San Francisquito Creek

HEC-RAS Model Third-Party Peer Review

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PREPARED FOR:

SAN FRANCISQUITO CREEK
JOINT POWERS AUTHORITY

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Glossary of Terms and Definitions

Composite Roughness	Roughness may vary along the wetted perimeter of a channel. To calculate the mean velocity of flow in a channel section, HEC-RAS calculates an equivalent (composite) n-value for the entire channel area that weights the various defined elements.
DEM	Digital Elevation Model. A representation of the bare earth topographic surface excluding trees, buildings, and other surface objects.
HEC-RAS	Hydrologic Engineering Center River Analysis System. Software created by the U.S. Army Corps of Engineers designed to perform one-dimensional and two-dimensional hydraulic calculations for a full network of natural and constructed channels, and overbank and floodplain areas.
Hydraulic Grade	The sum of the pressure head and elevation head. In open channel flow, the water surface elevation.
Hydraulic Grade Line	The surface or profile of water flowing in an open channel or a pipe flowing partially full. If the pipe is under pressure, the hydraulic grade line is the level water would rise to in a vertical tube connected to the pipe.
Hydrograph	A plot showing the rate of flow (discharge) as a function of time past a specific point.
Hyetograph	A graphical representation of the distribution of rainfall over time.
ICM	An advanced integrated catchment modeling software that incorporates complex hydraulic and hydrologic network elements.
Lateral Structure	Defined largely parallel to the channel alignment, lateral structures represent natural or manmade features such as a creek bank, floodwall, levee, or a spillway that connect 1D channel segments to 2D flow areas. Flow can be in either direction depending on the relative hydraulic grades between the 1D channel and the 2D overbank area.
LiDAR	Light Detection and Ranging is a remote sensing method that uses light in the form of a pulsed laser to measure variable distances to the Earth. These light pulses, combined with other data recorded by the airborne system, generate precise, three-dimensional information about the shape of the Earth and its surface characteristics.
Superelevation	A rise in the water surface at the outer bank with an accompanying lowering at the inner bank.
USGS	United States Geological Survey is a federal agency working in the areas of biology, geography, geology, and hydrology.
Vertical Datum	A surface of zero elevation to which heights of various points are referenced.
Water Surface Elevation	The height relative to a known vertical datum of floods of various magnitudes and frequencies in creeks, rivers, floodplains, or coastal areas.
Water Surface Profile	A graphical representation showing the elevation of the water surface of a watercourse for each position along a river or stream at a certain flood flow.
Water Year	The 12-month period beginning October 1, for any given year through September 30 of the following year. (USGS)

Certification

This report has been prepared under the direct supervision of the undersigned, who hereby certifies that he is a Registered Professional Engineer in the State of California.

1 Executive Summary

The San Francisquito Creek Joint Powers Authority (SFCJPA or JPA) is funded by the cities of East Palo Alto, Palo Alto, Menlo Park, the San Mateo County Flooding and Sea Level Resiliency District, and the Santa Clara Valley Water District to "lead projects that mitigate the risk of flooding along the San Francisquito Creek and the Bay."[1]

A working hydraulic model that replicates San Francisquito Creek's behavior during large discharge events is foundational to SFCJPA's charge.

The JPA continually improves its ability to monitor and collect data related to the behavior of the creek during larger storm water discharge events. A significant flooding event occurred on December 31, 2022 – the second largest on record – when San Francisquito Creek overflowed its banks and the resulting flooding damaged personal property and public infrastructure in East Palo Alto, Menlo Park, and Palo Alto. That significant event also provided information about creek bank overtopping during more extreme storms that was not previously available. This information and data have helped the JPA re-calibrate its hydraulic model and adjust project planning accordingly.

1.1 Purpose

The purpose of this evaluation is to perform a third-party review of both the existing and recalibrated Valley Water HEC-RAS model, evaluate its ability to replicate the NYE22 flood event, and modify the model to best represent flooding caused by spills from San Francisquito Creek.

The first task is to evaluate how well the model replicated the observed New Year's Eve 2022 event. A second task is to provide independent model calibration of the New Year's Eve Storm using an integrated storm drain system and creek model (InfoWorks' proprietary Integrated Catchment Model or ICM). A third task is to evaluate the U.S. Geological Survey (USGS) adjustment of the instantaneous peak discharge on December 31, 2022 and place USGS's published discharge in its historical context.

1.2 Background

This evaluation spans the reach of San Francisquito Creek between the USGS streamflow gage at the Stanford Golf Course and Highway 101. The review was initiated because the existing HEC-RAS model did not fully predict all areas of bank overtopping during the December 31, 2022 (NYE22) storm event. As a result, the Santa Clara Valley Water District (Valley Water) updated the model in 2023 using different values for creek roughness.[2] The area described in this study is a subset of the San Francisquito Creek watershed scale HEC-RAS hydraulic model that has been used as the engineering basis of design for the Urban Reach 2 flood reduction capital project. The overall watershed model is also being used by Stanford University for their Searsville project.

[1] "About the JPA," San Francisquito Creek Joint Powers Authority website, sfcjpa.org.
[2] Roughness is an estimation of the amount of channel bed friction that can be due to bed materials (sand, silt, gravel, cobbles), vegetation, channel section uniformity or variability, channel bends, debris or other natural or manmade features. The roughness coefficient is used to calculate flow depths and water surface elevations in open channels. Smooth surfaces have a lower roughness coefficient, with higher values for more gravelly and weedy areas.

To accomplish this review, Schaaf & Wheeler obtained both the existing and recalibrated model from Valley Water, survey data collected at overtopping locations, photographic and video evaluation of the event, and observed channel conditions and high-water marks from the NYE22 Storm.

The ICM evaluation traces creek overflows away from the creek based on storm drainage system capacity, street orientation, and topography. This helps verify that the modeled creek overflows in HEC-RAS are appropriate in location and magnitude. Routing the overflows only in HEC-RAS without acknowledging the impact of local storm drainage capacity tends to overestimate the depth of inundation away from the creek compared to observation. The temptation is to then reduce modeled overflows artificially in HEC-RAS to better replicate observed flooding. It is important to avoid that temptation so that the HEC-RAS model used as the engineering basis of design reflects creek performance under current conditions.

The NYE22 event was the second highest instantaneous flow of record since measurements began in 1931. San Francisquito Creek overflowed its banks, and the resulting flooding was detrimental to the communities adjacent to the creek, affecting businesses, multi-family housing, and private residences in East Palo Alto, Menlo Park, and Palo Alto, damaging personal property and public infrastructure.

During the New Years Eve 2005 event, localized flooding was experienced near Bayshore Freeway, but the NYE22 event was the first storm since February 3, 1998 to have flows significantly exceed the creek's bank full capacity and flood adjacent neighborhoods. The NYE22 event also provided the data needed to evaluate and adjust the previous model, and test the storm drain systems and improvements made since the 1998 event.

1.3 Results

Results of this third-party peer review may be summarized as:

- This evaluation demonstrates that local storm drainage systems have residual capacity to accommodate some of the water spilled from San Francisquito Creek. While HEC-RAS is not capable of the type of integrated analysis that can be completed using ICM, a well-calibrated HEC-RAS model is wholly sufficient for the evaluation of creek capacity based on creek channel and bridge crossing configurations.

- Due to the natural topography, bank overflows from San Francisquito Creek do not re-enter the creek until they are collected by the streets and storm drain systems and are pumped at East Palo Alto's O'Connor Street Pump Station and Palo Alto's San Francisquito Creek Pump Station.

- The peak discharge during the NYE22 Storm occurred when the creek was already bank full. In these conditions, the creek geometry and creek roughness are the most important factors to predict overtopping.

- This review confirms the adequacy of the recalibrated HEC-RAS model to replicate observed outbreaks in San Francisquito Creek, but also notes the sensitivity of the model to assigned roughness and channel geometry that is within the normal uncertainty of the model itself.

- The ICM is used to compare the model results to reflect actual conditions more accurately away from the creek in the flooded neighborhoods. The ICM integrates creek flows with measured flow from the USGS rain gage in the upper watershed, the storm drain systems and pump stations from East Palo Alto, Palo Alto and Menlo Park. This provides a better understanding of the peak flow magnitude through the downstream urbanized area that is within a typical range of error. The ICM estimates a peak 6,080 cubic feet per second (cfs) discharge compared to the USGS gaged flow rate of 5,880 cfs.

- The ICM would require further adjustment to reproduce the observed creek spill into East Palo Alto along Woodland Avenue east of Euclid Drive. For example, observed flooding of the apartment complex on Manhattan Avenue is not predicted by ICM. Based on the sensitivity of model overbanking to slight changes in model parameters, this could likely be achieved without significantly changing right bank overflows.

- The overall impact of the 2023 survey data is relatively small. However, spilling upstream of the Pope/Chaucer bridge was greater with the new survey data incorporated.

- Fine adjustments to Valley Water's model help to better understand the creek dynamics, channel roughness, and bank elevation details.

- The recalibrated HEC-RAS can be used moving forward for planning and design of the Reach 2 Project, with the understanding that this is a dynamic system with more uncertainty as to how the system might perform under different conditions than is typical of engineered systems in San Mateo and Santa Clara Counties.

- The review confirms both Valley Water's and USGS' conclusions that the model over-estimated creek capacity. The recalibrated model has been corrected as described in this document.

- Provisional discharges estimated during the New Year's Eve 2022 event initially led many to believe that the storm more closely approached the 1998 event's historical peak. However, based on USGS observations of channel conditions and direct measurement of stream velocity on the receding limb of the storm, it became clearer that the stage at the gaging point was elevated due to channel roughness and tailwater on the control structure. It is because of that complex relationship between gaged stage and channel conditions that the USGS made the decision to adjust the peak NYE22 discharge downward to 5,880 cfs. We do not find discrepancies or errors in the methods and process employed by the USGS to adjust their flow measurements.

- A review of rainfall and streamflow statistics indicates that the NYE22 event, the second largest on record, was an approximately 30-year creek discharge event. By comparison, the largest discharge on record (7,200 cfs) was in February 1998 and a 70-year return period. The third largest discharge on record (5,560 cfs) was in December 1955 and a 25-year return period.

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2 Peer Review Objectives

This section of the report describes the creek reach evaluated, objectives of the peer review, and specific tasks assigned.

2.1 Creek Reach Evaluated

This peer review spans the reach of San Francisquito Creek between the USGS streamflow gage at the Stanford Golf Course and Highway 101. The focus is on what the SFCJPA refers to as "Urban Reach 2" or the "Upstream Project". Reach 2 encompasses the creek from the Middlefield Road crossing downstream to where U.S. Highway 101 crosses the creek. Work downstream of Highway 101, or "Reach 1", is complete so the lower reach of the San Francisquito Creek has sufficient capacity to safely accept discharges from an improved Reach 2. Figure 2-1 highlights San Francisquito Creek and its designated reaches.[3]

2.2 Peer Review

The peer review was initiated because the existing HEC-RAS model did not fully predict all areas of bank overtopping during the December 31, 2022 (NYE22) storm event. As a result, the Santa Clara Valley Water District (Valley Water) updated the model in 2023. The area described in this study is a subset of the San Francisquito Creek watershed scale HEC-RAS hydraulic model that has been used as the engineering basis of design for the Urban Reach 2 flood reduction capital project. The overall watershed model is also being used by Stanford University for their Searsville project.

The purpose of this evaluation is to perform a third-party review of both the existing and recalibrated Valley Water HEC-RAS model, evaluate its ability to replicate the NYE22 flood event, and modify the model to best represent flooding caused by spills from San Francisquito Creek.

2.3 Peer Review Tasks

Specific peer review tasks assigned by the SFCJPA are:

- **Task 1** is to review Valley Water's HEC-RAS model for the subject reach. Results from the Valley Water model are compared to observed flooding during the NYE22 event and modifications are then made to the model so that it better replicates the observed event.

- **Task 2** is to calibrate an integrated catchment model of San Francisquito Creek and its floodplains to the NYE22 flood event, to provide independent corroboration for the modified HEC-RAS model.

- **Task 3** is to evaluate the U.S. Geological Survey's adjustment of their estimate for the peak discharge experienced during the NYE22 event at their San Francisquito Creek streamflow gage. Their final published discharge estimate is used to perform a flood-frequency analysis for annual instantaneous peak discharge based on the long-term streamflow record. This allows the NYE22 discharge event to be placed in its statistical context.

[3] US Army Corps of Engineers, Continuing Authorities Program, Section 205, San Francisquito Creek, California

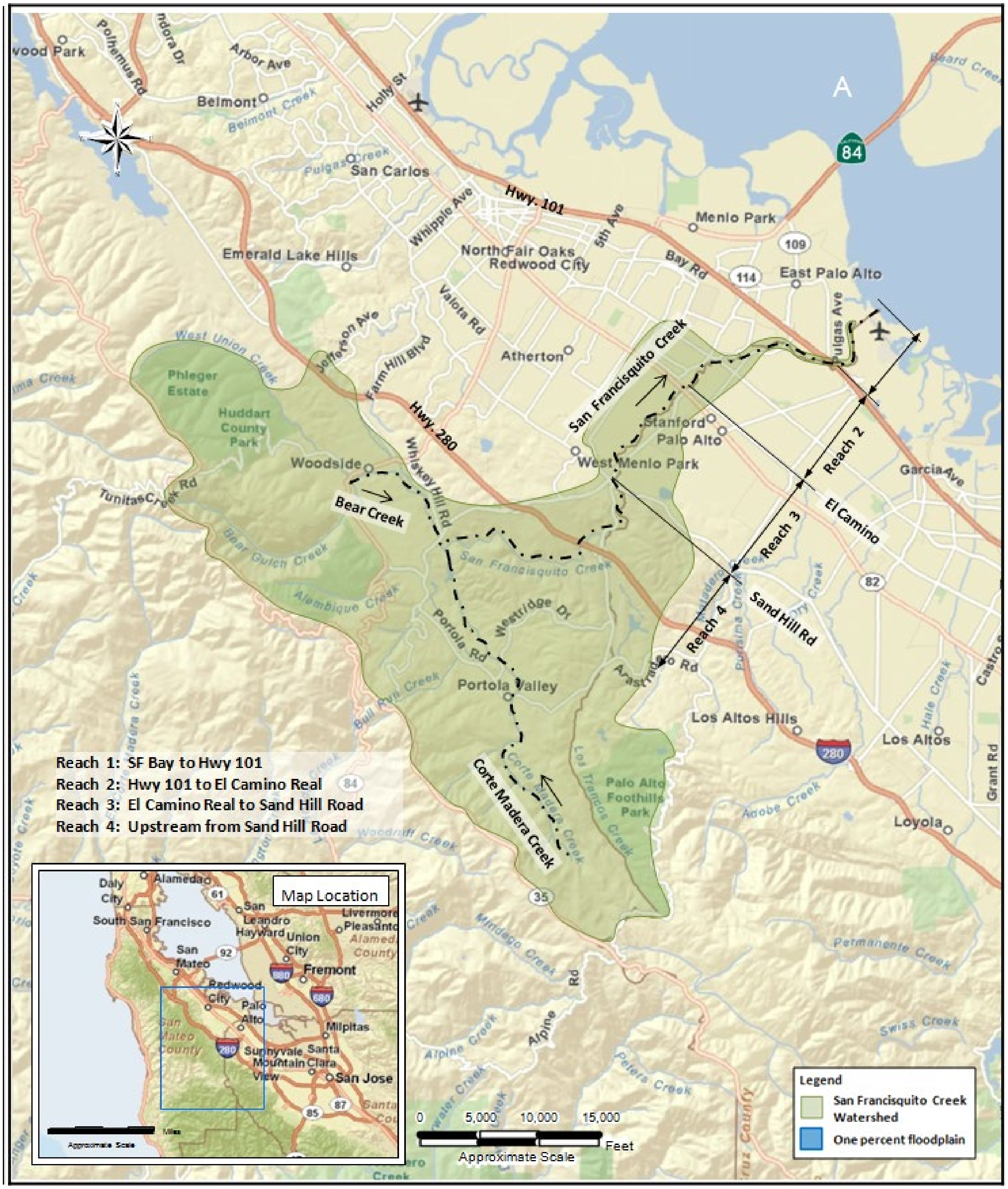


Figure 2-1: Designated San Francisquito Creek Reaches (USACE)

3 Review of Valley Water HEC-RAS Model

Valley Water's HEC-RAS model of San Francisquito Creek includes a one-dimensional (1D) river and cross section model of the creek, connected by lateral structures[4] to a two-dimensional (2D) flow area that routes spill from the creek between El Camino Real and Highway 101. The model was modified by Valley Water staff to include the published flows recorded by the USGS at their San Francisquito Creek at Stanford gage during the NYE22 flood event, with a multiplier to represent additional flow entering the channel downstream from the gage.

3.1 Model Overview

Model geometry provided by Valley Water is shown in Figure 3-1, overlain on the 2020 Santa Clara County LiDAR Digital Elevation Model (DEM). The location of the USGS gage is indicated approximately with a red circle. The model domain consists of creek cross sections approximately every 100 feet. A sample cross section from the model is shown as Figure 3-2, noting that natural levees are visible on both banks of the creek.

Manning's roughness values are assigned to the main channel, left bank, and right bank for each cross section. Many of the modeled sections are defined with natural levees at high points on each bank. This is necessary to confine the defined active flow conveyance area of the creek channel to be between the natural banks, since the cross sections include points beyond that active flow conveyance area that are outside the creek and below the bank elevation. Otherwise, HEC-RAS would place a vertical "glass wall" at each end of each cross section and include flow conveyance area in its calculations that does not exist. Most of the Valley Water model cross sections are based on their previous field surveys rather than the 2020 Santa Clara County LiDAR DEM. An example of the ground elevations obtained from the DEM at the cross-section location presented as Figure 3-2 is superimposed as a lighter section. It should be noted that LiDAR-based channel sections are often not as reliable as field-survey based sections due to interference of vegetation cover and water.

Lateral structures are defined for the natural creek banks and manmade floodwalls as they occur on either side of the creek between Alma Street and Highway 101, connecting the 1D creek sections to 2D areas whenever the calculated water surface exceeds the defined elevation of those lateral structures. The elevations of the lateral structures are defined by LiDAR or surveyed ground elevations in some locations and by known or surveyed flood wall crest elevations in other locations. This varies based on bank conditions throughout the reach. Levee and lateral structure definitions also capture the height of some solid fencing at certain private properties on the right bank in Palo Alto. Channel banks are defined as left (Menlo Park and East Palo Alto) and right (Palo Alto) looking downstream.

The Valley Water model uses the recorded flows from the USGS San Francisquito Creek at Stanford University gage as an inflow boundary condition, with a 1.068% scaling factor to represent additional inflows to the creek downstream of the station. This represents an overall modeled peak flow of about 6,280 cfs, compared with the USGS gaged peak of 5,880 cfs.

[4] Lateral Structures are surveyed embankment elevations- that can be natural or manmade features such as a creek bank, floodwall, levee, or a spillway that are used to connect the 1D model to the 2D flow area. For a 1D river reach in HEC-RAS, there is only one single water surface elevation value at a cross section, but these values can vary along river profile direction. Different high water position settings will determine how a lateral structure is "connected" or "correlated" to cross sections, which will in turn impact how elevations along river profile are interpolated and applied in the model.

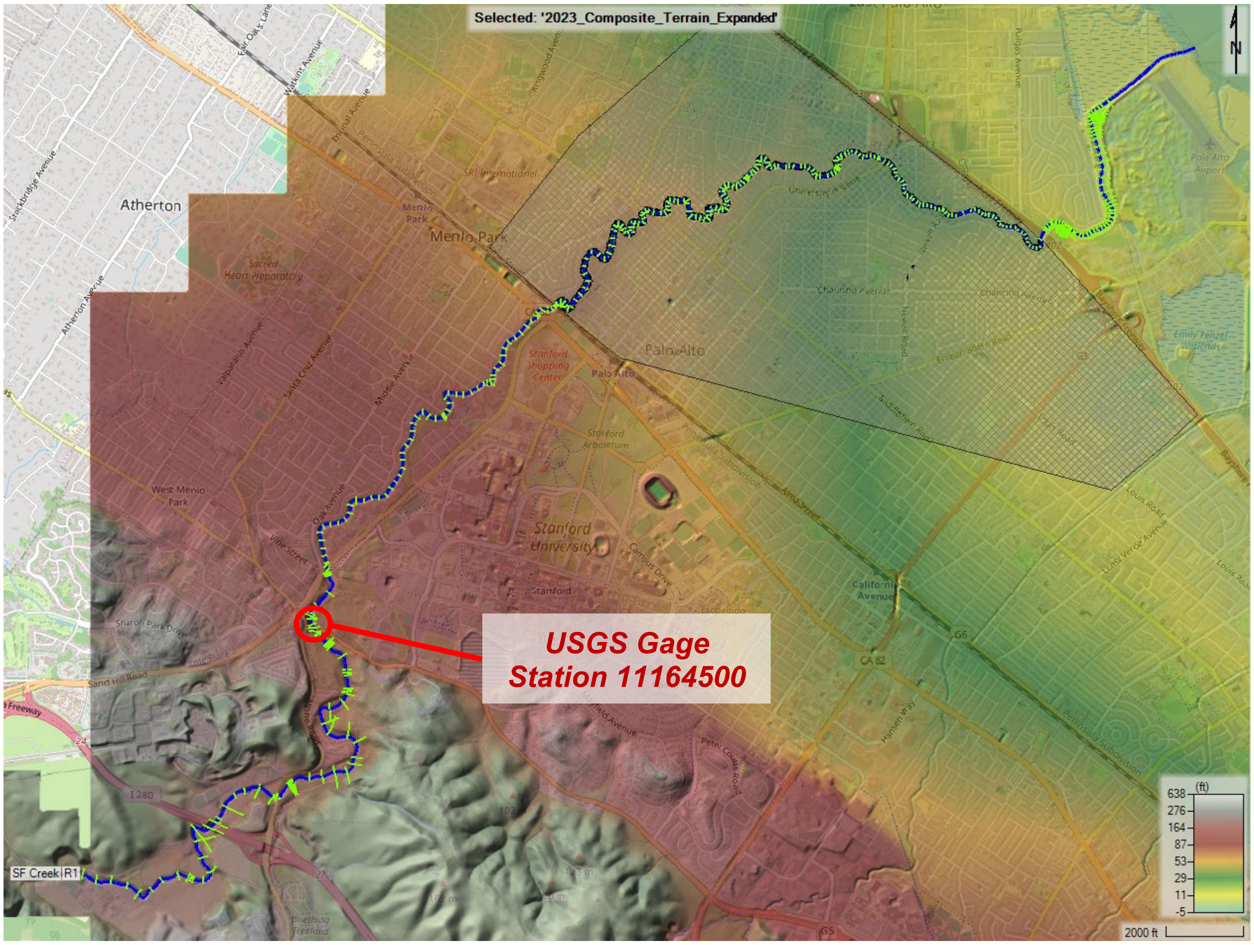


Figure 3-1: Existing HEC-RAS Model Geometry with USGS Gage Station Location Annotated

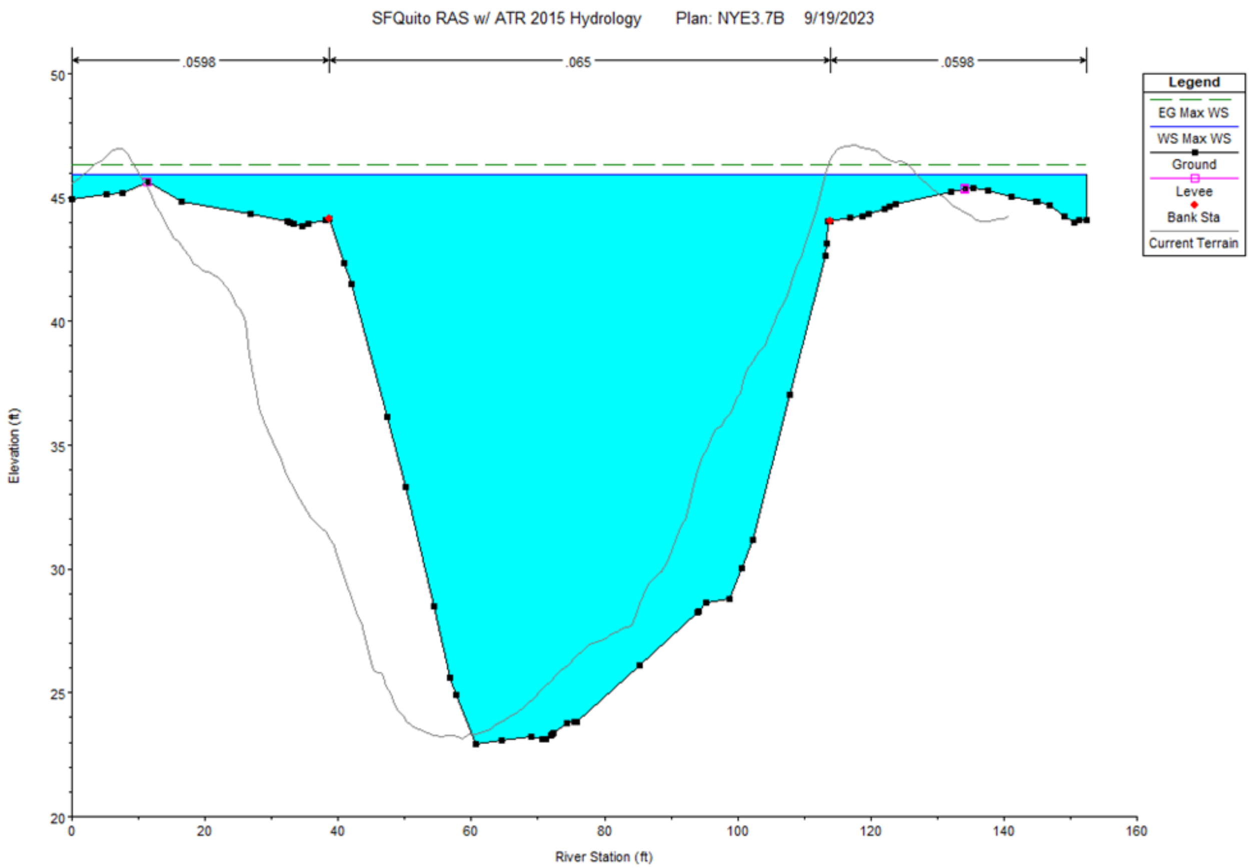


Figure 3-2: Example Existing HEC-RAS Model Cross Section

3.2 Existing Model Evaluation

Schaaf & Wheeler staff walked San Francisquito Creek with Valley Water staff and representatives from the SFCJPA and other local agencies on August 23, 2023. Conditions in the creek, including vegetation, relative bank height and high-water marks were documented to aid in evaluating model inputs and the modeling methodology.

3.2.1 Channel Roughness

Based on photos and aerial imagery, Schaaf and Wheeler developed land cover polygons representing variable roughness in the main channel, side slopes, and overbanks. Initial estimates of roughness were assigned, and the polygons overlain on the model's land cover mapping as shown by Figure 3-3. In addition to vegetation cover, channel roughness, represented as n-value or Manning coefficient, can be considered a lump parameter representing the effects of bed forms, sediment transport, superelevation at bends and other three-dimensional flow behavior to reproduce that flow behavior averaged in a single dimension.

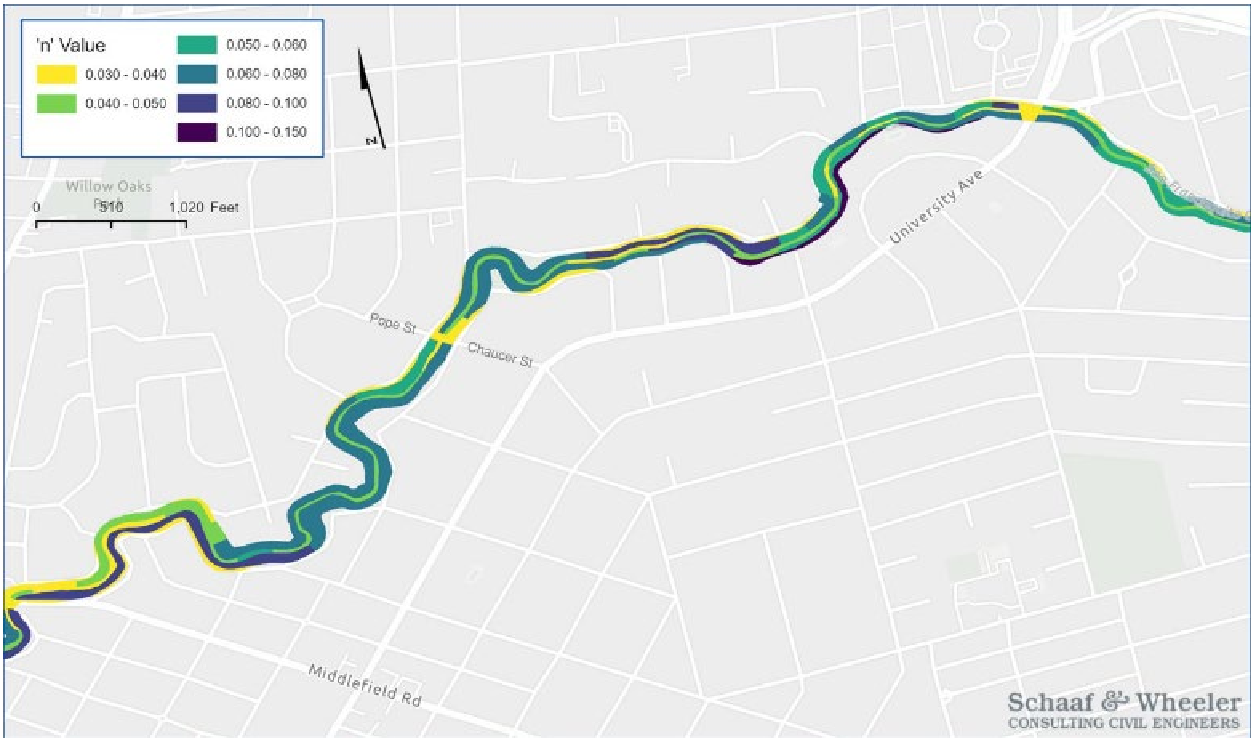


Figure 3-3: Initial Spatially Varied Roughness Assignment (Middlefield Road to University Avenue)

For example, sacked concrete provides more resistance to flow than would smaller cobbles, which in turn provides more resistance to flow than would gravel, sand, or silt. Thick riparian (woody) vegetation provides more resistance to flow than emergent wetland vegetation or no vegetation at all. San Francisquito Creek has a very dynamic and mobilized bed during large discharge events. This dynamism creates an undulating bed that transports a significant volume of sediment during storms. Significant sediment transport requires more flow energy than does a system without as much sediment and the net effect in lumped parameter, fixed-bed hydraulic modeling is a "rougher" channel with higher "n-value".

The channel module of HEC-RAS performs one-dimensional unsteady flow calculations. This means that a water surface elevation or hydraulic grade is calculated at every model cross section at every time step modeled.

The updated land cover file was used to assign horizontally varied Manning's values to the cross sections. After the model ran with the initial estimates of roughness, based on field reconnaissance to evaluate spill, the initial roughness estimates were found to significantly overestimate spill from the creek almost universally.

Consequently, roughness values were downscaled uniformly by 20 percent and then 30 percent as a sensitivity analysis measure. Roughness estimates were then further refined to better match observed high water marks and spill locations along the creek, without evaluating how well the 2D portion of the model reflected observations of flooding away from the creek banks.

Ultimately, this adjustment to estimated channel roughness results in more modeled in-channel roughness variability. An example cross section using the Valley Water geometry but with more varied Manning's values are provided as Figure 3-4 to illustrate this point.

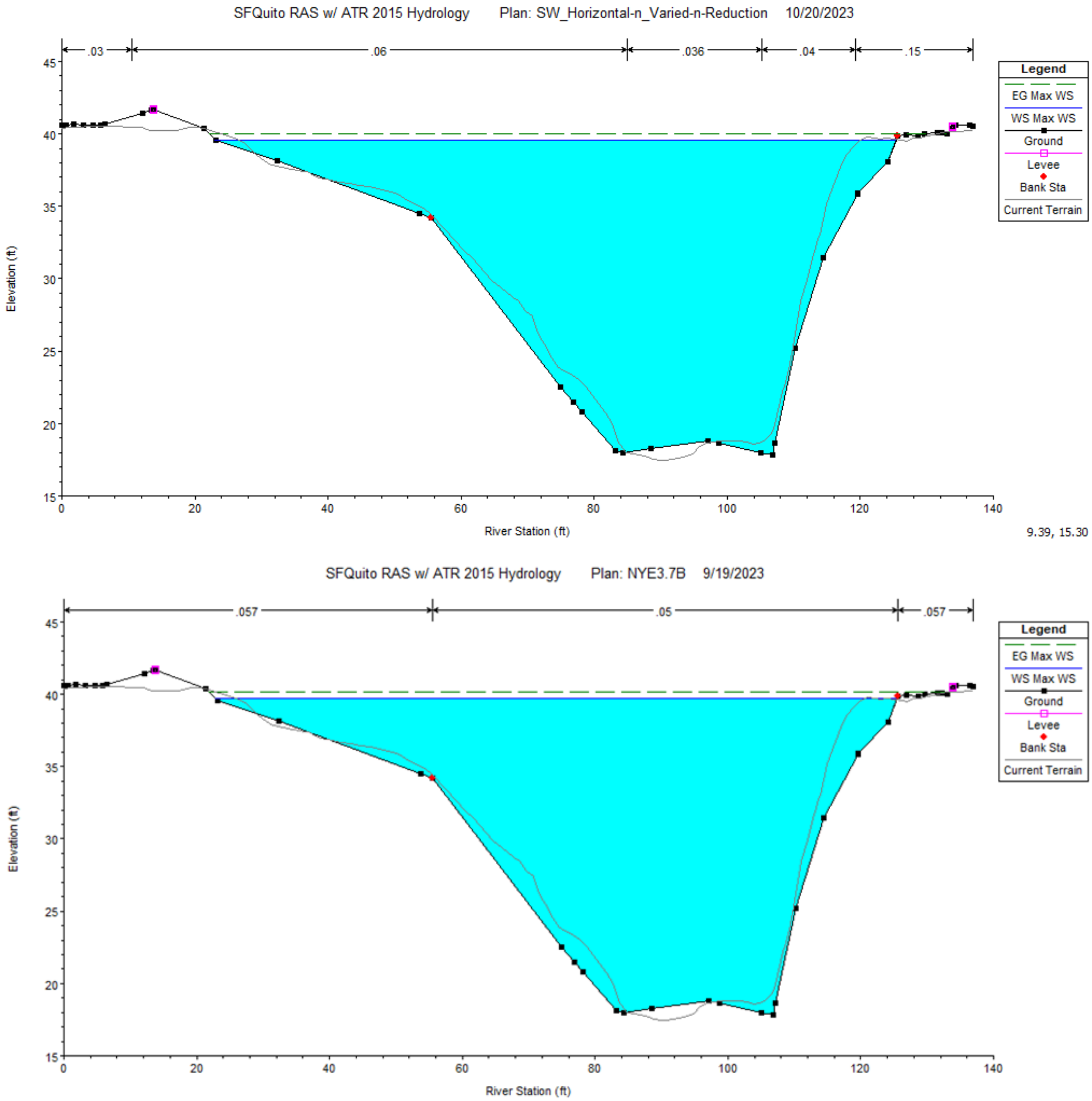


Figure 3-4: Revised Cross Section Roughness (top) Compared to Existing Model (bottom)

For the cross section shown, the revised main channel roughness is lower than in the existing model. However, the lower value only applies effectively to the channel bottom, where flow depths are greater and resistance from vegetation is less likely to impact flow velocity. The left bank side slope roughness within the red channel bank markers is represented by a comparatively higher value while the right bank side slope is less than the existing model main channel roughness, meaning there is less resistance to flow along the Palo Alto bank at this location and flow is moving faster than previously assumed.

At this section, which is just upstream of the private pedestrian bridge between Pope/Chaucer and University Avenue, the composite roughness for the main channel (between the bank markers) is 0.048 in the revised model, which is close to the composite roughness found in the existing Valley Water model. However, there is more variability in composite section roughness within each reach represented in the revised model. Given the dynamic nature of the NYE22 flood event, this variability has proven necessary to replicate the observed creek spills.

The best way to compare the results of this process is to examine the existing model main channel n-values (which already represent a composite n-value between the top of bank points) against the composite main channel value from the revised model (calculated by HEC-RAS at the maximum depth). Table 3-1 provides a comparison of n-values in various reaches that connect to the 2D areas. Within each of these reaches, the Valley Water model's main channel roughness is uniformly assigned for all cross sections. Model parameters upstream of CalTrain and downstream of Highway 101 were not altered with this effort, because flows were not observed to have left the channel banks in those locations during the NYE22 event and there is no evidentiary basis for adjustment. Rather, the focus was on creek areas where the roughness likely had the greatest effect on hydraulic grade and overflow rate and volume from the Creek to the 2D surfaces, based on observed flow behavior during the New Year's Eve event. Table 3-1 also summarizes revised model composite channel n-values, which are graphically shown for the reach of greatest numerical adjustment, between Caltrain and Middlefield Road, by Figure 3-5.

Table 3-1: Main Channel 'n' Value Composite Comparison

Reach Start	Reach End	Valley Water Channel 'n'	Revised Model Composite Channel 'n'		
			Minimum	Maximum	Average
Caltrain	Middlefield Rd	0.0408	0.043	0.075	0.062
Middlefield Rd	Pope/Chaucer	0.065	0.043	0.065	0.054
Pope/Chaucer	University Ave	0.050	0.041	0.070	0.053
University Ave	Newell Rd	0.050	0.030	0.058	0.045
Newell Rd	Highway 101	0.035	0.031	0.053	0.041

Other than the creek reaches from Caltrain to Middlefield, average composite n-values in the revised model are close to the existing model main channel n-values. However, the range of n-values in each reach includes some values that are significantly higher than the existing model. These localized high roughness areas can have a substantial impact on hydraulic grades. Higher values tend to reduce the flow velocity and raise the water levels in the creek. Even if that impact is limited to a short reach of the creek, localized high roughness values can make the difference between full containment and spill over the banks to the 2D surface. Localized high roughness segments of the creek throughout the evaluated reach also tend to be where the greatest debris racking might be expected, which cumulatively results in an even higher hydraulic grade line or Water Surface Profile (WSP).

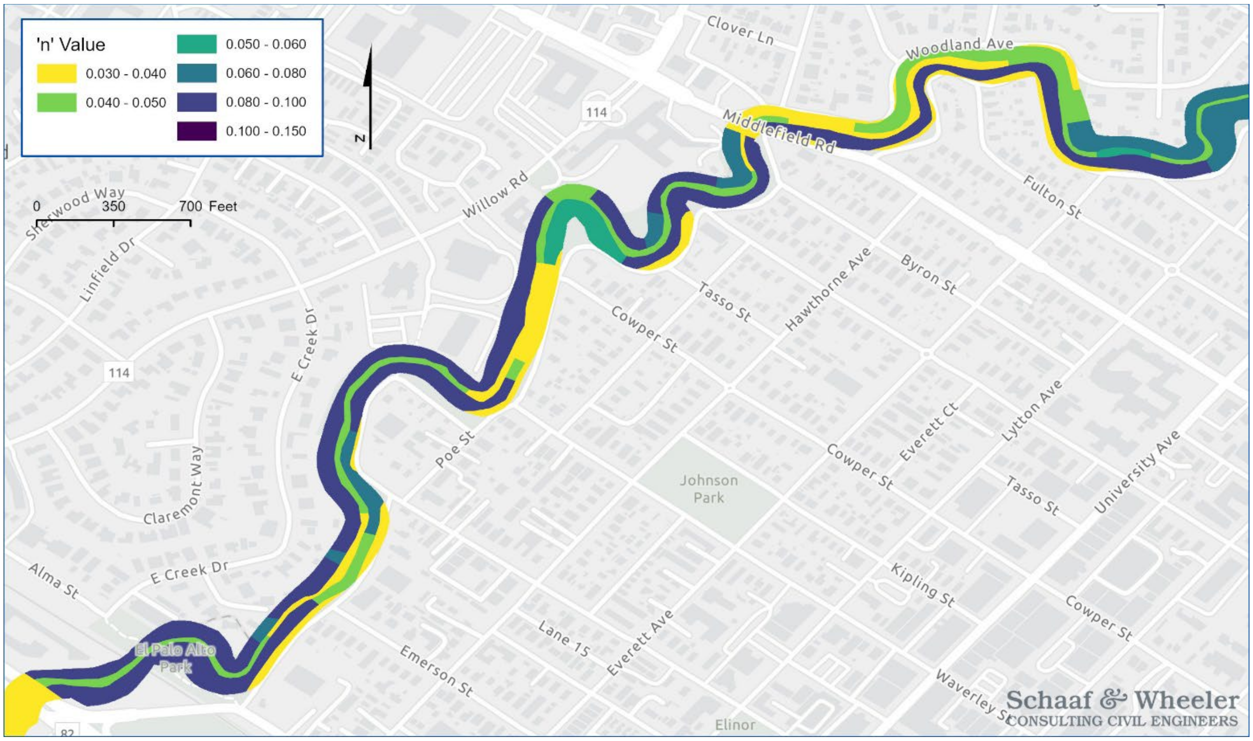


Figure 3-5: Revised Spatially Varied Roughness Assignment from Caltrain to Middlefield Road

Another location that sees an impact from this effect is the area just upstream of the Pope-Chaucer bridge. The Valley Water model does not predict significant spill occurring upstream of Pope-Chaucer bridge. However, photos and videos taken during the NYE22 storm show overbank flows occurring both over the left bank floodwall and on the right bank just upstream of the crossing.

The revised horizontally varied n-values that are based on observed site conditions and aerial imagery produce modeled spills just upstream of the Pope-Chaucer bridge. Although the model still does not produce spill over the left bank floodwall, the modeled hydraulic grade line (HGL) is within 0.1 foot of the floodwall crest. At this point, additional losses at channel bends or debris bulking may be represented well by a small additional increase in n-values and the accuracy of the modeled left bank floodwall elevations would need to be verified through a field survey to be sure the increase in roughness required to replicate observed overbanking is not explaining the variation between modeled bank elevations and actual bank elevations.

3.2.2 Channel Bends

There are dozens of significant bends within the creek's alignment. The 1D methodology used by HEC-RAS calculate water surface elevations does not directly address the hydraulic impact of the sinuous alignment or superelevation, which can be significant. The traditional mechanism in a one-dimensional model is to increase channel roughness (n-values) to replicate the observed behavior. Those adjustments are reflected in n-values previously described, graphed, and tabulated. Figure 3-6 shows the results of a separate two-dimensional in-channel model prepared to directly address superelevation, which is about one foot at outside bends.

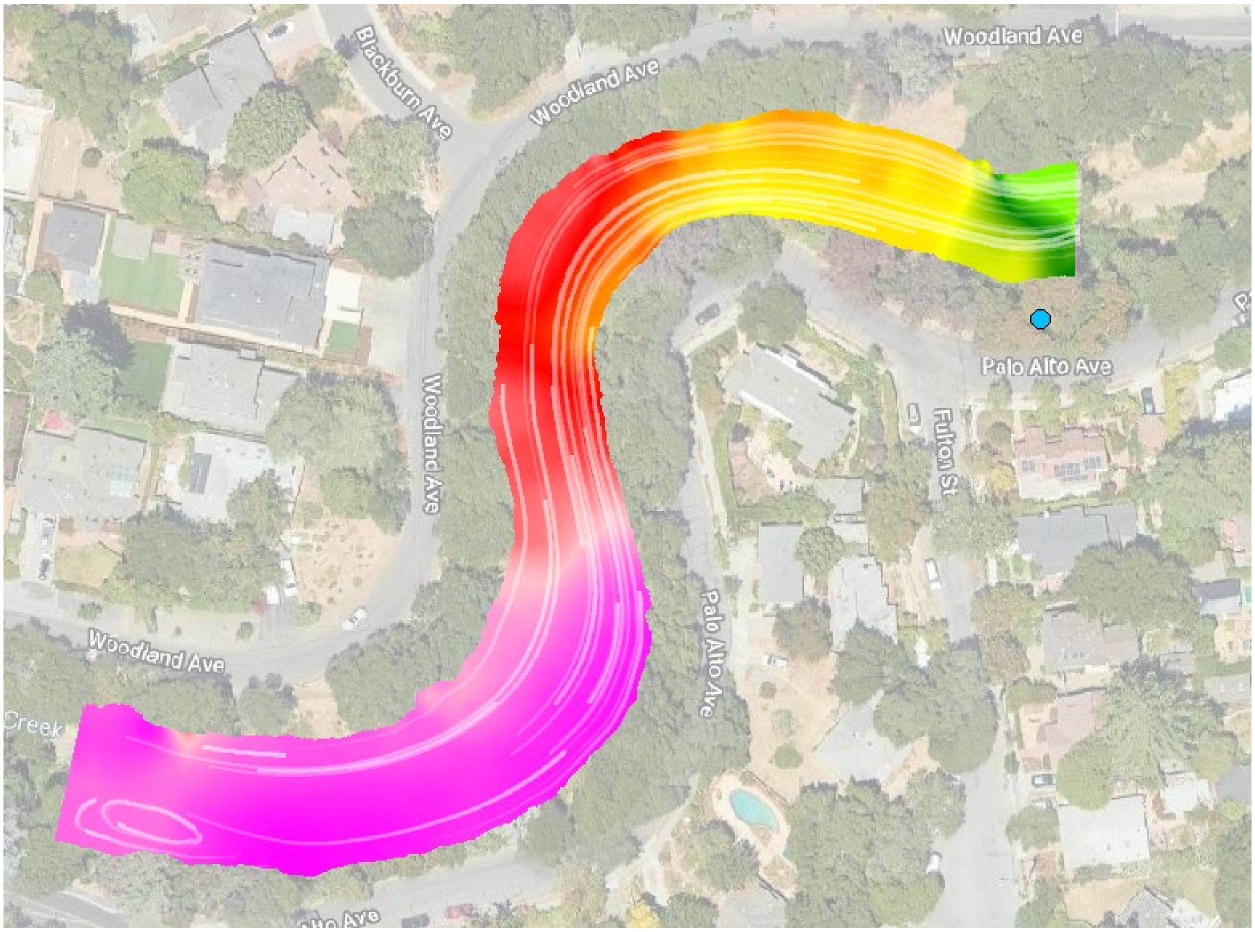


Figure 3-6: Sample 2D Channel Flow Model at Creek Bends with Streamflow Lines

Superelevation is typically added to the average water surface elevation calculated by HEC-RAS, so this means the foot of additional water depth caused by superelevation around an outside bend that is observed must be accounted for in the channel roughness adjustment.

3.2.3 Lateral Structures

While certain lateral structure (LS) elevations are defined by concrete flood walls, others are defined by ground elevations at or adjacent to the creek banks or cross section limits. Creek overbanking during the NYE 2022 event occurred primarily at locations where earthen banks are locally lower than the adjacent banks in that reach. It is important to ensure that the lateral structures accurately capture the location and elevation of the natural bank elevations and top of levees/floodwalls throughout the model.

One lateral structure in the existing model where elevations appear to be set based on the 2D area cell faces is shown in Figure 3-7. At this location, the lateral structure alignment extends to the middle of the roadway. One identified issue with the existing model is that the lateral structure elevations are lower than the levee points defined by the cross sections. Modeled levee points do not prevent flow from spilling over the lateral structure, and this discrepancy results in an over-estimation of spill at certain points, particularly on the north (left bank) side of the creek.

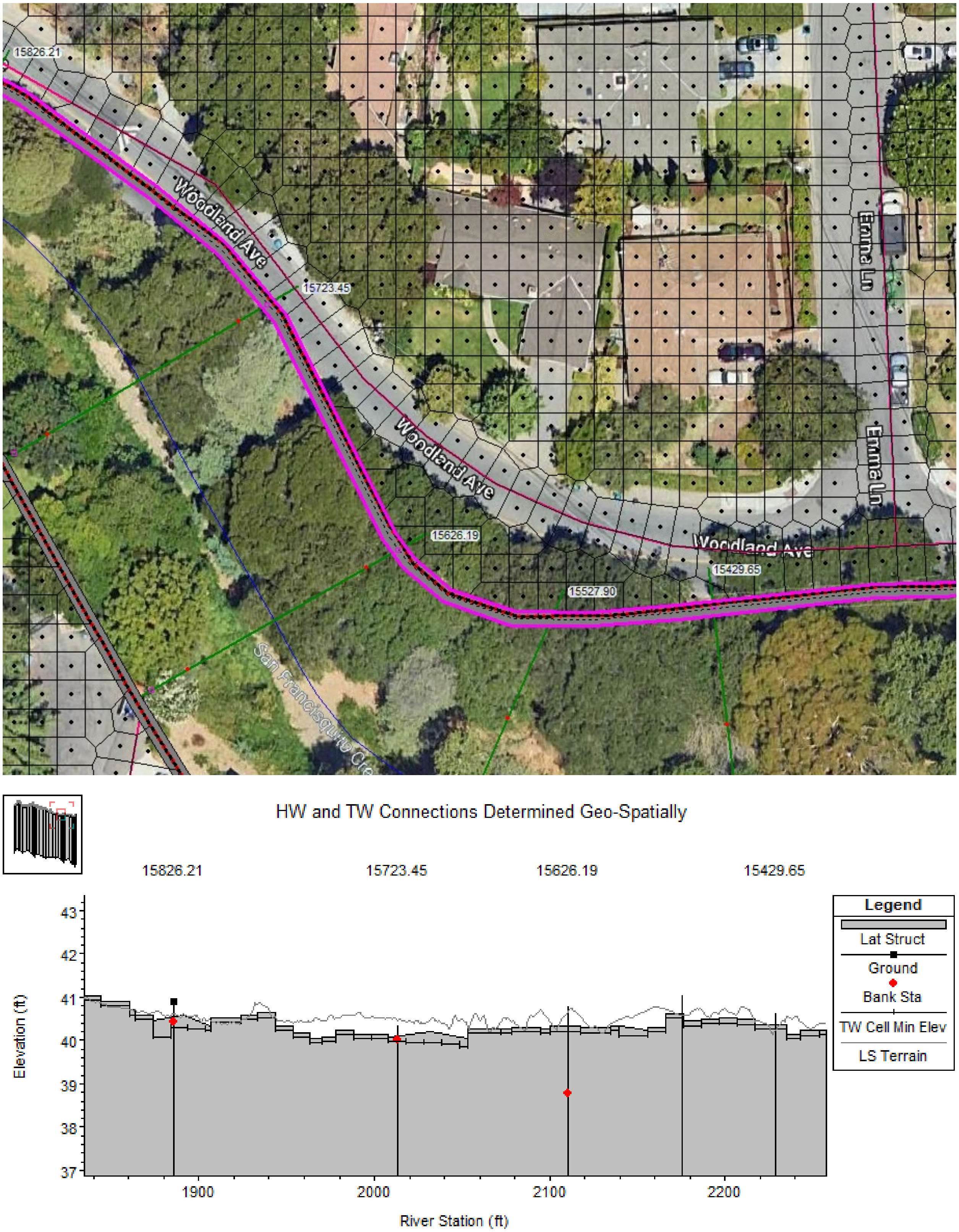


Figure 3-7: Lateral Structure Adjacent to Woodland Ave at Emma Lane (Existing Model)

Lateral structure alignments have been adjusted horizontally to better match the likely location of high points in the terrain, which contain creek flow until spilling would first occur. These structures are geo-referenced, and the model is capable of extracting elevations from the LiDAR terrain. Most surveyed cross sections indicate that the LiDAR is a reliable source of ground elevation data at the top of the creek banks, compared to within-channel elevations as previously discussed. Figure 3-8 provides an excellent example of this.

Lateral structures need to accurately represent spilling conditions regardless of cross section levee point definition. Even if a levee is defined within a cross section, if the adjacent lateral structure is set to a lower elevation, the model will allow spill from the channel when no spill should be taking place. To represent flow overbanking more accurately from the creek into adjacent 2D areas, the modeled lateral structures need to be placed where the creek banks or a levee/floodwall structure are physically located relative to the channel cross section and the lateral structure elevations need to be set to match the creek bank elevation or top of floodwall/levee.

There are locations in the model where levee points are above lateral structure elevations. Cross section 14530.33 provides an example of this where the existing model is likely overpredicting spill volume. Figure 3-8 shows the 2D result, which makes it clear that spill is occurring from section 14530.33. However, the cross-section plot indicates that the water surface elevation does not exceed the defined left bank levee point at this location.

Figure 3-9 provides the maximum depth result in the vicinity of the same section after the lateral structure is realigned to better match the high point along the left bank and elevations are updated.

3.2.4 Channel Survey Impact to Model Performance

Valley Water provided updated cross sections based on field surveys taken in August and September 2023 in proximity to known NYE22 spill locations. Schaaf & Wheeler incorporated that survey into the model using tools built into the RAS-Mapper application. This allows for some evaluation of the impact of the combination of geomorphic change since the last survey and potentially higher quality data than that used for the existing model. Since the survey was taken after the storm, there is no certainty that the revised geometry is fully representative of channel bed conditions that were present during the earlier event itself, when it would have been impossible to survey; however, the newly surveyed geometry probably provides a better representation of channel bank conditions during the storm than do the existing model sections.

An "all else equal" comparison of two model scenario inundation extents is shown as Figure 3-10. The modeled scenarios both incorporate adjustments to roughness values in the creek and modifications made to the lateral structures and 2D areas to better represent bank conditions. One run is based on the original model cross sections and the other is modified with the updated Valley Water survey points.

These runs were completed before final refinements to lateral structure modeling were completed to better capture spill characteristics over the left bank at Pope/Chaucer bridge and the lack of observed spill over the right bank at Southwood Drive.

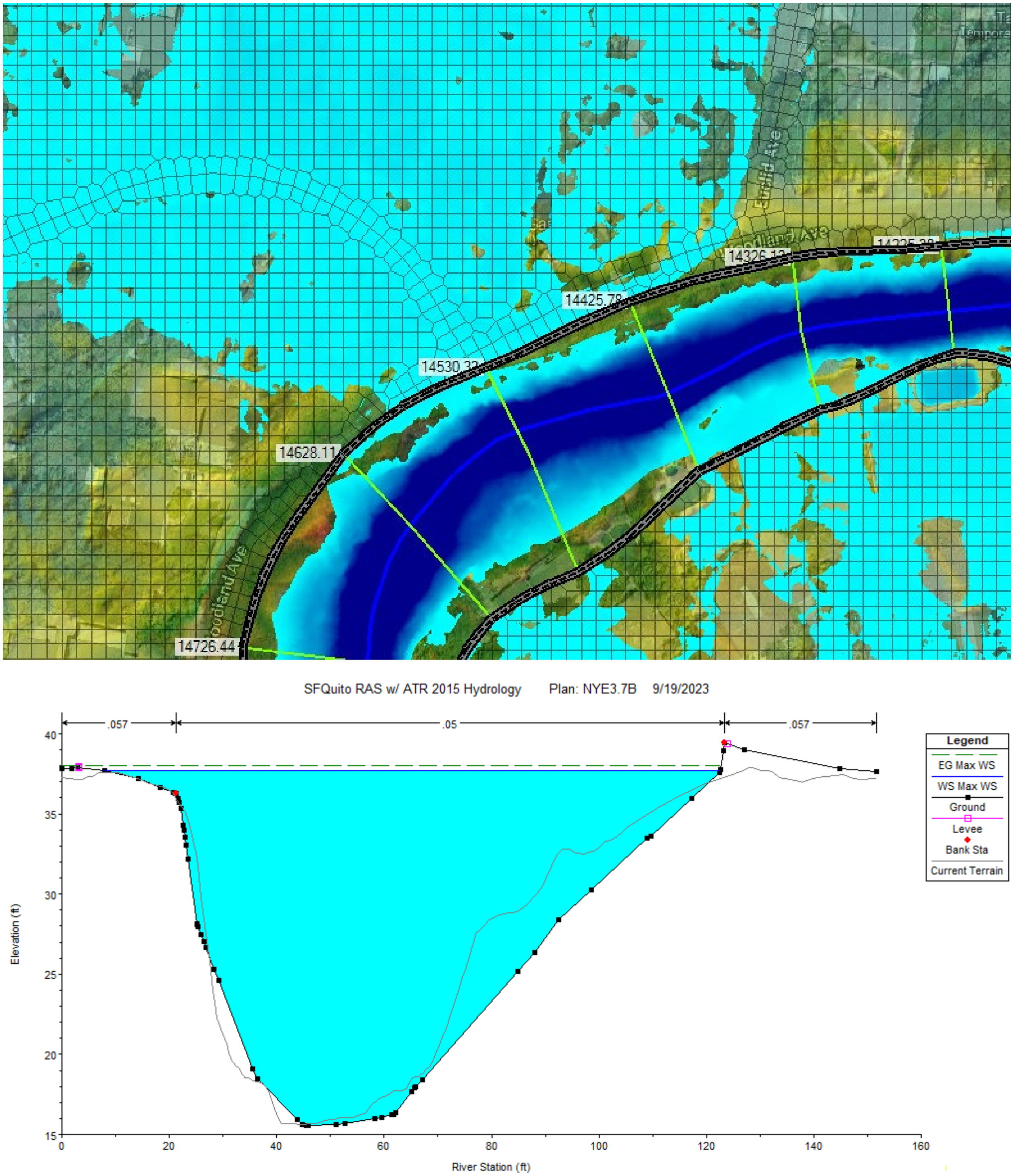


Figure 3-8: 2D Results and XS 14530.33 from the Existing Model

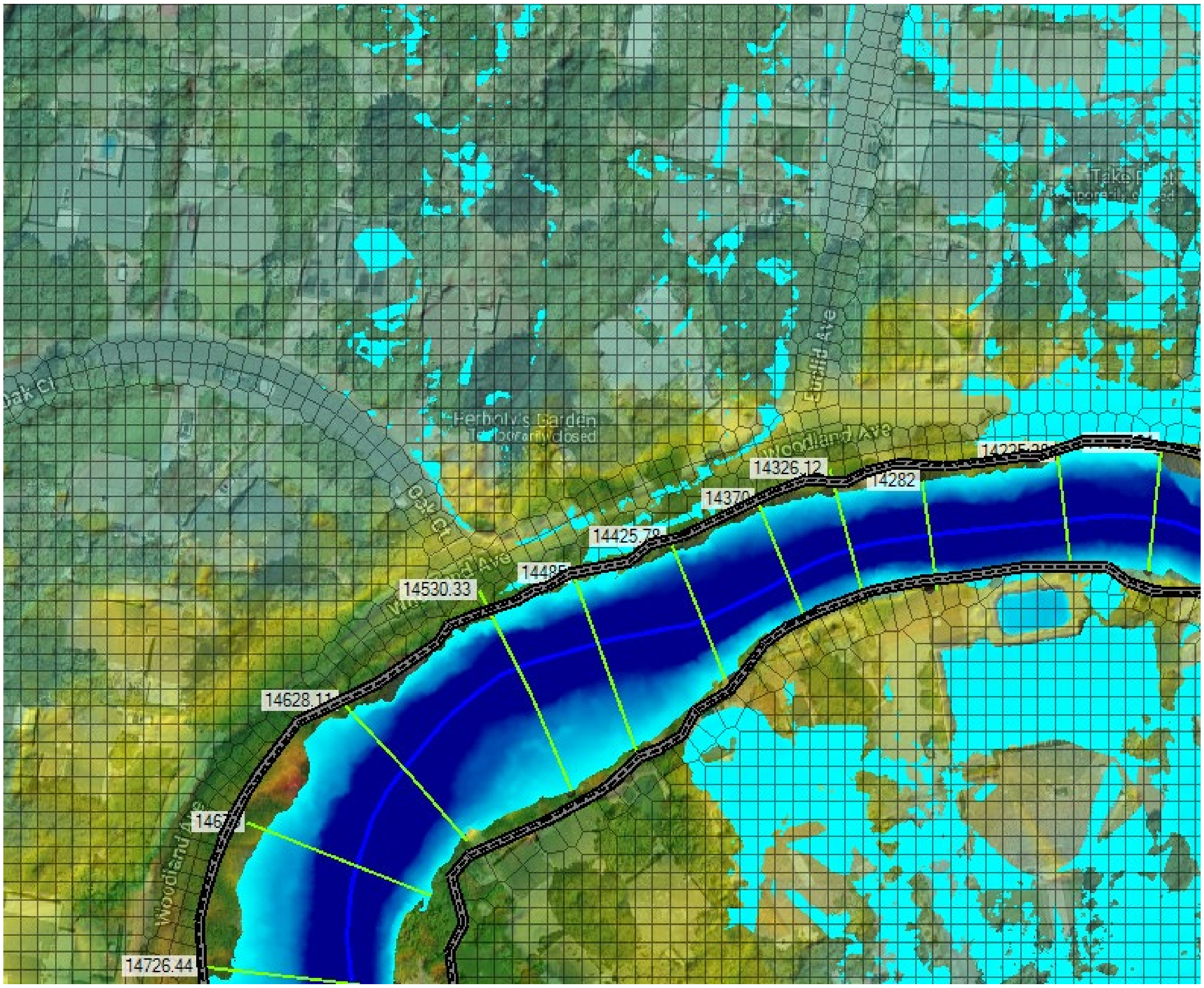


Figure 3-9: 2D Result near Section 14530.33 with Realigned Lateral Structure

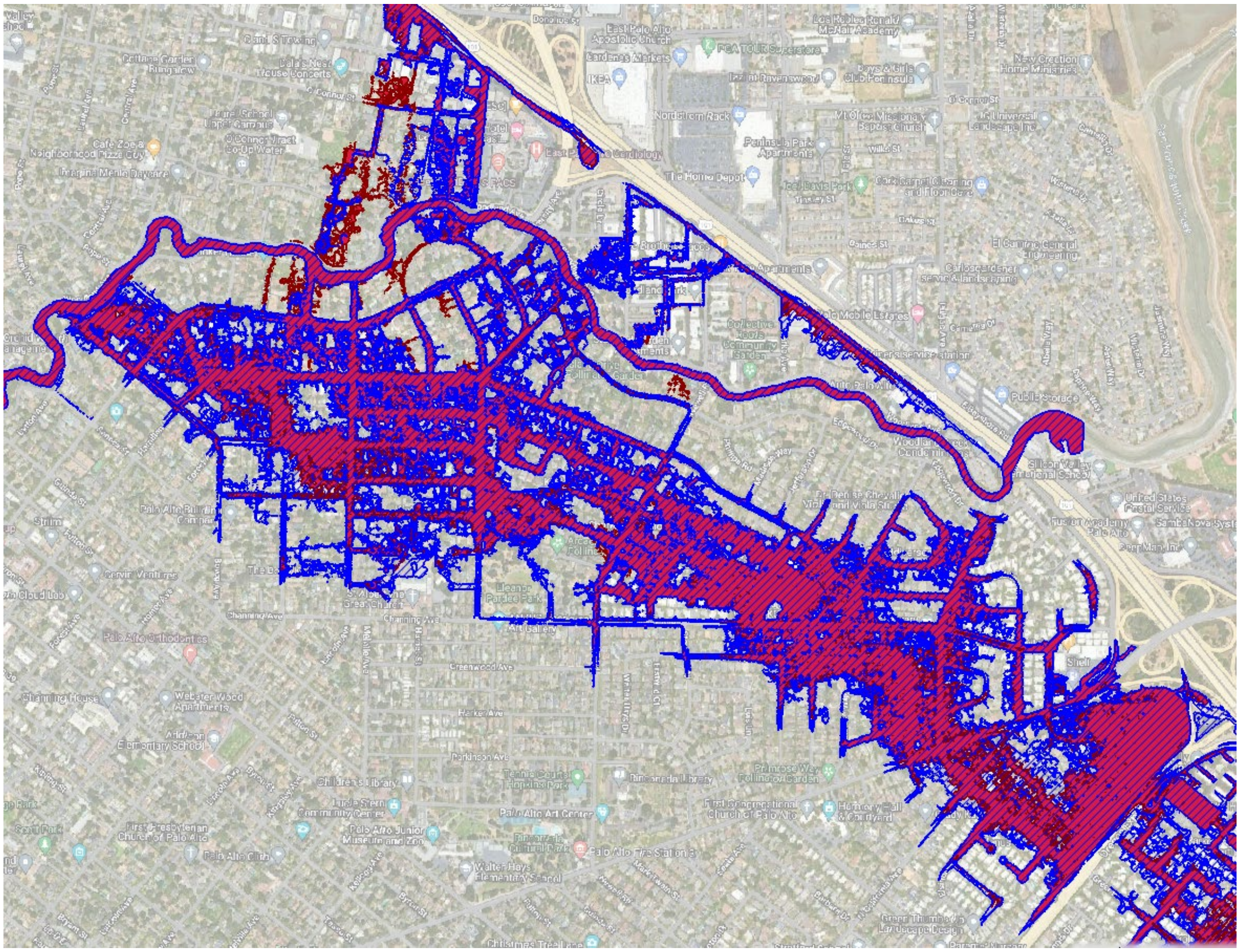


Figure 3-10: Comparison of Model Results Before (hatched blue) and After (solid red) Incorporating New Channel Survey

Once the new survey data are incorporated into the model, the model shows greater spilling upstream of Pope/Chaucer bridge. This is likely due to a localized accretion of materials along the channel bed during the storm event compared to bed elevations that are based on prior surveys. Since the long-term channel bed profile is generally stable, this change may be more transitory and due to event-based sediment accretion. There also appears to be some minor reduction in spills to the north of the creek due to channel incision and widening just downstream (Figure 3-11). However, the overall impact of the survey is relatively small. Changes in the channel bed may have some impact on spill from the creek, at least during this approximately 30-year peak flood event.

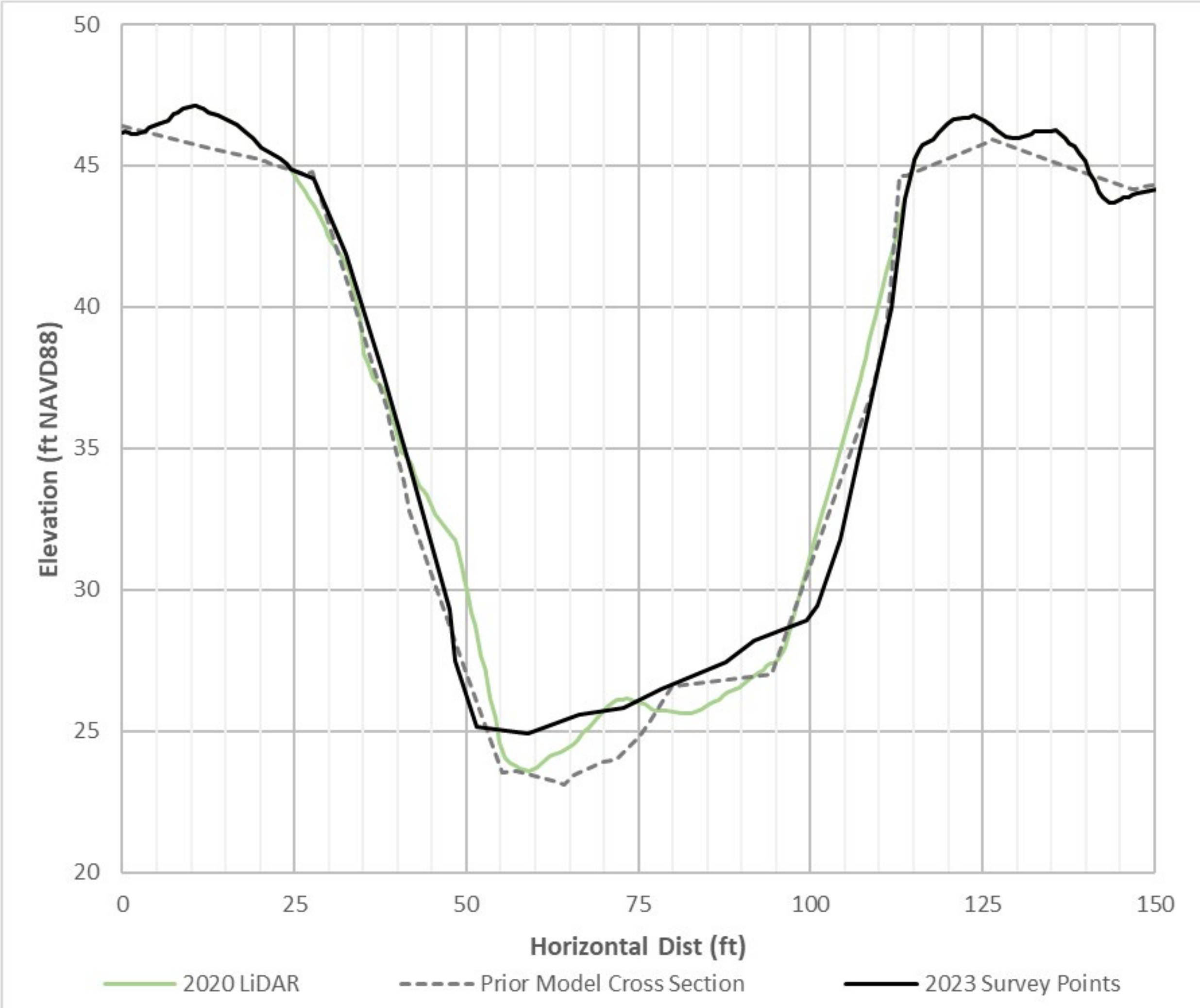


Figure 3-11: Comparison of 2023 Cross Section Survey with 2020 LiDAR and Valley Water Model Section Data Upstream of Pope/Chaucer Bridge

3.3 Adjusted HEC-RAS Model Results

The maximum depths of overbanking of up to 12 inches produced by the Valley Water run calibrated to replicated flooding extents at Duveneck Elementary is shown in Figure 3-12. The maximum depths predicted by the adjusted HEC-RAS model are shown in Figure 3-13 and predict a greater flooding extent than the high-water marks (HWMs) indicated with yellow dots. Note that Figure 3-12 and Figure 3-13 show the results from the original Valley Water HEC-RAS model and the adjusted HEC-RAS model for the NYE22 event, respectively, and the effects of storm drain systems in East Palo Alto, Menlo Park, and Palo Alto are not included in either model.

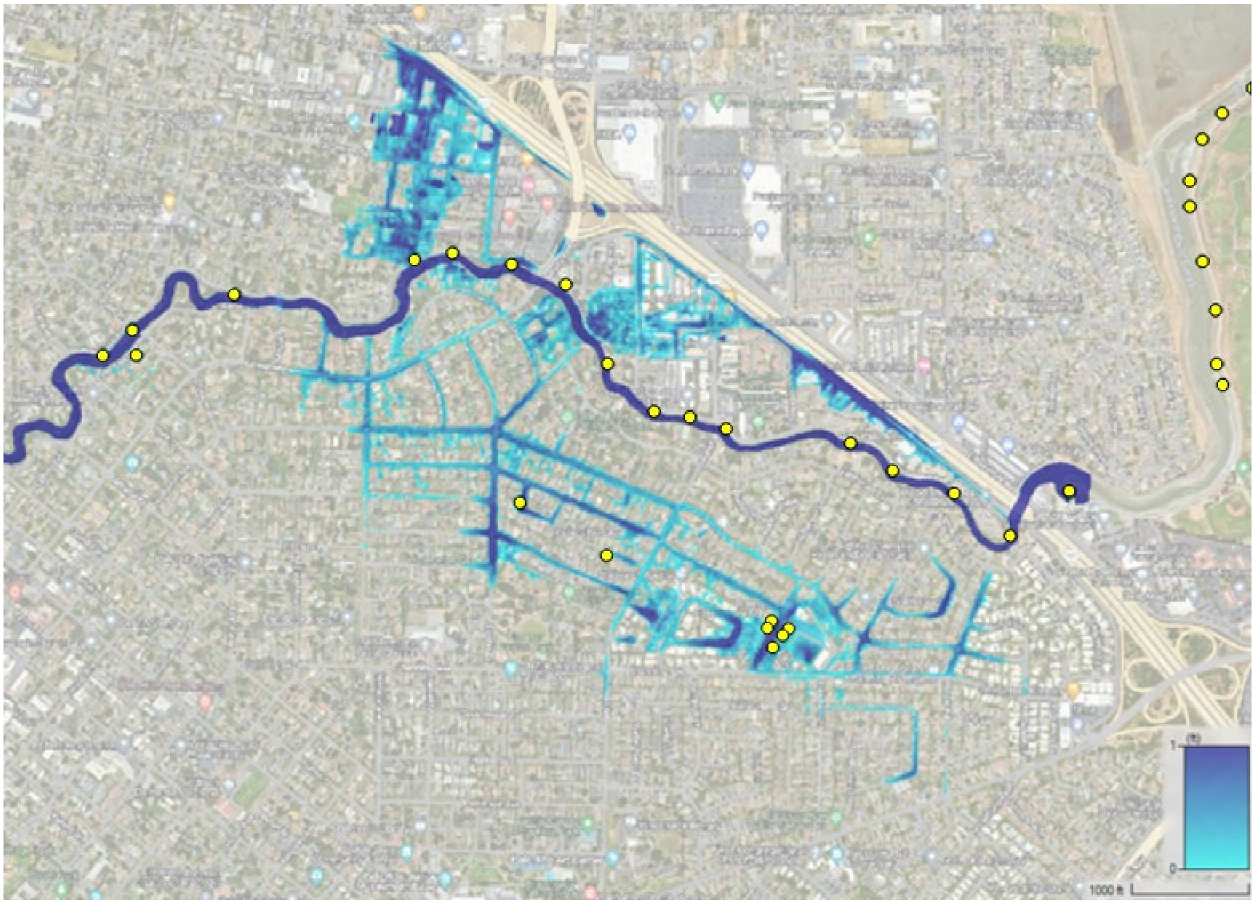


Figure 3-12: Original HEC-RAS NYE22 Model Results (maximum depth) with High Water Marks as Yellow Dots

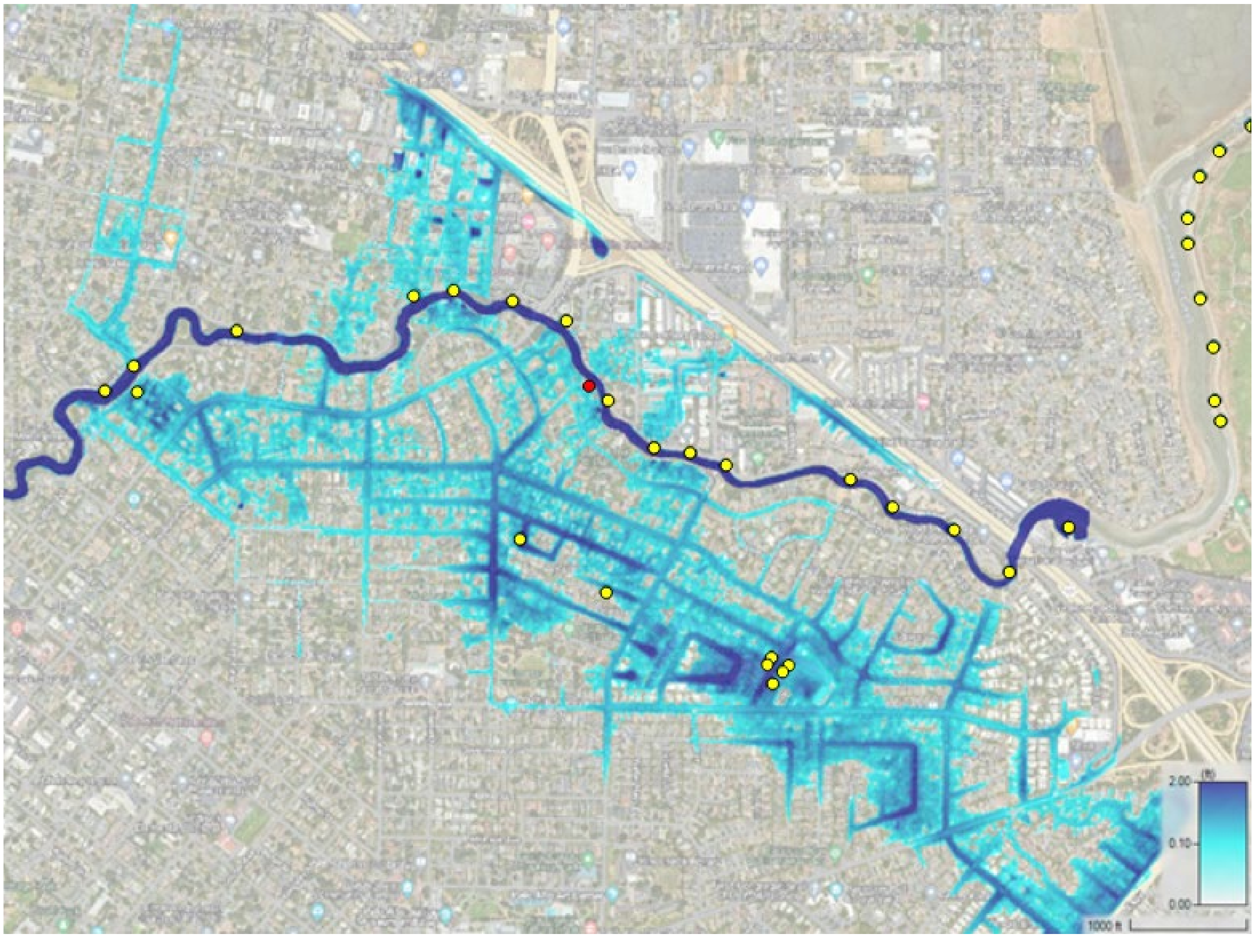


Figure 3-13: Adjusted HEC-RAS Geometry NYE22 Model Results (maximum depth) with High Water Marks as Yellow Dots (Southwood Drive location shown as red dot)

Most of the observed high water marks away from the creek are within the right overbank floodplain on the Palo Alto side. City of Palo Alto Public Works staff noted that they did not observe a spill on the south side of the creek downstream of Southwood Drive, shown as a red dot in Figure 3-13. A small adjustment was made to right bank roughness through a 200-foot reach of the creek downstream of that location, illustrating the sensitivity of the model to roughness values. This could also be a reach that requires refinement of modeled lateral structure elevations to better reflect spills to the north and south. However, the model represents observed high water marks more closely with this final adjustment.

In East Palo Alto, an apartment complex on Manhattan Avenue was flooded, likely from north bank creek overflow finding its way to Woodland Drive. Overflows move away from the creek to the north toward the obstruction formed by Highway 101. Manhattan Avenue and Euclid Avenue are the main conveyances for this flow. Menlo Park observations include creek spills to the left bank at the Pope/Chaucer bridge, bank overtopping along Woodland Avenue near Oak Court and Euclid Avenue and overtopping near Emma Lane and Lexington Drive.

Street flooding on El Camino Real between Middle Avenue and the creek was also observed as was street flooding on Laurel Street, Middlefield Road, and Alma Street. This flooding was likely due to local storm drain capacity limitations rather than creek overflow.

The result of the model run incorporating observations made in East Palo Alto, Menlo Park, and Palo Alto is shown in Figure 3-14. Note that these results are from the final adjusted HEC-RAS model and do not include the effects of local storm drain systems.

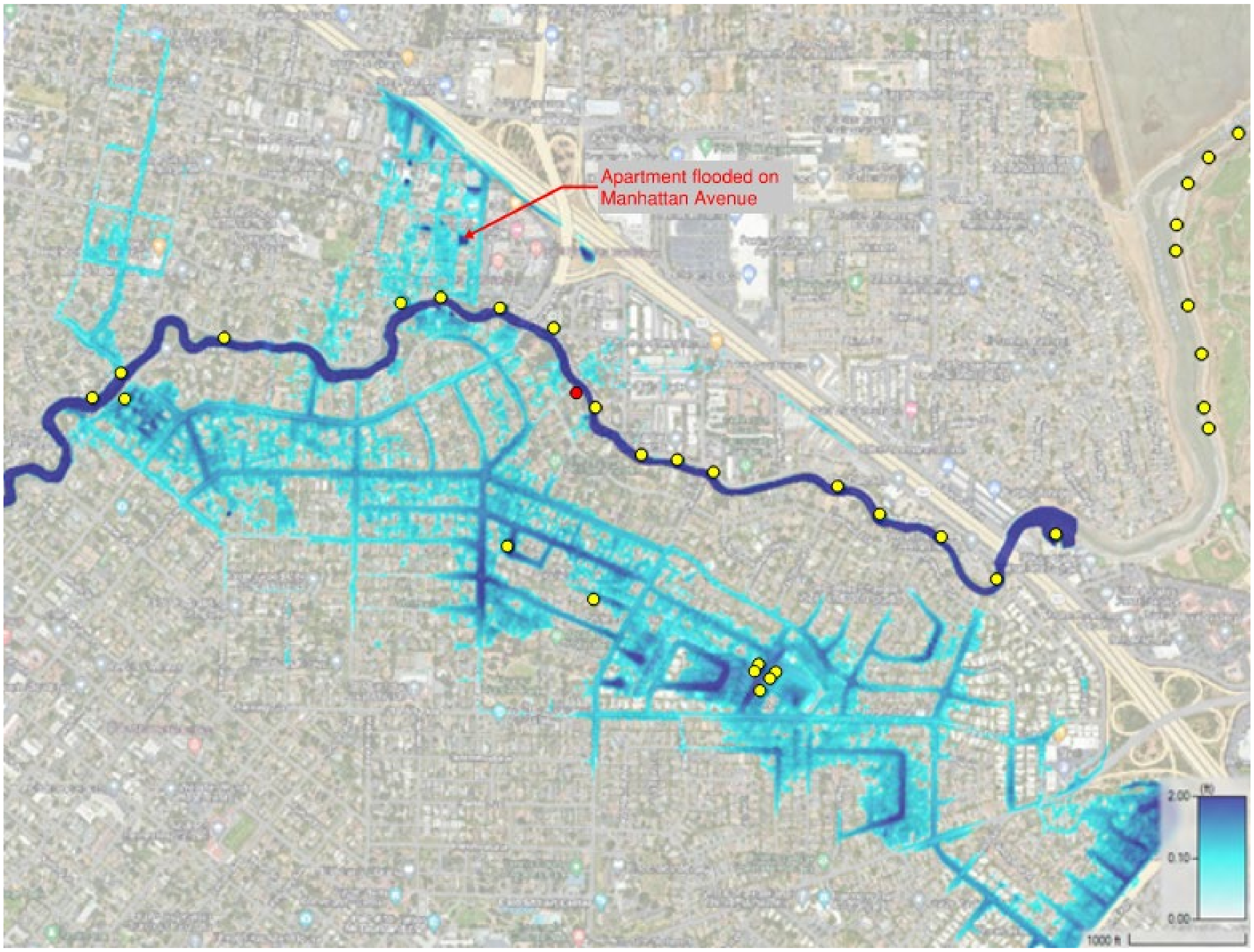


Figure 3-14: Final Adjusted HEC-RAS Geometry NYE22 Model Results (maximum depth) with South Bank Roughness Adjustment to Reduce Spill Downstream of Southwood Drive (red dot)

3.4 HEC-RAS Model Conclusions

HEC-RAS can be used moving forward for planning and design, understanding that this is a dynamic system with more uncertainty as to how the system might perform under different conditions than is typical of engineered systems like straight, earthen, or concrete-lined trapezoidal channels in San Mateo and Santa Clara Counties.

As such, the following adjustments to the HEC-RAS model have been completed digitally and are made available for SFCJPA and Valley Water review and use:

1. Horizontally varied roughness coefficients have been added to the updated model to develop more spatially varied roughness values, since locally high roughness appears to have had an impact on hydraulic gradients in the creek and played a part in inducing spill over the banks.

2. The 1D creek channel model is modified to better represent bank conditions by:

    a. Trimming cross sections back to the high points on each bank.

    b. Realigning the lateral structures to those creek bank high points so they accurately represent the flow spilling from the creek.

    c. Adjusting the 2D area as required to align closely to the revised lateral structures.

    d. Updating contraction and expansion coefficients around bridges. The unsteady coefficient table was blank when Schaaf & Wheeler first reviewed the model.

The adjusted HEC-RAS model is the best tool for predicting creek flow behavior and developing flood control projects. However, its value in predicting flooding away from the creek is limited by its lack of ability to consider pipe systems and pump stations. These can be important considerations, particularly given the complexity of the pipe systems and interconnectedness between the Matadero Creek and San Francisquito Creek pump stations, which were not examined in detail with this analysis. If the determination of representative flooding extents away from the creek within adjacent neighborhoods during a creek overbanking event is of importance, an integrated model such as ICM can be used to ensure that stormwater system conveyance and pump stations are properly accounted.

Additional refinements to the HEC-RAS calibration may be useful. However, it is important to consider that roughness in the creek can vary considerably in time. It may be more useful for Valley Water and/or their consultants to evaluate this calibration in the context of whether this event occurred during a period when roughness in the creek may have been higher or lower than average. If the adjustment of gaged flow rates by the USGS is any indication of those conditions, San Francisquito Creek may have been in a "rougher" than average condition, even within the urban area.

4 Integrated Creek and Stormwater System Modeling

This section describes the second peer review task and how an independent integrated creek and stormwater system model has been used to verify results of the adjusted HEC-RAS model.

4.1 Limitations of HEC-RAS Model

One of the drawbacks of using the HEC-RAS model as a standalone tool for replicating New Year's Eve flooding is that it does not include the East Palo Alto, Menlo Park, and Palo Alto storm drainage systems that likely had capacity available to remove some spill from the surface and convey it away from the creek and to East Palo Alto's O'Connor Pump Station and Palo Alto's San Francisquito Creek Pump Station. Calibrating the HEC-RAS model to accurately replicate the timing, peak magnitude, and volume of spill as well as high water marks observed along City streets is essentially not possible with HEC-RAS alone.

An integrated model that includes the creek flow, storm drain systems, pump stations, and a 2D surface grid is the best tool to attempt to reproduce the flooding that was documented during the storm outside of the creek. To this end, Autodesk InfoWorks' proprietary Integrated Catchment Model (ICM) is used. Schaaf & Wheeler used an existing ICM prepared for Valley Water under separate contract several years ago by updating the San Francisquito Creek model portion of ICM with the revised HEC-RAS geometry described in Chapter 3. The ICM is run with the New Year's Eve rainfall timeseries for the upper watershed and urban areas.

Because the ICM includes local storm drain system catchments downstream of the USGS gage, using this independent model should also allow for a better understanding of the magnitude of additional runoff into the creek downstream of the streamflow gage at Stanford. The Valley Water HEC-RAS model uses a scaling of the gaged flows based on additional drainage area downstream. This is a simplified approach that potentially does not capture the effects of variable drainage area sizes and characteristics downstream of the gage.

This discharge scaling proved to be unnecessary for modeling the bank full NYE event. There are only four significant local drainage outfalls to San Francisquito Creek between the USGS gaging station at Stanford and the San Francisquito Creek Pump Station at East Bayshore Road. Menlo Park and Palo Alto have storm drain outfalls to the creek at El Camino Real; Menlo Park has an outfall to the creek at Middlefield Road; and Palo Alto has an outfall at Guinda Street. The ICM shows no significant additional runoff from local storm drains adds to the peak discharge of the creek downstream of the USGS gage until the San Francisquito Creek Pump Station.

4.2 NYE22 Rainfall

Schaaf & Wheeler collected a sizable library of rainfall data for the NYE22 event. The ICM rainfall timeseries are a product of data from the California Data Exchange Center (CDEC) system at the Pulgas gage, local radar-derived rainfall from the Town of Woodside, and California Nevada River Forecast Center (CNRFC) hourly records of rainfall at the Palo Alto Airport. Figure 4-1 shows the precipitation timeseries used to model the NYE22 event in ICM. Watersheds above Alameda de las Pulgas, Santa Cruz Avenue, and Junipero Serra Boulevard rely on the timeseries labeled "Woodside Radar Rainfall" while more urbanized areas downstream are characterized by the "Urban Area Rainfall" timeseries, which is weighted towards the Palo Alto Airport CDEC record.

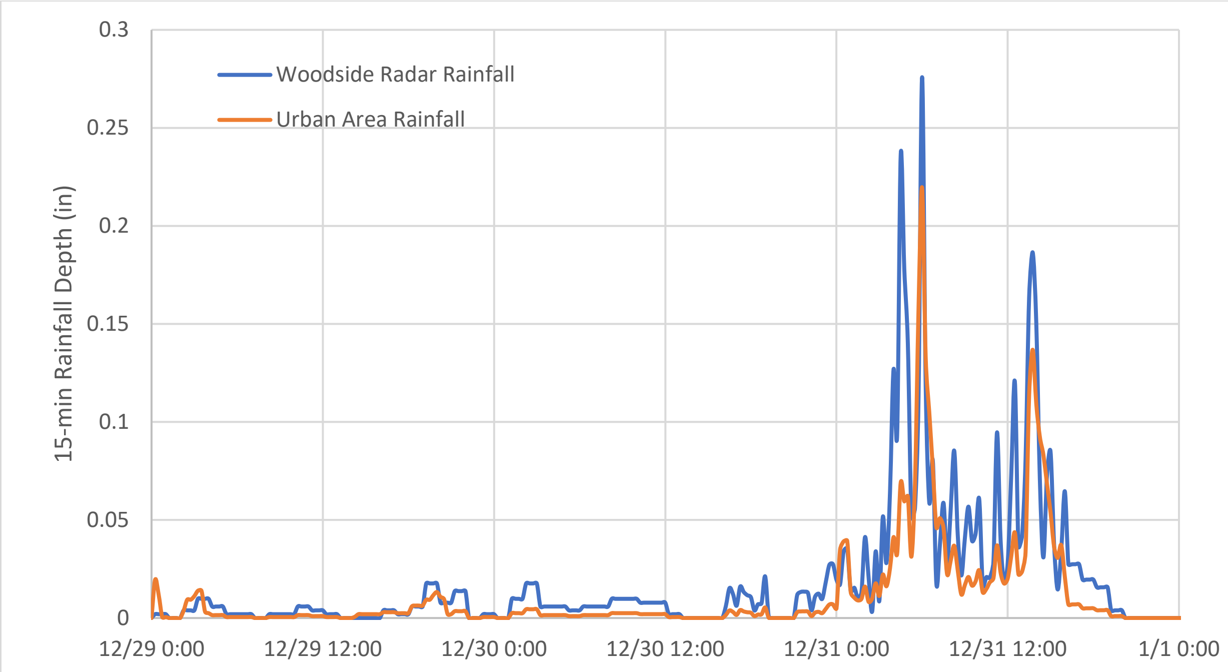


Figure 4-1: Rainfall Timeseries Used in the Integrated Catchment Model

These data cover the highest and lowest elevations of the San Francisquito Creek drainage area and interpolation and distance weighting techniques have been applied to develop rainfall timeseries for both the upper watershed and the lower watershed, which includes urban areas in Menlo Park, East Palo Alto, and Palo Alto.

Rainfall return-periods form one useful metric for the magnitude of the event. However, they cannot be used in isolation to evaluate the return period of the runoff. This event was unique and included multiple distinctive depth-duration-frequency relationships. Rainfall statistics for various durations at the available gages are provided as Table 4-1. Annualized return periods are from NOAA Atlas 14.

Table 4-1: Rainfall Statistics for NYE22 Storm Event

Duration	Pulgas CDEC Gage	Woodside Radar Rainfall	Palo Alto Urban Area Rainfall
10-min	n/a*	< 1-yr	< 1-yr*
15-min	n/a*	< 1-yr	2-yr
30-min	n/a*	< 1-yr	5-yr
1-hour	25-yr	1-yr	10-yr
2-hour	30-yr	1-yr	10-yr
3-hour	35-yr	2-yr	8-yr
6-hour	20-yr	10-yr	5-yr
12-hour	65-yr	20-yr	35-yr
24-hour	25-yr	10-yr	20-yr

*Data are not available for this interval. Return periods are estimated.

Clearly the return period for precipitation at each evaluated duration interval varied significantly across the study area during New Year's Eve 2022. However, it is important to note that the local drainage systems in East Palo Alto, Menlo Park, and Palo Alto experienced at least a 10-year, 1-hour rainfall event. Shorter durations are generally important to the capacity of inlets and pipe systems.

Both East Palo Alto and Palo Alto rely on large stormwater pump stations to provide positive drainage from pipe systems into San Francisquito Creek. This means that volumes generated from longer storm durations are equally important to the function of various portions of the system. With longer duration storms of greater rainfall depth, available storage within the storm drains and street collection systems is taxed, so that when overflows from the creek arrive at the storm drain system after the local runoff has begun to recede, there is diminished local drainage capacity and the creek overflows cannot be accommodated by the storm drainage systems, leading to ponding in lower-lying areas.

Also noteworthy is the return period of 30 to 35 years for the Pulgas CDEC gage. This roughly matches the return period of the peak flows at the San Francisquito Creek at Stanford University USGS gage during the storm (5,880 cfs) as discussed in Chapter 6. The gaged flow is shown overlain on rainfall timeseries in Figure 4-2.

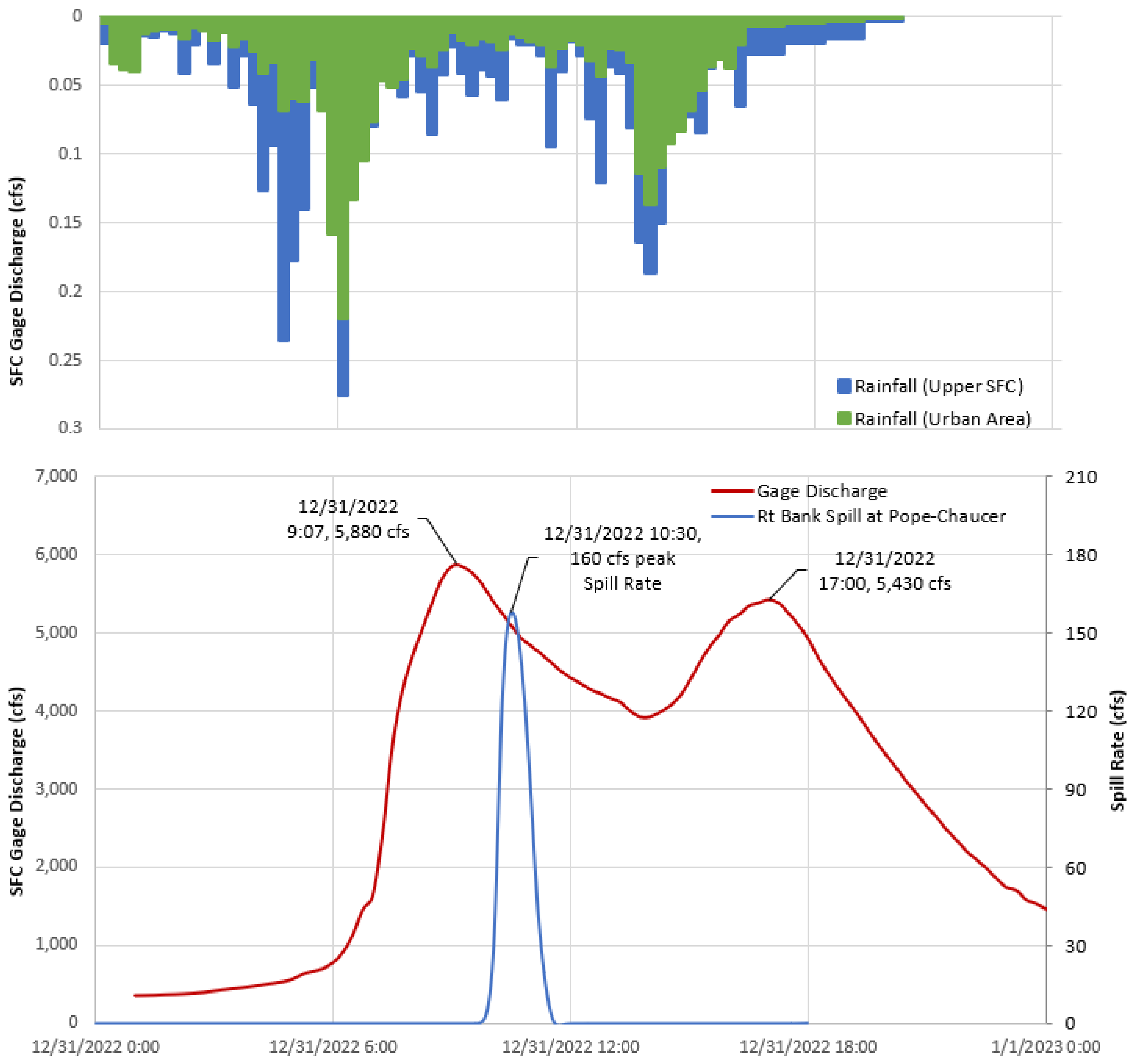


Figure 4-2: 15-minute Rainfall Timeseries and San Francisquito Creek USGS Gage Discharge

This plot includes 15-minute monitored discharge at the USGS gage location upstream of the points where spill from the creek occurred. This has been superimposed on the spill across the right bank lateral structure just upstream of Pope/Chaucer bridge from the HEC-RAS model. The lag time between the gage location and Pope/Chaucer bridge is just over an hour and 20 minutes.

Local runoff from highly urbanized areas with storm drainage systems generally occurs on sub-one-hour time scales. Runoff moves quickly across pavement and through pipe systems. By observation, spills from the creek occurred during the lull between the two distinctive peaks in the urban rainfall hyetograph,[5] at a point in time when local storm drain systems are most likely to have capacity available during this storm. To evaluate the relationship between local runoff, pump system function, and creek overbank spill, the integrated creek/storm system/2D ICM model is needed since HEC-RAS has no direct way to evaluate storm system capacity availability during the period when flooding was caused by creek spills.

Quantitative high-water marks were obtained by Valley Water in Santa Clara County. Similar measured high-water marks in San Mateo County are not available. Therefore, while the ICM model includes storm drain systems in East Palo Alto, Menlo Park, and Palo Alto, model result verification is somewhat easier in Palo Alto. This statement applies only to event flooding away from the creek banks. Observations were available on both sides of the creek to calibrate and verify the HEC-RAS model's replication of creek overbanking.

4.3 Rainfall Verification

The USGS gage provides a point of known runoff discharge that can be used to evaluate whether the rainfall input estimates peak runoff during the storm with reasonable accuracy. With the upper and lower watershed rainfall timeseries input into the ICM, the peak flow estimated by the model at the gage is approximately 6,080 cfs. This is only slightly more than the gaged flow rate of 5,880 cfs. The model estimates discharge at the gage location to within approximately 3 percent of the peak gaged discharge peak (Figure 4-3), which itself was adjusted by the USGS based on a measurement with up to 5 percent error. Based on that result, the rainfall and hydrology inputs to the model provide a reasonable representation of the NYE22 storm.

To maintain a reasonable level of accuracy in ICM, the upper watershed has been replaced in a final model run with the gaged flow rates from the USGS. The model has been truncated to the gage location, with that time series used as a hydrograph boundary condition. Rainfall remains associated with downstream catchments in the model, and this initial run provides confidence that those catchments are producing a reasonable estimate of runoff magnitudes downstream of the gage.

[5] A hyetograph is a graphical representation of the distribution of rainfall over time. It is usually represented by a bar graph showing rainfall amount versus time. A hydrograph is a curve showing the streamflow versus time.

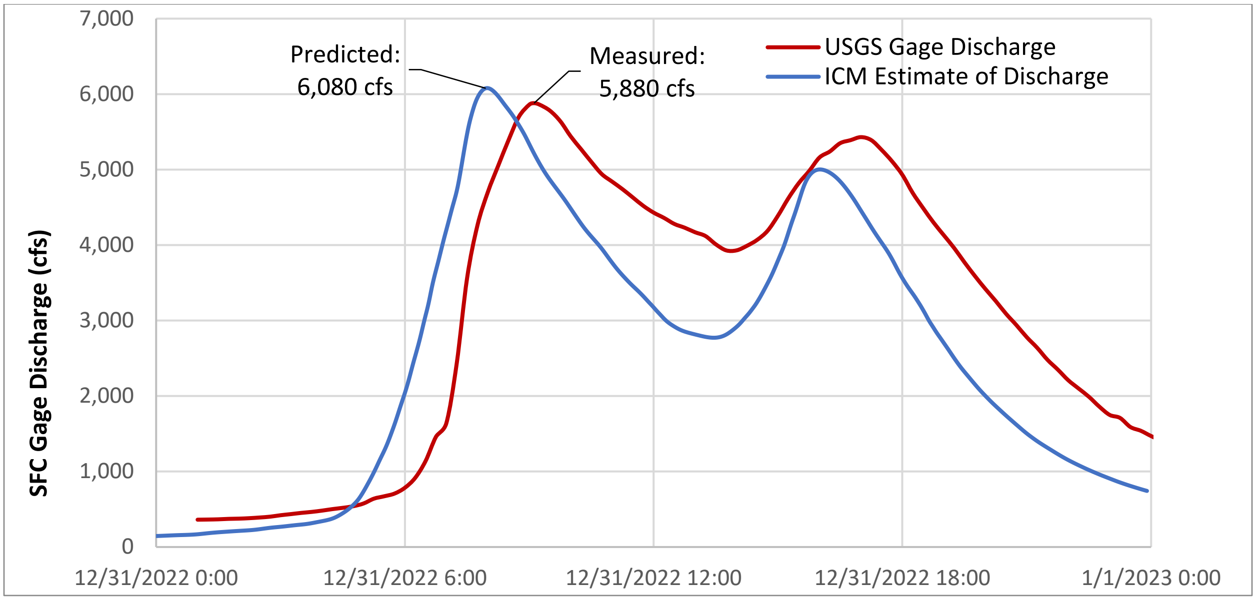


Figure 4-3: ICM Prediction of Streamflow at the USGS Gage Location

4.4 Integrated Catchment Modeling Results

ICM results incorporating storm drains in East Palo Alto, Menlo Park, and Palo Alto, and incorporating the modified HEC-RAS model geometry and roughness, are shown as Figure 4-4.

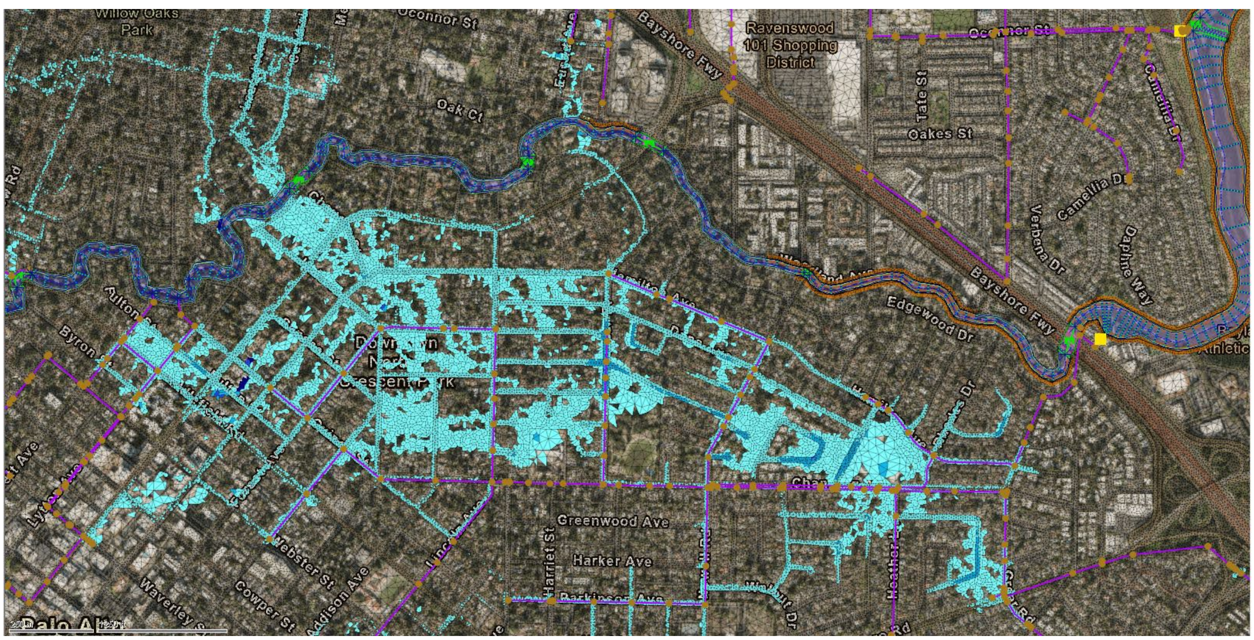


Figure 4-4: ICM Result with River Geometry Updated Based on the Final Adjusted HEC-RAS Model

The ICM shows that with the adjustments to the RAS model described in Chapter 3 translated to the integrated cities-wide storm system model, urban flooding extents can be replicated when compared to estimated high-water marks provided by Valley Water and information provided by Menlo Park and Palo Alto.

It is noted that the revised HEC-RAS model, adjusted based on observations of conditions in the creek and aerial imagery, predicts creek overbank spills as flow rates, spill locations, and spill volumes that when routed away from the creek using ICM also replicate observed experiences during the storm event.

The ICM uses the same creek geometry as the HEC-RAS model, but the models' calculation engines are different, so using identical creek geometry does not produce identical results. As shown in Figure 4-4, the ICM would require some further adjustment to reproduce the observed creek spill into East Palo Alto along Woodland Avenue east of Euclid Drive. For example, observed flooding of the apartment complex on Manhattan Avenue is not predicted by ICM. Based on the sensitivity of model overbanking to slight changes in model parameters, this could likely be achieved without significantly changing right bank overflows. However, since the intent of using ICM is to verify behavior away from the creek rather than to replace the HEC-RAS model, this additional effort has not been expended.

4.5 Integrated Catchment Modeling Conclusions

Schaaf & Wheeler has applied ICM as an integrated tool for evaluating stormwater interior system performance during the New Year's Eve event. Although the model is not perfectly calibrated, it does indicate that a significant volume of spill during the event was kept off the floodplain surface by local storm drain systems; compared with the HEC-RAS model results, which omit the function of the pipes and pump station. The HEC-RAS model cannot therefore be calibrated in isolation from those system components, even if it is to be used as a standalone tool for evaluating spill or future flood protection for San Francisquito Creek.

5 USGS Published Discharge at Streamflow Gage

The third assigned task is to evaluate the U.S. Geological Survey's adjustment of peak discharge estimate at their San Francisquito Creek streamflow gage for publication. The published discharge estimate is used to perform a flood-frequency analysis for annual instantaneous peak discharge based on the long-term record as described in Chapter 6. This allows the NYE22 discharge event to be placed in its statistical context.

5.1 USGS Procedures for Collecting Streamflow Data

The United States Geological Survey (USGS) manages a large network of stream gages. Their Santa Cruz Field Office manages the stream gage for San Francisquito Creek at Stanford University. They follow four basic steps for collecting streamflow data:[6]

1. Establish a suitable site and construct a gage house to hold the equipment needed to measure and record the height of the water surface (gage height or stage). The stream gage for San Francisquito Creek at Stanford has been operating and recording creek stage since Water Year 1931, which began October 1, 1930.
2. Measure the gage height (stage) of the creek using a stilling well and record the water level at (in this case) 15-minute intervals. An outside reference gage, typically a vertical graduated scale called a staff gage, is periodically used to verify that the recorded gage heights from the stilling well are the same as the physical water levels in the creek.
3. A stage-discharge relationship is computed and used to relate the recorded water levels to instantaneous discharge. The rating curve for the specific creek location is developed by measuring both discharge and stage in the field and relating discharge to stage numerically in the form of a plot known as a rating curve. Instantaneous discharges throughout the year can be determined from the rating curve and the record of creek stage (gage height).
4. Since factors such as debris, sediment, and vegetation growth can affect the stage-discharge relationship, the rating curve must be checked periodically, preferably during periods of higher creek flow for better accuracy. The storm event of New Years Eve 2022 afforded the USGS one such opportunity to check and adjust the rating curve during a period of high flow. Discharge was estimated independently of the stage rating curve by dividing the creek into segments and using a current meter to measure average flow velocity and water depth within each segment. The product of width, average depth, and average flow velocity within each segment is summed to obtain total creek discharge.

5.1.1 Application of Stage-Discharge Relationship

The stage-discharge relationship is applied to gage height to produce an instantaneous flow record. The USGS aggregates instantaneous flows to produce statistical data for daily flow, monthly flow, and peak annual flow in cubic feet per second (cfs).

[6] USGS, Water Science School, 2018, https://www.usgs.gov/special-topics/water-science-school/science/how-does-usgs-collect-streamflow-data

The condition of the creek bed and banks near the stream gage can change the stage-discharge relationship at a given point in time. These conditions may vary based on a variety of factors, including drought conditions, the magnitude of prior storm events in the same season, and sediment and gravel moving through the channel. However, these conditions can be simplified by considering two broad conditions for a given flow rate:

1. A "clean" channel, with little sediment and debris accumulation and/or with little vegetation will move water through it more efficiently, with less depth.
2. A channel with a greater degree of sediment and debris accumulation or very dense vegetation has higher roughness and requires greater depth for that same flow rate.

The USGS evaluates channel conditions and chooses an appropriate rating curve for any given storm event by taking direct measurements of flow velocities and depths across the channel. This is a more time-consuming effort, but it is necessary to ensure that the conversion from constantly gaged stage to flow rate is as accurate as possible throughout the record. Measurements are considered "provisional" until the USGS staff verifies their accuracy with all available information at their disposal.

5.1.2 Data Collection on New Years Eve 2022

The New Years Eve storm event included the highest direct USGS measurement of flow rate for San Francisquito Creek in its 84-year record, taken at approximately noon on December 31, 2022. That measurement indicated that the provisional peak flow rate estimated from the stage-discharge relationship was significantly overstated. This is because after a long period of time without significant rainfall and flow rates to clear the channel banks of vegetation and debris, the creek was in a more heavily roughened condition at the gage location than conditions on average. This resulted in flow rates that are lower than what the stage-discharge curve, which is based on less roughened creek conditions, predicted at the relatively high measured flow depth.

Based on an initial evaluation of the measurement and conditions observed in the field by USGS staff, a preliminary adjustment was made to the stage-discharge rating. Then, after the field measurement and storm record was further evaluated, a final adjustment was made, bringing the adopted peak flow for the storm to 5,880 cfs. Historical USGS measurements offer some insight into how reasonable this adjustment was from the initial provisional peak flow rate of 7,420 cfs published live on December 31, 2022. Figure 5-1 graphically illustrates approximate stage-discharge adjustments from provisional to final, plotted over the entire range of measured streamflow values. While these curves are not those used by the USGS, they show that the provisional estimate was based on a cleaner channel condition. If this had been the case, the USGS flow measurement would have been closer to 5,500 cfs. Other historical measurements for stages between 7 feet and 10 feet in depth were indicative that the channel conditions have historically been even more roughened than during the New Years Eve 2022 event.

The highest creek stage recorded on December 31, 2022 represents the peak annual flow for Water Year 2023. This section of the report documents our review of the methods and well documented process followed by the USGS to adjust their published flowrates based on recorded creek stage and field conditions on the day the peak flow for Water Year 2023 was recorded. Our review did not discover discrepancies or errors in USGS' methods or process.

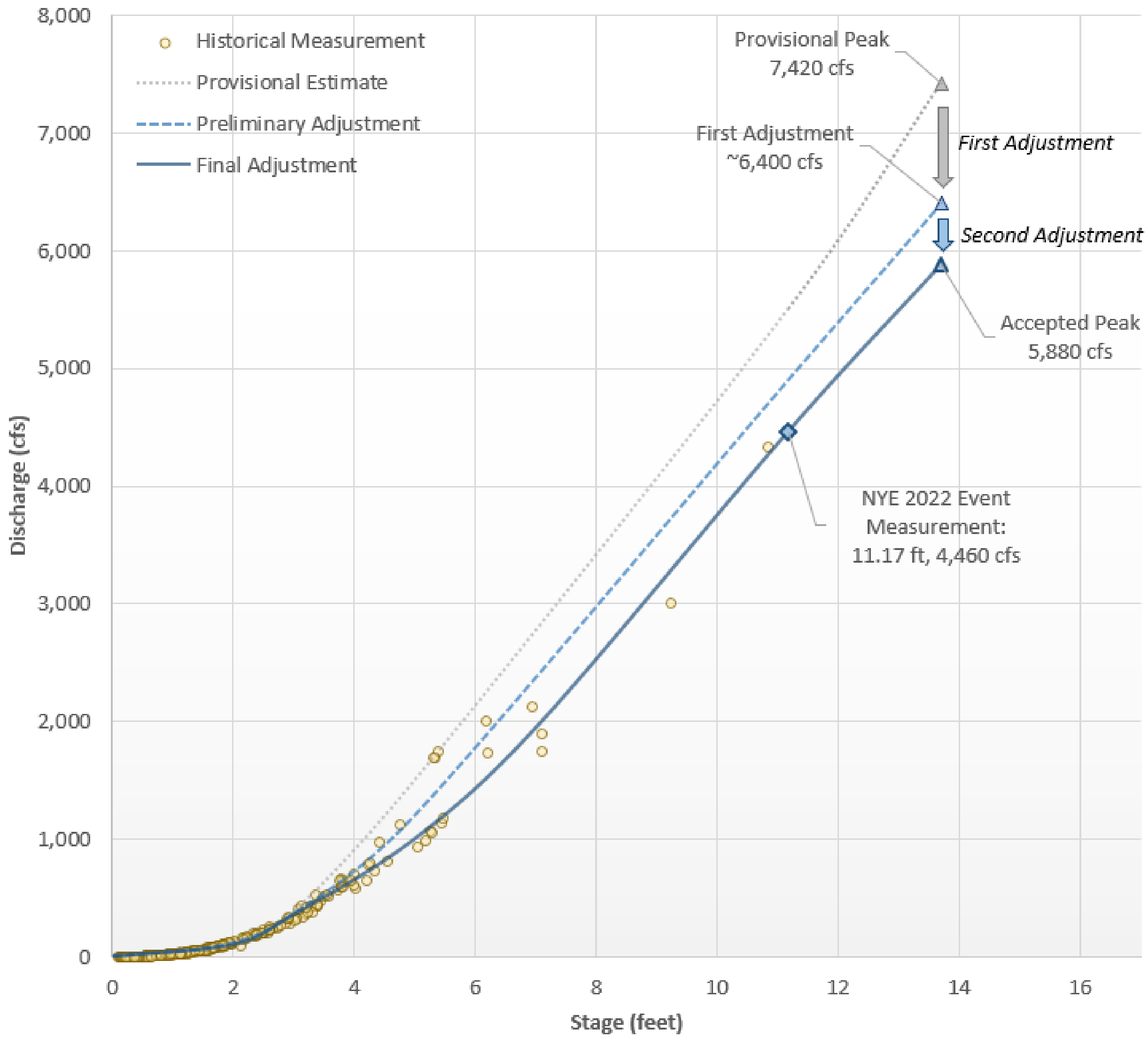


Figure 5-1: Approximate Stage-Discharge Curve Adjustment for the NYE22 Storm Event

5.2 San Francisquito Creek Gage Details

The San Francisquito Creek gage at Stanford University is located upstream of where the creek crosses Junipero Serra Boulevard near the Stanford Golf Course (Figure 5-2). The gage is equipped to measure and store creek stage (depth) data automatically every 15 minutes on the quarter hour. Barring equipment or telemetry failures, this results in a complete record of stage and streamflow that can be used for a multitude of purposes – calculating stream flow statistics, predicting potential flooding, or constructing and calibrating hydraulic models.

Creek stage is a measurement of water surface elevation at an arbitrary point and provides an indication of water depth at that location. San Francisquito Creek stage is measured from a 36-inch diameter corrugated metal pipe (CMP) stilling well (Figure 5-3) upstream of a concrete weir control structure in the creek (Figure 5-4).

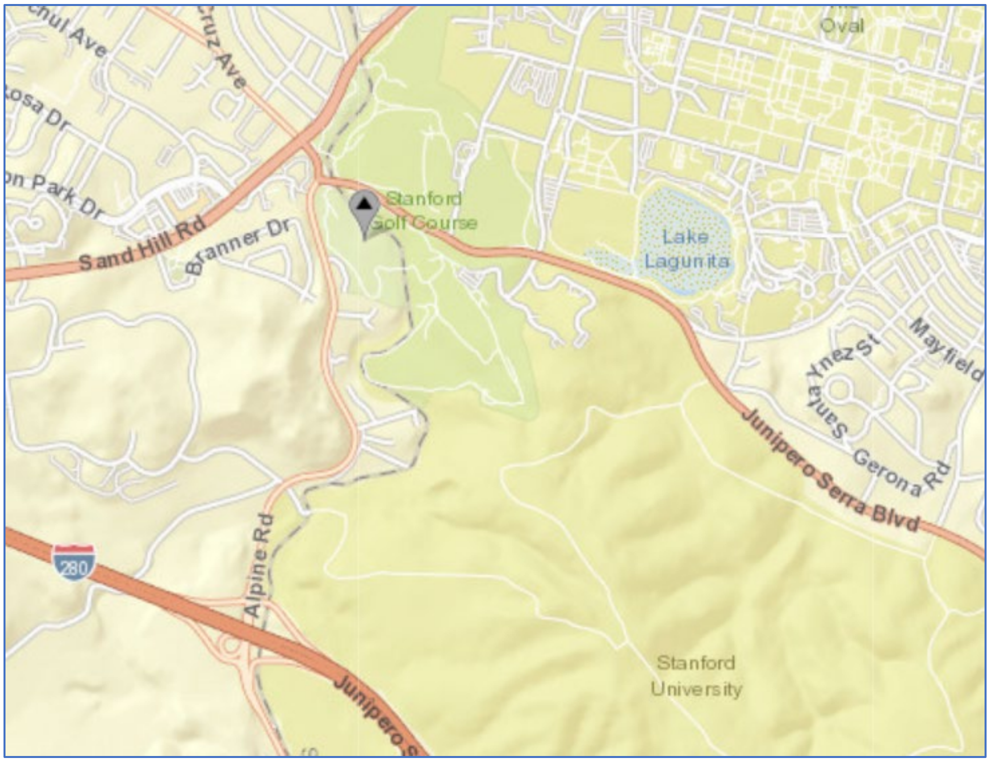


Figure 5-2: San Francisquito Creek at Stanford Gage Location (source: USGS)

Figure 5-3: San Francisquito Creek at Stanford Gage Stilling Well

Figure 5-4: Concrete Weir Control Structure Downstream of the San Francisquito Creek Stilling Well

The concrete weir structure stands about three feet above the stream's downstream thalweg and spans approximately 40 to 50 feet across the channel. Given an extensive understanding of the behavior of various types of weir structures and an array of stream flow measurements, a rating curve has been developed by the USGS that relates the stage measured in the stilling well to expected discharge.

5.3 Data Measurement

Stream stage is the most practical measurement to monitor and log on a long-term basis. A stage-discharge relationship has been developed to relate that measured stage to a flow rate.

The San Francisquito gaging site includes a concrete control structure just downstream of the stilling well (Figure 5-4). This control structure is assigned a rating curve, which is a known relationship between stage and discharge over the structure for a given set of conditions, from which streamflow is indirectly calculated.

A simple diagram of a stilling well configuration is shown as Figure 5-5. According to Stephen Huddleston at the USGS, equipment specifics are generally not public information, but the San Francisquito Creek gage is a a simple setup with a data logger and a shaft encoder recording gage that uses a float, string, and pulley system to measure the depth of water in the well. The shaft encoder device provides measurements to a datalogger and satellite telemetry equipment that handles data storage and transfer.

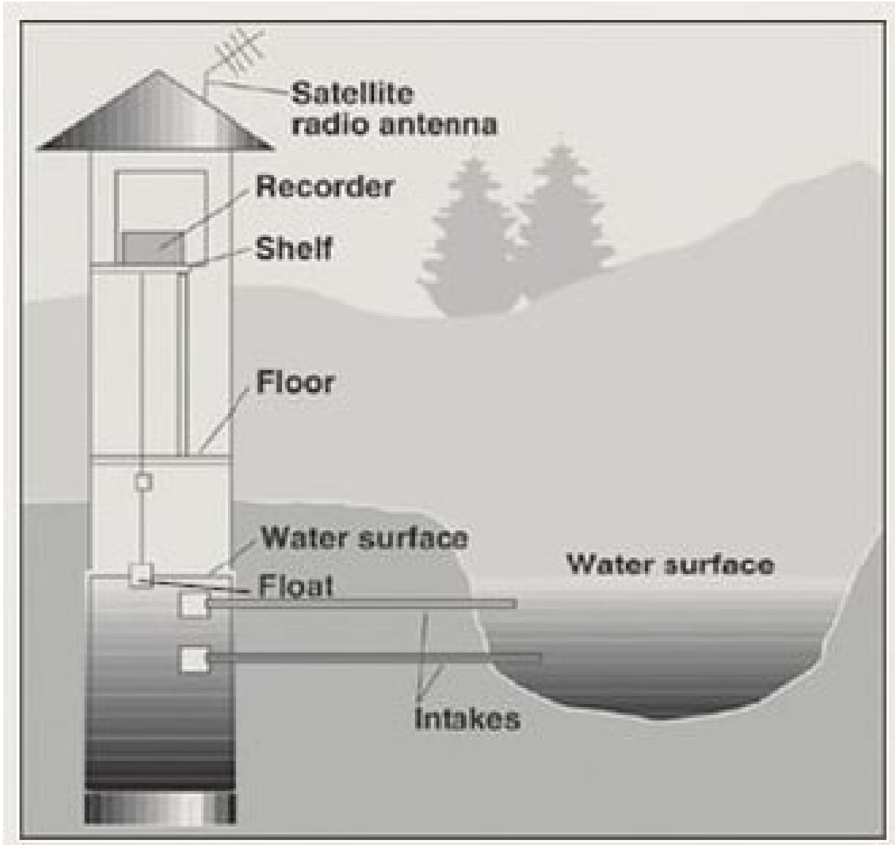


Figure 5-5: Diagram of a Stilling Well with Data Recording Equipment (source: USGS)

5.4 Data Adjustment

This evaluation of data adjustment focuses on discharge, which is a calculated number based on the relation between gage height and stream flow and evaluates factors affecting the determination of discharge, sources of error, and how provisional data are reviewed by the USGS.

The stage associated with any given streamflow is influenced by several factors that do not remain constant over time, including:

- Stream bed characteristics (elevation and material size), which are influenced by the energy of stream flow;
- Vegetation density and health, which vary through wet and dry years and can be impacted heavily by high stream flow events; and
- Debris accumulation and entanglement with vegetation.

The rate of flow over the weir for a given measured stage can be altered considerably by conditions downstream when the weir becomes submerged by tailwater, which likely occurred on December 31, 2022. The relationship between stage and expected flow can vary significantly when the weir is submerged. The cumulative impact of the movement of streambed materials, the condition of vegetation at flood stages, and the presence of debris all represent elements of the downstream channel's "roughness".

Settlement and accretion of rocks and sediment on the channel bottom, coupled with very dense, healthy vegetation or excessive debris accumulation effectively block flow area in the channel's cross section. Displacement and movement of stream bed material away from a given point in a stream, thin vegetation, and little debris results in a cleaner, more efficient channel capable of conveying more runoff for the same stage at the gaging station. This means that the same stage can occur for many different flow rates, and vice versa. For example, a 100-year peak flow rate occurring after the channel has been scoured and cleared of debris may occur with the same peak stage as a 50-year peak flow occurring early in the season when vegetation is dense, tangled with debris, and the channel bed has not been scoured.

A combination of velocity and depth measurement is the best way to acquire a more accurate assessment of streamflow at any given time. However, it's not practical to measure velocity regularly. Velocities can vary significantly both vertically and horizontally at any given point in a stream, and direct measurement of flow velocity distributions is a time-consuming task. It is, however, a necessity to measure stream velocities in the water column on occasion to decide whether adjustments are required to the gaging station's rating curve for some period.

The general method by which measurements are taken is illustrated in Figure 5-6. Velocity is measured at one or more selected points in the vertical, which are then applied to a partial rectangular area (segment) horizontally. Segments extend laterally from half the distance from the preceding vertical to half the distance to the next vertical, and vertically from the water surface to the sounded depth.

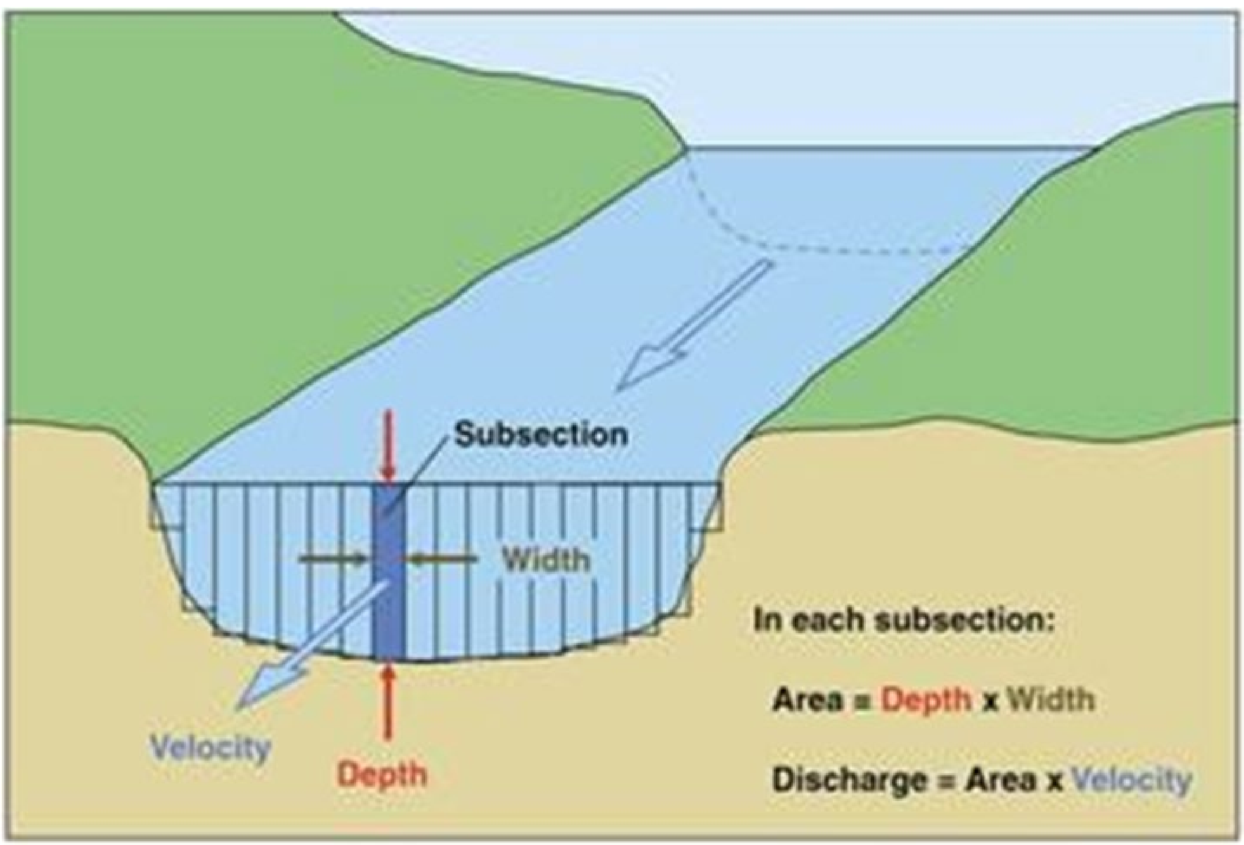


Figure 5-6: Stream Discharge Estimation from Velocity Measurements (source: USGS)

The exact means and location of streamflow measurement at the San Francisquito Creek gage have changed over time at the station. Low flow measurements are often taken when depths and velocities are not hazardous by individuals with handheld equipment in the channel. Historically, some higher flow measurements were taken from a bridge near the concrete weir (Figure 5-4). However, that bridge has been condemned. Recent measurements during high flow events, including the New Years Eve 2022 event, have been performed from a nearby golf cart bridge, located approximately 600 feet downstream of the gaging station.

Several variables and conditions are recorded during measurements, including:

- Date/time of measurement
- Channel bed stability at the measurement point
- The condition of flow in the channel (steady vs unsteady or highly variable)
- The type of equipment used
- The duration of the measurement
- The change in gaged depth during the measurement
- A rating of the overall "quality" of the measurement (good, fair, poor, etc.)

Examining the full range of USGS streamflow measurements and stages at the gage (Figure 5-7) shows how geomorphology can affect the acceptance and/or adjustment of the gaging station's estimated discharge.

Below a stage of 3.75 feet, the discharge measurements remain relatively consistent for any given elevation. This is an indication that for flow rates up to approximately 500 cfs, the concrete control structure does not experience significant variability in tailwater conditions that would cause a large deviation from the expected discharge curve. Beyond that point, the impact of variable stream bed and bank conditions is clearer. Two ranges are annotated on the plot in Figure 5-7. For a flow rate of 1,750 cfs, measured stages have varied by about 1.7 feet. Likewise, for a gaged stage of approximately 5.4 feet, measured flow rates have varied by approximately 600 cfs.

The New Years Eve Storm produced the highest flowrate ever <u>directly</u> measured by the USGS staff at the San Francisquito Creek at Stanford University gage. The measurement of 4,460 cfs was made on December 31, 2022 at 11:49 am Pacific Standard Time. The NYE 2022 measurement was made using a crane from the cart path bridge with a 100-pound sounding weight and a Price AA type velocity meter. Velocity measurements were taken across the channel over a period of approximately one hour. From the start of the measurements to their completion, the gaged height at the stilling well dropped by approximately 0.71 foot.

Measurements are evaluated to estimate potential error in each segment horizontally, and for the time-weighted estimate of total discharge. Some segments of the NYE 2022 measurement were estimated to have greater than 5% error, so the measurement was rated overall as "poor".

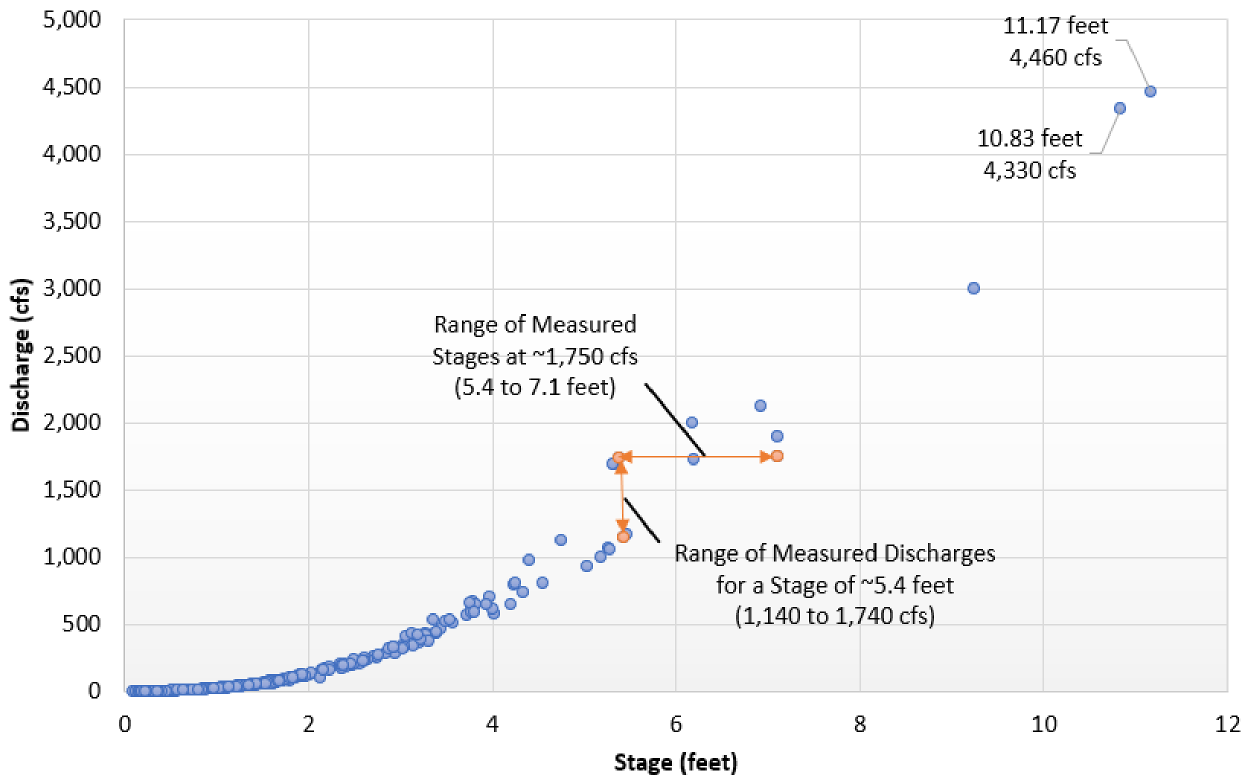


Figure 5-7: USGS Measurements of Stage and Streamflow for San Francisquito Creek at Stanford

5.5 Provisional Discharge Estimate During NYE22 Event

Provisional streamflow estimated from the gaged stream stage was on the order of 7,400 cfs (Figure 5-8). However, the measurement taken during the receding limb of the storm's discharge hydrograph indicated that after an extended period of drought, the condition of the channel bed and banks downstream of the gaging station were particularly rough. Vegetation and debris built up that had not been washed downstream by a high flow, channel forming event in many years. Rough downstream channel conditions increased tailwater on the control structure, thereby increasing the hydraulic grade line upstream at the gaging point. Before the measurement was fully evaluated, the USGS made a preliminary adjustment, placing the peak on the order of 6,400 cfs (Figure 5-9). That provisional adjustment is captured as a sudden drop in flowrate shown live by the USGS web feed shown in Figure 5-8 at about 3:00 or 4:00 in the morning of December 31. With the measurement fully evaluated, the USGS chose a final stage-discharge rating for the gage location, which placed the peak at 5,880 cfs.

Given that observed bank conditions and the measurement of a lower flow rate than the provisional rating curve would have provided an 11.17-foot depth, the USGS revised the stage-flow relationship used for the NYE 2022 storm's discharge. Considering the measurement's "poor" rating, a discharge error of 5% would place the actual peak discharge in the range of 5,590 - 6,170 cfs. This still lies below the initial peak provisional discharge of 7,420 cfs.

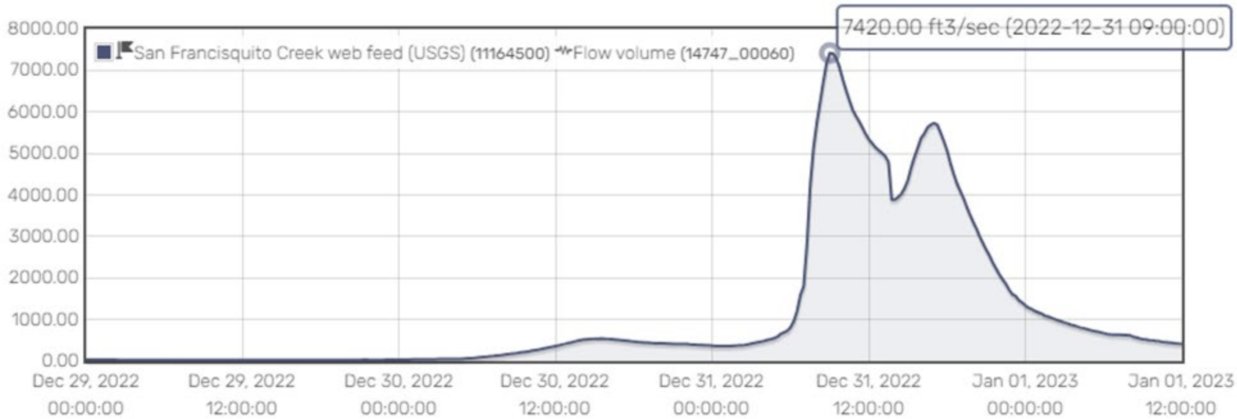


Figure 5-8: Provisional Streamflow Data (San Francisquito Creek JPA OneRain Website)

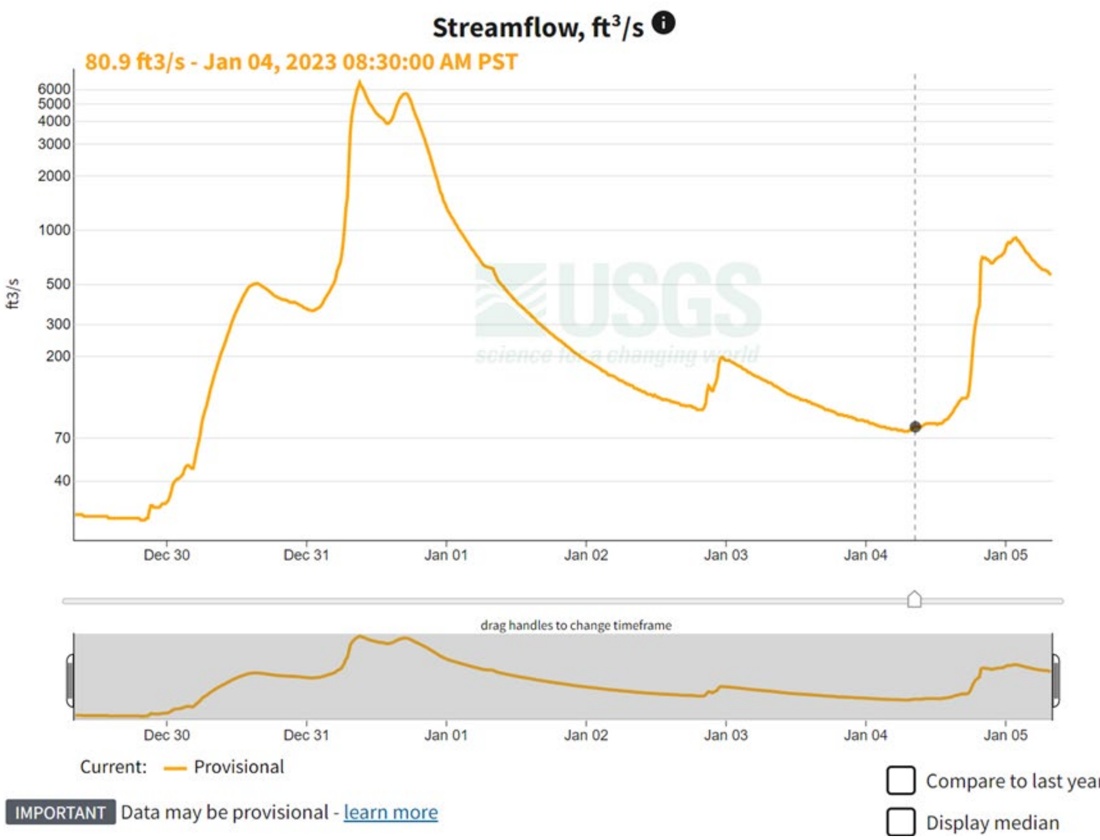


Figure 5-9: Provisional Streamflow Data for San Francisquito Creek from the USGS Gage Website on January 5, 2023 after an Initial Downward Adjustment

5.6 Adjusted Stage-Discharge Rating Curve Based on Measured Discharge

The New Years Eve 2022 event provides an interesting data point for comparison to the maximum historical discharge conditions in 1998. The measurement taken post-peak in February 1998 gave a clear indication that the channel downstream was not heavily affected by factors such as thick vegetation, debris, and/or an elevated channel bed. Adding the estimated peak of 7,200 cfs at 13.4 feet stage from that year to the plot in Figure 5-10 and connecting the dots provides a very approximate stage-discharge curve for that “clean, efficient” condition.

Likewise, adding the NYE 2022 estimated peak of 5,880 cfs provides an approximate stage-discharge for the "roughened" downstream condition. These are shown in Figure 5-11, with little difference at low stage, increasing to more notable differences in discharge at higher stages where bank roughness is more impactful.

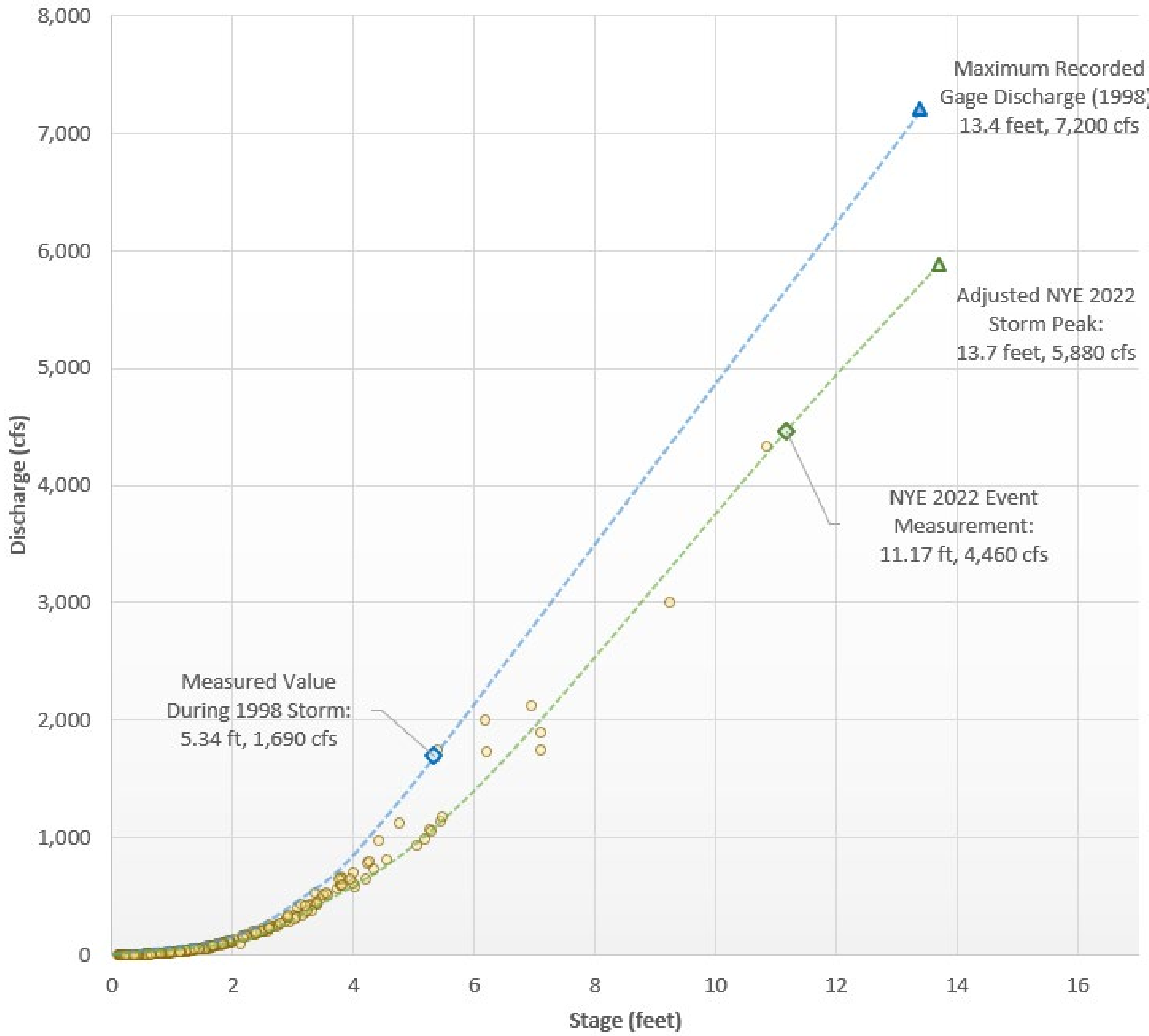


Figure 5-10: Approximate Stage-Discharge Curves Based on Flows Measured in 1998 and 2022

The curves in Figure 5-10 are approximate and only meant to roughly demonstrate the concept of the variability of rating curves used by the USGS. They illustrate the impact of channel conditions on two of the highest recorded peak flows in the San Francisquito Creek drainage area. A flow rate nearly 20% less than the 7,200 cfs historical peak rate corresponded to a measured water surface elevation that was 0.3 foot higher. Conceptually, this would apply across the full range of the stage-discharge relationship and not just at a single point.

Plotting additional approximate stage-discharge curves better illustrates the range of variability over the years (Figure 5-11). The 1958 measurement was the second highest directly measured flow rate (4,330 cfs at a stage of 10.83 feet) and was taken near the peak discharge for the year. This measurement was like the 2022 NYE event measurement in both stage and discharge. Water Years 1940 and 2008 also included significant field measurements (1,890 cfs and 3,000 cfs for 1940 and 1,120 cfs for 2008).

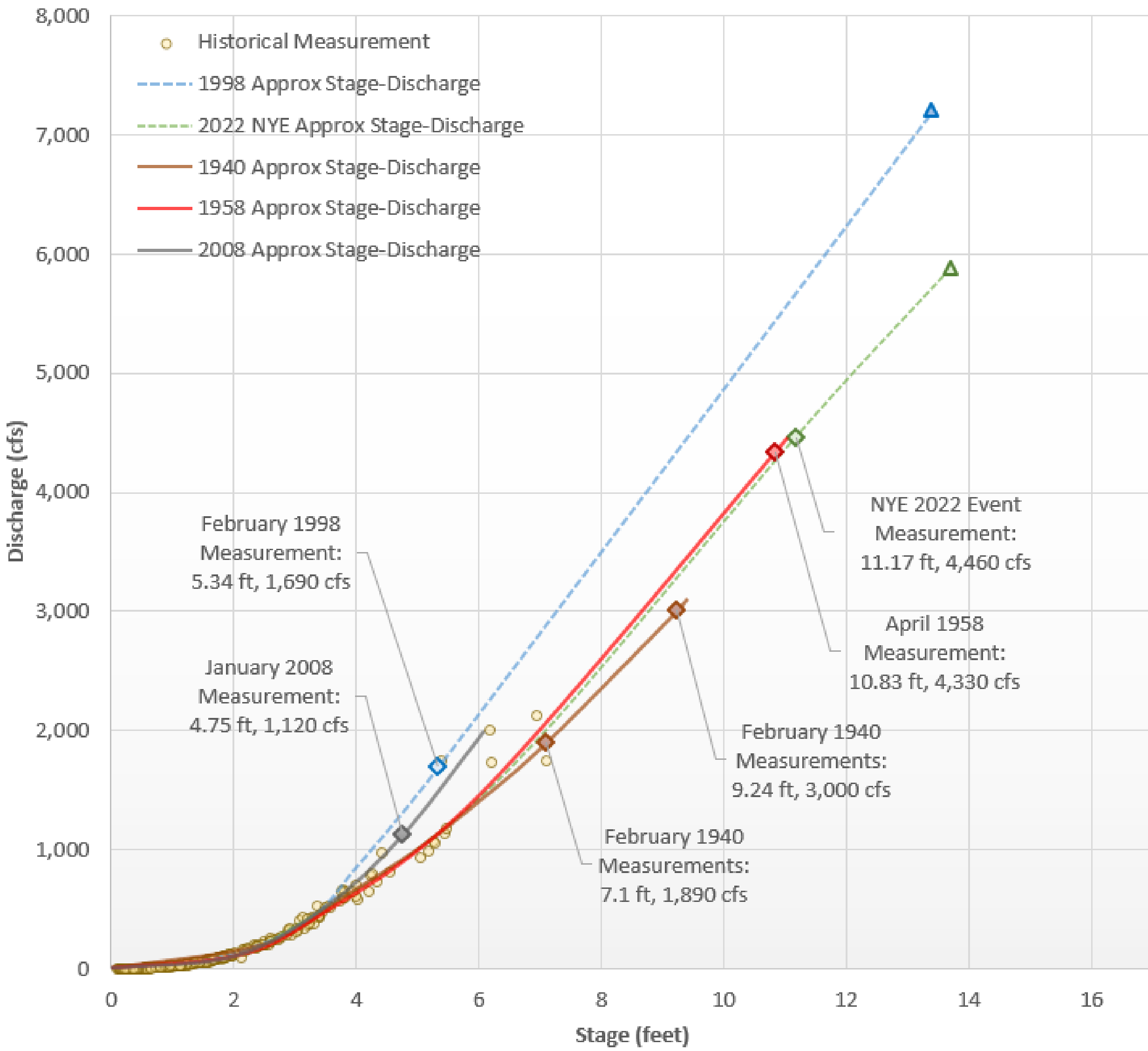


Figure 5-11: Approximate Stage-Discharge Curves for April 1958, February 1998, NYE 2022 Events

These events are chosen for this analysis because they included a measurement taken while the creek was flowing beyond four feet in depth at a date and time near the peak annual discharge, indicating that they were likely representative of channel conditions during the recorded peak. There are other water years with relatively high peak flows. However, their measurements were taken on a significantly different date than the peak or were not taken when depths were sufficient to illustrate channel conditions without other information (e.g. photos or USGS staff notes on channel roughness).

5.7 Published Discharge Hydrograph for NYE22

After making the adjustments described herein, USGS published the NYE22 event hydrograph shown as Figure 5-12.

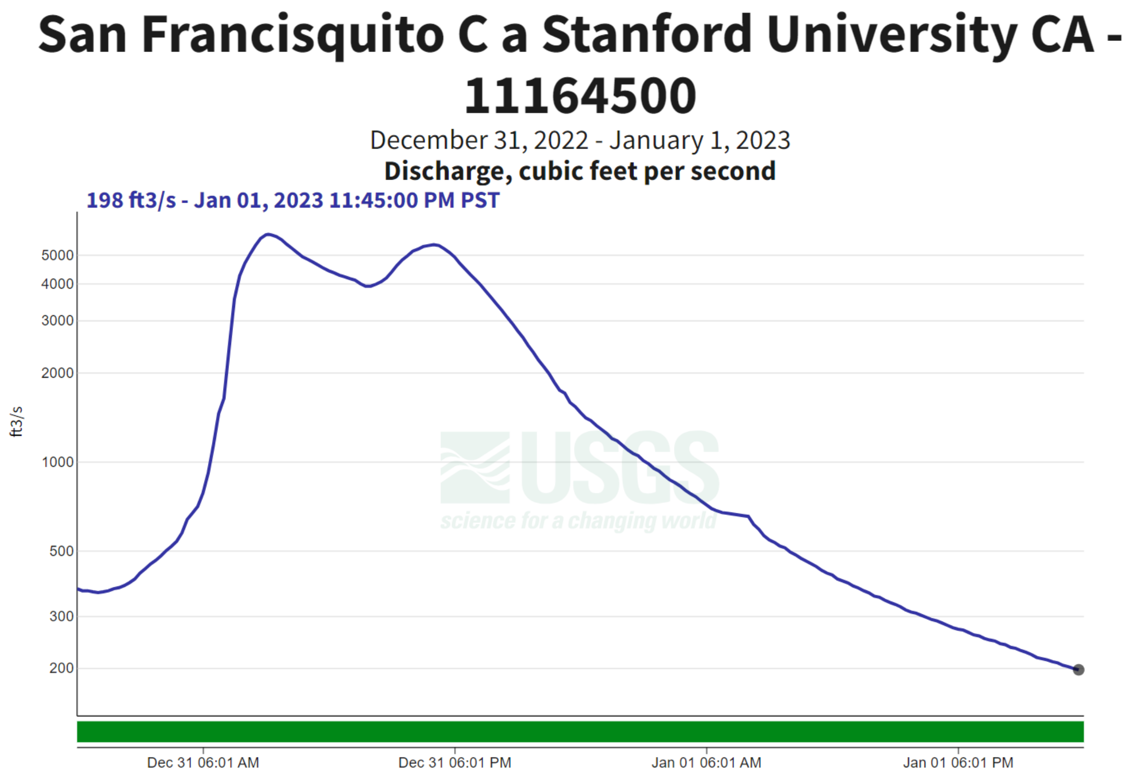


Figure 5-12: Published Discharge Hydrograph for NYE22 Event

5.8 Updated Streamflow Record

The San Francisquito Creek gage has been operational since October 1, 1930, with data available as summarized by Figure 5-13. Peak streamflow recorded by the station and verified for every complete water year in the record is shown in Figure 5-14. The final adjusted peak discharge of 5,880 cfs recorded on December 31, 2022 is highlighted on the chart as the peak discharge for Water Year 23. There are no records for Water Years 1942 through 1950.

Estimating streamflow from measured stage is far from an exact science. The relationship of automatically collected stage data to stream flow rate must be frequently evaluated based on more direct measurement of flow rate to determine the appropriate rating curve for any given storm. The USGS has applied and refined this practice over decades.

Provisional discharges estimated during the New Year's Eve 2022 event initially led many to believe that the storm more closely approached the 1998 event's historical peak. However, based on USGS observations of channel conditions and direct measurement of stream velocity on the receding limb of the storm, it became clearer that the stage at the gaging point was elevated due to channel roughness and tailwater on the control structure. It is because of that complex relationship between gaged stage and channel conditions that the USGS made the decision to adjust the peak NYE22 discharge downward to 5,880 cfs. We do not find discrepancies or errors in the methods and process employed by the USGS to adjust their flow measurements as described herein.

DESCRIPTION:

Latitude 37°25'24", Longitude 122°11'18" NAD27
Santa Clara County, California, Hydrologic Unit 18050003
Drainage area: 37.4 square miles
Datum of gage: 112.69 feet above NAVD88.

AVAILABLE DATA:

Data Type	Begin Date	End Date	Count
Current / Historical Observations (availability statement)	1987-07-02	2023-10-10	
Daily Data			
Discharge, cubic feet per second	1930-10-01	2023-10-09	30689
Daily Statistics			
Discharge, cubic feet per second	1930-10-01	2023-03-22	30488
Monthly Statistics			
Discharge, cubic feet per second	1930-10	2023-03	
Annual Statistics			
Discharge, cubic feet per second	1931	2023	
Peak streamflow	1931	2021-10-24	83
Field measurements	1931-12-27	2023-09-19	776
Field/Lab water-quality samples	1958-01-10	2017-05-03	26
Water-Year Summary	2005	2022	18

OPERATION:

Record for this site is maintained by the USGS California Water Science Center
Email questions about this site to California Water Science Center Water-Data Inquiries

Figure 5-13: Summary of Available Data, San Francisquito Creek Gage 11164500 (source: USGS)

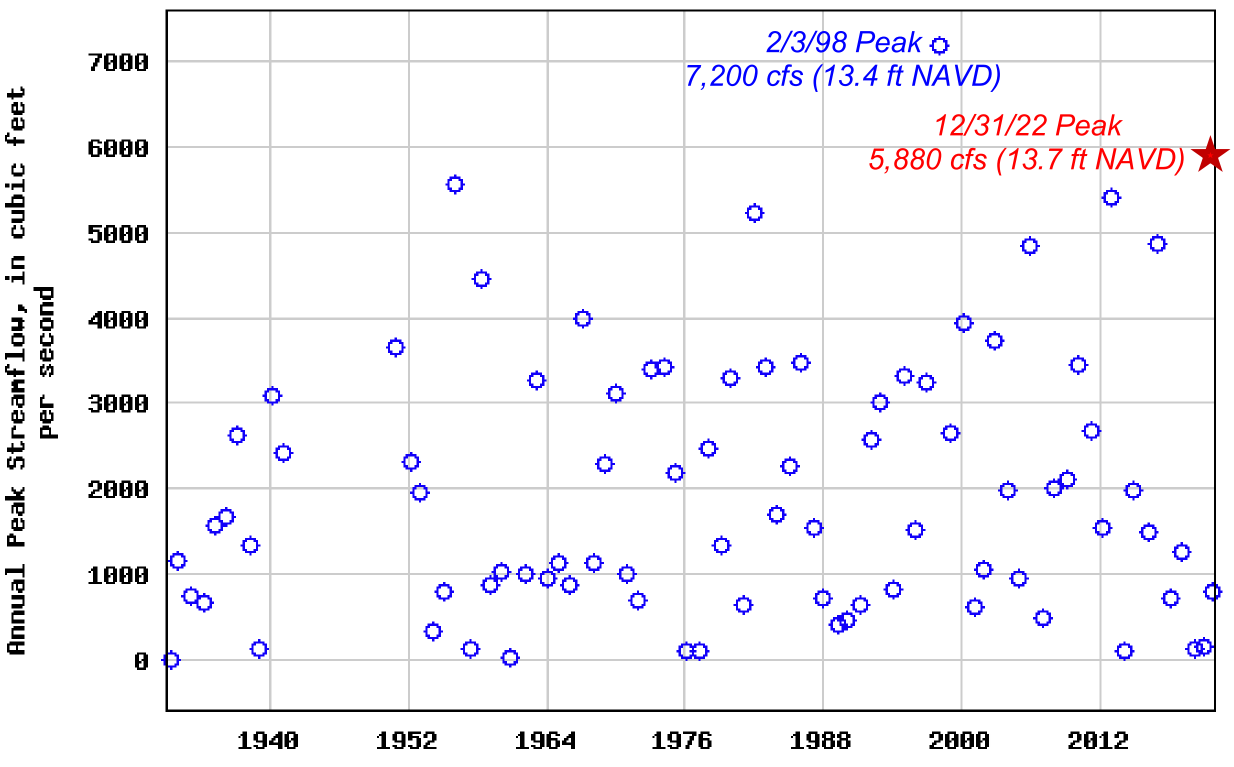


Figure 5-14: Plot of Annual Peak Discharge Since 1931 (excluding 1942-1950)

6 USGS Streamflow Statistics Review

The published instantaneous peak discharge for December 31, 2022 is the annual maximum instantaneous discharge for Water Year 2023. This section describes the flood-frequency analysis performed for the entire streamflow record through Water Year 2023. It is noted that Water Year 2024 lasts through September 30, 2024 and as such remains an incomplete record.

6.1 Previously Published Peak Discharge Statistics

The USGS last published one-percent statistics for the San Francisquito Creek gage in 2010, using data recorded through Water Year 2006.[7] The gage was evaluated as part of a larger effort to develop regional skew and flood frequency estimates throughout the state of California. When that analysis was done, USGS Bulletin 17B methods[8] were applied to the gages analyzed in the report. This pre-dated the final publication of the USGS Bulletin 17C methodology.[9] Gage analysis parameters and flow statistics from that study are summarized in Table 6-1.

Table 6-1: Summary of San Francisquito Creek Gage Statistical Analysis by USGS (2010)

Parameter	Value
Station Skew	-0.483
Station Mean Square Error	0.153
Regional Skew	-0.592
Regional Mean Square Error	0.140
User-Specified Low Outlier Threshold	620 cfs
1% Chance (100-year) Peak Discharge	7,690 cfs
2% Chance (50-year) Peak Discharge	6,660 cfs
4% Chance (25-year) Peak Discharge	5,610 cfs
10% Chance (10-year) Peak Discharge	4,200 cfs

[7] Parrett, C., Veilleux, A., Stedinger, J.R., Barth, N.A., Knifong, D.L., and Ferris, J.C., 2011, Regional skew for California, and flood frequency for selected sites in the Sacramento–San Joaquin River Basin, based on data through water year 2006: U.S. Geological Survey Scientific Investigations Report 2010–5260, 94 p.

[8] United States Department of the Interior, Geologic Survey, Office of Water Data Coordination, Guidelines for Determining Flood Flow Frequency, Bulletin #17B, March 1982.

[9] England, J.F., Jr., Cohn, T.A., Faber, B.A., Stedinger, J.R., Thomas, W.O., Jr., Veilleux, A.G., Kiang, J.E., and Mason, R.R., Jr., 2018, Guidelines for determining flood flow frequency—Bulletin 17C (ver. 1.1, May 2019): U.S. Geological Survey Techniques and Methods, book 4, chap. B5, 148 p

6.2 Gage Statistics Revision

Two methods are now available for evaluating peak flow statistics: Bulletin 17B and Bulletin 17C. Since the publication of Bulletin 17B in 1982, the USGS continued to research flood processes and statistical methods and incorporated their findings into the Bulletin 17C update, published in 2019. Some stated purposes of the update were to expand the ability to use data intervals (rather than only discrete values) and censor data, incorporate a generalized approach to identifying statistical low outliers in flood data, and provide improved confidence interval computation methods (with an update to the previously used Grubbs-Beck outlier test).

Ultimately, Bulletin 17C applies a different methodology for estimating distribution parameters than Bulletin 17B. Much of the reasoning for these changes is not necessarily relevant to this effort, as we are not applying data intervals or paleo flood estimates to extend the record. However, the new methods are comparatively applied nonetheless to evaluate their efficacy in updating statistics for San Francisquito Creek.

Both methods recommend the use of weighted station and regional skew values, and both methods recommend applying skew and mean square error values estimated by the USGS for a given gage.

With the 2023 water year complete, this analysis includes the 5,880 cfs peak discharge rate as part of the data record, resulting in 84 years of recorded peak flow rates. The updated estimates use HEC-SSP software, which has both Bulletin 17B and 17C methodologies built in.

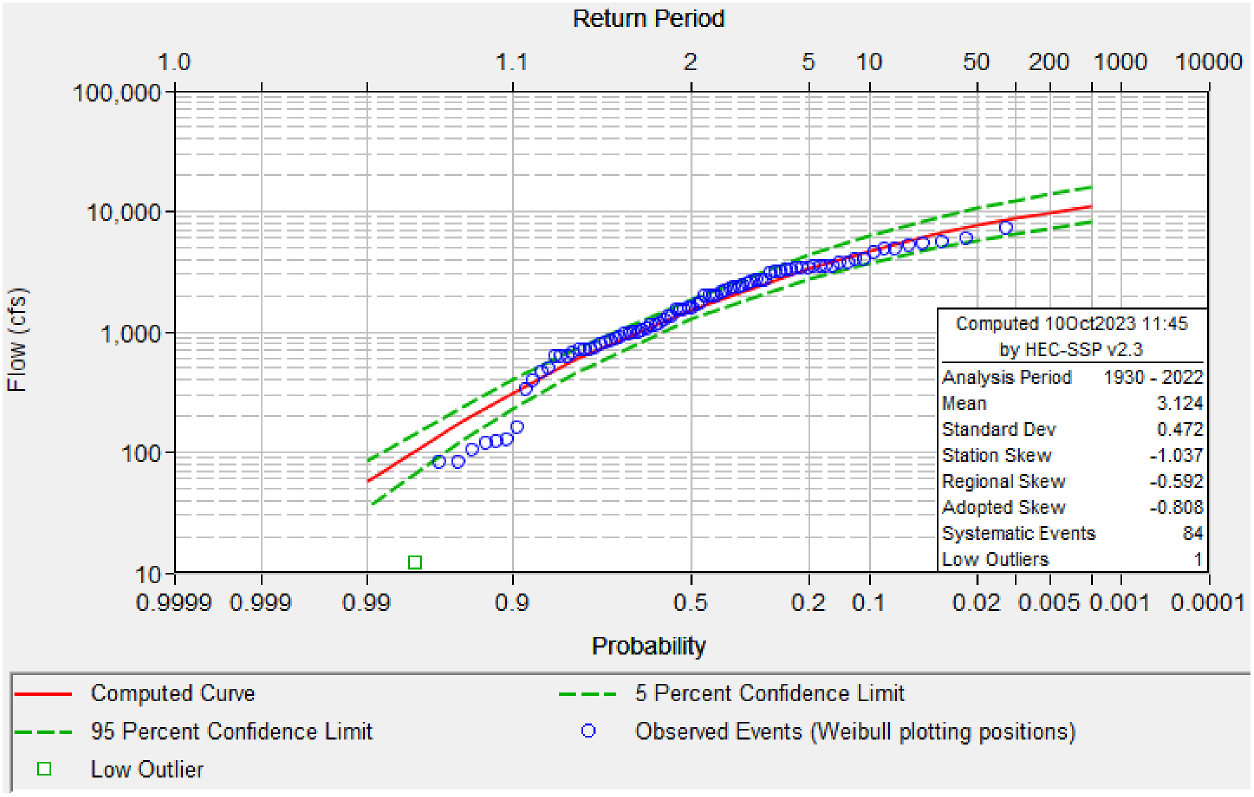
6.2.1 No User-Defined Low Outlier

A good starting point for this analysis is to input regional skew, utilize the "weighted skew" option, and allow the software to determine low outlier values by its own Grubbs-Beck testing alone. Outliers are data points that depart significantly from the trend of the remaining data. Retaining or deleting these outliers can substantially affect the statistical parameters computed from data sets, especially for small sample sizes. The treatment of low outliers can significantly impact skew estimates, which tend to drive flood quantile estimation in California. As stated in USGS Bulletin 17B, "all procedures for treating outliers ultimately require judgment involving both mathematical and hydrological consideration."

For Bulletin 17B, this results in an estimated 1% chance exceedance discharge of approximately 8,690 cfs, with a single identified outlier. For Bulletin 17C, this results in an estimated 1% chance exceedance discharge of 8,360 cfs with 42 identified outliers. Results are summarized by Table 6-2 and shown graphically in Figure 6-1.

Table 6-2: Summary of San Francisquito Creek Gage Statistical Analysis using HEC-SSP with Peaks through WY 2023

Parameter	Bulletin 17B	Bulletin 17C
Number of Outliers	1	41
Outlier Threshold	41.6 cfs	1,560 cfs
Station Skew	-1.037	-1.183
Weighted Skew	-0.808	-0.642
1% Chance (100-year) Peak Discharge	8,690 cfs	8,200 cfs



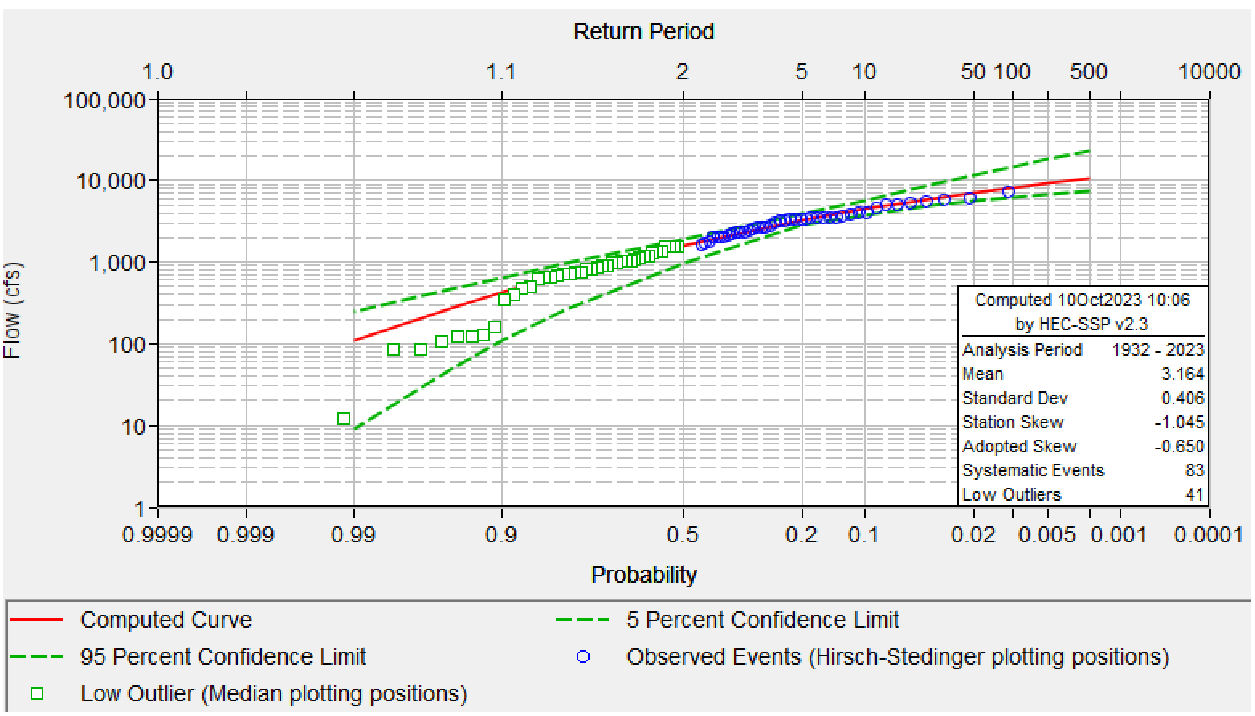


Figure 6-1: Bulletin 17B and 17C Results for San Francisquito Creek with Default Outlier Testing

6.2.2 *Modified Low Outlier Testing*

An appropriate low outlier threshold should be defined when applying either the Bulletin 17B or Bulletin 17C method. The USGS analysis of the gage with data through Water Year 2006 determined a low outlier threshold of 620 cfs. It is clear from Figure 6-1 that default Bulletin 17B methods defined a much lower value threshold for statistical outliers, while 17C methods identified a much higher threshold value.

Bulletin 17B confidence intervals do not capture the variability in flow on the low end of the annual peak range. This is where low outlier thresholds should be carefully considered. Various data sets have been examined to identify the drivers for such low peak flows recorded by the San Francisquito Creek streamflow gage. The Henry Coe Park precipitation gage near Morgan Hill has a robust record of precipitation in the general area for 1979 – 2021 and is used as a surrogate for the general amount of rainfall in any water year. Total annual precipitation values prior to 1979 have been estimated based on state-wide data to approximate local precipitation corresponding to the full San Francisquito Creek gage record. Unsurprisingly, the lowest peak discharge values correspond with lower-than-average annual precipitation, as shown in Figure 6-2. (Mean annual precipitation at Henry Coe is 27.5 inches.)

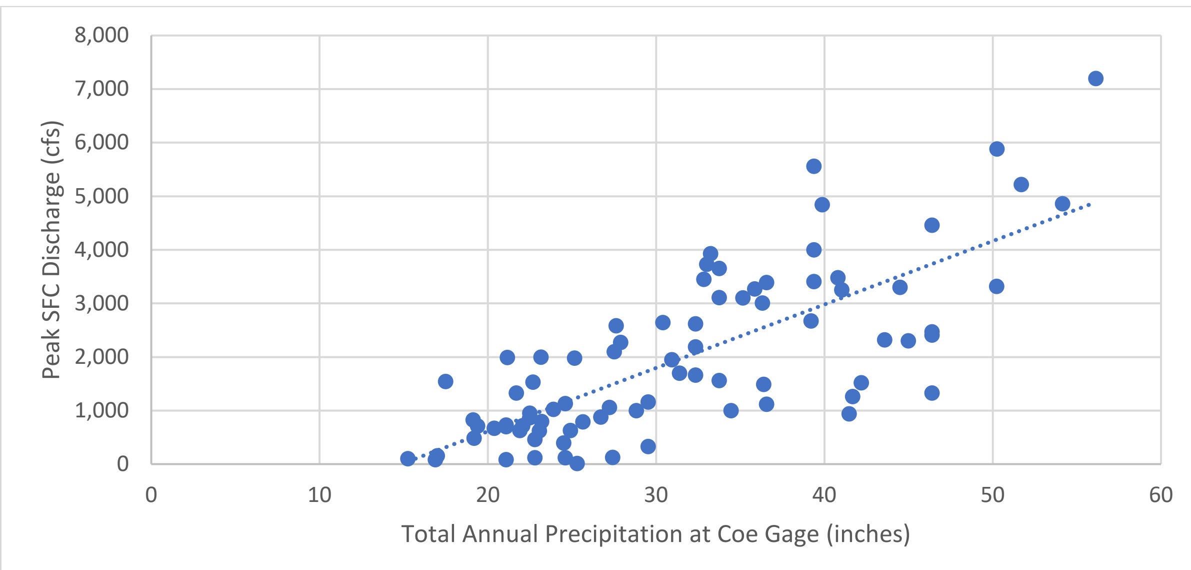


Figure 6-2: Peak Annual Discharge for San Francisquito Creek Compared to Total Annual Precipitation at Henry Coe Park near Morgan Hill

This on its own is not sufficient to consider climate patterns over a longer time scale. The US drought monitor provides monthly indices for a long historical period. The indices consist of the areal percentage of Santa Clara County experiencing various severities of drought conditions. These have been acquired, aggregated by simple weighting on a monthly interval, and averaged for each year in the San Francisquito Creek record to evaluate drought's impact on peak discharge in San Francisquito Creek, and presented as Figure 6-3.

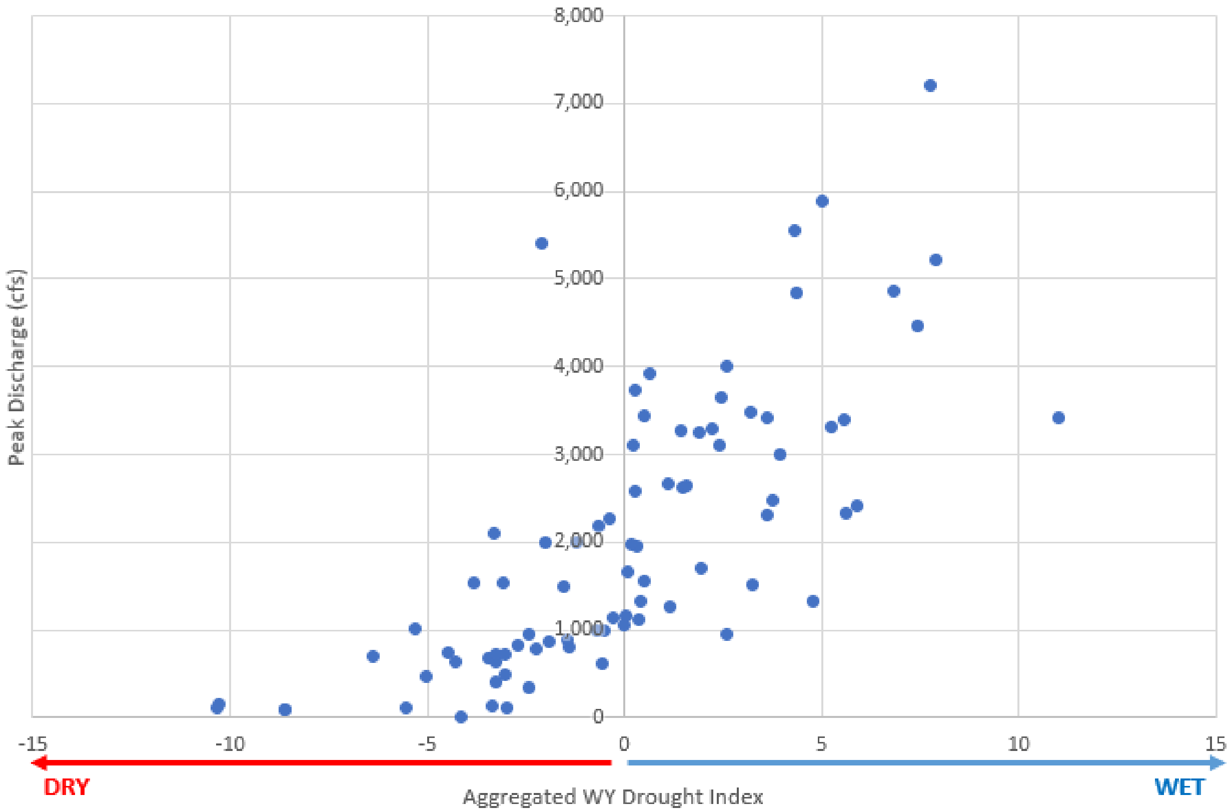


Figure 6-3: Peak Annual Discharge for San Francisquito Creek Compared to Aggregated Water Year Drought Indices for Santa Clara County

It becomes clear from these data that drought conditions have a major influence on annual peak flows in San Francisquito Creek. The lowest recorded peak flow rates correlate with periods of severe drought in the area.

Calibrated hydrology models applying the Soil Conservation Service (SCS) Curve Number methodology have historically shown that antecedent moisture conditions (AMC) in the San Francisquito Creek watershed, representing soil moisture within the basin preceding a storm, are roughly 1.75 to 2.0 (on a scale of 1 to 3) depending on storm duration. In years with little rainfall during drought periods, it is conceivable that the AMC would move well towards 1, representing dry conditions preceding a rainfall event. The reason this is important is that dry soil coupled with little rainfall results in little runoff to the creek where streamflow is measured.

It is important to understand that even in a severe drought year, the AMC before an event producing an annual peak discharge can be close to average. This all depends on how and when precipitation occurs in any given year and how the watershed soils wet and dry between events. A drought year where most of the annual precipitation occurs in a relatively short period of time, for example, can lead to an average or above average AMC condition prior to a single precipitation event producing peak discharge. On the other hand, a drought year with precipitation events that are significantly spread out through the wet season is more likely to produce a smaller peak discharge.

Confirming this would require an in-depth evaluation of precipitation records and antecedent moisture conditions for the storms that caused each annual peak discharge. For the purposes of this statistical exercise, however, that level of analysis is unnecessary, given the strong correlation between drought indices, precipitation depths, and peak annual discharge.

Ultimately, the below-average rainfall and streamflow conditions can heavily influence the statistical methods applied by Bulletin 17B and 17C. Low flows increase negative station skew, which while weighted using a regional skew, can cause over-estimation upper flood quantiles at the less frequent return periods, which tend to be the most important return periods for the planning and design of flood control and stormwater handling facilities.

It is likely appropriate, therefore, to consider these low values as statistical outliers.

6.2.2.1 *Low Outlier Sensitivity*

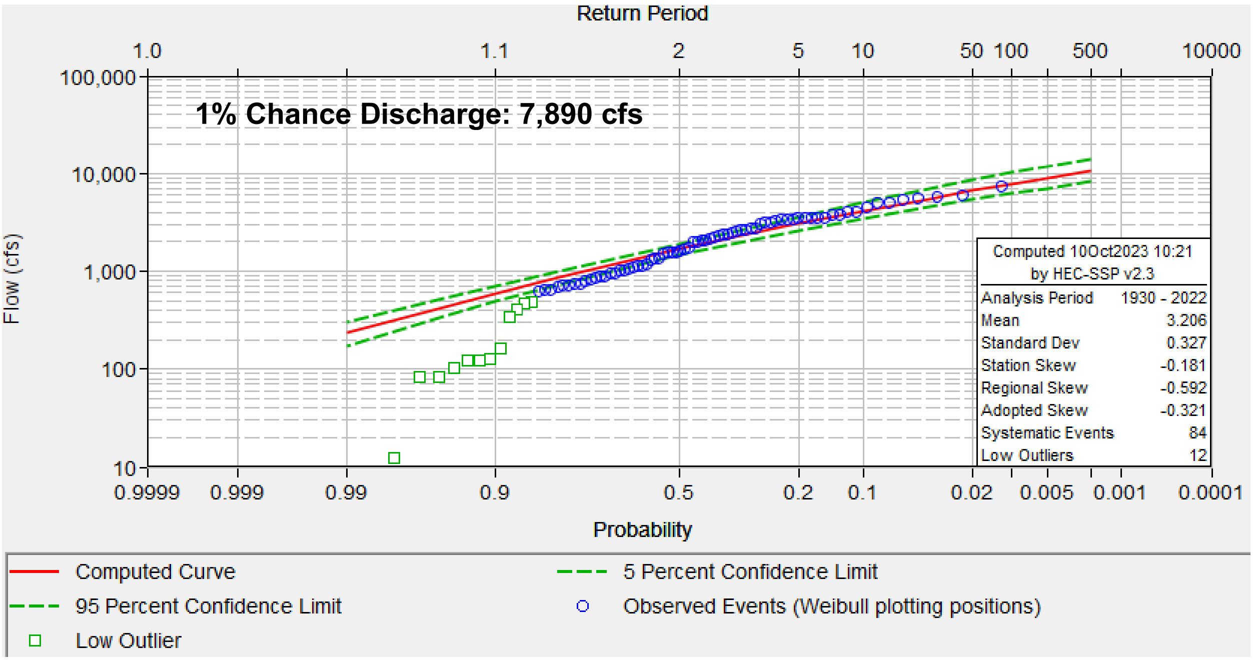
Starting with the Bulletin 17B methodology, the low outlier threshold is manually entered iteratively until the values used to generate the expected value curve do not fall significantly outside of the calculated confidence intervals. The results of the modified 17B analysis are shown in Figure 6-4. The same thresholds are then applied using Bulletin 17C methodology in Figure 6-5.

Bulletin 17C methodology is more sensitive to low outlier threshold adjustment than is using Bulletin 17B. A good choice for an initial low outlier threshold is 200 cfs, as those years stand out based on plotting position alone. However, that threshold produces an extreme result for the 100-year discharge, making it clear that there are still what the USGS refers to as "influential low floods" in the record. The second adjustment to 500 cfs removes those influential low flood events and produces a 100-year expected value close to the initial Bulletin 17C result presented in Figure 6-4.

6.2.2.2 *Selecting a Bulletin 17 Method and Low Outlier Threshold Adoption*

Use of Bulletin 17C for this gage may not be entirely appropriate, as low peaks appear to carry more influence than desired in shaping the confidence intervals and statistical fit. In contrast, we consider Bulletin 17B to be the most appropriate methodology to apply to data recorded at the San Francisquito Creek gage, as the methodology maintains a reasonable low outlier threshold and does not give excessive weight to low flow values when estimating confidence intervals. Based on an examination of climate record, extraordinarily dry conditions, and high abstraction of rainfall into soils is the most important factor in years where low outlier peak discharge has occurred. We prefer that these events not have significant weight in the flood frequency analysis, since they do not represent more average conditions in the basin during an annual peak runoff event.

The Bulletin 17B low outlier test is used to benchmark an appropriate adopted threshold. Based on the sensitivity analysis, this process begins with the removal of peak discharge values below 200 cfs. Then, additional years of record are removed until the low outlier test applied to the remaining values showed that they should not be removed from the record. With values below 200 cfs removed, the calculated 17B low outlier threshold is 205 cfs, indicating that it is appropriate to consider those values to be low outliers. With the next highest annual peak flow value (332 cfs) removed, the calculated low outlier threshold is 224 cfs, indicating that the 332 cfs peak value should remain in the record and included in the frequency analysis.



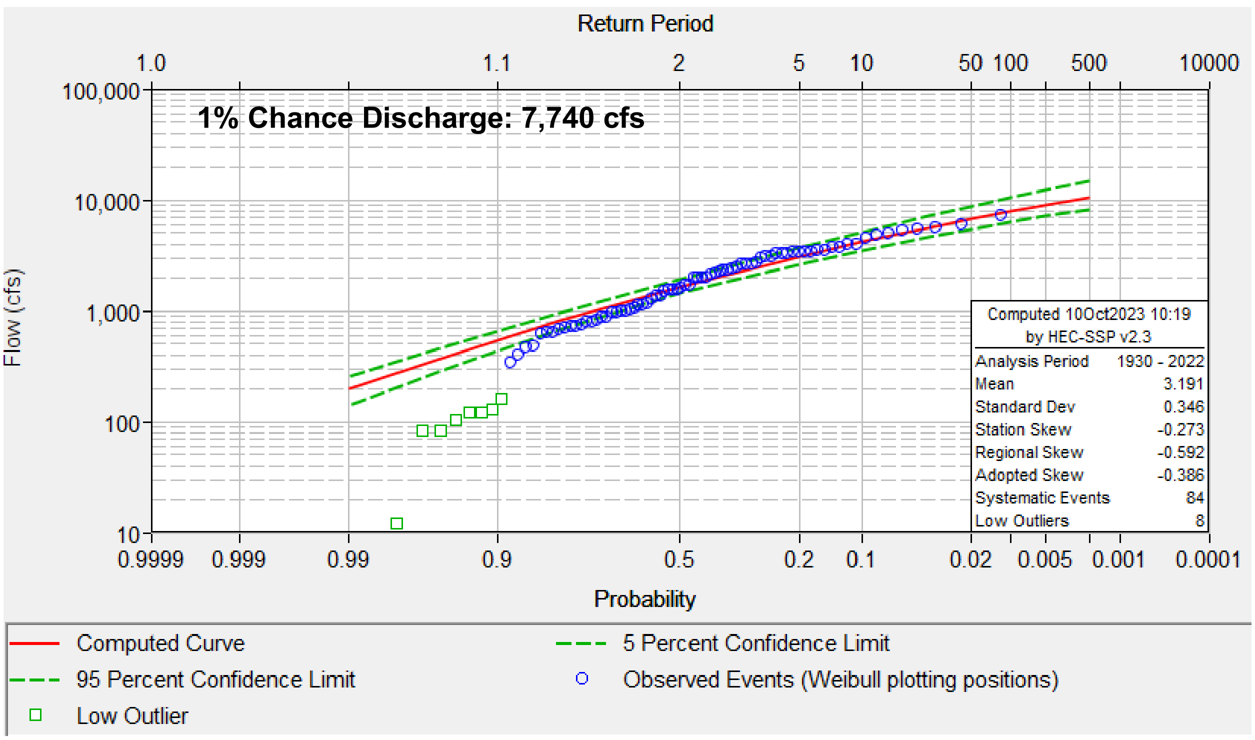
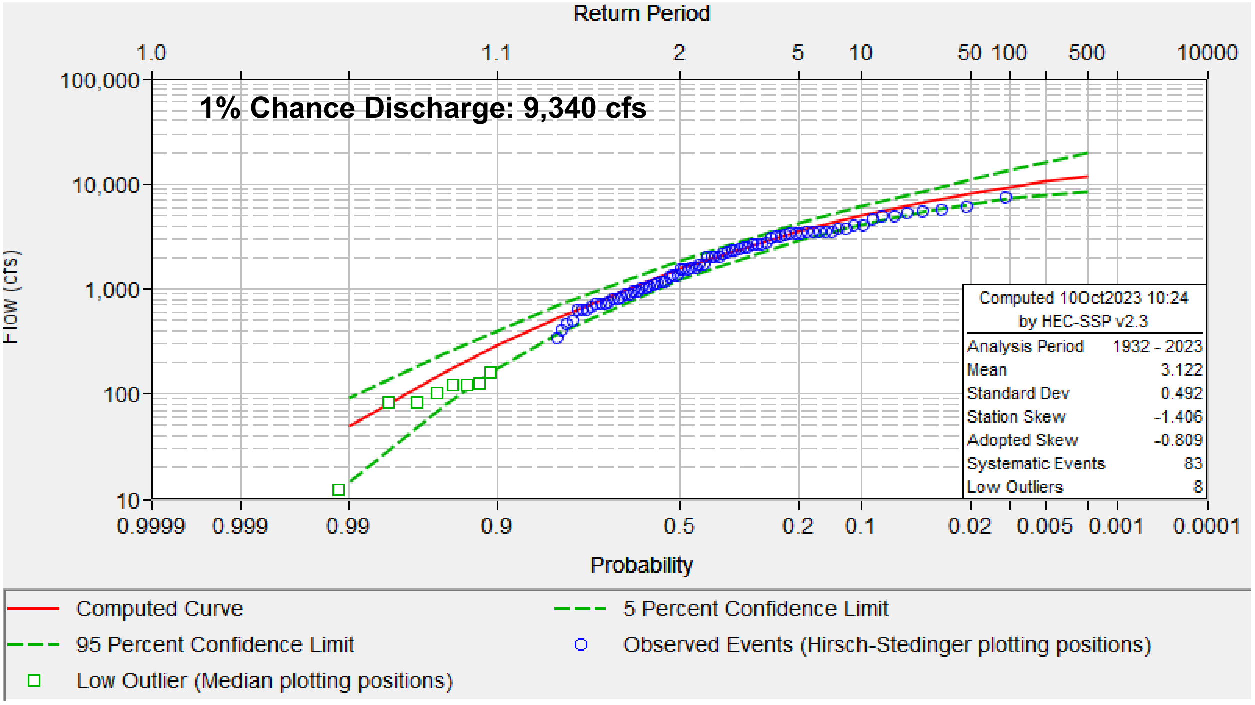


Figure 6-4: Bulletin 17B Analyses with a 200 cfs Low Outlier Threshold (top) and a 500 cfs Low Outlier Threshold (bottom)



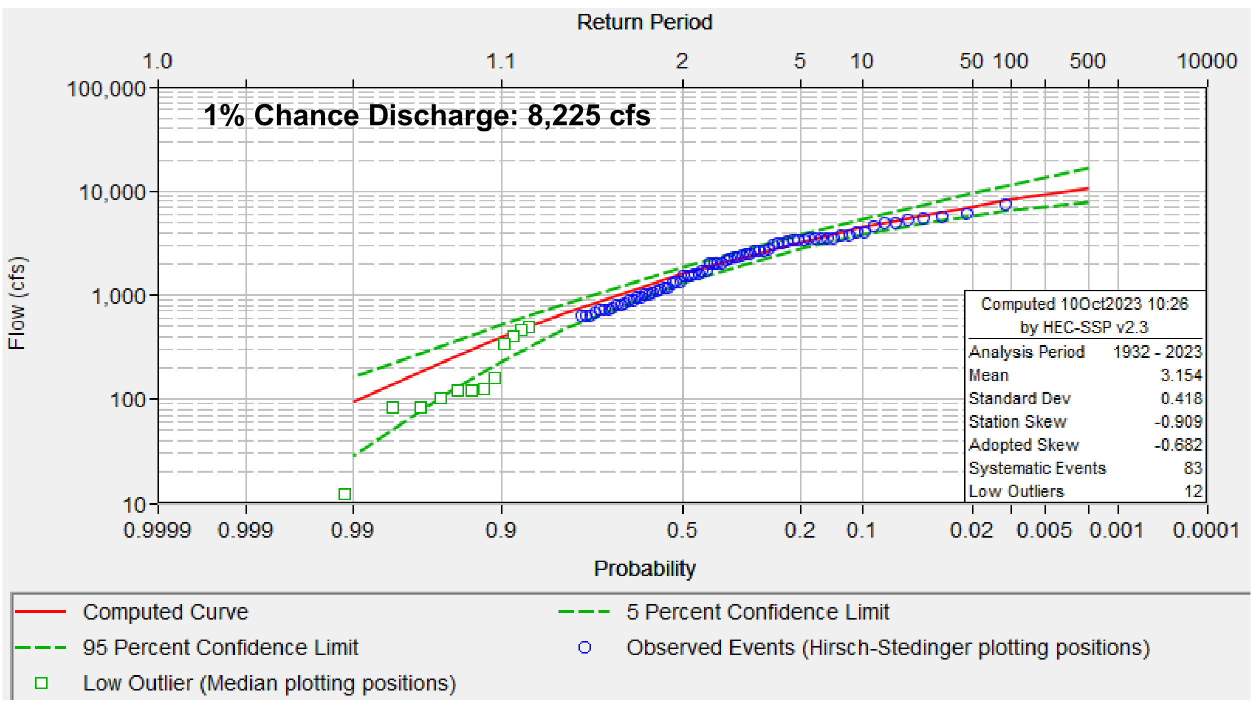


Figure 6-5: Bulletin 17C Analyses with a 200 cfs Low Outlier Threshold (top) and a 500 cfs Low Outlier Threshold (bottom)

6.3 Impact of Additional Record on Flood Frequency Estimates

USGS publications only use data through Water Year 2006 to estimate a 1% chance (100-year) peak discharge for the San Francisquito Creek gage. Their analysis estimated a 1% chance peak discharge of 7,690 cfs. With 200 cfs appropriately set as the low outlier threshold as previously described and an additional 17 years of record through Water Year 2023, the revised 1% chance peak annual discharge for San Francisquito Creek at Stanford is approximately 7,890 cfs. This represents a 2.6% increase over the prior USGS estimate.

As the second highest recorded peak annual streamflow for San Francisquito Creek, a natural question might whether that event on its own has a significant impact on flood frequency curves. Analysis presented up to this point includes Water Year 2023 in the record.

A Bulletin 17B analysis of data through Water Year 2022 (not including the NYE 2022 event peak) with the same 200 cfs low outlier threshold results in a 1% annual chance peak discharge of 7,600 cfs. This remains very similar to the USGS estimate, even with 16 years of additional data past 2006.

The inclusion of a single event between a 25- and 50-year magnitude in the updated record increases the 1% peak discharge estimate at the gage location by nearly 300 cfs, or by about 4%.

6.4 Revised Flood-Frequency Analysis

With the adoption of an acceptable statistical method (provided by Bulletin 17B) and the determination of a reasonable low outlier threshold of 200 cfs supported by hydrological evidence, revised peak statistics based on weighted skew as recommended by the USGS have been calculated. A summary of the accepted statistical analysis results is provided in Table 6-3, compared with prior gage analysis by the USGS in 2010.

Table 6-3: Summary of Revised San Francisquito Creek Gage Statistical Analysis

Parameter	USGS 2010 Analysis	Revised Analysis
Station Skew	-0.483	-0.181
Station Mean Square Error	0.153	0.077
Regional Skew	-0.592	-0.592
Regional Mean Square Error	0.140	0.140
Weighted Skew	-0.808	-0.321
1% Chance (100-year) Peak Discharge	7,690 cfs	7,890 cfs
2% Chance (50-year) Peak Discharge	6,660 cfs	6,735 cfs
4% Chance (25-year) Peak Discharge	5,610 cfs	5,605 cfs
10% Chance (10-year) Peak Discharge	4,200 cfs	4,150 cfs

Using this flood frequency analysis, the highest peak discharge on record of 7,200 cfs (WY98) is a 70-year event; the second highest peak discharge on record of 5,880 cfs (WY23) is a 30-year event; and the third highest peak discharge on record of 5,560 (WY56) is a 25-year event.

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