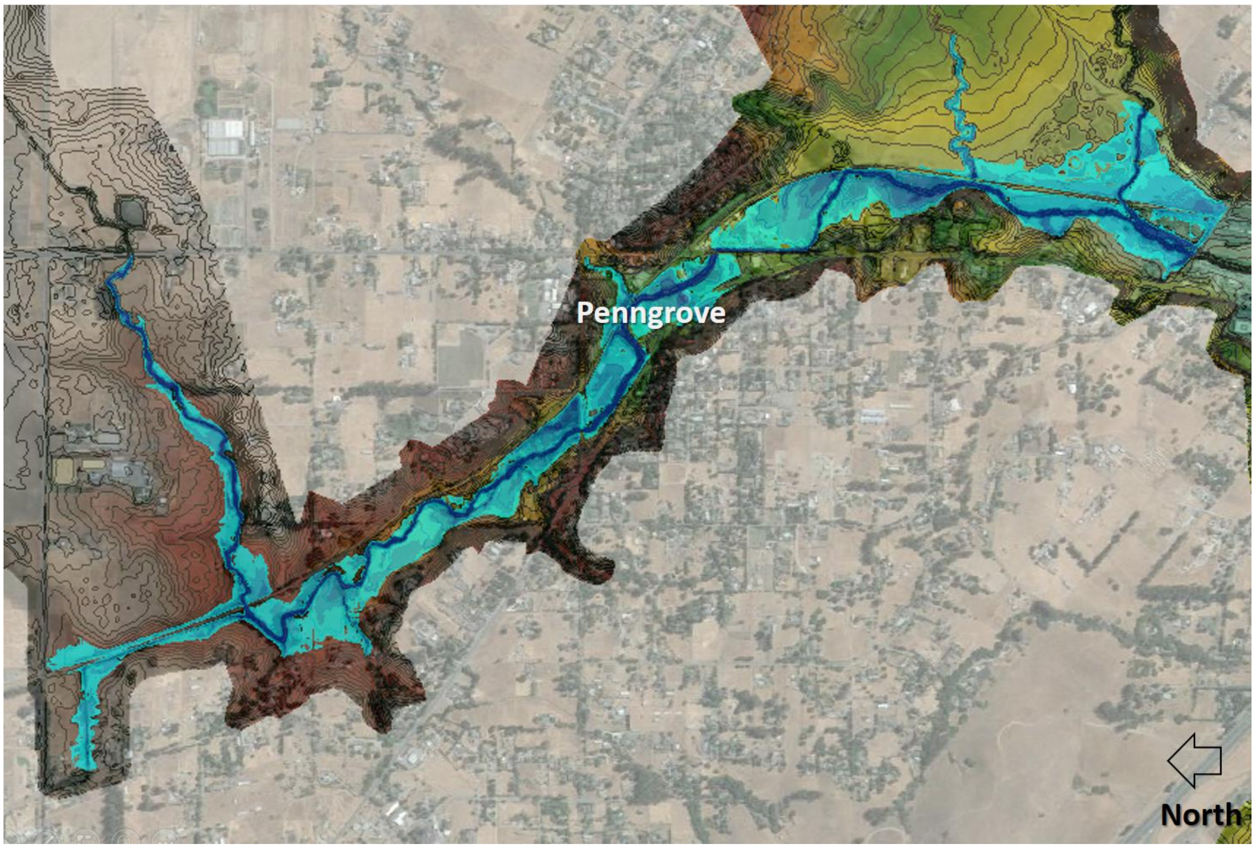
Lichau Creek Near Penngrove
Flood Mitigation Feasibility Report



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<u>Attachments</u>

1 Introduction

Sonoma Water, as part of their *Stormwater Management-Groundwater Recharge Program* in the Upper Petaluma River Watershed, is working towards developing projects to reduce flooding in downstream communities in the Petaluma River watershed. In support of this effort, Sonoma Water contracted with Prunuske Chatham, Inc. (PCI) to evaluate the feasibility and effectiveness of stream modification and storage projects within a 3-mile reach of Lichau Creek to reduce flooding in the town of Penngrove, CA (Figure 1). Portions of Penngrove currently experience some level of flooding on nearly an annual basis, with several residential and business areas that suffer damage during large flood events.

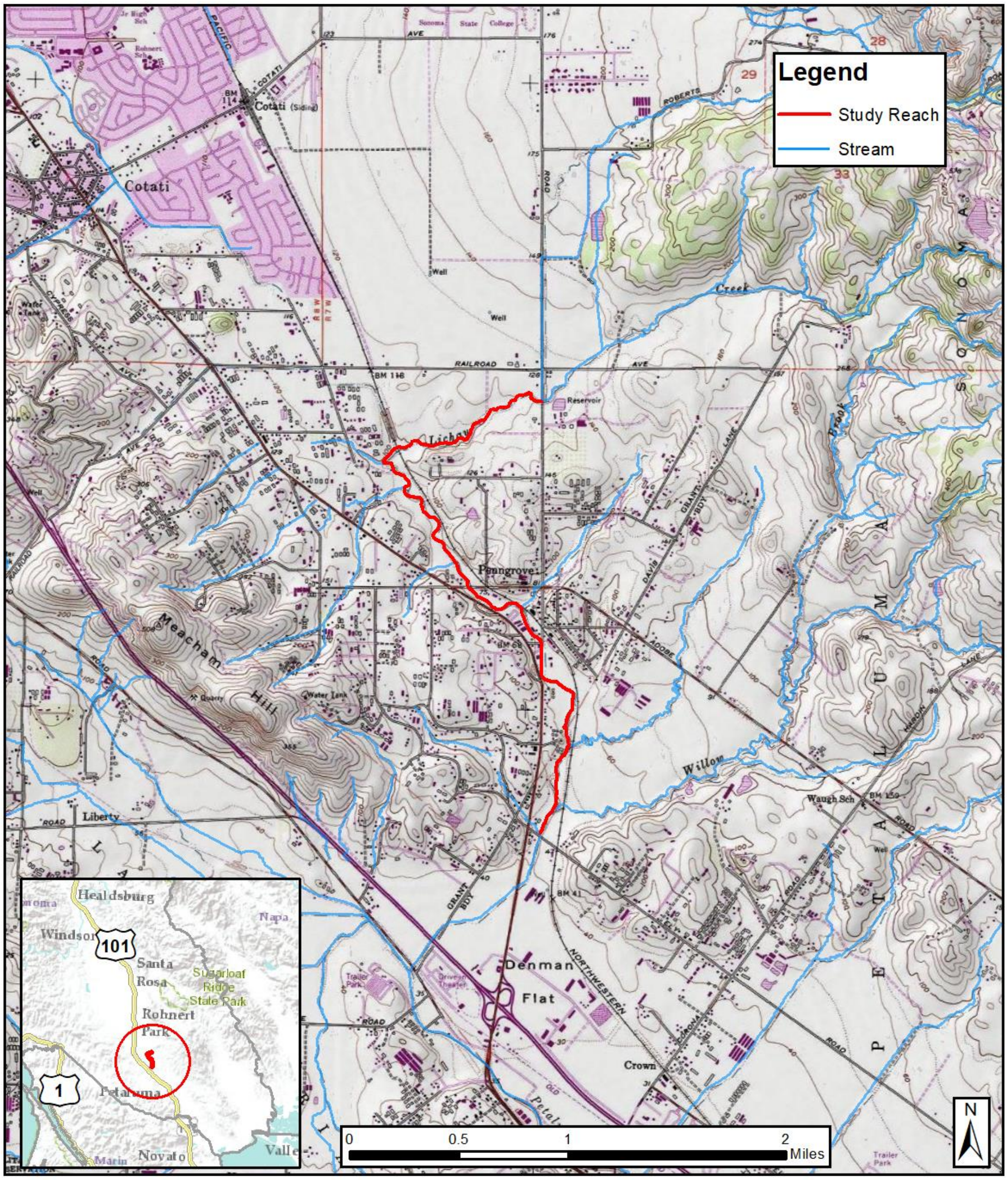


Figure 1. Site map of Lichau Creek project reach.

The goal of this feasibility study is to develop a thorough understanding of flooding in the Penngrove reach of Lichau Creek and to determine if there are potentially viable projects within the reach that could reduce the frequency and extent of flooding that impacts the community. Using detailed hydraulic models, the effectiveness of alternative approaches to reduce the magnitude and duration of the design flood was assessed. Additional objectives include increasing groundwater recharge and maintaining or improving instream habitat for wildlife.

2 Study approach

To determine the feasibility and design parameters of potential in-channel and floodplain modifications, site conditions, floodwater volumes and pathways, and topographic opportunities were studied. PCI worked with Sonoma Water, other consultants, members of the Zone 2A Advisory Committee, and the community to compile the required data and information. PCI prepared an existing conditions hydraulic model to represent flooding patterns and locations along Lichau Creek within the project reach. Utilizing the results from this model and the reach-site specific opportunities and constraints, several concept-level flood mitigation alternatives were developed. We evaluated their individual and collective effectiveness at reducing peak flow volumes and flood elevations in Penngrove. The effectiveness of the proposed flood mitigation approaches was analyzed by comparing existing and design condition flow hydrographs, flood extent and depth maps, and water surface profiles. This section documents data used in the analyses and the assumptions and data used to create the hydraulic models.

2.1 Site evaluation and data collection

Developing an accurate and detailed terrain map of the project area was critical for the modeling and site design. A base map of the site was prepared using the 2012 LiDAR data for Sonoma County (Sonoma County Vegetation Mapping and Lidar Program, 2020) and aerial photographs. Visual review of the LiDAR DEM map coupled with our initial site reconnaissance indicated the need for additional survey to more accurately define channel geometry and infrastructure within the floodway. Sonoma Water staff secured access for surveying on a limited number of properties within the project reach. Information collected at these accessible sites was used to make reasonable assumptions about channel geometry and conditions in other non-accessible areas.

The LiDAR data was ground-truthed by PCI using a Total Station and RTK GPS and found to generally be in good agreement with the surveyed points in areas without dense vegetation. In these areas, the discrepancy between surveyed points and LiDAR is generally within 0.1-0.3-feet. In riparian areas or overbank areas with dense vegetation, the LiDAR is unable to penetrate the vegetative canopy and ground point density is limited (see Appendix A for further description of LiDAR accuracy and point density). In areas with poor point density and where access was granted, PCI conducted field surveys to capture more terrain definition. To field check and refine the terrain in larger, rural stretches of the creek, PCI walked the channel and made measurements of toe-to-toe and top-of-bank widths (Figure 2). Riffle crests and other critical channel elevation points were measured with an RTK GPS or estimated by surveying a point in an adjacent open area, then transferring the elevation to the channel bed using a site level. These site walks were also used to document areas with increased hydraulic roughness, or where additional topographical surveys were needed to capture critical infrastructure. These site walks led to additional surveys using a Total Station and RTK GPS at the Adobe Rd Bridge, the Petaluma Hill Rd Bridge, and a flood wall surrounding the Penngrove Village Mobile Home Park.

Figure 2. Photos of surveyed riffle crest (top left), log jam causing elevated hydraulic roughness (top right).

PCI utilized hydrologic and hydraulic data and study results from several flood studies within the watershed. An objective was to tie the studies together and reduce effort needed to complete this feasibility study. The outside studies and data used by PCI include:

- **Baseline Model Build Technical Memorandum, Upper Petaluma River Watershed Flood Control Project** (Balance Hydrologics, 2018): An extensive hydrologic and hydraulic study of the entire Upper Petaluma River Watershed was recently completed by Woodard & Curran and Balance Hydrologics. This study conducted extensive hydrologic and hydraulic modelling for the upper Petaluma River Watershed and utilized HEC-HMS to determine peak flow hydrology for all watersheds tributary to the Petaluma River. The Balance Model coupled these hydrology inputs with a separate HEC-RAS2D hydraulic model of the tributaries and the Petaluma River. These two models were calibrated together to produce hydraulic results that aligned with measured flow data during measured storm events and the City of Petaluma's stormwater model. Balance Hydrologics provided PCI with design-flow hydrographs for Lichau Creek and tributaries within our project area.
- **Sonoma County Flood Insurance Study** (FEMA, 2008): A recently updated analysis of 10-year and 100-year flood peak discharges and water surface elevations at key locations throughout the Petaluma River watershed. One of FEMA's cross-sectional analysis sites is within the project area near the Penngrove Fire Station. This location is also the site of a streamflow gauge. Peak flow rates and water surface elevations from this study were used as the target values to calibrate the existing conditions hydraulic model.

In addition to the hydrology data described above, PCI measured flows within the project reach during a large storm event on December 15, 2016. Minor flooding was occurring in Penngrove at the time, and we estimate that this event was between a 2- and 5-yr return interval annual peak flow. Discharge, velocity, flow depth, and overbank flood extent data collected during this event was used to calibrate and validate the existing conditions model (See Appendix A).

The FEMA Flood Insurance Study estimates the 10-year, 50-year, and 100-year return intervals. When other typical return interval flows are referred to, the USGS web application StreamStats estimates are used. The FEMA return interval flow estimates are significantly higher than StreamStats' estimates.

Unless otherwise specified in the remained of this document, the FEMA estimated return intervals will be used.

2.2 Hydraulics and Hydrology

Hydraulic models of the project site were developed using HEC-RAS version 5.07, a 2-D unsteady flow modeling software platform developed by the USACE. The project's hydraulic model extends from the upstream crossing of Petaluma Hill Road down through Penngrove to the Ely Road Bridge (*Figure 3*) and includes the alluvial valley areas. See **Appendix A** for the detailed description of the hydraulic model development and existing conditions project-area flood extent maps.

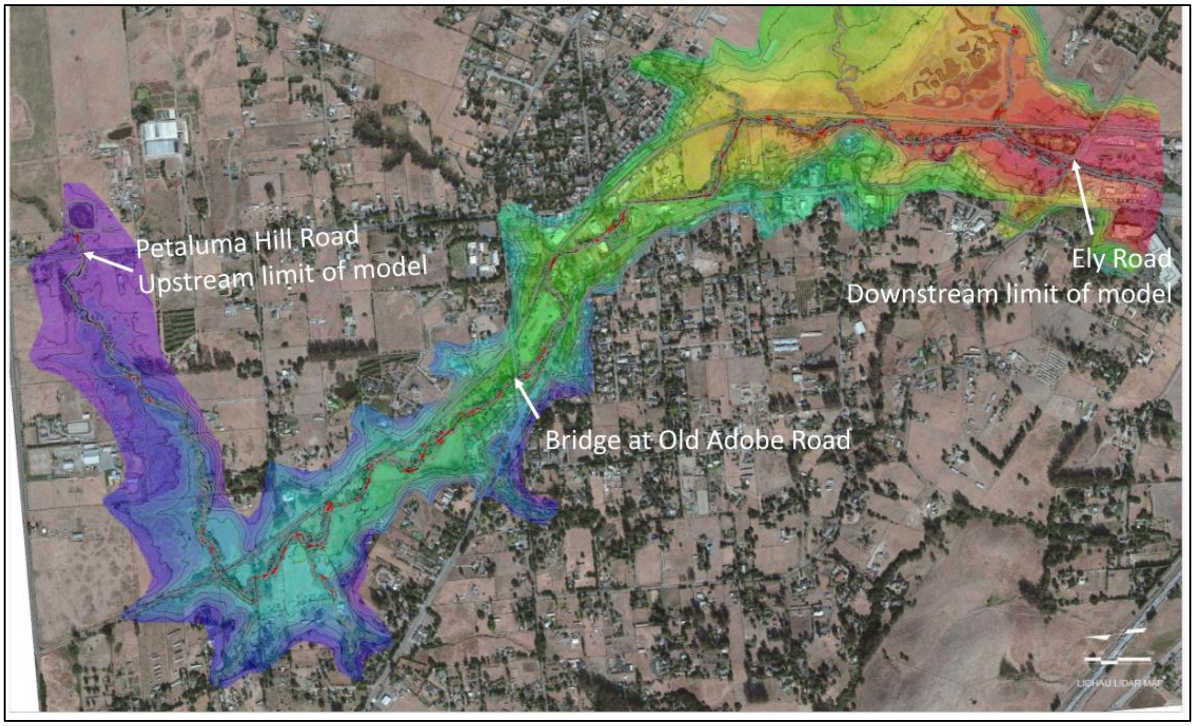


Figure 3. Project model extents shown by LiDAR terrain with elevation banding.

At the outset, this study had an objective to evaluate and develop potential projects to reduce impacts of the 100-year flood event. However, after initial model runs indicated that predicted flow volumes and flood depths within the town of Penngrove during the 100-yr storm are so great that the available flood mitigation alternatives don't provide meaningful benefits, the project objectives were recalibrated to evaluating the 10-yr storm event. A flood extent and depth map of a modeled 100-year flood event is provided in Appendix A for reference and comparison to the 10-year flood event.

Storm event hydrographs used in the hydraulic modelling effort were initially provided by Balance Hydrologics, and were extracted from their model of the Upper Petaluma River Watershed (Balance Hydrologics, 2018), as described previously and referenced hereinafter as the Balance Model. PCI obtained 13 separate flow hydrographs representing flows from each of the tributaries within the project study area (*Figure 4*). Hydrographs were provided for both the 10-year and 100-year return interval storms.

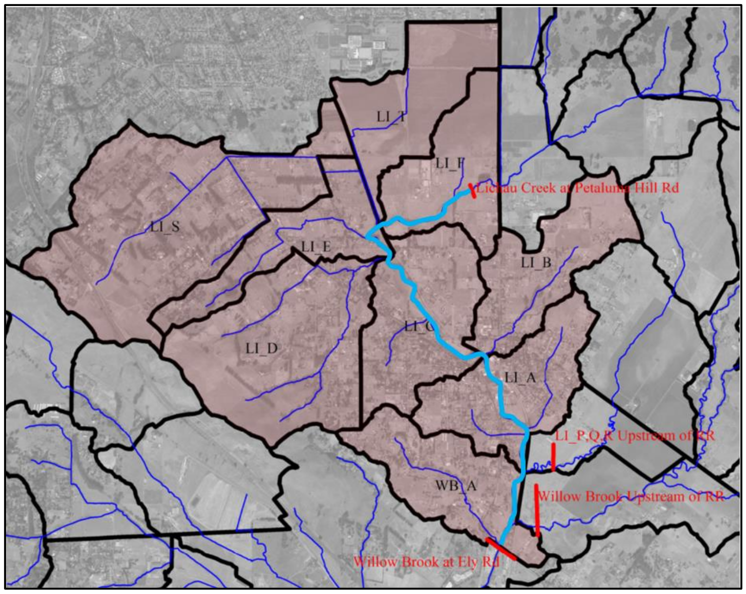


Figure 4.. Illustration of the tributary watersheds (light-red shaded areas) that PCI received storm hydrographs from the Balance Model, with several stream confluences/boundaries (red lines) where input flow hydrographs were provided from the Balance Model.

At the beginning of the modeling effort for this study, PCI used the exact hydrographs used in the Balance Model to depict the 10-year storm event and input them into our existing conditions model. However, PCI's hydraulic model utilizes different channel refinements (geometry) and hydraulic roughness (Manning's n) values than the Balance Model. As a result, PCI's predicted Water Surface Elevations (WSELs) did not align with WSEL results from the Balance Model and appeared significantly higher than stream gage or anecdotal accounts suggested. Given that our objective was to model the 10-year flood event as accurately as possible, PCI evaluated the options available to address this WSEL discrepancy. We decided to switch to using the FEMA 10-year peak flow in Penngrove (FEMA, 2008) instead of the Balance Model's 10-year peak flow. To make this switch, PCI iteratively scaled the individual tributary hydrographs down, while maintaining their shape, so that the resulting modeled peak flow through the town of Penngrove aligns with the FEMA-estimated flood peak (*Figure 5*). By scaling down the hydrographs to correspond to the FEMA 10-year peak, our modeled WSELs fell into alignment with gage data, FEMA's estimated 10-year WSEL, anecdotal accounts, and the Balance Model's 10-year WSEL.

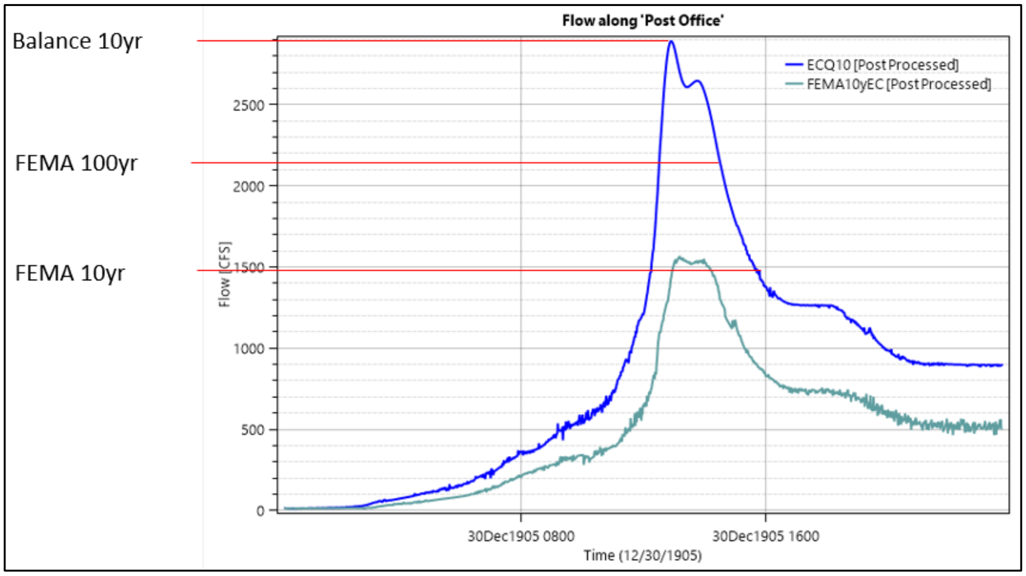


Figure 5. PCI's original Balance Model-based 10-year storm hydrograph at Penngrove (blue line) versus the scaled down hydrograph (teal line) designed to closely fit the FEMA-predicted 10-year storm peak in Penngrove.

In addition to researching and ultimately using the FEMA 10-year peak flow discharge for the study, PCI estimated additional peak flow rates at Penngrove using a range of standard methods (*Table 1*). This allowed us to evaluate the approximate frequency of initial breakout flows and the effectiveness of the flood mitigation alternatives.

Table 1.Comparison of peak flows through Penngrove estimated using different standard methods.

Hydrologic Method	Qbkf	Q2	Q5	Q10	Q25	Q50	Q100
Basin Transfer Method from Nearby Gage (Sonoma Ck @ Aqua Caliente)*1:	458	619	1015	1255	1525	1699	1856
Sonoma County Flood Insurance Study*2:	**-**	-	-	1480	-	1970	2160
StreamStats (USGS):	**-**	372	755	1040	1410	1700	2010
*1: Scaled by watershed area and mean annual precipitation							
*2: For Lichau Creek upstream of confluence of Penngrove Creek							

3 Existing Site Conditions

As shown above in *Figure 1* and *Figure 3*, the overall project extent for this study runs from Lichau Creek's upstream crossing with Petaluma Hill Road downstream through the town of Penngrove to the Ely Road bridge. Portions of Lichau Creek within the study area were walked to field check LiDAR accuracy and to estimate hydraulic roughness. In sections of the creek that PCI did not have access to, aerial photos and observations from the nearest road right-of-way were used to infer channel conditions. The study area can be broken out into four different reaches, each bounded by bridges[1] and each exhibiting slightly different channel and floodplain conditions that define flood impacts, as well as the opportunities and constraints for flood mitigation projects.

[1] Descriptions of the bridges within the project area (in order from upstream to downstream): 1) the SMART Train crossing is a full spanning bridge supported by 24" diameter wooden pillars in the center of the channel, 2) the Old Adobe Road stream crossing at the downstream end of the middle reach is a full spanning concrete bridge with concrete abutments, 3) the Petaluma Hill Road crossing is a concrete bridge with two center piers/walls for mid-span support, and 4) the Ely Road crossing has a concrete deck and abutments, with a single row of encased concrete piers near the toe of the right bank.

In the upper project reach, from the upstream Petaluma Hill Road crossing downstream to the SMART train railroad crossing, Lichau Creek runs through large agricultural properties that appear to be primarily cattle ranches (*Figure 6*). No access was secured for properties in the upper reach. The channel appears to be relatively wide, and along most of this reach the banks have little riparian vegetation. Because of the lack of dense trees or shrubs the LiDAR data has good definition within the active channel and on the floodplain. The wide floodplain has no infrastructure and is used primarily for grazing. It offers opportunities to do large scale detention projects.

Figure 6. Aerial imagery of upper project reach from the upstream Petaluma Hill Road crossing to the SMART Train railroad crossing.

Downstream of the SMART Train crossing and upstream of Old Adobe Road the channel begins to narrow and develop a mature riparian corridor (*Figure 7*). This middle project reach can be characterized as moderately incised. Small inset floodplain benches are present in several locations along the channel and full spanning debris jams are relatively frequent. The channel bed composition is mainly fine gravel to medium cobble. There is a dense riparian buffer with mature trees along nearly the entire reach. The overbanks are mostly pastureland and hayfields. There is no significant infrastructure on the floodplain (*Figure 8*), and thus there may be opportunities for floodplain detention. However, the parcels are smaller in this reach than in the upper reach, and detention basins would likely require the participation of multiple landowners. The channel and floodplain are constrained to the northeast by the SMART rail tracks.

Figure 7. Aerial imagery of middle project reach from SMART Train railroad crossing to Old Adobe Road Bridge.

Figure 8. Photos showing typical channel geometry and conditions (left) and open pastureland in overbanks (right).

Within the town of Penngrove (Center Reach)—the reach between Old Adobe Road and the downstream crossing of Petaluma Hill Rd—the channel becomes increasingly confined. The floodplains have been developed upon; the town infrastructure is encroaching heavily on the channel throughout much of the reach (*Figure 9*). At the upper end of the reach is a parcel owned by V-Dolan Trucking, which has a large paved/gravel parking area along the left bank (looking downstream). According to V-Dolan staff, this parking area floods regularly. Along the right bank of Lichau Creek across from the parking lot is an open area that is also owned by V-Dolan. During one of the site walks, a representative of V-Dolan indicated to PCI that, as this area is not being utilized for their operations, they would likely be amenable to a flood reduction project located there.

Figure 9. Aerial imagery of Penngrove Center Reach from Old Adobe Road Bridge to Petaluma Hill Road Bridge.

In the middle of the Center Reach is the Penngrove Village Mobile Home Park (Mobile Home Park), which, according to community members, experiences minor flooding on a relatively frequent basis ("every couple of years"). To try to reduce flooding frequency and depths, a CMU block floodwall has been installed at the top-of-bank along much of the length of the Mobile Home Park (*Figure 10*). During one of the site visits, a resident of the Mobile Home Park indicated that another layer of CMU blocks was recently installed (in 2018) in response to a flood event that had overtopped the wall. Downstream of the Mobile Home Park, the channel is overgrown with dense riparian vegetation and access to the channel is very limited. Several large industrial properties and shopping areas are found between the Mobile Home Park and the second Petaluma Hill Road crossing. The left and middle span of this crossing is backwatered during low flow conditions from a riffle crest downstream. The right bay inside the crossing has visible sediment deposits. The upstream end of the crossing is densely overgrown with young willows and blackberries (*Figure 10*). Due to the density of development on the floodplain, there is limited space for large-scale flood mitigation projects in downtown Penngrove.

Figure 10. Photos from the Penngrove Center Reach: Penngrove Village Mobile Home Park with floodwall (top), channel during storm flows near V-Dolan yard (left) and Petaluma Hill Road bridge looking downstream (right).

Immediately downstream of the Petaluma Hill Road crossing, the channel is confined on the right by a long concrete retaining wall. The left bank floodplain is the Penngrove Community Park and a hay field (*Figure 11*). The channel in the section adjacent to the Park is maintained and the riparian vegetation is sparse (*Figure 12*). Further downstream, to the confluence with Willowbrook Creek and the Ely Road crossing, Lichau Creek is confined between the SMART Train tracks on the left bank and smaller residential properties on the right bank. The infrastructure on these residential properties appear to be set back from the floodplain and above the 10-year flood extents.

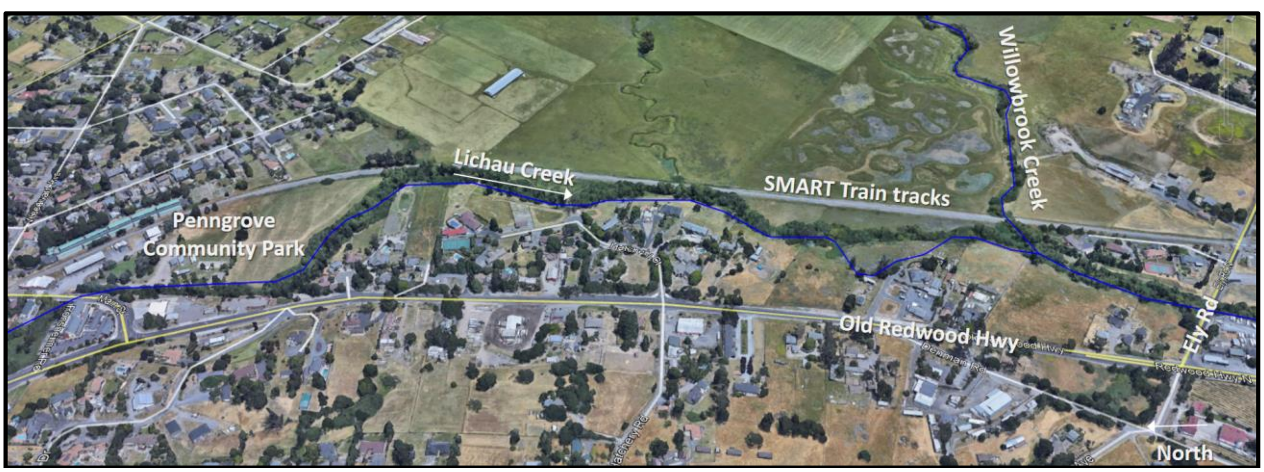
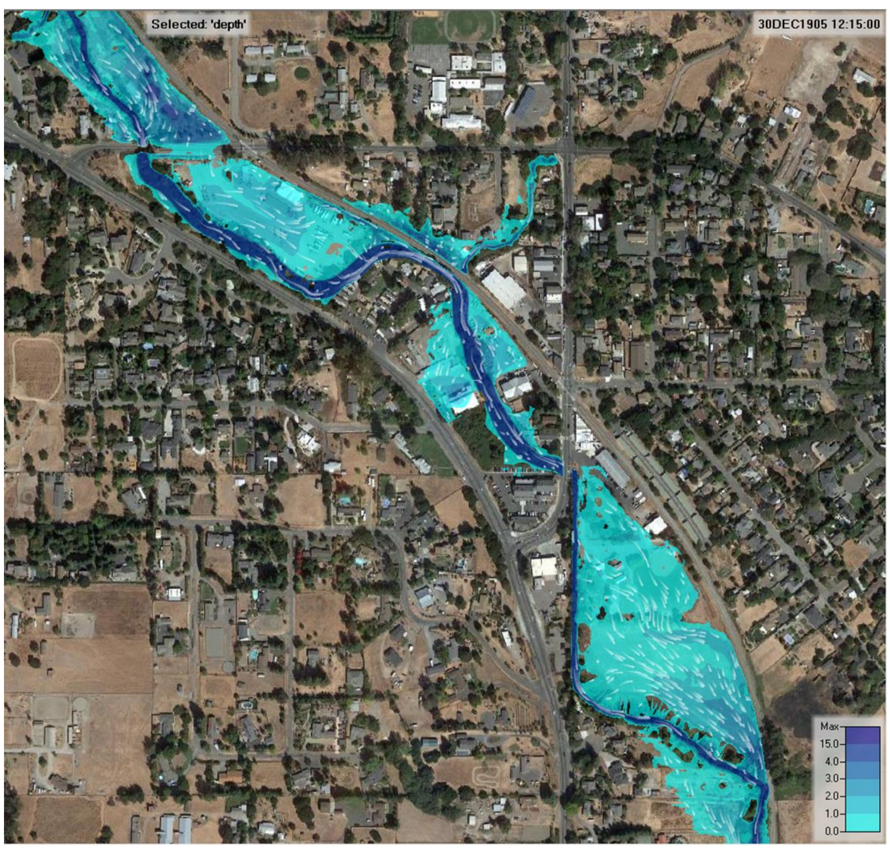


Figure 11. Aerial imagery of lower project reach from Penngrove Community Park to Ely Road.

Figure 12. Concrete retaining wall with 48" stormdrain outlet on opposite bank from the Penngrove Community Park (left) and typical channel near the downstream end of the baseball field in the park (right).

4 Penngrove existing conditions flooding

Within the town of Penngrove, flooding first begins along the bank adjacent to the V-Dolan yard, as well as the area between the mobile home park and the Post Office, and the Community Park just downstream of the Petaluma Hill Road Bridge (*Figure 13*). Based on the hydraulic model results, some nuisance flooding occurs at these locations with moderate storms that produce flows around 350 cfs (approximately a 1- to 2-year event) and progressively gets worse with larger flood events. At a 10-year return interval flood, most of the properties adjacent to the creek experience inundation, with depths ranging from six inches to four feet. See Appendix A for maps showing flood extents in the entire study area.



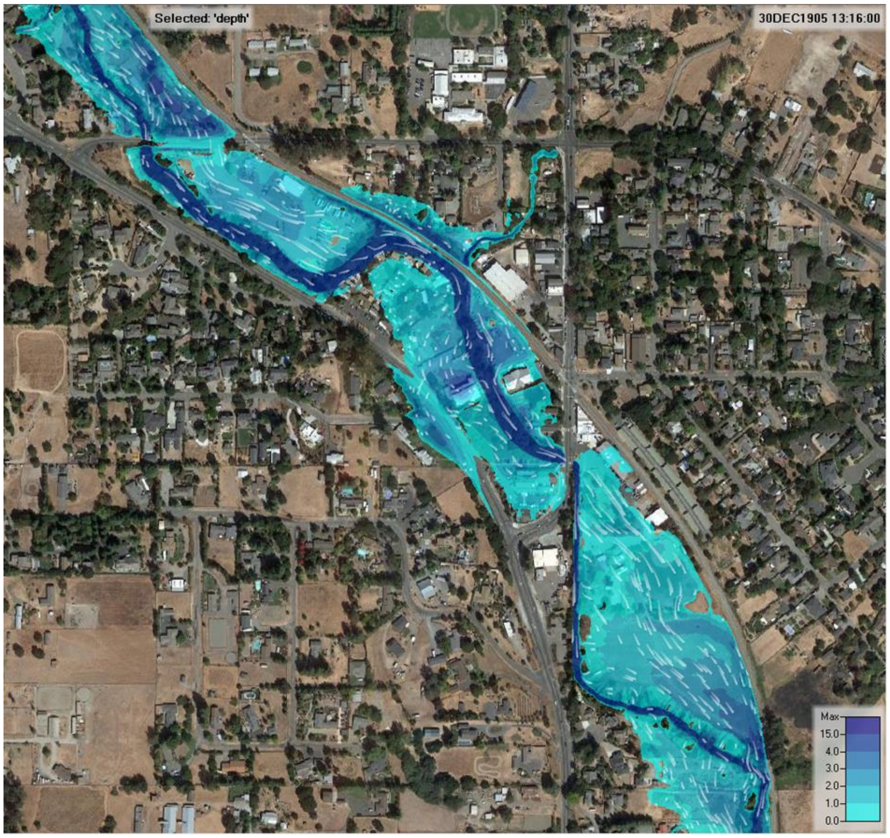


Figure 13. Flood locations, extents, and depths within Penngrove between the 5- and 10-year event (1050 cfs) (top) and during FEMA's predicted 10-year flood event (1,480cfs) (bottom).

Water begins to overtop Old Adobe Road at roughly 650 cfs (between a 2- and 5-year flood) and flow into and through the V-Dolan trucking yard. A small gravel levee has been built along the length of the yard, which provides some flood protection at lower, frequent annual storm events, but it quickly gets overtopped at larger flood events. During the FEMA 10-year event all of the yard and the buildings are flooded. The floodwaters spilling over Old Adobe Road accelerate and re-enter Lichau Creek at the downstream end of the yard (*Figure 14*). Flow depths on this floodplain range from one to four feet.

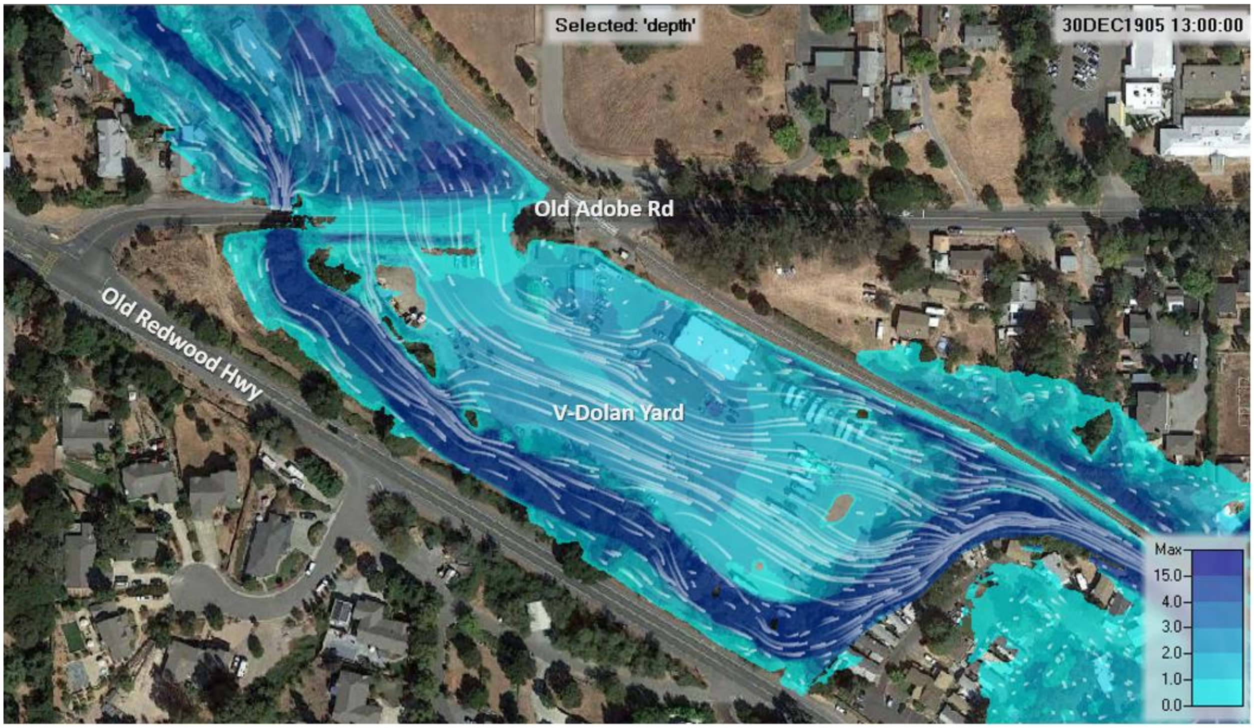


Figure 14. Existing condition predicted flood depths and extent during the FEMA 10-yr storm peak from Old Adobe Road through the V-Dolan yard.

The floodwall along the right bank downstream of the V-Dolan yard protects the Mobile Home Park from flooding during small, more frequent flood events. As flows increase, the Mobile Home Park begins to flood from the downstream end and adjacent property at about 1,050cfs, between the 5- and 10-year event. At FEMA's predicted 10-year peak flow, most of the Mobile Home Park has one to two feet of standing water in it. The downtown business district, including the Post Office, Penngrove Station, and the Grove Plaza have floodwaters running through the parking lots and possibly damaging buildings (*Figure 15*).

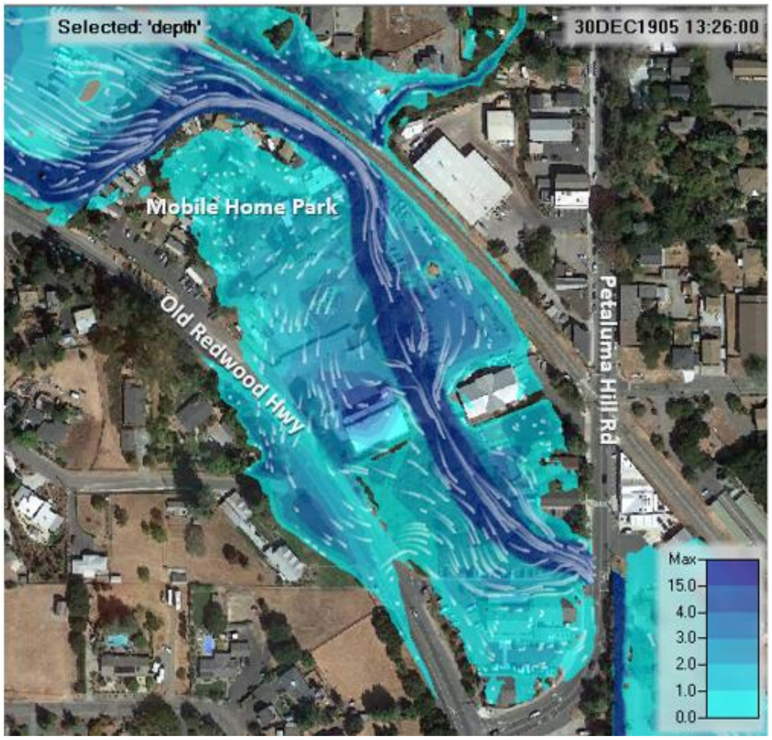


Figure 15. Existing condition predicted flood depths and extent during the 10-yr storm peak in downtown Penngrove.

Downstream of Petaluma Hill Road, the Penngrove Community Park on the left bank experiences extensive flooding with breakout flows occurring along the entire adjacent length of the channel. Because the riparian zone is narrow and the vegetation is heavily maintained, the floodwaters running through the park accelerate as they run down the length of the floodplain (*Figure 16*). The concrete retaining wall along the right bank protects the fire department from flooding; it is one of the few locations in downtown Penngrove that appears to not be threatened by the 10-year storm flooding.

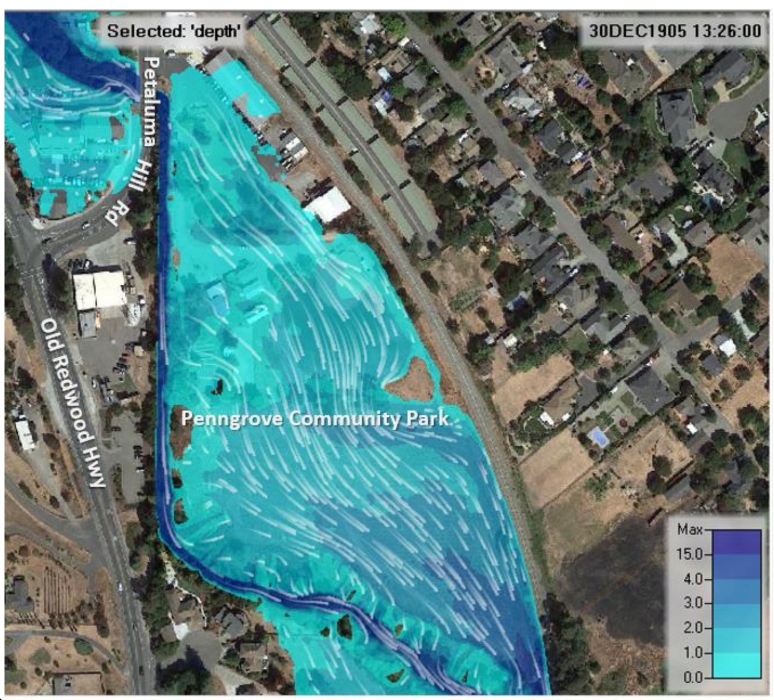


Figure 16. Existing condition predicted flood depths and extent during the 10-yr storm peak in the Penngrove Community Park.

Downtown Penngrove and its homes and businesses adjacent to Lichau Creek are at high risk of flooding due to the fact that they are located in the valley bottom on the alluvial floodplain. With its position in the lower watershed, downstream from several communities and a network of rural residential neighborhoods and roads, the hydrology of the watershed has been significantly altered and it is likely that flooding has become more frequent in the last century. Although flooding in Penngrove's location is somewhat inevitable, it does appear that channel constrictions within the downtown area may be causing elevated water surfaces during high flows. The existing-condition 10-year WSEL plot shows two ridges, or high spots, in downtown Penngrove (labelled "Constriction 1" and "Constriction 2" in) indicating that some channel or floodplain condition is causing water to back up. Where water backs up it will flood more adjacent areas on the floodplain and those flooded areas will tend to be deeper than if the floodwaters had an unrestricted flow path downstream.

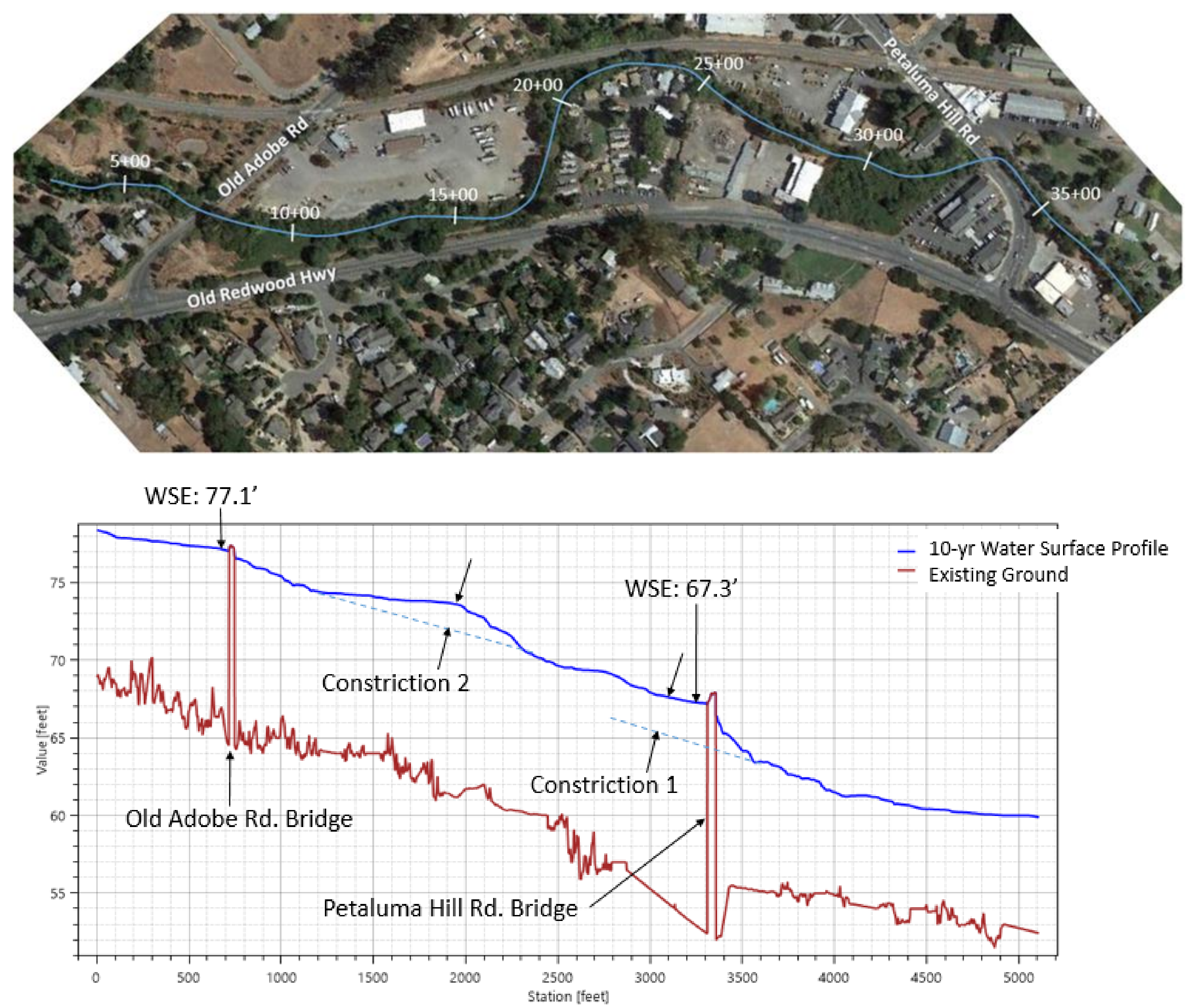


Figure 17. *Aerial view of Penngrove with station reference (above). WSEL profile plot (below).*

Constriction 1 occurs at the Petaluma Hill Rd bridge, and its impacts translate upstream at least 1,000 feet. The downtown business complexes adjacent to the bridge, such as Penngrove Station and Grove Plaza are impacted by the constriction at the Petaluma Hill Road Bridge. The constriction could be caused by either reduced flow capacity through the bridge or a flow restriction immediately downstream of the bridge where the channel makes a nearly 90-degree bend. Both possible causes were evaluated and the results of the analysis are presented below in Section 5.1.

Constriction 2 occurs on the bend adjacent to the Mobile Home Park where the channel and floodplain is constrained by the elevated SMART Rail tracks. The constriction in the channel and floodplain area reduces flow capacity in this reach. The acceleration of overbank flows through the V-Dolan yard and their rejoining of the in-channel flows at this bend may also contribute to the elevated water surfaces in the Constriction 2 zone. Options to address this constriction are presented in Section 5.2.

5 Flood Mitigation Alternatives and Hydraulic Results

Flood impact mitigation for a community such as Penngrove that is at the bottom of the watershed and built on the floodplain typically requires a watershed-wide approach to a) reduce the amount and timing of stormwater delivery to the system and b) increase channel and floodplain capacity where possible. This project was focused on localized opportunities to increase floodplain storage and channel capacity. Topographic maps and aerial photographs were used to determine areas where projects could potentially be implemented without impacting houses and other structures, such as open fields and undeveloped riparian zones. Within the town of Penngrove, opportunities to remove the constrictions described in the previous section were prioritized. A suite of flood mitigation alternatives were developed and hydraulically modelled to evaluate their effect on flood depths and extents within the town of Penngrove. The alternatives analyzed included:

1. Constriction modifications associated with the Petaluma Hill Road bridge. The two scenarios analyzed in this alternative included clearing sediment from under the bridge and modifying the channel downstream of the bridge.
2. Reach-scale channel widening to increase active channel capacity through Penngrove. Three floodplain bench scenarios were analyzed for this alternative.
3. Large-scale floodplain detention in open fields upstream of Penngrove to attenuate peak flows. Detention basins and floodplain lowering alternatives were evaluated.

Actions that would significantly impact or remove existing infrastructure, drastically change the current land use, have a scale so large as to be completely infeasible, require long-term repetitive maintenance, or exacerbate flooding downstream were not evaluated. Thus, projects such as secondary channels through the town of Penngrove, large storm drains to divert water around the town, or manually clearing vegetation throughout long reaches of the existing channel were ruled out as being impractical.

Also, no flood mitigation approaches were evaluated for the reach downstream of the Penngrove town center (downstream of Penngrove Community Park). Because the existing conditions model did not indicate conditions in this reach were contributing to flooding in Penngrove (i.e. no constrictions or backwatering), no critical infrastructure is located in zones flooded by the FEMA 10-year event, and the floodplains are relatively narrow and constrained by the SMART Rail tracks, we focused our flood mitigation analyses on alternatives to reduce flooding conditions that risk public safety and property.

5.1 Petaluma Hill Road Bridge Constriction Alternatives

The existing conditions hydraulic model results indicate that water surface elevations, upstream of the Petaluma Hill Road Bridge in the downtown business district, may be raised two feet or more during the 10-year flood event due to a channel constriction in the vicinity of the bridge (Figure 17). Two possibilities for the constriction were considered and modeled included clearing of sediment within the bridge (Bridge Sediment Removal Alternative) and widening out the channel at the bend immediately downstream of the bridge (Bank Widening Alternative).

5.1.1 Bridge Sediment Removal Alternative

Initial site inspections and channel surveys by PCI indicated that the right (south) bay of the Petaluma Hill Road bridge is partially filled with sediment. PCI's first attempt to eliminate the hydraulic constriction at the Petaluma Hill Rd bridge involved creating a model run with this sediment removed (Bridge Sediment Alternative) (*Figure 18*).

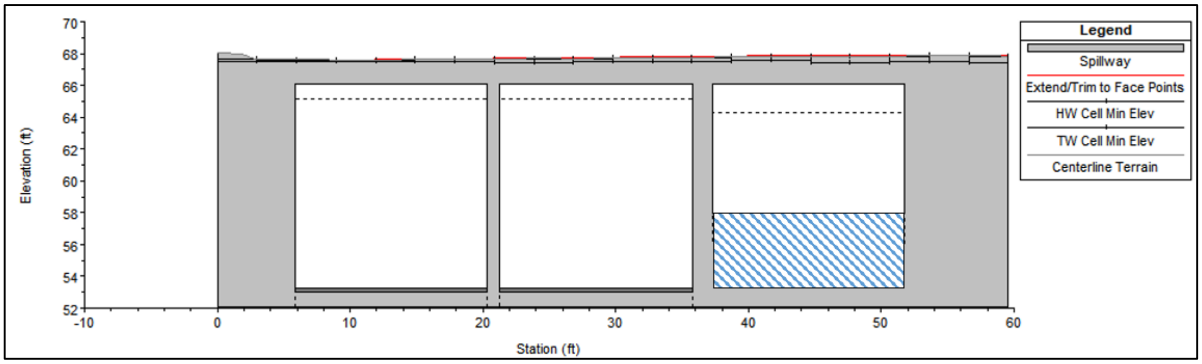


Figure 18. Image of HECRAS geometry for the Petaluma Hill Rd bridge showing sediment that was removed in the right bay (hatched area) for the Bridge Sediment Alternative model run.

Hydraulic modelling results from this alternative indicate that clearing sediment out of the right culvert bay has no measureable effect on peak flow WSELs (*Figure 19*). These results are likely indicative that the hydraulics through, and upstream of, the bridge are controlled by a downstream constriction.

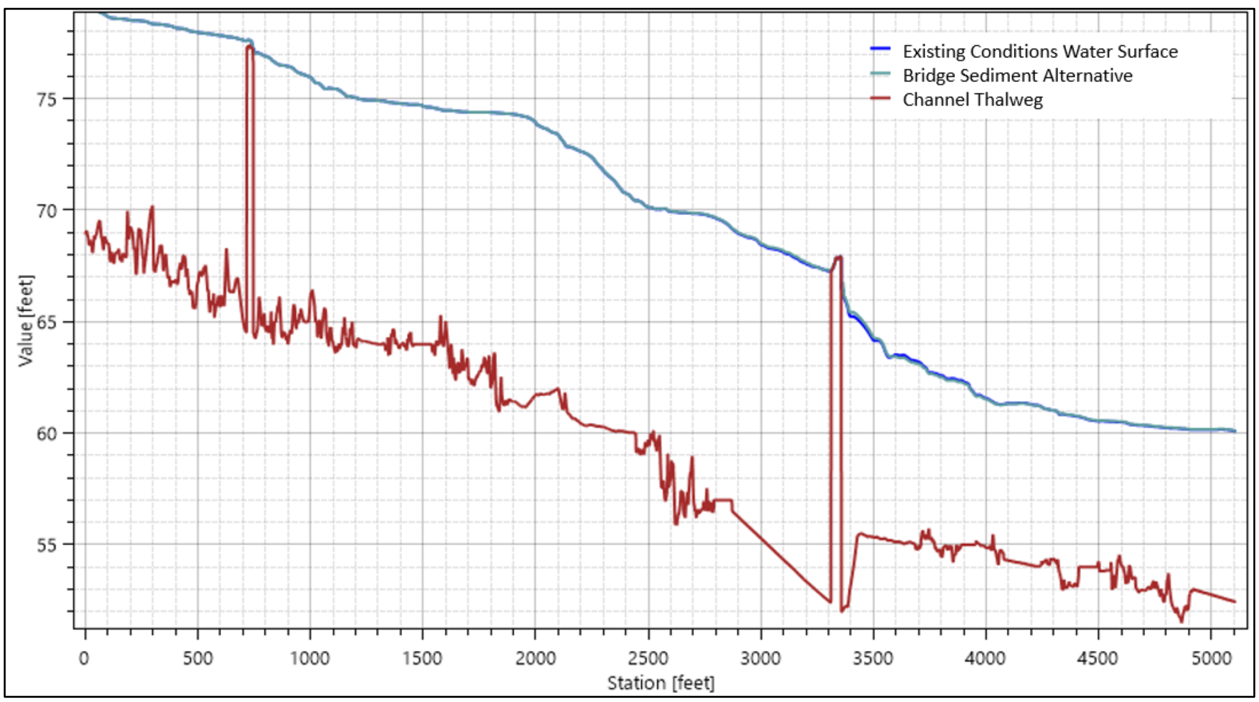


Figure 19. 10-yr storm WSEL plot comparing Existing Conditions with the Bridge Sediment Alternative. Note that existing and Bridge Sediment Alternative WSELs are essentially the same throughout the project reach.

5.1.2 Bank Widening Alternative

Results from the Bridge Sediment Alternative indicated that it is a hydraulic constriction downstream of the Petaluma Hill Rd bridge causing the backwater through and upstream of the bridge at high flows. Under existing conditions, as flow exits the bridge, it is forced into a hard right bend and into a narrow channel with a vertical retaining wall along the right bank. The modeled Bank Widening Alternative widened the channel downstream of the bridge on the left bank to create a smoother transition between the bridge and the downstream channel. The concept design widened the channel by a maximum of 40 feet through the downstream riffle crest. Additional modifications were made to the existing channel by smoothing out minor constrictions along the left bank that could potentially be contributing to the constriction (*Figure 20* and *Figure 21*).

Figure 20. Bank Widening Alternative. Grey outlines indicate extent of channel widening. White line shows location of cross section in Figure 21.

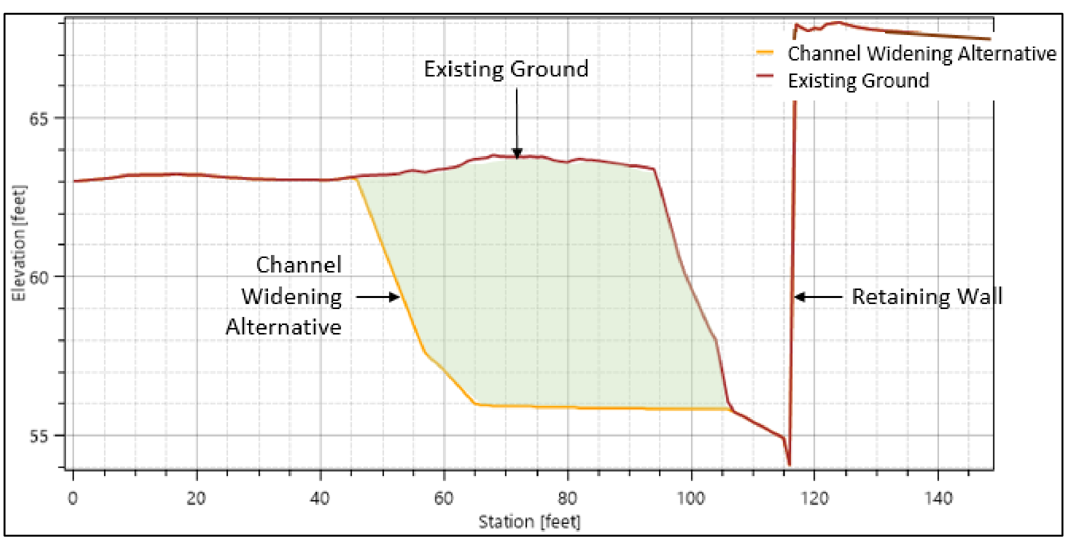


Figure 21. Cross section of Bank Widening Alternative. See Figure 20 for cross section location.

Model results from the Bank Widening Alternative indicate a reduction in WSEL of ~1 foot immediately upstream and ~1.5 feet immediately downstream of the Petaluma Hill Rd bridge would be achieved during the FEMA 10-year storm peak. A water surface lowering from removing the downstream constriction at the bridge propagates approximately 800’ upstream, to near the downstream end of the Mobile Home Park (*Figure 22*). Though this alternative may have a limited effect at the higher flows, it would provide additional benefits during smaller magnitude events by reducing the frequency and duration of flooding during the nuisance storm events.

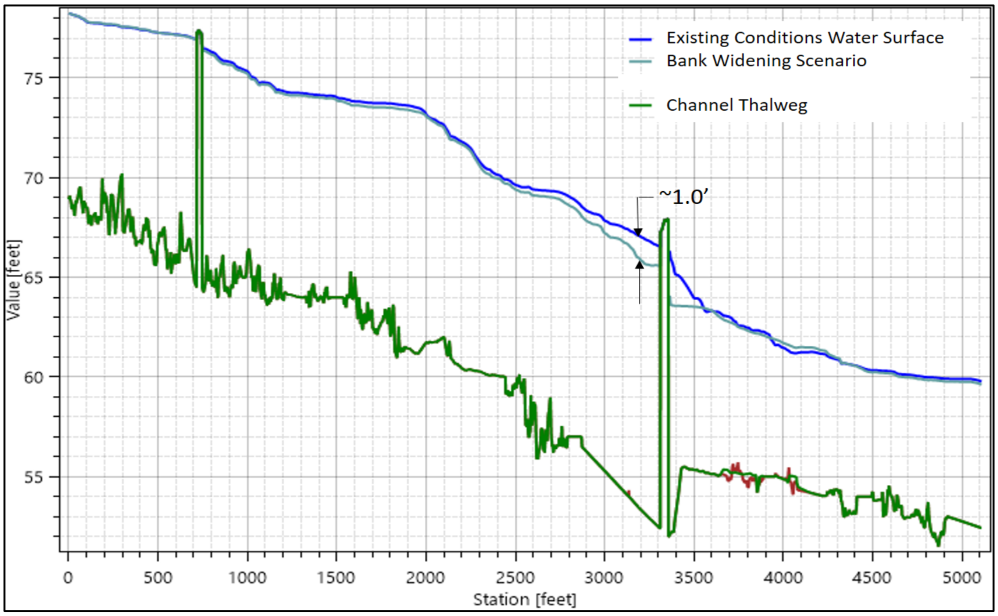


Figure 22. 10-yr storm WSEL plot for Existing Conditions and the Bank Widening Alternative.

Based on this WSEL plot, the bridge itself may be a constriction; however, we did not run additional models to evaluate this possibility further. We also did not conduct a sensitivity analysis to determine the optimal bank width and geometry for this Bank Widening Alternative. Reducing the constriction does reduce flooding severity in the downtown business district area, and thus we deem it to be a preferred alternative for flood mitigation consideration.

5.2 Floodplain Bench Alternatives

Development along the banks of Lichau Creek in Penngrove has resulted in areas with a narrow, simplified channel through town. It is likely that channel fill has created these narrow spots where the cross sectional flow area is reduced. This narrowing slows down flows and creates a backwater that propagates upstream, causing an elevated water surface. It also pushes more water onto the floodplains and into the industrial yards, parking lots and businesses within the town center. The floodplain bench alternatives were aimed at evaluating the effect of widening the active channel area and increasing channel capacity.

Three different inset floodplain concept design options were investigated to increase channel capacity and ultimately reduce the magnitude of flooding on adjacent properties. Floodplains with average widths of 10’, 20’, and 30’ were modeled (*Figure 23* and *Figure 24*). The floodplains were placed in areas with minimal infrastructure and include floodplains that alternate from bank-to-bank to provide continuous channel widening from Old Adobe Road to Petaluma Hill Road. Where possible, only one side of the channel received a floodplain bench to minimize impacts. However, the 30' floodplain alternative required floodplains on both sides of the channel downstream of the Mobile Home Park to avoid existing buildings. The 20' floodplain alternative included a side channel on the opposite bank from the V-Dolan yard, where the 10' and 30' alternative included a floodplain. This side channel was assumed to be comparable to an actual 20' inset floodplain, and was modelled to examine the flow patterns and flood benefits possible by using the unused field adjacent to the V-Dolan yard.

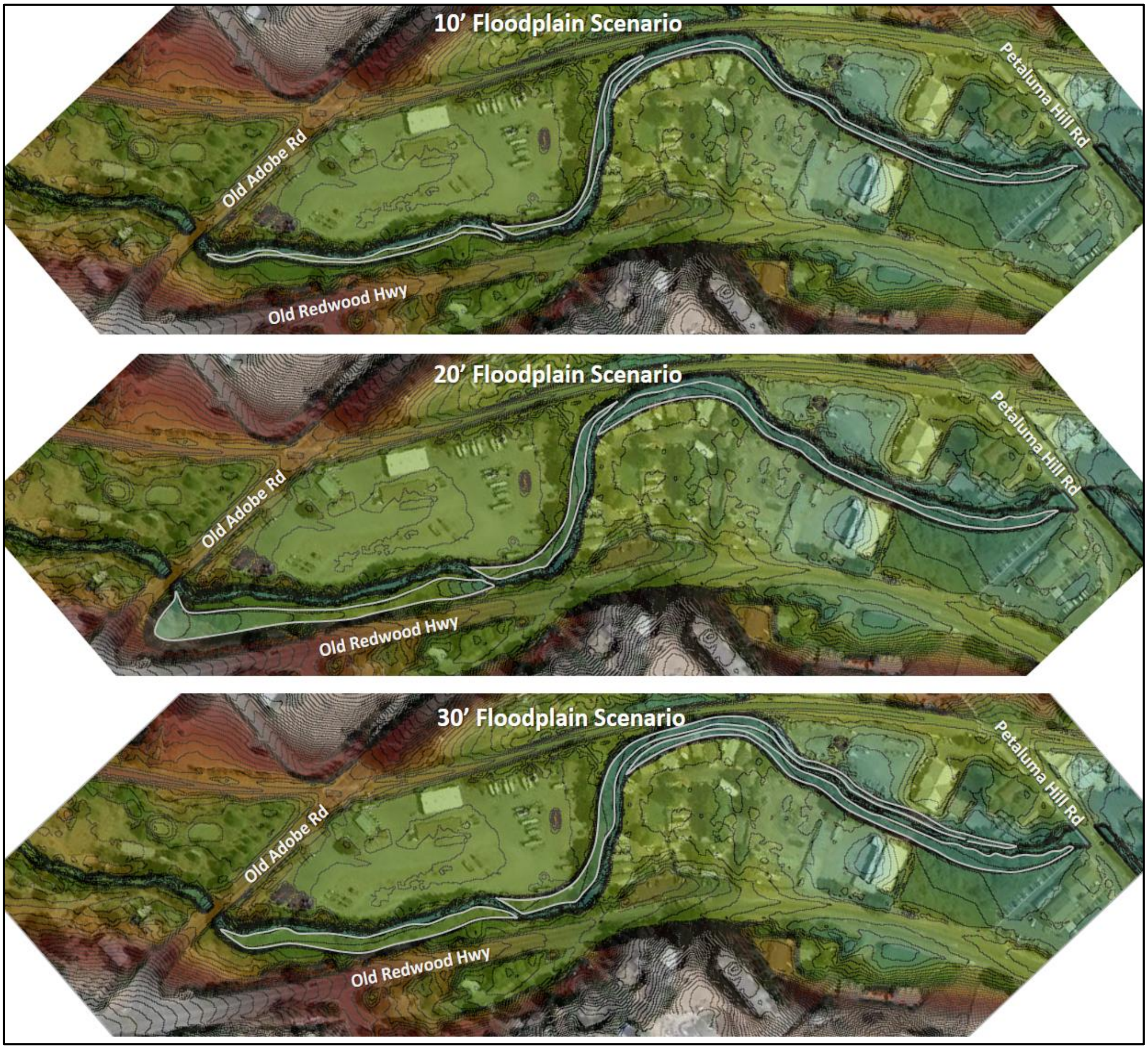


Figure 23. Floodplain Bench Alternatives (10', 20', and 30', respectively from top to bottom). Grey outlines indicate outer extent of floodplains modelled for each alternative.

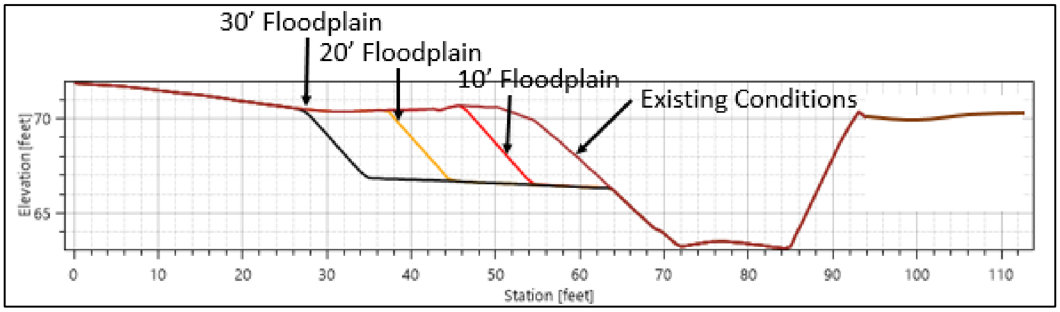


Figure 24. Typical cross section showing the three different floodplain bench alternatives.

Hydraulic results for the Floodplain Widening Alternatives indicate that all of the alternatives result in some lowering of the FEMA 10-year peak water surface elevations through Penngrove, but the reduction is mostly contained between the Old Adobe Rd and Petaluma Hill Rd bridges (*Figure 25*). The reduction in WSEL is greatest around the bend adjacent to the Mobile Home Park with maximum reductions of ~1.25 feet, ~1.75 feet, and ~2.5 feet for the 10', 20', and 30' floodplain alternatives, respectively.

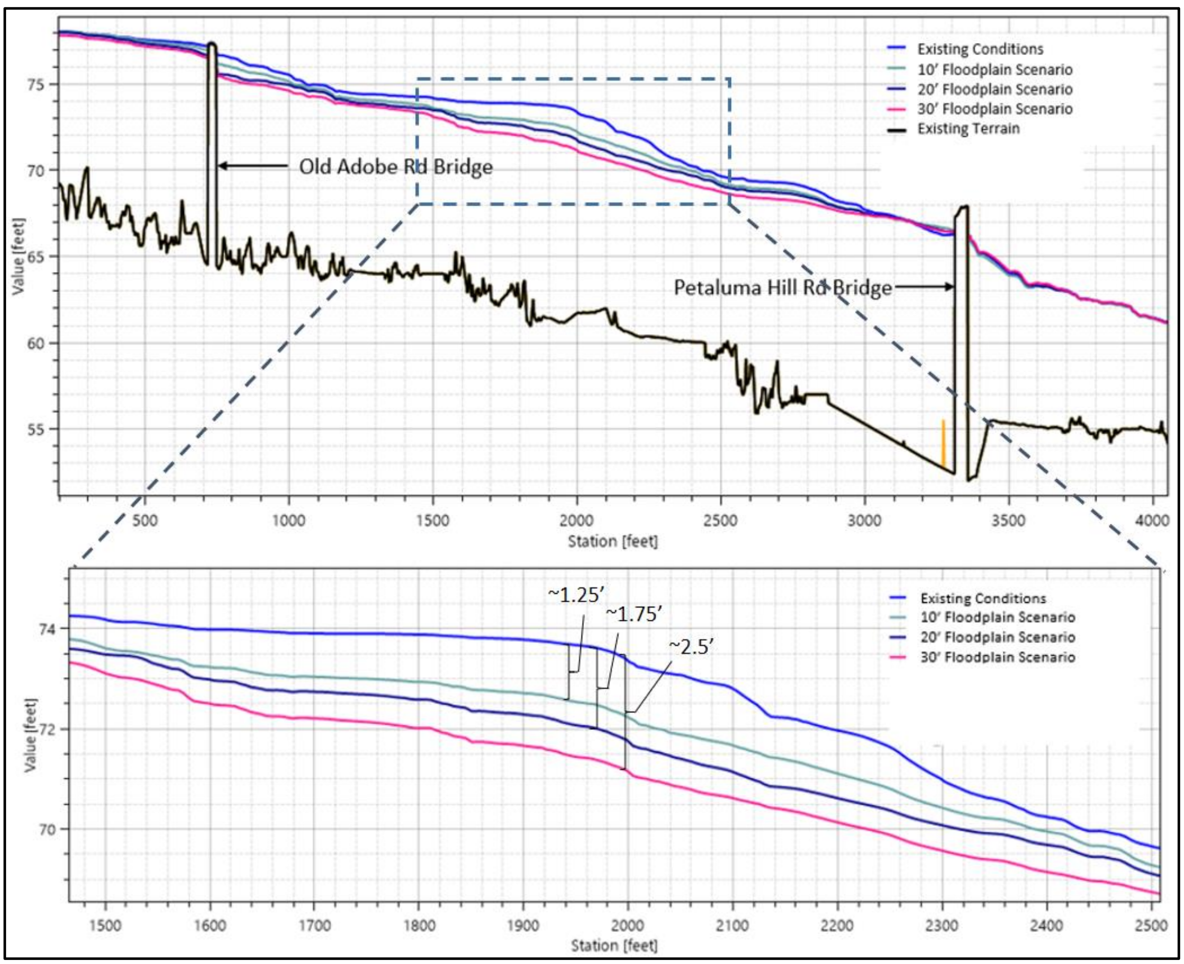


Figure 25. 10-yr storm WSEL plots comparing Existing Conditions with the 10', 20', and 30' floodplain alternatives.

Although all three alternatives include floodplains that extend downstream to the Petaluma Hill Road bridge, the benefits of increasing channel capacity disappear approximately 300 feet upstream of the bridge. This is due to the channel constriction downstream of the bridge that creates a backwater which propagates through the bridge (further described and analyzed in Section 5.1).

During the 10-year flood event, the 10’ Floodplain Alternative alone provides a relatively modest reduction in flooding in areas with existing infrastructure. Flood depths in the V-Dolan yard are reduced by approximately 6 inches, and nuisance flooding is somewhat reduced through portions of the Mobile Home Park and businesses in the Grove Plaza; but the overall extents of flooding are largely unchanged. Greater benefits for V-Dolan and the Mobile Home Park are seen with 20’ and 30’ floodplain benches, with the most significant being that standing water depths are kept largely to one foot or less within the Mobile Home Park and two feet or less within the V-Dolan yard (*Figure 26*).

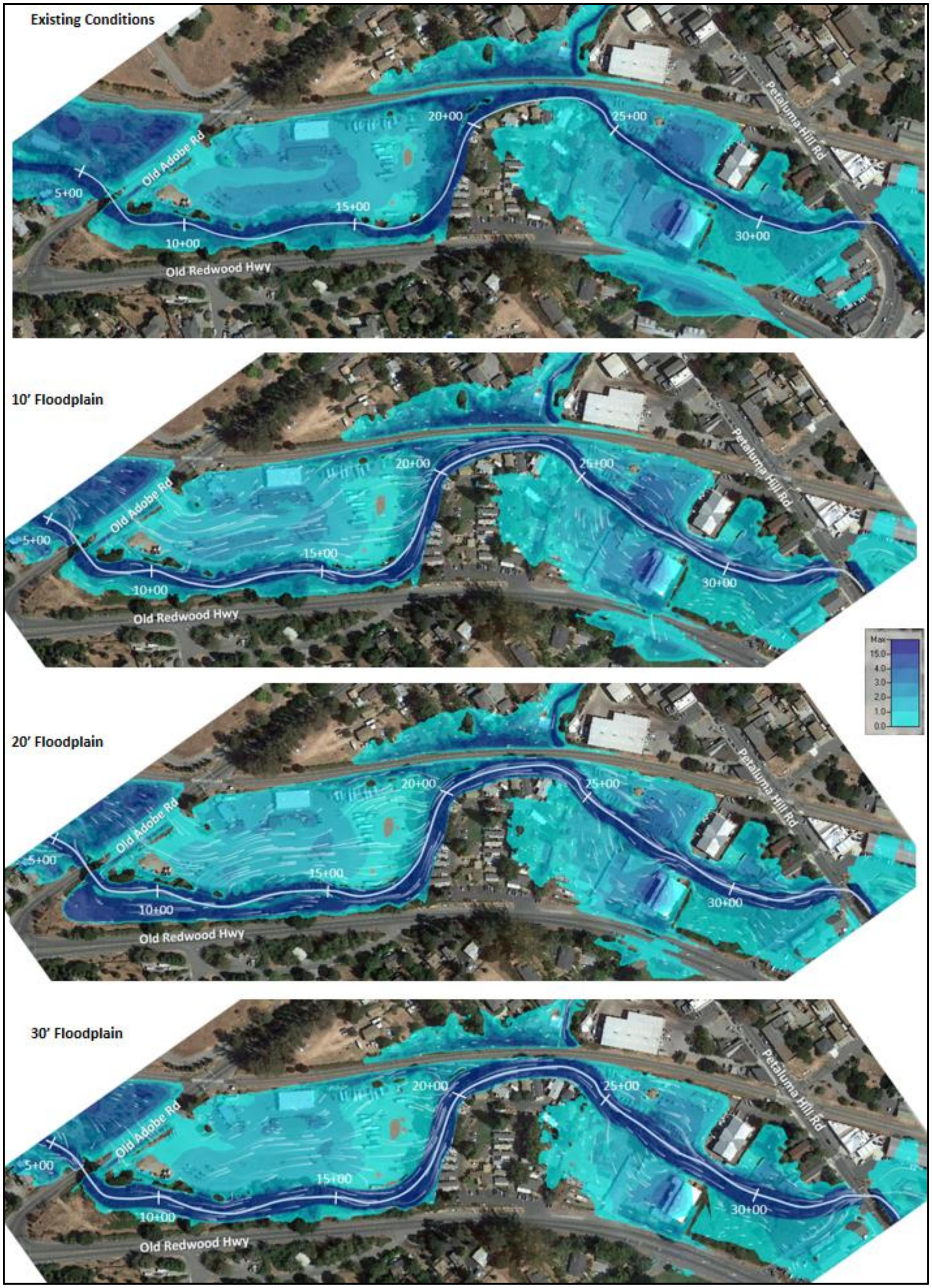


Figure 26. Water depths during the FEMA 10-yr flood peak for the three Floodplain Bench Alternatives for Downtown Penngrove.

As noted above, several locations within this reach begin flooding at flows much less than the 10-year event. During these more frequent events, the Floodplain Bench Alternatives may provide more beneficial flood reduction results. On December 15, 2016, moderate flooding occurred through the town of Penngrove. During this event, flooding was present across Old Adobe Rd, through the V-Dolan yard, in parking areas adjacent to the Post Office, and in the Community Park downstream of the Petaluma Hill Rd. bridge. PCI conducted a site visit at the peak of this event to perform a flow measurement and document water surface elevations in order to calibrate the hydraulic model (See Appendix A for model calibration data and photos of flooding). The flow measurement conducted during this flood event resulted in a peak flow estimate of 870-cfs; which is likely somewhere between the 2-yr and 5-yr return interval storm. Hydraulic results for this more frequent storm show similar reductions in flood depths during the calibration flow event as for the 10-yr event, which would translate to significantly less nuisance flooding during the 2-5 year storm events (Figure 27 & *Figure 28*).

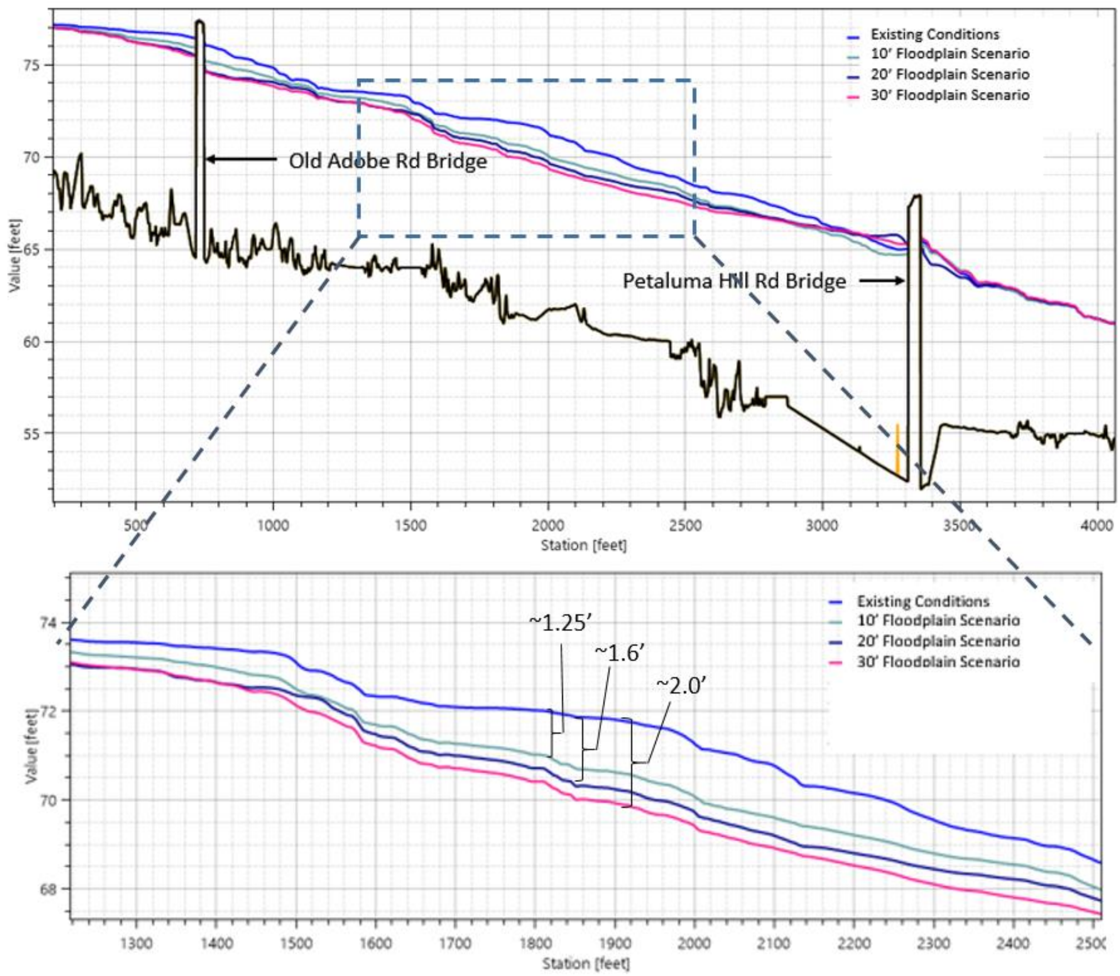


Figure 27. *Calibration storm event (~870-cfs) WSEL plots comparing Existing Conditions with the 10', 20', and 30' floodplain alternatives.*

Figure 28. Simulated water depths during the 12/15/16 (Calibration) flood event under existing conditions (top) and the three floodplain bench alternatives (bottom three).

5.3 *Upper Floodplain/Detention Basin Alternatives*

Upon review of the in-Penngrove flood mitigation alternatives results, it was apparent that additional approaches would be needed to fully mitigate flooding impacts of the 10-year storm in Penngrove. Flood peak attenuation (e.g. reducing the flood volume) would be needed. Flood attenuation can be achieved through management at the source, such as by increasing upland permeability and disconnecting impermeable surfaces from stormwater drains, or by developing detention areas throughout the watershed.

For this project several detention alternatives were evaluated upstream of Penngrove between Petaluma Hill Road and Old Adobe Road. The idea behind detention is to hold a portion of flow during the rising limb of a flow hydrograph, then slowly release the water back into the main channel after the peak flow. For detention storage to be effective during a given storm event, adequate capacity needs to be available to continue to accept flows until the desired design storm hydrograph begins to crest. If all available storage becomes full before the peak flow occurs, then the basin will have limited effect. Because of this, the flood reduction benefits of detention basins are significantly decreased for flows above the storm event for which they are designed. Two different detention concepts were considered for this study: floodplain detention and basin detention.

5.3.1 Lowered Floodplains Alternative

The initial detention approach that was evaluated was the Lowered Floodplain Alternative. All of the floodplain elevations throughout the valley upstream of Penngrove were lowered to begin flooding at approximately the 2-year flood elevation (*Figure 29*). The expectation was that this approach would slow and hold a greater volume of water on the floodplains during high flow events.

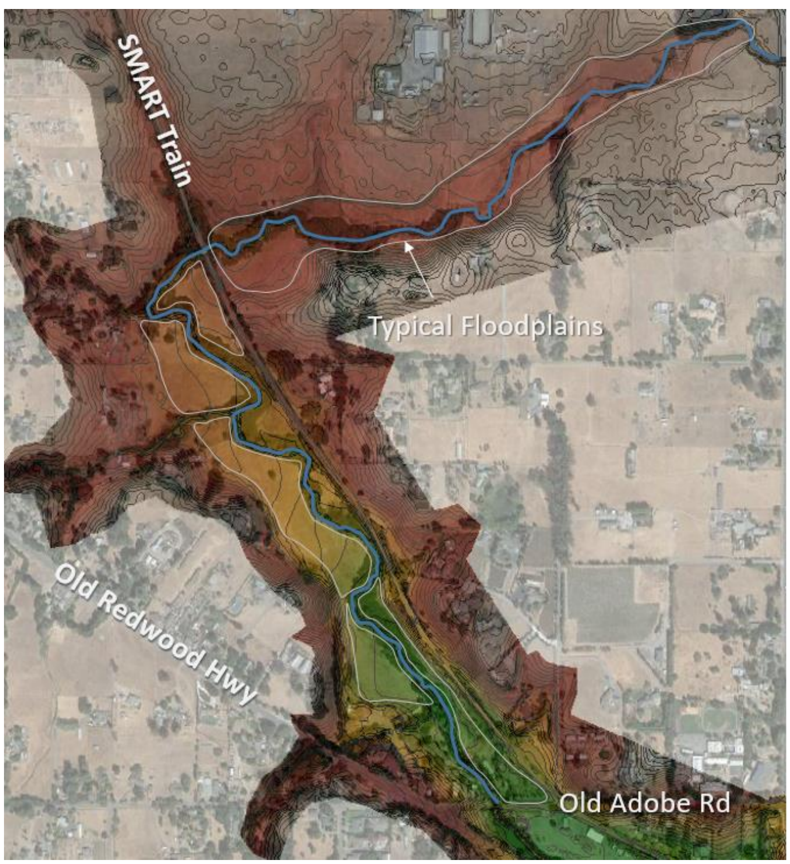


Figure 29. Floodplain Alternative. Grey outlines indicate outer extent of floodplains lowered and modelled.

The hydraulic results from this alternative indicate that lowering the floodplains to hold more water did not reduce the 10-year flood peak in Penngrove, but instead slightly increased it. Though this result was not expected, it provided insight into the complexities of hydraulic modelling and flow hydraulics. After analyzing these results and verifying that the hydraulic model was working correctly, PCI's explanation for the increase in peak flow is that the large expansive floodplains have less hydraulic roughness and sinuosity than the main channel and are thus increasing effective channel capacity and transferring flood water downstream at a faster rate (*Figure 30*). If the floodplains had a higher roughness than the main channel (i.e. willow thickets and not grazed grasslands), or if they did not allow flows to short circuit the main channel, the results might indicate that lowering the floodplains is effective at reducing flows downstream. Further investigation into lowered floodplains in this upper reach to reduce downstream flooding was abandoned.

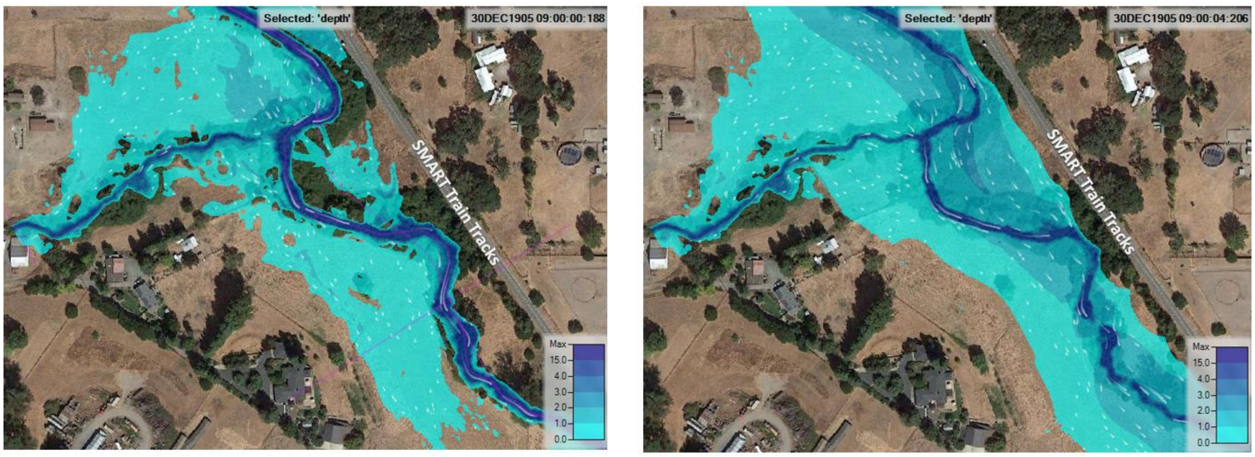


Figure 30. Depth comparison of Existing Condition (left) and Floodplain Detention Alternative (right). Note that the Floodplain Detention Alternative allows more water to access the overbanks, but creates short circuiting that is not present in Existing Condition

5.3.2 Detention Basins

The second detention scenario that was analyzed required creating discrete detention basins in the open fields between Petaluma Hill Road and Old Adobe Road. Two different detention basin alternatives were modelled: a maximum storage alternative (Max Detention Alternative), where ten open fields were utilized as detention basins; and a Select Basin Alternative, where a subset of two of the most promising basins were selected and analyzed separately.

5.3.2.1 Max Detention Alternative

The Max Detention Alternative was modelled to gain an understanding of the approximate maximum flood reduction benefit possible with detention basins placed in all identified potentially available fields in the upper and middle reaches. The basins were designed to roughly take up as much open area as possible without extending into nearby hillsides or areas with elevated terrain. The bottom elevation of each basin was set at the elevation of the adjacent channel bed in Lichau Creek near the downstream end of each basin to allow for positive drainage as flood stage decreases. They would require a pipe with a flap gate to prevent low flows from entering the basin, while allowing the basins to drain after each storm. These drains were not included in this analysis. The total storage volume of all the detention basins combined for the Max Detention Alternative is approximately 90 acre-feet (*Figure 31*).

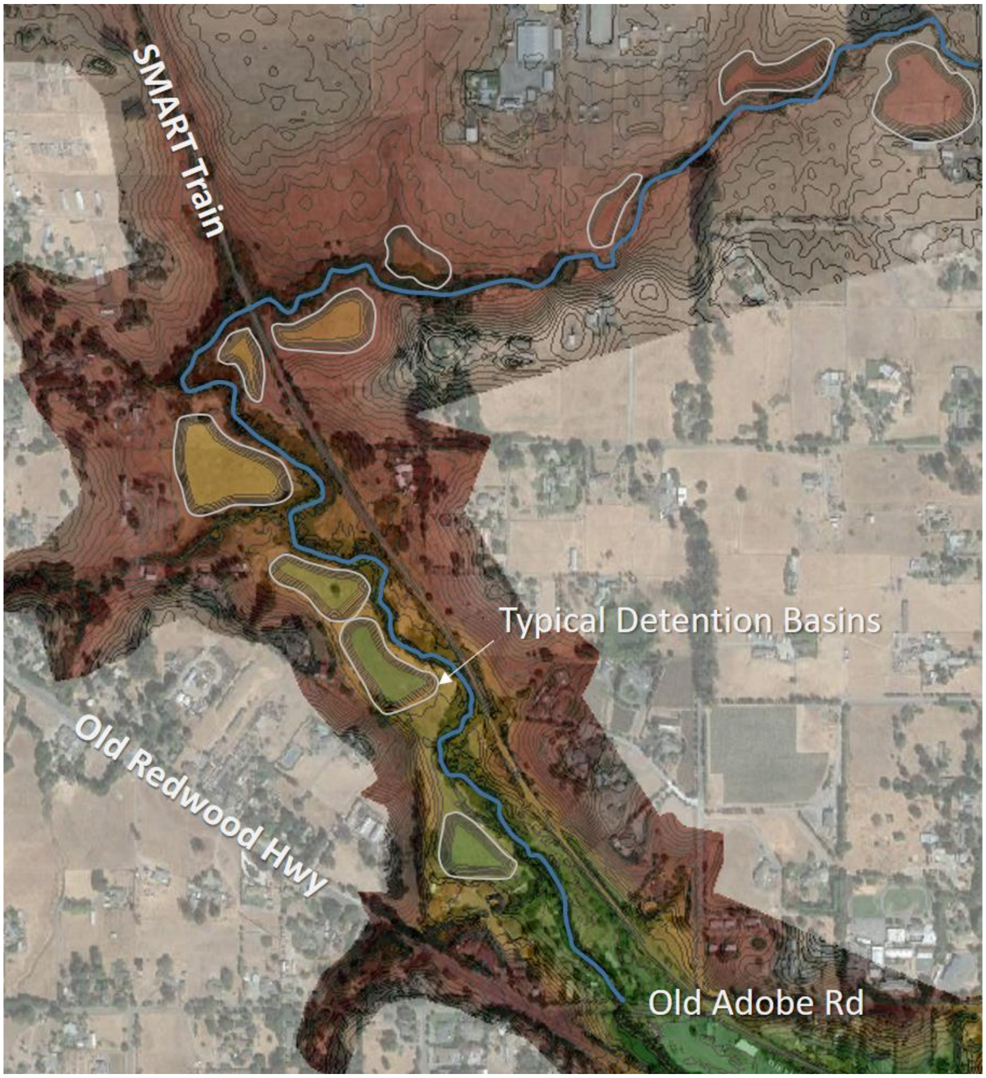


Figure 31. Max Detention Alternative. Grey outlines indicate extent of each detention basin.

Under Existing Conditions, the open fields between the SMART Train tracks and Old Adobe Road become inundated at flows as low as ~400 cfs. The fields upstream of the SMART Train tracks start to become inundated at much higher flows, around ~1,000 cfs. In order to allow for the greatest peak flow attenuation possible, the detention basins need to remain empty during the rising limb of the design hydrograph until some flow threshold is reached where peak flow attenuation is desired. Because flooding in Penngrove begins to occur at approximately 700 cfs, this was selected as the target flow rate for the basins to start accepting water.

In order to prevent the basins from filling up at flows lower than the target flow, many of the basins downstream of the SMART Train tracks were modelled with embankments. These embankments were designed by analyzing the Existing Condition hydraulic model and setting each top-of-embankment elevation equal to the WSEL at the target flow rate. Since the existing fields generally slope in the down valley direction, the embankment heights range from less than 1 foot on the uphill side to a maximum of 2 feet on the downhill side (*Figure 32*).

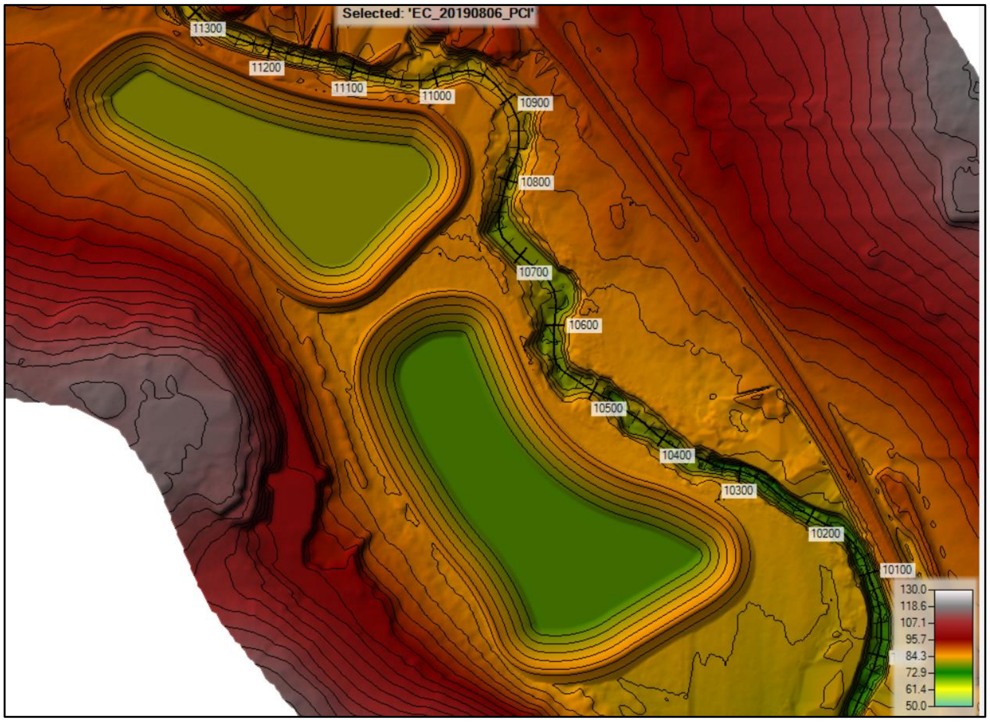


Figure 32. Typical Embankments in basins along the downstream end of the reach.

Hydraulic results for the Max Detention Alternative indicate that significant peak flow attenuation is possible with the basins modelled (approximately 90 acre-feet of total detention storage). The addition of the basins reduced the 10-year peak flow just upstream of the Old Adobe Rd crossing from ~1,500cfs to approximately ~850cfs (*Figure 33*).

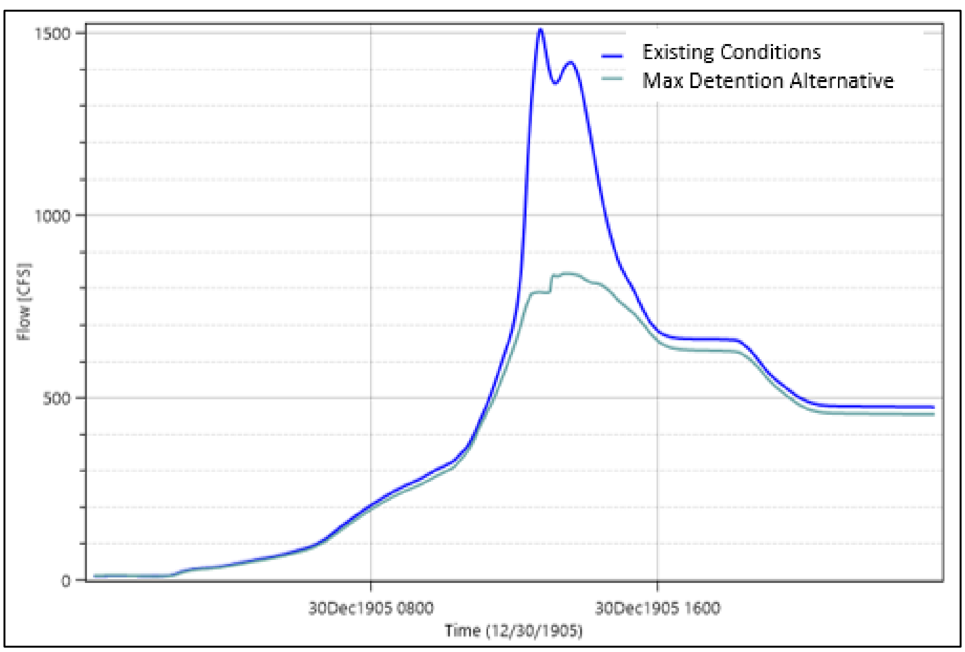


Figure 33. Existing and design condition 10-year hydrographs for the Max Detention Alternative through a cross section just upstream of Old Adobe Rd.

The reduction in peak flow from the Max Detention Alternative translates to a reduction in flood depths of close to 2-feet through the Center Reach of Penngrove during a 10-year event (*Figure 34*). Note that water surfaces elevations are very similar for the two profiles downstream of the Petaluma Hill Rd bridge. This is a result of water being able to exit the channel through this area along the left bank adjacent to the Community Park at a relatively low flow, which acts as a “pressure relief valve” that prevents a significant rise in stage with a corresponding rise in flow.

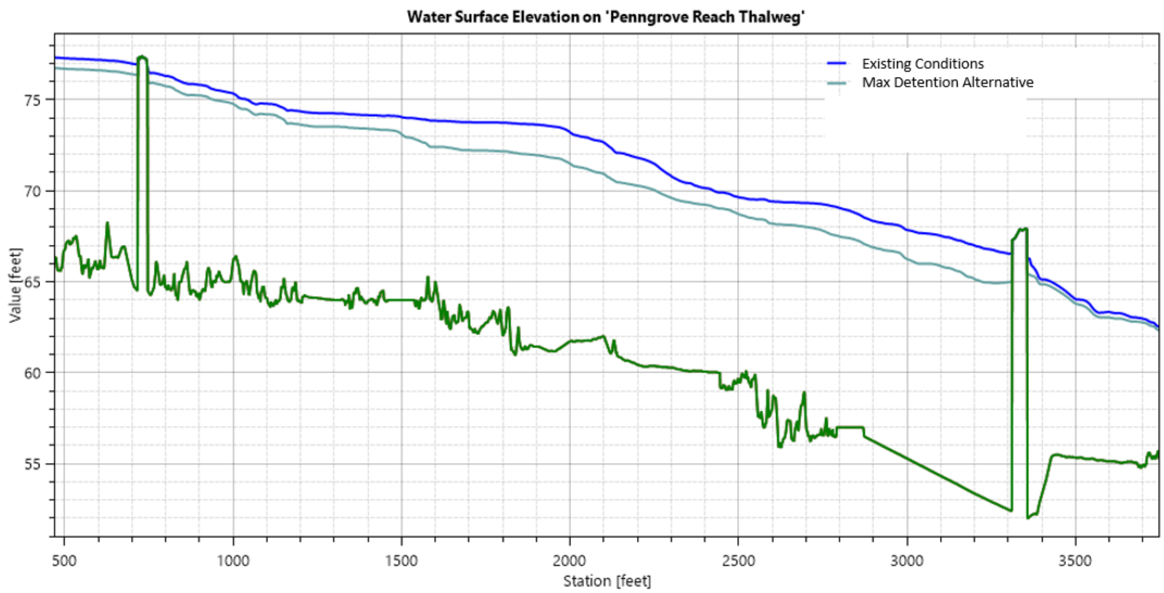


Figure 34. Existing and design condition 10-year water surface profile plot for the Max Detention Alternative through the Center Reach of Penngrove.

5.3.2.2 Select Basin Alternative

Because of the potentially prohibitive cost of the Max Detention Alternative, two of the more promising basins were selected for a smaller scale detention alternative (Select Basin Alternative). Both basins selected for this alternative are upstream of the SMART Train tracks in open fields that currently experience little or no inundation during the 10-year event. This is desirable as they will not negatively affect hydraulics and groundwater recharge during the more frequent flooding events by blocking off access to the existing floodplains. Inlet weirs were designed for these basins to begin accepting flow at the same stage that Penngrove begins to flood (~700 cfs). The total detention storage volume of the basins modelled is approximately 31 acre-feet (*Figure 35*).

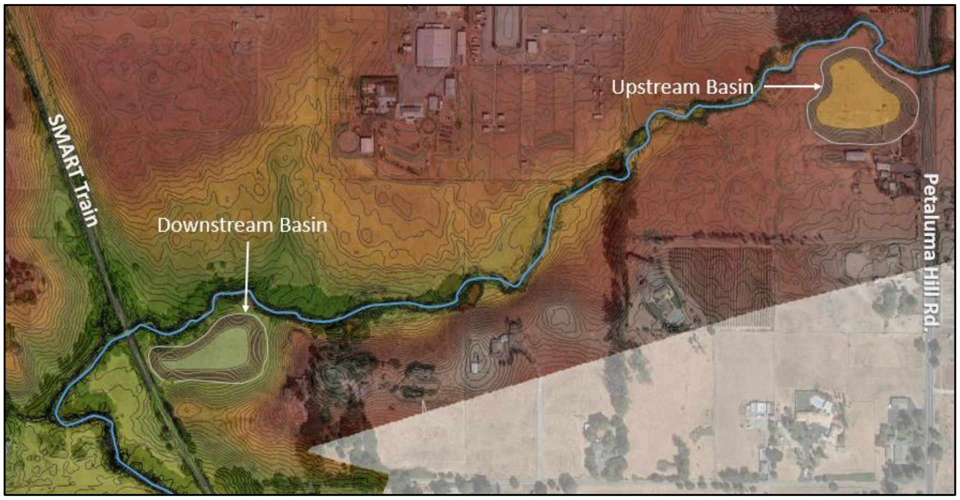


Figure 35. Detention basins included in the Select Basin Alternative.

Results from this alternative indicate that the two selected basins do create a significant reduction in the peak flow immediately downstream of the basins; however, the reduction in peak flow is somewhat washed out as additional tributaries enter the channel downstream of the basins. The most upstream basin modelled reduces the peak flow from 1,005 cfs to 750 cfs—approximately a ~25% reduction in the peak flow rate. The combination of both basins reduces the peak flow from 1,120 cfs to 790 cfs; a ~30% reduction in the peak flow rate. However, by the time the peak flow occurs at Old Adobe Rd, the peak is reduced from 1,580 cfs, to 1,430 cfs—approximately a 10% reduction in flow. Nonetheless, the Select Basin Alternative does shorten the duration of the peak event (*Figure 36*).

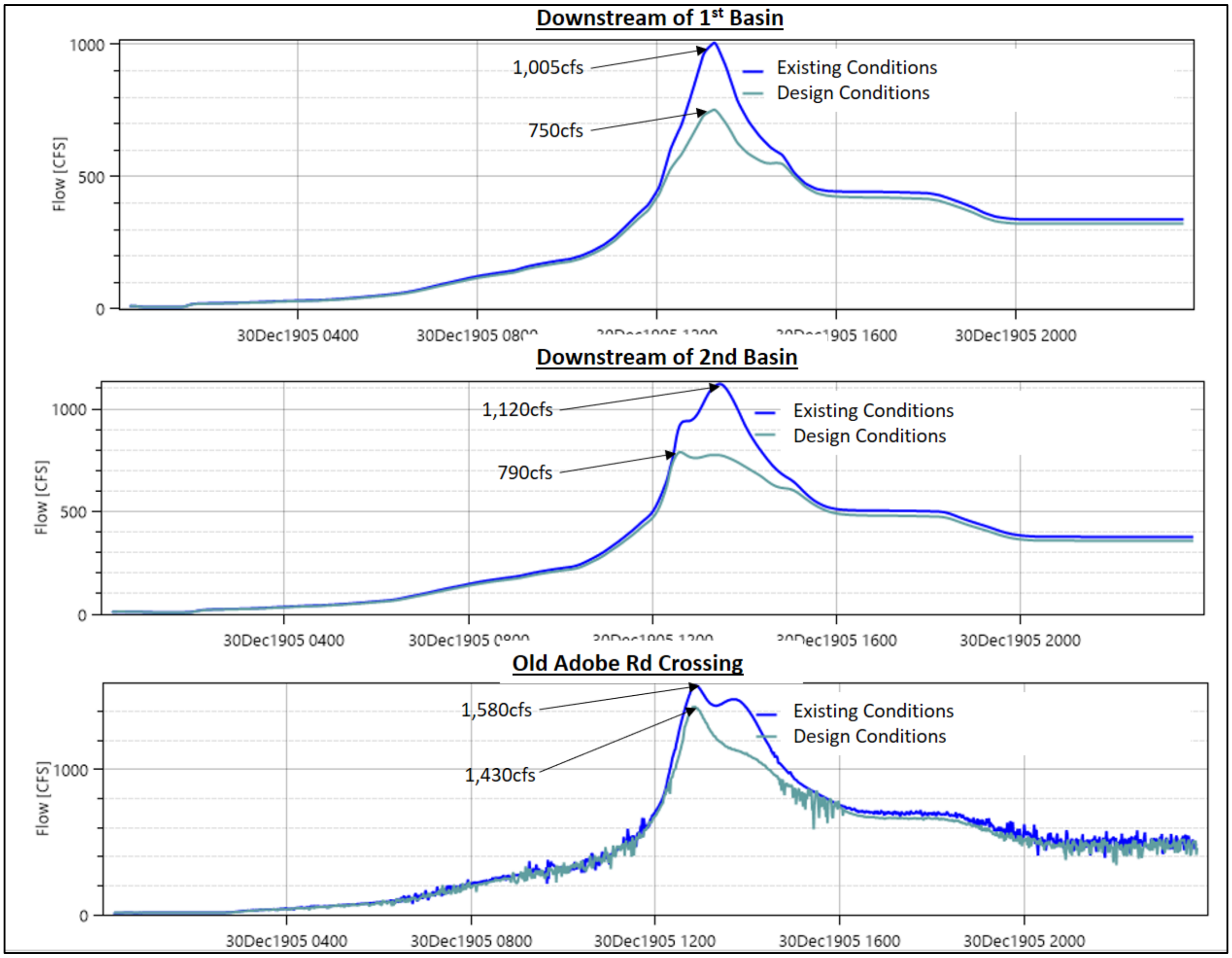


Figure 36. Existing and design condition hydrographs for the Select Basin Alternative in three locations: Top shows results from most upstream basin only, middle shows results just downstream of the second basin, bottom shows peak flow attenuation from Select Basin Alternative at Old Adobe Road.

An important note regarding the detention basin results is that the hydraulics presented in this analysis are very specific to the timing and magnitude of storms for the individual tributaries being modelled. The efficacy of detention basins is highly dependent on the magnitude and duration of flows entering the basins. The magnitude and duration of flows in Lichau Creek are specific to the precipitation events modelled for the individual tributaries. During an actual storm event, the timing and intensity of the precipitation is highly stochastic, and under a different storm hydrograph scenario, the modeled detention basins may actually provide greater flood reduction benefits than shown.

5.4 *Combined Alternatives*

After evaluating the various alternatives independently, model runs were prepared that combined several of the more promising alternatives to evaluate how they work together to mitigate flooding in Penngrove (*Figure 37*). The two combinations we modeled are:

- Combination Alt1: the 20’ Floodplain Alternative combined with the Bank Widening Alternative.
- Combination Alt2: the 20’ Floodplain Alternative, the Bank Widening Alternative, and the Max Detention Basin Alternative.

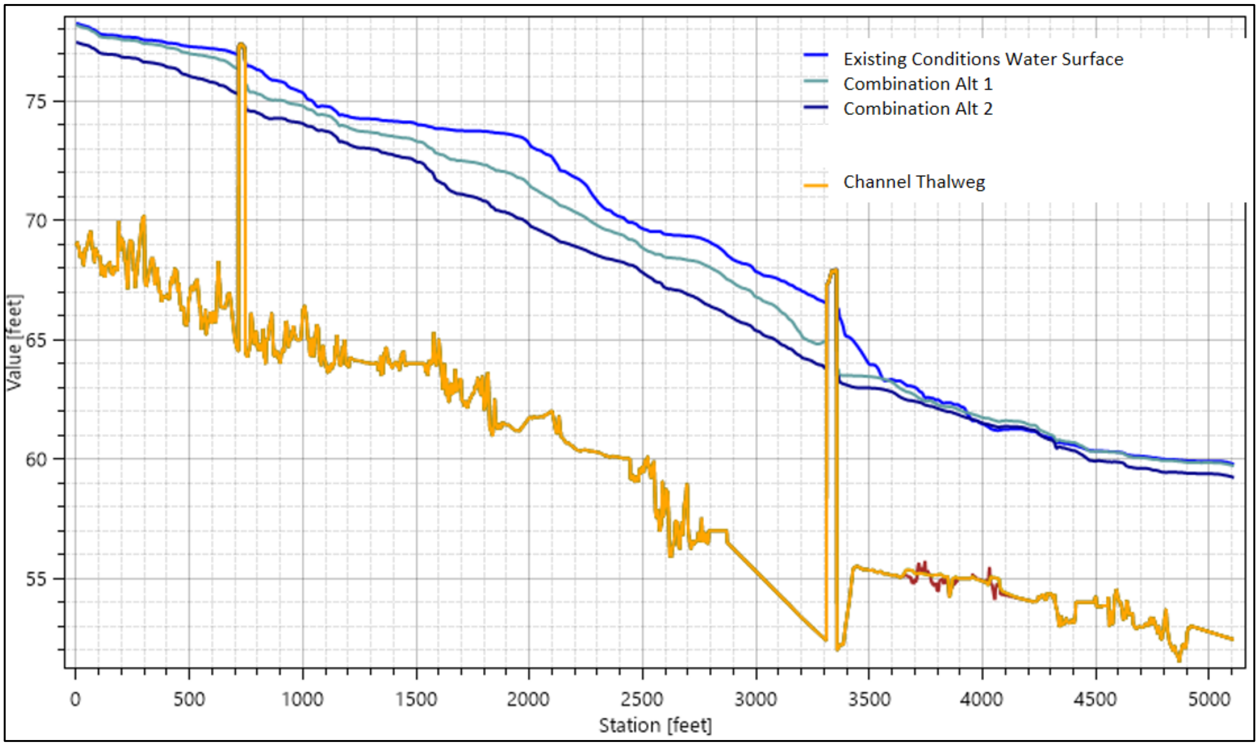


Figure 37. Water surface profiles for the 10-yr storm event through Penngrove showing model results for Existing Conditions and the two Combination Alternatives.

The results indicate that addressing the constrictions within the Penngrove Center Reach (Combination Alt1) largely eliminates the backwater conditions that exacerbate flooding. This alternative reduces the water surface elevations by a maximum of ~1.75 feet and an average of ~1 foot through Downtown Penngrove. The Mobile Home Park and Grove Plaza see significant reductions in flooding extent and potential impacts (*Figure 38*).

Adding in the Max Detention Alternative (Combination Alt2) further lowers water surfaces through the town by a maximum of ~3.5 feet and an average of ~2.25 feet during the 10-year event. Most of Penngrove does not flood if significant upstream storage attenuates the peak. The only locations that see shallow nuisance flooding under the Combination Alt2 is the V-Dolan yard and portions of other industrial parking/storage areas in the middle of the reach.

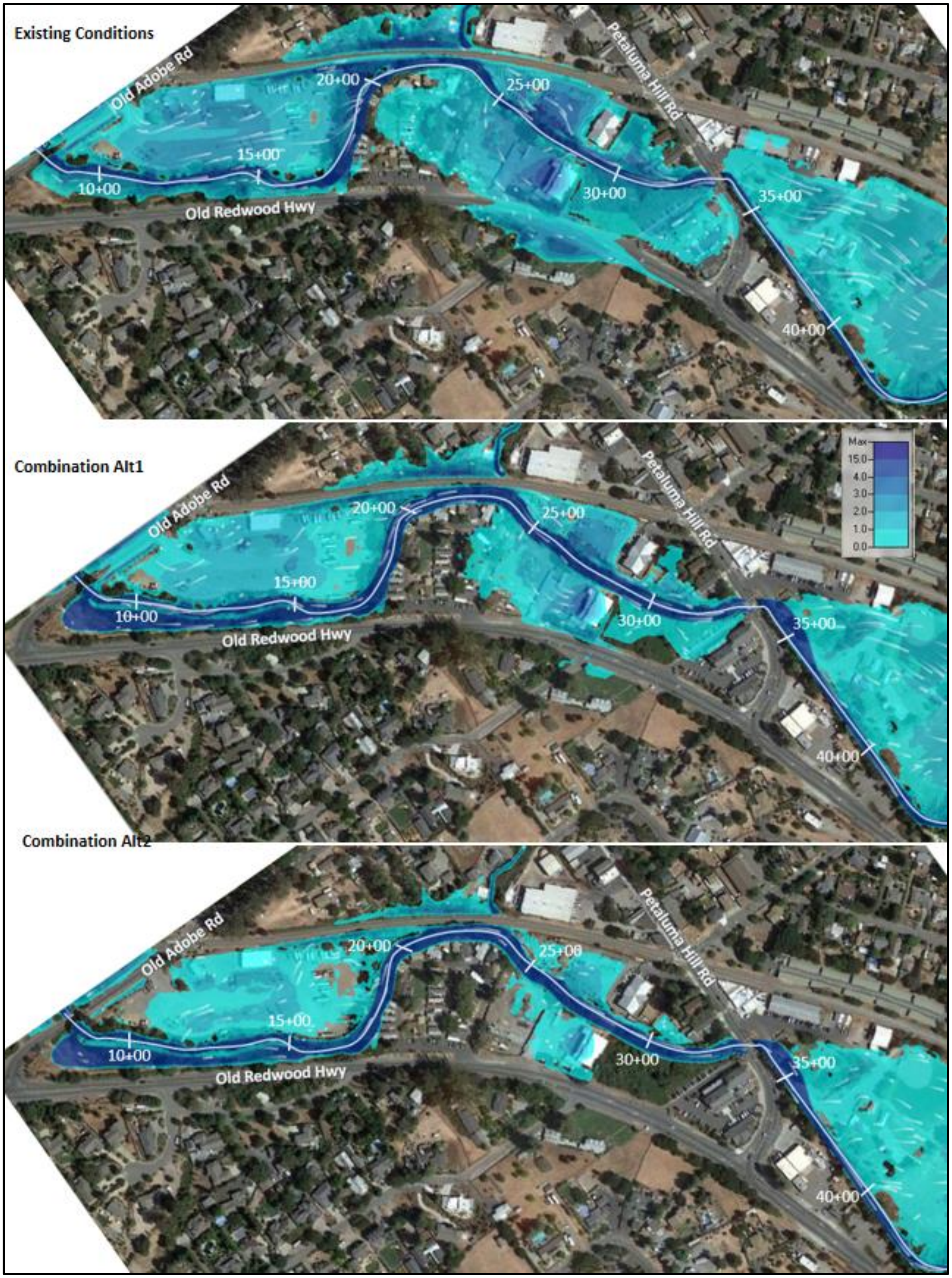


Figure 38. Water depths and flooding extents during the 10-yr storm for Existing Conditions and the two Combined Alternatives in downtown Penngrove.

To get a better understanding of how the proposed designs would reduce the frequency of flooding through Penngrove, the flows for both design alternatives were increased until the water surface profiles around the Mobile Home Park were similar to the Existing Condition 10-yr profile (*Figure 39*). In order for the design alternatives to produce the same flood depths as the Existing Condition 10-yr event, the flows needed to be ramped up to ~2,160 cfs (at the Post Office), which corresponds to the FEMA 100-year flow. Effectively, this means that the flood depth that would normally occur every 10 years under existing conditions would now occur every 100 years under design conditions. Note that both Alt 1 and Alt 2 design alternatives have very similar results at this higher flow rate because the detention basins are full after the 10-year flood.

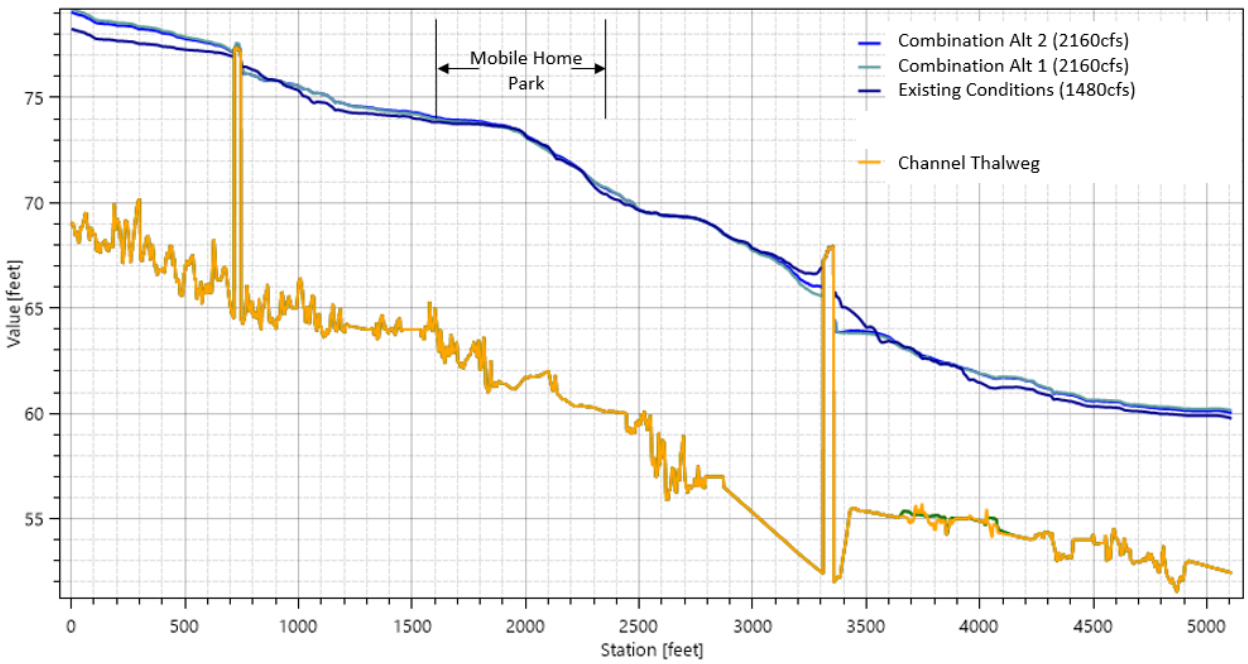


Figure 39. WSEL comparison plot showing Existing Condition WSEL profile at 1480 cfs (FEMA 10-yr) and Design Alternatives at 2160cfs (FEMA 100-yr).

At the model calibration flow event (870cfs), Combination Alternatives 1 and 2 reduce the flood depth by up to 1.8 feet near the Mobile Home Park and approximately 1 foot in the V-Dolan yard (*Figure 40*). This reduction eliminates road flooding at Old Adobe Rd., prevents overbank flooding along the right bank from the Mobile Home Park down through Petaluma Hill Rd, and significantly reduces flood depths near the Post Office (*Figure 41*). Note that flood results for both design alternatives are essentially the same at this flow rate because the detention basins in Combination Alt 2 haven't received enough flow to significantly reduce the downstream flow rate.

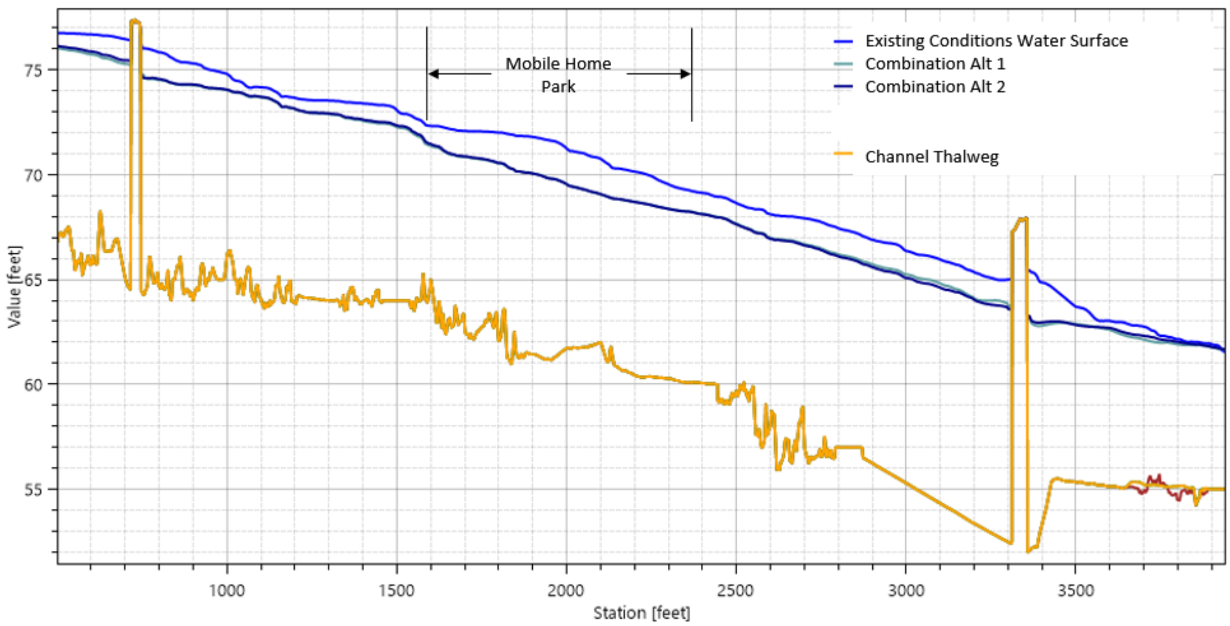


Figure 40. Calibration flow (870cfs) water surface profiles though the Middle Reach in the Existing Conditions model and Combination Alternatives 1 and 2.

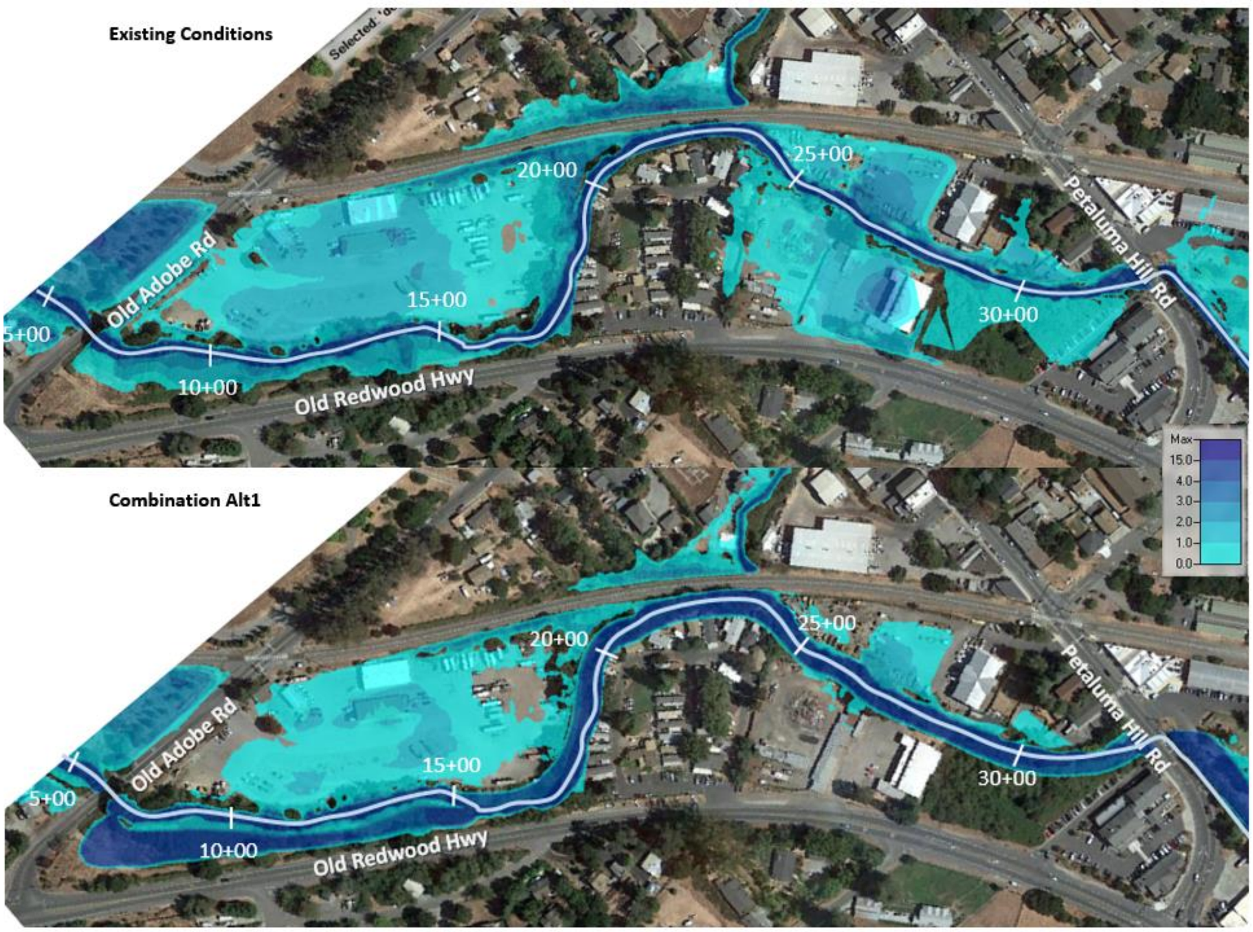


Figure 41. Calibration flow (870cfs) flood inundation maps though the Middle Reach in the Existing Conditions model and Combination Alternative 1.

6 Discussion

Securing significant 10-year flood control benefits for the town of Penngrove will require implementing multiple flood mitigation projects, both within the town center and upstream. The results from this feasibility study show that channel capacity needs to be increased throughout downtown Penngrove (Bank Widening Alternative @ Petaluma Hill Road bridge and Floodplain Benches Alternative). This would reduce flooding depths and extents on town center roads and parking lots. It would also reduce flooding in the Mobile Home Park. To largely eliminate flood impacts to roads and businesses in Penngrove, flood peak detention projects in the upper watershed or in the floodplains upstream of town (Max Detention Alternative) will be required. Based on our analysis a minimum of 90 acre-feet of detention is needed near the peak of the storm to successfully attenuate the 10-year flood; however, 30 acre-feet (Select Basin Alternative) was found to provide measurable flow reductions and provide some level of flood benefit to downtown Penngrove. Refer back to *Figure 37* for an illustration of the results.

Implementing projects represented by the Combination Alt1 Alternative would provide some immediate relief for Penngrove businesses and residents during the smaller, more frequent flood events. It is PCI's recommendation that the constrictions within the downtown Penngrove reach be addressed, where possible. This includes widening the channel immediately downstream of the Petaluma Hill Road bridge near the entrance to the Penngrove Community Park and excavating inset floodplains along the banks from Old Adobe Road down to Petaluma Hill Road. The floodplains can range from approximately 10-feet wide to 30-feet wide or more, as localized site conditions allow. Wider floodplains provide more conveyance; flood depths and extents improve commensurate with the width of the adjacent floodplain bench.

We recognize that large-scale projects to detain urban stormwater and stream overbank flows upstream of the project to attenuate flood peaks will likely be a longer term development prospect. Pursuing options for one or more detention basins on the floodplains in the study area's upper and middle reaches could contribute to mitigating downstream impacts of floods with 5- to 10-year recurrence intervals. These basins would need to be designed to only accept flows from the main channel at a specified design flow rate and will likely only provide meaningful peak flow attenuation during a relatively narrow band of the design hydrograph. Large, less frequent flood peaks will need to be controlled higher in the watershed at the sources of stormwater accumulation.

The alternative designs prepared for this hydraulic modeling analysis were developed at a rough concept level based on LiDAR terrain and aerial photographs. The analyses provide guidance on probable outcomes from an overall flood mitigation perspective. The 10-year flood hydrographs that were used to evaluate existing conditions and design conditions flooding is only representative of a potential 10-year storm event flood. The spatially variable and stochastic nature of precipitation in this region, coupled with climate change, contribute to the inherent uncertainty in this type of analysis.

Future phases of flood control planning and design for Lichau Creek and Penngrove will require extensive outreach to landowners, detailed site surveys, and additional modeling work to dial in site-specific floodplain widths, elevations, and lengths for optimal flood conveyance. There are many unknowns regarding the constructability of any of the proposed alternatives, including the presence of utilities or contaminated soils, landowner interest/willingness to consider projects, etc. However, there are several projects that may have the potential to move forward in the near term, based on outreach response during this feasibility phase. PCI recommends outreach to V-Dolan Trucking to gauge level of willingness to develop inset floodplains along the right bank immediately downstream of the Old Adobe Road bridge and at the downstream end of their yard on the left bank, across from the Mobile Home

Park. The other priority outreach is to the City and the organization that owns/manages the Penngrove Community Park to begin discussions on widening the channel downstream of the bridge.

Planning-level construction cost estimates were developed for several of the key alternatives that were shown to provide valuable levels of flood control (*Table 2*). The cost estimates are largely based on grading volumes, labor, and trucking costs for the excavation work, with contingency for site specific details incorporated. The higher end of the cost range for each alternative also incorporates design and permitting costs. Land procurement or building demolition was not taken into account. Once sites have been selected for flood mitigation project design, and site-specific opportunities and constructability constraints are worked out, the construction costs may vary from the estimates made at this rough concept stage.

Table 2. Planning level construction cost estimate for project alternatives

Alternative	Planning Level Construction Cost
Bank Widening Alt:	$350K-$650K
20' Floodplain Bench Alt:	$2M-$4M
Max Detention Alt:	$21M-$39M
Select Basin Alt:	$7M-$13M

A final element for consideration in the planning and implementation of flood mitigation projects is the evaluation of potential impacts on and improvements to wildlife, natural resources, and land uses. Creating inset floodplains in the urban reach of downtown Penngrove will provide a range of benefits long-term for the stream ecosystem, however there will be short term impacts. Large-scale detention basins excavated into the floodplains can be designed to function for existing land uses (grazing, hay production) but may also have both detrimental and beneficial impacts on wildlife and hydrology. *Table 3* provides a summary of potential benefits and impacts of the proposed flood mitigation alternatives.

Table 3. Summary of resource benefits and impacts of alternative flood mitigation actions.

Action	Excavate inset floodplain benches or small side channels	Excavate large-scale detention basins into floodplains
Alternative	Floodplain Bench Alternative, Bank Widening Alternative	Max Detention Basin Alternative, Select Basins Alternative
Benefits	Creates more complex in-channel habitat for wildlife including high-flow refugia for native fish, provides wildlife corridors through urban area, increases potential native plant habitat	Potentially increase groundwater recharge, potentially create seasonal wetlands
Impacts	Removes existing mature trees, potentially increases water temperatures until new riparian corridor matures, potentially reduces usable area on properties	Reduces shallow groundwater storage area, may lower water table in adjacent floodplain areas, potential fish stranding, alters future land use options

Resource trade-offs will need to occur to reduce the frequency, extent, and impacts of flooding in the town of Penngrove. There are no easy solutions to providing flood protection for the community and residents along Lichau Creek. This feasibility study provides insight into the level of effort and actions needed to provide flood control for small frequent storms up to the 10-year flood event.

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