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1 INTRODUCTION

The Bayfront Canal-Atherton Channel watershed is a predominantly urban area in San Mateo County which includes the Town of Woodside, Town of Atherton, City of Menlo Park, City of Redwood City, and parts of unincorporated County (Figure 1-1). Areas in the watershed have experienced repeated flooding over the last 60 years, with 40 significant flood events from 1951 to date. These events frequently inundate local roads and, during larger events, have damaged private property. As recently as the storm of February 7, 2017, the Atherton Channel flooded Marsh Road near the Highway 101 exit. Impacted residents of the cities and unincorporated County, including disadvantaged communities, have urged that action be taken to improve the safety and economic health of their neighborhoods (Town of Atherton 2017).

Both Bayfront Canal and the tributary Atherton Channel drain to a low-elevation, tidally influenced area that is severely limited in its ability to efficiently discharge and safely detain stormwater. Currently, a 2-year or greater rainfall will cause flooding to low-lying areas adjacent to Bayfront Canal. Additionally, the area from south of Bayfront Canal to Highway 101 is within a coastal flood-risk zone, with much of this area below the 10-year tide elevation (BKF 2017). Forecasts for sea-level rise indicate the severity and frequency of tidally influenced flooding in the watershed will increase with time (BCDC 2011). Previous flood management studies (BKF 1983, 1988, 2013; Nolte Associates 2001; S&W 2002) assessed watershed hydrology, analyzed hydraulic issues, capacity limitations, and explored opportunities and constraints for providing flood relief to the impacted communities (BKF 2017). Alternatives to mitigate individual flooding problems have been proposed in previous efforts, but most are constrained by the interrelationship of the flooding issues, existing development, and the potential for a site-specific solution to worsen flooding in other locations.

The County of San Mateo Department of Public Works, in cooperation with the City of Redwood City, City of Menlo Park, Town of Atherton, Town of Woodside, and the County of San Mateo (hereafter referred to as the “Collaborative”) led an effort to build upon previous work efforts and studies and develop this Flood Management Plan (FMP) to identify and prioritize regional improvement projects that can attenuate flood flow peaks and/or reduce downstream flood risks to the Bayfront Canal-Atherton Channel watershed, while maximizing the potential to incorporate multiple additional benefits. These multi-beneficial projects include hydraulic infrastructure solutions, as well as stormwater capture projects such as green infrastructure (GI) street improvements or centralized facilities that divert storm drain or creek flows for detention, infiltration, or reuse.

A combination of hydrologic and hydraulic models was developed to evaluate the extent of flooding in the Bayfront Canal-Atherton Channel watershed for the 25-year, 12-hour rainfall event, and to evaluate management scenarios. The 25-year rainfall event (storm size occurring with a frequency of once every 25 years) provided a conservative basis for evaluation of the benefits of management scenarios, however, the recommendations of the FMP will have greater benefits in terms of reducing flood impacts for typical storms occurring on a more regular basis. The U.S. Army Corps of Engineers (USACE) model HEC-HMS was used to simulate watershed hydrology and predict inflows to a separate 2-dimensional XPSWMM model (Innovyze 2018) to simulate the hydraulics of the storm drain and channel network and evaluate the benefits of hydraulic infrastructure management solutions. To assess the potential benefits of stormwater capture projects in the watershed, a combination of the Loading Simulation Program C++ (LSPC) (Shen et al. 2004) and the U.S. Environmental Protection Agency (USEPA) System for Urban Stormwater Treatment and Analysis Integration (SUSTAIN) (Riverson et al. 2014, USEPA 2009) was used to simulate stormwater runoff and capture, with results informing the above XPSWMM model in terms of reducing stormwater flows to the hydraulic system.
This FMP includes an evaluation of constraints and opportunities for each proposed improvement project, estimated construction cost, likely permitting needs, and operations and maintenance needs. The FMP also provides recommendations for continued monitoring and evaluation of implementation progress, including the identification of stream gauge locations for use in flood monitoring and flood warning systems, and to further inform future model calibration.

Figure 1-1. Bayfront Canal and Atherton Channel watershed in eastern San Mateo County.
2 OVERVIEW OF THE WATERSHED

Both Bayfront Canal and Atherton Channel discharge stormwater to the San Francisco Bay via Flood Slough. Bayfront Canal begins in Redwood City by Douglas Court and runs west to east along the southern edge of salt ponds (Figure 2-1, left) until reaching Flood Slough near Marsh Road. Atherton Channel discharges directly into Bayfront Canal near Marsh Road before Bayfront Canal drains into Flood Slough and the Bay adjacent to Bedwell Bayfront Park. Due to the capacity constraints of Bayfront Canal and Atherton Channel, areas along both streams are subject to frequent flooding. These capacity issues arise more acutely when high tides align with large storm events.

The combined flow discharges from Bayfront Canal and Atherton Channel are conveyed through a tide gate control structure into Flood Slough (Figure 2-1, right). Taken together, the Canal and Channel convey runoff from 5,492 acres (approximately 8.6 square miles).

![Figure 2-1. Bayfront Canal near the salt ponds (left) and the tide gate control discharging water to Flood Slough (right).](image)

During a flood event, areas in Atherton, Redwood City, Menlo Park, and unincorporated San Mateo County are impacted by flooded streets, residences, and businesses particularly in areas adjacent to the Bayfront Canal and Atherton Channel (Redwood City 2018). Ponded flood water to the south of Highway 101, unable to enter the Bayfront Canal because of the highway, is introduced by a series of pumps and culverts. Other locations include areas within the Friendly Acres and North Fair Oaks neighborhoods, as well as within the vicinity of the Douglas Avenue, Broadway, 5th Avenue, and Athlone Terrace Pump Stations (Figure 2-2).
Figure 2-2. Areas in the Bayfront Canal watershed that experience significant flooding on a regular basis.

Two primary factors contribute to the flood conditions experienced within the Bayfront Canal-Atherton Channel watershed: (1) insufficient stormwater infrastructure to convey or detain stormwater, and (2) environmental effects such as tidal influences and sea-level rise. Both the conveyance system facilities and environmental factors are described below.

**Bayfront Canal** – Bayfront Canal is the lowest point in the watershed and conveys stormwater out to Flood Slough. Sources of water into Bayfront Canal include the Douglas Avenue Pump Station, Broadway Pump Station (via the Douglas Avenue Pump), 5th Avenue Pump Station, and Atherton Channel. During high tides, the Bayfront Canal acts as a storage pond until the tide recedes and the Canal can drain.
Bayfront Canal and Atherton Channel Watershed Flood Management Plan

Bayfront Canal Tide Gates – All flow to the Bayfront Canal must pass through the Bayfront Canal Tide Gates to reach San Francisco Bay.

Highway 101 – Highway 101 acts as a barrier that prevents surface flow from southwest of Highway 101 from entering the Bayfront Canal. Culverts and pump stations (Douglas Avenue and 5th Avenue Pump Stations) convey some storm volume across Highway 101, but not all. As a result, flooding occurs on the southwest side of Highway 101 during major storm events (BKF 2017).

Douglas Avenue Drainage Area – The Douglas Avenue drainage area is southwest of Highway 101 served by the 5th Avenue and Douglas Avenue Pump Stations. This low-lying site, which includes the Stanford Outpatient Center, floods during frequent events (e.g. a 2-year rainfall) (BKF 2017).

Atherton Channel – The Atherton Channel is the primary source of runoff to the Bayfront Canal. During intense rain events, flow can spill directly into North Fair Oaks or the Friendly Acres Neighborhood before reaching the Bayfront Canal. Flooding can make vehicular travel along Haven Avenue and Marsh Road hazardous or even prohibit passage entirely.

North Fair Oaks – North Fair Oaks is an unincorporated neighborhood within San Mateo County. A portion of North Fair Oaks southwest of the railroad tracks floods frequently. Some runoff to this area is pumped at the Athlone Pump Station into Atherton Channel. However, pumping more flow into Atherton Channel could exacerbate flooding downstream.

Tidal Influence – Tidal gates into Flood Slough are closed during periods of high tide, preventing tide waters from flowing back into the Bayfront Canal. However, when rainfall occurs during the high tide, watershed runoff fills the Bayfront Canal until either the tide recedes or the Canal exceeds the tidal elevation. During relatively frequent rain events (e.g. 2-year storms), the Bayfront Canal and portions of the Atherton Channel overtop and flood the adjacent Friendly Acres neighborhood, a low-lying residential and industrial area to the south of the Canal. Thus, the level of protection provided by various proposed improvement projects in previous studies (BKF, 2017) depends on the tide level at the time of the peak rainfall. Significant storm events are typically associated with low barometric readings, strong winds, and increased stormwater runoff into the Bay. As a result, tide levels are often higher during significant storm events than would otherwise occur during a typical lunar tide cycle.

Sea Level Rise – The National Research Council (2012) projects sea level rise of approximately 3 feet in San Francisco Bay by year 2100 and notes it could be as high as 5.5 feet relative to year 2000 tide conditions. However, sea-level rise of even 3 feet could inundate much of the watershed during even more common high tides. Furthermore, the County of San Mateo Sea Level Rise Vulnerability Assessment (2018) concludes that sea-level rise will aggravate stormwater flooding problems along the Bayfront Canal. Flood-prone areas in the watershed are already below average high tide elevations occurring during storm events. Sea-level rise will reduce the duration during which these areas and the Bayfront Canal itself are able to drain ponded runoff.

A range of corrective measures have been investigated to provide long-range improvements that will reduce the potential for flooding within the Bayfront Canal watershed. In 2017, Stanford University and BKF Engineers completed the Bayfront Canal Hydrology and Hydraulic Evaluation (BKF 2017), which included hydrologic and hydraulic evaluation of the following potential improvements in various combinations:

1. Connecting to managed ponds
2. Pumping to Flood Slough
3. Increasing the height of the top of berm along Bayfront Canal
4. Increasing pumping capacity of 5th Avenue and Douglas Pump Stations
5. Increasing pumping capacity of Athlone Pump Station
6. Storing runoff within the Town of Atherton
7. Increasing the area of the Tide Gates

The solutions presented in the above analysis do not address the interrelationship of the flooding issues, existing development, and the potential for an integrated solution that would benefit multiple locations. Flood issues could be improved significantly by a combination of the solutions listed above. This FMP builds off of the knowledge provided in the previous Bayfront Canal Hydrology and Hydraulic Evaluation (BKF 2017) to guide investigations, identifies and prioritizes improvement projects to attenuate flood flow peaks and/or reduce downstream flood risks to the Bayfront Canal system, and provides a comprehensive flood management solution for the impacted watersheds.

3 CHARACTERIZATION OF WATERSHED HYDROLOGY

Understanding of the hydrologic conditions in the Bayfront-Atherton Channel watershed starts with a review of the characteristics and conditions that influence stormwater runoff. Section 3 provides a summary of the factors influencing watershed hydrology, use of the watershed hydrologic model to assess existing storm flows to the channel and canal system, and the development of design storm hydrographs for subsequent linkage to the hydraulic model.

3.1 Summary of Watershed Hydrology

Hydrology refers to a set of interconnected natural processes that describe how water moves through a system (e.g., surface flow, evapotranspiration, infiltration, interflow). These processes are influenced by several physical characteristics of the watershed. In a natural watershed, hydrology may be primarily driven by soil type, percolation rates, and topography. However, in urban watersheds, hydrology may instead be dominated by impervious land cover, engineered storm drain systems, and inflows to the urban system (e.g., excess irrigation or other dry-weather flows). The primary factors that influence flood hydrology in the Bayfront Canal-Atherton Channel watershed are discussed below and include rainfall, land cover, soils, and topography.

3.1.1 Rainfall

Rainfall is one of the primary driving factors of watershed hydrology. Two factors of rainfall precipitation affect flood conditions downstream: the depth and intensity of the storm event. The rainfall depth during a flood event influences the flood volume, while the precipitation intensity affects the timing and magnitude of peak flow. Rainfall variability across the watershed also impacts hydrology. Orographic effects typically produce more precipitation at higher elevations. Figure 3-1 shows the spatial variability of rainfall across the watershed using the 30-year average annual precipitation totals from the Parameter-elevation Regressions on Independent Slopes Model (PRISM). Higher rainfall totals are observed in the upper watershed, where orographic effects drive higher precipitation in the foothills of the Santa Cruz mountains. Based on PRISM, the average annual rainfall across the Bayfront Canal-Atherton Channel watershed is 20.6 inches.
The term “land cover” may describe the amount of impervious surface (imperviousness) on a landscape, or the physical material at the surface of the landscape and how it is used (land use). Imperviousness is the percentage of land that is covered by impervious area. Impervious area primarily refers to artificial surfaces, such as roads, parking lots, and rooftops whose materials are impenetrable to water, but may also include highly-compacted soils. Imperviousness is an important driver in the hydrology of urbanized watersheds. Because natural land cover that allows for the infiltration of water into native soils is replaced with impervious area during urban development, a higher percentage of precipitation is converted to surface runoff. This excess of surface runoff is what contributes to flooding.
downstream. Figure 3-2 shows the imperviousness in the watershed. Approximately 32% of the Bayfront Canal-Atherton Channel watershed is covered by impervious surfaces, based on the 2011 National Land Cover Database (NLCD). Much of the imperviousness is concentrated along the highly-developed portion of the lower watershed to the northwest. Much of the upper watershed features single-family residential plots with relatively low imperviousness.

![Figure 3-2. Imperviousness in the Bayfront Canal-Atherton Channel watershed (2011 NLCD).](image)

Land use is also an important consideration in the characterization of watershed hydrology. Land use typically includes classifications like bare soil, forest, urban (developed) land, agriculture, and water. Figure 3-3 and Table 3-1 shows a breakdown of the land uses within the watershed based on
2011 NLCD. The system consists predominately of developed land use of varying intensity (92% of watershed), with natural landscape (mixed forest, grassland, and scrub) near the headwaters.

Figure 3-3. Land use in the Bayfront Canal-Atherton Channel watershed (2011 NLCD).
Table 3-1. Land use breakdown in the Bayfront Canal watershed.

<table>
<thead>
<tr>
<th>Land Use</th>
<th>Area (acres)</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open Water</td>
<td>12.7</td>
<td>0.2%</td>
</tr>
<tr>
<td>Developed, Open Space</td>
<td>2,227</td>
<td>40.6%</td>
</tr>
<tr>
<td>Developed, Low Intensity</td>
<td>1,208</td>
<td>22.0%</td>
</tr>
<tr>
<td>Developed, Medium Intensity</td>
<td>1,048</td>
<td>19.1%</td>
</tr>
<tr>
<td>Developed, High Intensity</td>
<td>571</td>
<td>10.4%</td>
</tr>
<tr>
<td>Barren Land</td>
<td>0.8</td>
<td>0.0%</td>
</tr>
<tr>
<td>Evergreen Forrest</td>
<td>18.3</td>
<td>0.3%</td>
</tr>
<tr>
<td>Mixed Forest</td>
<td>173</td>
<td>3.1%</td>
</tr>
<tr>
<td>Shrub/Scrub</td>
<td>25.3</td>
<td>0.5%</td>
</tr>
<tr>
<td>Grassland/Herbaceous</td>
<td>201</td>
<td>3.7%</td>
</tr>
<tr>
<td>Cultivated Crops</td>
<td>6.2</td>
<td>0.1%</td>
</tr>
<tr>
<td>Herbaceous Wetlands</td>
<td>1.6</td>
<td>0.0%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>5,492</strong></td>
<td><strong>100%</strong></td>
</tr>
</tbody>
</table>

3.1.3 Soils

Natural soils are often classified based on texture, grain size, and grade. Classifications include clay, silt, loam, sand, gravel, and intermediate classifications (e.g., clay-loam, sandy-loam). For hydrologic purposes, soils may be more broadly classified based on drainage properties. These “Hydrologic Soil Groups” are organized from A to D, representing well-drained to poorly-drained soils, respectively. Under high rainfall intensity, poorly-drained soils will produce more runoff than well-drained soils. Figure 3-4 shows Hydrologic Soil Group in the watershed from the Natural Resources Conservation Service (NRCS). A large portion of the watershed contains Group C soils, which produce more runoff than Group A and B soils. Adequate soil data is often lacking in highly urban settings due to high amounts of impervious area. Due to soil compaction associated with urban development, these areas are often approximated as Group C or D soils. The soil type is unknown in more urban parts of the watershed.
Topography describes the physical terrain of the watershed. Slope, or the change in elevation, is the driving aspect of topography that influences hydrology. Steeply-sloped terrain leads to less ponding and infiltration compared to mildly-sloped terrain, resulting in more runoff. In addition, slope determines the velocity and travel time of surface runoff, having a significant impact on the timing and peak of flood flows. Figure 3-5 shows percent slope calculated from a 10-meter Digital Elevation Model (DEM) from the United States Geological Survey (USGS) National Elevation Dataset. The
upper watershed in the foothills of the Santa Cruz mountains is steeper, while most of the lower watershed is located on relatively flat terrain.

Figure 3-5. Slope in the Bayfront Canal-Atherton Channel watershed (USGS National Elevation Dataset).

3.2 Hydrology Model

The previous Bayfront Canal Hydrology and Hydraulic Evaluation (BKF 2017) provided a characterization of the watershed hydrologic conditions that are considered for assessing flooding conditions and evaluating proposed improvement projects. The study resulted in the development of a linked hydrologic and hydraulic modeling system based on a combination of HEC-HMS (hydrologic) and
XPSWMM (hydraulic). The HEC-HMS model included partitioning the Bayfront Canal-Atherton Channel watershed into ten subwatersheds that drain to key points of interest for flood management (Figure 3-6). The area within each model subwatershed is listed in Table 3-2. The HEC-HMS model included assumptions for impervious area and soil characteristics to utilize the NRCS Curve Number (CN) method for simulation of surface runoff (BKF 2017).

Figure 3-6. Bayfront Canal-Atherton Channel hydrologic model subwatersheds.
Table 3-2. Drainage areas of Bayfront Canal-Atherton Channel hydrologic model subwatersheds (BKF 2017).

<table>
<thead>
<tr>
<th>Subwatershed</th>
<th>Total Drainage Area (acres)</th>
<th>Impervious(^1) (%)</th>
<th>CN(^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Douglas</td>
<td>166</td>
<td>95</td>
<td>78</td>
</tr>
<tr>
<td>Broadway</td>
<td>205</td>
<td>78.9</td>
<td>78</td>
</tr>
<tr>
<td>2(^{nd}) Ave</td>
<td>415</td>
<td>67.4</td>
<td>78</td>
</tr>
<tr>
<td>Selby</td>
<td>573</td>
<td>30</td>
<td>47</td>
</tr>
<tr>
<td>5(^{th}) Ave</td>
<td>284</td>
<td>61.3</td>
<td>78</td>
</tr>
<tr>
<td>Bayshore</td>
<td>205</td>
<td>78.3</td>
<td>78</td>
</tr>
<tr>
<td>N</td>
<td>168</td>
<td>46</td>
<td>78</td>
</tr>
<tr>
<td>North Fair Oaks</td>
<td>545</td>
<td>47.9</td>
<td>56</td>
</tr>
<tr>
<td>M</td>
<td>563</td>
<td>32.7</td>
<td>47</td>
</tr>
<tr>
<td>J-L</td>
<td>2,368</td>
<td>33</td>
<td>47</td>
</tr>
<tr>
<td><strong>Total (acres)</strong></td>
<td><strong>5,492</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^1\) Santa Clara County Drainage Manual was used as guidance for assigning imperviousness based on land uses within each drainage area (Santa Clara County 2007), and adjusted based on analysis of local development conditions.

\(^2\) Curve Numbers based on Hydrologic Soil Groups identified by the NRCS Web Soil Survey.

The *Bayfront Canal Hydrology and Hydraulic Evaluation* (BKF 2017) also determined rainfall distributions for design storms with recurrence intervals of 2, 5, 10, 25, and 100-years. Rainfall distributions for each storm were developed by averaging California Department of Water Resources (DWR) rain data for gages within Menlo Park and Palo Alto. The Santa Clara Valley Water District Mean Annual Precipitation Map (Santa Clara County 2007) was used to vary rainfall intensity through the drainage area. The 12-hour rainfall distributions for each of the recurrence interval design storms are shown in Figure 3-7. These rainfall distributions were used as the primary input to the model for simulation of watershed hydrology and storm flows to the Bayfront Canal-Atherton Channel hydraulic conveyance system.
3.3 Assessment of Existing Hydrologic Conditions

Based on the HEC-HMS model reported in the previous section, the *Bayfront Canal Hydrology and Hydraulic Evaluation* estimated design storm runoff volumes for each of the recurrence intervals. Table 3-3 provides a summary of the predicted runoff volumes for 12-hour duration\(^1\) storms for each of the model subwatersheds (Figure 3-6). In order to assess flood conditions in the Bayfront Canal-Atherton Channel hydraulic conveyance system (Section 4.2) and to evaluate flood management scenarios in the FMP (Section 6), the 25-year recurrence interval, 12-hour duration storm predicted by the HEC-HMS model was used as input to the XPSWMM model of the hydraulic system.

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\(^{1}\) According to *Bayfront Canal Hydrology and Hydraulic Evaluation* (BKF 2017), the 12-hour storm creates worse flooding conditions than the 1-hour, 6-hour, or 24-hour storms.
Table 3-3. Model-predicted runoff volume for each subwatershed and recurrence interval (12-hour storm duration) (BKF 2017).

<table>
<thead>
<tr>
<th>Subwatersheds</th>
<th>HEC-HMS Runoff Volume (ac-feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2-yr</td>
</tr>
<tr>
<td>J-L</td>
<td>152.6</td>
</tr>
<tr>
<td>M</td>
<td>25.2</td>
</tr>
<tr>
<td>North Fair Oaks</td>
<td>35.7</td>
</tr>
<tr>
<td>N</td>
<td>12.8</td>
</tr>
<tr>
<td>Bayshore</td>
<td>23.1</td>
</tr>
<tr>
<td>5th Ave</td>
<td>26.5</td>
</tr>
<tr>
<td>Selby</td>
<td>23.5</td>
</tr>
<tr>
<td>2nd Ave</td>
<td>41.7</td>
</tr>
<tr>
<td>Broadway</td>
<td>23.2</td>
</tr>
<tr>
<td>Douglas</td>
<td>21.7</td>
</tr>
</tbody>
</table>

4 CHARACTERIZATION OF THE HYDRAULIC SYSTEM

Stormwater runoff is conveyed across the Bayfront Canal-Atherton Channel watershed via a complex hydraulic conveyance system of storm drains, pumps, conduits, and open channels. For the purposes of flood management, the hydraulic system may be thought of as a network of pathways from flood-prone areas that divert water across subwatershed boundaries. Stormwater will pond or surge from the network into the flood-prone areas until the hydraulic system can move water into the Bayfront Canal and out to San Francisco Bay. Historically, there are multiple populated flood-prone areas within the watershed that experience flooding on a regular basis:

1. Bayfront East residential and commercial district (Redwood City and Menlo Park)
2. Broadway Pump Station vicinity (Redwood City)
3. Douglas Pump Station vicinity (Redwood City)
4. 5th Avenue Pump Station vicinity (Redwood City)
5. Bayfront West residential and commercial district (Redwood City)
6. North Fair Oaks neighborhood (County of San Mateo)

Figure 4-1 provides a schematic of these flood-prone areas and illustrates the interconnected flooding problems. For example, while increased pump capacity at the Douglas Avenue Pump Station might abate local flooding, the added volume to the Bayfront Canal could worsen the situation along the Bayfront East flood-prone area. Solutions posed for site-specific drainage problems must consider the hydraulic connection between sites. Flood reduction measures at any one site could worsen flooding in others by moving excess stormwater to areas unequipped to drain water already inundated by local flooding.
4.1 Summary of the Hydraulic Conveyance System

The Bayfront Canal is at the downstream terminus of the drainage system collecting water from the entire watershed. The bulk of stormwater runoff is conveyed into the Bayfront Canal by five major components:

- A 78-inch diameter storm drain that sends water from 2nd Avenue, Selby Lane, and Broadway under Highway 101 into the Bayfront Canal
- A 72 cubic feet per second (cfs) pump feeding into a 42-inch diameter force main at the Douglas Avenue Pump Station into the upstream end of the Bayfront Canal
- A 300 cfs pump at 5th Avenue feeding into two 48-inch and two 42-inch diameter force mains on the north side of Highway 101
- Gravity storm drains in the areas around the Bayfront Canal itself
- The Atherton Channel, which directs flow from Town of Atherton and North Fair Oaks.

After being joined by the Atherton Channel, the Bayfront Canal drains through five tide gates into Flood Slough, an inlet of the San Francisco Bay. Flood Slough and San Francisco Bay are tidal, and water levels in the Bayfront Canal must be higher than the tide elevation for the Bayfront Canal to drain. Therefore, the timing of water levels in Bayfront Canal is strongly dependent on the timing of inflows into Bayfront Canal relative to the diurnal cycle of the tides during the storm event. Storm events with peak inflows into Bayfront Canal concurrent with the high tide will result in more flooding along Bayfront Canal than a similar event with peak inflows concurrent with the low tide.

While every flood event is unique by virtue of different rainfall patterns and tidal conditions, the way stormwater creates flooding throughout the watershed can be summarized as resulting from two factors: (1) the short time it takes for rainfall to enter the drainage system and (2) the limited ability of the Bayfront Canal to drain. The watershed of Bayfront Canal is relatively steep and small, with minimal attenuation of flood hydrographs as they propagate through the system. Peak rainfall is likely to occur across the entire watershed nearly simultaneously, and peak flows from the various subwatersheds reach Bayfront Canal very close to the same time. Flooding due to these large events initially occurs due to local ponding, as rainfall overpowers local drainage inlets and infiltration rates. The ponded runoff must be pumped into the Bayfront Canal, or in the case of North Fair Oaks, into Atherton Channel. Since much of the flow can be quickly conveyed into the stormwater system, initial local flooding only occurs for a short duration before flooding along Atherton Channel downstream of Highway 101, and depending on tidal conditions, along Bayfront Canal. Flooding in those areas thus worsens as areas upstream discharge more stormwater into Bayfront Canal or the tide remains higher than the water level in the canal.

The following sections provide further descriptions of these hydraulic system components and addresses their limitations.
Figure 4-1. Schematic of the Bayfront Canal-Atherton Channel hydraulic system showing the interrelationship of flood-prone areas (in yellow).
## 4.1.1 Bayfront Canal

The Bayfront Canal is located immediately north of Highway 101 in Redwood City. The Canal runs from west to east, from Douglas Court to Marsh Road and is bounded to the north by salt evaporation ponds and to the south by residential and industrial properties. At its western end is the 78-inch siphon that introduces flow from 2nd Avenue, Selby Lane, and Broadway (Figure 4-2). Flood water to the south of Highway 101 that otherwise could not enter the Bayfront Canal because of the highway is introduced by a series of pumps and culverts. Atherton Channel flows into the Bayfront Canal a few hundred feet west of Marsh Road. The combined flow discharges into Flood Slough through a tide gate control structure. Taken together, the Canal and Channel convey runoff from approximately 8.6 square miles. The following provides an overview of key aspects of Bayfront Canal that influence its hydraulic conveyance.

*Figure 4-2. The upstream end of the Bayfront Canal at which the 78-inch siphon (left side) discharges, along with water from Selby (blue flap gate).*

### Embankment Heights

Along the Bayfront Canal, embankment heights vary. The degree of protection provided by the Bayfront Canal to the bordering communities varies with the embankment height. Typical embankment heights along different sections for both the north (dotted green) and south (solid green) sides of the channel are shown in Figure 4-3.

Figure 4-3 demonstrates the two-fold problem for flooding along the Bayfront Canal. First, the lowest portions of the south side of the embankment run along commercial and residential areas (Bayfront East) that depend on pumping from the 5th Avenue Pump Station to Bayfront Canal for flood relief. When tide elevations prevent the Bayfront Canal from draining, water is pumped into the Canal only to flow back over the embankments further downstream into the Bayfront East flood-prone area (Figure 4-1), recirculating the flood water, until the tide drops below 8 feet. Second, typical
embankment heights are lower on the south than the north side, which borders a mixture of open grassy areas and salt ponds. As tide levels rise, water pours preferentially into the commercial and residential areas due to the lower embankment. A long-term flooding solution should require the same degree of protection, and thus, equivalent embankment height on both sides of the Bayfront Canal.

Figure 4-3. Average embankment heights along the north and south side of Bayfront Canal.

Properties in some areas are protected by a combination of sandbags and privately-owned pumping systems that discharge into the Bayfront Canal. Photographs taken along the Bayfront Canal illustrate these ad-hoc flooding solutions by residential communities (Figure 4-4) and the disparity between the heights of the embankments on the north and south side (Figure 4-5).
Figure 4-4. Sandbags and small pumps (right) attest to ad-hoc attempts at flood control along Bayfront West.

Figure 4-5. Embankments along the north of the Bayfront Canal are often higher than those to the south.
DOUGLAS AND FIFTH AVENUE PUMPS

Ponding occurs within the low areas of 5th Avenue and Douglas Avenue during any rainfall more intense than a 2-year storm (BKF 2017). The Douglas Avenue Pump Station is unable to convey the runoff from Douglas Avenue and adjacent drainage areas rapidly enough, and there are few other channels by which water can enter the Bayfront Canal. As discussed above, with water elevations in the Bayfront Canal determined by tide elevations, any added volume has the potential of spilling into communities along the Bayfront Canal. Therefore, more pumping from either the Douglas Avenue or 5th Avenue Pump Stations could worsen flooding along the Bayfront Canal without improvements downstream.

TIDE GATES

Currently, water levels in the Bayfront Canal are entirely controlled by tide gates (Figure 4-6) at the eastern end of the Bayfront Canal. The tide gates allow water to leave the Canal but prevent San Francisco Bay tidewater from entering. The five 4-foot by 4-foot tide gates allow for a maximum of 825 cfs to be discharged to Flood Slough during low tide when water in the Bayfront Canal is at 8-feet elevation, approximately the elevation at which flooding from Bayfront Canal begins (BKF 2017). Given that peak flow rates in Bayfront Canal can exceed the capacity of the tide gates, flooding during large events can happen even when the tide does not prevent the Canal from draining.

Figure 4-6. The four tide gates at the mouth of the Bayfront Canal before Flood Slough, shown at low tide.

Flooding is exacerbated during periods when tide levels prevent the gates from opening. Stormwater fills the Bayfront Canal until either the tide recedes or the Canal exceeds the tidal elevation. Compounding the problem, significant storm events typically result in low atmospheric pressures, strong winds, and increased stormwater runoff into the Bay, making tides higher than they would be during a typical lunar tide cycle.
4.1.2 Atherton Channel

The Atherton Channel is the primary source of runoff to the Bayfront Canal. During intense rain events, flow can spill directly into North Fair Oaks or the Friendly Acres Neighborhood before reaching the Bayfront Canal. The Atherton Channel consists of a series of box culverts, open channels, and bridge crossings stretching from Town of Woodside downstream to the Bayfront Canal. When flow from Atherton Channel exceeds the capacity of the tidal gates, excess flow not only spills directly into the 5th Avenue and Bayfront East flood-prone areas (Figure 4-1) but can also propagate upstream of the Bayfront Canal, forcing water levels to rise. The following provides an overview of key aspects of the Atherton Channel that influence its hydraulic conveyance.

**Box Culverts**

The enclosed portion of Atherton Channel begins when the rectangular open channel feeds into a single 5-foot 6-inch high by 11-foot 7-inch wide box culvert, which transitions after 10 feet into a double chambered 5-foot by 20-foot box culvert running parallel to Marsh Road. The double box culvert extends for 3,400 feet until it emerges into an open channel along Rolison Road, briefly going subsurface again to cross beneath the Bayshore Freeway.

**Athlone Terrace Pump Station**

Flows in excess of the capacity of the box culvert at Fair Oaks Avenue will overtop Atherton Channel and travel northeast along Marsh Road to low-lying areas south of the Southern Pacific Railroad line, joining ponded local runoff in the North Fair Oaks flood-prone area (Figure 4-1). Much of the runoff reaches Athlone Terrace in the North Fair Oaks flood-prone area. The Athlone Terrace Pump discharges stormwater at a rate of 35 cfs through a subsurface conduit back to Atherton Channel where it crosses beneath the railroad tracks. Ponded stormwater typically will not overtop the railroad embankment, so the North Fair Oaks flood-prone area largely depends on the Athlone Terrace Pump for relief. As with the Douglas Avenue and 5th Avenue Pumps, the Athlone Terrace Pump could make downstream flooding into the Bayfront East flood-prone area more severe.

**Downstream Bridges**

Once the Atherton Channel emerges from the culvert below Highway 101, the sudden change to a gentler slope forces flows into a subcritical behavior, for which flow depths are greater and velocities are slower. Two double-chambered box culverts underneath road crossings in the Channel to the north of Highway 101 present the danger of overtopping under these conditions. Backwater effects due to high water levels in the Bayfront Canal worsen flood conditions. Figure 4-7 shows the bridge at Haven Avenue during high tide conditions in the aftermath of a rain event. Flow at the confluence remains constrained by the tide and forces water from Atherton Channel out of its bank and into the streets.
4.2 Assessment of Existing Hydraulic Conditions

A hydraulic numerical model, based on XPSWMM, provided a tool to assess existing flooding conditions in the Bayfront Canal-Atherton Channel watershed. The XPSWMM model was originally developed to support the *Bayfront Canal Hydrology and Hydraulic Evaluation* (BKF 2017), with further modifications to represent key management scenarios considered for the FMP. XPSWMM can simulate ideal conveyance scenarios (i.e., channels and pipes flowing at maximum capacity). This is particularly important for the Atherton Channel, for which low water depths depend on high velocities. When rapid, stable flow is disturbed, the water surface depth in the channel can increase suddenly, leading to flow out of the banks and into neighboring communities. The XPSWMM model is a useful tool to account for the anticipated movement of stormwater during storm events.

4.2.1 Hydraulic Model

XPSWMM is a 1D/2D computational tool based on code developed by the EPA for modeling the interaction of stormwater and urban drainage systems (Innovyze 2018). XPSWMM mimics flooding hazards for storm and tide events through simulation of the quantity, spatial distribution, and timing of stormwater. The model evaluates and reports depth and volume of flood-prone areas based on storage capacity characteristics derived from topographical data. In the model, flooding can be succinctly characterized in three ways:

- The total **volume** of water entering the flood-prone area during the simulation
- The **depth** from the peak water surface to the lowest ground elevation in the area
- The **area** flooded, computed as a function of the depth.

Figure 4-7. Haven Avenue bridge across Atherton Channel during high water levels in the Bayfront Canal, looking downstream.
The model of the Bayfront Canal-Atherton Channel hydraulic system includes ten locations at which hydrographs may be assigned. Water then moves from those input nodes via numerous links representing roads, weirs, pump stations, and open channels. The model includes four existing pump stations and two main open channels (Bayfront Canal and Atherton Channel). Model outflow locations are limited to the tide gates connecting Bayfront Canal to Flood Slough and overtopping of the north berm along Bayfront Canal into the Cargill Salt Ponds.

### 4.2.2 Flooding Extents

The XPSWMM hydraulic model was used to assess the extent of flooding resulting from the 25-year, 12-hour storm predicted by the HEC-HMS hydrology model of the watershed (Section 3.3). Table 4-1 summarizes the XPSWMM results for each of the flood prone areas (Figure 4-1) and the corresponding flood volume for the existing condition.

#### Table 4-1. Existing flood conditions resulting from the 25-year 12-hour storm.

<table>
<thead>
<tr>
<th>Flood-Prone Area</th>
<th>Source of Flooding</th>
<th>Volume (acre-feet)</th>
<th>Maximum Depth (feet)</th>
<th>Area (acres)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broadway</td>
<td>Local Drainage</td>
<td>49.4</td>
<td>2.5</td>
<td>5.3</td>
</tr>
<tr>
<td>Douglas</td>
<td>Local Drainage</td>
<td>44.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2nd Avenue</td>
<td>51.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Broadway</td>
<td>5.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Selby</td>
<td>9.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>110.8</strong></td>
<td><strong>4.0</strong></td>
<td><strong>23.2</strong></td>
</tr>
<tr>
<td>5th Avenue</td>
<td>Local Drainage</td>
<td>60.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Douglas</td>
<td>53.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>114.2</strong></td>
<td><strong>3.1</strong></td>
<td><strong>65.0</strong></td>
</tr>
<tr>
<td>Bayfront West</td>
<td>Bayfront Canal</td>
<td>19.0</td>
<td>3.1</td>
<td>6.3</td>
</tr>
<tr>
<td>Bayfront East</td>
<td>Atherton Channel</td>
<td>120.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bayfront Canal</td>
<td>103.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>223.7</strong></td>
<td><strong>2.0</strong></td>
<td><strong>62.6</strong></td>
</tr>
<tr>
<td>North Fair Oaks</td>
<td>Local Drainage</td>
<td>79.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Atherton Channel¹</td>
<td>0.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>79.8</strong></td>
<td><strong>3.3</strong></td>
<td><strong>37.9</strong></td>
</tr>
<tr>
<td><strong>Total Flooding for All Flood-prone Areas</strong></td>
<td></td>
<td><strong>597</strong></td>
<td></td>
<td><strong>200</strong></td>
</tr>
</tbody>
</table>

¹ Flows entering the Atherton Channel upstream are assumed to be supercritical (i.e., a Froude number < 1.0) based on a calculation of normal depth and independent analysis (NV5)

A map (Figure 4-8) of flood-inundated areas during a 25-year, 12-hour storm, with an elevated tide, shows extensive flooding along the Bayfront Canal, Highway 101, and to the south of the Southern Pacific railway line.
Figure 4-8. Map of potential flooding extents in the Bayfront Canal-Atherton Channel watershed for the 25-year, 12-hour storm and an elevated tide.
The sensitivity of the flood-prone areas to flooding in other parts of the watershed differs based on location and the conveyance capacity of the hydraulic system leading to and from each area. The following are key findings from the modeling analysis:

- Broadway is sensitive only to direct inflow from its upstream drainage area. Reducing inflows from the drainage area upstream of Broadway will not benefit other flood-prone areas.

- North Fair Oaks floods from local runoff and some surcharge from the Atherton Channel. The elevation of this flood-prone area is too high to be affected by the hydraulics in the downstream sections of the Atherton Channel. The embankment for the Southern Pacific railroad line acts as a barrier to water either entering from or leaving to the north.

- The Douglas and 5th Avenue flood-prone areas are most sensitive to inflows from areas around 2nd and 5th Avenue, with minor contributions from Broadway and Selby. Inflows to the Atherton Channel can impact stormwater storage depths at Douglas and 5th Avenue by establishing a backwater effect in Bayfront Canal.

- Bayfront West is most significantly influenced upstream from Bayshore inflows and downstream from the Atherton Channel.

- Bayfront East is impacted from inflows throughout the watershed, as it is located downstream from every inflow to the Bayfront Canal and is impacted from downstream backwater conditions caused by the Atherton Channel.

In summary, the interrelationship of flood-prone areas in the watershed demonstrates that while some improvements benefit local flooding problem, others are felt in multiple locations.

4.2.3 Assessment of Bayfront Canal Hydraulics

As previously discussed, the severity of flooding along the Bayfront Canal is related to the uneven embankment heights along its length. When tide elevations prevent the Bayfront Canal from draining, water is pumped into the Canal only to flow back over the embankments further downstream into the Bayfront East flood-prone area, recirculating the flood water until the tide drops below 8 feet. The following are conclusions from model analysis of key components of the Bayfront Canal.

78-Inch Siphon

In the case that the 78-inch siphon connecting the Douglas Avenue area with the Bayfront Canal becomes blocked, flood relief for Broadway and Douglas Avenue largely depends on the Douglas Avenue Pump Station. Mimicking such a blockage, model simulations with the 78-inch siphon removed show that flood depths rise 0.5 feet at 5th Avenue and Douglas flood-prone areas, but there are only minor changes in Bayfront East and Bayfront West.

Cargill Properties

The Bayfront Canal is bordered along the length of its north side by property owned by the Cargill salt company (Figure 4-1). During a 25-year storm event, nearly 40% of stormwater that overcharges the Bayfront Canal flows north into these salt ponds. Since they are not designated floodways, long-term flood management cannot depend upon the significant flood relief provided by these commercial properties. Flood mitigation measures should provide the same degree of protection along both banks of the Bayfront Canal.
4.2.4 Assessment of Atherton Channel Hydraulics

Due to its steep slope (0.4%), the upstream box culvert is rated to pass high flows (up to 900 cfs) rapidly downstream (NV5 2015). The combination of a steep slope and low friction along the concrete surface results in a supercritical flow condition (a combination of lower water depths and rapid velocities for a given volume). However, hydraulic analysis and observations of flooding along Marsh Road originating from Atherton Channel suggest that the supercritical condition is unstable and can pass into subcritical flow (in which depths are greater, and velocities are slower). Particularly during a large storm event when debris (e.g., branches) is introduced into the open channel and increases the resistance to flow, water levels may overtop the banks and surge west into the North Fair Oaks flood-prone area.

Flooding from Atherton Channel is observed in the model under both sub- and supercritical flow conditions upstream, with the distribution of the spills being the key difference. Figure 4-9 shows the approximate flows at which Atherton Channel spills under supercritical upstream conditions. The bulk of the spill from the Channel makes up over one-third (64 of 186 acre-feet) of the flood volume entering the Bayfront East flood-prone area. For conditions when flow is restricted at the inlet, flooding into North Fair Oaks could begin at a flow of 430 cfs, less than half the peak of the 25-year storm event.

![Figure 4-9](image_url)

**Figure 4-9.** Discharge at which spill begins along Atherton Channel (plan view) under existing conditions.
5 PROPOSED PROJECTS TO REDUCE FLOOD RISKS

Stormwater is generally captured (e.g., detention basins) or conveyed (e.g., larger pumps, larger conduits) to alleviate flooding conditions in the watershed. Stormwater runoff in the Bayfront Canal-Atherton Channel watershed can be infiltrated or treated through green infrastructure (GI) measures or stored for later release in detention basins. Hydraulic improvements, such as pump upgrades or increasing channel capacity, can increase stormwater conveyance to alleviate flooding. The following provides an overview of potential stormwater capture and hydraulic improvement projects that were evaluated for the FMP.

5.1 Stormwater Capture

To date, there have been several countywide planning initiatives that evaluate opportunities for stormwater capture projects. A Stormwater Resource Plan (SRP) for the County of San Mateo watersheds was developed by the San Mateo Countywide Water Pollution Prevention Program (SMCWPPP), a program of the City/County Association of Governments of San Mateo County (C/CAG), to evaluate opportunities for stormwater capture, treatment, and use (SMCWPPP 2017). The SRP is required by the State Water Resources Control Board to allow stormwater capture projects to be eligible for State grant funds (i.e., Proposition 1). The main goals of the SRP were to identify and prioritize opportunities for stormwater capture projects in San Mateo County through detailed analysis of watershed processes and surface and groundwater resources, input from stakeholders and the public, and analysis of multiple benefits that can be achieved. In addition to the SRP, the Municipal Regional Stormwater Permit (MRP) (Order No. R2-2015-0049) requires San Francisco Bay Area cities and counties to develop Green Infrastructure Plans (GI Plans) (MRP Provision C.3) that outline how agencies plan to integrate GI with existing infrastructure to meet multiple objectives, including the reduction of Polychlorinated Biphenyls (PCBs) and mercury loads to San Francisco Bay to address Total Maximum Daily Loads (SFBRWQCB 2006, 2008, and 2015). At the time of development of this FMP, each city within the Bayfront Canal-Atherton Channel watershed and San Mateo County were developing GI Plans to address their jurisdictional areas. The GI Plans build upon the stormwater capture projects identified as part of the SRP to identify GI implementation strategies to address PCB and mercury load reductions to be achieved by the year 2040.

Common to each of these plans is the focus on GI to achieve stormwater capture on a regional scale. GI describes a collection of structural control measures whose purpose is to mimic pre-urbanization (natural) hydrology, while using a set of common treatment mechanisms (e.g., infiltration, storage, filtration, detention). While the processes utilized by various GI practices are similar, GI can be categorized into three types of stormwater capture projects: (1) Regional Projects, (2) Green Streets, and (3) Low Impact Development (LID). Each type of stormwater capture project has the potential to provide the dual benefit of reducing peak storm volumes and flows and contribute to the goals of the FMP in terms of reducing flooding issues in lower portions of the watershed. The three types of stormwater capture projects are described in more detail in the following sections.

5.1.1 Regional Projects

Regional stormwater capture projects are large-scale facilities that capture and treat runoff from both on- and off-site. Off-site runoff is typically routed to the facility via diversion directly from storm drains, channels, and streams to allow for the treatment of stormwater from larger drainage areas. Regional stormwater capture facilities consist of both subsurface and above-ground features that treat stormwater runoff through a variety of mechanisms. Regional projects may infiltrate captured runoff into native soils, potentially replenishing groundwater storage and restoring natural hydrology, or may store and treat runoff for later use to offset on-site water demand.
Subsurface features may be designed as open-bottom chambers to promote infiltration or lined for storage, detention, or filtration of captured runoff. Additionally, subsurface systems may be constructed below open space or parking lots while retaining intended functional use post-construction. Example photographs of subsurface regional stormwater capture structures are shown in Figure 5-1.

Photos from Los Angeles County Department of Public Works

**Figure 5-1. Example subsurface regional stormwater capture features.**

Above-ground regional stormwater capture projects are those that detain captured runoff in natural or engineered depressions for treatment. These facilities may take the form of detention basins, retention ponds, or constructed wetlands. Some above-ground facilities may be designed to maintain some recreational use (e.g., athletic fields in a detention basin) through the dry season. Figure 5-2 shows example photographs of above-ground regional stormwater capture projects.
Within San Mateo County, there are several opportunities for regional stormwater capture projects. The SRP identified projects within public parcels to provide regional capture and infiltration/treatment of stormwater and included conceptual designs to support further planning and designs. Figure 5-3 shows regional project opportunities on public parcels identified by the SRP in the Bayfront Canal-Atherton Channel watershed. Project opportunities are categorized into high,
medium, and low priority based on the project scores from the multi-benefit prioritization process in the SRP. There are 89 parcels in the watershed that are identified as regional project opportunities.

Following completion of the SRP, C/CAG, cities, and the County have continued to develop conceptual designs for Regional Project opportunities identified in the SRP. For example, the Town of Atherton has partnered with Caltrans to investigate designs of the Cartan Field Stormwater Capture Project (Figure 5-4). The Cartan Field project is a subsurface filtration gallery with a storage volume of 6 acre-feet. Due to site constraints, the project does not feature infiltration and instead captures runoff, filters, and slowly meters flow back to the storm drain system. Through coordination with the
Town of Atherton, the Cartan Field project is considered in the FMP for further evaluation in terms of reducing downstream flooding conditions (Section 6).

A significant portion of regional project opportunities identified in the SRP exist on parcels with public open space, parks, and parking lots. While some of those opportunities are on land managed by the respective municipality (e.g., public parks), many exist on land belonging to schools or other public entities that are not necessarily managed by the municipality. Schools are often prime sites for large-scale stormwater capture, as many have the large available open space (e.g., parking lots, play fields) required for a regional project footprint. These projects require a great deal of coordination with the
school district and public in terms of gaining necessary partnerships and buy-in but represent a significant percentage of opportunities (approximately 20% of public parcels in the County) for siting regional stormwater capture projects.

An example hypothetical project at such a site exists in the unincorporated County community of North Fair Oaks, at the Everest Public High School. The site is situated near a large storm drain, allowing for the capture from a large drainage area. Open space beneath the existing parking lots and blacktop playground may support a large project footprint without disturbing the existing use after construction is completed. Additionally, partnership with the school may provide an invaluable educational experience for the public on the importance of multi-benefit stormwater and flood mitigation projects. Priorities of the partnering school may also be met as part of the collaboration. For example, construction of regional projects at these sites may provide an opportunity for resurfacing and enhancement of current play areas, safety improvements along pedestrian routes to the school, installment of solar panels above parking stalls, or other solutions that best meet the school’s needs. A project at the Everest Public High School site is hypothetical and was not considered for further evaluation in the FMP in terms of reducing downstream flooding, but is included in the FMP as a demonstration of the types of projects that could be co-located with multiple schools in the watershed, particularly in flood-prone areas such as North Fair Oaks. Figure 5-5 shows an example project drainage area and footprint at the school for visualization of the amount of drainage area that can be addressed by a single project at a school.
Figure 5-5. Footprint, drainage area, and diversion point for a hypothetical regional project at a school site.

5.1.2 Green Streets
GI retrofits of existing streets, implemented linearly along the public right-of-way, are generally called “Green Streets.” Green streets can utilize a variety of GI practices to treat stormwater runoff. Practices range from bioretention, permeable pavements, infiltration dry wells, and vegetated swales. The practices used in green streets are intended to imitate natural hydrology, providing relief from local flooding issues, water quality improvement, and other multiple benefits. GI in the right-of-way are typically implemented in conjunction with street design techniques that improve the safety and access for cyclists and pedestrians. When implemented in this manner, projects are sometimes also referred
to as “Complete Streets”, “Living Streets”, or “Sustainable Streets.” Figure 5-6 shows examples of GI implemented along the public right-of-way that make up a green street.

![Example green street features](images)

Photos from San Mateo County Sustainable Green Streets and Parking Lots Guidebook (SMCWPPP 2009)

**Figure 5-6. Example green street features.**

Within San Mateo County, there are numerous opportunities for green street projects. The SRP identified projects along the public right-of-way to provide treatment of stormwater and included conceptual designs to support further planning and designs. Figure 5-7 shows green street project opportunities as street segments (defined by one block) identified by the SRP in the Bayfront Canal-Atherton Channel watershed. Project opportunities are categorized as high, medium, and low priority based on the project scores from the multi-benefit prioritization process in the SRP. There are
approximately 1,300 street segments in the watershed that are identified as green street project opportunities.

![Green Street Project Opportunities](image)

**Figure 5-7.** Green street project opportunities in the Bayfront Canal-Atherton Channel watershed (SRP).

### 5.1.3 Low Impact Development

LID utilize similar GI practices as green streets. Instead of being implemented in the roadway, LID is typically implemented on parcels to treat runoff from impervious area on-site. Like green streets, LID practices also encompass bioretention, permeable pavement, and swales (Figure 5-6). Additionally, they may also include rain barrels, cisterns, and green roofs that are often designed to capture, store,
or treat runoff from impervious roof surfaces. LID can be further divided into two categories: (1) Regulated Projects and (2) LID on public parcels.

Regulated Projects are those GI projects that are regulated under Provision C.3 of the MRP. Provision C.3 requires new development and redevelopment projects that create and/or replace defined amounts of impervious surface to implement post-construction control measures to address stormwater runoff generated on-site and comply with other applicable elements of the provision. For Regulated Projects in the early years of C.3 implementation, stormwater treatment may have been achieved through non-GI means, such as underground vault systems or media filters.

Projects on public parcels that are not regulated under Provision C.3 may also be considered LID. These projects are most often implemented on city or County-owned land by the respective municipality to serve as demonstration pilot projects. These projects promote the adoption of GI, inform future GI design and implementation, and serve as educational tools to the public. While an important part of the implementation strategy for many jurisdictions, the bulk of LID projects is likely to come from future Regulated Projects as urban areas are redeveloped.

5.2 Hydraulic Improvements

The Collaborative, after iterative discussions, selected five general hydraulic improvements for further evaluation in the FMP design process:

1. A siphon draining Bayfront Canal into managed ponds along Ravenswood Slough
2. A pump station at Flood Slough that will bypass the existing tide gates
3. Floodwalls along Bayfront Canal to increase flood capacity,
4. Increased capacity at the existing pumps throughout the system, and
5. Larger culverts along Atherton Channel.

The *Bayfront Canal Hydrology and Hydraulic Evaluation* (BKF 2017) proposed the first four suggested improvements, while the fifth improvement developed out of the results of the modeled existing conditions. The following provides an overview of each of these proposed hydraulic improvement projects.

5.2.1 Siphon from Bayfront Canal

To augment discharge from the Bayfront Canal, two 5-foot by 8-foot box culverts have been designed that will divert stormwater from Bayfront Canal into salt ponds along Ravenswood Slough. A diversion structure (composed of a weir and trash rack) will accept flow that would otherwise pass through the tide gates and convey it first to a forebay and then to two salt ponds via the proposed siphon. Water control structures consisting of combination slide and flap gates will control flow into another two ponds that are influenced by the tidal conditions in Ravenswood Slough. Figure 5-8 shows the conceptual design of the project as viewed from above, along with a schematic of how water travels from the Bayfront Canal into the managed ponds.
Following a 25-year storm event, the managed ponds fed by the two 5-foot by 8-foot box siphons will drain within 1 to 2 days, depending on the tide stage and whether they are empty or full at the start of the event. Draining stops once the tide level in Flood Slough reaches the elevation of the water surface in the ponds, then continues as the tide recedes.

With the siphon in place, the flood depth in Bayfront East is reduced by almost 2 feet and drops below flood depth about 9 hours faster. Stormwater recedes more rapidly with the siphon in place at the other flood-prone areas as well. Bayfront West drain time is reduced from 20 to 7 hours, and the drain time is reduced from 6 hours to 1 hour for both the Douglas and 5th Avenue flood-prone areas. Overall, the siphon reduces accumulated flooding during the 25-year event by 50 acre feet.
5.2.2 Flood Slough Pump

A pump station could be installed to pump flows from the Bayfront Canal directly to Flood Slough, bypassing the tide gates. Such a pump has the potential of lowering water levels along the entire channel. The system, as conceived, would be composed of high volume, low-head pumps in a station adjacent to the tide gates, up to a maximum pumping rate of 1,500 cfs, after which the flow rate in the Bayfront Canal becomes the limiting factor.

Figure 5-9. Pump station similar to the one at 5th Avenue (above) is recommended to increase conveyance from Bayfront Canal into Flood Slough.

A pump of this size would likely require a significant capital cost for construction, operation, and maintenance. Additionally, the footprint required for a station to house it, along with utilities, would comprise a significant area in the vicinity of Flood Slough. However, combined with other flood mitigation measures in the watershed, the pump could be downsized without a loss of effectiveness.

5.2.3 Bayfront Canal Flood Embankments

Any resilient solution to flooding along the Bayfront Canal must address the varying heights, and levels of protection, along the north and south sides of the Canal. A combination of raised embankments and pumping is basic to any plan adopted. Vinyl sheet piles could be deployed along the narrow footprint along the south side of the Bayfront Canal and would prove more durable than steel in the corrosive marine environment. Similar sheet piles have been used in Redwood City along Redwood Shores (Figure 5-10).
5.2.4 Increased Pumping at Douglas and Broadway Pump Stations

Increased conveyance in the Bayfront Canal does not directly benefit areas to the south of Highway 101, a conclusion found by the model results of existing conditions (Section 4.2.3) and the previous Bayfront Canal Hydrology and Hydraulic Evaluation (BKF 2017). In lieu of increased storage, pumping is the only way to reduce flooding in these areas. If implemented in conjunction, the proposed Bayfront Canal embankment improvements and Flood Slough Pump would mitigate the added volume from the proposed upgrades to the Douglas and Broadway pump stations.

In the model, a scenario where the pumps at Douglas Avenue and Broadway were directed past Bayfront Canal and directly into the outfall past the tidal gates was evaluated. Simulations with that configuration showed that maximum water levels in the Bayfront Canal were unaffected by the change. As a result, redirection of the pumps was not pursued further and only the increased capacities were incorporated into further evaluations for the FMP (Section 6).

5.2.5 Increased Pumping at the Athlone Pump Station

Pumping from Athlone Terrace, used in conjunction with stormwater capture, is the best way to address the persistent flooding in North Fair Oaks. As with the Douglas and Broadway pumps, further study is needed appropriately size the peak pumping rate.
5.2.6 Increasing Culvert Capacity along the Atherton Channel

The bridges crossing Atherton Channel at Haven Court and Haven Avenue (Figure 5-11 and Figure 5-12) are potentially undersized for a 25-year storm event, especially when vegetation along the upstream banks is overgrown. With an opening height of 4-feet 4-inches, the cross-sectional area is much less than the upstream channel. The sudden loss in capacity, combined with milder slope in the lower reach, can turn this bridge into a bottleneck, forcing stormwater from the Channel into the Bayfront East flood-prone area.

Figure 5-11: Open section of Atherton Channel above the Haven Avenue bridge (looking upstream).
In conjunction with the Flood Slough Pump, widening of the existing culverts to match the top width of the existing open channel segments is expected to eliminate the spill into Bayfront East from the Atherton Channel. Combined with limited floodwalls along the bridges and headwalls on the bridges themselves, the increased capacity would allow for greater discharge from the Athlone Terrace Pump Station.

6 EVALUATION OF FLOOD MANAGEMENT SCENARIOS

This FMP evaluates how the combination of proposed projects identified in the previous section can safely control a 25-year, 12-hour storm event while minimizing flooding. This evaluation was performed using the XPSWMM hydraulic model of existing conditions (Section 4.2), with modifications in order to simulate combinations of the proposed projects. The proposed stormwater capture and hydraulic improvement projects were organized into three thematic scenarios for analysis. Scenario 1 focuses only on hydraulic improvements that can be made to the existing conveyance system. Scenario 2 examines how only stormwater capture in the upper watershed is manifested as flood volume reduction in the flood-prone areas. Scenario 3 represents a composite of solutions from Scenario 1 and 2 to reduce reliance on a single approach.

Model evaluation of proposed projects was based on the following four steps:

1. Disconnect the various flood-prone areas (e.g. North Fair Oaks, Bayfront East) to contain flow in the main channels
2. Raise weir heights to retain all flow in the Bayfront Canal and the Atherton Channel
3. Assess the maximum water surfaces along the channels
4. Modify or introduce other flood control structures as needed.
Through several iterations of the fourth step, several flood protection measures can be suggested for reducing flood risks (Section 5.2).

### 6.1 Scenario 1: Evaluation of Hydraulic Improvements

The Bayfront Canal cannot currently pass a 25-year storm flow, and Figure 6-1 dramatically illustrates why surcharge occurs along the channel. In order to contain the entire volume of the 25-year storm event and provide the same degree of protection along the channel, embankment heights along both the north and south side of the Canal would need to be raised to 14 feet to allow for the maximum water surface elevation of 12 feet and 2 feet of freeboard. At the least protected sections of the Canal, this would require 6-foot floodwalls. The floodwalls would likely lead to nuisance flooding upstream as Bayfront Canal water levels would submerge storm drain inlets. The storm drain outlets would also require flap gates and routine maintenance to ensure flow did not back up through the connections.

A 1,500 cfs pump drastically reduces peak water surfaces by negating the tidal influence. Figure 6-1 shows downstream water levels drop to 4 feet, just above the crest of the diversion weir into the salt ponds. Still, water levels are less than a foot below the lowest section of the embankment, and they remain a threat to Bayfront West upstream.

![Figure 6-1. Maximum water elevation along the Bayfront Canal for various conditions of increased conveyance.](image)

Atherton Channel (Figure 6-2) presents a different set of problems stemming from capacity limitations at the upstream end and the bridges along Haven Avenue. At the downstream end, water levels (and flooding) are dictated by depths in the tidally influenced Bayfront Canal. The 1,500 cfs pump draws down the water surface and eliminates overbank flooding at the confluence.
Flooding at the culverts is not eliminated. Upstream, under existing conditions, spill into North Fair Oaks would be expected when flows exceed 940 cfs. For the 25-year event, given the peak of 970 cfs, this would result in 0.3 acre feet of stormwater added to the local inflow. Downstream, large amounts of spill would run from the bridges into Bayfront East (Section 4.2.4). A solution is needed to allow the pinch points to take in more water. Since raising the road crossings would likely require major adjustments to existing infrastructure such as roadways, a more convenient strategy may be to widen the box culvert to match the existing open channel width, effectively doubling the capacity. Wider culverts, with the Flood Slough pump, eliminates all but spill into North Fair Oaks.

6.2 Scenario 2: Evaluation of Stormwater Capture

In order to evaluate the benefits of the stormwater capture projects identified in Section 5.1, a two-step process was undertaken to estimate the capture of stormwater runoff and the impacts on the 25-year storm hydrographs predicted by the hydrology model (HEC-HMS) and used as inputs to the hydraulic model (XPSWMM). This required the use of a separate model in order to simulate the functionality associated with the various types of stormwater capture projects, including storage, infiltration, and outflow processes. To support GI Plans currently under development throughout San Mateo County for each city and unincorporated County area, and to address requirements of the MRP to demonstrate that pollutant reduction goals are met through GI implementation, C/CAG is currently developing a linked hydrologic and GI modeling system to represent the various projects identified in Section 5.1 (SMCWPPP 2018a and 2018b). Referred to as the Reasonable Assurance Analysis (RAA), the C/CAG modeling system (hereafter referred to as RAA models) includes linkages of LSPC (Shen et al. 2004) and SUSTAIN (Riverson et al. 2014, USEPA 2009) for simulation.
of hydrology and stormwater capture project processes, respectively. The following summarizes the steps for utilizing the various models for evaluation of stormwater capture project benefits for the FMP:

1. **Estimation of Stormwater Runoff Capture (RAA Models)** - The RAA models were utilized to simulate the 25-year, 12-hour storm and the stormwater capture associated with GI project identified in Section 5.1. The Cartan Field stormwater capture project was removed from the model since the mechanism for routing stormflows into the project is through pumping from Atherton Channel, and therefore is represented separately in the XPSWMM model for evaluation of flood reduction benefits (Step 2 below). The RAA models were then used to determine the percent reduction of the 25-year, 12-hour storm volume, associated with the stormwater capture projects, for each of the hydrologic model subwatersheds (Figure 3-6).

2. **Evaluation of Reduced Flooding Impacts due to Stormwater Capture (XPSWMM)** – Based on the percent reductions of storm volumes estimated in Step 1, the 25-year, 12-hour hydrographs (determined by the HEC-HMS hydrologic model) used as inputs to the XPSWMM existing condition model were adjusted. XPSWMM was also used to represent the Cartan Field regional stormwater capture project. The modified XPSWMM model was then used to evaluate the impacts of the stormwater capture projects in terms of reducing flood impacts.

The following sections provide further discussions and results of the above steps.

### 6.2.1 Estimation of Stormwater Runoff Capture

As discussed in Section 5.1, the MRP requires San Francisco Bay Area cities and counties to develop GI Plans (Provision C.3) and PCBs and Mercury Control Measure Implementation Plans (Provisions C.11 and C.12) to provide pollutant load reductions sufficient to meet TMDLs. A key component of these plans is a RAA that quantitatively demonstrates that proposed GI will result in sufficient pollutant load reductions (SFBRWQCB 2015). To support the development of GI Plans throughout the County for each municipal jurisdiction, including GI Plans for Redwood City, the Town of Atherton, the City of Menlo Park, and San Mateo County, to address areas within the Bayfront Canal-Atherton Channel Watershed, the RAA models were used to simulate each of the stormwater capture project categories outlined in Section 5.1. The RAA also considered existing stormwater capture projects that are currently operational in the watersheds, and LID assumed to be incorporated within future areas projected for development or redevelopment. All stormwater capture projects considered in the RAA are assumed to be implemented by 2040, when PCB and mercury load reductions associated with GI are to be met per the MRP. The RAA demonstrates that a 17.6 percent reduction of cohesive sediment, achieved through implementation of GI, will be sufficient to address MRP requirements for both PCBs and mercury. The RAA assumed that each city and unincorporated County are to equally address this 17.6 percent reduction within their jurisdiction.

To help plan for cost-effective GI implementation between now and 2040, a sequencing of stormwater capture project categories was assumed for the RAA. Figure 6-3 shows the implementation sequence for projects in the watershed. The project categories incorporated in the model include:

1. **Existing Projects**: Stormwater treatment and GI projects that have been implemented since Fiscal Year 2004/05. This is primarily all projects that were mandated to treat runoff via the MRP, but also includes any public green street or other demonstration projects.
2. **Future New and Redevelopment**: Projects that will be subject to MRP requirements to treat runoff via LID and is based on spatial projections of future new and redevelopment tied to regional models for population and employment growth by 2040.

3. **Regional Projects (identified)**: The Cartan Field regional stormwater capture project (Section 5.1.1) was considered in the RAA model.

4. **Green Streets**: The SRP identified and prioritized opportunities (High, Medium, and Low) throughout the watershed for retrofitting existing streets with green infrastructure in public rights-of-way (Section 5.1.2).

5. **Other GI Projects (to be determined)**: Other types of GI projects on publicly-owned parcels, representing a combination of either additional parcel-based LID or other Regional Projects. The SRP screened and prioritized public parcels for opportunities for onsite LID (Section 5.1.3) and Regional Projects (Section 5.1.1). These opportunities need further investigation to determine the best potential projects.

![Figure 6-3. Example implementation sequencing of GI categories.](image)

Table 6-1 summarizes the results of the RAA in terms of the specific suite of stormwater capture projects for the Bayfront Canal-Atherton Channel watershed to meet the sediment reduction goal. Results in Table 6-1 are reported in terms of the “capacities” for each type of project within each municipal jurisdiction, or the combined total storage volume for each project type through which stormwater can be routed through and subject to detention, infiltration, or reuse.
Table 6-1. Summary of stormwater capture project capacities from the RAA within the Bayfront Canal-Atherton Channel watershed.

<table>
<thead>
<tr>
<th>Jurisdiction</th>
<th>Stormwater Capture Project Capacity</th>
<th></th>
<th>Green Streets</th>
<th></th>
<th>Other GI Projects (TBD)</th>
<th>Total GI Capacity (acre-ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Existing Projects</td>
<td>Future New &amp; Redevelopment</td>
<td>Cartan Field</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td>Atherton</td>
<td>0.36</td>
<td>0.17</td>
<td>1.92</td>
<td>0.16</td>
<td>2.53</td>
<td>0.07</td>
</tr>
<tr>
<td>Menlo Park</td>
<td>2.10</td>
<td>5.41</td>
<td>1.50</td>
<td>0.91</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Redwood City</td>
<td>3.15</td>
<td>4.12</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Unincorporated</td>
<td>0.51</td>
<td>4.61</td>
<td>1.74</td>
<td>1.89</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Woodside</td>
<td>--</td>
<td>0.25</td>
<td>0.75</td>
<td>--</td>
<td>0.08</td>
<td>--</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>6.12</strong></td>
<td><strong>14.56</strong></td>
<td><strong>5.91</strong></td>
<td><strong>2.96</strong></td>
<td><strong>2.61</strong></td>
<td><strong>0.07</strong></td>
</tr>
</tbody>
</table>

Color Gradient: Relative GI Capacity. Darker is higher.

The suite of stormwater capture projects listed in Table 6-1 also contribute to the improvement of local flood conditions by retaining or detaining stormwater that could otherwise flood roadways or properties. To assess the stormwater runoff that can be captured for the 25-year, 12-hour storm forming the basis of analysis for the FMP, the rainfall distribution associated with the storm (Figure 3-7) was configured within the RAA models in order to simulate conditions with and without the projects. As a result of the stormwater capture projects (i.e., Existing Projects, Future New & Redevelopment, Green Streets, and Other GI Projects TBD), Figure 6-4 and Figure 6-5 summarize percent reductions of runoff volume and peak discharge, respectively, for each of the subwatersheds corresponding to the hydrologic model (Figure 3-6). Figure 6-6 provides an example of the modeled storm volume and peak flows, or “hydrograph,” for subwatershed J-L. The figure shows the change in peak flows and storm volume for the 25-year storm with and without GI, corresponding to percent reductions presented in Figure 6-4 and Figure 6-5. As previously discussed, the benefits of the Cartan Field stormwater capture project (also in subwatershed J-L) were represented separately in the XPSWMM model (discussed in next section) due to the fact that the project pumps water from the channel rather than reducing stormwater discharges to the channel.
Figure 6-4. Percent volume reduction for the 25-year, 12-hour storm for each subwatershed

Figure 6-5. Percent peak flow reduction for the 25-year, 12-hour storm for each subwatershed
6.2.2 Evaluation of Reduced Flooding Impacts due to Stormwater Capture

In order to assess the benefits of the stormwater capture projects in terms of flood reduction, the XPSWMMM model was modified based on the reduced storm flows demonstrated in the previous section. To modify XPSWMM, the percent reductions for the 25-year, 12-hour storm volume (Figure 6-4) and peak flow (Figure 6-5) were used to adjust the storm hydrographs used as input to XPSWMM. By adjusting the hydrographs used by XPSWMM (and estimated using the HEC-HMS hydrology model reported in Section 3.2), this ensured that benefits of the stormwater capture projects could be directly compared to the existing condition scenario (Section 4.2).

The XPSWMMM model was also reconfigured to represent the Cartan Field regional stormwater capture project. The Town of Atherton preliminary conceptual design of the Cartan Field project assumes a pump rate of 40 cfs from Atherton Channel, which was represented directly in XPSWMM. The pump rate of 40 cfs was assumed through the duration of the 25-year storm until the 6 acre-feet of the project storage volume is met (1 hour and 50 minutes of operation).

The XPSWMM model for Scenario 2 showed noticeable reduction in flood volumes (Table 6-2) throughout the watershed, with a total reduction of nearly 102 acre-feet in flood-prone areas. Reduction in flooding resulting from stormwater capture projects is based on the following factors:

1. Runoff production itself is reduced, meaning less water entering the flood-prone areas
2. Peak flows and their duration times are reduced, resulting in less overbank flow

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2 The figure illustrates the variability of rainfall and modeled flows throughout the duration of the 25-year, 12-hour storm, and the change in flows resulting from the implementation of GI in the subwatershed.
3. Volume reduction from one source has benefits in multiple flood-prone areas.

Table 6-2. Runoff volume into each flood-prone area for the 25-year, 12-hour storm under existing conditions and full build-out of stormwater capture projects by 2040.

<table>
<thead>
<tr>
<th>Flood-Prone Area</th>
<th>Source of Flooding</th>
<th>Flood Volume (acre-feet)</th>
<th>Existing Hydrology</th>
<th>Hydrology with Stormwater Capture Projects (GI Projects and Cartan Field)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broadway</td>
<td>Local Drainage</td>
<td>49.4</td>
<td>44.5</td>
<td></td>
</tr>
<tr>
<td>Douglas</td>
<td>Local Drainage</td>
<td>44.2</td>
<td>40.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2nd Ave</td>
<td>51.6</td>
<td>42.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Broadway</td>
<td>5.3</td>
<td>3.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Selby</td>
<td>9.7</td>
<td>7.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Total</strong></td>
<td><strong>110.8</strong></td>
<td><strong>93.9</strong></td>
<td></td>
</tr>
<tr>
<td>5th Ave</td>
<td>Local Drainage</td>
<td>60.3</td>
<td>54.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Douglas</td>
<td>53.9</td>
<td>42.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Total</strong></td>
<td><strong>114.2</strong></td>
<td><strong>97.1</strong></td>
<td></td>
</tr>
<tr>
<td>Bayfront West</td>
<td>Bayfront Canal</td>
<td>19.0</td>
<td>14.6</td>
<td></td>
</tr>
<tr>
<td>Bayfront East</td>
<td>Atherton Channel</td>
<td>120.7</td>
<td>50.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bayfront Canal</td>
<td>103.0</td>
<td>72.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Total</strong></td>
<td><strong>223.7</strong></td>
<td><strong>122.7</strong></td>
<td></td>
</tr>
<tr>
<td>North Fair Oaks</td>
<td>Local Drainage</td>
<td>79.3</td>
<td>75.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Atherton Channel¹</td>
<td>0.5</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Total</strong></td>
<td><strong>79.8</strong></td>
<td><strong>75.4</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Total Flooding (ac ft)</strong></td>
<td><strong>597</strong></td>
<td></td>
<td><strong>448</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Total Reduction (ac ft)</strong></td>
<td><strong>-</strong></td>
<td></td>
<td><strong>149</strong></td>
<td></td>
</tr>
</tbody>
</table>

¹ Flows entering the Atherton Channel upstream are assumed to be supercritical (i.e., a Froude number < 1.0) based on a calculation of normal depth and independent analysis (NV5)

Stormwater capture alone will not eliminate flooding in any single area. Stormwater capture impacts the Bayfront Canal and Atherton Channel very differently. Tidal influence, once again, dominates the maximum water elevation in the Bayfront Canal (Figure 6-7). The runoff reduction has negligible impact on the maximum stage at the confluence of the Bayfront Canal and the Atherton Channel. So, while 37% less volume enters the flood-prone areas of Bayfront East and West during the storm event, the peak inundation limit is still consistent with the peak tidal elevations in Flood Slough. The reduction in total flood volume is the result of a shorter period of inundation. Stormwater capture in the upper watershed is the only proposed change that eliminates spill from the Atherton Channel into North Fair Oaks (Figure 6-8).
Figure 6-7. Water surface elevations along Bayfront Canal with and without stormwater capture projects.

Figure 6-8. Water surface elevations along Atherton Channel with and without stormwater capture projects.
6.3 Scenario 3: The Flood Management Plan

The results from Scenarios 1 and 2 illustrate the need for a multi-faceted approach to improve the multiple pathways that stormwater can become a flood threat (e.g. tidal backwaters, limited culvert capacities, etc.). The conceptual approach follows a process that moves from solutions at the top of the watershed down to the outlet at San Francisco Bay, including the following steps:

1. Maximize stormwater capture in the upper watershed
2. Incorporate siphon to Managed Ponds
3. Increase conveyance to the Bayfront Canal and Atherton Channel
4. Determine a reasonable floodwall threshold along the Bayfront Canal
5. Size the Flood Slough Pump for that threshold, plus freeboard (e.g., 2 feet).

Scenario 3 accounts for all flow reductions associated with the stormwater capture projects identified in Section 5.1 and considered in Scenario 2. In addition, the pumps at Broadway and Douglas Avenue were doubled in size (from 72 to 150 cfs). The pump at Athelone Terrace was increased from 35 to 100 cfs to take advantage of widened culverts beneath the two bridges along the Atherton Channel above Highway 101. A top elevation of 12 feet for floodwalls along Bayfront Canal was set as an achievable design goal. This required limiting the maximum water surface to 10 feet NAVD 88 in order to allow for 2 feet of freeboard.

Sizing the Flood Slough Pump Station requires balancing the upstream opportunities for flood mitigation, feasibility of floodwalls, and the investment in the pump itself. Figure 6-9 shows the flow levels in the Bayfront Canal for pumps ranging in size from 300 to 1,500 cfs, in conjunction with the combination of solutions proposed in Scenario 3. Larger pumps lead to uniform drops in the water surface elevations along the Canal down to a pump capacity of 900 cfs. At less than that rate, upstream benefits are diminished. Comparisons of the maximum water surface elevations in the Bayfront Canal (Figure 6-10) and Atherton Channel (Figure 6-11) with water surfaces due to pumping alone show that the Flood Slough Pump can be reduced from 1500 cfs to 900 cfs to arrive at a comparable level of protection. A capacity of 900 cfs was chosen for the preferred size of the pump at Flood Slough that could, in conjunction with the other improvements, allow for a 12-foot floodwall along Bayfront Canal.

The FMP includes the following components:

- A siphon consisting of two 5 foot by 8 foot chambers draining into the Managed Ponds
- The stormwater capture projects suggested by the RAA model
- The Cartan Field regional stormwater capture project
- A pump station at Flood Slough with a capacity of 900 cfs
- Widening the culverts in Atherton Channel downstream of Highway 101
- Increasing the pump capacity at 5th Avenue from 30 to 300 cfs
- Floodwalls along Bayfront Canal to elevation 12 feet NAVD 88
- Floodwall along Atherton Channel to height 2 feet above the existing bank
- Increasing pump capacity at Broadway, Douglas Avenue, and Athelone Terrace.

The multi-faceted approach outlined in the bulleted list results in major improvements over the results of Scenario 1 or Scenario 2 alone.
Figure 6-9. Maximum water surface elevation in Bayfront Canal for various pump sizes at Flood Slough.

Figure 6-10. Maximum water depths along Bayfront Canal from a mixed solution compared to pumping alone.
Figure 6-11. Maximum water depths along Atherton Channel from a mixture of measures and pumping alone.

As shown in Figure 6-12, the implemented FMP is predicted to provide significant reduction of flooding compared to existing conditions (Figure 4-8) for the 25-year rainfall event. With flooding from the Bayfront Canal and Atherton Channel eliminated, Table 6-3 summarizes the remaining local runoff that must be stored or conveyed from each flood-prone area in order to further reduce flooding impacts to the areas depicted in Figure 6-12. This additional flood volume can be addressed through additional stormwater capture projects beyond those determined through the RAA to be needed by 2040 to address pollutant reduction goals set by the MRP (Table 6-1).

To meet the additional need for stormwater capture, further planning is recommended to evaluate opportunities for regional stormwater capture projects that can be located on public land (e.g., parks, schools, Caltrans properties). Section 5.1.1 summarized multiple opportunities for regional projects that were identified by the SRP. Schools represent a major opportunity for regional projects within or near flood-prone areas, as few parks are within urban areas of the watershed where stormwater can be diverted from storm drains or pumped from channels. Section 5.1.1 summarized a hypothetical regional project that could be located at a school in North Fair Oaks, but further coordination is needed with the school district and public to obtain buy-in and partnership on this project or other school properties. These regional projects provide an ideal opportunity to incorporate multiple-benefit designs that provide enhancements to schools, but the school district, stakeholders, and public will need to be engaged in terms of incorporating these aspects into the project design.
Figure 6-12. Map of potential flooding extents based on the Scenario 3 (without additional regional stormwater capture projects) for the 25-year, 12-hour storm and an elevated tide.
Table 6-3. Potential changes to the flooding throughout the watershed for the 25-year, 12-hour storm with the implementation of the Flood Management Plan

<table>
<thead>
<tr>
<th>Flood-Prone Area</th>
<th>Source of Flooding</th>
<th>Mixed Solution Scenario</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Volume (acre-feet)</td>
<td>Maximum Depth (feet)</td>
<td>Inundation Area (acre)</td>
<td></td>
</tr>
<tr>
<td>Broadway</td>
<td>Local Drainage</td>
<td>44.5</td>
<td>1.9</td>
<td>4.8</td>
<td></td>
</tr>
<tr>
<td>Douglas</td>
<td></td>
<td>40.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Local Drainage</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2nd Ave</td>
<td>40.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Broadway</td>
<td>0.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Selby</td>
<td>8.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>92.5</td>
<td>3.9</td>
<td>20.4</td>
<td></td>
</tr>
<tr>
<td>5th Ave</td>
<td>Local Drainage</td>
<td>54.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Atherton Channel¹</td>
<td>0.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Douglas</td>
<td>25.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>85.7</td>
<td>2.8</td>
<td>57.8</td>
<td></td>
</tr>
<tr>
<td>Bayfront West</td>
<td>Bayfront Canal</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>Bayfront East</td>
<td>Atherton Channel¹</td>
<td>0.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bayfront Canal</td>
<td>0.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>North Fair Oaks</td>
<td>Local Drainage</td>
<td>75.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Atherton Channel¹</td>
<td>0.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>79.3</td>
<td>2.9</td>
<td>27.1</td>
<td></td>
</tr>
<tr>
<td>Total Flood Volume (ac-ft)</td>
<td></td>
<td>342.3</td>
<td>110.1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

¹ Flows entering the Atherton Channel upstream are assumed to be supercritical (i.e., a Froude number < 1.0) based on a calculation of normal depth and independent analysis (NV5)

7 CONCLUSIONS AND RECOMMENDED PLAN

The previous section summarized the recommended FMP to reduce flooding impacts for the 25-year critical storm event. The 25-year storm was selected as a conservative, long-term level of protection for the FMP, however, the management solutions will have a more pronounced benefit in terms of reducing flooding during typical storms occurring in any given year. As a result, implementation of the FMP will likely result in near-term benefit and provide much-needed relief for flood-prone areas. Planning for flood resiliency requires a balance between selecting projects that can be implemented in the short-term for immediate flood prevention and anticipating projects that address long-term goals, such as protection from sea-level rise. For the Bayfront Canal-Atherton Channel watershed, a balance may also be reached between near-term flood management in the lower watershed, such as pumping into the Bayfront Canal, and long-term projects that would capture or reduce stormwater in the upper watershed before it becomes a flood threat.
7.1 Additional Benefits for Each Proposed Component

To the extent possible, flood improvement projects should seek to incorporate multiple benefits. These additional benefits can provide increased likelihood for funding and implementation, through increased opportunity for state and federal grants, in addition to furthering support from stakeholders and the public. The following are example additional benefits that can be considered for flood improvement projects.

STREAM CORRIDOR ENHANCEMENT

Atherton Channel could present several opportunities along its length for habitat restoration that would also create designated overbank areas, despite its urban setting and concrete construction. Once the channel emerges to the south of Highway 101, the concrete trapezoidal channel is flanked by green spaces. Figure 7-1 shows a typical section before it goes under Highway 101. Similar to the corridors in Figure 5-11 and Figure 5-12, the banks provide space that could be further developed for designated floodways.

Figure 7-1. Atherton Channel above Highway 101 becomes a constrained open channel (looking downstream).

SEA LEVEL RISE RESILIENCY

The County of San Mateo Sea Level Rise Vulnerability Assessment (2018) concludes that sea-level rise will aggravate stormwater flooding problems along the Bayfront Canal. The National Research Council (2012) projects sea level rise of approximately 3 feet in San Francisco Bay by year 2100 and notes it could be as high as 5.5 feet relative to year 2000 tide conditions. Currently, Highway 101 and much of Bayfront Canal act as a barrier from the 100-year tide. However, sea-level rise of even 3 ft could inundate much of the watershed during even more common high tides. Flood-prone areas in the watershed are already below average high tide elevations occurring during storm events. Sea-level
rise will reduce the duration during which these areas and the Bayfront Canal itself are able to drain ponded runoff.

While it is not the intention of the FMP to mitigate sea level rise, components of the final plan may anticipate the additional strain that will be placed on the existing system given higher tides. For instance, embankments along the Bayfront Canal could face more frequent high tides and storm surges, thereby providing protection to interior areas as well as increasing the conveyance of the canal.

7.2 Cost Estimates

Material costs for the suggested hydraulic improvement projects fall within three categories: 1) vinyl sheet piling; 2) box culverts; and 3) pumps. Table 7-1 presents the associated unit cost for each, based on recorded bids with Caltrans and quoted prices from suppliers.

Table 7-1 Unit costs for the various hydraulic improvements suggested in the Flood Management Plan

<table>
<thead>
<tr>
<th>Item</th>
<th>Unit Cost ($)</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vinyl Sheet Piling</td>
<td>55</td>
<td>square foot</td>
</tr>
<tr>
<td>Box culvert - cast in place</td>
<td>1,000</td>
<td>cubic yard</td>
</tr>
<tr>
<td>Box culvert - precast</td>
<td>800</td>
<td>linear foot</td>
</tr>
<tr>
<td>Pump Station</td>
<td>10,000</td>
<td>cfs</td>
</tr>
</tbody>
</table>

Based on these unit costs, estimated total costs for the material components of each project are outlined in Table 7-2. Final costs would require further estimation of construction and permitting needs.

Table 7-2 Unit costs for the various hydraulic improvements suggested in the Flood Management Plan

<table>
<thead>
<tr>
<th>Proposed Hydraulic Improvement</th>
<th>Total Cost ($1M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bayfront Canal Floodwalls (L: 2 x 5,207'; H: existing to 12' NAVD 88)</td>
<td>4.01</td>
</tr>
<tr>
<td>Atherton Channel Floodwalls (L: 2 x 1,955'; H: 2')</td>
<td>1.43</td>
</tr>
<tr>
<td>Atherton Channel Culvert Replacement – 5’ x 10’ precast (x 4)</td>
<td>0.23</td>
</tr>
<tr>
<td>Atherton Channel Culvert Replacement – 5’ x 10’ cast in place (x 4)</td>
<td>0.35</td>
</tr>
<tr>
<td>Flood Slough Pump Station (pump only) – 900 to 1,500 cfs</td>
<td>9 to 15</td>
</tr>
<tr>
<td>Athlone Pump Upgrade (pump only)</td>
<td>0.70</td>
</tr>
<tr>
<td>Broadway and Douglas Pump Upgrade (each, pump only)</td>
<td>0.10</td>
</tr>
</tbody>
</table>

The Flood Slough Pump would require land acquisition for the station and is potentially costly. The cost of new infrastructure (e.g. a station house) as well as construction costs related to altering existing infrastructure (e.g. powerlines) are highly dependent on the final design. The long-term tradeoff between energy costs required for a submersible pump and the initial investment for a propeller pump, which can operate with a lower dynamic head, would need to be considered.
The costs for stormwater capture projects were not developed for the FMP, since much of those capital costs will continue to be developed through implementation of GI Plans being developed by the cities and San Mateo County. If additional regional stormwater capture projects are identified to provide additional stormwater capture, cost estimates for those projects will be developed on a case-by-case basis, since the designs of the stormwater capture facilities, necessary pumps, and other multiple-benefit features (e.g., park or school enhancements) will be specific to the site and decisions of stakeholders and/or funding partners (e.g., schools, Caltrans, County or city parks).

### 7.3 Ranking and Ordering of Flood Improvements

Table 7-3 summarizes the benefits and relative costs of the proposed components of the FMP. Ranking in the table is based on the number of flood-prone areas that would benefit from each improvement. For example, pumping directly from Bayfront Canal to Flood Slough will address flooding in five of the flood-prone areas (with only North Fair Oaks exempt), whereas the Athlone Terrace Pump Station would deal solely with local flows into North Fair Oaks.

<table>
<thead>
<tr>
<th>Number of Flood-prone Areas Benefitted</th>
<th>Flood Improvement Measure</th>
<th>Relative Cost</th>
<th>Sea-Level Rise Benefits</th>
<th>Increase Green Space</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>Stormwater Capture Projects¹</td>
<td>$$$$ - $$</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>5</td>
<td>Flood Slough Pump Station (900 cfs)</td>
<td>$$$$$</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Bayfront Canal Floodwalls</td>
<td>$$$$</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Atherton Channel Culvert Replacement</td>
<td>$$</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Atherton Channel Floodwalls</td>
<td>$$$</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Increased Pumping, Broadway Station</td>
<td>$$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Increased Pumping, Douglas Ave Station</td>
<td>$$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Increased Pumping, Athlone Terrace Station</td>
<td>$$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

¹ As discussed in the previous section, costs for stormwater capture projects will be further determined through ongoing implementation of GI Plans prepared by the cities and County. Other large regional project costs can vary significantly depending on the size, complexity of the design, and the characteristics of the site.

While the ranking in Table 7-3 is based on the total number of areas that benefit from a flood improvement measure, other considerations, such as the sequencing of improvements, needs to be evaluated. For example, upgrades to Athlone Terrace Pump Station without widening of the downstream culverts in Atherton Channel may worsen flooding in other areas. This is just one example, and the interrelation between the proposed flood improvements needs to be evaluated in more detail to inform future prioritization of projects.

### 7.4 Permitting Needs

This section provides permitting considerations that may impact project cost, schedule, and complexity. It is not intended to be a comprehensive list of permits but rather a summary of permits likely needed for various project alternatives. An idea of the unique requirements for each will assist in comparing alternative approaches for implementation. Further permitting needs will likely be identified and addressed as part of the design process.
Since none of the project area falls within designated flood projects or within floodways, there is no need for USACE 408 permits. The project area is also not within FEMA jurisdiction. The project also does not support runs of Central Valley Steelhead and should not require coordination with National Marine Fisheries Service. Key considerations for permitting include:

1. **Municipal Regional Stormwater Permit**: All stormwater capture projects have the potential to contribute to city/County goals for GI implementation to address MRP requirements for PCB and mercury load reductions. Separate GI Plans are currently being developed by each of the cities and San Mateo County that will include approaches and goals for implementing GI projects within each jurisdiction. Implementation of stormwater capture projects should be consistent with the approaches tailored for each city/County GI plan addressing projects within their respective municipal jurisdiction.

2. **San Francisco Bay Conservation and Development Commission (BCDC)**: Work within the Bayfront Canal and lower Atherton Channel will likely require a permit from the BCDC. The BCDC has regulatory authority over the bay and within 100 feet of the shoreline. Installation of a new pump station, flood walls, and channel improvements are unlikely to fit into Regionwide Permits. The BCDC permit will require that public views and public access not be obstructed by proposed projects. The improvements affected by this permit will likely include floodwalls along Bayfront Canal, a new Bayfront Canal floodwall, and the crossing over the Atherton Channel at Haven Avenue.

3. **Section 404 of the Clean Water Act**: All of the Bayfront Canal, as well as Atherton Channel below Highway 101 crossing may potentially be classified as wetland habitat. Any improvement that temporarily or permanently impacts this area will require a 404 permit from USACE. The improvements affected by this would likely include the crossings over Atherton Channel downstream of Highway 101, a new Bayfront Canal pump station, and potentially ancillary impacts from the Bayfront Canal floodwall.

### 7.5 Operations and Maintenance Needs

Selection of any proposed flood management measures would need to consider long-term operational and maintenance needs:

1. **Floodwalls**: Stability of pile-driven walls is a primary concern. Installation of floodwalls would require driving the sheet piles to a depth approximately equal to the height above ground level. Long-term stability would depend on the compaction of the supporting ground on either side. Along with proper initial ground preparation, safeguarding the channel interior side from erosion or weakening would need to be a part of regular inspection. Occasional replacement of damaged sections may be necessary, so ensured access should be a consideration.

2. **Box Culverts**: Culverts along the Atherton Channel, whether replaced or not, should be monitored and cleared of debris and sediment to maintain design conveyance. Headwalls and decks for the culverts downstream of Highway 101 should be inspected periodically.

3. **Pumps**: Electricity costs are the major operational cost for pumping, with yearly costs depending on use and cost per kilowatt hour. Regardless of the pump capacity selected, it is recommended that the amount be divided among at least three pumps to reduce the chance of total system failure.

On-going maintenance for any of the proposed solutions would also need to follow the guidelines outlined with the permitting requirement detailed above.
A final consideration for operation is the increased possibility of nuisance flooding in localized areas. A head differential that prevents gravity feed storm drains from emptying into the major channels is one drawback of increased water depths. Storm drains along the Atherton Channel (Figure 7-2) and the Bayfront Canal (Figure 7-3) allow ponding water to drain from small areas such as parking lots and roadways. Their function, of course, depends on water levels at the bottom of the drain to be less than at the inlet. Over time, as problematic ponding areas are identified, localized flood solutions, such as GI or other regional stormwater capture solution, will need to be investigated.

Figure 7-2. Example of a storm drain along Atherton Channel can be submerged during backwater tidal conditions.
7.6 Recommendations for Stream Gauge Locations

Due to the uniformity of Bayfront Canal-Atherton Channel watershed, the timing of peak flows from the various subwatersheds reaching the Bayfront Canal are generally coincident or nearly coincident. The timing of the peak flows also occurs shortly after the peak rainfall occurs, limiting the ability to forecast peak flows for the purpose of adjusting management schedules. Stream gage locations would be ideally located on the bayside of the tide gates, in Bayfront Canal near the confluence with Atherton Channel, and on Atherton Channel near the Marsh Road culvert entrance. These locations would provide information to pump station operators and emergency responders to help optimize performance and provide timely reaction to rising water levels.

Installing a stream gage in Flood Slough will provide pump operators at Fair Oaks, Broadway, Douglas, and 5th Avenue with information on existing tide levels and if tide levels are rising or falling. If tide levels are falling, pump operators may wish to maximize pump operations to drain as much water from the system ahead of rising tides. Similarly, pump operators may wish to reduce pumping and maximize storage in sumps and infrastructure if tide levels are reaching critical high tide elevations.

Installing a stream gage at the confluence of Bayfront Canal and Atherton Channel will provide data on water levels within Bayfront Canal and the lower Atherton Channel. The gage can be used to alert when flood levels are rising within this area and are at or near critical levels where flooding may begin to occur. Comparison of this gage to the Flood Slough gage can help identify when the tide gates may be clogged with debris (significantly higher flows in Bayfront Canal than in Flood Slough), or when the tide gates may not be functioning (rising water levels in Bayfront Canal without storm inflow). The stream gage at this location would also provide pump operators with information on when pumping could be maximized (when water levels were falling or well below channel capacity), or when pumping rates should be slowed (prior to when overtopping may occur).
Installing a stream gage upstream of Marsh Road on Atherton Channel would provide information to downstream pump stations about when to slow pumping rates into the Channel or Bayfront Canal due to expected inflows from the Channel. Similarly, as water levels rose to toward top of Channel elevations, alerts could provide emergency personnel with opportunities ahead of time to address the flooding. Similarly, if debris were lodged in the downstream channel, the stream gage would show abnormally-high water levels and help indicate where the blockage exists.

8 REFERENCES


NV5. 2015. *Town of Atherton Townwide Drainage Study Update*. Prepared by NV5 under the direction of Town Atheron. San Jose, CA.

Redwood City. 2017. Memorandum of Understanding between the Redwood City, City of Menlo Park, Town of Atherton, and County of San Mateo County for the planning, designing and permitting of flood protection measures within the Bayfront Canal and Atherton Channel Watershed.


