Sea-level rise impacts on shallow groundwater in Moffett Park

A technical addendum to the Moffett Park Specific Plan

November 2021

Prepared for the City of Sunnyvale

Sunnyvale

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Contents

1. Introduction

Sea-level rise (SLR) can raise the shallow groundwater table near coastal shorelines, with the pace and extent of groundwater rise depending on the geologic and hydrologic conditions of the shallow aquifer and the surrounding soils. Rising groundwater can damage buried infrastructure, roadway subgrades, and building foundations, re-mobilize buried soil contaminants, increase liquefaction risk, cause construction challenges, and can ultimately emerge above the ground as surface flooding. Higher water tables also reduce channel drainage capacity for stormwater, adding to surface flooding problems. Traditional shoreline flood risk management structures like levees and floodwalls are generally not designed to address groundwater rise associated with sea-level rise, though they can include subsurface elements to reduce groundwater flow rates. Adaptive strategies like expanding capacity of stormwater systems, raising finished floor elevations, cutoff walls, pumping, and waterproofing buried utilities can help increase community resilience to rising groundwater levels.

Moffett Park, part of the City of Sunnyvale, is located near the San Francisco Bay (Bay) shoreline. Former salt ponds and wetland restoration areas separate Moffett Park from the Bay. Development in Moffett Park requires an understanding of the existing and potential future groundwater levels to inform climate-smart development and infrastructure planning, as extreme rainfall events and SLR are likely to exacerbate flood risk. For more information about SLR and flood impacts in Moffett Park, refer to the Sunnyvale SLR Adaptation Strategy, a technical addendum to the Moffett Park Specific Plan (MPSP) (ESA & SFEI, 2020). The present technical addendum builds on this previous work and provides additional context about the existing and future shallow groundwater table, its projected impacts, and potential adaptation strategies to address these impacts within Moffett Park.

2. Background

Where shallow freshwater aquifers are connected to oceans and estuaries, the rate of rise in groundwater levels in response to rising sea levels is determined by geologic and hydrologic conditions near the shoreline. In “recharge-limited” areas the elevation of the groundwater table is controlled primarily by rainfall, with a higher water table observed during and after rainfall events, and a lower water table during the dry seasons and drought years. Water tables in recharge-limited areas near the shoreline will likely rise at the same rate as sea levels. In other areas, SLR pushing groundwater levels upward can result in more groundwater discharge into channels, limiting the overall rise in the water table. This dynamic occurs in “topography-limited” systems (Michael et al., 2013) (Figure 1). The rate of groundwater rise in topography-limited systems may be slower than the rate of SLR; however, impacts are still likely to occur. For example, saltwater intrusion (saline groundwater moving inland) will be exacerbated by SLR in topography-limited systems, and a reduction in stream channel capacity can mean exacerbated flood impacts during storm events.

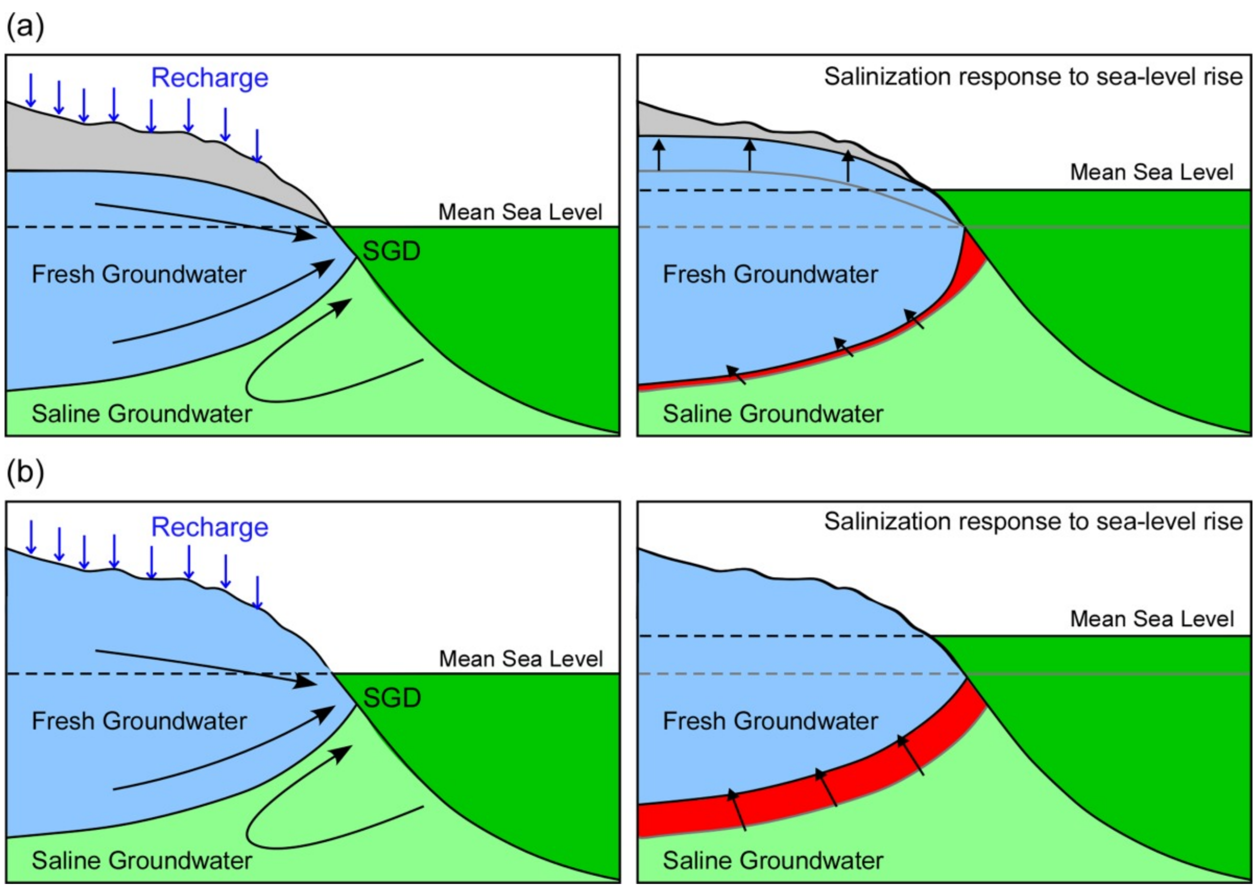

Figure 1. Diagram of (a) recharge-limited and (b) topography-limited coastal groundwater systems. “SGD” is submarine groundwater discharge. From Michael et al. (2013).

A recent analysis of the projected impacts of rising sea levels on the long-term equilibrium shallow groundwater table along the California coast (Befus et al., 2020) found that for about 70% of the state's coastline, including Moffett Park, the total rise in the water table was limited by discharge to channels ("topography-limited"). However, the low-lying urban areas around San Francisco Bay with poor surface drainage may be among the most vulnerable to groundwater hazards (Befus et al., 2020). The northern part of Moffett Park falls into this category as it is a subsided area mostly below mean high tide with a stormwater system that requires pumping to discharge to the Bay.

As sea levels rise, higher mean water levels in the Bay will likely cause shallow groundwater to rise in Moffett Park, first affecting subsurface infrastructure and eventually causing groundwater emergence. The minimum depth to groundwater measured is approximately 3-6 feet below the ground surface, so groundwater is unlikely to be emergent before sea levels rise three feet, which is likely by the end of the 21st century (CNRA-OPC, 2018). The minimum depth to groundwater generally occurs during or after heavy rainfall events in wet winters with above-average rainfall.

Layers of dense clay found below the ground surface in the Moffett Park area may also affect the relationship between sea-level rise and the water table. The rate of groundwater flow through a dense clay layer is very low. Long-term rise in mean sea level can affect the water table even if rates of flow are slow, but the slower flow rates are likely to attenuate the inland rise of groundwater. Some information about the hydrogeology in Moffett Park is provided in the following section. A more robust analysis of subsurface geology and its impact on future groundwater flow dynamics is needed, and will require a detailed 3-dimensional hydrogeological groundwater model.

3. Review of existing information

A. Topography

Much of the Moffett Park area is below the high tide elevation (Figure 2). Berms separate the former salt evaporation ponds bayward of the city from the low-lying urban area. Regional groundwater pumping from the deeper aquifer from the early 1900s through the mid-1960s led to widespread ground subsidence of up to 8 ft in some places, consolidating the subsurface soils (Figure 3). From the 1960s to present, the rate of subsidence has largely been halted by reducing groundwater extraction for drinking water and recharging the deeper aquifers (Santa Clara Valley Water District, 2016). The ground elevation is highest in the southwest corner of Moffett Park, and the ground surface slopes down to the northeast. The corresponding groundwater flow direction is also to the northeast, as shown on Figure 2 (AECOM, 2019; Brown and Caldwell, 1987; Earth Resources Technology, Inc, 2020).

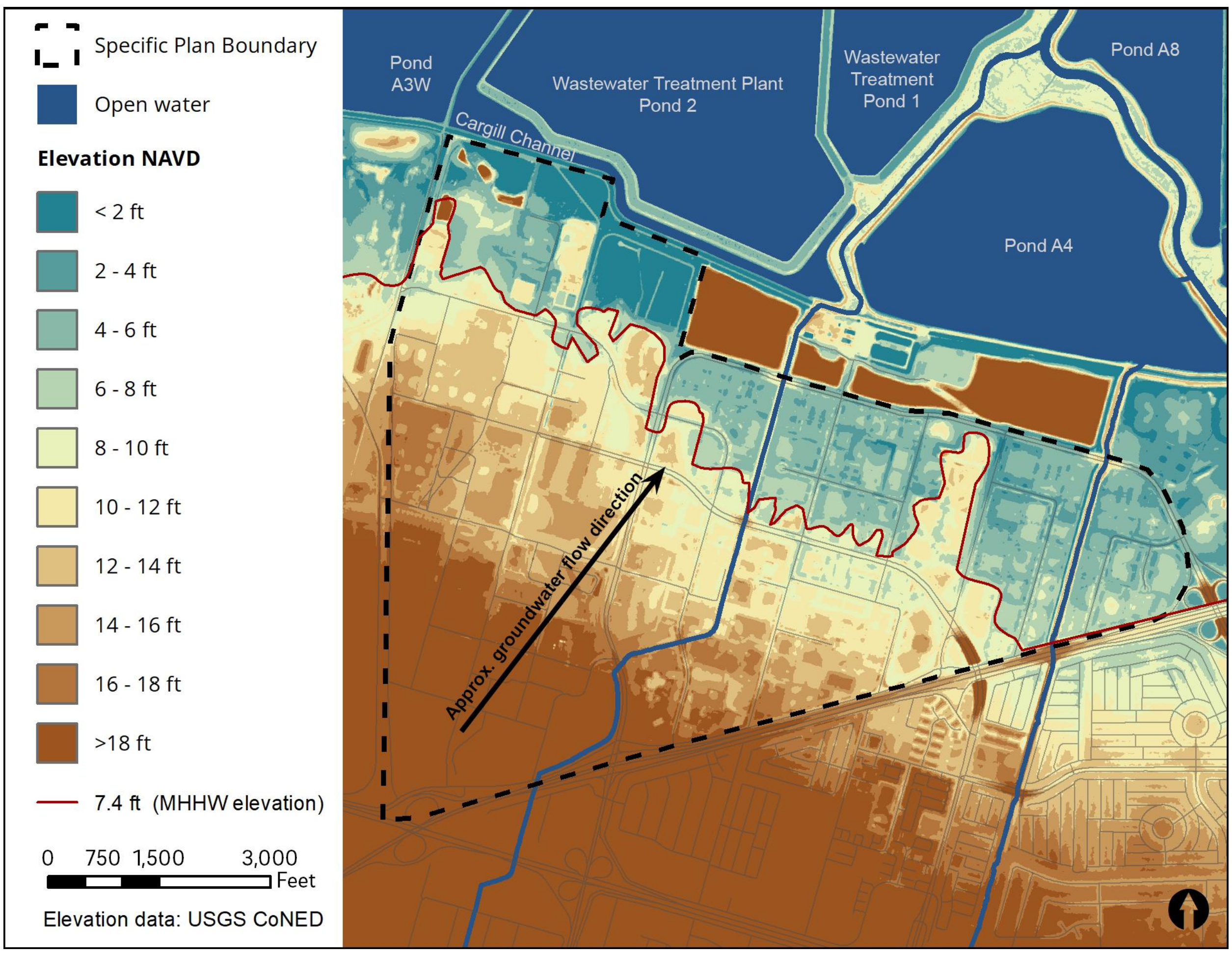

Figure 2. Topography of Moffett Park. Mean Higher High Water is about 7.4 ft NAVD (North American Vertical Datum of 1988).

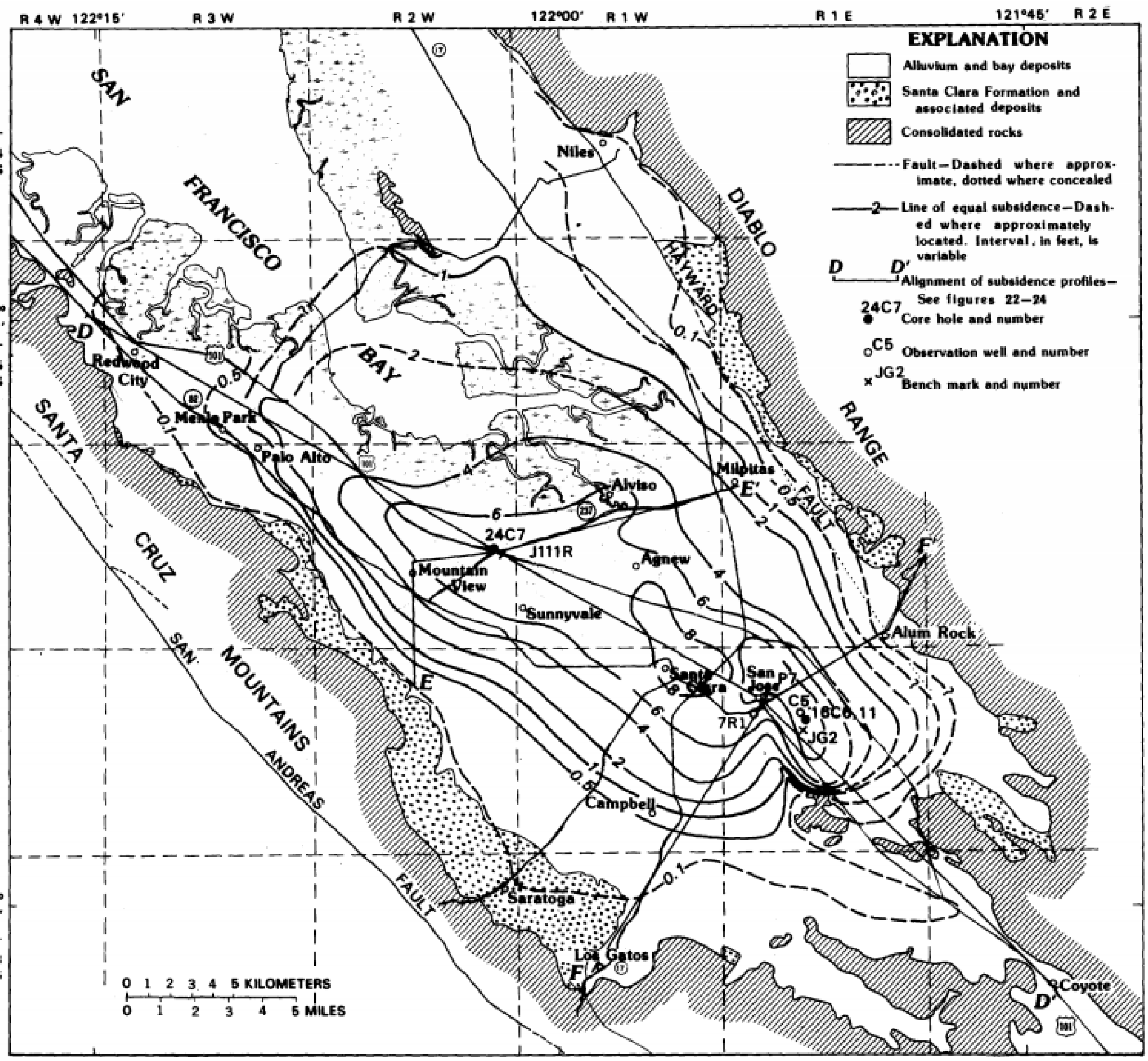

FIGURE 21.—Land subsidence from 1934 to 1967, north Santa Clara County.

Figure 3. From 1934 - 1967, land along the Sunnyvale shoreline subsided about 6 feet, largely due to groundwater withdrawals. Figure from Poland & Ireland, 1988.

B. Hydrogeology

The Moffett Park area lies at the bayward edge of a system of convergent alluvial fans in the Santa Clara Valley. As stream banks shifted laterally over time, they left behind alluvial and sedimentary deposits of sand, clay, and silt (Helley et al., 1979). Nearer the Bay, tidal deposits also influenced geologic conditions, and organic-rich clays can be found up to 10 feet above mean sea level in the surficial deposits of this area (Brown and Caldwell, 1987). Therefore, the subsurface geology of the Moffett Park area is complex, with lenses of fine-grained clays interwoven with coarser sandy deposits (AECOM, 2019; Brown and Caldwell, 1987; Ecology and

Environment, Inc., 1990; Iwamura, 1980; Santa Clara Valley Water District, 2016). The majority of the groundwater is found within larger pore spaces in the coarser deposits (i.e. the larger pore spaces can hold more water). The clay layers are less permeable so groundwater moves very slowly through them. In Moffett Park there is a large area of thin, sinuous, near-surface aquifers, which have limited connectivity with one another and the Bay and are separated by clay aquitards (Figure 4).

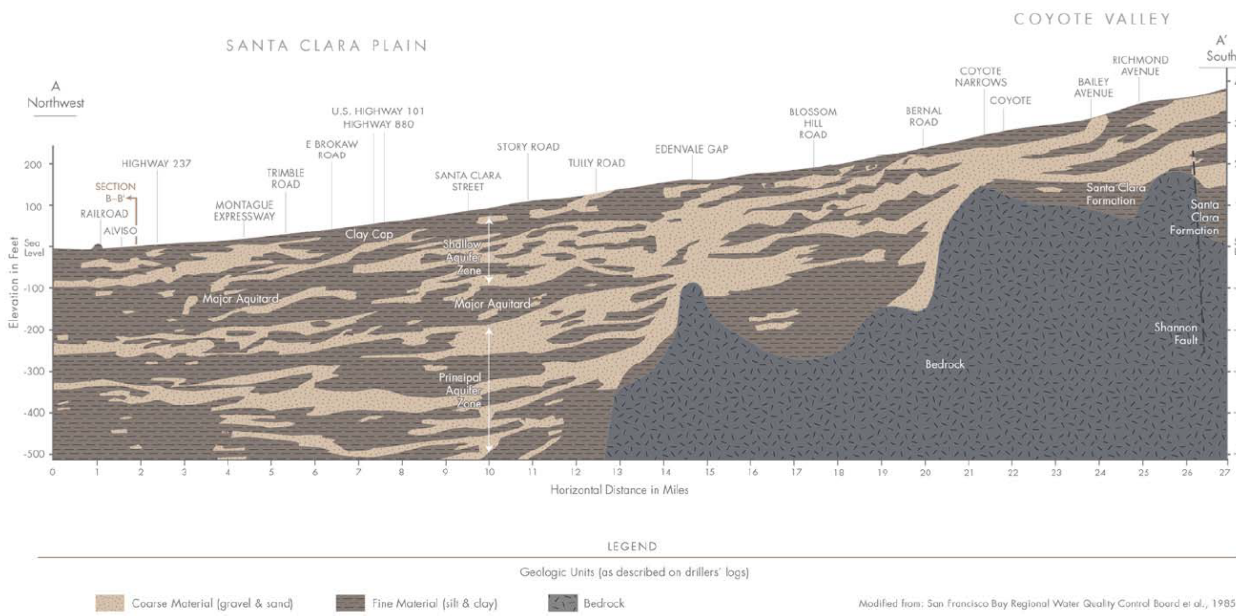

Figure 4. Drawing of the complex geology underlying the Moffett Park area, showing aquifers interspersed with layers of dense clay. The shoreline is toward the left side of the figure. Figure from SCVWD (2016).

According to soil survey data in the SSURGO (Soil Survey Geographic Database: field survey data compiled by the National Cooperative Soil Survey), soils in the area are poorly drained, and a typical soil profile is clay to 35 inches below ground surface, with clay loam, gravelly loam, and clay layers below (USDA-NRCS, n.d.). The shallowest aquifers in Moffett Park are composed of silty/clayey sands. They are found at 5-25 feet below ground surface and are about 5-20 feet thick (Brown and Caldwell, 1987; Ecology and Environment, Inc., 1990). Underneath this layer a clay aquitard mostly seals off the upper aquifer. There is some connectivity between the upper and deeper aquifers (Figure 5), and some evidence of saltwater intrusion in both layers.

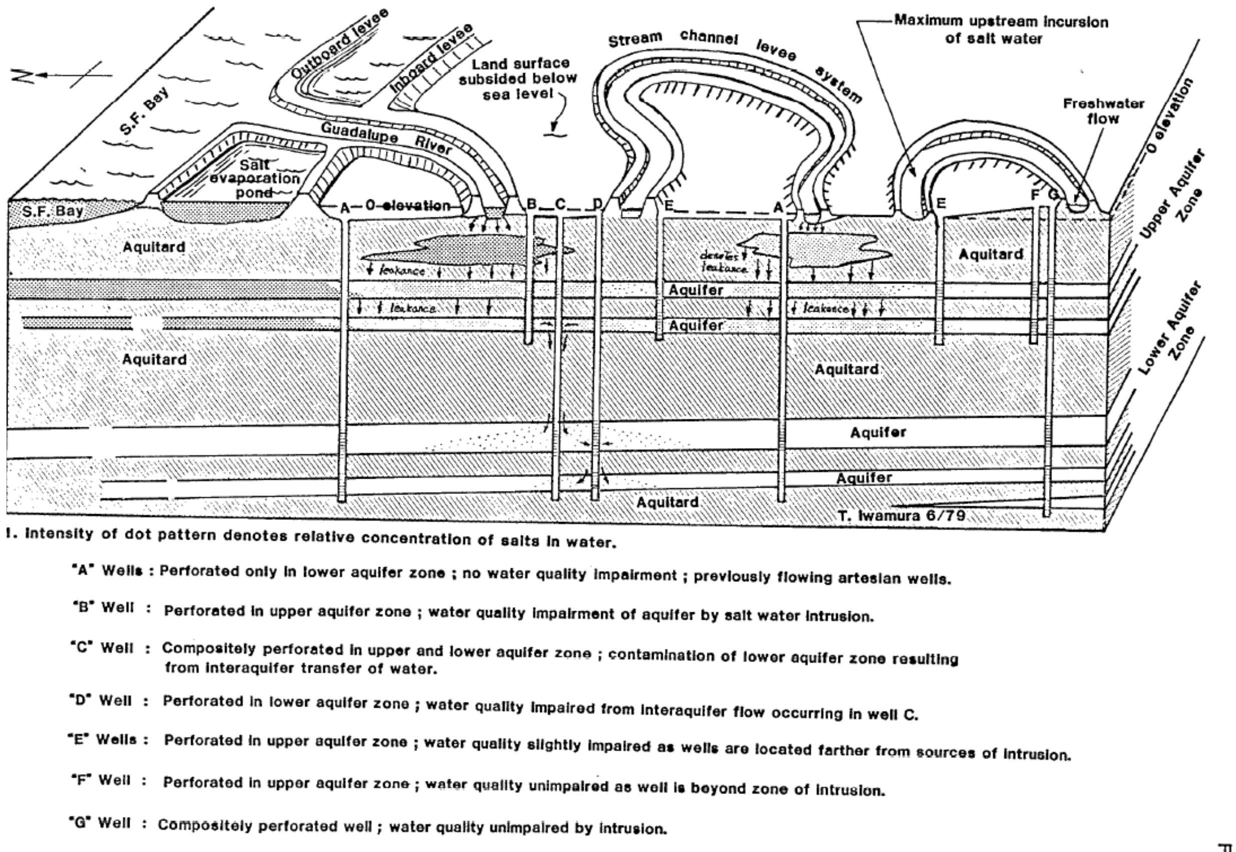

Figure 5. There is some recharge from the surface into upper aquifers, though extensive aquitards restrict movement between aquifers. Figure from Iwamura (1980).

Rainfall is the main source of fluctuation in the groundwater table. A 1985-1986 investigation of groundwater underlying Moffett Park that measured depth to water on a monthly basis found that rainfall affected groundwater levels seasonally, though the water table fluctuated by less than a foot from the wet season to the dry season (Brown and Caldwell, 1987). Consistent with other low-lying areas near the Bay shoreline, the highest water table elevations were measured at the end of the wet season in the late spring/early summer, and the lowest water table elevations at the end of the dry season in late fall.

There is some evidence of connectivity between the open drainage channels and shallow groundwater in and near Moffett Park. For example, farmers in the baylands area along the tidal reaches of the Guadalupe River historically reported damage to crops from saltwater intrusion (Iwamura, 1980). An investigation in the 1980s found there was a connection between the Lockheed stormwater channel (which runs from south to north along E Street) and the shallow aquifer (Brown and Caldwell, 1987). A similar condition likely exists at the stormwater ditch adjacent to the Sunnyvale East Channel. The Sunnyvale East and West channels themselves are primarily earthen (i.e. not concrete-lined) in Moffett Park; however, the channel beds are at higher elevations above today's groundwater levels. Multiple investigations of possible hydraulic connections between shallow groundwater in the Moffett Park area and the Bay have found little evidence of tidal influence on shallow groundwater levels except near tidal channels (Behrens & Gurdak, 2020; Brown and Caldwell, 1987)). More information on tidal connectivity is provided in Section D of this chapter.

C. Contamination

Groundwater and soils in the Moffett Park area have been impacted by the history of industrial activities in the area and cleanup efforts at contaminated sites. Much of the public documentation about groundwater conditions in Moffett Park is associated with contamination from Lockheed Plant One and other sites (e.g. Sunnyvale Naval Industrial Reserve Ordnance Plant, Onizuka Air Force Station, and leaking underground storage tank cleanup sites) where remediation and monitoring has been required by regulatory agencies. Lockheed Plant One is an approximately 660-acre site on the western side of Moffett Park (Figure 6). Manufacturing and chemical facilities were built at the site in the early-to-mid-twentieth century and construction was largely completed by 1963 (Ecology and Environment, Inc., 1990). The Regional Water Quality Control Board issued a cleanup order in 1988 due to pollutant impacts to soil and groundwater from contaminants including volatile organic compounds (VOCs), hexavalent chromium, and nitrate. To manage the contaminated groundwater plume, which was traveling east, a groundwater extraction and treatment system with 11 extraction wells was installed and has been operating since 1993 (Regional Board, 2000). The extraction system remains in place, removing and treating about 60 gallons of groundwater per minute and discharging treated groundwater to the City of Sunnyvale sanitary sewer system. Not all of the extracted groundwater comes from the shallowest aquifers; the wells are screened in both the shallowest aquifer as well as two deeper ones. The system removed a total of 33 million gallons of groundwater in 2017 (AECOM, 2019) and so far has been effective at preventing plume migration and removing VOCs (Regional Board, 2000).

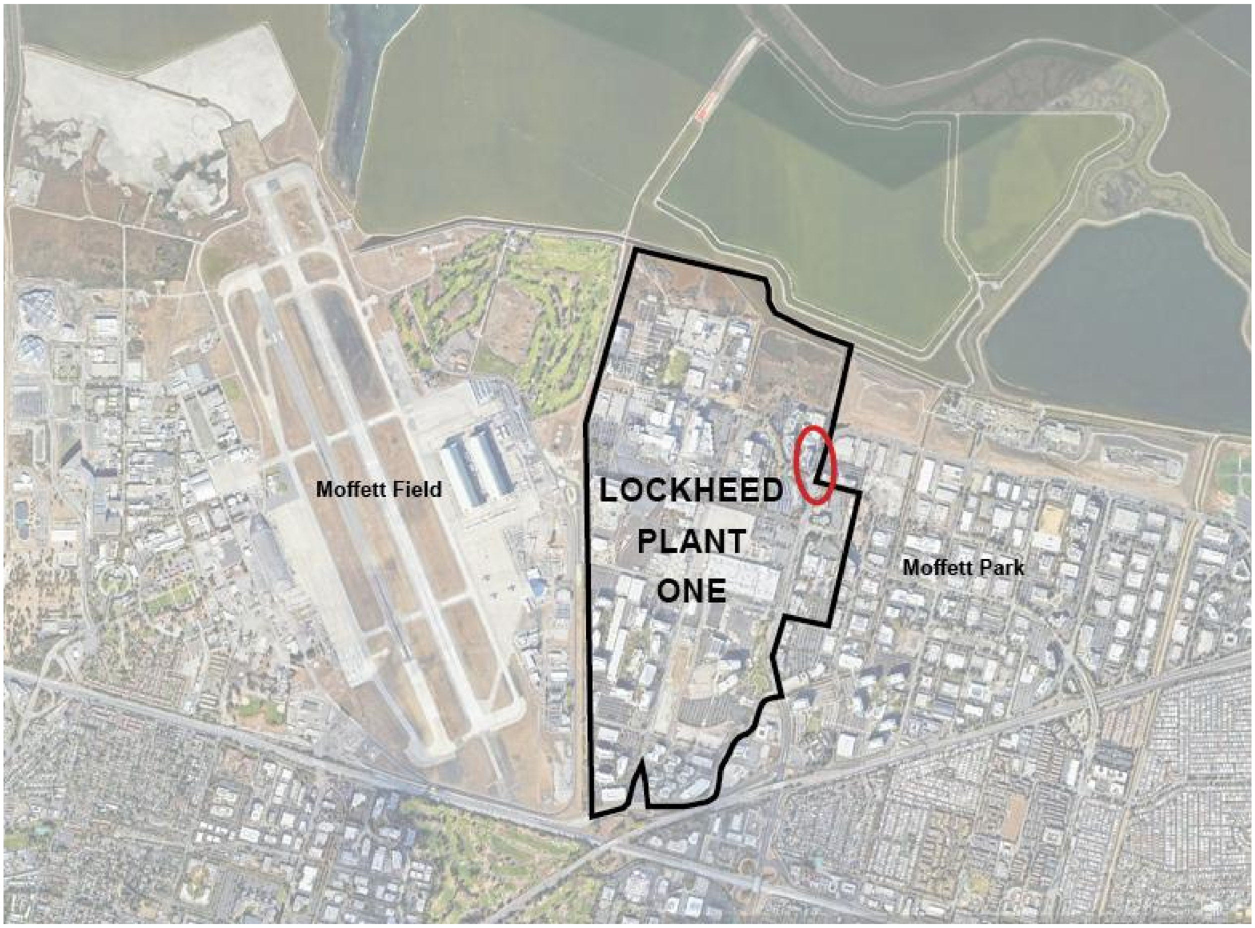

Figure 6. Approximate boundary of the original Lockheed Plant One facility. The red oval indicates the approximate location of the extraction and treatment system. Figure based on Figure 1 from Regional Board (2000).

Another source of groundwater contamination near Moffett Park (outside the Specific Plan area) is the Superfund site at Moffett Field (former Navy, current NASA campus), which has more than 30 hazardous waste sites. The Moffett Field site has been under a cleanup order since 1989, and groundwater extraction and treatment are used as a remedy for VOCs. The site includes 11 extraction wells at two locations. The smaller northern system pumps and treats 20 gallons of groundwater per minute and discharges to Stevens Creek. The larger southern system pumps and treats up to 120 gallons per minute and is discharged into the NASA stormwater retention pond. In 2019 the NASA extraction system removed and treated more than 21 million gallons of groundwater (Earth Resources Technology, Inc, 2020).

Pumping affects groundwater levels, and the Lockheed and NASA extraction systems cause localized depressions in the water table. A map of groundwater levels at the NASA campus created using measured groundwater elevations shows the relatively contained area of influence around each extraction well (Figure 7).

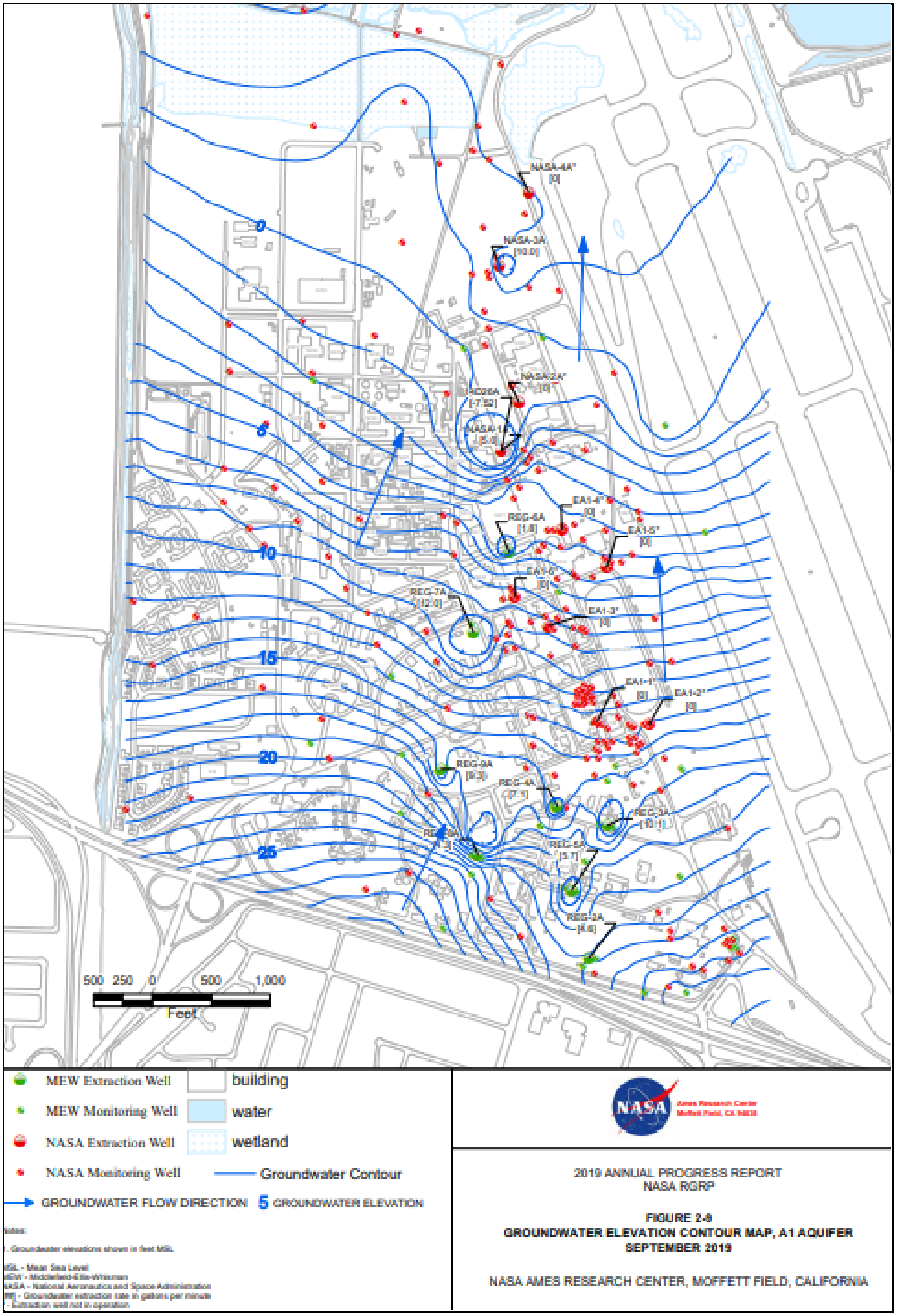

Figure 7. Though the NASA Ames Research Center and Moffett Field campus is west of the Moffett Park study area, this contour map provides a good example of the localized influence of extraction wells on the water table in the general vicinity of Moffett Park. Elevations are feet MSL. Figure from Earth Resources Technology, Inc, 2020.

The City of Sunnyvale landfill, located just north of Moffett Park, is also under an order from the Regional Water Quality Control Board to monitor and maintain groundwater quality (Regional Board, 2004). The landfill closed in 1993 and is capped from above but is not lined below. To prevent groundwater contamination, landfill leachate (water seeping through the landfill waste) is extracted in 8 locations. The extraction system intercepts leachate and prevents it from flowing into sewer pipes to the adjacent Water Pollution Control Plant, which is not equipped to treat the types of contaminants present in the leachate with its regular treatment process. Though the leachate contains VOCs, no compounds in the leachate nor the groundwater beneath the landfill exceed USEPA criteria, and all contaminants are stable or declining (Regional Board, 2004). The extraction system maintains leachate levels at about the same elevation as groundwater levels.

D. Historical & present groundwater elevations

An empirical source of information about groundwater levels that has been used in multiple regional and local assessments of groundwater conditions (May et al., 2020; Plane et al., 2019) is the Water Board's Geotracker database, which tracks groundwater quality and the depth to the groundwater table in monitoring wells at contaminated sites such as Lockheed Plant One in Sunnyvale. Figure 8 shows the minimum depth to water information (the highest groundwater table elevation) for the Moffett Park area from the Geotracker database, 2005-present. In Figure 8, the wells in the Geotracker database have been selected to display only monitoring wells measuring the shallowest aquifer that have minimum depth to water values measured during the wet season. Depth to groundwater decreases going toward the Bay and is zero (at ground surface) at the Lockheed Martin stormwater ponds where there are seasonal wetlands.

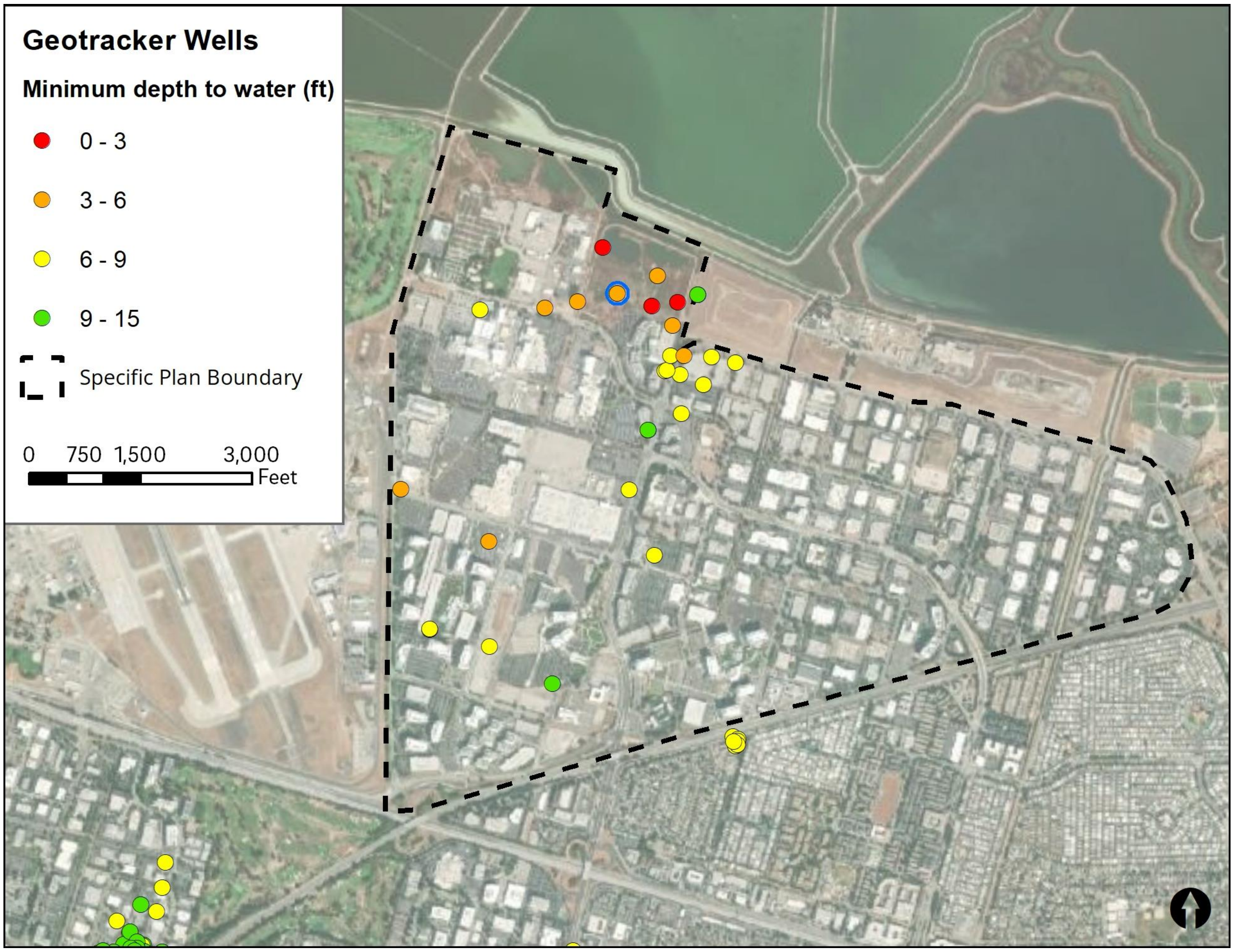

Figure 8. Minimum measured depth to water values from ground surface at Geotracker wells in the Moffett Park area. Many wells have minimum values in the 6-9 foot range. Wells near the Lockheed Martin stormwater ponds in the northwest of Moffett Park have measured depth to water values less than 6 feet. Time series data for the well circled in blue is shown in Figure 9 below.

Plotting data from individual wells over time can also provide useful insights. Though some monitoring wells have been in place since the 1980s, information is only readily available through Geotracker from 2005 onward. The time series show that most wells have a fairly stable depth to water over time, with seasonal fluctuations. See Figure 9 for a typical example. Water tables are higher in the wet season (April values in Figure 9) and lower in the dry season (October values in Figure 9. Most monitoring wells are sampled twice per year to track seasonal differences, but the highest and lowest annual water level elevations may not be captured using this infrequent monitoring approach.

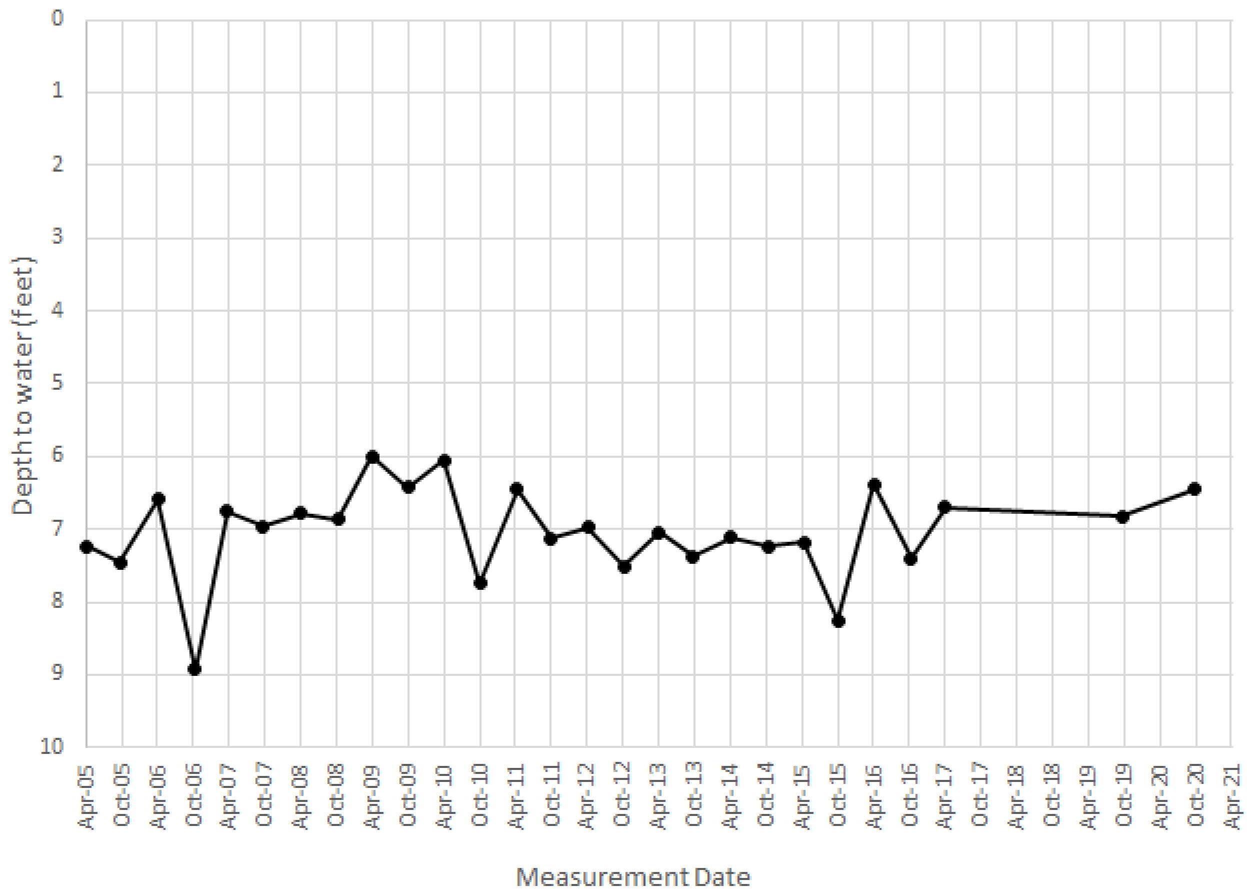

Figure 9. Depth to water over time at an example monitoring well (the well with global ID SL1821F605, field point 175-10, circled in blue in Figure 8 above). This well is located north of 1st Ave and south of the Lockheed stormwater ponds. Note shallower measurements taken in April and deeper measurements taken in October.

A recent regional analysis provides depth to water maps for the coastal communities along the San Francisco Bay shoreline (including Sunnyvale) based on Water Board Geotracker data (Plane et al., 2019) (Figure 10). The analysis used depth to water measurements from the monitoring wells in the database, tidal datums in the Bay, and a digital elevation model of the ground surface to create an interpolated existing shallow groundwater surface. The maps are based on the minimum measured depth to water values at each well between 1996 and 2016 and approximate the highest annual groundwater surface, which is likely to occur during wet winters. In Moffett Park, the shallowest depth to water values are found near the Lockheed Martin stormwater ponds and the Sunnyvale East channel. The depth to water values in Moffett Park largely fall within the 3 to 9 foot range (i.e., the existing groundwater surface is about 3 to 9 feet below the ground surface). The Plane et al. (2019) analysis only mapped areas within one kilometer of an existing monitoring well; therefore a groundwater surface was not produced for the area near the Sunnyvale East stormwater channel.

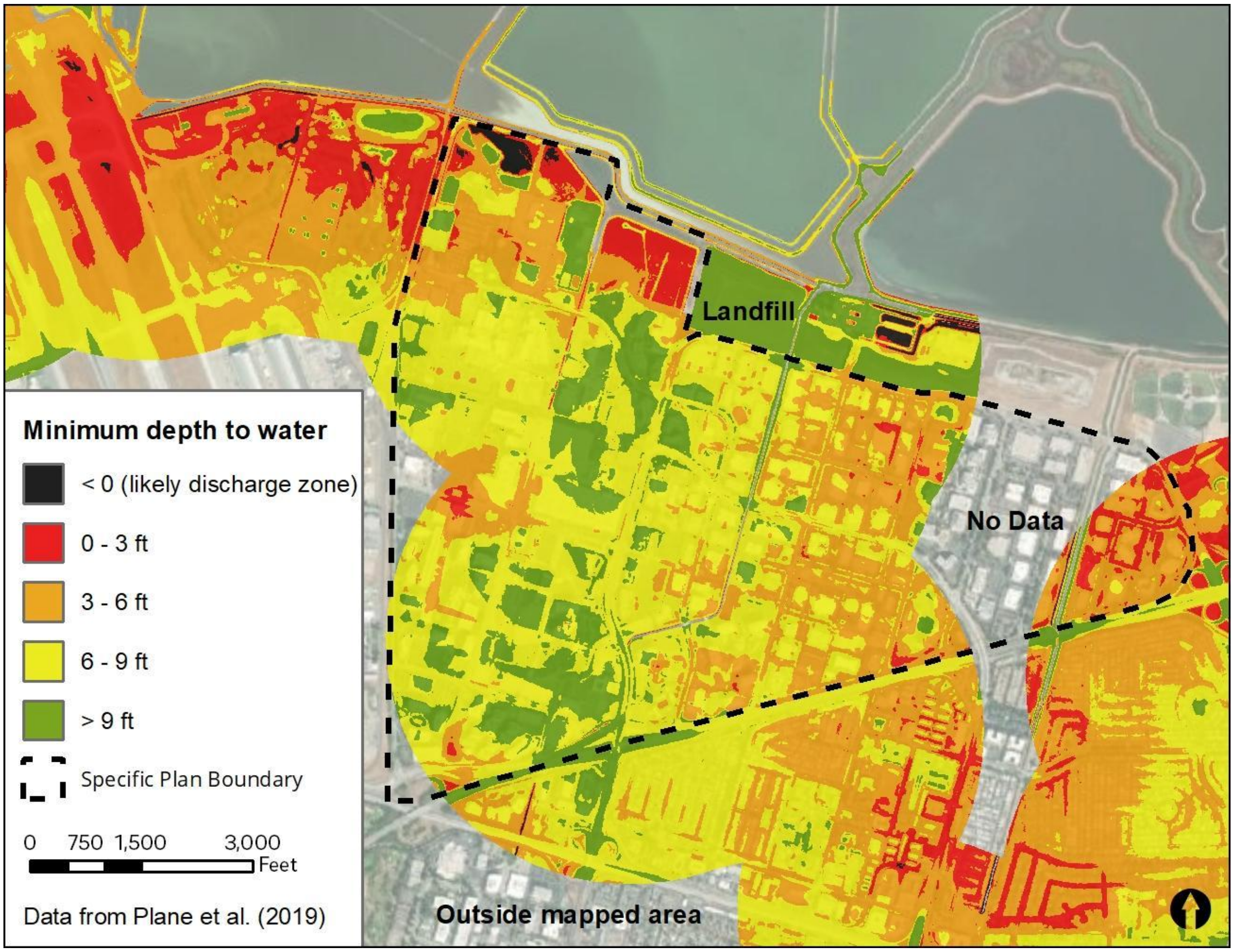

Figure 10. Estimated depth to water in Moffett Park, based on an interpolation between measured values in the Geotracker database.

Additional depth to water data sources were also reviewed. For example, the California Department of Water Resources (DWR) maintains a database of well completion reports with depth to water information, though most measurements are from 1990 or earlier. Figure 11 shows selected points from the DWR database, digitized and georeferenced to approximate locations on the map. This dataset provides additional coverage east of Lockheed Plant One, where most of the wells in the Geotracker database are located. The points from the DWR database are generally consistent with the regional mapping from Plane et al., 2019 and help validate accuracy of the interpolated groundwater surface. However, a DWR well completion report from 1982 provides a depth to water measurement west of the Lockheed extraction wells that is not consistent with the groundwater surface. It is likely that changes to ground surface elevations at this site have occurred over the past 40 years, and/or the installation and operation of the nearby Lockheed groundwater extraction system could explain the discrepancy.

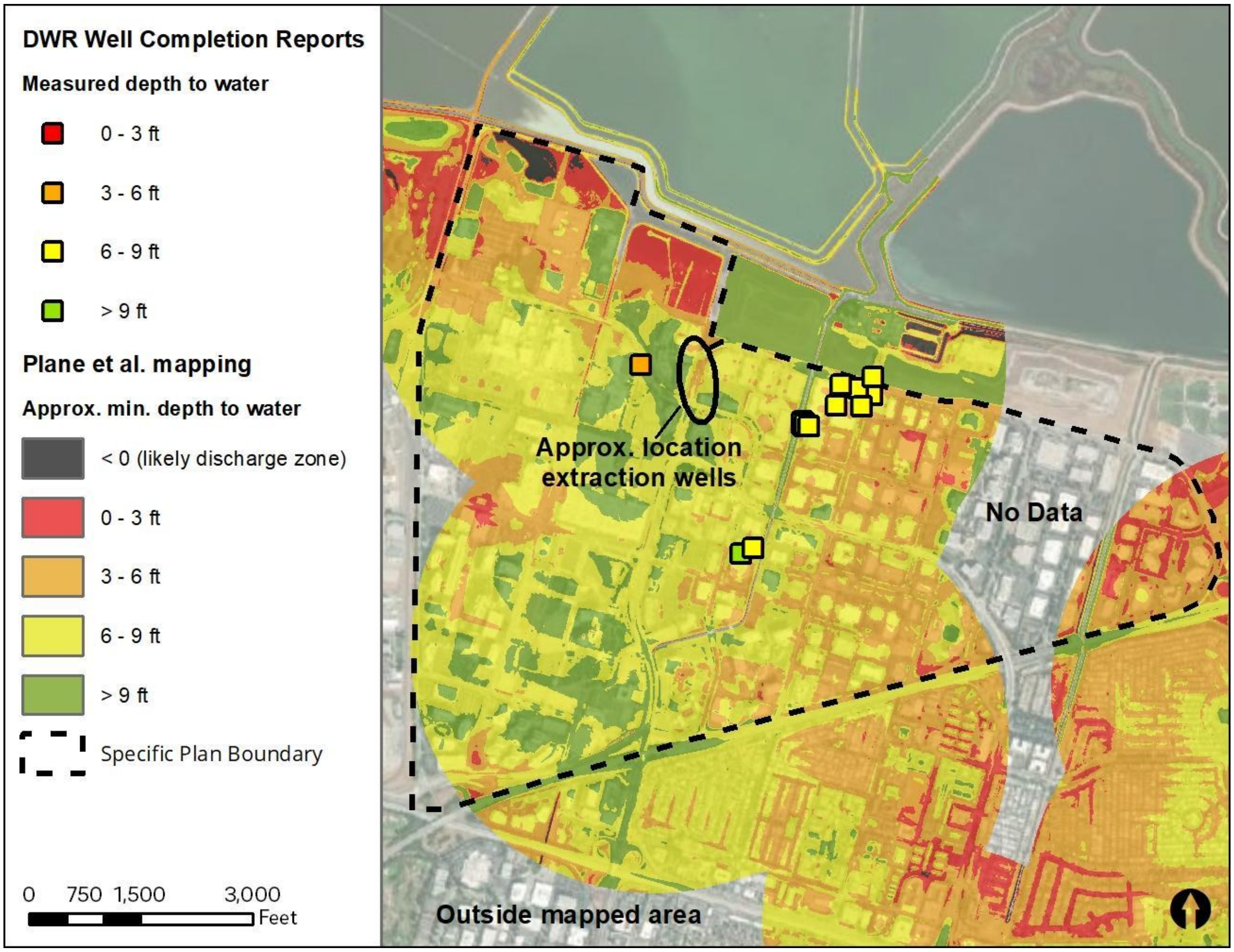

Figure 11. Depth to water information from the DWR Well Completion Reports database generally matches the mapping in Plane et al (2019).

Another way of visualizing the data is to look at groundwater elevation (relative to NAVD88) rather than depth to water (Figure 12). The mapping in Figure 12 is based on a quick interpolation of the points shown in Figure 8 (refined Geotracker dataset). Groundwater elevation maps (as opposed to depth to water) allow for examination of relative groundwater elevations across Moffett Park, especially given the building pads, landfill, and other modified topographies that are reflected in the depth to water mapping. The groundwater elevation map shows the water table elevation declining from higher elevation areas down to the shoreline. Despite the lack of data between Sunnyvale East and West channels from the Plane et al. (2019) study (Figure 11), it is expected that the groundwater elevation contours are generally consistent with the area to the west (south of the landfill and nearer Sunnyvale West Channel), and that this area likely has similar depth to groundwater conditions to the area to the west (3-6 feet depth to water).

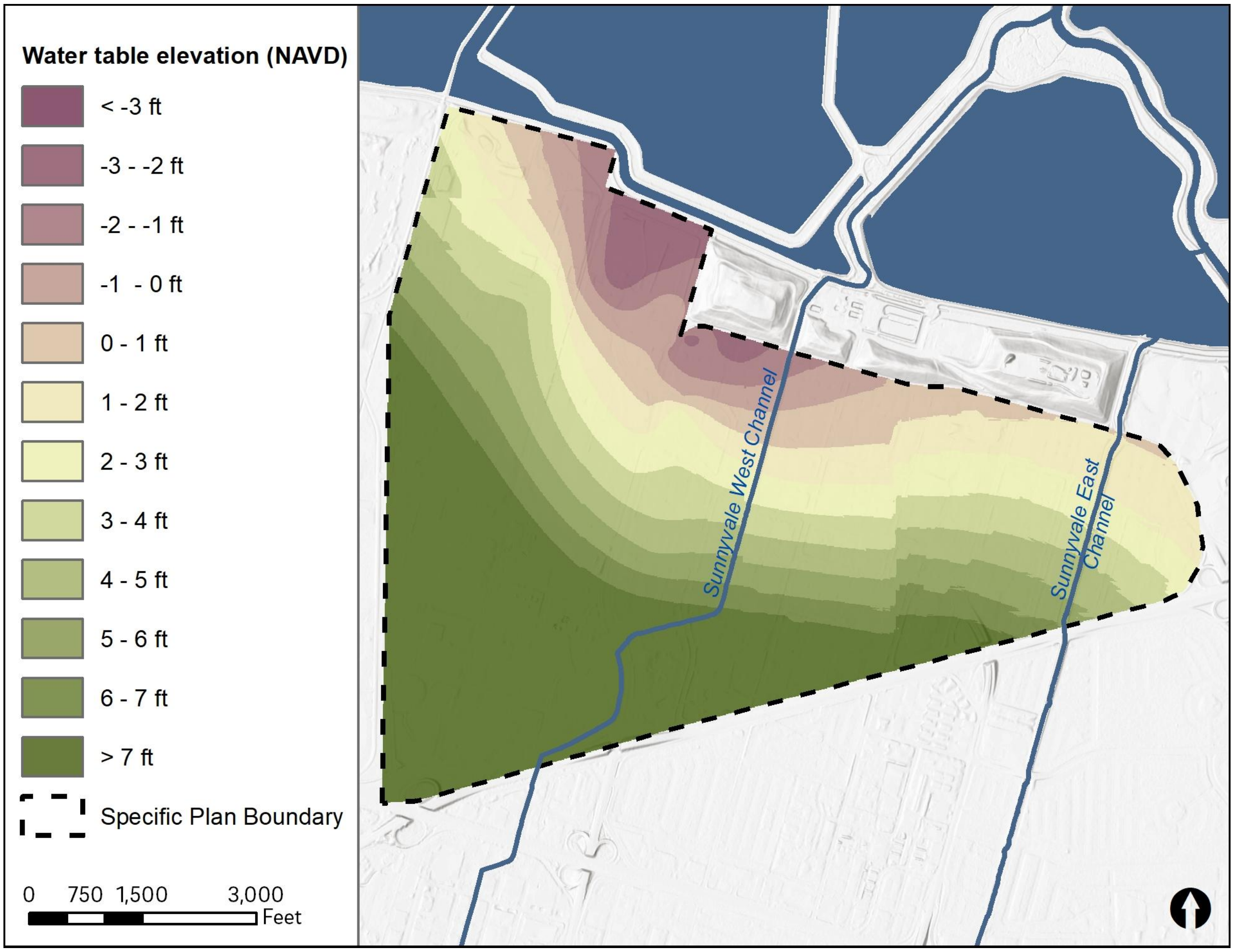

Figure 12. Groundwater elevations in Moffett Park decline going northeast toward the shoreline. Interpolation based on depth to water data from Geotracker and ground elevation data from the USGS CoNED digital elevation model. Lack of depth to water data in the eastern portion of Moffett Park means values may be less accurate in this area.

The groundwater surface can also be explored in areas where ponding water is visible above the ground surface. Based on Google Earth's historical imagery, the elevation of the water surface in the Lockheed stormwater retention ponds (northwest corner of Moffett Park) has remained at or below about 0 ft NAVD over the last decade, which is fairly consistent with measured values from nearby monitoring wells. It is not clear to what extent the stormwater management system (pumping from the adjacent channel) may be affecting water levels in the ponds. Further investigation is warranted.

E. Tidal Influence

In places where tidal fluctuations can be observed in monitoring wells, sea-level rise is likely to result in a direct rise in the groundwater surface. However, long-term rise in mean sea levels may affect the water table regardless of tidal connectivity today. Multiple studies over the years have examined groundwater elevations in and near the Moffett Park area to assess the influence of the tides on the shallow aquifer. These studies (Behrens & Gurdak, 2020; Brown and Caldwell, 1987) found that, in general, no tidal influence was measurable at the locations monitored.

A recent study conducted by Valley Water examined the change in water levels and chloride concentrations at 20 wells of varying depths, as shown in Figure 13. Only two of the wells (Wells 1 and 2) were measuring water levels associated with the shallowest aquifer (5-20 ft below ground surface) and neither well exhibited tidal fluctuations. However, two wells near the Guadalupe River (Wells 3 and 4) exhibited a tidal response, and the authors hypothesized that bridge construction activities at CA-237 had pierced the thick mud, creating a connection between the Bay and aquifer near the well locations.

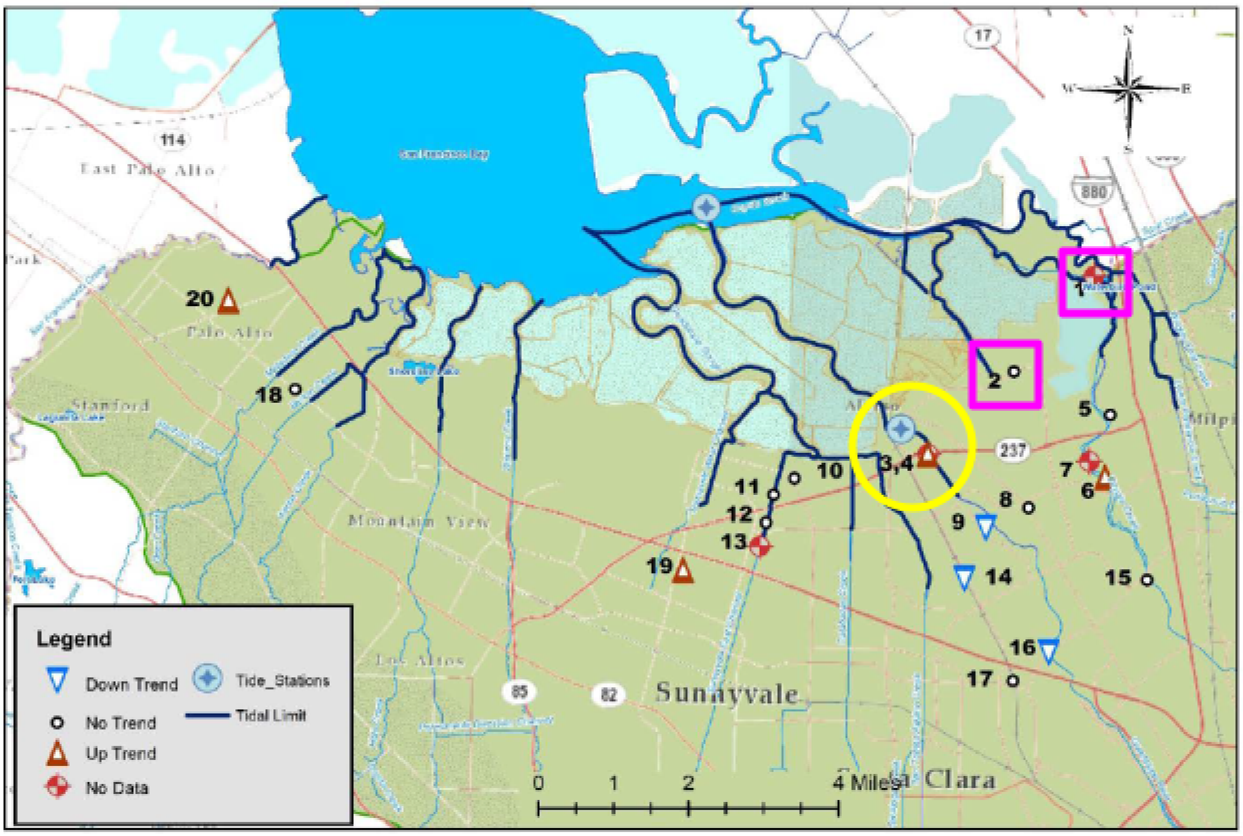

Figure 13. Wells 3 and 4, indicated by the yellow circle, showed a tidal signature. The shallower of these two wells measures the aquifer 27-32′ below ground surface and the deeper well measures the aquifer 73-78′ below ground surface. Wells 1 and 2, indicated by the pink squares, measure the shallow aquifer. Figure adapted from Behrens & Gurdak, 2020.

Due to geologic conditions (clay layers with low hydraulic conductivity), the rate of groundwater flow is likely several orders of magnitude slower than tides. Tides rise and fall twice per day in the Bay, and in the far South Bay the tides can have a range of more than 8 feet (the difference between the highest and lowest tidal elevations). However, groundwater generally moves at a very slow rate, measured in feet per year (or feet per decade) and not feet per day. Thus, tidal influence is not evident in Moffett Park's water table.

The presence of the former salt evaporation ponds bayward of Moffett Park may further mute tidal influence on the groundwater table inland of the ponds. Water levels in the former salt ponds bayward of Moffett Park are managed with hydraulic connections to the Bay. The water surface of the ponds is maintained at about mean sea level: approximately 3-4 ft NAVD (a muted tidal response may occur depending on the management of the hydraulic connections). Tidal fluctuation in groundwater levels is most likely to be seen near tidally influenced channels. This was the case in the Valley Water study referenced above (Behrens & Gurdak, 2020) (Figure 13).

Though the water table in Moffett Park is not tidally influenced today, this does not necessarily indicate that it will not be affected by changing sea levels in the future. Sea-level rise is a slow-paced (and generally monotonically rising) trend often measured in millimeters per year. This rate is more comparable and consistent with groundwater movement than tidal fluctuations, and more likely to influence a longer-term rise in the groundwater table.

4. Future change in groundwater levels

The two major climate variables that affect the elevation of the groundwater table are sea level and rainfall. According to recent projections, sea levels in San Francisco Bay are likely to rise 3.4 feet by 2100, with a rise of 6.9 feet possible (CNRA-OPC, 2018). Rainfall projections are less certain, but the frequency of extreme rainfall events is likely to increase (cal-adapt.org) and rainfall patterns are expected to become volatile with periods of extreme drought separated by more intense extreme storms (He & Gautam, 2016).

A. Modeling of future change

The regional mapping developed by Plane et al. (2019) examined the response of the shallow coastal groundwater surface to SLR using a linear rise in groundwater levels with SLR (i.e. 1 foot of SLR = 1 foot of groundwater rise). The linear approach assumes an unconfined, recharge-limited aquifer.

The shallow aquifer underlying Moffett Park is complex, with silty/clayey sands intermixed with ribbons of more impermeable clay, and portions of the aquifer may be confined at the surface. The surface-expressed groundwater in the Lockheed stormwater retention ponds currently lies several feet below mean sea level, suggesting limited connectivity between the Bay and groundwater. The area may also be somewhat topography-limited, as indicated by surface expression of groundwater in these ponds. With Moffett Park's geologic conditions and the potential for rising groundwater to be drained into the stormwater system, the linear model may not be the best fit for Moffett Park.

However, the water table is likely to respond to a rise in mean sea levels over the long term, even in areas with low hydraulic conductivity. Therefore, although it is possible that the linear approach may overestimate groundwater rise in this area, assuming a 1:1 rise of groundwater with sea level provides a useful upper bound for planning purposes.

Dynamic modeling, which accounts for groundwater recharge and discharge, can provide insights about rising groundwater that the linear model cannot. Befus et al. (2020) used MODFLOW, a US Geological Survey hydrologic model that simulates the flow of groundwater, to assess the response of the long-term equilibrium groundwater surface to SLR along the entire California coast. The modeling provides useful context about regional change in groundwater conditions due to SLR. However, the 10-meter resolution of the model does not capture the complex local stormwater drainage channel and pumping systems of Moffett Park. The model also relies on homogenous soil characteristics, with three model variations representing three soil hydraulic conductivity values. Although the model predicts topography-limited conditions for Moffett Park, the model also predicts much higher groundwater levels under existing conditions than measured values indicate. The differences between modeled values and depth to water measurements from wells throughout the area indicate that the stormwater management system and accurate hydraulic conductivity data to represent the variable soil conditions are important input datasets needed for adequate characterization of the groundwater surface of Moffett Park.

B. Factors affecting future groundwater levels

The rate of groundwater rise in Moffett Park may be reduced if rising groundwater is intercepted by the retention ponds and stormwater collection system and routed to the Lockheed Martin channel and the stormwater ditch west of Sunnyvale East Channel for pumped removal. The stormwater channels flow to pump stations, so any groundwater discharged to them will still need to be pumped out to the Bay.

Change in ground surface elevations can also affect the relative rise in groundwater levels. Ground subsidence has been largely halted in the area due to Valley Water's water import and recharge policies. Though unlikely, increased rates of subsidence in the future could decrease relative depth to water. Raising ground levels also affects depth to water. Though placement of fill does not affect groundwater elevations, it does increase depth to water by placing structures higher above the water table.

Changes to management of the ponds along the shoreline may also affect future groundwater levels. Today, berms surrounding the former salt evaporation ponds protect the Sunnyvale area from flooding and may limit tidal influence on aquifers in the Moffett Park area. Changes to the management of these ponds in the future as they are restored may affect groundwater dynamics by bringing the tides in closer to the developed areas. The impact of tidal restoration on groundwater dynamics in adjacent areas is an important question for the San Francisco Bay region that has not yet been thoroughly investigated.

Even with tidal restoration, it is unlikely that a tidal signal will be seen in shallow aquifers across Moffett Park due to the clayey soils which slow groundwater flow. Since storm surges also occur at the tidal time scale, it is unlikely that the impacts of Bay storm surge events would be seen in Moffett Park's water table. Instead, the slow upward creep of mean sea levels is more likely to drive changes in aquifer conditions. Because groundwater levels are higher in the wet season, impacts will be observed first during wet winters when the groundwater surface is at its highest.

5. Impacts

Due to existing groundwater elevations and geologic conditions, Moffett Park will not be the first place in the Bay to experience severe impacts from rising groundwater. However, given the low ground elevations, the stormwater system's dependence on pumping, potential impacts to the wastewater system, and several contaminated sites in the area, it is important to consider impacts that may need to be addressed to keep the area safe and infrastructure functional as the climate changes. Monitoring and modeling can help pinpoint the onset and magnitude of future risks as the state of knowledge about this climate impact evolves (see Chapter 7), and adaptation strategies are implemented to mitigate impacts (see Chapter 6).

The following list outlines some of the impacts of rising groundwater that may affect Moffett Park as sea levels rise.

- **Corrosion.** Groundwater rise is caused by a toe of saline groundwater intruding farther inland. Near the shoreline, groundwater may become more saline as a result of SLR. A recent Valley Water study found an increasing trend in groundwater salinity over the last 15 years in several of the wells that were measured. This was especially true for wells nearer the Bay (Behrens & Gurdak, 2020). Increasing salinity can increase potential for corrosion of subsurface infrastructure.

- **Buoyancy.** Rising groundwater can exert buoyant forces on foundations, buried utility lines, pipes, roads, and other infrastructure, causing these structures to float or shift.

- **Seepage.** Subsurface structures can be subject to flooding via groundwater seepage through permeable places in the walls and floor.

- **Infiltration.** Groundwater can enter stormwater and sanitary sewer pipes through cracks and joints. Many wastewater agencies already manage this impact today, but flows are likely to increase with rising groundwater levels. Infiltration into sewer pipes can slightly lower groundwater levels in adjacent areas, but also has the effect of reducing capacity for stormwater and/or sanitary sewer flows and potentially causing backups in the system.

- **Liquefaction.** Higher water tables can increase liquefaction risk during an earthquake. Witter et al. (2006) assigned liquefaction susceptibility categories to geologic deposits around the Bay partly as a function of groundwater depth within the deposit. Moffett Park's liquefaction risk today is rated as "moderate," already accounting for the high water tables in this area. Areas primarily composed of mud are unlikely to liquify; the hazard is more severe in areas of artificial fill and areas with alluvial sand lenses. Given the level of damage associated with liquefaction events, it is worth considering the potential for increased risk from rising groundwater levels and designing new structures accordingly.

- **Damage to vegetation.** Saturated soils and higher salinity levels can damage plants that are not adapted to these conditions.

- **Contaminant mobilization.** SLR may affect the movement of contaminated groundwater plumes. Existing remediation sites at the NASA Moffett Field and Lockheed Martin campuses, as well as the Sunnyvale landfill, will need to address the impacts of changing groundwater conditions on their operations. So far, the groundwater extraction and treatment systems have been effective at containing groundwater plumes, but SLR may mean modifications are required for managing contaminated groundwater. Facility managers and regulatory agencies will need to work together to address this adaptation challenge.

- **Emergence flooding.** Across much of Moffett Park, depth to water is 3-6 feet, and in many places groundwater is deeper than 6 feet below ground surface. Therefore, emergence flooding is unlikely to be a concern in the near future: subsurface impacts will be seen sooner. Flooding as a result of rising groundwater may first be seen during storm events in wet winters. As average water table elevations increase, groundwater may seep into channels, increasing base flow and decreasing channel capacity, so that when storms occur there may be reduced capacity to convey stormwater. When SLR exceeds three feet or more (likely toward the end of the century, but possible as early as 2070), emergence flooding may become a regular occurrence if adaptation strategies are not implemented.

6. Adaptation strategies

Multiple approaches can be used to address the risk of rising groundwater, including strategies to accommodate more water in the urban landscape, improve the existing drainage system, make structures more resilient, and reduce groundwater levels at the site and district scales. Other Bayfront cities that are already grappling with the impacts of rising groundwater are actively implementing adaptation strategies to reduce future damage. For example, Palo Alto has expanded the types of projects that require geotechnical investigation to ensure that designs adequately account for water table elevations today and in the future. In Alameda, trenches for utility lines are being over-excavated and filled with crushed rock in areas where high water tables are impacting pipelines, as well as in areas where groundwater is anticipated to rise and impact pipelines in the future.

The strategies described in this chapter provide a framework for the types of adaptation actions that could be implemented to manage changing groundwater conditions in Moffett Park. A combination of these strategies may be necessary, with larger-scale strategies employed toward the latter half of the century as the rise in sea levels approaches three feet and beyond. Some strategies will be easier to implement during the redevelopment process, and should be considered in design guidelines.

A. Add three feet to groundwater design levels

For many of the impacts listed in the previous section, adaptive design strategies already exist. Geotechnical investigations of existing groundwater levels and soil corrosion potential are required by the California Building Code, which is adopted by the City of Sunnyvale's code. When indicated by geotechnical investigations, building design strategies are used today to mitigate many of the impacts listed in the previous section. Examples include corrosion-resistant materials, wall and foundation designs that resist lateral and uplift pressure from shallow groundwater, drain tile and sump pumps to manage seepage, foundations designed for possible liquefaction, and waterproofing of belowground electrical lines.

When geotechnical investigations are conducted, a design groundwater level is recommended based on historical maximum groundwater conditions. Given that historical conditions are no longer a reliable predictor of future groundwater levels, it is advisable to consider a higher design level that is more representative of projected future conditions. This is true for structures of all types, including those constructed at and below grade, as well as utility trenches, roadbeds, etc. For example, in the case of possible future undergrounding of power lines at the Sunnyvale East Channel, higher future groundwater levels should be considered in the design process.

The Moffett Park Specific Plan's SLR strategy targets improved flood protection for up to three feet of SLR, providing about a 50-year buffer as sea levels are not projected to rise three feet until 2070 or later (ESA & SFEI, 2020). Adding three feet to the historical maximum groundwater level as a design guideline is a conservative strategy for the 50-year planning horizon (see Chapter 4). Though designing for higher groundwater levels could increase construction costs, it may be cheaper to design with a factor of safety than repair damages later. In addition to designing for higher groundwater levels, it is advisable to plan for more saline groundwater conditions than the current levels, using waterproof and/or corrosion-resistant materials below the design level.

Many wastewater facilities already have subsurface structures and use adaptive below-grade design techniques as they are frequently located near the Bay in areas with shallow groundwater. A recent geotechnical investigation for the upgrades at the Sunnyvale Water Pollution Control Plant provides a useful example, as there are proposed below-grade structures that will need to be constructed below groundwater levels (Fugro Consultants, Inc., 2016). Geotechnical studies provide guidance on engineering, dewatering for construction, and other considerations for design and building in areas with shallow groundwater.

B. Account for higher groundwater levels in stormwater system upgrades

An overhaul of the stormwater system would improve the City of Sunnyvale's ability to manage combined flooding by increasing capacity for water entering developed areas from rainfall, overtopping, and groundwater. Stormwater system upgrades should take into account higher groundwater levels in addition to higher sea levels and the potential for more intense rainfall events. Pump station capacity may need to be improved, especially as increased infiltration to the stormwater system adds to baseline pumping requirements.

In other urban areas along the SF Bay shoreline, like Redwood Shores, Alameda, Bay Farm Island, and Foster City, groundwater already drains from developed areas to constructed channels and from there to pump stations. Ditches in Moffett Park likely already drain some groundwater to pump stations, and flows of groundwater in the stormwater system will likely increase as sea levels rise. One adaptation strategy could be to take advantage of natural discharge (exfiltration from groundwater into channels due to topographic limitation) by expanding capacity of surface channels and/or increasing the density of channels. Preserving open space adjacent to existing channels increases flexibility for future modifications to increase channel capacity for groundwater flows in addition to stormwater runoff. New channels could be added in areas with the shallowest groundwater to help convey flows to pump stations. Due to the discontinuous aquifer system, effects of this adaptation strategy are likely to be localized to the area around each channel, rather than felt at the district scale. However, if the channel collection system focuses on the north side of the district, between the district and the Bay, it may be better positioned to attenuate the effects of SLR in the Bay on the rest of the district.

The low hydraulic conductivity of Moffett Park's soils may mean it is more feasible here than in other places to use pumping as a technique to stay ahead of rising groundwater levels. French drains could be used to direct shallow groundwater away from sensitive infrastructure to basins and/or channels. When groundwater levels are lower, the channels and basins may be dry. During the wet season they would fill with groundwater, acting as detention basins. Pumps could remove water from the channels, creating a positive pressure gradient to wick groundwater from the developed areas. This system would also allow for easy monitoring of groundwater levels.

C. Site open spaces to allow more groundwater and stormwater detention

Groundwater is shallowest (emergent) in Moffett Park at the Lockheed Martin stormwater ponds. Protecting open space around this area and allowing more room for stormwater and groundwater detention in the future is advisable. In addition to protecting open space along the Sunnyvale East Channel and stormwater ditch (Figure 14), it may also be advisable to protect more open spaces in the eastern portion of Moffett Park and in the adjacent area east of the Moffett Park Specific Plan boundary, with depressions designed as seasonal detention ponds for groundwater and stormwater. Siting public green spaces in low-elevation areas and designing them to accommodate temporary or seasonal floodwaters can increase their function as multi-benefit spaces. Connecting these spaces to one another and to the stormwater system could allow more flexibility of use over the long term as environmental conditions change.

Figure 14. Stormwater channels, pumps, and ponds in Moffett Park (MPSP study area shown with a dashed line).

D. Encourage site-scale designs that accommodate higher groundwater levels

In addition to district-scale interventions for siting stormwater detention and riparian open spaces, it is also possible to implement parcel-scale interventions to increase resilience to rising groundwater. In areas that will require a great deal of fill material to meet required finished floor elevations, it may be possible to use cut-and-fill strategies to create on-site detention and/or retention ponds and generate fill for building pads in the process. One emerging creative design strategy is to build floating or pile-supported structures on the resulting artificial ponds, allowing more space for water in the urban environment (see Hill & Henderson 2021 for details and diagrams of floating structures). Raising finished floor elevations with fill is an effective strategy to reduce vulnerability to rising groundwater, but it can be costly and material is limited. Using local fill material can decrease construction costs and free up material for the region to use in other critical SLR adaptation projects.

When green stormwater infrastructure is used to reduce stormwater runoff volume and pollutants entering storm drains, ensure that interventions are designed with rising groundwater in mind. Green infrastructure designed to current groundwater levels may not function as well when groundwater rises nearer to the ground surface. Underdrains connected to the stormwater system can help ensure green infrastructure installations continue to function even if rising groundwater levels slow infiltration rates.

The planting palette used in landscaped areas can also be designed with groundwater conditions in mind. In places where groundwater is well below the ground surface, it is best to use drought-tolerant plants that require less water. In places where groundwater is near the surface, use plant species adapted to wet conditions with higher salinity (refer to the plant palettes included in the MPSP Urban Ecology Technical Report, Appendix C) (SFEI, 2020).

F. Encourage consideration of SLR in groundwater remediation plans

Though mobilization of buried contaminants by rising groundwater may be an issue in many places, not just in Moffett Park, no comprehensive strategies currently exist for the Bay Area or California to assess, and if necessary, to address this potential threat. Changes to remediation strategies at individual sites may be required to ensure public safety if groundwater levels rise and cause contaminants to spread to new locations. The City of Sunnyvale can coordinate with regulatory agencies like the Department of Toxic Substances Control and the Regional Water Quality Control Board to encourage the consideration of SLR and rising groundwater in updates to remediation plans and requirements for contaminated sites and landfills.

G. Install a cutoff wall

A longer term strategy (i.e. beyond three feet of SLR) could be to install a cutoff wall or seepage barrier to reduce connectivity between Bay water levels and groundwater in Moffett Park. More study and engineering would be required to determine the potential effectiveness of this strategy, the locations where a cutoff wall would be useful, and the depth of the barrier that would be required. One option may be co-locating the cutoff wall with the proposed shoreline levee improvements. This strategy may not be the most practical solution because in addition to preventing flows coming in, it prevents groundwater flow outward to the Bay, interrupting natural dynamics and trapping more groundwater inland of the barrier that needs to be managed. However, since Moffett Park already has groundwater levels lower than mean sea level and a stormwater system to discharge water to the Bay, the stormwater system provides the foundation for managing water on the landward side of a cutoff wall. Exploration of the utility and feasibility of barrier installation would require further study of groundwater flow paths with dynamic modeling.

7. Data needs and potential next steps

This technical memorandum outlines existing knowledge about groundwater conditions in Moffett Park. However, the information presented here is incomplete. There is less information about groundwater levels on the east side of Moffett Park than the west side, where there is a wealth of information from monitoring wells at Lockheed Plant One. It is still unclear where the individual aquifers are connected to one another, to channels and ponds, and to the Bay. Groundwater levels along the shoreline today are below mean sea level, and further investigation is needed to better understand the factors causing this condition. Future studies, including implementation of a long-term monitoring strategy, could better calibrate and validate models, and inform the design of stormwater and groundwater management upgrades.

A valuable near-term investment would be to track groundwater levels over time in the area where there is no long-term tracking of groundwater levels: the east side of Moffett Park. Figure 15 shows approximate locations for groundwater monitoring that would help create a more complete picture of groundwater conditions in Moffett Park.

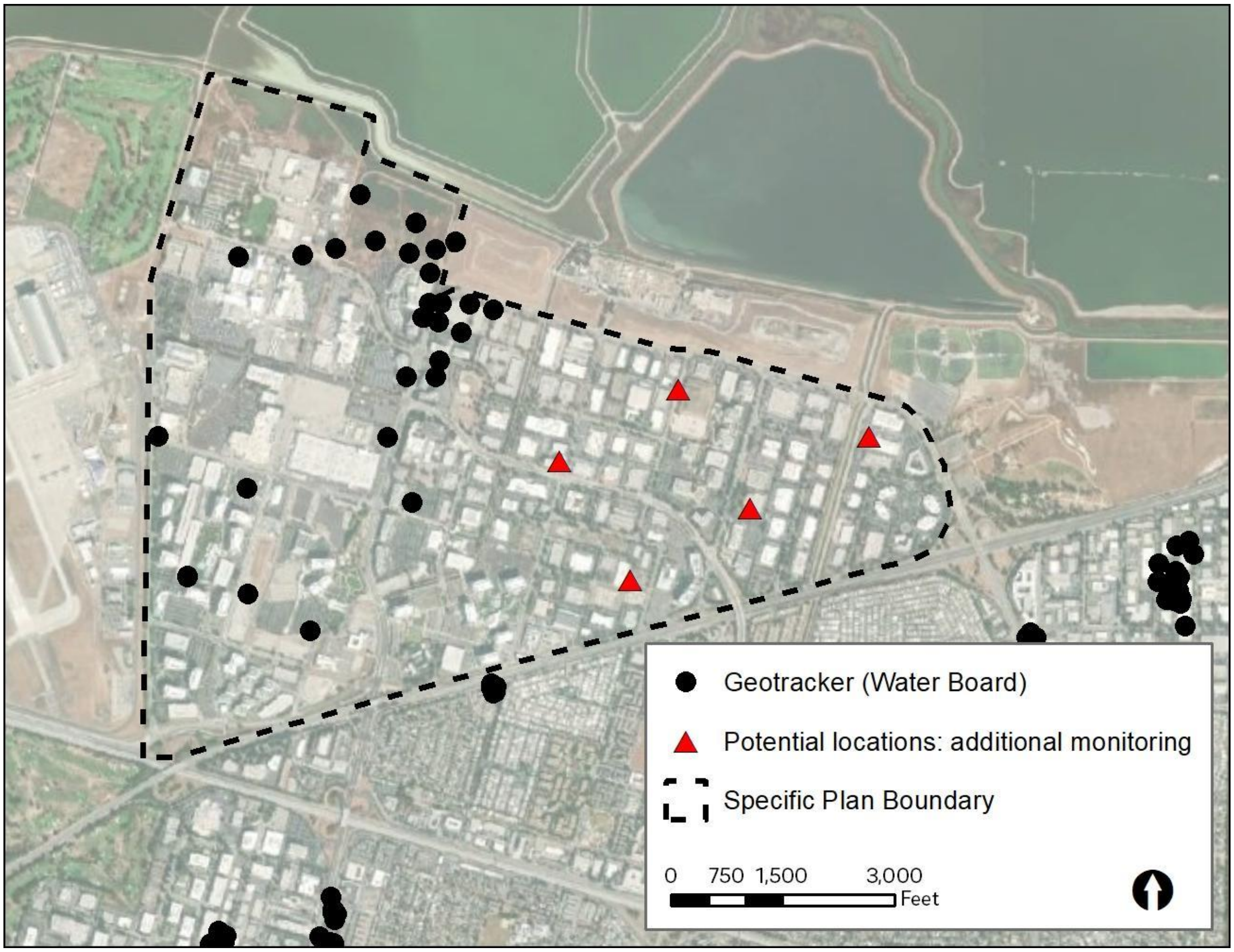

Figure 15. Adding monitoring locations east of the Lockheed monitoring wells could help create a more comprehensive dataset of groundwater conditions.

It may not be necessary to bore new wells to do this monitoring if levels in existing wells can be measured more frequently. According to Valley Water's well database, there are many existing monitoring wells in this area. There are about 40 wells in the database on the east side of Moffett Park that measure the shallow aquifer (total depth ≤ 45 ft) and are listed as "active", though the depth of the screened intervals, the condition, and the accessibility of these wells is unclear (Figure 16). Groundwater monitoring data is not collected, or at least not posted, for any of these wells except one. Data for this well, located adjacent to the Sunnyvale East Channel, is collected once per year in the dry season. Data from the monitoring wells at the landfill could also be leveraged to help better understand groundwater conditions along the shoreline north of Moffett Park.

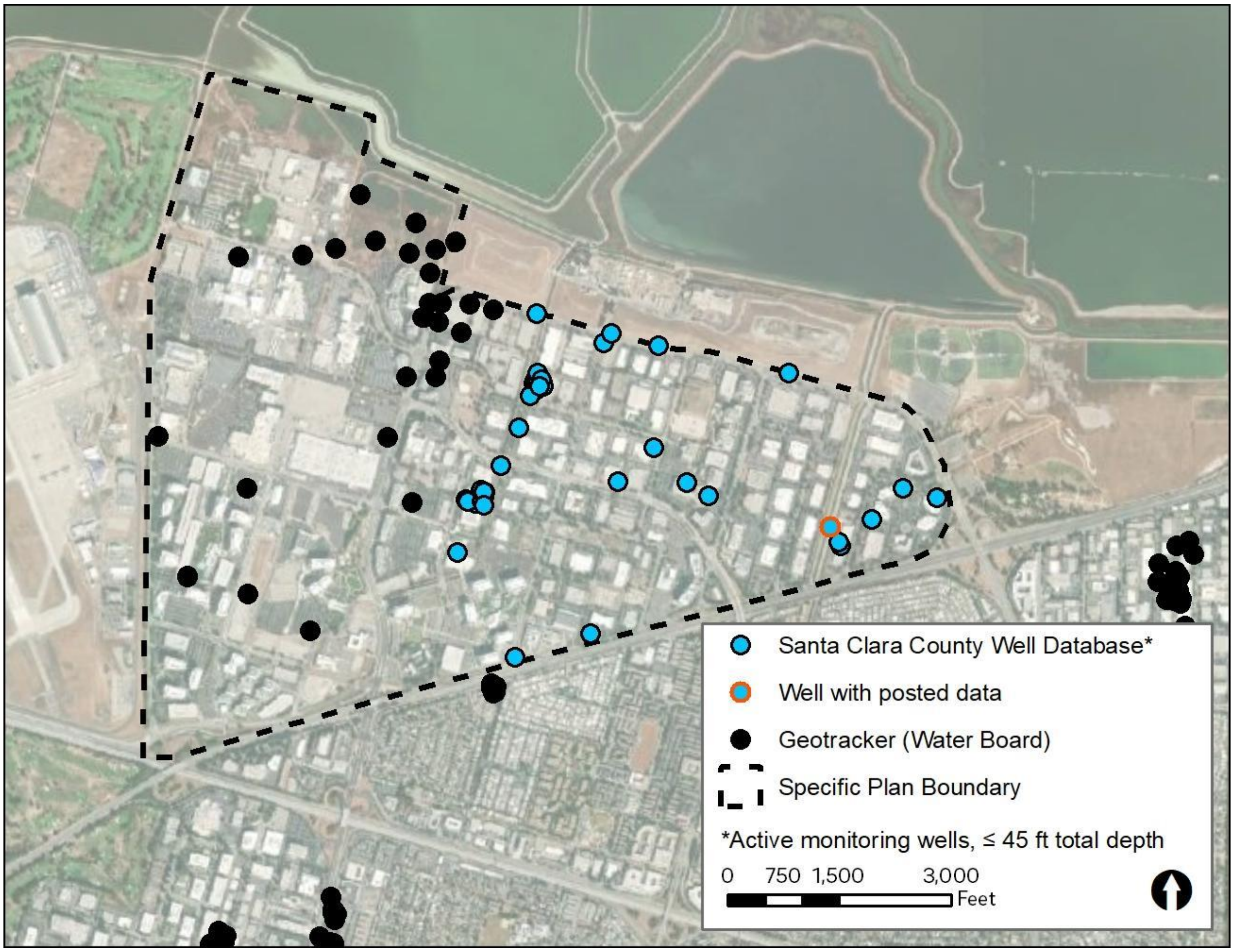

Figure 16. There are about 40 wells in the data gap area east of the Lockheed Martin monitoring wells that could be monitored more frequently for depth to water conditions.

Both short- and long-term monitoring of groundwater levels in the shallow aquifer of interest (<10 ft depth) would provide useful tools for adaptive management and decision making. Table 1 outlines major management questions, the hydrologic questions that could help answer them, and the data that would be needed to address the hydrologic questions.

Table 1. Management questions that need to be answered to inform planning, along with associated hydrologic questions and data needs.

Management Questions	Hydrologic Questions	Data Needs
● What is the range of groundwater levels over a year? Will they impact development? ● How will groundwater levels change over time? Will they impact development in the future? ● What groundwater levels should be used for structure and stormwater system design?	● What soil types and hydraulic conductivities are present in Moffett Park? How interconnected is the shallow aquifer in Moffett Park? Where is it interconnected?	● Soil and hydraulic conductivity mapping ● Depth to water and salinity data collected simultaneously hourly at multiple monitoring wells over a period of one year.
	● What is the seasonal variability in the water table and how do intense rainfall events affect groundwater conditions?	● Monthly measurements over a period of years.
	● How will long-term SLR impact groundwater levels in Moffett Park?	● Monthly averaged measurements over a period of years, filtered to remove seasonality.

Implementing a groundwater monitoring plan, using either new or existing wells, could help provide valuable data for Moffett Park. If the data collected is highly variable across wells, it may be valuable to add more wells to gain a finer-resolution dataset. As described in Table 1, different frequencies of measurement are required to answer different questions, but all of the questions require more frequent data collection than once or twice a year, which is the current practice.

High-frequency monitoring (hourly) requires use of data loggers, which measure depth to water, or depth to water and salinity. The data loggers can be periodically downloaded or connected via the cell network to automatically transmit data. Data loggers collect water elevation data using pressure transducers, which require a separate barometric correction sensor, and measure salinity using a proxy of conductivity. One barometric correction sensor would suffice to cover the whole MPSP area. Data loggers could be strategically placed for a period of intensive monitoring at 5 to 10 wells across Moffett Park. The monitoring frequency could then be scaled back, and depth to water and salinity data could be collected either by manual measurement or data logger on a monthly basis.

A key to understanding existing and future groundwater levels and flow patterns in Moffett Park will be development of a 3D subsurface map of soil type and associated hydraulic conductivity. This map would be an essential input to future groundwater models, as an important variable in hydrogeologic modeling is hydraulic conductivity, which describes the rate of groundwater flow through pore spaces. Hydraulic conductivity varies between geologic types: clay substrates have lower hydraulic conductivity, and sand substrates have higher hydraulic conductivity. With Moffett Park's heterogeneous soil types, mapping will be required to refine the inputs to a future groundwater model.

Local-scale dynamic modeling will be useful when designing future changes to Sunnyvale's drainage system, including changes to help manage rising groundwater. When designing upgrades to the system, understanding how adaptation strategies will affect flow patterns will be essential. Groundwater flow and transport models like MODFLOW can help elucidate these dynamic processes. Coupled surface-groundwater flood modeling that considers rainfall hydrology, the stormwater system, groundwater, and potentially coastal flooding, will be required to make informed decisions about the hazards and to design improvements for an integrated stormwater and groundwater management system.

Partnerships will be essential going forward to ensure streamlined data collection, analysis, and communication of results. Valley Water is responsible for managing groundwater in Santa Clara County. Under the California Sustainable Groundwater Management Act (SGMA), Valley Water's groundwater management plan must be updated every five years. Valley Water is currently in the process of updating the groundwater management plan for 2021. While the primary focus of the work is on deeper water supply aquifers, shallow groundwater is also relevant to the plan and coordination on development of future monitoring plans may be in the mutual interest of both Valley Water and the City of Sunnyvale. Rising groundwater is also an area of growing research interest more broadly. Connections with academic institutions can be leveraged to get students involved in monitoring and modeling efforts, providing an educational opportunity for emerging researchers and bringing in scientific expertise.

Setting up a monitoring plan is a near-term action that would help Moffett Park start to increase resilience to rising groundwater. Better data can feed into more accurate models, which will help engineers create more successful adaptation strategies in the future. Coordinating with partners to develop a monitoring plan can set the foundation for collaborative development of adaptation strategies over the longer term.

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