

January 12, 2015

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SUBJECT: Summary of Analysis of Flooding at Green Valley Road and Mitigation Alternatives

Overview

The objective of this study, initiated and coordinated by the Gold Ridge Resource Conservation District, is to evaluate flooding mechanisms and develop feasible alternatives to mitigating the frequency and extent of flooding at Green Valley Road. In addition to damages to private property, flooding periodically makes Green Valley Road impassable and a risk to public safety. Continuing and increasingly frequent flooding is damaging Green Valley Road, creating a significant road maintenance issue. Flooding also creates risks to endangered coho salmon that may become stranded or otherwise harmed on the floodplain, particularly in the vineyard east and north of Green Valley Road.

This summary document seeks to inform stakeholders regarding:

- the history of riparian and floodplain conditions and flooding of Green Valley Road by Green Valley Creek,
- causes of flooding under current conditions, and
- alternative strategies to mitigate flooding.

Our analysis of flooding is based on review of publicly available County and State documents, historic aerial photography, topographic data from an aerial LiDAR survey in October 2012 and field surveys in January/February 2013, assessment of geomorphic conditions, a quantitative sediment source assessment of the contributing watersheds of upper Green Valley Creek and Purrington Creek, sediment transport analysis, and hydrologic and hydraulic modeling of flood flows under existing conditions and a variety of scenarios simulating flood mitigation alternatives.

Geomorphic Setting

The portion of Green Valley Road (GVR) that is frequently flooded by Green Valley Creek (GVC) is about 300 ft long and runs parallel to GVC as it approaches the bridge crossing of GVC (Figure 1). The confluence of Green Valley Creek (drainage area 6.1 sq. mi.) and Purrington Creek (drainage area 3.7 sq. mi.) is located about 0.6 miles upstream of the bridge. About 0.3 miles downstream of the bridge, Green Valley Creek joins Atascadero Creek.

The slope gradient of Green Valley Creek declines substantially as it emerges from the more confined valleys of Green Valley Creek and Purrington Creek as it approaches Green Valley Road. The typical slope in the lower portion of Purrington Creek and in Green Valley Creek upstream of the confluence of Purrington Creek is about 0.006 (0.6%). Below the confluence with Purrington Creek, the overall slope declines significantly to about 0.0017 (0.17%), including a reach about 600 ft (200 m) long where the gradient is near zero and where a high flow channel has historically diverged from the primary channel. The channel gradient gradually steepens downstream from this point to the bridge (0.0023), and



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steepens downstream of the bridge to 0.0033 (Figure 2). The average channel gradients noted above are indicative of reach-scale changes in channel gradient; the change in gradient is gradual.

Channel banks are high (about 10 ft or more under current conditions) and confine stream flow until a point about 0.3 miles upstream of the Green Valley Road Bridge, where channel confinement by high banks declines. At this location, a floodplain channel appears to have historically diverged from Green Valley Creek and flowed along the base of the low hill occupied by the Green Valley Cemetery (Figure 3). The location of this point of flow divergence corresponds to the near-zero gradient reach (Figure 2), and is also the point in Green Valley Creek where an historic and active floodplain begins.

During periods of peak stream flow, at the point of flow divergence, lower bank height allowed for lateral spread of flow into a historic swale-like floodplain channel. At present, this historic floodplain channel remains active; however, the historic primary channel has been abandoned and a new (“modern”) primary channel has become established (Figure 3).

Downstream from the point of flow divergence, flow depth and velocity declines relative to that in the more confined channel upstream, reducing sediment transport capacity over a distance of about 0.1 mile where the channel reaches the sharp bend in Green Valley Road adjacent to the Green Valley Cemetery (“Cemetery Curve”). Channel capacity in the modern primary channel near Cemetery Curve in 2014 is believed to be around 100 cfs, and excess flow spills across Green Valley Road (Figure 2). Ground elevation in the vineyard field lying to the east of Green Valley Road is about 2 to 8 ft lower than channel elevations above Green Valley Road (Figure 4), consequently, much of the peak flow of Green Valley Creek is routed across the vineyard toward the northeast where water drains into Atascadero Creek above its confluence with Green Valley Creek (this is discussed in greater detail below). Deposits of sediment three feet thick or more have closed the upper end of the historic primary channel of Green Valley Creek except during periods of flood flow. The lower portion of this channel nearer to the bridge has been less affected by sedimentation and can be described as a backwater slough, and likely provides velocity refugia for over-wintering salmonids. The modern primary channel has reportedly been used by steelhead for spawning.

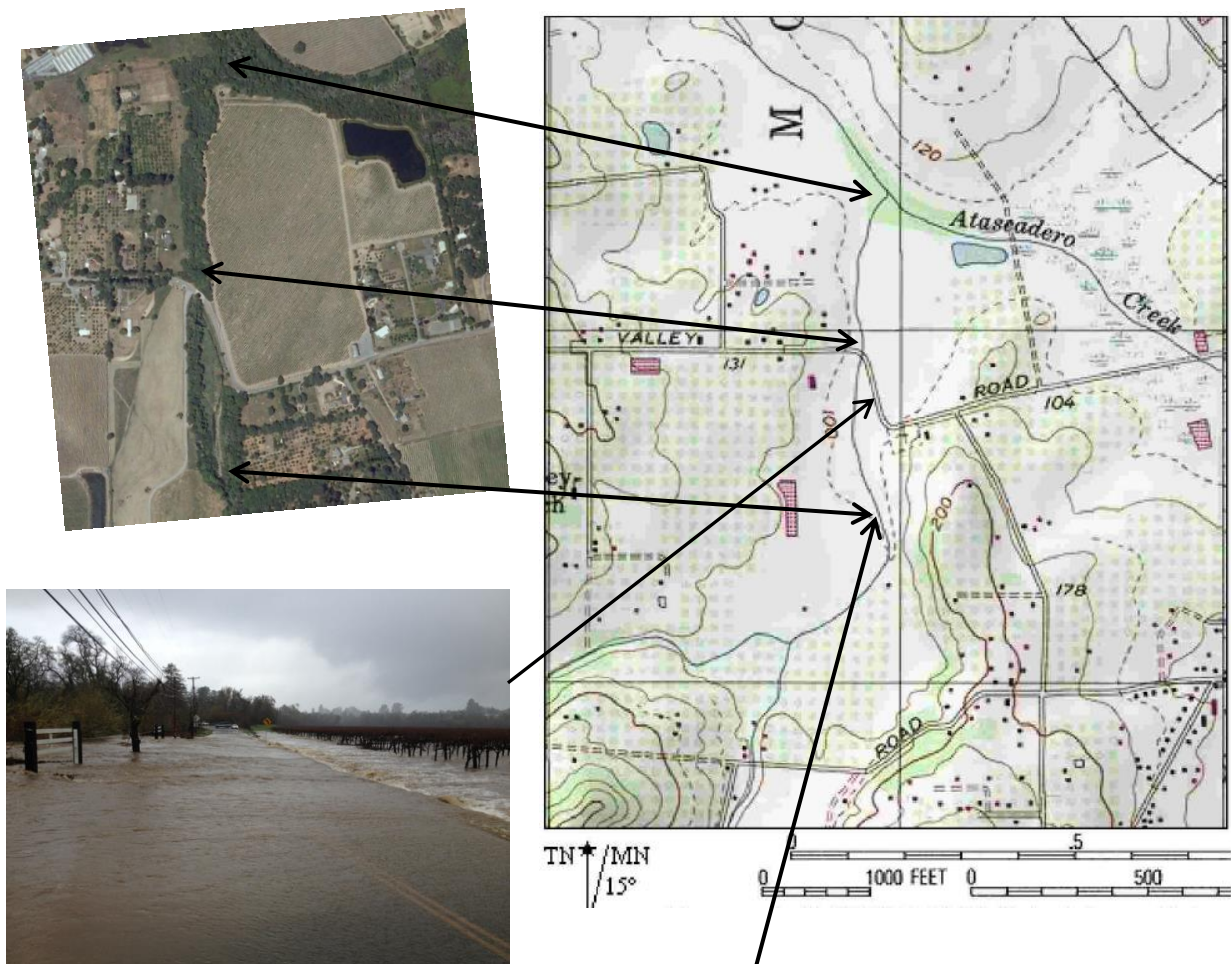


Figure 1. Vicinity map, Green Valley Road at Green Valley Creek. Lower left photo of flooding over Green Valley Road, December 2012 (photo courtesy of John Green)

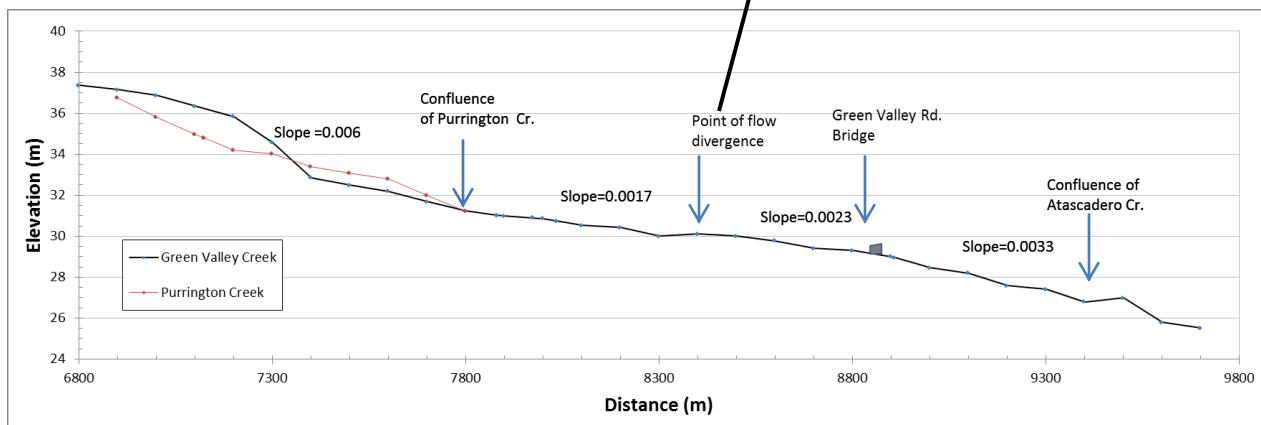


Figure 2. Long profile of Green Valley Creek above Atascadero Creek (note length units in meters).

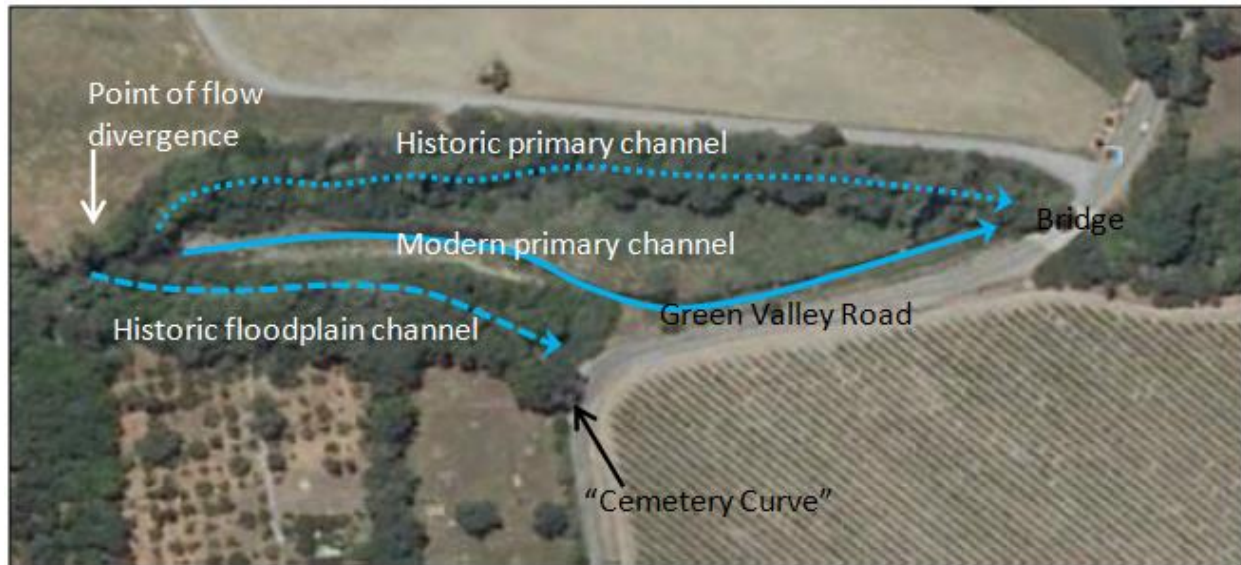


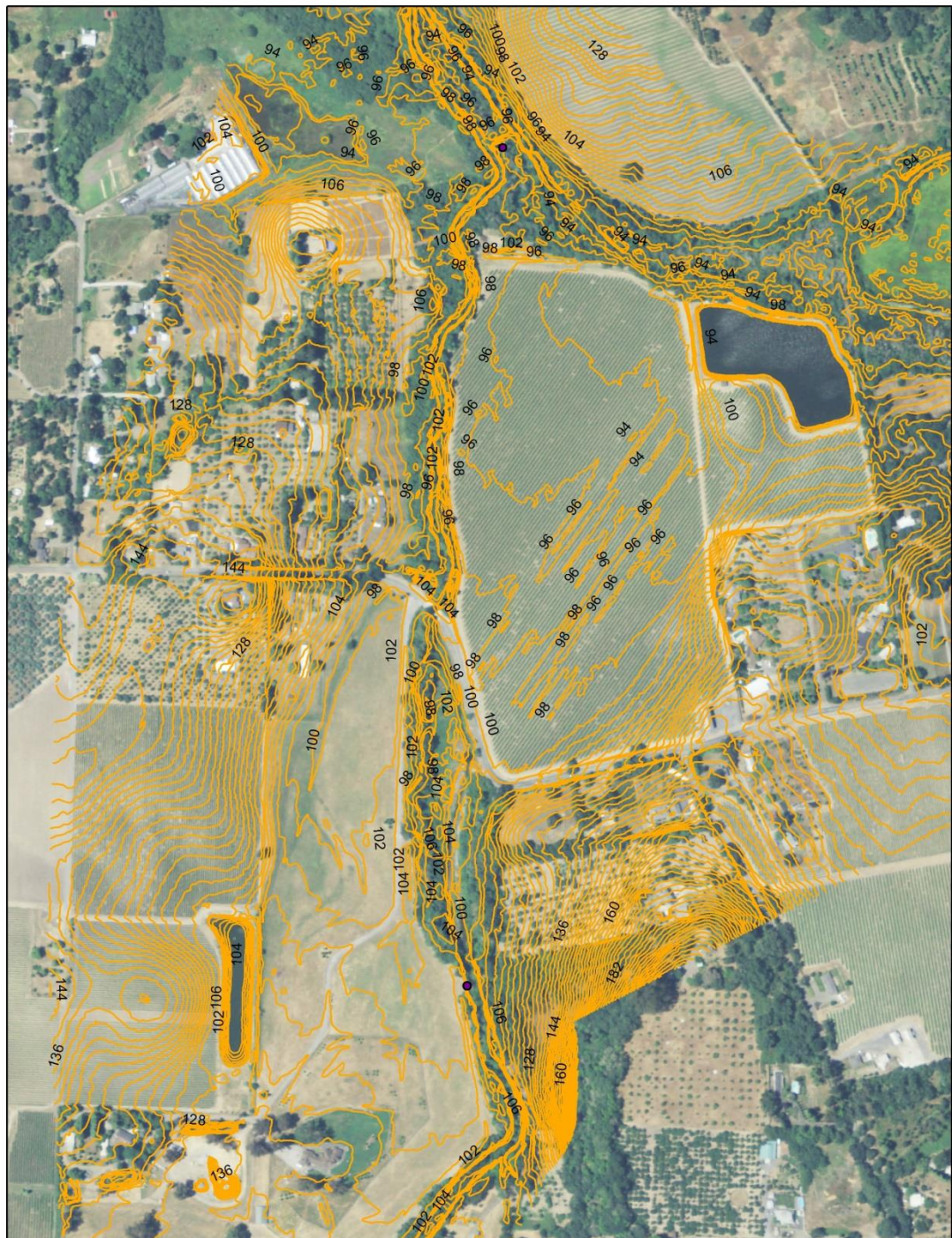
Figure 3. Channels of Green Valley Creek near Green Valley Road Bridge.

Erosion and Sedimentation

Our field investigation of reach of Green Valley Creek extending from the confluence of Purrington Creek to just beyond the bridge found that most of the sediment in the channel is gravel. Five samples of the bed material indicate that 70% of sediment is gravel or larger (> 2 mm diameter), and 90% is coarse sand or larger (> 0.5 mm). Furthermore, 95% of the sediment is less than about 25 mm (1 inch) in diameter. Consequently, to the extent that channel sedimentation contributes to flooding, it is gravel-size sediment eroded from the watershed that is of primary concern.

Watershed erosion processes contribute to sedimentation and flooding in the vicinity of Green Valley Road. The most evident sources of sediment in the lower watershed is mass wasting of soil from stream bank erosion and landslides on stream banks in the valleys formed by Purrington Creek and Green Valley Creek, however, these sources contain relatively little gravel. Bank erosion and streamside landslides in steeper tributary streams have a greater potential for contributing gravel to stream channels. Erosion from roads, cultivated fields and drainage systems may be substantial, but coarse sand and gravel from these sources is not as effectively delivered to mainstem channels that carry this bed load sediment downstream.

Our sediment source assessment of Upper Green Valley Creek and Purrington Creek completed December 2014 indicates that gravel in these watersheds originates primarily in the Green Valley Creek watershed, with minor contributions from Purrington Creek. The estimated rate of delivery of gravel to the vicinity of Green Valley Road is about 410 cubic yards per year, of which 277 cubic yards is attributed to erosion associated with roads. Bank erosion and small streamside landslides account for the remainder, with 71 cubic yards per year estimated to originate from tributary streams and 62 cubic yards from the mainstems of Purrington and Green Valley Creek. Road erosion rates were extrapolated from surveys of roads to quantify sediment savings that could be realized by road improvements; we believe these data tend to over-estimate actual erosion. Consequently, the sediment assessment suggests minimum annual gravel erosion rates in the watershed of about 133 cubic yards, ranging up to 410 cubic yards depending on the actual quantity delivered from roads. Large scale landslides are not included in this estimate, and could be significant.



-2 Foot Contours



0 250 500 1,000 Feet

Figure 4. Topographic map of Green Valley Creek and Atascadero Creek study area.

Note: Elevations contours < 94 ft are not generally labeled except for the 92 ft contour in the northeast corner of the vineyard adjacent to the reservoir and Atascadero Creek.

The estimated annual rate of sand-sized sediment delivery to stream channels is about 2,200 cubic yards; this size material comprises up to about 30% of the bed material, and is found in increasing proportions in deposits on stream banks and the floodplain. Sand is transported in suspension and as bed load, and appears to be the size of material most significant for floodplain sedimentation.

In both Purrington Creek and upper Green Valley Creek, there is abundant evidence of stream bank erosion and channel incision. In Purrington Creek channel incision is ongoing in part because the underlying sandstone bedrock of the Wilson Grove Formation is weak and vulnerable to erosion in the stream bed. Based on a channel spanning tree root of a large Douglas-fir observed in Purrington Creek, the rate of channel incision was estimated to be about 0.1 ft/year over about the past 50 years. In Green Valley Creek, the bedrock is resistant to erosion and the extent of incision is therefore limited. Nevertheless, it is evident that long-term channel incision and resultant bank erosion has occurred over a period of decades or longer, and is likely to continue. Historic channel incision in the watershed may be related to the processes of sedimentation and floodplain expansion that appear to be occurring at present in the vicinity of the confluence of Green Valley Creek and Atascadero Creek, and near Green Valley Road.

There are widespread indications of channel bed aggradation in lower Purrington Creek and in Green Valley Creek above the Purrington Creek confluence. Numerous mature alder trees, both living and dead, that initially grew from lower bank or bar elevations are now below the water surface at their roots. There are also gravel and sand bars that have buried the base of established trees to depths of 2 to 3 ft in some locations. These indicators of channel bed aggradation extend down Green Valley Creek to Atascadero Creek.

Sediment diameter distributions in Green Valley Creek and Purrington Creek also suggest, as described below, that sedimentation is occurring in Green Valley Creek in the vicinity of Green Valley Road where the stream channel gradient and confinement declines. OEI geomorphic assessments of Purrington Creek (2010) and Upper Green Valley Creek (2013) characterized typical channel surface sediment size (diameter) distributions. In Purrington Creek, median surface sediment sizes range between about 12 and 23 mm; in Upper Green Valley Creek, the median ranges between about 14 and 39 mm. Within a few hundred feet downstream of the confluence with Purrington Creek, the median surface sediment size was about 15 mm in 2013, and declined to 10 mm or less beginning at the flow divergence.

Sub-surface sediment size distributions are representative of the bed load moving through the channel. Sub-surface sediment was sampled at five locations in 2013 in the reach between the Purrington Creek confluence and a point just downstream of Green Valley Road; one such sample was collected in lower Purrington Creek in 2010. The two upstream-most of these six samples (including the 2010 sample from Purrington Creek) had median diameters of 6 and 7 mm (average 6.5 mm), while the four more downstream samples had median diameters of 3, 4, 5 and 6 mm (average of 4.5 mm). This apparent decline of 2 mm (about 30%) in the median diameter of the sub-surface sediment size distribution can be interpreted to indicate a decline in the size of sediment transported and implies a regime of sediment deposition.

Systematic decline in sediment size on streambeds as described above is typically correlated with declining slope, and where this occurs over relatively short distances, net sediment deposition (sedimentation) typically occurs. The available data for channel slope and sediment size, along with observations of buried mature riparian trees, strongly indicate ongoing sedimentation and channel aggradation in the lower reaches of Green Valley Creek above Atascadero Creek.

We estimated bed load (i.e. gravel and sand) sediment transport rates in the reach we analyzed with an numerical hydraulic model (discussed below). Bed load transport is a complex process, and numerous equations have been developed to estimate bed load transport rates. Using hydraulic data from our model of stream flow, we estimated that during the design flood of 950 cfs bed load transport rates in the confined reach upstream of the channel divergence range between about 100 and 200 cubic yards and declines to a fraction of that rate where flood flows cross Green Valley Road. This significant decline in estimated bed load transport rate is another strong indication of sediment deposition.

Historical data regarding stream bed elevation at the Green Valley Road Bridge provides documented evidence of long-term sedimentation. County of Sonoma Department of Transportation and Public Works provided as-built diagrams for the Green Valley Creek Road Bridge over Green Valley Creek. In 1968, the channel bed at its deepest point was about 14 ft below the top of the bridge deck at its upstream edge. Observations by fisheries researchers working in Green Valley Creek report that a person could walk under the bridge upright around the year 2000, indicating that the elevation difference between the channel and the bridge deck was about 7.5 ft at that time. In spring of 2013, the elevation difference between the low point of the stream bed and the bridge deck was 5 ft. These data allow estimates of the channel aggradation rate: for the period 1968-2000, mean annual aggradation was about 0.20 ft. For the period 2000-2013, the rate was about 0.19 ft/yr. The channel bed aggraded about 9 ft at the Green Valley Road Bridge since 1968, a mean rate of 0.2 ft/yr. Over a 1,000 ft reach centered on the bridge that appears prone to sedimentation and using an estimate of the mean channel bed width of 22 ft, this aggradation rate suggests about 160 cubic yards per year of sediment deposition, of which sand likely comprises at least 30% of total sedimentation. This quantity of sediment deposition is plausible given estimated annual inputs of gravel in the watershed in the range of about 130 to 400 cubic yards.

Sedimentation has also occurred in Atascadero Creek upstream of the confluence with Green Valley Creek. The rate of aggradation in Atascadero Creek is not well-documented at this time, however, an observer familiar with operation of the Graton water treatment facility located about 0.5 miles upstream along Atascadero Creek reported about 5 to 6 ft of aggradation since about 1979 at a point near the channel of Atascadero Creek. This suggests a mean aggradation rate of about 0.15 to 0.18 ft/yr, similar to that documented at the Green Valley Road Bridge.

Causes of sedimentation could include accelerated watershed erosion and increased flow resistance caused by the growth of dense riparian vegetation. Gradual sedimentation reduces channel capacity by reducing the cross-sectional area of the channel. Dense riparian vegetation increases flow resistance, particularly during periods of flood, reducing water velocity. Sediment transport capacity is proportional to water velocity, so this tends to increase the rate of sedimentation. Reduction in water velocity also increases flow depth. Hence, there is significant interaction between the process of sedimentation, riparian vegetation condition, and flooding.

The situation in lower Green Valley Creek is further complicated by a similar set of interactions in Atascadero Creek and Green Valley Creek below the confluence of Atascadero Creek. Flows in Atascadero Creek encounter a densely vegetated floodplain, and significant sedimentation has occurred. These combined effects raise the elevation of flood flows. During periods of flood, flows descending from Green Valley Creek encounter a pool of water on the Atascadero Creek floodplain. This creates a hydraulic backwater effect, causing a greater tendency for high water, flooding and sedimentation in Green Valley Creek. It is likely that this phenomenon has become more pronounced over recent

decades, and has probably contributed to aggradation of Green Valley Creek in the vicinity of the Green Valley Road Bridge, adding to the effects of sedimentation and increased riparian zone vegetation in Green Valley Creek. Evidence for this assessment from interpretation of historic aerial photography is discussed below.

Historic Riparian Zone Conditions and Patterns of Flow

The recent history of channel and floodplain conditions in the vicinity of Green Valley Road and the Atascadero/Green Valley Creek confluence was investigated primarily using historic aerial photography, supplemented by information from local observers and available State and County records regarding the bridge and streambed alterations in the reach upstream of the bridge. Following is a narrative describing our understanding of past changes in channel conditions and the evolution of the channel and floodplain in this area as it exists at present. Significant developments are enumerated and discussed below. The discussion is illustrated by aerial photo interpretation summarized in Figure 5a & 5b.

1. Growth and expansion of riparian vegetation in the Atascadero/Green Valley Creek channel and floodplain. There has been significant growth of riparian zone vegetation along Green Valley Creek and Atascadero Creek, as can be seen in the series of aerial photographs spanning the period 1942 to 2006 (Figure 5a & 5b). In 1942, much of the area currently occupied by dense riparian woodland and wetlands had either grass cover or shrubs and trees at much lower density. The extent of dense riparian shrubs and trees along Atascadero and Green Valley Creeks can be seen to expand substantially from 1942 to 1961 to 1980.

This gradual change in vegetation could have resulted from changes in management of floodplain vegetation (i.e. cessation of agricultural activity), but is also consistent with gradual sedimentation and channel aggradation, widening floodplain and a higher water table. It is likely that agricultural practices in the late 1800's and early 1900's included active drainage of riparian wetlands with grazing and planting in these areas. This appears to have been the case in Atascadero Creek based on conditions revealed in 1942 aerial photography. We believe that it is likely that agricultural practices c. 1900 or earlier cleared riparian areas and provided for accelerated drainage.

2. Gradual shift in the pattern of flow in Green Valley Creek near the Green Valley Road Bridge. As shown in Figure 5a, the change in flow pattern is believed to have occurred as a result of the colonization of riparian areas by dense native and exotic vegetation and gradual sedimentation in Atascadero Creek and Green Valley Creek at their confluence beginning between 1942 and 1961. This initiates gradual sedimentation in Green Valley Creek above the confluence of Atascadero Creek.

In 1942 and 1961, Green Valley Creek occupies its historic primary channel, and a historic floodplain channel diverges from the main channel and flows along the base of the hill occupied by Green Valley Cemetery. The historic floodplain channel appears to be routed across or under Green Valley Road at Cemetery Curve in a ditch on the east side of Green Valley Road, rejoining Green Valley Creek downstream of the bridge.

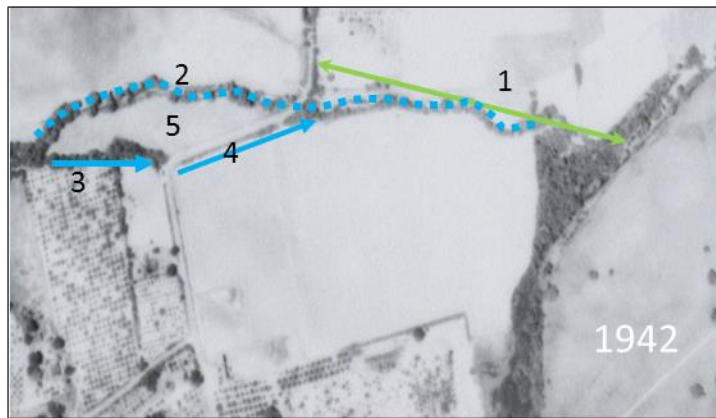
In 1980, the vegetation in this ditch has grown, and there is a subtle indication of flow to the northeast into the field north and east of Cemetery Curve (Fig. 5a). Sedimentation of Green Valley Creek has presumably begun to affect channel capacity by this time.

In 1987, one year after a historic flood on the Russian River, there appear to have been significant changes in flow patterns (Fig. 5b). Distinct channels and substantially expanded stands of riparian vegetation are present in the field east of Green Valley Road. The strip of land between Green Valley Creek and Green Valley Road (a farm field or pasture through 1980) shows signs of overbank flow from Green Valley Creek from west to east downstream of the point of flow divergence.

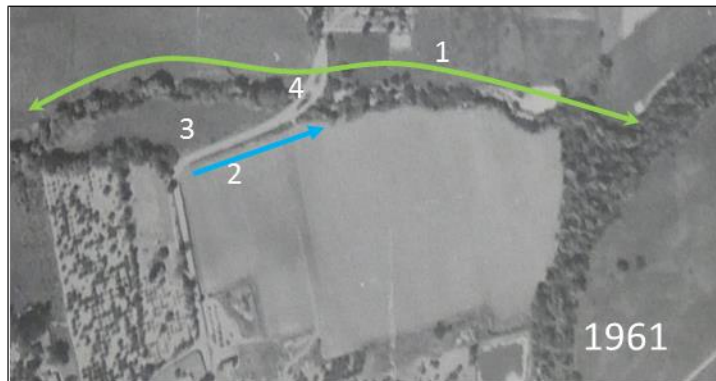
In 1999, a new path of stream flow of Green Valley Creek appears in the alignment of the modern primary channel (Fig. 5b). The evolution of the channel in this area was influenced by efforts by the landowner to repair stream bank damage and to harvest accumulated silt, sand and gravel by agreement with California Department of Fish & Game (CDFG). The field east of Green Valley Road in 1999 is under cultivation as a vineyard (this change occurred prior to 1993), and evidence of flood flows across Green Valley Road and the vineyard to the northeast is readily apparent.

3. Sedimentation of Green Valley Creek and establishment of a modern primary channel alignment. As previously discussed, observers reported that there was sufficient space under the bridge to walk under it upright around the year 2000, indicating about 6 ft of clearance between the channel bed and the bottom of the bridge deck. At that point in time (c. 1999, Fig. 5b), about 6.5 ft of sedimentation had occurred since 1968. In 2004, CDFG issued a Streambed Alteration Agreement (SAA) with the property owner to excavate about 500 cubic yards of sediment from the floodplain west of Green Valley Road about 300 ft upstream of the bridge and west of what is describe in the SAA as the “overflow channel”, which corresponds to the location of the modern primary channel as it nears the bridge. In addition, the SAA permitted thinning of willows and pruning low branches along 400 ft of “overflow channel” to reduce flow resistance, removal of down woody debris, and enlargement of the “overflow channel” approaching the bridge using hand tools.

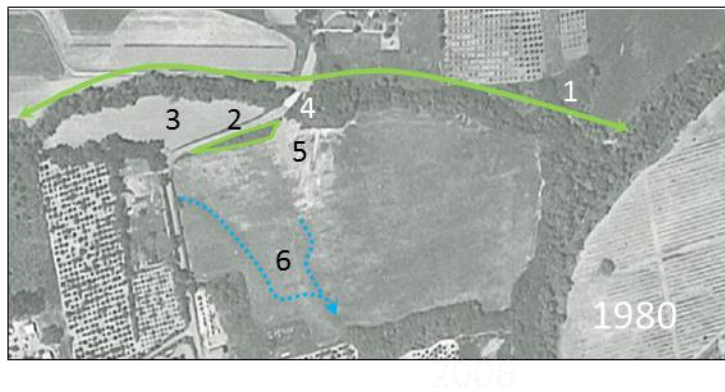
Following regional flooding that occurred Dec. 31, 2005, it is clear in the 2006 photograph (Fig. 5), that Green Valley Creek’s flood flows were routed through the modern primary channel, across Green Valley Road, and across the vineyard to the northeast toward the topographic low point near a reservoir at the edge of Atascadero Creek. It is likely that sedimentation during this event contributed to the in-fill and abandonment of the historic channel of Green Valley Creek. Riparian vegetation has begun to grow in the former farm field adjacent to and west of Green Valley Road between Cemetery Curve and the bridge. The 2006 photo reasonably represents current conditions, however, the extent and density of riparian vegetation in and near the new channel of Green Valley Creek has significantly increased since that time. Flooding of Green Valley Road has become more frequent; a local property owner observes that as of 2012, one inch of rain in a 24-hour period produces enough runoff to overtop Green Valley Road.



1. Sparse riparian vegetation along Green Valley Creek (GVC) and at confluence with Atascadero Creek (AC); (green line).
2. Primary channel of GVC (dotted blue line).
3. Historic floodplain channel (HFC) (blue line) diverges from mainstem GVC and flows through riparian veg. to “Cemetery Curve”.
4. HFC flows routed in ditch (blue line) adjacent Green Valley Rd (GVR) back to mainstem GVC downstream bridge on east bank.
5. Agricultural field between GVC and GVR.



1. Growth/expansion of rip. veg. along GVC and at confluence with AC (green line).
2. HFC flows routed in ditch (blue line) adjacent GVR back to GVC downstream bridge.
3. Ag. field between GVC and GVR.
4. Second bridge span added upstream of historic bridge span.



1. Growth/expansion of rip. veg. along GVC and at confluence with AC (green line).
2. Growth/expansion of rip. veg (green polygon) in ditch adjacent GVR
3. Ag. field between GVC and GVR.
4. Modern bridge configuration built 1968; 14ft elevation difference from bridge deck to channel in 1968
5. Indications of fill (light patches) at downstream end of ditch near bridge.
6. Indications of flow across southeast corner of field east of GVR (dotted blue lines).



Figure 5a. Summary interpretation of historic aerial photography, 1942-1980.



1. Growth/expansion of rip. veg. along GVC and at confluence with AC (green line).
2. Growth/expansion of rip. veg. in ditch adjacent GVR (green polygon).
3. Indications of overbank flow across ag. field between GVC and GVR (dashed blue line).
4. Development of channel across field east of GVR consistent with interruption of ditch flow c. 1980 (dashed blue line).



1. High flows routed in modern primary channel alignment through former ag. field from point of flow divergence (blue line).
2. Elimination of ditch adjacent GVR.
3. Aggradation of 6.5 ft at bridge since 1968.
4. Evidence of broad flood flow path across vineyard field east of GVR consistent with flood flow patterns c. 2012.
5. Earthen levee (construction date unknown)



1. Significant channelized flow across former ag. field in modern primary channel alignment (blue line)
2. Establishment of new riparian/wetland vegetation (green polygon) in former ag. field
3. Evidence of broad flow path across vineyard field east of GVR consistent with flood flow patterns c. 2012.



Figure 5b. Summary interpretation of historic aerial photography, 1987-2006.

Hydrologic and Hydraulic Analysis for Green Valley Creek at Green Valley Road

To evaluate flooding mechanisms and identify feasible flood mitigation strategies, it was necessary to develop a hydrologic model to simulate design storms and a hydraulic model to simulate stream flow through the reach of Green Valley Creek that is prone to frequent flooding. There are many techniques and models that could be utilized for these purposes. For this study, we synthesized rainstorms to use as input to a watershed model simulating runoff process. The watershed model produces simulated hydrographs for Green Valley Creek. A related hydraulic model was used to simulate flow routing in the channel and on the floodplain, as well as to evaluate alternatives for flood mitigation.

Ideally, a flood mitigation study utilizes stream flow records from long-term gauging stations monitoring the river or stream of interest. Although short-term gauging records for Green Valley Creek have recently become available from monitoring studies conducted by the Center for Ecosystem Management and Restoration (CEMAR) under the auspices of the Russian River Coho Partnership, the available data are insufficient for estimating flood magnitude and frequency.

One available alternative is to estimate flood magnitude and frequency using regional flood frequency equations developed by the US Geological Survey (USGS) based on data from stream gauges with lengthy periods of record in the region of interest. The USGS computer program National Streamflow Statistics V6.0 (NSS) estimates flood magnitude and frequency based on drainage area, mean annual rainfall, and watershed elevation. The NSS prediction method utilizes a multiple regression equation, and NSS output provides a mean estimated discharge as well as an estimate of the error range of the estimate (Table 1). The predicted magnitude of flow for any given recurrence interval has a relatively wide prediction interval. Consequently, the peak flow estimates from the USGS NSS method given in Table 1 have limited value for this study; these estimates were used to constrain and loosely calibrate a watershed model as described below.

Table 1. Flood frequency and magnitude estimates for Green Valley Creek near Green Valley Road.

Recurrence Interval (yrs)	Mean Prediction	Low Range Prediction (cfs)	High Range Prediction
2	645	265	1570
5	1220	585	2550
10	1630	812	3290
25	2180	1120	4240
50	2590	1330	5050
100	3020	1510	6030
200	3420	1710	6860
500	3960	1930	8130

Design Storm Rainfall

To estimate flood magnitude and frequency, we determined characteristics of design rainstorms using techniques from *NOAA Atlas 14 (Volume 6, Version 2.0)*¹ and modeled watershed runoff processes. OEI previously developed a physically-based, spatially-distributed model of Purrington Creek (OEI 2010) utilizing the model code MIKE SHE² and is developing a model for the entire Green Valley Creek watershed to its confluence with the Russian River including Atascadero Creek. The hydrologic model for upper Green Valley Creek to its confluence with Atascadero Creek was available, so we elected to use it to simulate stream flow hydrographs for this flood mitigation study.

The watershed hydrologic model simulates runoff processes and stream flow from rainfall inputs to the model and produces a corresponding stream flow hydrograph. To simulate peak stream flow events we obtained rainfall depths distributed over the watershed for the 24-hour storm durations for 2-, 10-, and 100-year recurrence intervals, and then synthesized design rainstorms using a balanced rainfall distribution over 10-minute intervals. The normalized cumulative precipitation curve (Figure 6) describes the distribution of rainfall as a proportion of total rainfall for 24-hour design storms. Based on experience from a recent analysis in the region³, we found that this rainfall distribution produced simulated hydrographs that closely matched observed runoff hydrographs for a small coastal watershed.

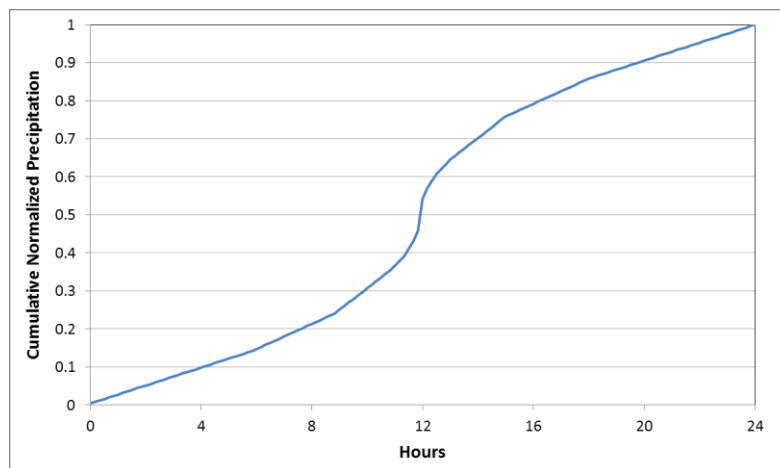


Figure 6. Normalized cumulative precipitation curve for 24-hour design storms for input to hydrologic model.

Maximum accumulated 24-hour rainfall depths for the 2-, 10- and 100-yr storms were 120, 200 and 280 mm, respectively. These values are equivalent to about 4.7, 7.9 and 11.0 inches of rainfall.

¹ Perica, Sanja et al. *NOAA Atlas 14: Precipitation-Frequency Atlas of the United States, Volume 6 Version 2.0 California*. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Weather Service, 2011.

² DHI (www.dhigroup.com)

³ OEI (2013). Easkoot Creek Hydrology and Hydraulics Study. Prepared for Marin County Flood Control and Water Conservation District.

Design Storm Hydrographs

The watershed hydrologic model produced a simulated flow hydrograph (Figure 7) based on the synthesized rainstorm inputs shown in Figure 6. The 2-year rainstorm produced peak stream flow of about 951 cfs; compared to USGS predictions (Table 1), this is about 50% higher than the mean estimate for a 2-year recurrence interval flow, but well within the range of prediction. Observations from two recent storms on 2/9/2014 and 12/11/2014 provide a means of qualitatively evaluating the accuracy of the flow estimate. The flood extent and degree of road overflow predicted with the hydraulic model for the 951 cfs flow was greater than what was observed during the February 2014 storm and somewhat less than what was observed during the December 2014 storm. Rainfall totals (24-hr) at the CIMIS Santa Rosa gauge located east of Sebastopol (the nearest hourly gauge) for these two events were 4.3 and 4.2 inches respectively. These rainfall totals are close to the 2-yr estimate of 4.7 inches and the qualitative comparison of simulated flood extents and the observations from the two recent events suggest that the model estimate of the 2-yr flow is reasonably accurate.

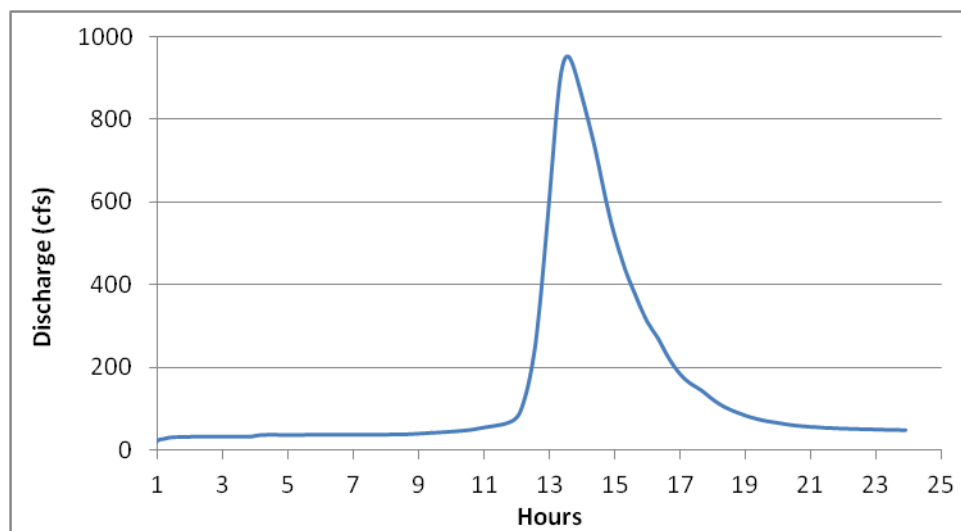


Figure 7. Green Valley Creek simulated hydrographs for the 2-year synthesized rainstorm.

During the alternatives analysis it became apparent that the severity of the flooding conditions and site constraints were such that it would not be feasible to provide flood protection for events much larger than the 2-yr event. Thus the focus of the analysis became finding a solution that would substantially reduce high frequency flooding of Green Valley Road; the 2-yr event was selected as the most appropriate flow magnitude for our assessment of flood mechanisms and mitigation strategies.

Hydraulic Model

The model MIKE FLOOD⁴ was used to simulate flow routing through the channel and floodplain of Green Valley Creek from a point just below its confluence with Purrington Creek to a point just downstream of its confluence with Atascadero Creek (Figure 1). MIKE FLOOD combines a one-dimensional model for

⁴ DHI - (www.dhigroup.com)

channelized flow (MIKE 11, similar to HEC-RAS) with a two-dimensional model for flow on the floodplain (MIKE 21).

The hydraulic model requires topographic information: a series of channel cross-sections for the one-dimensional channel flow model and a digital terrain model (DTM) for the two-dimensional floodplain flow model. In the autumn of 2012, OEI obtained grant funding from California Department of Fish and Wildlife for a LiDAR-based topographic mapping project for the channel and floodplain areas of Green Valley Creek and its principal tributaries. The LiDAR data produced a 1-ft contour interval map of the floodplain and channel. These data were supplemented with field surveys of topography in the vicinity of Green Valley Road early in 2013 using a total station survey instrument. The field survey data were used to evaluate the accuracy of the LiDAR DTM, particularly in the channel and riparian zone where dense vegetation canopy and the water surface of Green Valley Creek were likely to interfere with the LiDAR data. A report summarizing this evaluation of the LiDAR data was produced by OEI in February of 2013.

Using the LiDAR DTM, with a few adjustments based on field topographic data, the MIKE FLOOD model was constructed. In addition to topographic information, the model requires that flow resistance (roughness) values be assigned for the model area; these were assigned using a combination of roughness values from scientific literature and experience from other similar projects. The hydraulic model was calibrated by evaluating locations where flooding has/has not been observed or reported by local property owners. This calibration included limited adjustments to roughness values used in the one-dimensional channel model as well as refinements to topographic representations of the boundary between one-dimensional channel flow and two-dimensional floodplain flow, primarily along the eastern channel margin upstream of Cemetery Curve. The hydraulic model calibration was based on the 2-year stream flow under current conditions.

The simulated distribution and maximum depth of flow on the floodplain under existing conditions for the 2-year event is shown in Figure 8. At maximum, approximately 443 cfs (47% of the total flow) exits the channel on the right bank and flows over Green Valley Road and into the vineyard along the reach upstream of the bridge. The bridge itself does not overtop, however maximum water surface elevations are above the bridge soffit. The vineyard floods both from the road overtopping and, along its northern edge, from backwater flooding caused by high water surfaces in Atascadero Creek. Portions of the pasture on the left (west) bank floodplain become inundated due to backwater flooding through the culvert located just west of the bridge. The patterns of flooding depicted in Figure 8 (peak discharge of about 951 cfs) are consistent with that observed during the two recent events in February and December of 2014. In particular, the extent of submergence over Green Valley Road, the location and extent of flow to the northeast across the vineyard, and the ponding of water in the northeast corner of the vineyard in the Atascadero Creek floodplain were observed during both events.

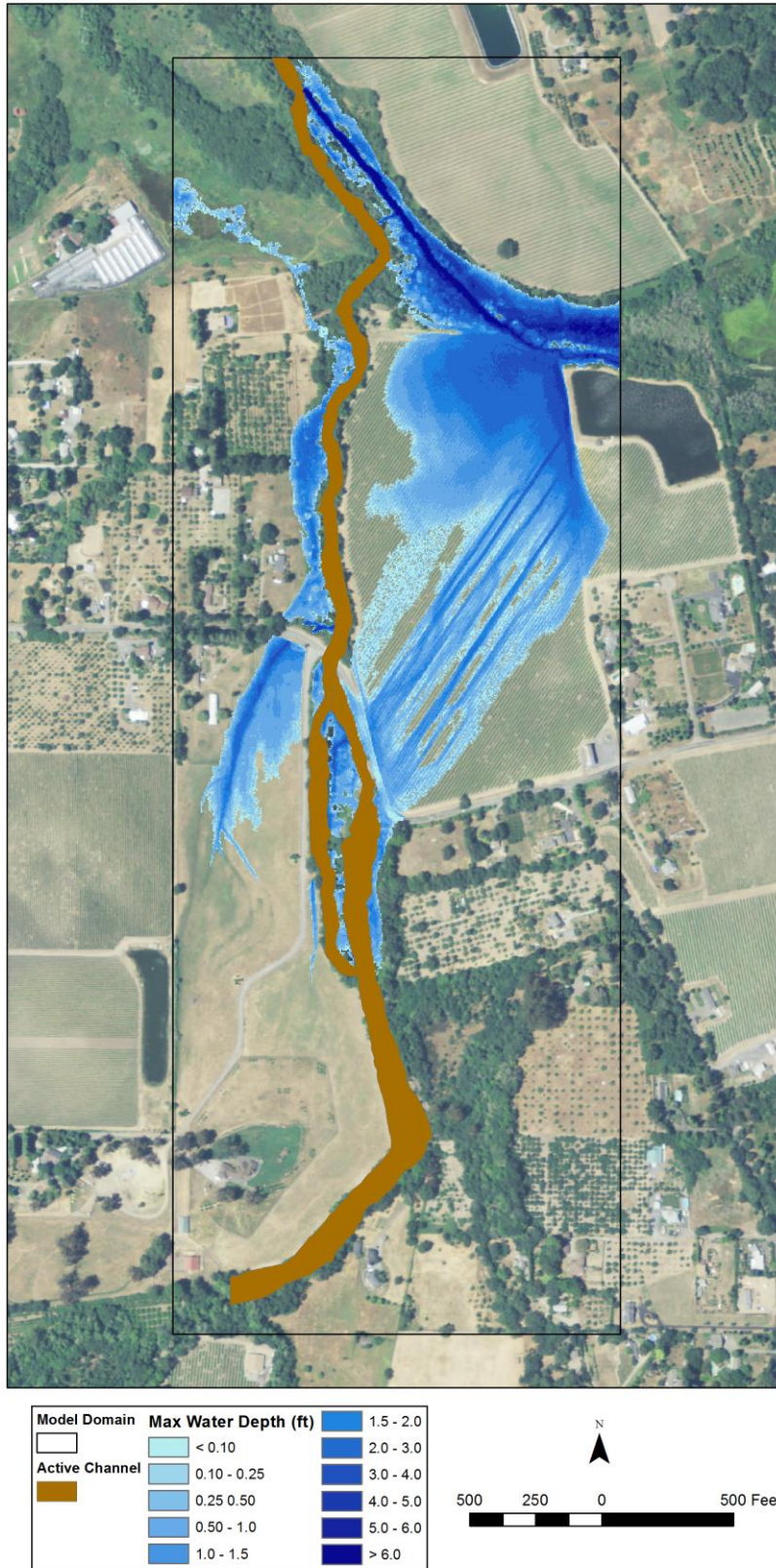


Figure 8. Baseline Flood, 2-year Recurrence Interval

Alternatives to Mitigate Flooding

The primary objectives of this study are to evaluate flooding mechanisms and develop and evaluate feasible actions that could reduce the frequency and extent of flooding across Green Valley Road. In addition to damages to private property, flooding periodically makes Green Valley Road impassable, and continuing flooding across Green Valley Road may prove a risk to the integrity of the road grade itself. As of late December 2014 local residents have engaged county officials in response to the most recent flooding events which have degraded the road surface and required emergency repairs. Moreover, flooding across the road and the vineyard creates risks to endangered coho salmon. It is generally assumed that efforts to prevent flooding across Green Valley Road will simultaneously address existing flood impacts to downstream property, Green Valley Road, and coho salmon. Consideration is also given to potential flooding impacts to property west of Green Valley Creek and upstream of the Green Valley Road Bridge, as well as habitat conditions for coho salmon during periods of peak flow for which mitigation alternatives are developed.

The hydraulic model, MIKE FLOOD, provides model outputs that can be evaluated in great detail with respect to the spatial distribution, depth, velocity and direction of flow in the floodplain (two-dimensional model domain) and the depth and velocity in the channel (one-dimensional model domain). This level of detail may be useful in evaluating the effects of a smaller set of alternatives on fish habitat conditions and for design and engineering. Such detailed model output data are not presented here.

The approach to evaluating alternative flood mitigation strategies was developed in consultation with Gold Ridge RCD. This process involved conceptualizing alternatives, devising a means to represent them in the hydraulic model, running the model for each alternative scenario, and evaluating the alternative's effectiveness. The primary means to evaluate effectiveness of flood mitigation was by comparing model results for water surface elevations and maximum extent and depth of flooding to that for existing conditions as shown in Figure 8.

Dredging of the active wetted stream channel was not considered in this analysis owing to the potential impacts on coho salmon and steelhead trout that are believed to inhabit this reach throughout the year. In addition, given the pattern of sedimentation observed, dredging would likely need to extend below the Green Valley Road Bridge to maintain a gradual downstream channel grade. Given the estimated sedimentation rate of 0.2 feet per year since 1968, and other evidence of sedimentation, further evaluation of potential future sedimentation impacts on flood mitigation alternatives may be required. Potential methods to manage sedimentation without causing undue harm or risk to salmonids would need to be considered in developing a feasible sediment management strategy.

A summary of the six most effective alternatives is provided in Table 2, including an assessment of the efficacy of each alternative mitigation strategy. The principal strategies considered to form flood mitigation alternatives were:

- A)** raising the elevation of Green Valley Road where it is susceptible to flooding,
- B)** increasing the channel capacity in the reach upstream of the bridge including:
 - re-opening the historic primary channel of Green Valley Creek (Fig. 3),
 - skimming accumulated sediment upstream of the bridge without channel dredging,
 - modifying the west bank of Green Valley Creek just upstream of the bridge
- C)** installation of a flood bypass channel(s) for Green Valley Creek to convey flows past the flood-prone reach of Green Valley Road to various locations downstream,

- D) replacing the existing bridge with a higher span, and
- E) re-positioning or removing the levee along the east bank of Green Valley Creek downstream of Green Valley Road.

A total of thirteen flood mitigation scenarios comprised of one or more of these five general strategies were modeled; each strategy is described below along with a discussion of the effectiveness of the strategy. The most effective strategies or combinations of strategies were used to develop six alternatives as summarized in Table 2. Flood extent and depth maps and water surface profiles for representative effective flood mitigation alternatives are also provided (Figures 9 through 16).

Strategy A - Elevating Green Valley Road

Green Valley Road was elevated uniformly by ~3-feet by modifying the model topography from the eastern side of the bridge through Cemetery Curve (a distance of ~900-ft). This proved to be effective at eliminating road flooding during the 2-yr event along the reach upstream of the bridge, however the roadway was instead flooded at the bridge itself. This result shows that under existing conditions, flow restriction at the bridge is not the principle cause of flooding, however when the road is elevated, more flow is conveyed to the bridge and the bridge becomes the limiting factor. It also suggests that in order for this strategy to be effective the bridge would need to be replaced in addition to the re-grading of the road profile (Figure 9). Alternatively (as discussed in more detail for Strategy E), removing the downstream levee relieves the constriction at the bridge enough such that bridge replacement may be unnecessary (Figure 10).

Maximum water surface elevations increase (relative to existing conditions) by 0.5 to 1.0-ft upstream of the bridge and 1.0 to 1.5-ft downstream of the bridge (Figure 11). The cessation of road overtopping results in a significant reduction in flooding in the southern portion of the vineyard, however significant flooding still occurs in the northern portion of the vineyard owing to backwater flooding from Atascadero Creek (Figure 9). In the western pasture significant increases in flood depths and flood extent occur as a result of the higher road grade. This phenomenon results from the combined effects of less water overtopping the road and the inability of the system to convey this water to the reach below the bridge caused by the backwater at the confluence with Atascadero Creek and the limited conveyance at the bridge which results in increased overbank flow along the left bank.

Strategy B - Increasing Conveyance Above the Bridge

Several actions are possible for increasing channel conveyance in the reach upstream of the bridge. These include re-activating the historic main channel by removing the plug of sediment that has been deposited at the channel head, skimming the bar deposit that has formed between the historic and present main channels, and widening the flow-restricting cross section on the left bank immediately upstream of the bridge by removing the large tree growing there as well as reshaping the left bank.

All three of these actions were implemented in the model and simulated in combination. Maximum water surface elevations decrease by as much as 1.0-ft in the vicinity of the historic main channel restored to allow flow, however elevation changes are relatively minor along the flood-prone reach upstream of the bridge (Figure 11). Road overtopping and vineyard inundation is reduced somewhat (Figure 16), but significant road overtopping still occurs (~23% reduction in maximum overtopping flow). The relatively minor improvements resulting from increasing conveyance above the bridge can be

attributed to the fact that flow is unable to move downstream effectively because of the constriction at the bridge which is exacerbated by the high backwater from Atascadero Creek.

Strategy C - High Flow Bypass

Two bypass configurations were explored; a western bypass that involves removing ~280-ft of the levee located along the left-bank upstream of the side-channel head and bypassing flows through the western pasture and back to Green Valley Creek below the bridge, and an eastern bypass that involves constructing four 100-ft long by 10-ft wide by 1.5-ft high box culvert along the right bank at the bend in the road (Cemetery Curve) and routing flows through a 34-ft wide by 4.5-ft deep channel through the vineyard and into Atascadero Creek (Figures 13 through 15). Initial simulations of the western bypass revealed that the capacity of the existing culvert that drains the western pasture back to Green Valley Creek just west of the bridge would be insufficient to handle the bypass flows. Thus the western bypass alternative also includes enlarging this culvert to a 16-ft wide by 3.3-ft high box culvert in order to avoid road overtopping at this location.

A maximum discharge of 454 cfs (48% of the total flow) entered the western bypass over the lowered levee. Some attenuation of the flow occurred within the western pasture and the peak outflow through the culvert west of the bridge was 368 cfs which is below but near the threshold discharge where road flooding would begin to occur at this location. The bypass was successful at partially mitigating the 2-yr road overflow and the peak overflow was reduced to 208 cfs (a reduction of 53% over existing conditions) (Figure 15). Peak water levels decreased by up to 0.5-ft relative to existing conditions in the flood-prone reach upstream of the bridge (Figure 12) and increased by ~0.6-ft below the bridge (the result of more flow reaching the downstream reach relative to existing conditions).

A maximum discharge of 429 cfs (45% of the total flow) entered the eastern bypass through the lateral box culverts. The bypass channel had sufficient capacity to handle this flow over most of its length. High backwater conditions from Atascadero Creek result in overtopping of the bypass channel at the downstream end. This overtopping does not increase vineyard inundation beyond that experienced under existing conditions because this area becomes inundated from backwater flooding regardless. The bypass was successful at partially mitigating the 2-yr road overflow and the peak overflow was reduced to 79 cfs (a reduction of 82% over existing conditions) (Figure 14). Peak water levels decreased by 0.4 - 0.7-ft relative to existing conditions throughout the flood-prone reach upstream of the bridge. Small reductions in water level (~0.2-ft) also occurred downstream of the bridge (Figure 12).

Combining the two bypasses effectively mitigates the road flooding for the 2-yr event (Figure 13). The western bypass carries a maximum of 373 cfs and the eastern bypass carries a maximum of 340 cfs, leaving only 238 cfs in the channel through the bridge section (note that channel changes since 2012 appear to have reduced channel capacity in the reach downstream of the eastern bypass; the model is based on 2012 topography). The double bypass configuration would provide a level of flood protection beyond the 2-yr event and could likely prevent road overflows for discharges up to 1,120 cfs (118% of the 2-yr flow). Peak water levels decreased by 0.6 to 1.7-ft relative to existing conditions in the flood-prone reach upstream of the bridge (Figure 12).

Strategy D - Bridge Improvements

This strategy involves replacing or elevating the existing bridge over Green Valley Creek. It was modeled by simply removing the bridge as a means of representing a best case re-design of the crossing whereby flow does not interact with the bridge deck at all. As a stand-alone action, replacing the bridge has

almost no effect on the road flooding. This is due to the fact that the limited channel capacity along the reach upstream of the bridge is the primary cause of the road flooding not the constriction at the bridge. When, however, the road overtopping is prevented by elevating the roadway as discussed for Strategy A, the bridge capacity becomes the limiting factor and bridge replacement would be beneficial.

Strategy E - Levee Removal

This strategy involves removing or setting back the existing levee along the right bank in the reach below the bridge. Removing the downstream levee has a significant effect on the maximum water surface elevations, reducing water levels by ~0.6-ft above and below the bridge and by 2.0 to 2.5-ft in the reach below the bridge (Figure 11). In the reach upstream of the bridge, however, the water surface elevations are not changed significantly, and thus as a stand-alone action the levee removal does not help solve the road flooding problems. That being said, the significant reduction in backwater effects at and below the bridge is very beneficial when considered in conjunction with the other strategies. Specifically, removing the levee effectively increases the capacity of the bridge possibly making bridge replacement unnecessary were Strategy A to be pursued (Figure 10). Similarly the reduced backwater improves the function of the western bypass discussed under Strategy C by allowing water to drain from the western pasture more effectively.

As a stand-alone action the levee removal results in increased vineyard inundation and completely eliminates the backwater flooding in the western pasture. This result serves to illustrate how the existing levee configuration amplifies the backwater effects propagating upstream from Atascadero Creek. We also investigated removing only a portion of the levee or setting-back the level some 30-ft into the vineyard. In both cases, the reduced backwater effects were significantly less than with the full levee removal though still large enough to make the levee modifications worth considering.

Summary and Recommended Next Steps

There are three alternatives that result in full mitigation of road flooding during the 2-yr flood event. Alternative 1 which combines elevating the road with replacement of the bridge, Alternative 2 which combines elevating the road with removal of the downstream levee, and Alternative 3 which combines the western and eastern bypasses (Table 2).

Three additional alternatives provide partial mitigation of the road flooding during the 2-yr event. Alternative 4 is the eastern bypass which reduced the peak 2-yr road overflows by about 82%. Alternative 5 is the western bypass which reduced the peak 2-yr road overflow by about 53%, and Alternative 6 are the three actions designed to increase conveyance through the flood-prone reach described as Strategy B above. This alternative decreases peak 2-yr road overflows by about 23% (Table 2).

Elevating the roadway results in significant increases in flooding of the western pasture upstream of the bridge including flooding of the driveway adjacent to the pasture. The driveway flooding could likely be eliminated by elevating the driveway, however it would be necessary to provide sufficient drainage beneath the driveway. If this is not accomplished, much of the benefit of the roadway elevation would likely be eliminated. If the roadway elevation strategy is to be pursued further, additional model runs are recommended to optimize the design of the road and driveway and associated drainage features.

Removing or laying-back the downstream levee is the only action that serves to reduce the backwater effect in lower Green Valley Creek. As such, modification or removal of the levee has the potential to

increase the effectiveness of most all of the other strategies. From a fisheries perspective, the various bypass options present both a challenge and an opportunity. If designed appropriately, both bypasses have the potential to create off-channel habitat for salmonids provided that passage and stranding issues can be avoided. The bypass and levee removal options may be more resilient to ongoing sedimentation compared to elevating the roadway in that they represent re-connection of historical floodplain areas and associated storage/sediment retention processes.

The eastern bypass includes a box culvert of limited height (1.5-ft) which is necessary because of the limited clearance between the streambed and the road surface and the need to avoid diverting lower flows. This limited height would make the operation of the bypass structure sensitive to debris clogging and changes in bed level. Optionally, the road grade could be increased in the vicinity of the structure to allow for greater flexibility in the structure design. In contrast, the western bypass does not rely on an inlet structure and would be expected to be less sensitive to debris clogging and changes in bed level.

Under any alternative to mitigate flooding, sedimentation is expected to continue, and ongoing sediment management will likely be required to maintain improved conditions that reduce flooding. Sediment management strategies have not yet been evaluated in detail.

Alternative	Description	Results
<p>1 Elevate Green Valley Road and Replace Bridge</p>	<ul style="list-style-type: none"> - Elevate Green Valley Road by 3-feet from a point ~300-ft west of the bridge to a point ~900-ft east of the bridge (Cemetery Curve) - Replace the existing bridge with a higher span 	<ul style="list-style-type: none"> -Eliminates road flooding for the 2-yr event - Increases flooding in western pasture - Eliminates flooding in southern portion of the vineyard
<p>2 Elevate Green Valley Road and Remove Downstream Levee</p>	<ul style="list-style-type: none"> - Elevate Green Valley Road by 3-feet from a point ~300-ft west of the bridge to a point ~900-ft east of the bridge (Cemetery Curve) - Remove the levee on the right bank downstream of the bridge 	<ul style="list-style-type: none"> -Eliminates road flooding for the 2-yr event - Decreases flooding in western pasture - Increases flooding in western portion of vineyard and eliminates flooding in southern portion
<p>3 Western and Eastern Bypasses</p>	<ul style="list-style-type: none"> - Divert high flows through the western pasture by partially removing the left bank levee upstream of the side-channel head and upsize culvert outfall back to Green Valley Creek - Divert high flows through a bypass channel through the vineyard and to Atascadero Creek 	<ul style="list-style-type: none"> - Eliminates road flooding for the 2-yr event - Increases flooding in western pasture - Eliminates flooding in southern portion of the vineyard
<p>4 Eastern Bypass</p>	<ul style="list-style-type: none"> - Divert high flows through a bypass channel through the vineyard and to Atascadero Creek 	<ul style="list-style-type: none"> - Reduces road flooding by 82% for the 2-yr event - Reduces flooding in western pasture - Reduces flooding in southern portion of the vineyard
<p>5 Western Bypass</p>	<ul style="list-style-type: none"> - Divert high flows through the western pasture by partially removing the left bank levee upstream of the side-channel head and upsize culvert outfall back to Green Valley Creek 	<ul style="list-style-type: none"> -Reduces road flooding by 53% for the 2-yr event - Increases flooding in western pasture - Reduces flooding in southern portion of the vineyard
<p>6 Conveyance Improvements</p>	<ul style="list-style-type: none"> - Remove sediment plug at head of historic main channel - Skim bar between present and historical main channels - Widen channel and remove tree upstream of the bridge 	<ul style="list-style-type: none"> - Reduces road flooding by 23% for the 2-yr event - Increases flooding in western pasture - Reduces flooding in southern portion of the vineyard

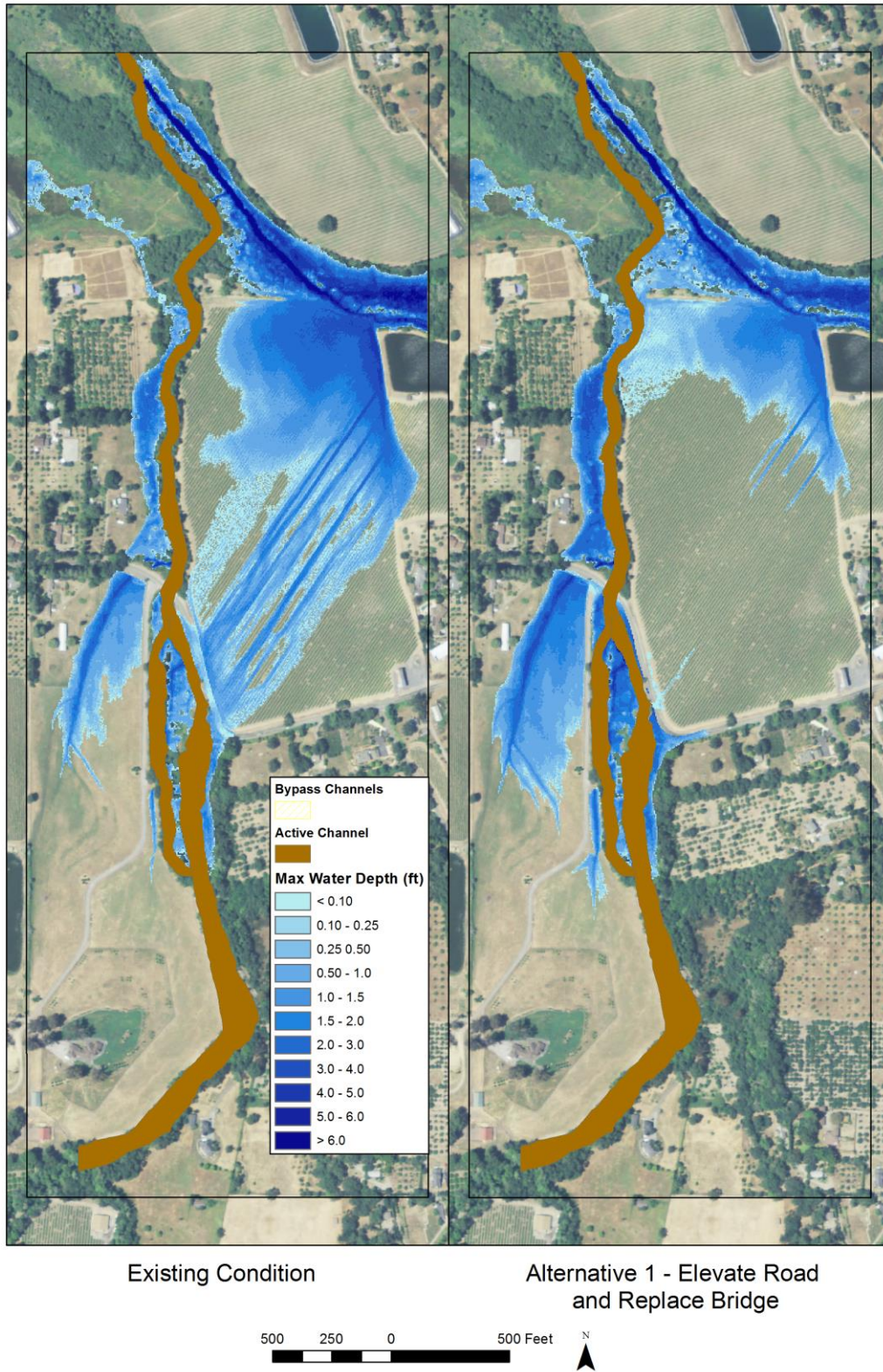


Figure 9. Comparison of Existing Conditions Flooding and Alternative 1 Flooding, 2-year Flow Event

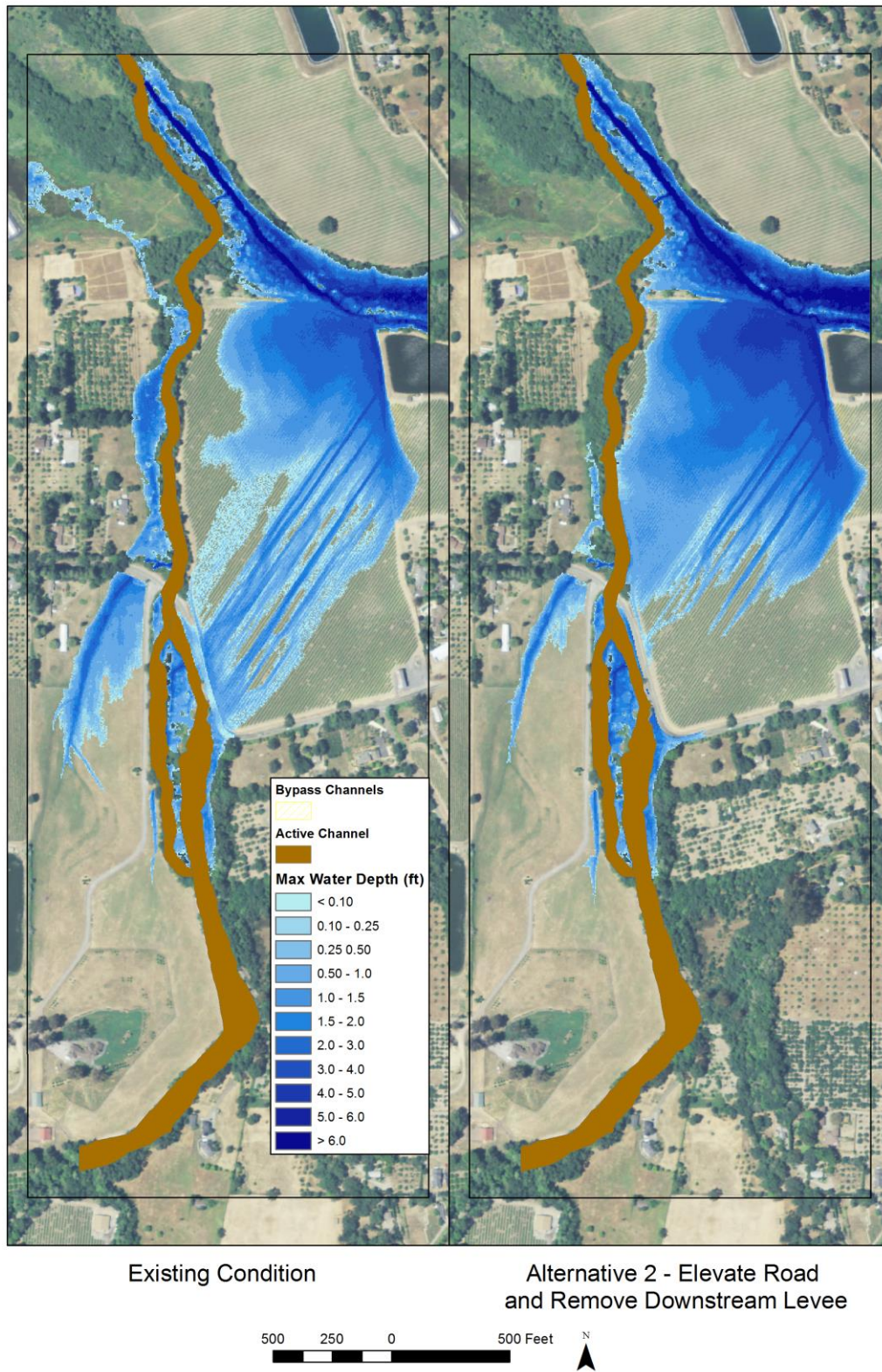


Figure 10. Comparison of Existing Conditions Flooding and Alternative 2 Flooding, 2-year Flow Event

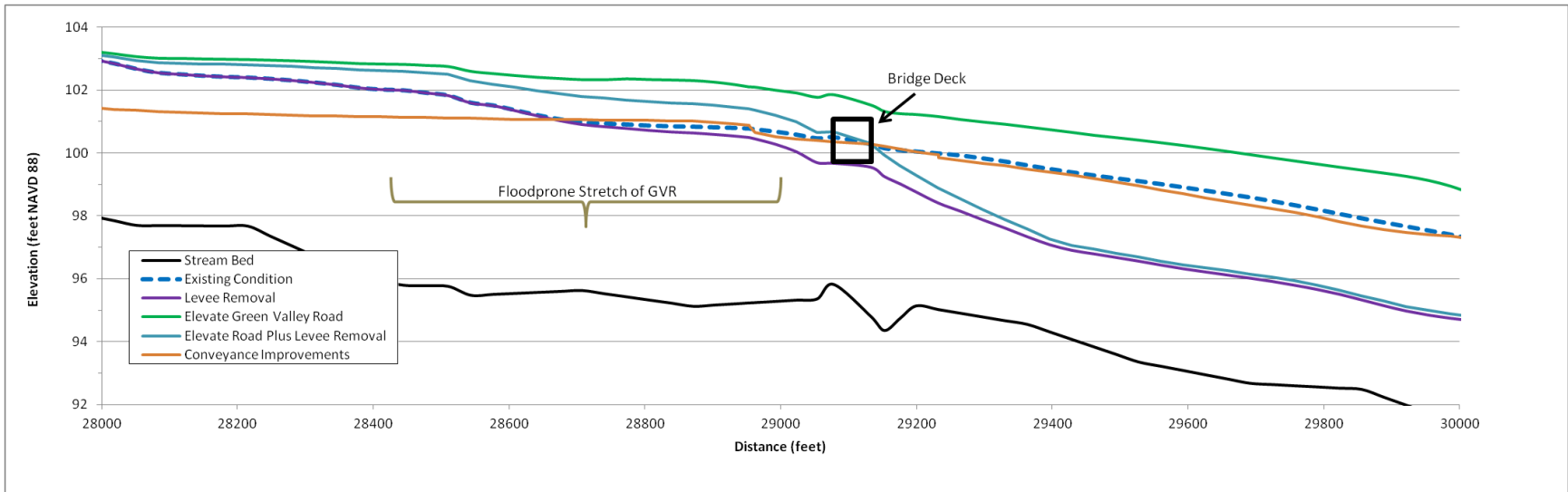


Figure 11. Comparison of Existing Conditions Water Surface Profiles and Water Surface Profiles for Various Alternatives Including Elevating Green Valley Road, Removing the Downstream Levee, and Conveyance Improvements, 2-year Flow Event

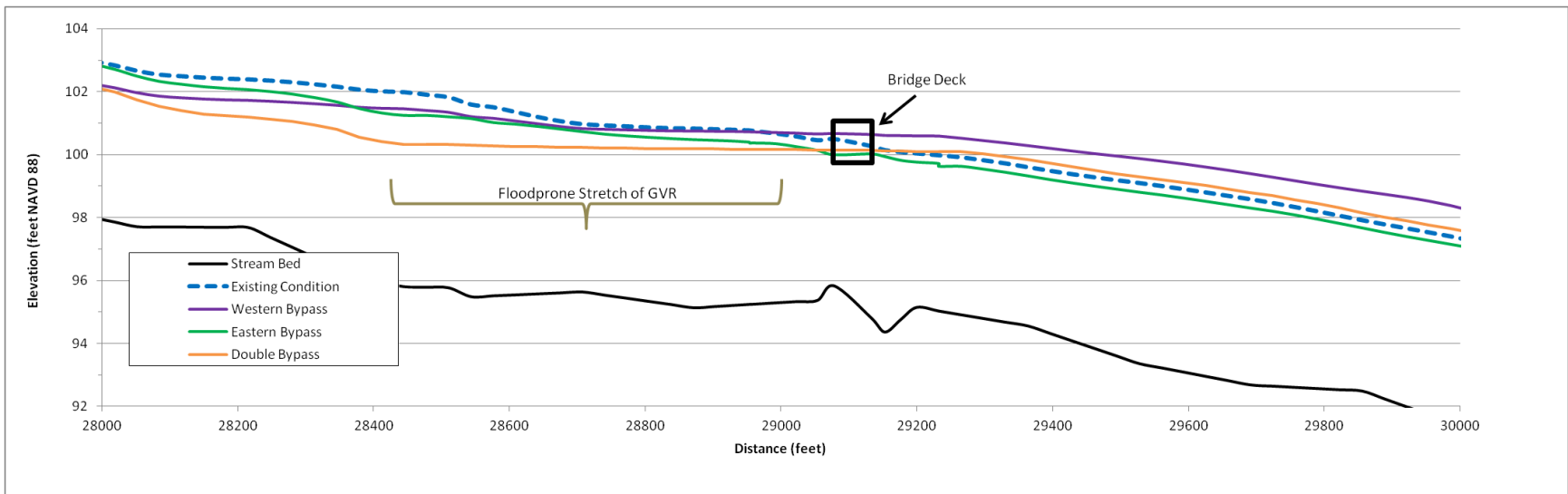


Figure 12. Comparison of Existing Conditions Water Surface Profiles and Water Surface Profiles for the Various Bypass Alternatives, 2-year Flow Event

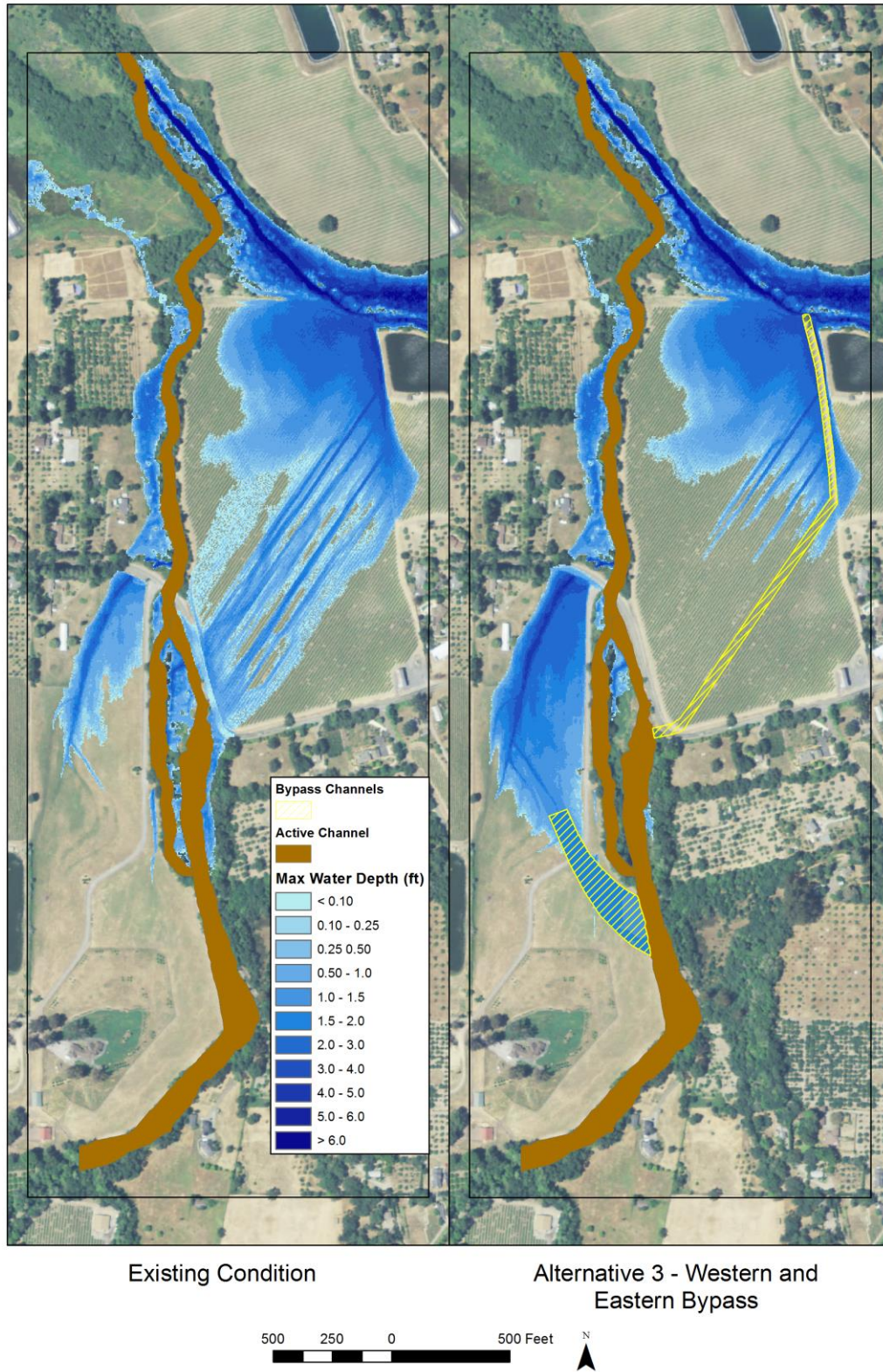


Figure 13. Comparison of Existing Conditions Flooding and Alternative 3 Flooding, 2-year Flow Event

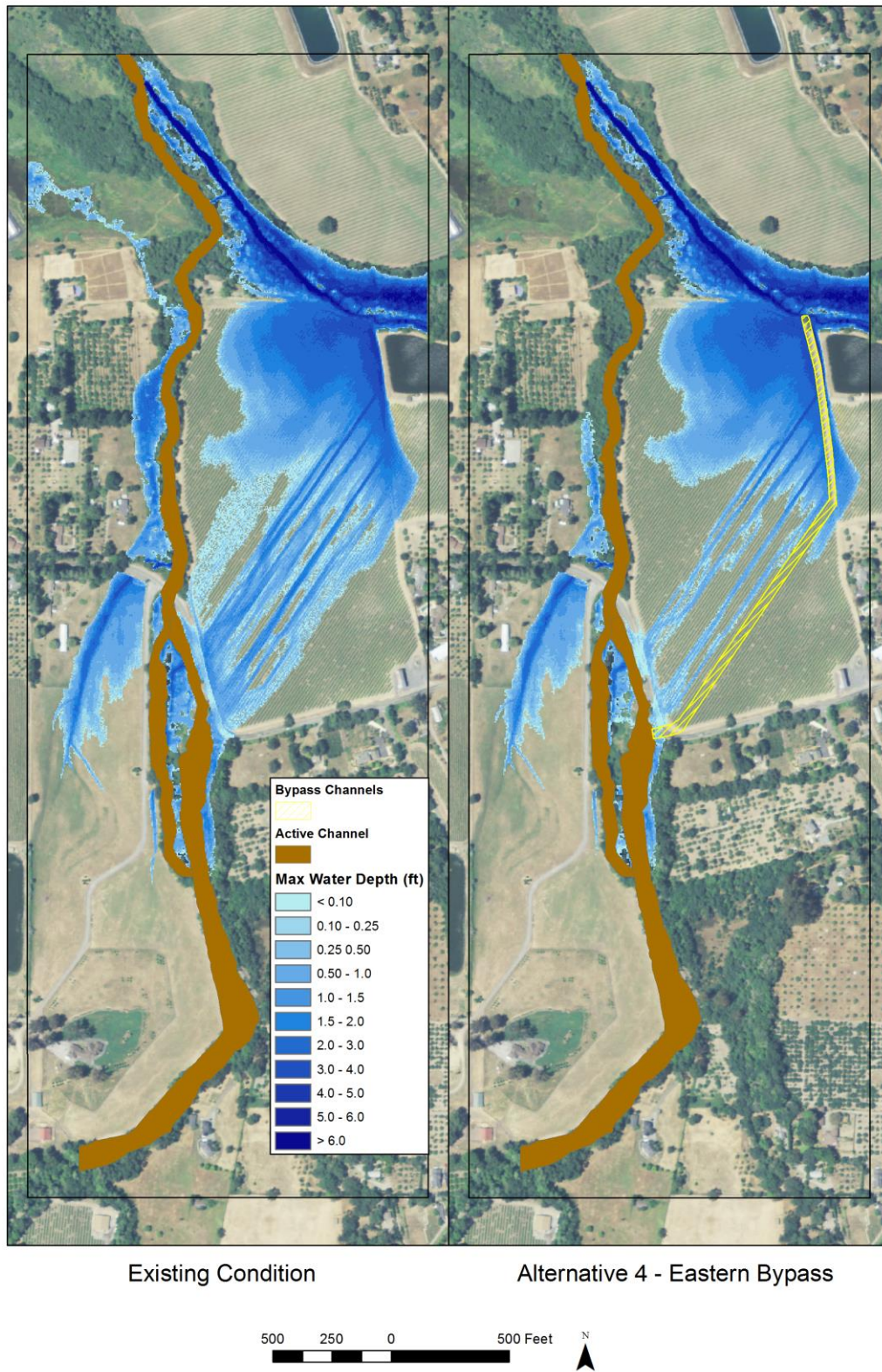


Figure 14. Comparison of Existing Conditions Flooding and Alternative 4 Flooding, 2-year Flow Event

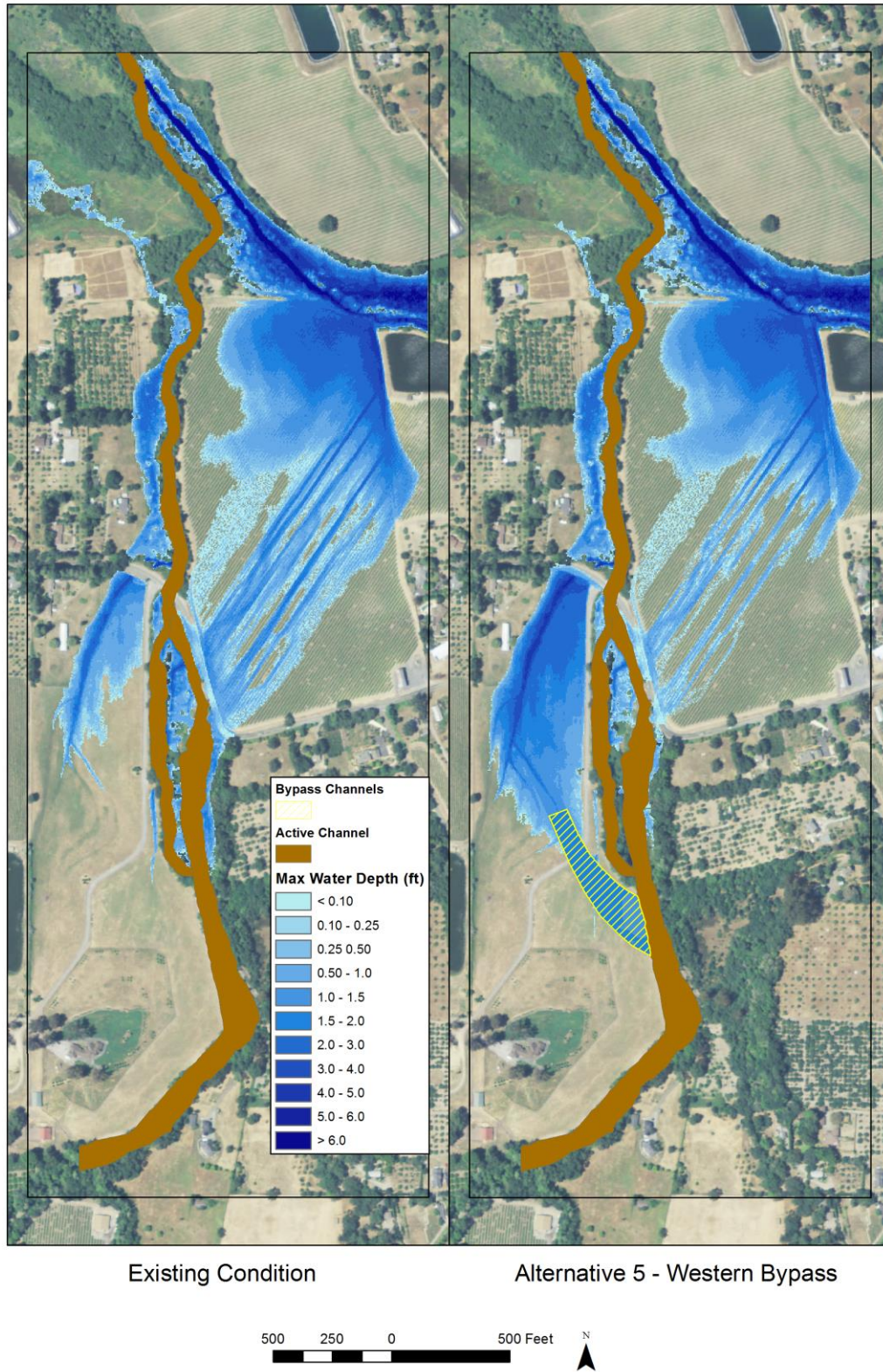


Figure 15. Comparison of Existing Conditions Flooding and Alternative 5 Flooding, 2-year Flow Event

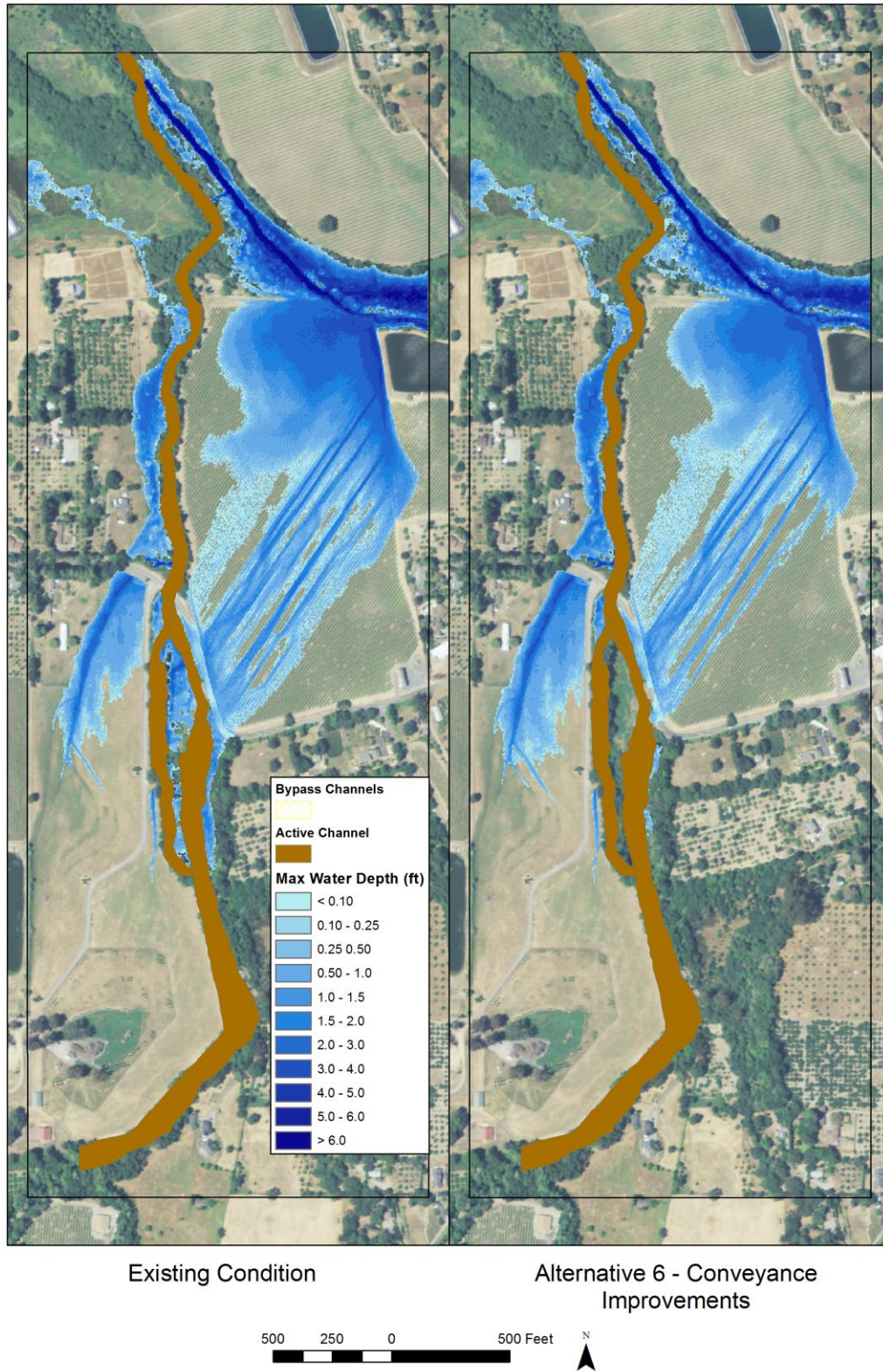


Figure 16. Comparison of Existing Conditions Flooding and Alternative 6 Flooding, 2-year Flow Event