.g., recharge) and outflows (e.g., discharge to the Bay, infrastructure management, or evapotranspiration) is expected to find a new equilibrium in the FWOP condition, where the receiving water condition within the Bay is at a higher mean elevation relative to the land surface. As a result, the occurrence of inland groundwater emergence is expected to increase in frequency and extent, within both the tidally influenced zone as well as within the zone of inland hydrologic control. Currently the city deals with high groundwater throughout the city and groundwater infiltration into sewer systems and sewage exfiltration into shallow groundwater have both been observed and modeled in shallow coastal groundwater systems where the groundwater tables occurred above and below the network, respectively (McKenzie et al., 2019; Su et al., 2020). Additionally, the elevated groundwater table may newly expose subsurface contaminants to mobilization, but further characterization of contaminant type and mobilization potential is required to provide a definitive conclusion (Port of San Francisco, 2023).

Finally, the increased elevation of the groundwater table and potential for increased salinity may increase deterioration and infiltration rates to buried infrastructure (i.e., pipes, structures, tunnels, etc.) which will require Operation, Maintenance, Repair, Replacement, and Rehabilitation expenditures to manage these impacts. None of these impacts have been monetized nor qualitatively evaluated for the purpose of alternative evaluation. With sufficient levels of sea level rise, low-lying areas of the city are expected to be retreated from due to the frequent occurrence of tidal flooding, and it is within these areas that groundwater emergence is expected to be a leading indicator of this condition.

B.1.5-6 Future With Project Conditions

In the FWP condition, several alternatives to manage coastal flood risk are proposed and evaluated to measure monetary and non-monetary benefits (Chapter 4, Main Report, *Appendix A: Plan Formulation, Appendix E: Economics*). The measures used within the range of alternatives can be divided into two groups: non-structural measures and structural measures. Non-structural measures that mitigate coastal flood risk may also reduce groundwater flood risk (e.g., below-grade floodproofing, structure elevation, relocation, etc.). Structural measures include varying types of shoreline coastal defense systems that are generally comprised of floodwalls and levees. Each structural system is assumed to have a partial depth subsurface cutoff wall to limit seepage and effectively reduce the tidal influence on the landside groundwater elevation. Additionally, due to seismic hazards present within the study area, the structural alternatives all assume ground improvement (e.g., deep soil mixing, jet grouting, compaction grouting, etc.) will be required to ensure the shoreline subsoils are sufficiently stabilized to meet operational and life-safety seismic performance criteria.

The alternatives introduce additional complexity into groundwater behavior in coastal settings. However, the additional infrastructure from the proposed lines of defense are not expected to cause issues to the groundwater levels more than what would be seen in the FWOP condition. Barriers, grouting, and compaction aimed at lowering liquefaction potential would also reduce permeability and potentially porosity, which could lead to higher water tables landside of the improvements. But dynamic signal changes in the groundwater levels would depend on the relative change of each alteration and the balance between the relative control of either inland hydrology or Bay water levels on the groundwater. Conversely, if the water table is already high and requires dewatering, the reduction of porosity and permeability could reduce the connectivity of the coastal groundwater system from the Bay, allowing for more efficient dewatering and less capture of infiltrated Bay water. Quantitative modeling or observation-based analyses would be required to determine the impacts of seismic stability improvements on groundwater responses with and without considering sea level rise and pumping.

The importance of storm sewers, underground water storage systems, and pumping all intersect within the water budget (groundwater and surface water) in setting mean groundwater table depth and its variability with sea level rise and precipitation. Groundwater infiltration into sewer systems and sewage exfiltration into shallow groundwater have both been observed and modeled in shallow coastal groundwater systems where the groundwater tables occurred above and below the network, respectively (McKenzie et al., 2019; Su et al., 2020). Similarly, the amount of pervious and impervious surfaces over a groundwater-shed has a considerable influence on both groundwater emergence and intrusion: more pervious green infrastructure solutions could reduce runoff but could enhance recharge and raise water tables, causing more groundwater emergence while also potentially reducing saltwater intrusion. Green infrastructure solutions near the Bay may also become less effective as the groundwater table rises.

The San Francisco shoreline is already highly modified, with substantial filled areas, seawalls, bulkheads, and wharves, and a variety of other shoreline structures. Limited areas within the study area have naturalized shorelines.

The alternatives proposed for the San Francisco Waterfront Coastal Flood Study were not analyzed in detail relative to groundwater flows and the inland water budget. Three elements of these alternatives are discussed relative to their potential groundwater impacts:

- Raising the seawall/shoreline infrastructure to keep rising Bay water levels from entering inland developed areas.
- Using water control structures (tide gates).
- Creating or enhancing natural or nature-based solutions or hybrid solutions to reduce wave energy and minimize coastal flood risks.

B.1.5-6.1 Raising the Seawall/Shoreline Infrastructure

Raising the shoreline to create coastal flood defenses is a common adaptation response to sea level rise. Figure B.1.5-4 presents a hypothetical existing shoreline section, with a seawall, Bay fill located behind the seawall, and a present-day tidal range below the existing elevation of the ground surface. Near the shoreline, the shallow, unconstrained groundwater table may fluctuate with the tides within a spatially variable zone of tidal influence set by the thickness of the aquifer and its hydraulic properties. Inland from this zone, the elevation of the groundwater table is controlled by hydrologic conditions (e.g., zone of inland hydrologic control). Groundwater flows from upland and inland areas toward the seawall.

If the seawall is raised and the inland ground elevation is also raised to accommodate future sea level rise, the inland groundwater table will also rise and future groundwater surface is maintained below the future ground elevation. Furthermore, if a fully penetrating cutoff wall was installed inland of the existing structure, the groundwater levels inland of the structure would rise until a sufficient hydraulic gradient was established to allow the upland groundwater to escape laterally around the barrier or until groundwater emergence led to seepage to the land surface.

Levees used as a line of defense is commonly done in developed areas, where adaptation strategies are limited to the shoreline areas. For this case, only the area adjacent to the shoreline is raised, and the ground surface elevation gradually slopes down to meet the existing grade. In this scenario, the zone of tidal influence may increase and create emergent groundwater conditions near the intersection of the new and existing ground elevations.

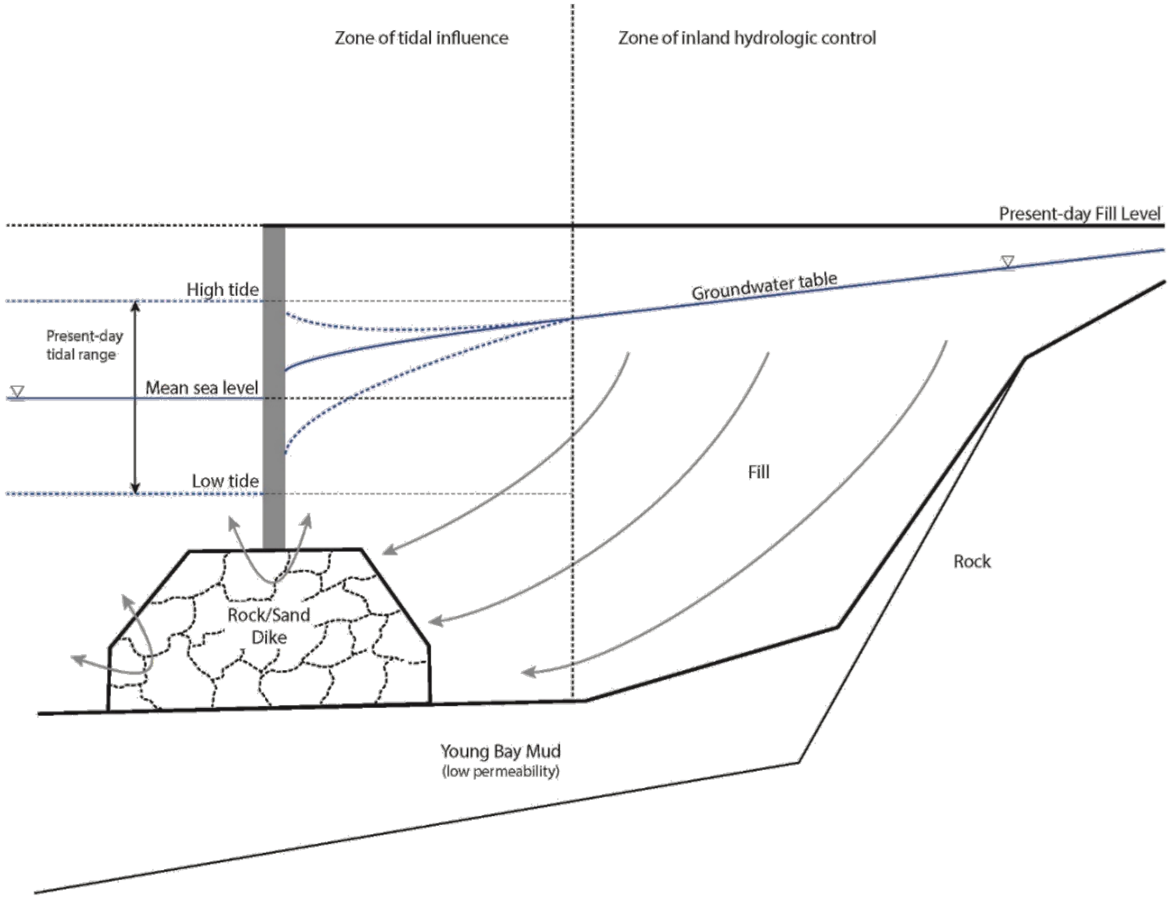


Figure B.1.5-4: Existing Seawall and Present-day Tides

Simplified representation of a coastal groundwater flow system with a seawall and fill area under existing conditions with no pumping.

B.1.5-6.2 Water Control Structure at Creek Inlets

One alternative considered includes water control structures (e.g., tide gates) at the mouth of both Islais and Mission Creeks. Tide gates would allow drainage to the Bay during lower tides and restrict inflow on higher tides, resulting in lower water levels in the protected areas. As sea level rise raises the elevation of low tides, the performance of a tide gate built today would decrease until little to no discharge flows out during low tide, shifting the system from being net drained to net impounded (Befus et al. 2023). In the longer-term, the water control structure would remain closed, and a pump station will be installed in the creek area behind the water control structures.

From theory (i.e., Darcy’s Law), maintaining a lower water level in the creek/lagoon with a water control structure would direct groundwater flow to this lower water level (i.e., to the creek). During high Bay levels, groundwater discharge to the creek could be increased. However, this effect requires more analysis on groundwater response timescales and groundwater discharge effects on the water budget of the creek.

B.1.5-6.3 Natural and Nature-based Solutions

One alternative considers large-scale retreat of industrial areas and Port of San Francisco working lands, and conversion of these areas to wetlands and nature-based solutions to reduce flood risk. The question of concern relative to groundwater is whether a large expanse (e.g., over 500 feet wide, measured perpendicular to the shoreline) of vegetation along the shoreline can help depress a rising groundwater level in response to sea level rise. Once established, a swath of water-intensive vegetation could transpire sufficient groundwater to reduce the effect of rising sea level. This vegetative barrier would likely have a cyclic effect on groundwater levels with transpiration occurring only during daytime, such that the net transpirative flux during the day would need to overcome the local groundwater flow conditions over the period without transpiration. In addition, the vegetation solution would need to allow the groundwater table to slope toward the Bay. If the groundwater table instead sloped inland, then Bay water would flow toward the vegetation and potentially lead to sufficient salinization to require salt tolerant species.

B.1.5-7 Conclusion and Next Steps

This qualitative groundwater assessment presents a summary of existing groundwater conditions along the San Francisco waterfront and potential FWOP and FWP groundwater conditions and challenges associated with the coastal flood risk mitigation alternatives. The following presents the conclusions from the qualitative groundwater assessment.

- The San Francisco waterfront has a groundwater table that is topography-limited meaning there is little topography to accommodate a rise in the water table. Thus, groundwater emergence is likely to occur, and saltwater intrusion would also occur as the water table gradient lessens with higher sea level.

- The CFRM measures are not expected to impact groundwater conditions more than what would be seen in FWOP.

- Partial cutoff walls to limit seepage below the coastal defense structures may mute the tidal influence on the groundwater table elevation in the nearshore area, which is perceived as a project benefit. However, due to the three-dimensional aspects of groundwater flow, the long-term equilibrium of groundwater inflow and outflow within the zone of inland hydrologic control relative to the performance of the FWOP and FWP condition is not known at this time.

- There is a high level of uncertainty in this item during the feasibility phase, and groundwater was not a primary driver for plan formulation. To lower this uncertainty and fully understand the scope of groundwater characteristics, field tests could be performed during the Preconstruction, Engineering and Design phase, including hydraulic parameter tests (e.g., pump or slug) and frequent (<30 min) groundwater level monitoring within a network of wells for several months, including over a winter season to capture the seasonal effects of precipitation. This information can inform future analysis of groundwater flow where soil and aquifer hydraulic properties, a three-dimensional hydrogeologic framework, topography, water sources, and tidal boundaries are considered. With a calibrated model of existing groundwater flow conditions, the proposed coastal flood risk mitigation infrastructure can be analyzed to understand hydrologic response including the need for inland drainage or groundwater management systems.

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