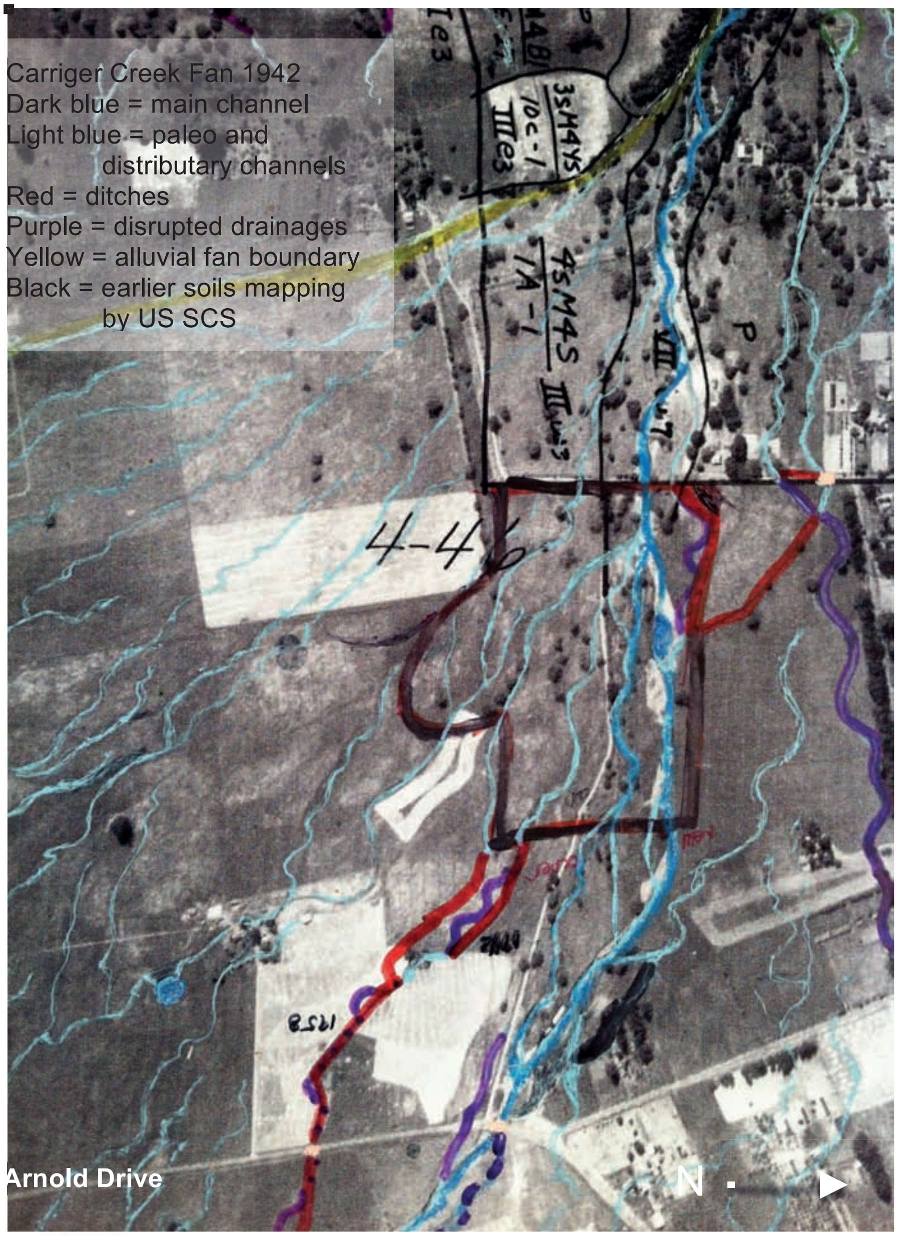
Sonoma and Carriger Creeks Alluvial Fan Assessment, Sonoma County, California

A Report for the Sonoma County Water Agency
and the
Southern Sonoma County Resource Conservation District



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I. INTRODUCTION

Presently, little information is available about natural fluvial processes in Bay Area channels traversing large active alluvial fans. This is likely because locally, many alluvial fans have become inactive because channels have become deeply incised and no longer flood or access their distributary channels, or they have been channelized or leveed to prevent flooding and lateral migration. Sonoma and Carriger Creeks, both located within Sonoma Valley and the Valley of the Moon Flood Control Zone 3A, have main channels that traverse large, coarse-bedded active alluvial fans that developed at the base of their watershed canyons. During times of moderate to severe flooding on alluvial fans, segments of remnant distributary and overflow channels become active, new avulsion channels form, and the geometry and gradient of the main channel can change from an eroding to a sediment depositing condition. This was observed during the 2005 December 31st storm that based upon the USGS stream gage data at Agua Caliente (gage # 11458500) was likely the largest flood within the Sonoma Creek watershed over the last two centuries (http://knowledge.sonomacreek.net/node/259).

Channels on active alluvial fans are inherently unstable. Development on these landforms combined with the occurrence of flooding, property damage, channel instability, and loss of mature riparian vegetation has prompted this study of the channel profiles of Sonoma and Carriger Creeks to improve our understanding of current conditions and recent changes along their alluvial fans.

Key to identifying possible influences of floods or even extended droughts is first identifying which portions of an alluvial fan are active and then knowing that: 1) sediment loads from the headwater uplands of these creeks can at times be extremely large or limited; 2) that the channel on the fan is temporally and spatially responsive to changes in sediment supply; 3) that former distributaries and overflow channels had and might still have important functions; and 4) that overflow channels can seek new pathways dictated by modern landscape change. Although a comprehensive study of the full nature of these alluvial fans has not been conducted, funding was provided to Watershed Sciences and The Southern Sonoma County Resource Conservation District (SSCRCD) by the Sonoma County Water Agency (SCWA) to survey the longitudinal profiles of Sonoma and Carriger Creeks over most of the length of their alluvial fans and to compare these profiles to former surveys conducted by Watershed Sciences. Such comparisons provide a way to quantitatively identify reaches that could be trending toward significant deposition or scour, and could become future sites of bank loss, overflow flooding, or avulsion channels. In addition to the longitudinal profiles, two cross sections per study site were surveyed at the upstream and downstream ends of the profiles to document channel geometry and estimate bankfull discharge.

During the last few decades several projects have been conducted over short reaches to reduce bank erosion in both Carriger and Sonoma Creeks. Both sites have also had sedimentation and backwater flooding issues at their highway bridge crossings. A comprehensive study of the full extent and nature of the alluvial fans, however, has not been conducted. For example, there is another project currently underway to evaluate opportunities for flood reduction over a portion of the alluvial fan on Sonoma Creek, yet the study does not extend to the apex of the fan. This project addresses certain aspects of the mainstem longitudinal profiles of the 1.84-mile Carriger Creek and the 1.32-mile Sonoma Creek along their alluvial fans, whereas the current full extent, location, and conditions of various overflow channels, distributaries, and braids are not rigorously treated here and would exceed the scope of this evaluation. Maps provided in this report of these secondary features should be considered as general sketches.

Objectives

The purpose of this project is to analyze the current mainstem channel conditions, causes of channel avulsion and instability, and to identify potential sites of future concern along Carriger and Sonoma Creeks on their alluvial fans.

Relationship to Other Projects

This project, along with future monitoring, could help ensure the success of existing and future projects on these unstable landforms. Assessment of the cross sections for this project provides data to the San Francisco Bay Regional Curves Project that is currently collecting data on bankfull channel geometry to help develop quantitative information for channel restoration design. EPA provided funding to Farwest Engineering and Watershed Sciences to conduct the Regional Curve Project.

Earlier during 2002, Watershed Sciences was funded by the SSCRCD to survey a longitudinal profile of the main channel of Carriger Creek on its alluvial fan. The methodology for that survey is the same as described here for this project, and for two other surveys performed by Watershed Sciences of Sonoma Creek that were conducted in 2008 and 2009 along the upper alluvial fan for the Sonoma Ecology Center (SEC) to develop conceptual plans to reduce flooding. Funding was provided by the SCWA.

Acknowledgments

Kevin Cullinen, Sumner Collins, and Michael Bower provided the careful assistance of stream surveying. The SSCRCD is gratefully acknowledged in providing much logistical support from Jason Sweeney and grant development from Susan Haydon. SCWA is thanked for funding this project and recognizing the value of quantitative fluvial geomorphic data.

II. BACKGROUND

Some Basic Fluvial Geomorphic Concepts

Channel stability is defined as the ability of a channel under a given climatic regime to maintain its cross-sectional form while laterally migrating across its alluvial deposit. *Bankfull discharge* corresponds to the flow that fills the channel to the insipient level of the floodplain, and is a term used to define the flow that has a central tendency of maintaining the stable channel form that is commonly associated with a floodplain. Dunne and Leopold (1978) suggest that under these conditions, bankfull discharge is responsible for most of the sediment transport over the long-term. It typically has a discharge that has a recurrence interval (RI) of 1.3 to 1.7 years. On the other hand, Andrews (1980) suggests that *Effective discharge* is the flow that mobilizes the largest fraction of the annual sediment load over a period of years and its RI can range from 1.8 to 3.3. The effective discharge, however, does not necessarily correspond to a floodplain bench.

To determine bankfull channel geometry, the parameters of stream gradient, bankfull width, both average and maximum bankfull depth, and floodprone width are measured (Rosgen, 1996). *Floodprone width* is the width measured at twice the maximum bankfull height from the *thalweg,* which is the deepest point of the channel at any given location. Floodprone width is often the most overlooked parameter for assessing stream stability. It is typically associated with the height and width of an area that is flooded during very large yet infrequent flood events. Conceptually, in a channel with stable bankfull geometry, if the floodprone width is broad enough, a large flood should be able to pass its water and sediment load without destabilizing the bankfull geometry. Above the elevation of the floodplain there can commonly be found former abandoned floodplains that represent earlier periods of stability and instability associated with channel incision. Abandoned floodplains are referred to as *terraces*. A channel is considered *entrenched* and therefore unstable when its floodprone width is less than 1.4 times its bankfull width (Rosgen 1996).

A *stable* channel will maintain its hydraulic geometry while laterally migrating across its floodplain under the current climatic regime. It will not degrade or aggrade its streambed in a manner that would cause its floodplain to be permanently abandoned. A stable channel might have short-term scour and filling, but permanent abandonment of the floodplain signifies an *unstable* channel that is either aggrading or degrading its bed. *Aggradation* and *degradation* are here considered long-term trends, whereas *scour* and *deposition* are short-term processes that do not signify a change in stability but are processes that occur during the normal flood cycle and annual regime.

When a channel abandons its floodplain through incision, *inner benches* might form as depositional features within the former banks. The inner benches might represent former streambed levels, depositional bars, or a new floodplain. Inner benches are not called the floodplain unless one of them represents the incipient level of bankfull discharge. An *inner bench floodplain* might only be a temporary feature until there is sufficient floodprone width to maintain the bankfull hydraulic geometry during large floods.

The constructs of both bankfull and effective discharge are difficult to apply with consistency on inherently unstable alluvial fan channels. This is because channels can have reaches with losing and gaining flow, and the channels can have infrequent but catastrophic events that are sometimes responsible for most of the sediment transport over the long-term. Estimation of incoming and outgoing discharge along alluvial fan channels is a key element in assessing the fluvial and hydrologic processes. Developing design standards for projects in alluvial fan channels requires estimates of bankfull cross sectional form that should be conducted over the length of the fan channel. This would typically be done on the most relatively stable segments of the fan, if they exist, but more likely involves measurement in reaches that have become entrenched but have newly forming inner floodplain benches that still represent the central tendency of a channel to develop a stable hydraulic geometry that transports a common sediment load.

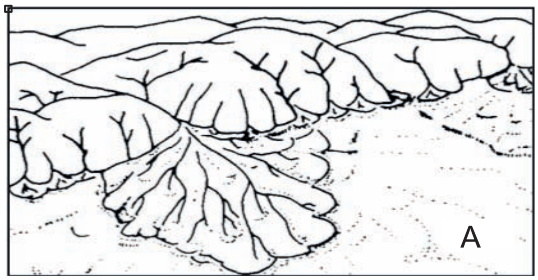
Alluvial Fans in General

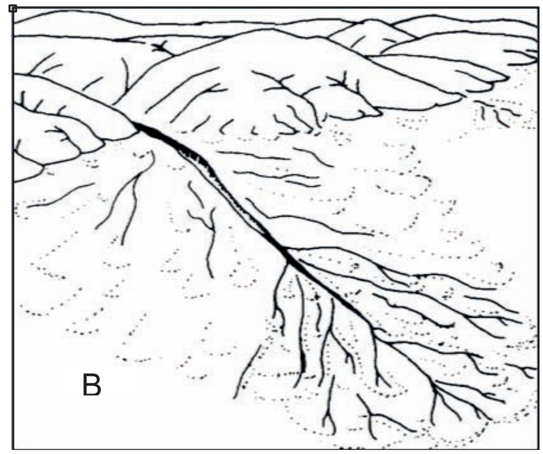
An *alluvial fan* is fan-shaped accumulation of sediment deposited at the mouth of a canyon or at the juncture of a tributary stream where the stream gradient flattens, causing discharge to slow and spread its sediment load. This happens at the hydrographic apex, which is the highest point on the alluvial fan where there is evidence of channel bifurcation and/or significant flow outside of the defined channel banks. This is where a fan is considered active, which means that sediment deposition, stream erosion, flooding, and unstable flow paths are possible. The apex of a fan, as opposed to its hydrographic apex, is the extreme upstream topographic extent of the landform and might not necessarily coincide with the hydrographic apex, depending upon where the fan is active. The fan apex can often be defined by a single thread channel, but if it is so deeply incised that it becomes a fan head trench where flooding is not possible, that portion of the fan is inactive. Downstream of the hydrographic apex, the main channel might break into or be accompanied by a series of distributaries, avulsions or overflow channels that could be braided or anastomosing, usually spreading increasingly smaller-sized sediment toward the toe of the fan. An example of an active fan at a stream confluence is shown in Figure 1.

The deposition of sediment and the continued building of an active fan is associated with a rapid reduction in stream power from the loss of channel confinement, decrease in slope, and loss in discharge as surface flow infiltrates into usually poorly sorted, coarse alluvium. Upstream of such fans, high relief watersheds can have punctuated deliveries of high sediment supply from processes associated with landslides, post fire erosion, and floods. After seasonal rainfall totals have caused soils to become saturated for example, debris slides initiated in the headwaters during intense prolonged rainfall can accumulate additional sediment from the channel (called bulking) as they flow downstream as debris torrents and then rapidly deposit their sediment and woody debris in fan channels. These catastrophic, yet short-lived events can often be the primary mechanisms of sediment supply that contributes to long-term fan aggradation, but common discharges and small floods can also be very effective at reworking the deposited sediment and causing the fan itself to become a source of sediment supply to the active channel.

Alluvial fans are associated with different phases of development. Lecee (1990) discussed findings by Harvey (1978, 1984 a, b) where the first phase of fan aggradation occurs during a period of net excess sediment supply, followed by the second phase of dissection during net sediment deficiency. Harvey proposed next that fan development reflects long-term progressive change complicated by

Figure 1. An example is shown of the alluvial fan at the confluence of Pine Creek with the larger Lewis Creek following the 1980 eruption of Mt. St. Helens in Washington. Notice the development of sinuous curvature in the larger straighter channel that developed after water and sediment was spread across the entire alluvial fan. Also note the many anastomosing overflow channels on the fan surface that has been building over thousands of years by punctuated catastrophic events. Photo by L. Collins, 1982.





Phases of Fan Development

Figure 2. Two phases in the development of alluvial fans under the influence of tectonic uplift are shown. Figure A shows the area of deposition adjacent to the mountain front. Figure B shows the area of deposition shifted down fan due to stream channel entrenchment (from Leece (1990) with permission to reproduce from Bull. 196R).

short-term response to climatic fluctuations and spatially variable trenching thresholds (see Figure 2). The trenching thresholds refer to the incision of a channel, commonly at the fan apex, where the channel has a gradient that is lower than the fan surface. The trench is usually deepest at the fan head and becomes progressively shallower downstream. Many fans show fan-head trenching, with the channel emerging on the fan surface at a mid-fan intersection point. Intersection point deposits occur at the point where the bed of a trench in an alluvial fan merges with the surface of the fan.

The shape of a fan can be influenced by tectonic controls, predominant size of the sediment supply, and by the confinement of the stream. Many fans at the base of steep mountain ranges are associated with normal faulting that raises mountains and drops valleys, especially throughout the basin and range topography of Nevada and Utah for example. Some Bay Area alluvial fans are also influenced by faulting, such as the upper fans of Alameda and Wildcat Creeks in the East Bay, where the predominant right lateral movement of the Hayward Fault also has a slight component of uplift, causing the East Bay Hills to rise. The alluvial fans along the western down-dropping side of the Hayward Fault have developed losing reaches due to the infiltration of their surface flow into deep alluvial deposits. Gaining reaches at these sites emerge near the toes of the fans.

Fluvial reworking of sediment on alluvial fans by erosion of the streambed and banks can become a primary source of sediment to the downstream channel, particularly during times of limited fluvial sediment supply from the uplands. This is when the fan head trench can become increasingly entrenched and elongated over the distance of the fan. Sediment supplied by erosion of fan channels can create new depositional lobes downstream of the fan toe, essentially elongating the fan. For example, this was observed in the Point Reyes Muddy Hollow Creek, as shown in Figure 3, after post fire sediment supply diminished following the

1995 Vision Fire (Collins and Ketcham, 2001). The hydrographic apex can be modified by frequent events while Harvey (1984) suggests that downstream fan locations are affected only by extreme events.

The variety of forms that channels acquire on alluvial fans can range from multiple to single thread, and shifting of the mainstem between two major distributaries near the hydrographic apex can be common. Bifurcations can occur by both stream capture of other fan channels eroding headward, by sediment deposition, or stream blockage from large woody debris (LWD) jams that cause overflow and avulsion. An avulsion channel is a new channel that forms from floodwater overtopping a channel bank. It is usually straighter and steeper . Field (2001) demonstrated that avulsions on fans in Arizona occurred where bank heights were low at channel bends. He showed that channel capture occurs when overland flow from the main channel accelerates and directs headward erosion of the smaller overflow channel into the main channel, and that this can be accomplished during frequent small-sized floods.

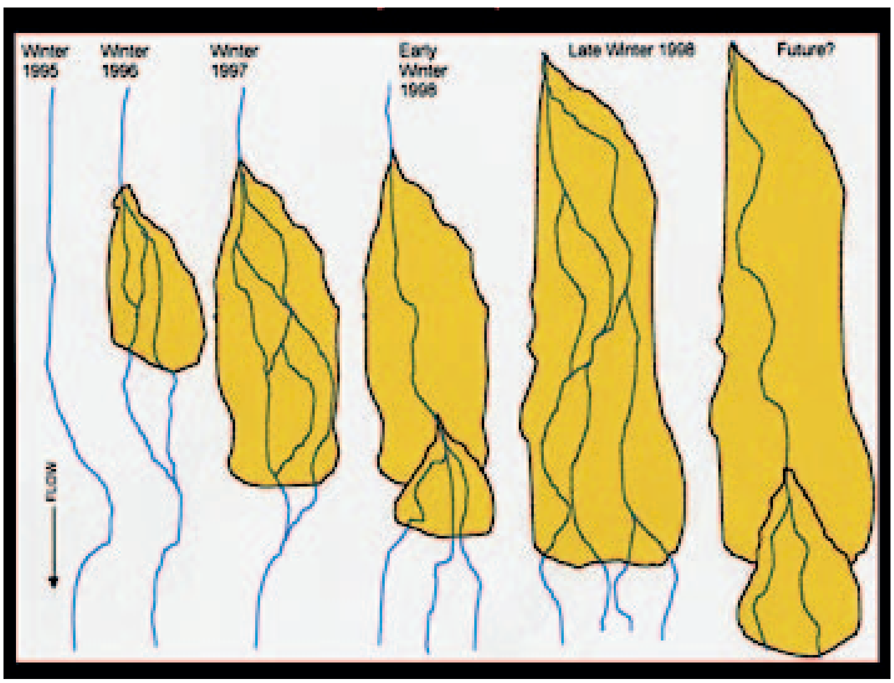


Figure 3. A conceptual sketch is shown of the progression of the post fire alluvial fan that developed after the 1995 Vision Fire within a confined valley at Muddy Hollow Creek, Point Reyes National Seashore (Collins and Ketcham, 2001). When the sediment supply and runoff was excessive from erosion of hydrophobic soils that developed in the upper watershed, the alluvial fan grew as braided channels distributed sediment across the valley floor. When sediment supply decreased during the early winter of 1998, a single thread channel developed on the fan. It incised and reworked the previously deposited sediment, transporting it farther downstream, creating a new lobe of deposition at the toe of the larger fan. During late winter 1998, which happened to be an El Nino year, landslides in the upper watershed increased the sediment supply, restarting the process of braiding over the entire fan.

Avulsions can also form at sites where woody debris jams have caused backwater flooding and excessive upstream sediment deposition. On the other hand LWD and debris jams can slow the downstream transport of sediment, and increase the number of pools that would be expected from channel sinuosity and pool-riffle sequencing. New avulsions often lack sinuosity and are therefore usually shorter in length than the original channel, which means that they will have a steeper gradient and more energy to either erode the channel and/or transport the sediment load.

Some channels braid while others anastomose. Braid bars can form islands, or be positioned transversely or laterally to the flow direction. Mid-channel bars in a single thread channel can signify impending or existing instability where the flow separation will induce bank erosion and eventual abandonment of one of the channel braids. Multiple active bars that shift in position while growing downstream and eroding upstream characterize braided channels. Braid bars are frequently submerged. They sometimes stabilize by deposition of fine sediment and subsequent growth of woody vegetation, by abandonment of the channel through lateral migration that can also be associated with subsequent incision or avulsion, and sometimes by the dominant large particle size that can be too coarse too move during usual or moderate events. Anastomosing streams are characterized by successive division and rejoining of flow around stable islands that are commonly vegetated and submerged less frequently.

Schumm and Hadley (1957) diagrammed a pattern of fluvial processes on fans with ephemeral discontinuous streams in Arizona that had a distinctive pattern of alternating deposition and erosion, as shown in the diagram in Figure 4. The diagram shows how channel flow diverges at over-widened sheetflood zones and causes sediment deposition and aggradation in the sheetflood zone, where adjacent banks are lower than the depositional lobe. Channelized flow emerges from various eroding channels that have created head cuts in the downstream end of the sheetflood zone that then converges into a single thread depositional channel. Schumm and Hadley discuss that channel backfilling caused by the headward migration of aggradational reaches can transform a deep channel into an area of sheetflooding over periods of tens to hundreds of years.

Collins *et al* (2002) described in Carriger Creek a sequential set of processes called “armored aggradation and lateral erosion/incision sequence”. Due to the very coarse nature of the cobble-dominated veneer overlying erodible Quaternary silt and clays of the Huichica Formation, the channel during very large floods could mobilize the coarse bed material and transport it to lower gradient reaches farther downstream, effectively armoring the bed and preventing bedload transport during lesser flows. During common, low RI floods, flows could erode the exposed underlying clay-rich banks and laterally migrate away from the armored bed, while incising a new deeper bed into the Quaternary clays below the level of the abandoned armored bed. Such smaller floods transport only the usual gravel-sized materials associated with discharges of

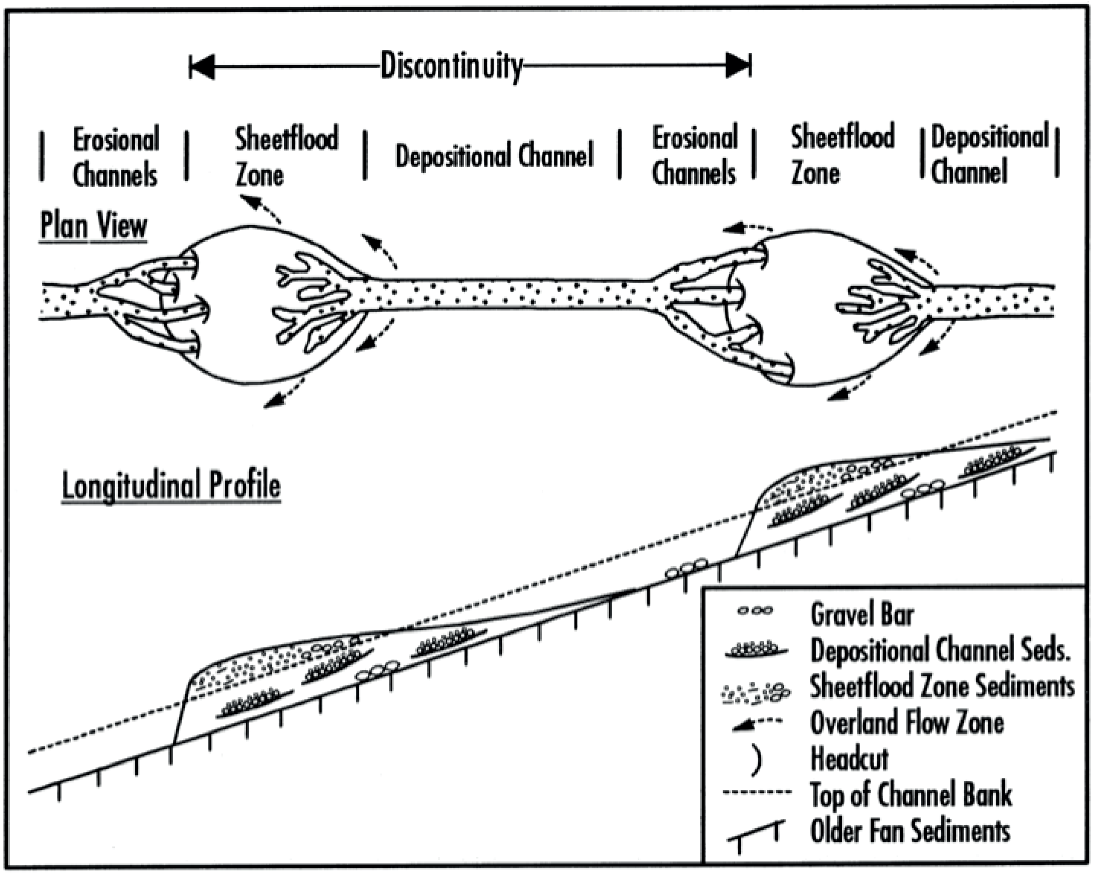


Figure 4. A schematic plan view and longitudinal profile of a discontinuous ephemeral-stream system shows the relationship between sheetflood zones, depositional and erosional channels, overland flow zones, and bank heights. Not to scale. Field (2001) from Schumm and Hadley, 1957, Bull. 1997.

bankfull or effective flow. Subsequently, during the next very large flood where cobble-sized bedload could be mobilized, it was transported into the newly incised, finer-grained bed causing it to become armored and reinitiating a new cycle of armored aggradation and lateral erosion/incision. This has created a stair-stepped morphology across the mainstream channel on the mid to lower reaches of the Carriger fan. It explains why some segments along the otherwise coarse-bedded channel have bald looking patches of exposed clay in the streambed (see Figures 5 and 6).

III. PHYSICAL SURROUNDINGS

Sonoma Creek at its Alluvial Fan

Mainstream Sonoma Creek to the toe of its alluvial fan at its confluence with Oakmont Ditch has a drainage area of about 8.4 sq mi. The fan is located upstream of Kenwood at the exit of Adobe Canyon in the upper Sonoma Valley. Highway 12 crosses the middle segment of the fan as shown in Figure 7. The fan is interspersed with vineyards, pastures, and widely spaced private residences. The highest peak in the Sonoma headwaters attains an elevation of 2,729 ft at

Figure 5. The top photo shows the coarse cobble bed of Carriger Creek, Feb 2012. The lower left photo shows the Quaternary Huichica clays exposed in a reach downstream of the upper photo along the lower Carriger Creek fan where small floods cause lateral migration into the clays and then incise the streambed that is not yet been armored by cobble transported by a large flood. The lower right photo shows the channel just downstream of the left photo that has not recently laterally migrated, incised, or abandoned its bed. Photos by L. Collins, June 2000.

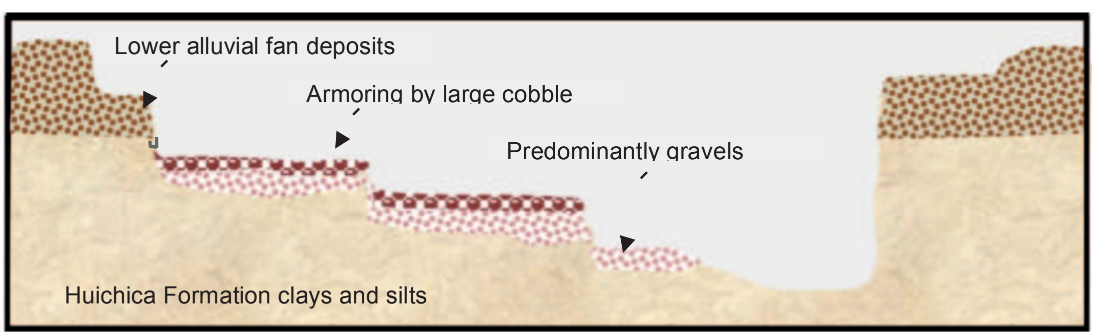


Figure 6. A diagram is shown of the stair-stepped sequence of armored aggradation and lateral migration/erosion that has been observed along the lower fan channel of Carriger Creek.

the top of Bald Mountain where mean annual rainfall can exceed 60 in/yr but mean average rainfall is about 38 in/yr for the vicinity (PWA 2010). From hydrographic apex to toe, the fan has a linear distance of about 1.1 mi, while the mainstream channel has a distance of 1.3 mi and a drop in elevation of about 55 ft.

The predominant geology of the uplands is volcanic flow rocks of Pliocene and early Miocene age. There is a minor amount of Cretaceous Franciscan sedimentary, volcanic, and serpentine rock types in the easternmost headwaters. Faults have not been mapped along the base of the mountains near Adobe Canyon, yet it is highly probable that the watershed is influenced by tectonic uplift of the mountains and down dropping of the valley. About 3.6 mi to the north, the USGS Scientific Investigations Map 2918 shows a northwest trending fault. If projected southward, it intercepts Sonoma Creek downstream of the fan apex, where the channel has a marked decrease in gradient about 2700 ft upstream of the Highway 12 Bridge. The hydrographic apex is about 2950 ft upstream of the bridge but is slightly downstream of the fan apex. The channel becomes a losing reach and intermittent about 2100 ft downstream of the upstream edge of the Highway 12 Bridge. Perennial flow is regained about 2200 ft downstream of the bridge along the toe of the fan.

Figure 7. The mainstream reach of Sonoma Creek is shown along its alluvial fan.

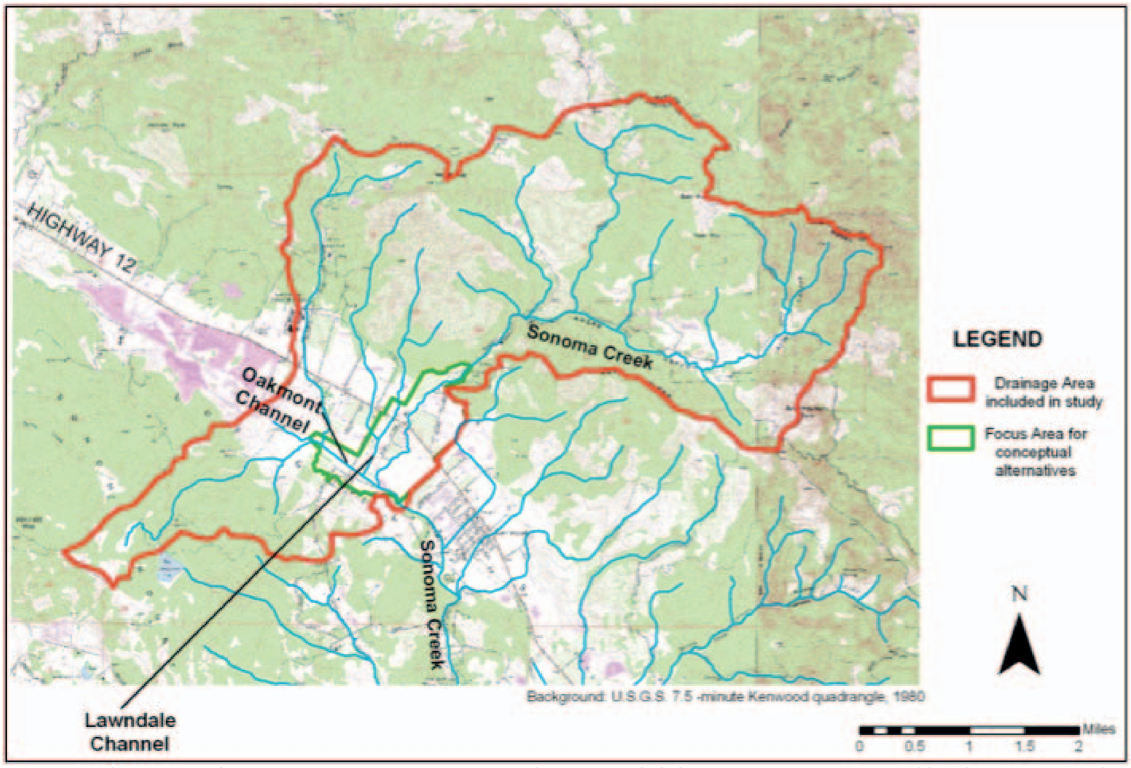


Figure 8. Sonoma Creek watershed is shown for the USGS gage at Kenwood (SEC *et al* 2010).

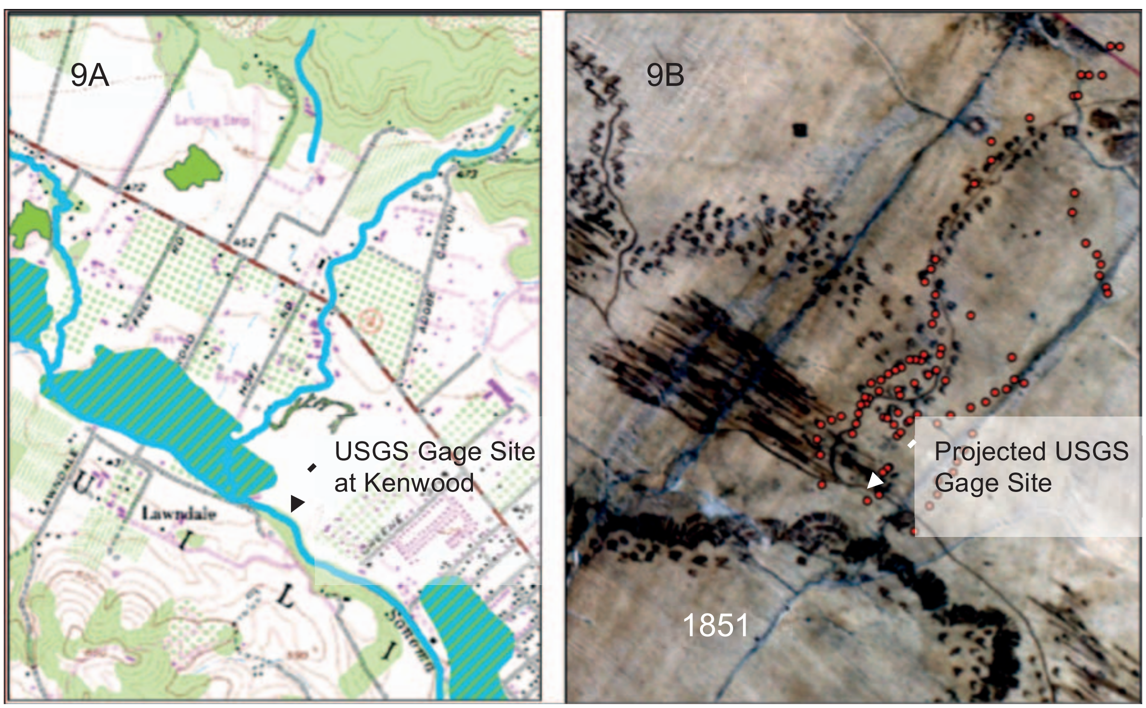


Figure 9A and 9B. The position of the 1851 historical wetlands is projected onto the 1980 topographic map (9A) and is shown as historically mapped in 1851 (9B). The red dots on the 1851 map show the GPS pathway of distributaries mapped by Collins and Dawson during 2008. as also shown in Figure 10 (next page) as blue, yellow, and green dots. Source of 1851 map Bancroft Library.

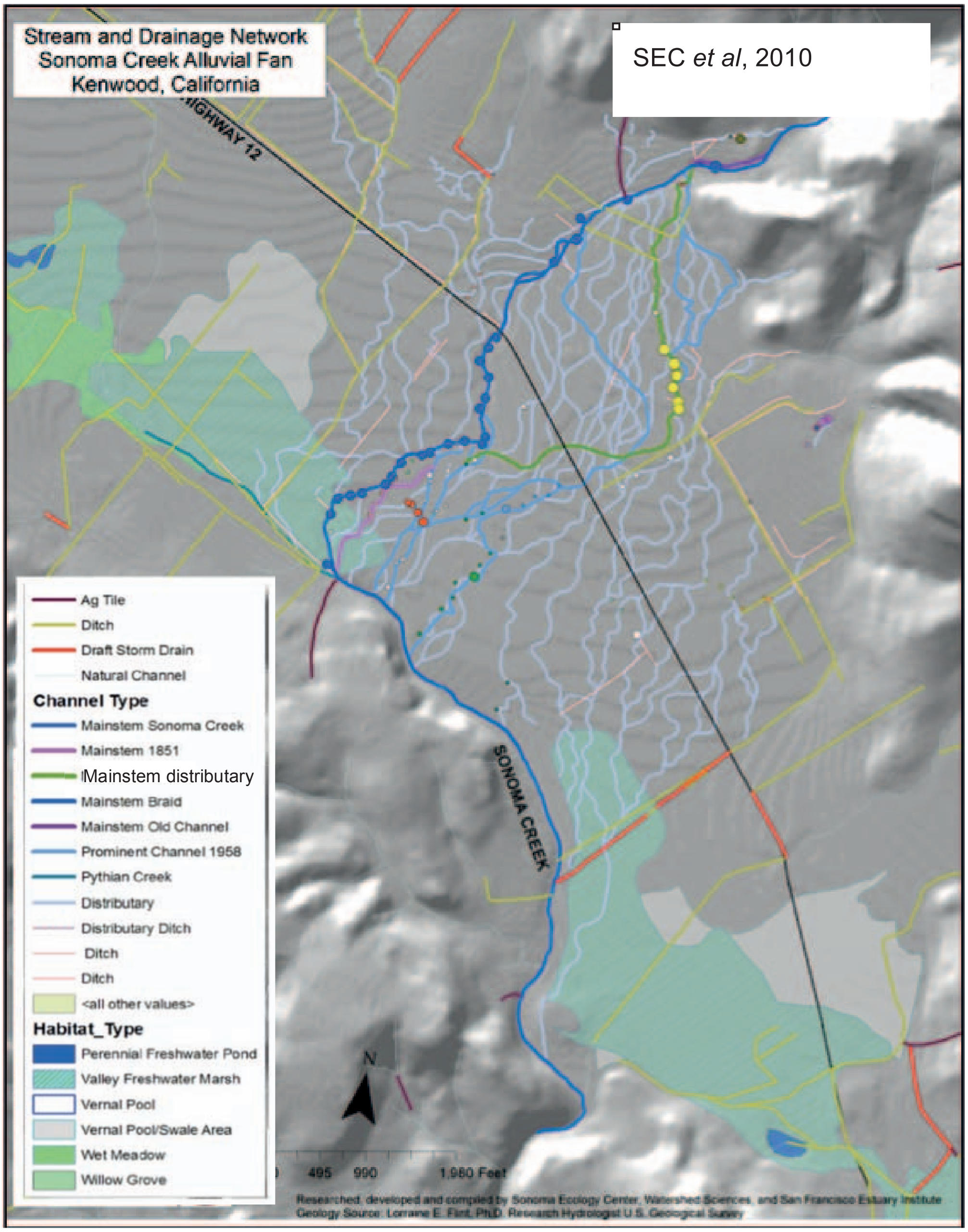


Figure 10. A shaded relief map is shown of the Sonoma Creek alluvial fan. The projection of GPS mapped distributaries, as mapped by L. Collins and A. Dawson (SEC *et al*, 2010), are indicated by lines with circles. The green line shown as the mainstem distributary was the pathway of the main channel sometime prior to 1851. Other distributaries and ditches, as indicated in the map key, were mapped by both historical aerial photo and field interpretation. Former wetlands shown in Figure 9 are shown as green polygons in this figure.

During 2009, a new USGS stream gage was installed on Sonoma Creek downstream of the Oakmont Ditch confluence. The gage site has a drainage area of 14.3 sq mi and is referred to as Sonoma Creek at Kenwood, Station #11458433. Its location is shown in Figure 9A. An older abandoned USGS gage about 2.5 miles upstream on Sonoma Creek operated between 1958 and 1978.

It had a drainage area of 6.01 sq mi and was referred to as Sonoma Creek near Kenwood, Station # 11458400. Peak stream flows are shown for these sites in the Appendix. PWA (2010) estimated the RI for the 2-yr, 10-yr, 25-yr, and 100-yr floods to be 311 cfs, 1557 cfs, 2,209 cfs, and 3,193 cfs, respectively.

The mainstream channel, distributaries, and paleo-channels on the Sonoma Creek alluvial fan were mapped previously by L. Collins and A. Dawson (Sonoma Ecology Center, 2010). Figures 9A, 9B, and 10 show these channels and the historical wetlands that previously existed in the upper Sonoma Valley. In their introduction to the historical ecology of Sonoma Creek, Dawson *et al* (2008) quote Boggs from 1871 who described Sonoma Creek in the vicinity of its alluvial fan as ‘spreading out and losing itself in the valley’ and ‘forming a kind of willow thicket and marsh or lagoon’. They conclude that historical evidence indicates that mainstem Sonoma Creek may have lacked a direct channel between the outlet of the Kenwood Marsh complex and Adobe Canyon. Alternatively, this author considers that a shallow main channel probably carried flow during the wet season to the freshwater marsh that probably had delta-like distributaries along its transitional margin, and that during periods of flooding, the numerous subsidiary fan distributaries carried flow to a shallow channel downstream of the freshwater marsh.

The wetlands at the toe of the fan set a natural base level for the gradient of the mainstream channel draining the alluvial fan. The base level would have varied within the boundaries of the fluctuating water level of the wetland. The Oakmont Ditch was created to drain the wetlands, but it is not clear when this first happened. Most likely, it was prior to 1851, because it is indicated in a map of the same vintage that shows a straight channel through the wetlands (see Figure 9). By ditching the wetlands, a new base level was artificially created and the functions of water detention and sediment storage were lost. About 8 to 10 ft of down cutting, as measured in a previous study by the author, has taken place since the onset of nonnative land use practices in Sonoma Creek (SEC 2006). The ditching and draining of the wetland was probably one of the first significant land use impacts initiating headward channel incision on the fan from its toe. The marsh historically functioned as a sponge regulating the volume and rate of runoff, storing winter floodwaters and releasing them gradually over many months, thereby minimizing peak flows. This function has been lost in the modern watershed.

To maximize the area available for agricultural practices on the fan, farmers would make every effort to drain wetlands, and prevent flooding or the dispersion of floodwaters into secondary channels across their fields. Some distributary channels were blocked and artificial levees (or berms) were constructed to inhibit overflow. Various structures of this kind have been observed along segments of the mainstream channel. By forcing more flow into the mainstream channel that has higher banks from the artificial levees, more water is contained in the channel, which forces adjustments in channel width and depth. This becomes a self-perpetuating process until sufficient bank erosion has created a floodprone width of sufficient size that floods can be passed without significant changes in channel geometry. This can take considerable time and often means that larger floods cause significant erosion of the channel until an appropriate geometry is attained. This is a mechanism by which in situ (in place) incision can also propagate downstream from the point of artificial levees or distributary blockages. The distributaries historically functioned to store sediment and regulate the rate and volume of peak runoff and base flow to Sonoma Creek through its valley. This function has been lost during moderate to small-sized floods that are now contained within the entrenched mainstream fan channel.

Upstream near the fan apex a former mainstream channel now functions as an overflow distributary during large floods. It is indicated in Figure 10 as a green line. The portion of the green line with yellow dots represents a reach measured in the field that had similar bankfull width dimensions as the current mainstream. This former channel flooded during December 2005. If existing USGS long-term gage records for Sonoma Creek at Agua Caliente are regressed with the record of the older Sonoma Creek gage near Kenwood, an estimate of 3,950 cfs in Adobe Canyon upstream of the fan apex is calculated for the December 2005 flood from the 20,300 cfs that occurred at Agua Caliente, where the RI was greater than 100 years. PWA (2010) estimated the 100-yr RI for the upper part of the alluvial fan in their project area to be about 3,194 cfs. These numbers might indicate that flow might be lost between the gage in the canyon and the upstream project area of PWA and/or that the 2005 flood was greater than a 100-yr event at the fan.

Sonoma Creek longitudinal profiles and cross sections were surveyed previously by L. Collins during December 2008 and June 2009 (SEC 2010). The long profile started at station zero at the upstream edge of the Highway 12 Bridge. The earlier survey extended about 2,400 ft upstream and the latter about 2,800 ft. These profiles are shown in Figure 11. Figure 12 shows the creek and location of the distance stations. Peak discharge at the Sonoma Creek at Kenwood gage, which includes Oakmont ditch, was 439 cfs during WY 2009, indicating that the flow was less than the 500 cfs 2-yr RI flow predicted by PWA (2010). As reported earlier by Collins (Sec 2010), groundwater recharge into the fan and continued drought-like conditions over the past two winters diminished the amount of discharge in the downstream fan direction. During the June 2009 survey the entire reach was dry, while during more normal conditions, perennial flow would have been observed at least within the uppermost 150 ft of the profile.

Comparison of the surveys indicated that during WY 2009 very minor bedload deposition, on the order of a foot or less, occurred through the middle reaches between stations 600 ft and 1,500 ft. This is where earlier bulldozing that was conducted to reduce bank erosion and flooding had caused the channel to become overly widened. Channel conditions change from an upstream narrow, slightly entrenched channel, to a wide, coarse-bedded depositional reach in this area. The upstream end of the profile ended at a distinct head cut 2,700 ft upstream of the bridge. Upstream of this the channel becomes more of a

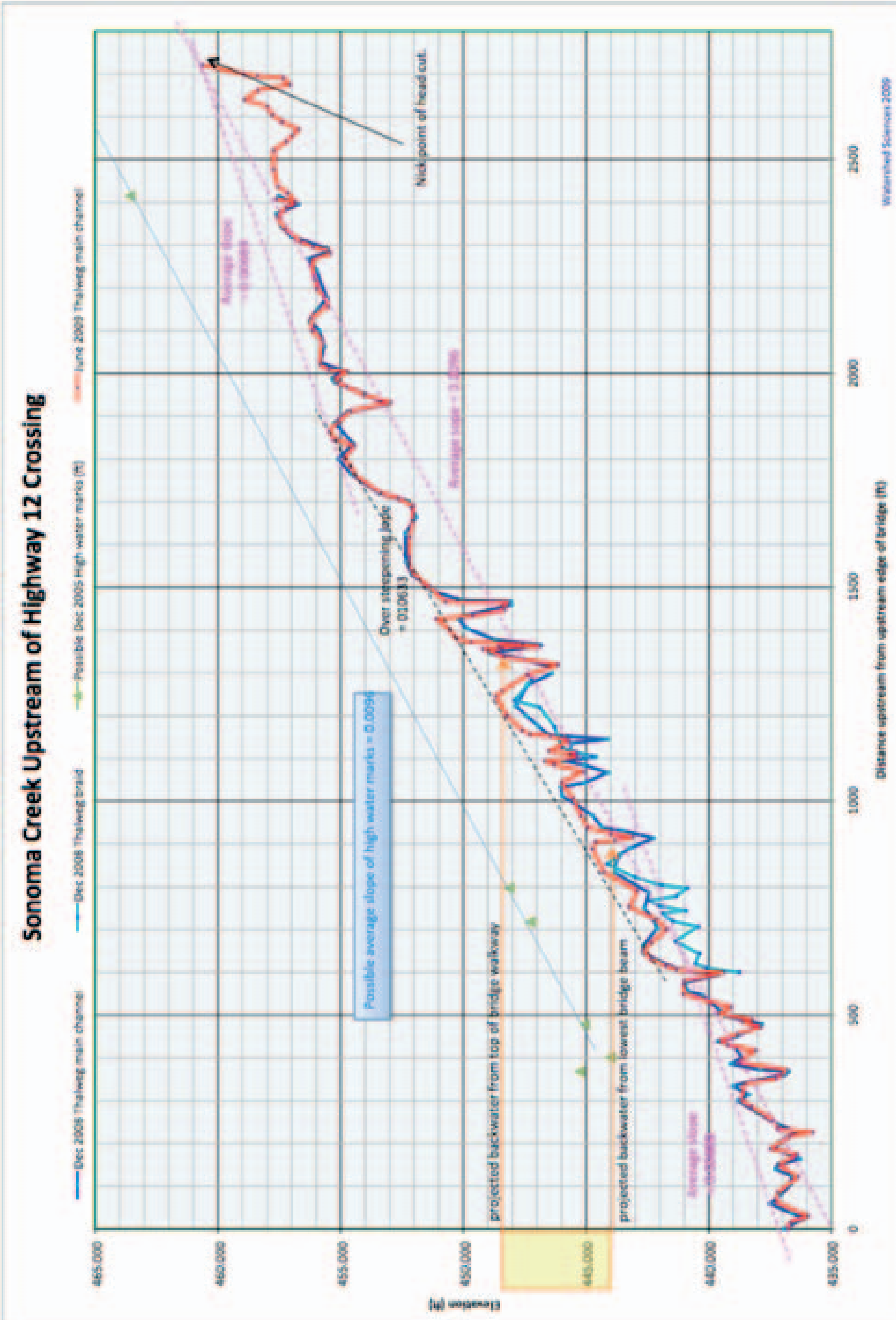


Figure 11. Two surveys from 12/2008 and 6/2009 are shown of Sonoma Creek that were conducted by L. Collins for an earlier project on the upper Sonoma Creek alluvial fan for a channel improvement plan (SEC, 2010).

Figure 12. Distance station locations are shown in white along Sonoma Creek upstream of the Highway 12 Bridge. Its two major channel braids are also shown. They are active channels at flows less than bankfull discharge. Red lines indicate cross section sites previously surveyed by PWA (2010). Map source: (Sec 2010).

step-pool system while downstream it is primarily a pool-riffle to plain bed system. Steepening of the channel gradient was indicated downstream of reaches that appear to be aggrading. Two channel braids that are inundated at flows less than bankfull discharge have formed within a zone that can be influenced by backwater flooding from the under capacity Highway 12 Bridge. The bridge site has been plagued by sedimentation, especially at its southern bore. It is common to see braided channels form upstream of such areas where water velocity slows from the reduced water gradient caused by the backwater flooding. Various stream gradients are indicated on the profile and an average slope of 0.0096 might represent the gradient that existed prior to significant past sedimentation between stations 1,500 ft and 1,900 ft and downcutting upstream of station 1,900 ft. The first 200 ft upstream of the bridge also shows the longer-term depositional zone above the line of the projected older stream gradient.

Carriger Creek at its Alluvial Fan

Mainstream Carriger Creek to slightly beyond the toe of its alluvial fan at its confluence to Felder Creek has a 5.6 sq mi watershed. At the Felder Creek confluence the creek's name is changed to Fowler Creek, which enters Sonoma Creek just north of Highway 121 in the lower Sonoma Valley. Arnold Avenue

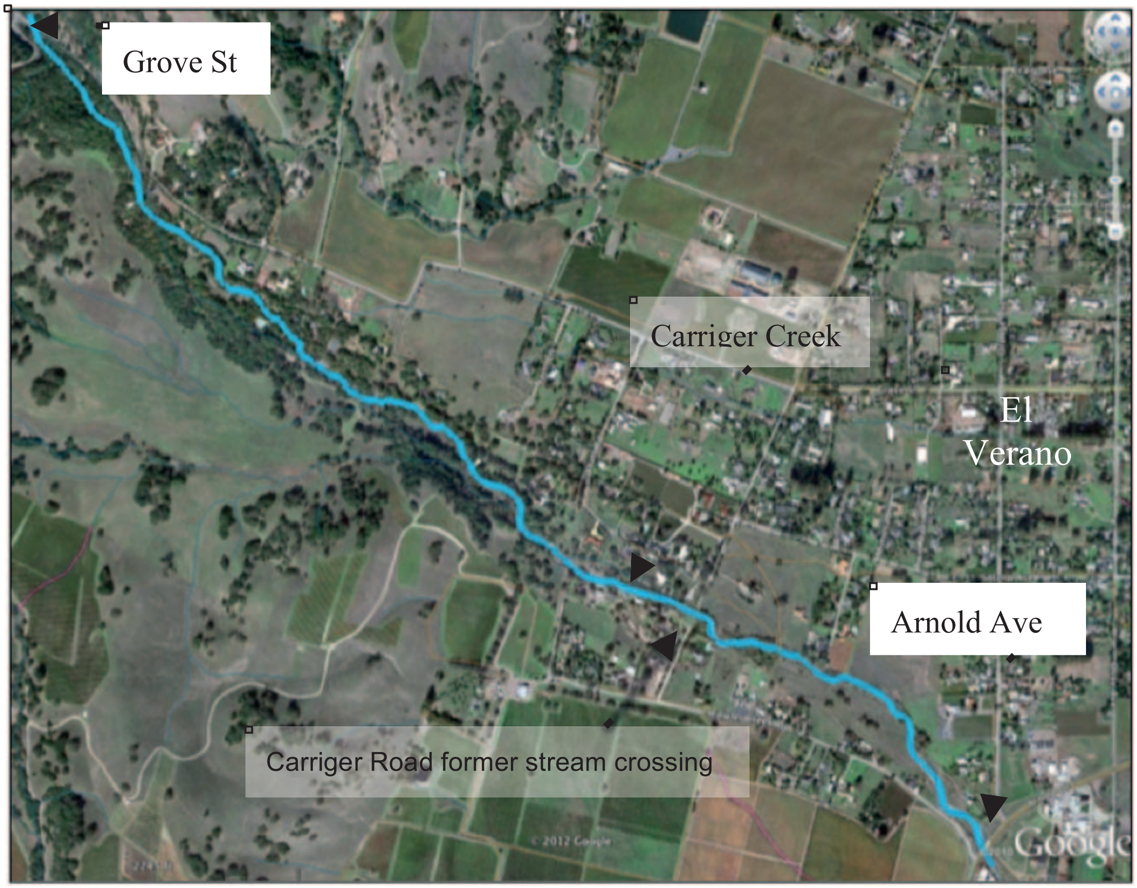


Figure 13. The mainstem Carriger Creek along the upper and middle portions of its alluvial fan Is shown flowing from left to right.

crosses the lower portion of the fan and Grove Street crosses the upper portion as seen in Figure 13. This section of the mainstream Carriger channel to slightly beyond and between these road crossings has been the primary area of study from upper to middle alluvial fan.

Figure 14 shows the watershed boundary of the mainstem Carriger Creek to the Felder Creek confluence. The highest peak in the Carriger headwaters is 2, 295 ft at the top of Sonoma Mountain. Mean annual rainfall for the upper watershed is about 40 in/yr. The linear distance from hydrographic apex to the toe of the fan, near Leveroni Road, is about 2.7 miles. The hydrographic apex is about 2.5 miles downstream of the fan apex. The fan apex is about in the same location of the Grove Street box culvert, which at its upstream edge has a distance station equivalent to 20,596 ft. The zero distance station is at the Felder Creek confluence and corresponds to survey stations in this report. The channel distance between Grove Street and Arnold Avenue is 2.1 mi. The upstream edge of the bridge at Arnold Avenue crosses at distance station 9,470 ft. Between the two bridge crossings the drop in creek elevation is 280 ft. Downstream at the toe of the fan the drop might be about 327 ft. Even though the Carriger watershed does not have one of the larger drainage areas in the Sonoma Creek watershed, it has the largest and steepest alluvial fan that is very coarse bedded with

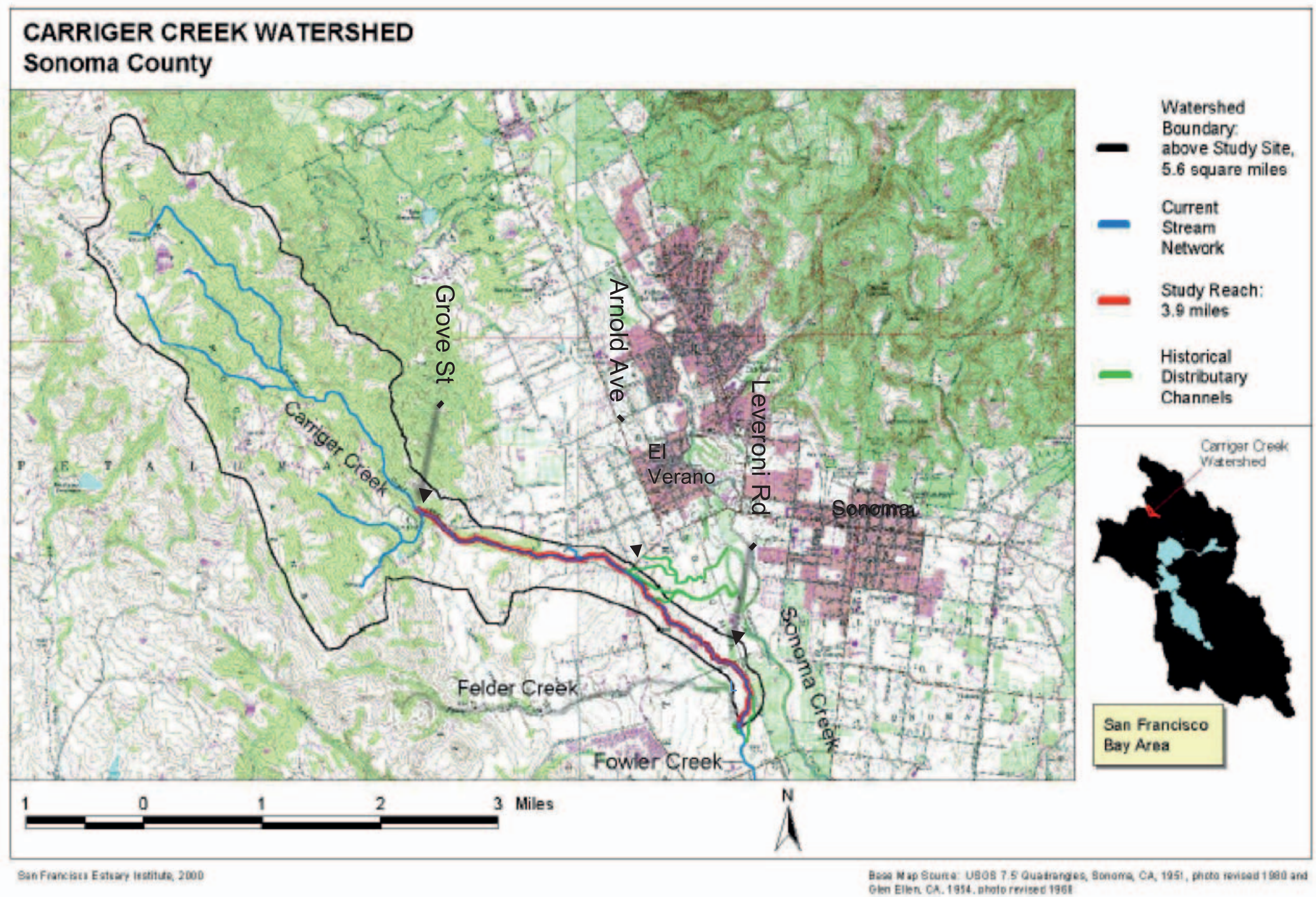


Figure 14. The mainstream study reach of Carriger Creek is shown in red, while the rest of its length and major tributaries are shown in blue. Carriger Creek's watershed boundary, is shown in black and begins upstream of its confluence with Felder Creek. Downstream of the confluence the name of the channel changes to Fowler Creek. Source: Collins *et al*, 2002

cobbles and small boulders dominating the streambed surface sediment size class over the upper and middle portion of the fan.

As seen in Figure 15, the predominant geology of the uplands is Pliocene and early Miocene basaltic volcanic rocks with some ash flow tuff and rhyolite (Fox, 1983). Tilted and relatively thick beds of diatomite interspersed through the area indicate that in the geologic past, large fresh water lakes existed in the upland volcanic environment. The lower portion of Carriger Creek flows across its Quaternary-aged, coarse-bedded alluvial fan where it intercepts alluvial terrace sediments deposited by Sonoma Creek. The middle portion of Carriger Creek canyon is defined by hummocky topography from a very large ancient landslide that was likely associated with catastrophic volcanism from millions of years ago, and perhaps associated with failure of one of the large lakes. The predominance of large cobbles and small boulders, coupled with the large size of the fan, small size of the watershed, and magnitude of discharge required to widely distribute such large bedload most likely reflects this large-scale event of the geologic past. Today, bankfull and effective discharges in Carriger Creek do not generally mobilize the boulders that comprise much of the streambed surface. Larger flood flows are required to transport these particles to any significant distance.

The Bennett Valley fault proper crosses Carriger Creek upstream of its fan apex. The right lateral fault also has tectonic uplift on its western side. It has a splay fault that crosses the fan at about station 17,200 ft. Another unnamed fault exists to the east that crosses Carriger Creek at about station 15,600 ft. Carriger Creek starts to have reaches that alternate with intermittent and perennial flow between stations 17,600 ft and 15,300 ft. Downstream of 15,300 ft the creek typically becomes dry over the rest of its fan during the summer and fall. Station 15,300 ft is about 1 mi downstream of the Grove Street crossing.

There has not been rigorous mapping of the distributary and braided channel system on the Carriger fan, yet both Figure 15 and the 1942 cover photo of this report show some pre-existing overflow and paleo-pathways of tributaries and distributaries. The earliest historical maps of Carriger Creek, such as the 1842 map shown in Figure 16, depict a tree-lined mainstream channel that disappears toward the toe of its fan, never connecting to Felder, Fowler, or Sonoma Creeks. If this mapping was correct, the alluvial fan functioned as a significant groundwater recharge zone.

The historical intersection point of the alluvial fan channel might have been roughly at the distance station corresponding to 7,100 ft. The bottom two photos of Figure 5 (page 10) depict what the channel looked like during 2008 in this vicinity. It can be seen that the elevation difference between the cobble-bedded stream and the valley flat is relatively small, especially in areas where the channel alternates from scouring to deposition. Based upon evidence from historical photos, Carriger Creek appears to have been ditched to a former abandoned but tree-lined channel between the approximate distance stations

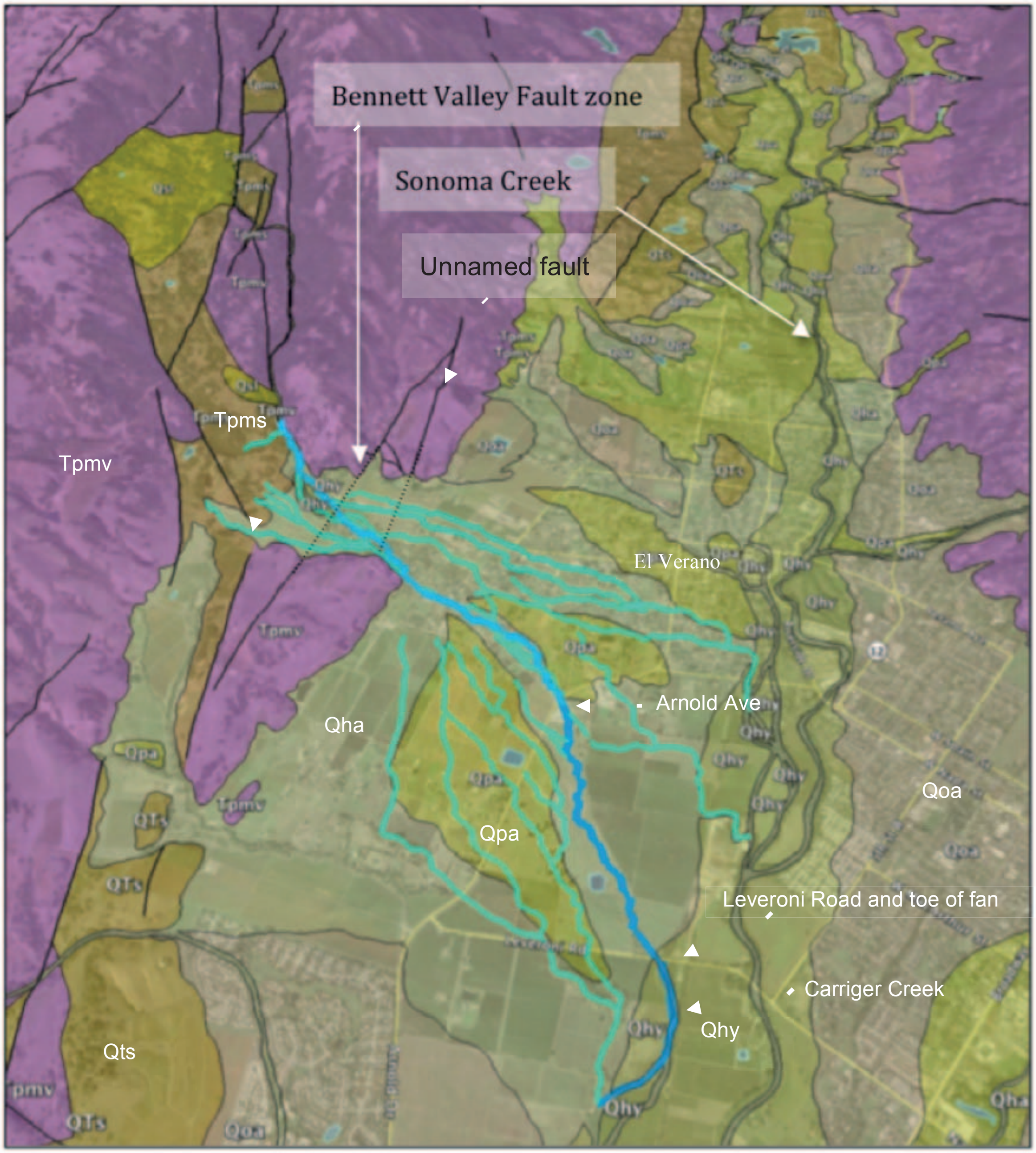


Figure 15. Blue and green streamlines are shown for this project and superimposed on the USGS geologic maps (Scientific Investigation Map 2918) and Google Earth Imagery. The map is oriented to look northward up the Sonoma Valley at the Carriger Creek fan. The heavy blue line represents the current position of Carriger Creek, while turquoise lines roughly show some pre-existing overflow, and/or paleo-pathways of tributaries and distributaries on the alluvial fan. The Bennett Valley Fault zone, a subsidiary splay fault, and an unnamed fault are shown crossing the upper portion of the fan. Downstream of the latter fault the creek is intermittent. The valley formed within Carriger Creek canyon is influenced by Quaternary-aged landsliding, (Qls). The hills shown as purple (Tpmv) are Plio-Miocene volcanic rocks, and the light orange are Pliocene to early Miocene sedimentary rocks (Tpms). The yellow areas are Quaternary-aged alluvial deposits: Qhy is late Holocene, Qha is Holocene, Qpa is Pleistocene, Qoa is early Pleistocene, and Qts is early Pleistocene or Pliocene.

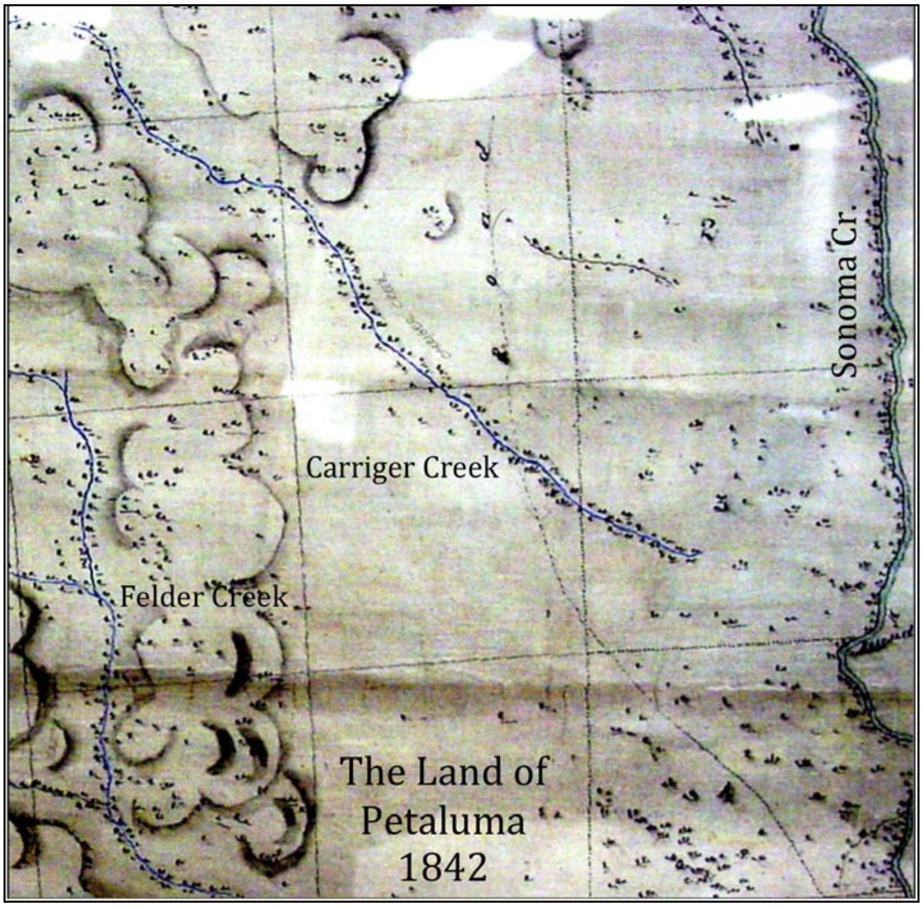


Figure 16. A portion of an 1842 of The Land of Petaluma map is shown. Carriger Creek was not mapped as having a continuous connection to Sonoma Creek, however the Felder/Fowler Creek system was shown to connect to Sonoma at the present day confluence. Source: SEC

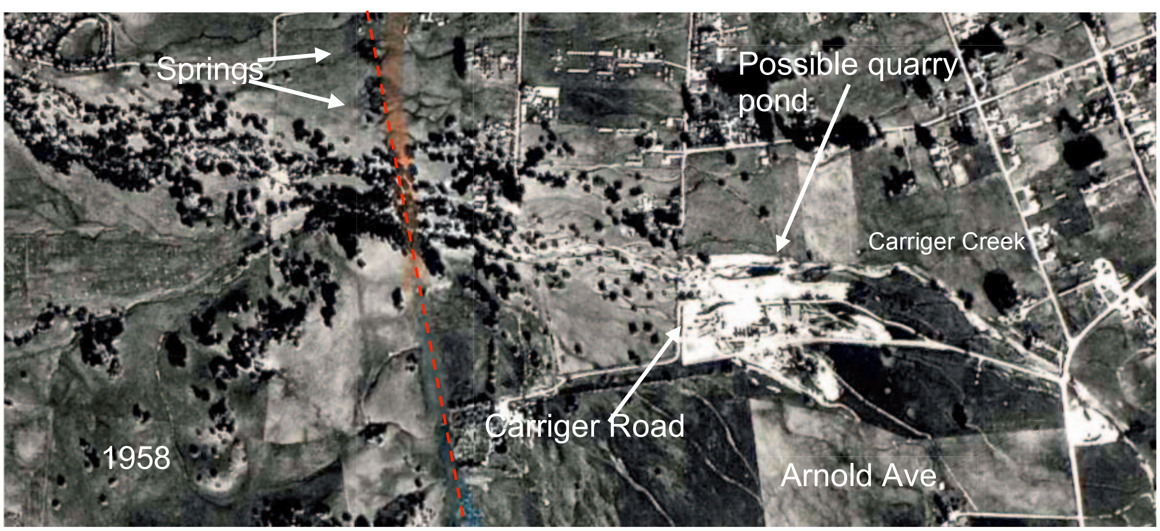


Figure 17. A 1958 aerial photo is shown of the Carriger Creek fan from Arnold Ave to about 0.3 mi downstream of Grove Street crossing. A gravel company was located just downstream of Arnold Avenue and a quarry pond appears to exist upstream of Arnold Avenue in the cleared area. Springs in the upper left section of the photo coincide with the projected trace of the unnamed fault that crosses the fan roughly near distance station 15,100 ft. Source: SSCRCD

of 6,600 ft and 3,300 ft, the latter of which corresponds to the Leveroni Road crossing. Downstream, the channel becomes increasingly incised towards its confluence. This might explain why Carriger Creek has a name change to Fowler Creek at the Felder Creek confluence. The significant impact of the ditching is that it connected Carriger Creek surface flow directly to Fowler and Sonoma Creeks, thereby increasing peak flood size and arrival time to the Schellville area of lower Sonoma Valley.

The modern watershed of the uplands has fairly sparse residential development within the mixed hardwood and coniferous forest. Grasslands on the upper western hillsides are primarily used for cattle ranching. The alluvial fan, while also sparsely developed, has mostly converted from ranching to viticulture during the last two decades. Broadly spaced residences exist along the mainstem creek, similar to the development pattern of the Sonoma Creek fan. During the mid 1950s, portions of the Carriger Creek streambed on its middle alluvial fan appear to have been used for gravel quarrying, as shown in the 1958 aerial photo in Figure 17. Riparian vegetation became noticeably missing from these reaches, downstream of distance station 12,900 ft, approximately where Carriger Road previously crossed the channel, see Figure 13 and 17.

Prior to 2000, increased rates of property loss from bank erosion, loss of riparian vegetation, lack of perennial flow, flooding, and loss of fish habitat in the middle and lower alluvial fan reaches raised concerns among local residents about the “health” of their watershed. This prompted a detailed quantitative field study by Collins *et al* (2002) of sediment sources and geomorphic changes along the lower 3.9 mi of Carriger Creek, upstream of its confluence with Fowler Creek.

Important findings of this earlier study were that the mainstream creek between Grove Street and Arnold Avenue had become increasingly unstable from the influences of non-native land use practices that started circa 1835. In particular, the combined influences of ditching downstream of Arnold Avenue, elimination of various distributary channels on the fan, gravel quarrying on the middle fan, and backwater flooding from various under-capacity bridges have caused the channel to adjust its geometry.

A synopsis of some findings from the earlier study is shown in Figure 18. For example, the volume of sediment supplied from bed incision was shown to exceed that from bank erosion in the upper and lower fan reaches. Bank erosion dominated the middle fan reaches, and it was suggested in the report that 60% of the modern sediment supply was initiated by land use practices, many of which can be considered legacy effects from the 1800s through the early 1900s.

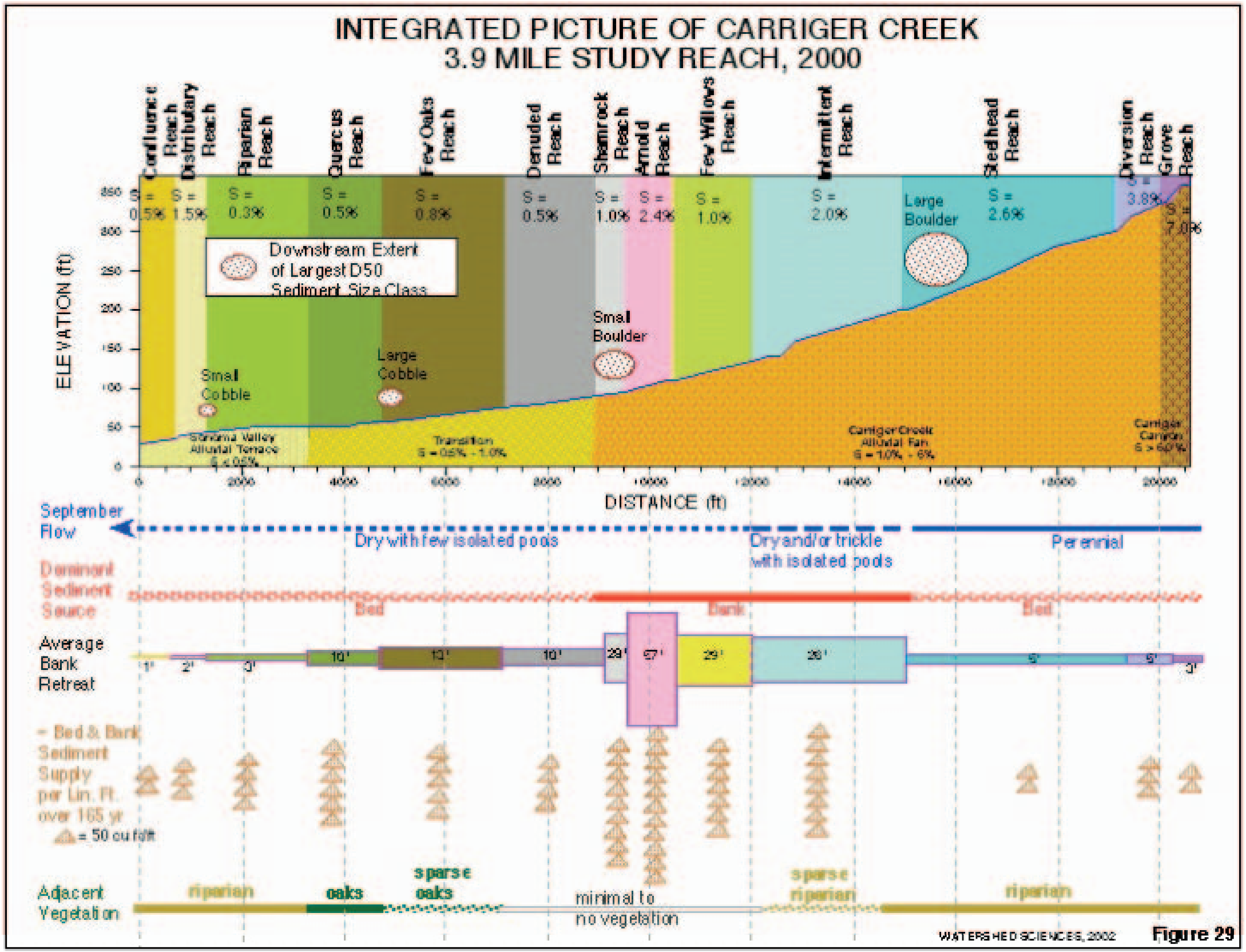


Figure 18. A chart from Collins et al (2002) is shown that indicates the slope of Carriger Creek from its mouth at Felder Creek to the Grove Street crossing. The slope shown here is derived from contours on the USGS 7.5 minute Sonoma Quadrangle. Different reaches were named based upon channel condition. They are color coded along the profile. The downstream extent of the dominant particle size class (D50) of the streambed is shown along the profile. The lower chart shows variations in the extent of seasonal flow, the dominant local sediment source (stream bed incision or bank erosion), the average amount of bank retreat (both banks combined), the total amount of sediment supply per reach per linear foot since 1835 (start of significant influences from European land practices), and a description of adjacent streamside vegetation. Source: Collins *et al* 2002.

During the 2000 field survey, measurements were also taken on the bankfull width at intervals of 300 ft and at points where extreme changes in channel geometry were observed. Figure 19 shows the variability in width that ranged from 15 ft to 74 feet. Reaches that appeared most stable had bankfull widths of about 27 ft to 30 ft. The average width was 32 ft. The approximate stations of 6,300 ft, 13,200 ft, 14,400 ft, and 16,800 ft were the widest reaches with respective widths of about 74 ft, 74 ft, 64 ft, and 54 ft. The narrow widths were in areas associated with either newly incising reaches within inner benches formed by abandoned streambeds, or mature riparian vegetation, generally in the upstream reaches, that had large woody roots that provide added cohesion to the banks.

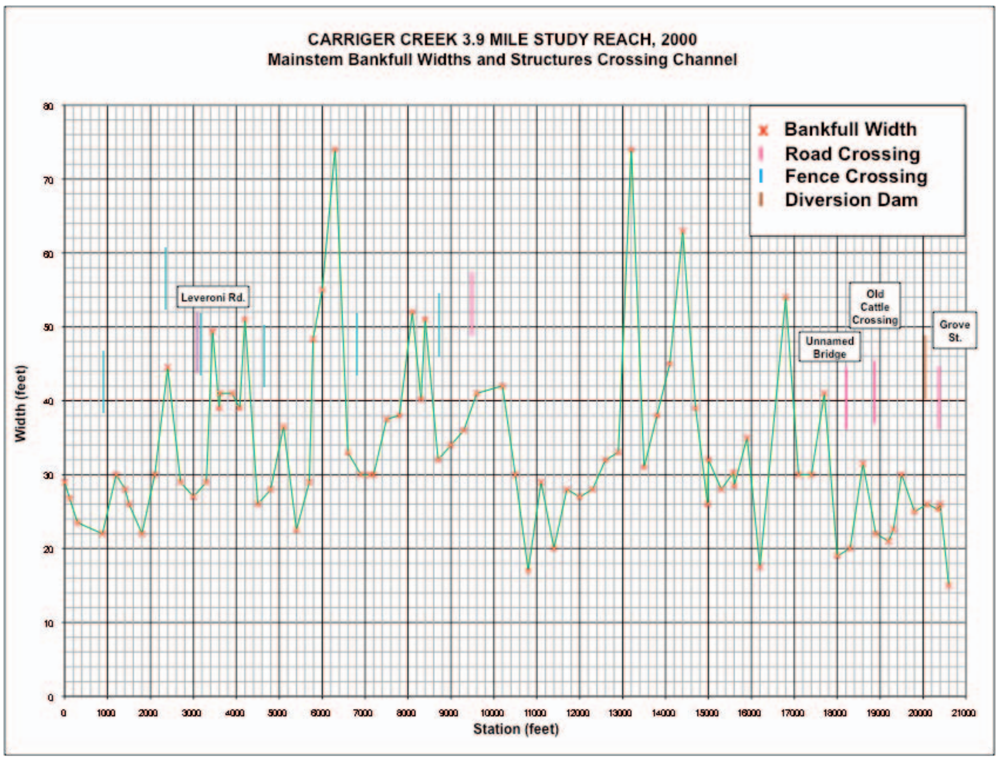


Figure 19. The variation is shown in the 2000 WY survey of bankfull width. The survey extended from Grove Street to the confluence of Felder Creek. Source: Collins *et al* 2002.

Shortly after the first geomorphic study was completed, Watershed Sciences was funded by the SSCRCD to survey several cross sections and a detailed longitudinal profile of Carriger Creek from Arnold Avenue to Grove Street. The results of the October 2001 survey are shown in Figure 20, which details the elevation of the streambed, water surface, and the banks of bankfull elevation and adjacent terraces. Generally, upstream of station 20,200 ft the channel was a step pool configuration, while more commonly the downstream channel alternated between a pool-riffle and plain bed configuration. It can be seen by the thin blue line in Figure 20 that perennial flow was maintained until about distance station 17,600 ft and then alternately flowed between surface and subsurface until about station 15,300 ft. Downstream of this, the channel was dry. Near station 16,200 ft the terrace banks were very close to the streambed elevation. This might be quite close to where a distributary historically flowed from the north bank, but more detailed mapping is required to fully characterize these channels. The profile shows that the difference between the elevation of the adjacent terrace banks and the streambed becomes small between stations 10,500 ft to 12,400 ft, and between 15,600 ft to 17,000 ft. This indicates that overbank flooding is likely in these areas, especially because the bankfull width is correspondingly narrow in these sections as indicated in Figure 19.

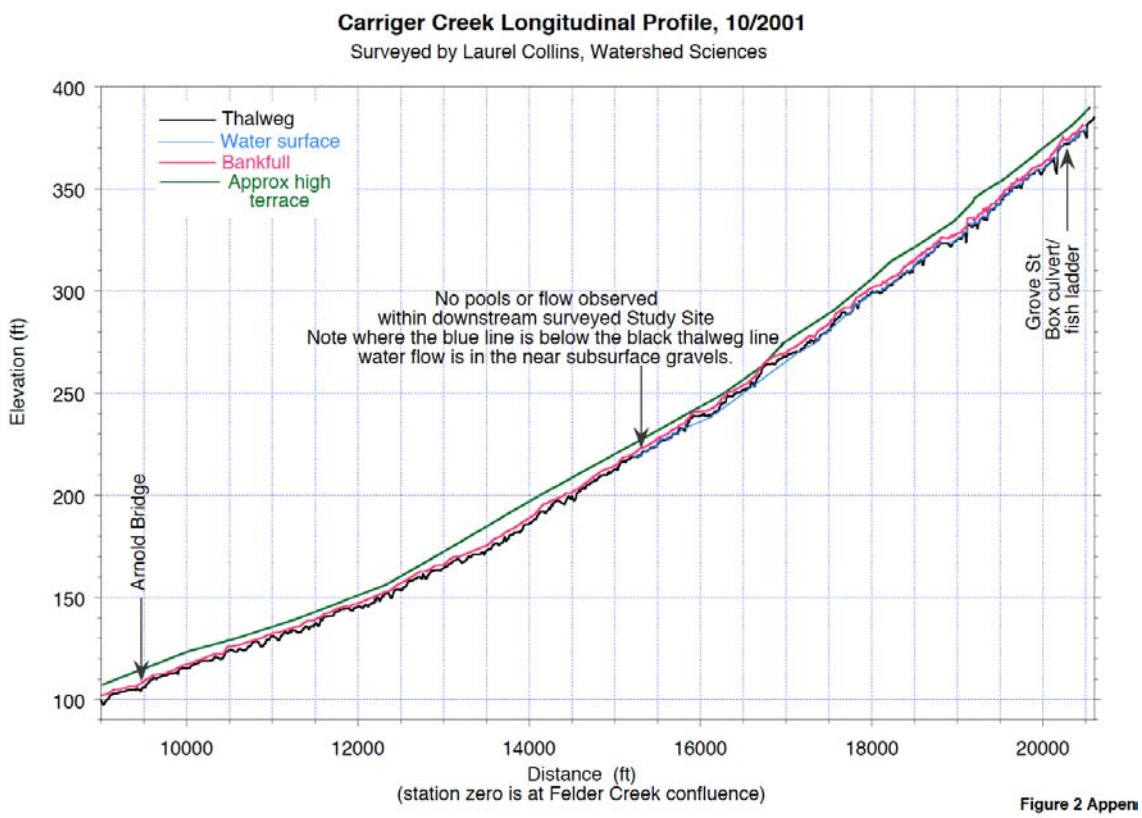


Figure 20. The surveyed longitudinal profile is compared to the one constructed from the USGS 7.5 minute Sonoma Quadrangle. Source: Collins *et al* 2002.

If the average stream gradient is delineated on the profile, as shown by the red lines in Figure 21, two areas that represent crossover points where the average stream gradient changes from steeper to more gentle can be seen near the midpoints of stations 12,800 ft and 17,500 ft. The one at 12,800 ft is just downstream of where Carriger Road previously intersected the channel. The possible gavel quarrying would have influenced the site. At the time of the 2001 survey, the channel upstream of this area had a change in width from 30 ft upstream of the midpoint of the crossover to 75 ft downstream of the midpoint. At the crossover midpoint at 17,500 ft near where a distributary channel separates at the north bank, the width also increased from 30 ft upstream of the midpoint to 40 ft downstream of the midpoint. Both crossover points seem to correspond to areas of long-term channel aggradation and to locations that were singled out to represent future areas of instability and channel avulsion.

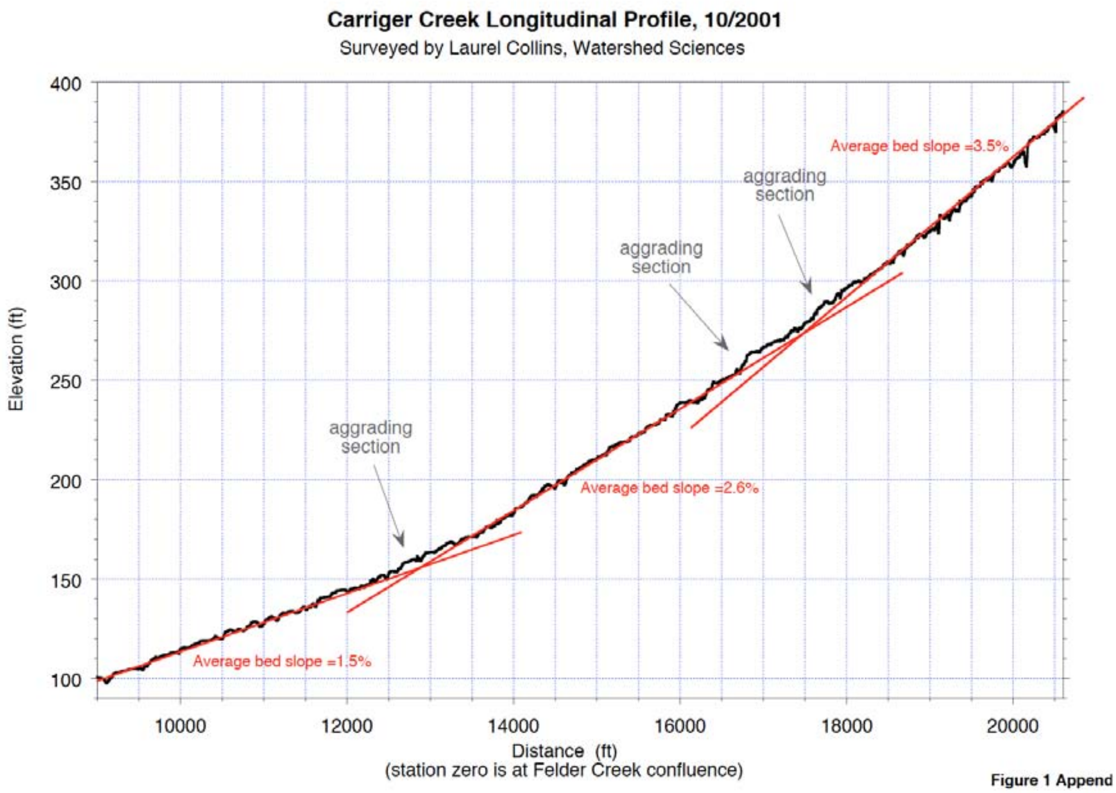


Figure 21. Red lines are shown to represent average gradient on this 2001 longitudinal profile. Collins *et al* (2002) suggested that long-term channel aggradation might occur at the locations where the red lines cross over each other. The crossover areas occur at major inflection points along the profile, Source: Collins *et al* 2002.

During the December 2005 storm, flooding on Carriger Creek was reported by the Natural Resource Conservation Service (NRCS 2006) to have caused a large volume of water to travel easterly, north of Carriger Creek, causing a tremendous amount of erosion and debris deposition. Flood depths against structures were measured to be two to three feet. The actual discharge associated with the flood is unknown, since there are no stream gage records for Carriger Creek. During the flood, some secondary braided reaches (which are within the active bankfull elevation) switched to become the mainstream braid, and former distributary channels above the bankfull elevation were also reoccupied. The flow in the distributaries did not necessarily follow historical pathways because they had also been influenced by modern landscape alterations. One of the distributaries that exits the north bank, possibly somewhere between distance stations 17,100 ft and 15,900 ft, might have functioned as a primary distributary. Interviews with landowners would be necessary to accurately map this distributary.

IV. METHODS

Laurel Collins conducted all stream surveying with assistance from the SSCRCD with Kevin Cullinen, Sumner Collins, or Michael Bowers. A centerline tape was pulled along the center of the active bankfull channel to develop distance stations for the surveys of streambed and water surface. At sections that had been previously surveyed and where flagging with notated distance stations could be found from the previous surveys, efforts were made to match the tape distance. Surveying of water surface (when present) and thalweg (deepest point of the channel) was accomplished with a Zeiss level and a telescoping fiberglass rod. Survey points were taken to define the features of riffles, runs, pools, and glides and data were entered into waterproof survey books. Flagging, annotated with distance stations, was tied at 100 ft intervals and survey paint was use to mark temporary turning points and benchmarks. The surveys were closed between known benchmarks at Grove Street and Arnold Avenue Bridge for Carriger Creek, and at the Highway 12 Bridge for Sonoma Creek. The table below shows information about the permanent benchmarks that were used for this and previous surveys. The accuracy of the bench marks has not been determined.

Benchmarks		
Carriger Creek		
Southeastern edge of box culvert at Grove Street	Nail set in road marked by white painted triangle	399.99 ft
Southwestern edge of Arnold Avenue Bridge	Brass Disk	116.94 ft
Sonoma Creek		
Southwestern edge Highway 12 Bridge	Cal Tans white paint point in white triangle	446.765 ft

Cross sections were surveyed with the level and distance stations were established by stretching a tape across the channel. When it was possible to determine location on an aerial photomap, 300 ft interval distance stations were depicted. In many areas this was not possible due to dense tree canopy and/or property restrictions. In both creeks there were some areas where a recreational grade GPS unit was used to aid in mapping the distance station locations. Using the combination of aerial photo mapping, previous information, and the GPS coordinates, an outline of the mainstream channel and approximate distance stations were plotted for each site on 2012 imagery from Google Earth Pro.

In Carriger Creek the survey was started at Grove Street and proceeded downstream. During the field surveying process, Grove Street was the zero distance station for which all the raw survey notes and flagging pertained, but for the purposes of the report and comparison to previous graphics, these stations were adjusted to reflect the zero station at the confluence of Felder and Fowler Creeks. In Sonoma Creek the field survey and the zero distance station started at the upstream edge of the Highway 12 Bridge and proceeded in a negative direction toward the apex of the fan and a positive direction downstream toward the confluence with Oakmont Ditch. In the upstream direction, the new negative distance stations matched the previous positive station numbers. In short, positive numbers increase in value with the direction of water flow, while negative numbers decrease upstream against the flow.

Each site had a cross section located at a riffle near the upstream and downstream ends of the profile. Care was taken to have relatively stable sites and not have the cross sections within zones of common backwater flooding. Annotated flagging was tied to vegetation to identify the cross section locations. Photographs looking upstream, downstream, and across each bank were taken. The end points of the cross sections were each documented with recreational grade GPS coordinates and had two rebar per bank where feasible: one close to the bank and another farther away, at the end of the cross section tape. Rebar were marked with flagging. A temporary benchmark was established near each site. The surveys and cross section plots were conducted with the standard that zero is on the right bank, and the right bank is for looking downstream.

Standard Wolman pebble counts were conducted on the riffle cross sections within the active bankfull channel 5 ft upstream and downstream of the cross section tape. The pebble counts were plotted to determine the size class represented by 50 percent (D50) and 84 percent (D84) to help characterize the cross section and to estimate roughness for discharge calculations.

After the end of the survey, the SSCRCD contracted with PVTS Vineyard Development Consultants to reoccupy and capture survey-grade GPS coordinates of the long profile end points and of each cross section. This information, as well as an explanation of methods, was provided separately to the SCWA by the SSCRCD, with the intent to provide a highly accurate location of each long profile and cross section in a GIS format for compatibility with existing data sets and available analyses tools.

Data for the profile and cross section surveys were entered into Excel spreadsheets that have been provided to the SSCRCD and the SCWA. Previous surveys were conducted using essentially the same methodology discussed here, except that GPS units were not used to help define the distance stations. The previous surveys were imported into the spreadsheets to plot and compare to the 2011 conditions. The profiles were graphed in Excel spreadsheets, while the cross sections were plotted using a Reference Reach Spreadsheet program developed by Dan Mecklenberg for the Ohio Department of Resources (2006). Digital Excel spreadsheets and a written report were provided to the SSCRCD and SCWA.

V. RESULTS

Sonoma Creek

The longitudinal profile of Sonoma Creek was surveyed during November 2011 before any significant flow events of the WY 2012 rainy season. Following the survey, the peak discharge was 835 cfs during March WY 2012 at the Sonoma Creek at Kenwood gage. For the previous years of 2011, 2010, 2009, the respective discharges were 1,020 cfs, 1,170 cfs, and 439 cfs. These flows were all higher than the PWA estimated 2-year RI of 314 cfs.

Results of the 2011 profile are shown in Figure 22. Closure to the benchmarks was plus or minus one inch. The approximate station locations are indicated in Figure 22. The thalweg gradient is shown in brown and water surface is shown in blue. As can be seen, Sonoma Creek was dry through the middle reach of its alluvial fan, yet flowing near the apex and toe. Although there are very local and short variations within reaches, the average stream gradient was determined for longer segments of similar grade, as shown in red lines above the thalweg profile. There are seven inflection points where gradient changes significantly. These are indicated as red X's in Figure 23. There is a short 200 ft segment upstream of the highway bridge that is not broken out separately for average gradient, yet it is quite flat due to sedimentation from the undersized capacity of the bridge. Upstream of the bridge significant slope breaks occurred at stations -2,699 ft, -1,868 ft, -849 ft, -400 ft. Downstream of the bridge they were at 1,158 ft, 2,800 ft, and 3,310 ft. These points are indicative of significant changes in channel geometry of the entrenchment and width/depth ratios. They reflect recent incision within historical patterns of fan building.

The steepest slope, 2.70 percent, is located along the apex of the fan where the channel has primarily step-pool morphology. Downstream of this the channel ranges from plain bed to pool-riffle morphology. The next steepest reach, 1.33 percent, is located upstream of the highway bridge between stations -400 ft and -849 ft. This channel reach has a secondary braid separated by a mid channel bar. The profile of the narrower, more wooded braid is indicated in the more detailed upstream profile comparison in Figure 24.

A fairly long reach upstream of the highway bridge has a uniform gradient of about 1 percent. All other reaches have a gradient less than 1 percent. The reach downstream of the highway bridge to about 1,400 ft has the longest, most uniform gradient of 0.59 percent. Downstream of this, just before the large westward bend between stations 1,400 ft and 1,600 ft, the channel steepens to 7 percent and then has short reaches that get steeper, flatter, and then steeper again toward the confluence of Oakmont Ditch. These last three short reaches reflect the 8 ft or more incision of the mainstem channel that was instigated by

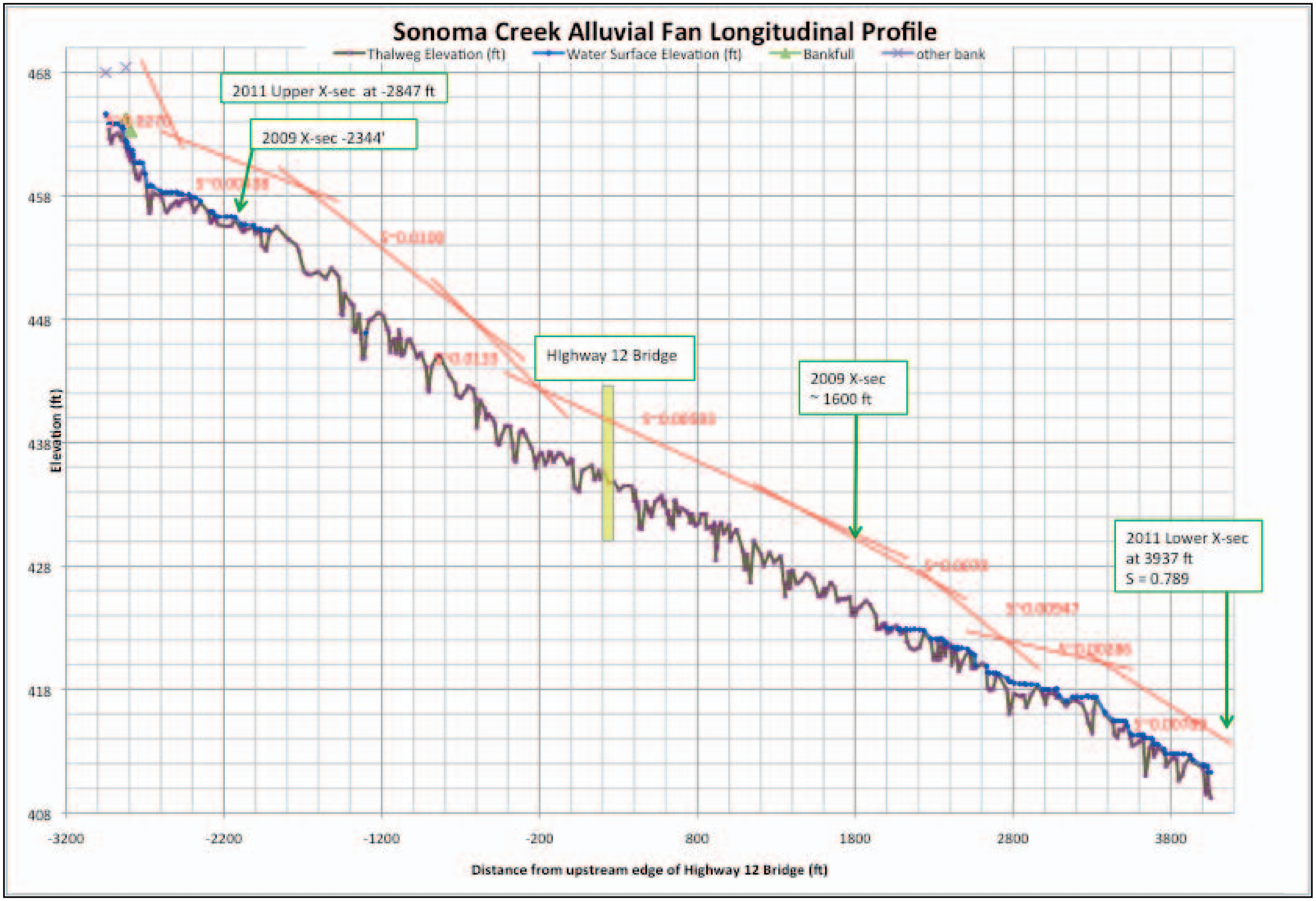


Figure 22. The November 2011 longitudinal profile is shown of Sonoma Creek along its alluvial fan. Station zero is at the upstream edge of the Highway 12 Bridge crossing.

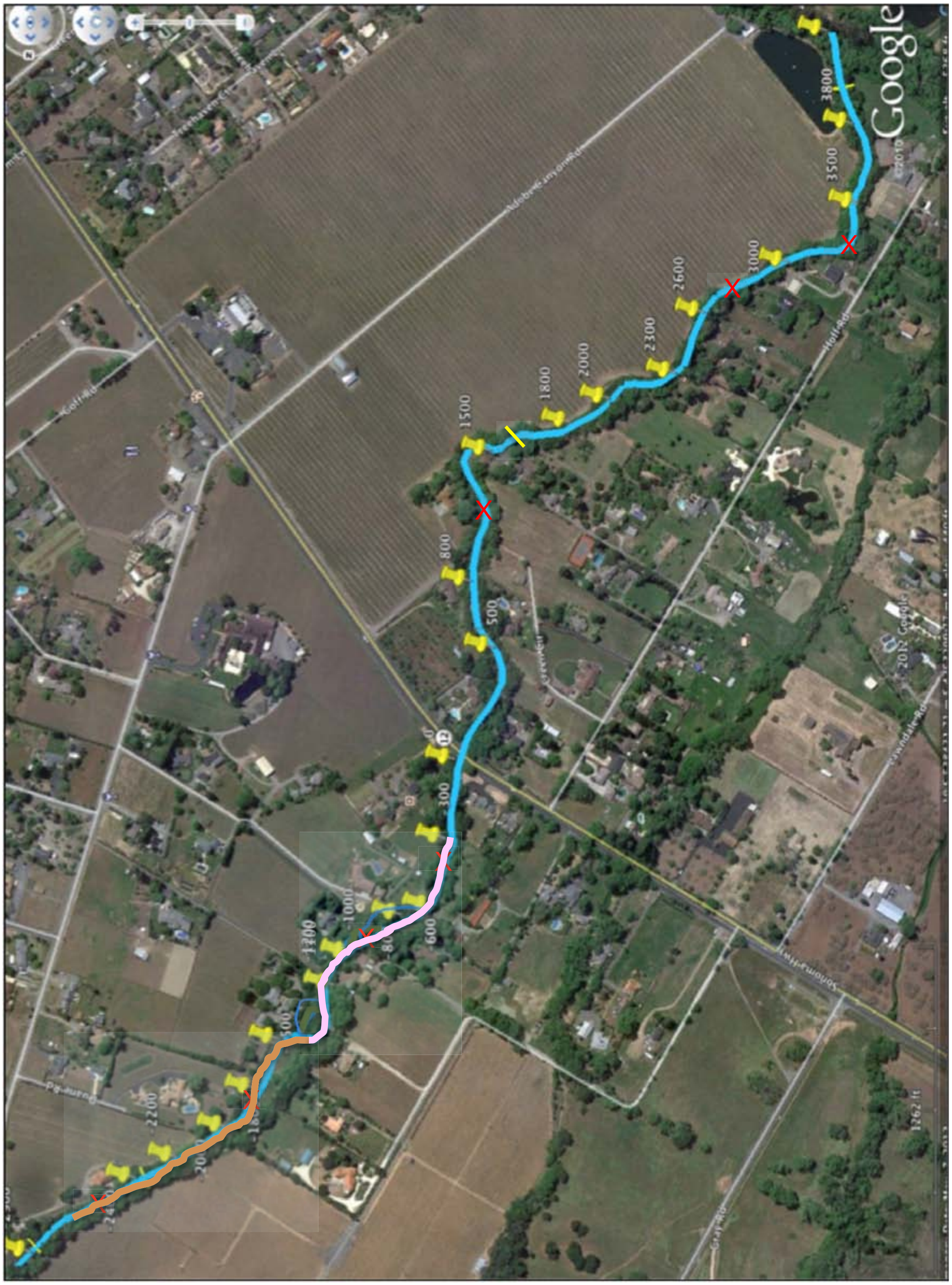


Figure 23. Rough estimates of distance stations in feet are shown at the yellow pinpoints along the mainstem Sonoma Creek, which is shown as a thick blue line. Thin blue lines represent active braids. The direction of flow is from the bottom of the picture toward the top. Red X's represent rough locations of where inflection points occur for significant changes in stream gradient. As indicated in Figure 24, the light brown line represents the reach that has had significant incision since WY 2009, while the light pink line represents the reach with significant deposition.

the ditching of the historical wetlands. Figure 10 shows that in 1958 there were prominent distributary channels upstream and downstream of the major westward bend. Also shown in Figure 10 is that the pre-1851 mainstem channel used to spread to the wetlands southward of the present day channel alignment.

Although comparative profile surveys in the reaches downstream of the highway bridge do not exist, field evidence indicates that there is active downcutting in the steeper 9.47 percent reach between stations 2,200 ft and 2,700 ft. Preliminary observations indicate that this reach has a narrow floodprone width relative to its bankfull width and that the channel is entrenched. Entrenched alluvial channels are typically unstable until sufficient floodprone width, greater than 2.2 times bankfull width, has been attained by bank erosion. To determine the extent of entrenchment, bankfull and floodprone width must be determined, yet these parameters can be particularly challenging to determine in alluvial fan channels that have losing and gaining reaches of flow, especially when they are inherently unstable.

Figure 24 shows the comparisons of the 2011 survey to previous profiles surveyed upstream of Highway 12. The red, yellow, and black lines represent the thalweg elevation during the respective years of 2008, 2009, and 2011. The narrower pink line represents the thalweg profile of the braided secondary reaches, which are more incised and are smaller channels than the main braids. The braided reaches are probably the result of the influences of backwater flooding from the highway bridge that has sediment deposition occurs even during moderate-sized floods. The large brown and pink arrows at the bottom of the graph show where between 2008 and 2011, the thalweg elevation of the streambed was dominated by either incision or deposition. The first 300 ft upstream of the bridge had minimal change.

Through the reach dominated primarily by recent incision, very little change occurred between 2008 and 2009. The peak flow during WY 2009 was probably close to bankfull discharge. The reach dominated by net deposition had slightly more change in the streambed than the incising reach, particularly near stations -1,400 ft and -900 ft, which are upstream and downstream of the upper mainstem braid. Between 2009 and 2011, there was more net incision and more net deposition than the previous time interval. This was probably due to the larger peak flows that were both roughly 2.5 times the bankfull discharge, as reported for the Sonoma Creek at Kenwood gage.

The reaches with the greatest amount of incision between 2008 and 2011 were at stations -2,100 ft and -1,600 ft. Much of this reach between -1,500 ft and -1,900 ft is characterized as plain bed morphology with little relief of the channel bed and virtually no pools. Station -1,900 ft is where the channel becomes intermittent and sediment deposition is likely associated with the loss of surface flow at this site. Stations -1,250 ft and -850 ft had the greatest amount of deposition, on the order of 1 ft in the thalweg. Both these stations were at the upstream extents of the mainstem braided reaches.

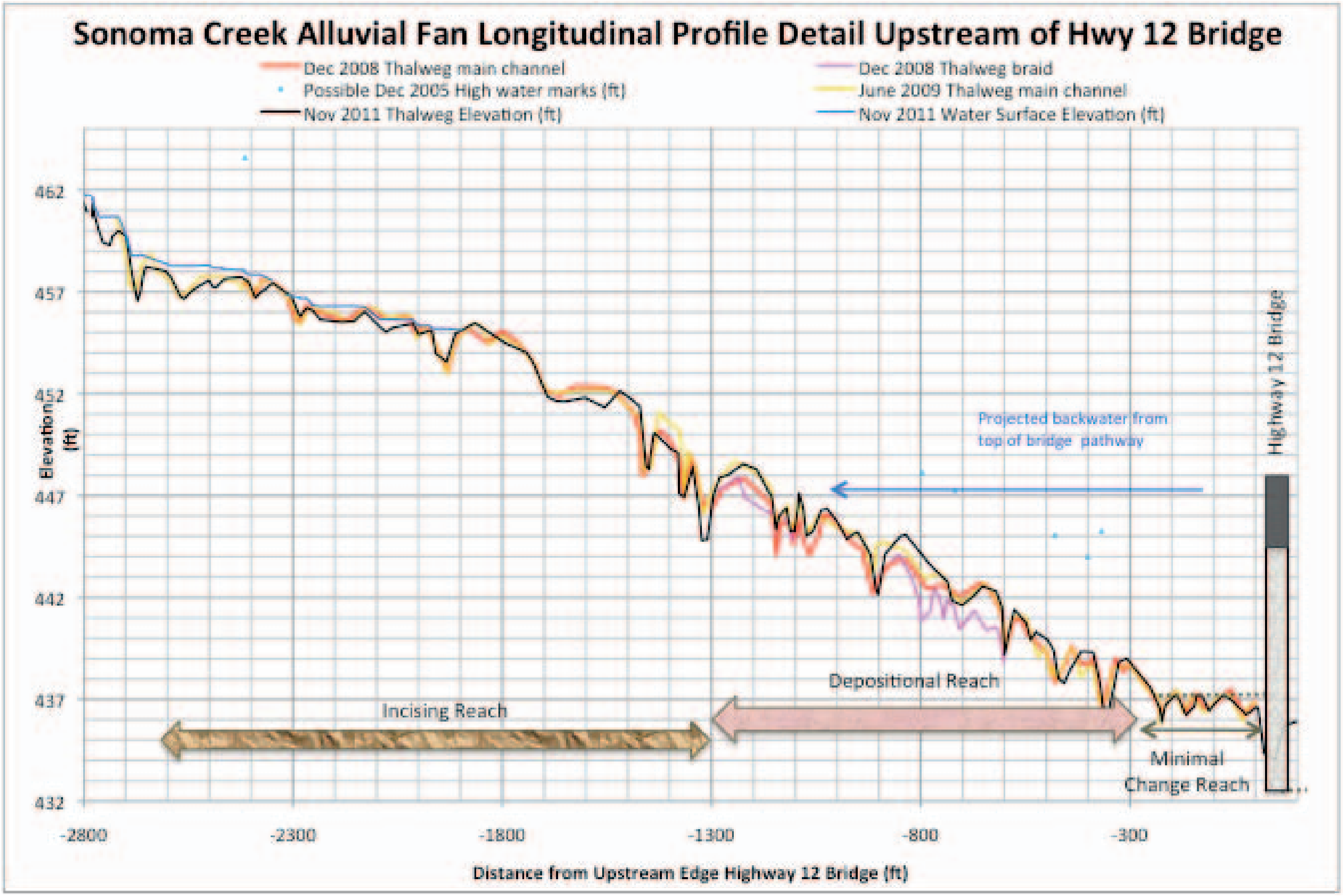


Figure 24. The changes in the thalweg profile are shown between 2008, 2009, and 2011 for the Sonoma alluvial fan reach upstream of the Highway 12 Bridge. The brown and pink arrows at the bottom of the graph indicate the dominant mode of incision or deposition.

The upstream Cross Section -2,847 ft, plotted from the Mecklenberg Spreadsheet Program (2006), is shown in Figure 25. Its data parameters for determining discharge are listed below the plot. The required input data of local bankfull flow gradient and the streambed materials as established by Wolman Pebble Counts are needed to compute discharge. A plot of the surveyed bankfull gradient is shown in Figure 25, and the cumulative distribution plot of the pebble count plot for establishing D50 and D84 is shown in Figure 26. Figure 27 shows a more detailed photo map of all 2011 and 2009 cross section locations, and Figures 28 through 30 show photographs of the 2011 Cross Section -2,847 ft.

Bankfull discharge at the uppermost Cross Section -2,847 ft is about 320 cfs. This is slightly more than the discharge at the next downstream Cross Section -2,344 ft, which had been surveyed earlier during 2009 but discharge estimates were revised for this project. The entrenchment and width/depth ratio indicate that this cross section should be a fairly stable reach with little incision or deposition expected unless there are substantial modifications made by man or from natural accumulations of woody debris.

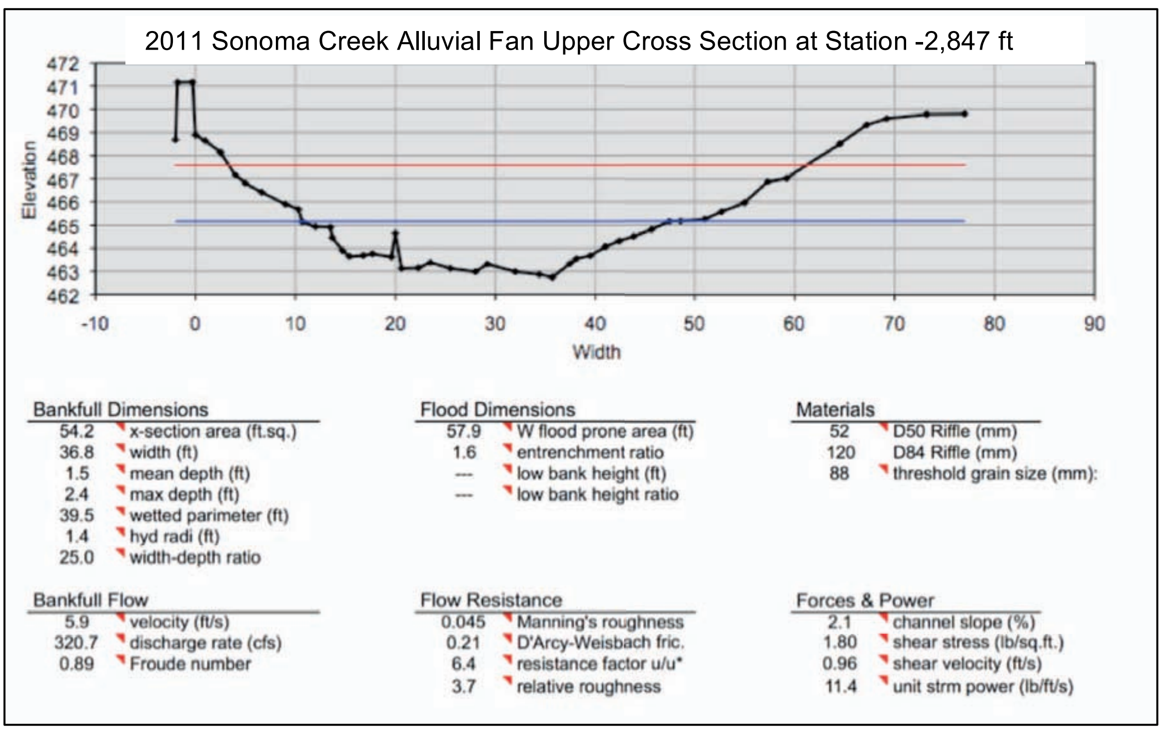


Figure 25. Cross Section -2,847 ft is plotted looking downstream. Dimensions needed to calculate discharge at the site are reported below. The blue line represents the estimated bankfull elevation and the red line represents the floodprone width.

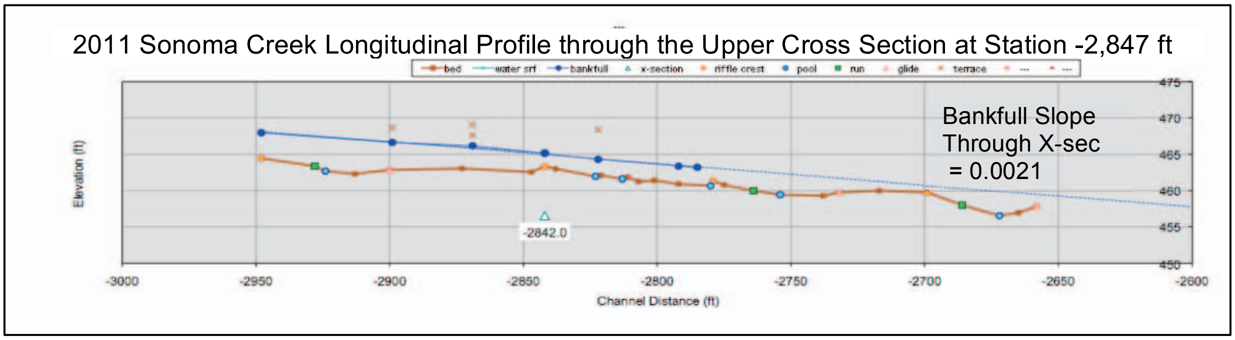


Figure 26. Estimated gradient is shown for the streambed thalweg and bankfull flow at Cross Section -2,847 ft in the perennial reach upstream of the highway bridge.

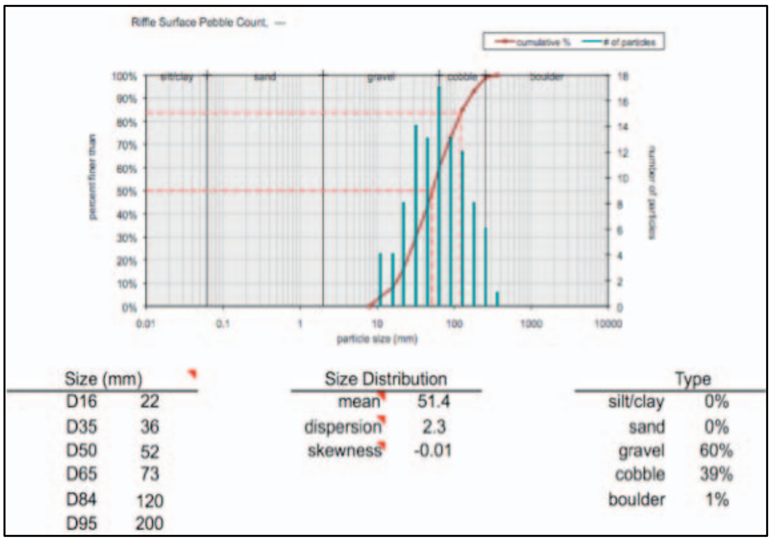


Figure 27. Sediment size distribution is shown for Sonoma Creek Alluvial Fan Cross Section -2,344 ft.

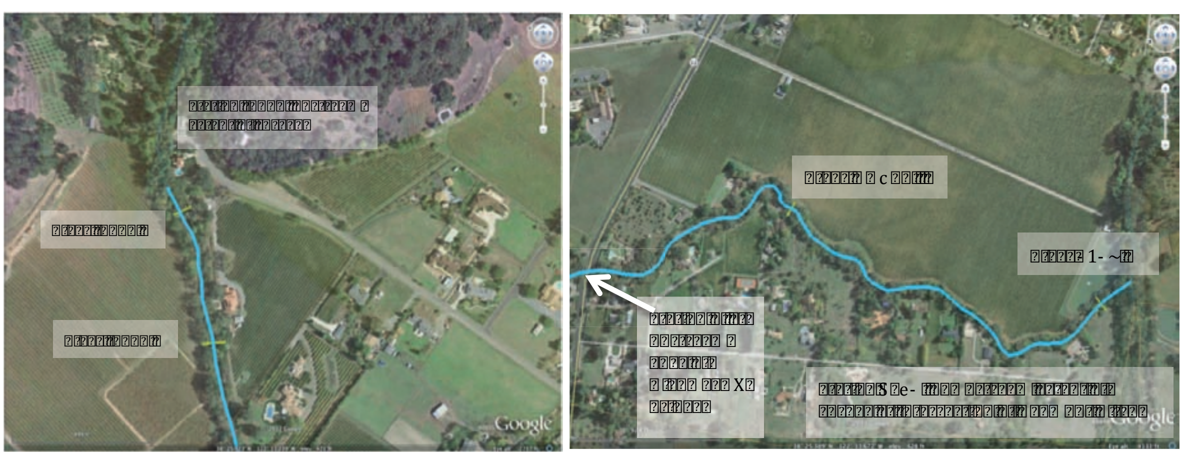


Figure 28. Location details of the Sonoma Creek cross sections are shown.

Figure 29. The upper 2011 Sonoma Creek Cross Section -2847 ft is shown looking upstream on the alluvial fan. Photos by L. Collins, Nov 2011.

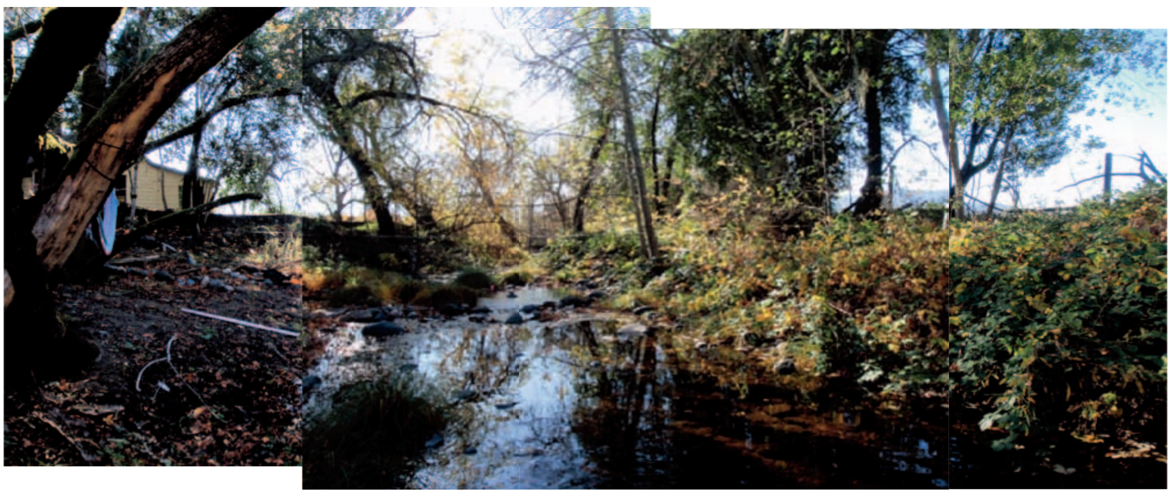


Figure 30. The upper 2011 Sonoma Creek Cross Section -2,847 ft is shown looking downstream on the alluvial fan. Photos by L. Collins, Nov 2011.

Figure 31. The left bank (left and middle photos) and right bank (right photo) are shown of the upper 2011 Sonoma Creek Cross Section -2,847 ft. Photos by L. Collins, Nov 2011.

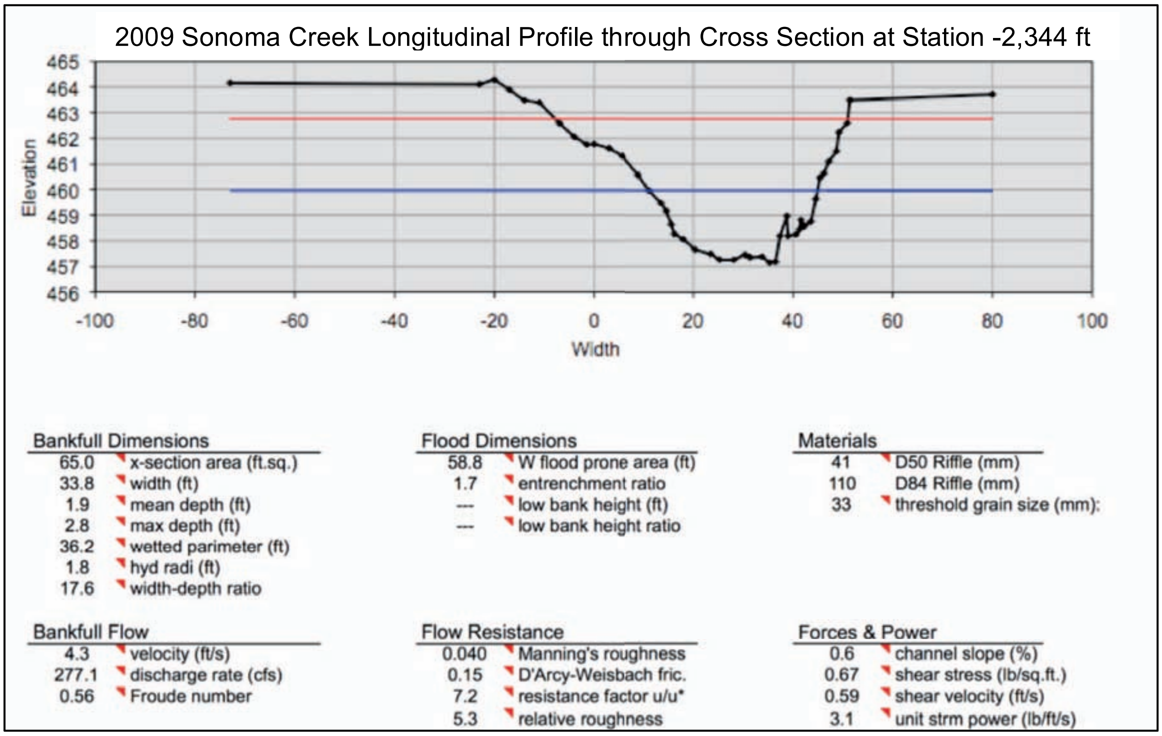


Figure 32. Cross Section -2,344 ft and its dimensions needed to calculate discharge at the site are shown. The blue line shows bankfull elevation and the red line shows floodprone width.

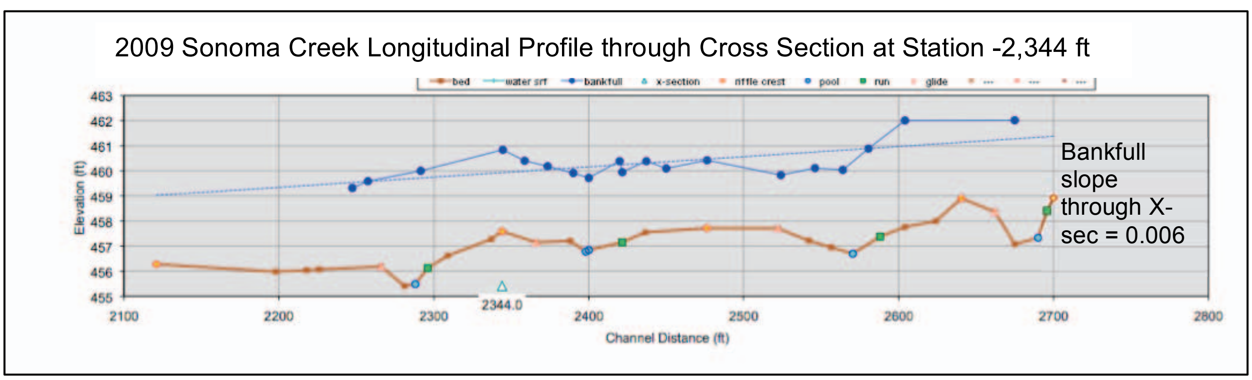
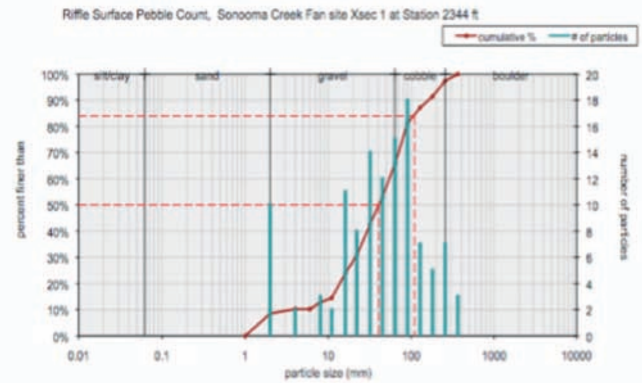


Figure 33. Estimated gradient of the streambed thalweg and bankfull flow is shown at Cross Section -2,344 ft in the intermittent reach upstream of the highway bridge.

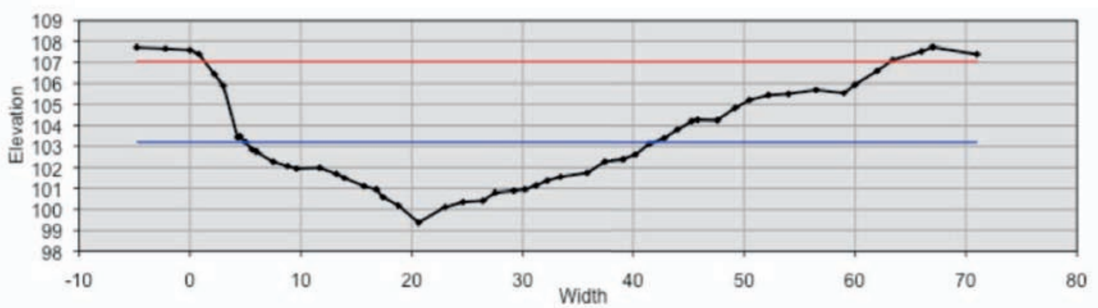


Size (mm)	
D16	12
D35	25
D50	41
D65	63
D84	110
D95	220

Size Distribution	
mean	36.3
dispersion	3.0
skewness	-0.05

Type	
silt/clay	0%
sand	9%
gravel	57%
cobble	32%
boulder	3%

Figure 34. Sediment size distribution is shown at Sonoma Creek Alluvial Fan Cross Section -2,344 ft.



Bankfull Dimensions	
68.7	x-section area (ft.sq.)
36.9	width (ft)
1.9	mean depth (ft)
3.8	max depth (ft)
38.0	wetted parimeter (ft)
1.8	hyd radi (ft)
19.8	width-depth ratio

Flood Dimensions	
200.0	W flood prone area (ft)
5.4	entrenchment ratio
---	low bank height (ft)
---	low bank height ratio

Materials	
50	D50 Riffle (mm)
140	D84 Riffle (mm)
42	threshold grain size (mm):

Bankfull Flow	
4.6	velocity (ft/s)
313.7	discharge rate (cfs)
0.60	Froude number

Flow Resistance	
0.042	Manning's roughness
0.17	D'Arcy-Weisbach fric.
6.9	resistance factor u/u*
4.1	relative roughness

Forces & Power	
0.7525	channel slope (%)
0.85	shear stress (lb/sq.ft.)
0.66	shear velocity (ft/s)
4	unit strm power (lb/ft/s)

Figure 35. Cross Section 1,600 ft and its needed dimensions to calculate discharge at the site are shown. The blue line represents the estimated bankfull elevation and the red line represents the floodprone width.

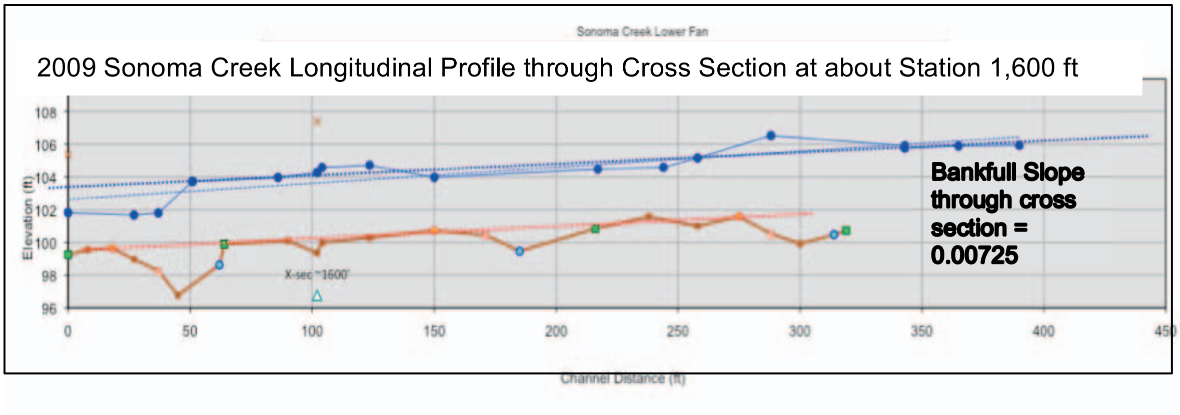


Figure 36. The estimated gradient is shown of the streambed thalweg and bankfull flow at Cross Section 1,600 ft in the intermittent reach downstream of the highway bridge.

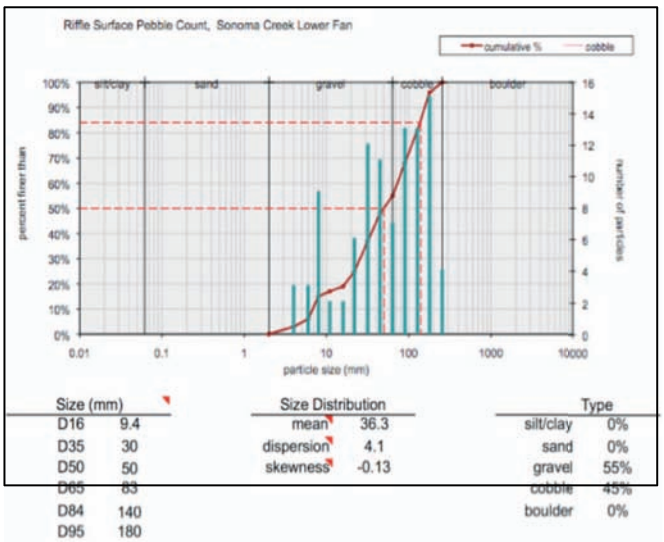


Figure 37. Sediment size distribution is shown for Sonoma Creek Cross Section 1,600 ft.

Figure 38. The lower 2011 Sonoma Creek Cross Section 3,937 ft is shown looking upstream in the photo on the left and looking downstream in the photo on the right. Photos by L. Collins Nov, 2011.


Figure 39. The lower 2011 Sonoma Creek Cross Section 3,937 ft is shown looking at the left bank (left photo) and the right bank (right photo) of on Sonoma Creek alluvial fan. Photos by L. Collins, Nov 2011.

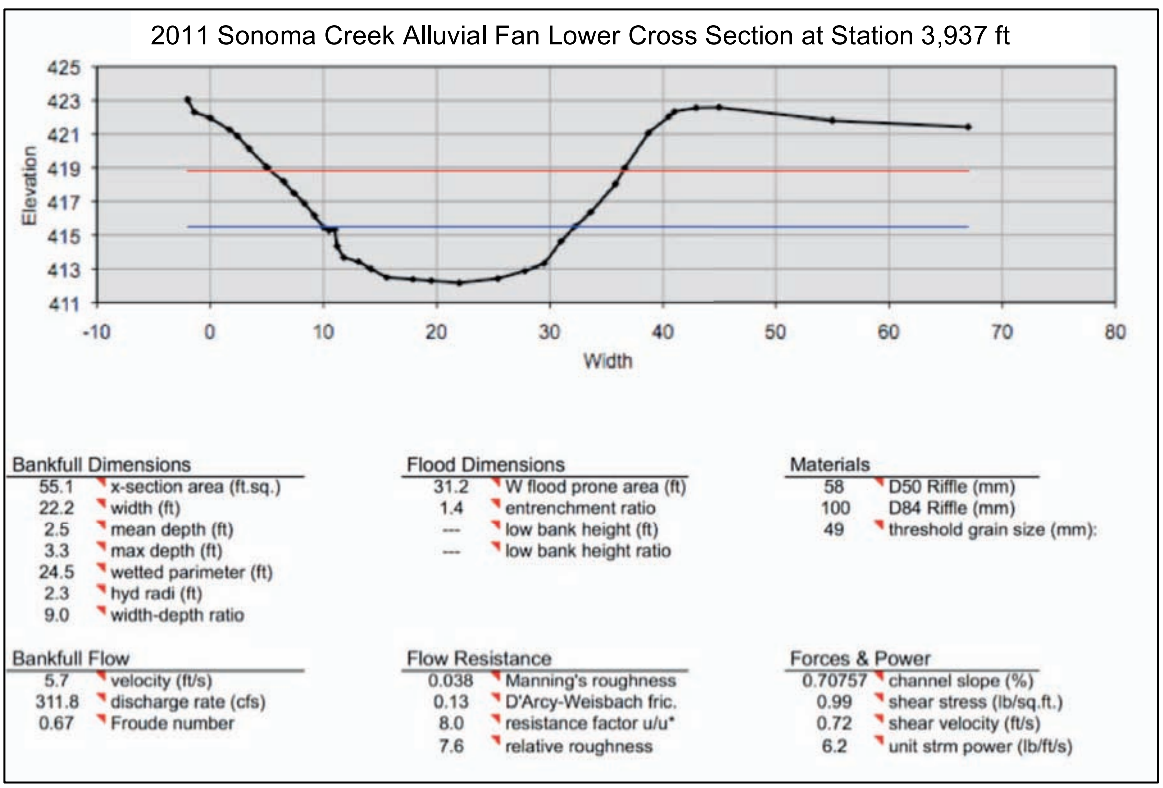


Figure 40. Cross Section 3,937 ft is shown with the dimensions needed to calculate discharge at the site. The blue line represents the estimated bankfull elevation and the red line represents the floodprone width.

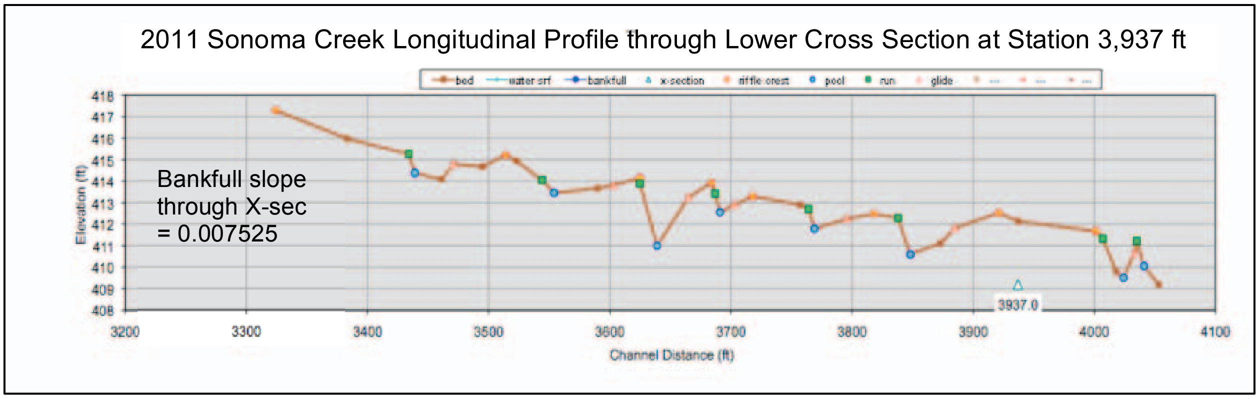


Figure 41. Estimated gradient is shown of the streambed thalweg and bankfull flow at Cross Section 3,937 ft in the perennial reach downstream of the highway bridge.

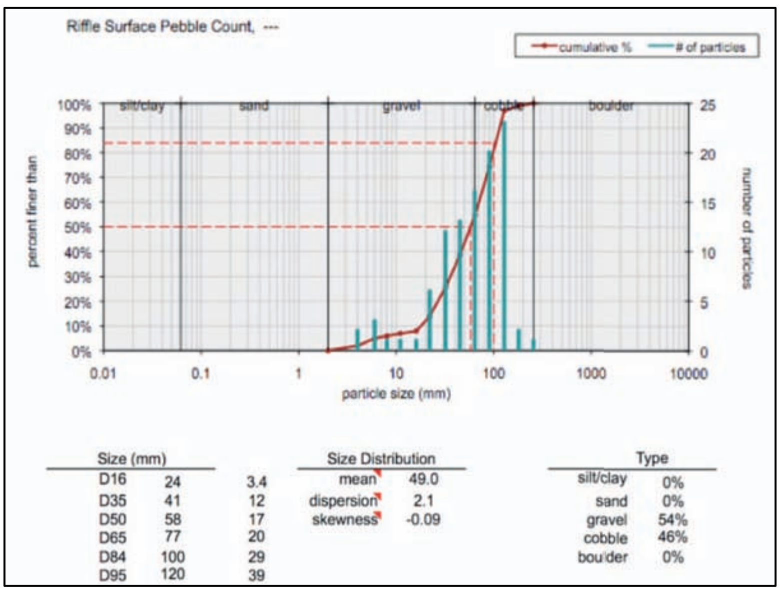


Figure 42. Sediment size distribution is shown at Sonoma Creek Cross Section 3,937 ft.

Similar data plots are shown for the 2009 Cross Section -2,344 ft in Figures 32, 33 and 34 and for the 2009 Cross Section 1,600 ft in Figures 35, 36, and 37. For the 2011 Cross Section 3,937 ft, photographs of the site are shown in Figures 38 and 39 and plots of the cross section, bankfull profiles and pebble counts are shown in Figures 40, 41, and 42.

Bankfull discharge is less at Cross Section -2,344 ft than at the upstream Cross Section -2,847. This is because Cross Section -2,344 is within the intermittent reach, which functions as a groundwater recharge zone, where surface flow converts to subsurface flow unless the groundwater table is saturated. Presently, the conditions that would create saturation of the alluvial fan are not known. This particular condition implies that a bankfull floodplain or inner bench within the incising or aggrading intermittent sections of the alluvial fan might not be well formed and/or difficult to recognize. This cross section has a width/depth ratio of 17.6 and an entrenchment ratio of 1.7, indicating that its geometry should provide a relatively stable channel form. Upon close inspection of the longitudinal survey data, this particular reach does not appear to have recent incision or deposition, yet it is in a reach that has had incision within the historical past as indicated by the presence of a head cut near station 2,700 ft.

Another cross section downstream of the highway bridge in the intermittent reach was surveyed in 2009 at station 1,600 ft. It is also included in this analysis to assess the channel geometry and establish whether discharge is gaining or losing at this site, which is just downstream of the major western bend and just upstream of where the channel regains perennial flow. This site has a width/depth ratio of 19.8 and its entrenchment ratio is 5.4 (meaning that its floodprone width is 5.4 times wider than its bankfull width). Unless there are unexpected changes to the local site, the channel geometry indicates that this reach should not have substantial incision or deposition. It probably functions primarily as a transport reach.

The next downstream Cross Section 3,937 ft was surveyed as the lower cross section for the 2011 project and is in the reach that regains perennial flow. This reach has a width/depth ratio of 9 and its floodprone width is only 1.4 times its bankfull width. It is an entrenched reach that would tend to experience increased bank erosion as it incises. It is possible that this site is also influenced by backwater from the confluence of Oakmont Ditch when and if discharges from the Oakmont ditch exceed those from Sonoma Creek.

The bankfull discharge at station 1,600 ft is estimated at about 314 cfs, more than the upstream intermittent cross section that had 277 cfs, but still less than the upstream perennial cross section near the fan apex that had 320 cfs. The farthest downstream perennial cross section at 3,937 ft has an estimated 312 cfs, very close in value to that of Cross Section 1,600 ft. These estimates of bankfull discharge are based upon field indicators of an inner bench or inflection point that might represent bankfull flow. These discharges should only be considered best approximations, but there is no doubt that the channel geometry reflects the loss and gain of discharge across the alluvial fan.

The 2-yr RI flow reported by PWA at the Kenwood gage site, which is downstream of the confluence of the Oakmont ditch is 314 cfs, which is very close to the bankfull flow predicted at the two lower cross sections on Sonoma Creek, upstream of the Oakmont ditch confluence. Based upon previous surveys of channels around the Bay Area (but not ones on alluvial fans), the RI of bankfull discharge in channels influenced by a moderate level of land use impacts tends to range from 1.2 to 1.7 years. It is beyond the scope of this project to determine the reason for the discrepancy, although it could be associated with any number of factors including the minimal amount of data that exists at the new Kenwood gage site, the method used to predict the RI's at the new gage site, the difficulty in evaluating bankfull geometry in an unstable channel, and/or using bankfull concepts in alluvial fan channels that have gaining and losing reaches.

Carriger Creek

The longitudinal profile of Carriger Creek was surveyed during September 2011 before any significant flow events occurred during WY 2012. Based upon looking at streamflow data for the Sonoma Creek gage at Agua Caliente, peak flows in Carriger Creek have probably not exceeded a 4-yr RI since WY 2006. Therefore, the major influences of the December 2005 flood on the stream gradient should still be apparent although some minor filling or deposition may have occurred during subsequent years.

The results of the 2011 longitudinal profile are shown in Figure 43. Closure to the benchmarks was plus or minus 3 inches. The approximate distance station locations upstream of the confluence with Felder Creek are indicated in Figure 44. The thalweg gradient is shown in black and water surface is shown in blue. The survey indicates that perennial flow diminished downstream and by station 14,500 ft the channel became completely dry. During fall of WY 2001 the channel was completely dry downstream of station 15,300 ft. Two large scour pools are indicated in the upper portion of the profile at the outfall of the Grove Street box culvert, and downstream of a concrete dam at station 20,175 ft. The reach shown as a yellow and dashed black line could not be surveyed due to lack of private property access.

Pink dashed lines beneath the profile show major inflections in the concave-shaped profile. The major breaks are at stations 17,700 ft and 12,800 ft. The crossover points of the pink lines might represent historical depositional zones, but currently these are not the sites of the most active deposition between years 2001 and 2011, as can be seen in Figure 45. At station 17,700 ft the difference between the elevation of the streambed and the top of the adjacent terrace banks become relatively small. This area might have long-term tectonic influences affecting the major change in gradient since it is upstream of the splay fault that was shown in Figure 15. Small differences between streambed and terrace height also occur at stations 16,000 ft, 15,800 ft, 12,800 ft, 11,900 ft, and 10,880 ft. These sites might represent where floods first emerge from the banks. Station 16,000 ft might be an area where recharge starts to become significant downstream of the down-dropping unnamed fault. This site is where the average local stream gradient is flatter than other locatons on the alluvial fan. It is about 0.77 percent. Station 1,600 ft is just downstream of the end of the reach that is showing recent deposition between stations 16,320 to 17,450 ft, as indicated by the pink horizontal arrow in Figure 45. This flat reach might be influenced by long-term tectonic uplift forcing the upstream deposition.

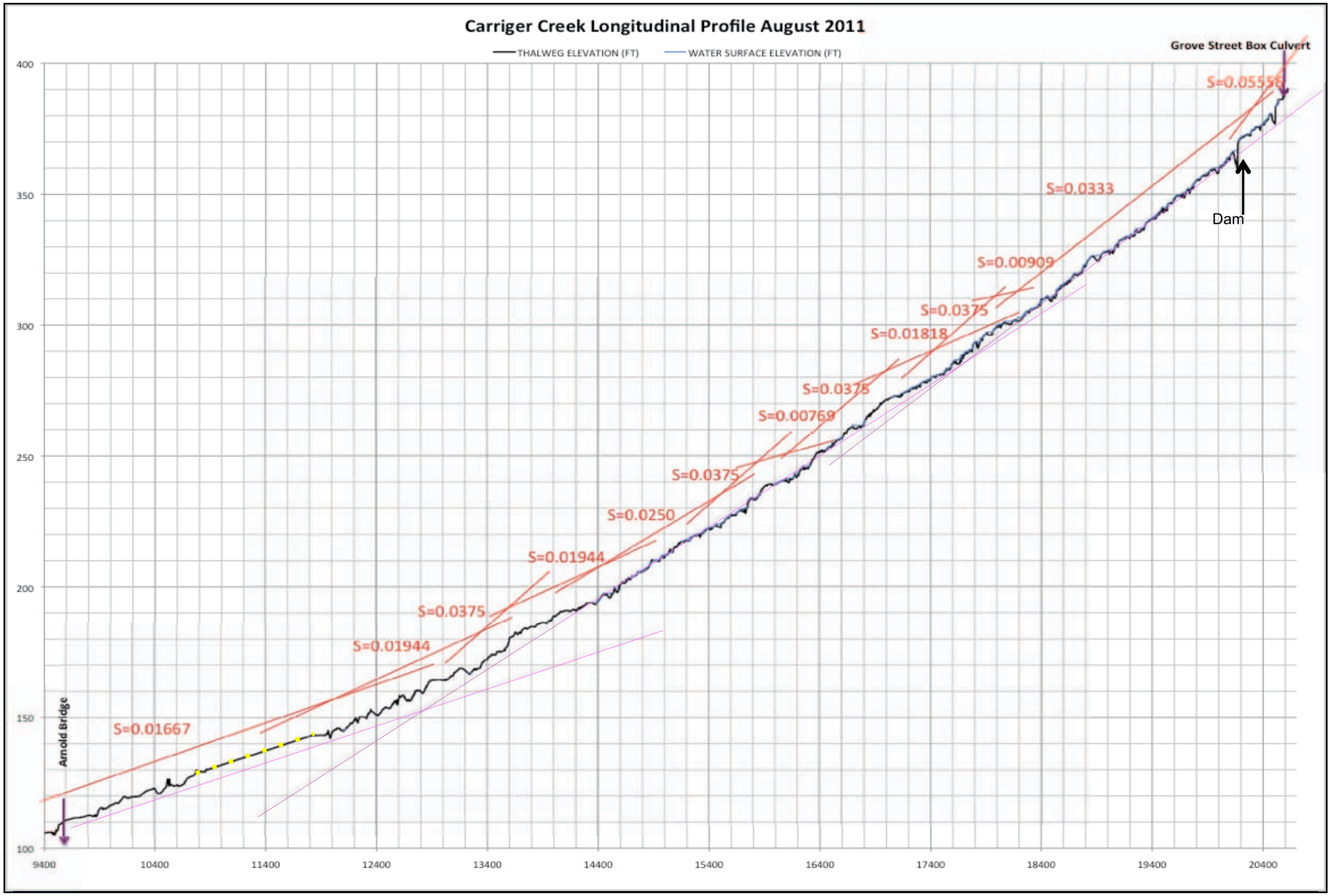


Figure 43. The October 2011 thalweg profile of Carriger Creek is shown along its alluvial fan between Arnold Avenue and Grove Street crossings. Station zero is at the confluence of Felder Creek at the beginning of Fowler Creek. The red lines above the profile represent average reach gradients, while the dashed pink lines represent larger inflection points along the concave-shaped profile channel. The dashed black and yellow line show the reach that could not be surveyed due to lack of private property access.

Figure 44. Estimates of distance station locations are shown at the yellow pinpoints along the mainstem Carriger Creek, which is shown as a thick blue line. The first sets of numbers are the distance stations in feet that are based upon zero being located at the confluence of Felder Creek. The numbers in parentheses are the stations established during the field survey with zero being located upstream of the Grove Street box culvert. As also indicated in Figure 45, the light brown lines represent the reaches that have had significant incision since WY 2006, while the light pink lines represent reaches with significant deposition. Several braided segments exist along the mainstem but they have not been mapped. The direction of flow is from top to bottom of the picture. Red X's represent approximate locations of inflection points where there are significant changes in stream gradient.

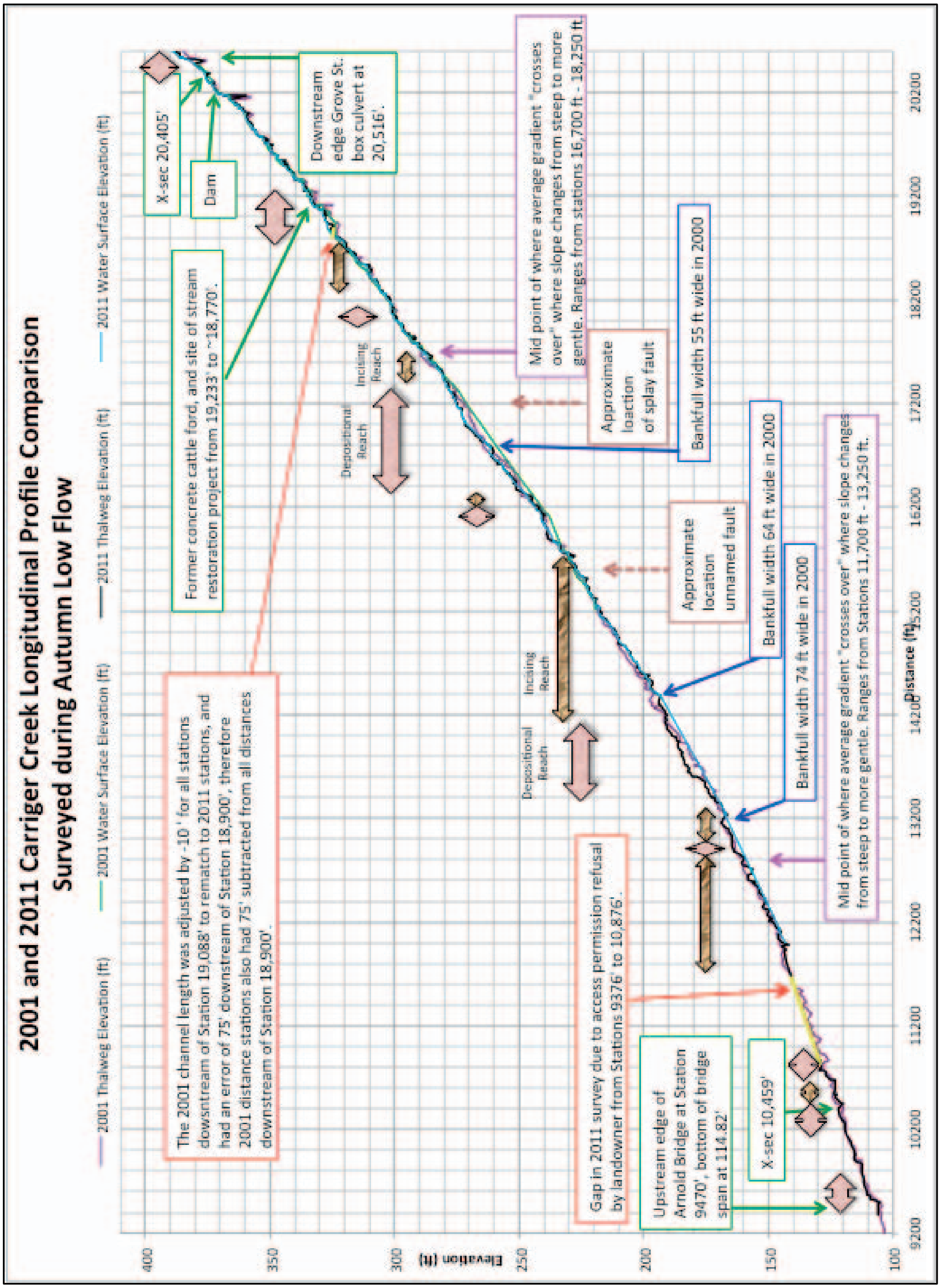


Figure 45. Changes between 2001 and 2011 of the thalweg profile are shown for the Carriger Creek alluvial fan upstream of the Arnold Avenue Bridge. Where the dominant mode has been incision or deposition, brown and pink horizontal arrows are indicated. The 2001 thalweg is shown in purple and the water surface is shown as green, whereas the 2011 thalweg is shown in black and the water surface shown in blue.

The average stream gradient was determined for short segments of relatively similar grade, as shown by red lines above the thalweg profile in Figure 43. There are 12 inflection points where stream gradient changes significantly. These are indicated as red X's in Figure 44. The slope breaks occur at roughly the following stations: 11,200 ft, 13,395 ft, 13,585 ft, 13,633 ft, 14,400 ft, 15,550 ft, 15,950 ft, 16,150 ft, 17,490 ft, 18,030 ft, 18,230 ft, and 20,375 ft. These points are indicative of significant changes in channel geometry associated with entrenchment and width/depth ratio, braiding and distributary channels, and historical patterns of fan building. Detailed channel mapping would be needed to show the location of all the braids and distributaries. Average gradient ranged from 0.77 percent to 5.55 percent. The steepest reach was at the apex of the fan and the gentlest reach was in the middle of the fan from station 15,800 ft to 16,100 ft.

Carriger Creek has not been gaged, yet the largest known flood of record at the USGS gage on Sonoma Creek occurred during Dec 2005, WY 2006. Since the earlier longitudinal profile was surveyed during October of 2001, it is possible to compare the 2011 profile and determine the changes that might have occurred during this extreme event. The gage site on Sonoma Creek at Agua Caliente shows that flows have not exceeded a 5-year RI since 2006. Therefore, the same is expected for flows in Carriger Creek since WY 2006.

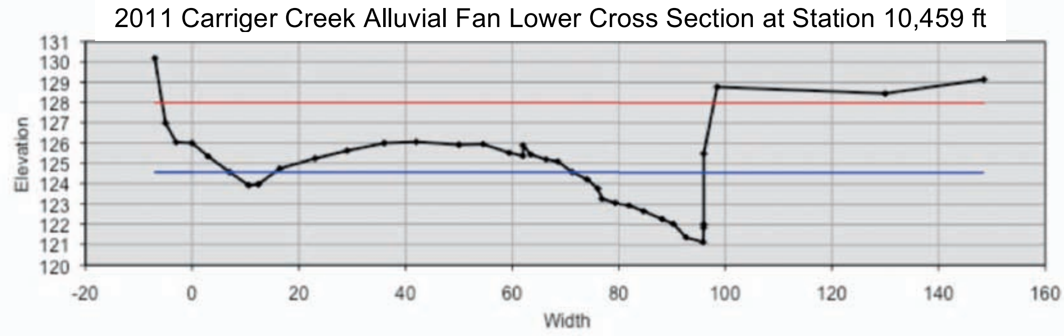
Figure 45 shows the comparison of the 2001 and 2011 profile surveys. Horizontal brown and pink arrows show respective sites of incision and deposition that occurred during this period. Significant deposition has taken place between stations 13,600 ft and 14,170 ft and between 16,320 ft and 17,300 ft. In some sections of the former reach, the amount of deposition has exceeded 6 ft. The maximum amount of incision measured in the thalweg profile was slightly more than 3.5 ft. Most of it was less than 2 ft. The total length of channel affected by net deposition is nearly equal to the amount influenced by net incision. This indicates that there is very little loss of streambed sediment from the system, and this is primarily due to the very coarse nature of the bed material. In Carriger Creek there are large depositional zones that seem to move and hold together as slugs of sediment that do not readily disperse.

The pattern of relatively flat reaches with steep downstream gradients at the end of the flats seems to be repeated, such as at stations 13,600 ft, 15850 ft, and 16950 ft. These sites appear to follow a pattern of sedimentation and sheet flooding, similar to that diagramed by Schumm in the longitudinal profile of Figure 4. Zones of sheet flooding do not occur however sedimentation of the streambed has not reached the elevation of the terrace banks and fine sediment load is too minimal to bury the coarse bed unless there was a major blockage of flow by perhaps a large debris jam. Such an occurrence could theoretically cause the mainstem channel to cut a new course, but in many areas the channel has become too wide to effectively trap woody debris. This is especially true in the reach downstream of the old Carriger Road crossing that might have been influenced by former gravel quarry activities and where there is minimal large woody vegetation remaining on the banks. The section between 15,000 ft and 16,400 ft is still relatively narrow, as indicated by Figure 19. Potentially, it could still be influenced by future woody debris jams. Debris jams can often be the mechanism for establishing sites of new distributary channels, which aid in providing off-channel refugia for fish during large floods.

Two cross sections were surveyed at stations 10,459 ft and 20,405 ft. The most relatively stable sites were sought near the endpoints. However, Cross Section 10,459 ft had to be placed over a thousand feet upstream of Arnold Bridge to remove it from the influences of backwater flooding from the bridge. Figure 46 shows photomap details of the cross section locations. Plots of the cross section, its dimensions, bankfull and thalweg gradient, and cumulative pebble count are shown respectively in Figures 47, 48, and 49 for station 10,459 ft. The bankfull discharge at the cross section, which is in an intermittent reach and therefore might also be a losing reach, is 278 cfs. Photos of the cross section are shown in Figures 50, 51, and 52.

The dimensions of Cross Section 10,459 ft indicate that it is fairly stable since it has a width/depth ratio greater than 12 and has a floodprone width that is 3.1 times its bankfull width. The site has a mid-channel bar that is above bankfull flow and is becoming colonized with riparian vegetation. The cross section intersects a dry pool rather than a riffle. An appropriate riffle site that represented a fairly stable configuration that was in a straight reach could not be found in the vicinity. Bar-pool channel morphology is developing from formerly braided channel morphology.

Figure 46. Details are shown of the location of the upstream Cross Section 20,405 ft in the photo on the left and the downstream Cross Section 10,459 ft in the photo on the right.



Bankfull Dimensions	
48.2	x-section area (ft.sq.)
33.1	width (ft)
1.5	mean depth (ft)
3.4	max depth (ft)
37.3	wetted parimeter (ft)
1.3	hyd radi (ft)
22.8	width-depth ratio

Flood Dimensions	
103.5	W flood prone area (ft)
3.1	entrenchment ratio
---	low bank height (ft)
---	low bank height ratio

Materials	
40	D50 Channel (mm)
100	D84 Channel (mm)
63	threshold grain size (mm):

Bankfull Flow	
5.8	velocity (ft/s)
277.7	discharge rate (cfs)
0.89	Froude number

Flow Resistance	
0.039	Manning's roughness
0.16	D'Arcy-Weisbach fric.
7.1	resistance factor u/u*
4.4	relative roughness

Forces & Power	
1.6	channel slope (%)
1.29	shear stress (lb/sq.ft.)
0.82	shear velocity (ft/s)
8.4	unit strm power (lb/ft/s)

Figure 47. The lower intermittent Cross Section 10,459 ft is shown at Carriger Creek with the dimensions needed to calculate discharge at the site. The blue line represents the estimated bankfull elevation and the red line represents the floodprone width.

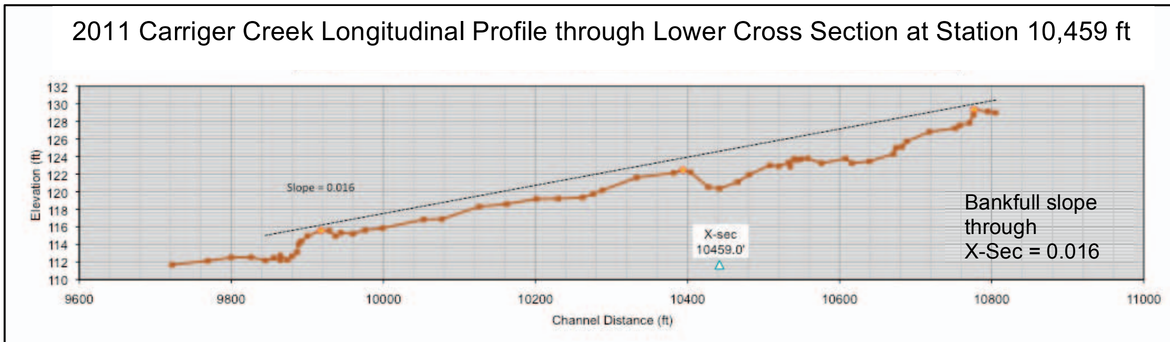
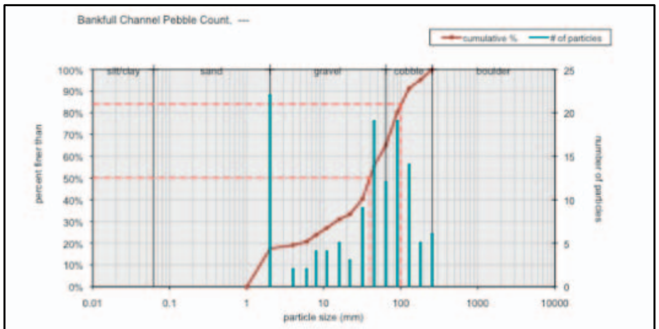


Figure 48. Estimated gradient of the streambed thalweg and bankfull flow at Carriger Creek Cross Section 10,459 ft are shown in the intermittent reach upstream of the highway bridge.



Size (mm)		Size Distribution		Type	
D16	1.9	mean	13.8	silt/clay	0%
D35	24	dispersion	11.8	sand	17%
D50	40	skewness	-0.35	gravel	48%
D65	64			cobble	35%
D84	100			boulder	0%
D95	180				

Figure 49. Sediment size distribution is shown for Carriger Creek Cross Section 10,459 ft.

Figure 50. The lower Cross Section 10,459 ft is shown looking upstream at Carriger Creek alluvial fan. Photos by L. Collins, Sept 2011.

Figure 51. Lower Cross Section 10,459 ft is shown looking downstream at the Carriger Creek alluvial fan. Photos by L. Collins, Sept 2011.

Figure 52. The Lower Cross Section Station 10,459 ft on Carriger Creek alluvial fan is shown looking at the left bank (photo on left), which has a mid-channel bar that is functioning as an inner floodprone bench, and at the right bank (photo on right), which has a higher terrace bank that is devoid of riparian vegetation. Photos by L. Collins, Sept 2011.

The bankfull discharge is 289 cfs at the upstream Cross Section 20,405 ft. It is a perennial reach. The discharge is slightly more than the downstream Cross Section 10,459 ft and channel morphology is closer to a step-pool system. The stream gradient of 3.5 percent is about two times steeper than the 1.6 percent of the lower cross section. Figures 53, 54 and 55 show the plots of cross section, bankfull gradient, and pebble count. The channel dimension of the upper Cross Section 20,405 ft indicates that the channel has a width/depth ratio of 15.6 and it is entrenched. It is therefore likely to incise its streambed rather than have deposition because its floodprone width is only 1.2 times its bankfull width. The substantial coarseness of the channel bed, which is primarily cobble and boulder, is why there is not evidence of substantial recent incision. Long-term evidence, however, such as 10-ft-high abandoned terraces indicates that incision has been the dominant process in this reach. The driver for the long-term degradation of the streambed is likely associated with tectonic uplift of the western side of the Bennett Valley Fault. The photographs of the site, seen in Figures 56, 57, and 58, provide a visual perspective.

General observations of the channel upstream of the alluvial fan have been made for a mile or more of the channel within the canyon. Carriger Creek for most all of this distance is set within incised terrace banks that appear to be eroding more after the Dec 2005 flood than before. The perception is that there is slightly more fine to coarse-sized gravel on the streambed in the lower half-mile above the Grove Street box culvert than observed during a 2001 reconnaissance.

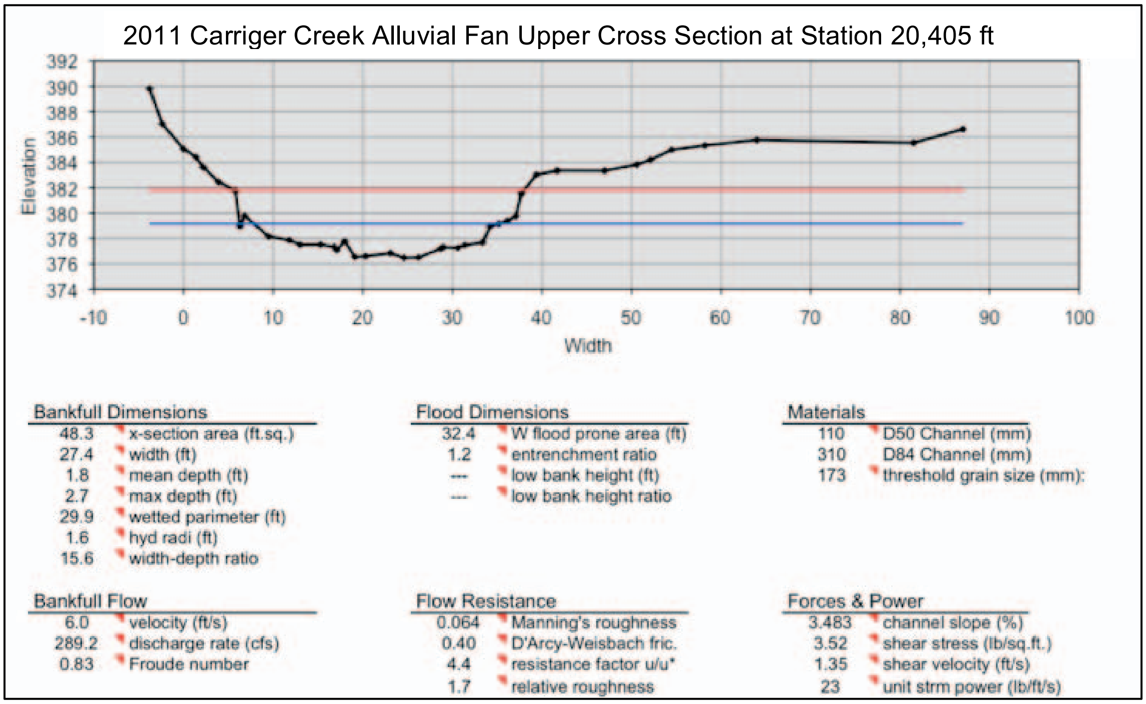


Figure 53. The upper perennial Carriger Creek Cross Section 20,405 ft downstream of the Grove Street box culvert is shown with the dimensions needed to calculate bankfull discharge. The blue line represents the estimated bankfull elevation and the red line represents the floodprone width.

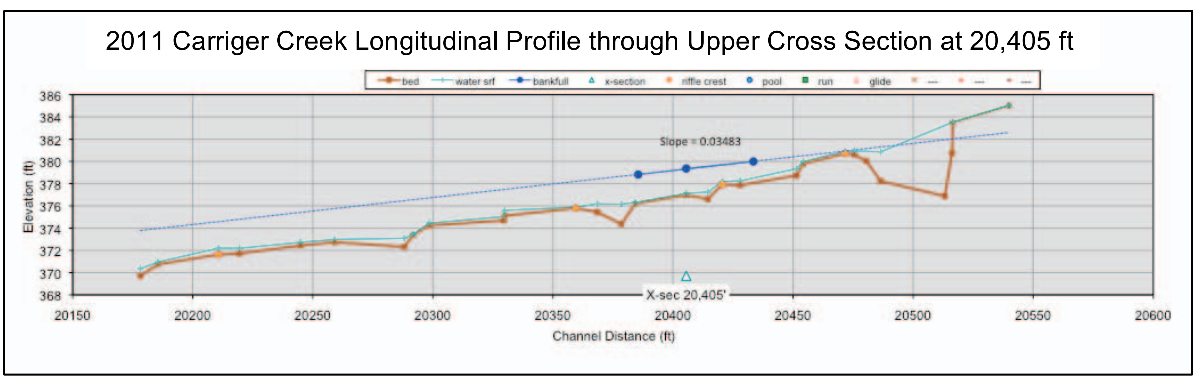
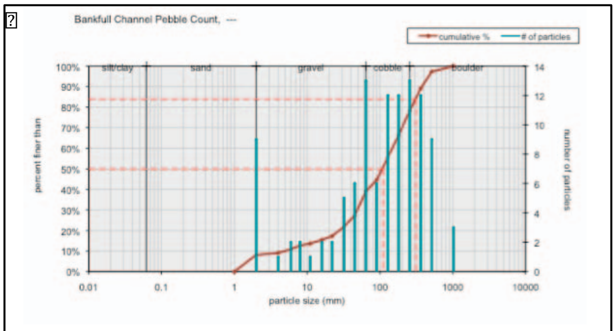


Figure 54. Estimated gradient is shown of the Carriger Creek streambed thalweg and bankfull flow at Cross Section 20,405 ft in the perennial reach downstream stream of the Grove Street box culvert.



Size (mm)		Size Distribution		Type	
D16	18	mean	74.7	silt/clay	0%
D35	57	dispersion	4.5	sand	8%
D50	110	skewness	-0.15	gravel	31%
D65	170			cobble	39%
D84	310			boulder	22%
D95	460				

Figure 55. Sediment size distribution is shown for Carriger Creek Cross Section 20,405 ft.

Figure 56. The upper Cross Section 20,405 ft on Carriger Creek near the apex of its alluvial fan is shown looking upstream at its very coarse bed. Photo by L. Collins Dec 2011.

Figure 57. Station 20,405 ft on the Carriger Creek alluvial fan is shown looking downstream at the Upper Cross Section. Notice the 10-ft-high terrace on the right bank. It indicates long-term incision at the site. Photo by L. Collins Dec 2011.

Figure 58. The Upper Cross Section at Station 20,405 ft on the Carriger Creek alluvial fan is shown looking at the high terrace on the right bank (photo on left) and looking at the right bank from the left bank (photo on right). Photos by L. Collins, Dec 2011.

VI. DISCUSSION AND CONCLUSIONS

Contrasting and Comparing Sonoma and Carriger Creek Alluvial Fan Channels

Historically, wetlands existed at the toe of the Sonoma Creek alluvial fan. They provided a stable base level to the stream gradient, as well as a catchment for finer sediment. The alluvial fan and its multitude of distributaries disconnected much of the headwater sediment supply of Sonoma Creek from its mainstem valley channel downstream of its alluvial fan. On the other hand, the historical maps of Carriger Creek indicate that it did not have enough flow to sustain a channel across its large fan. This is because the fan is relict of catastrophic volcanic processes that are no longer operating in the watershed. Both Sonoma and Carriger Creeks had significant legacy land use impacts that concentrated and connected most of the smaller floods into single channel, thereby providing more sediment supply from the headwater drainage networks and from the erosion of the remaining mainstem channels to down valley mainstem Sonoma Creek. In the past during large floods, excessive sediment supply from the upstream drainage networks was dispersed through a multitude of distributaries and overflow channels and mostly stored on the alluvial fans. Because flood flows were not concentrated in a single channel on the alluvial fans, flood peaks in Sonoma Creek were much more attenuated than they are today. Current landscape conditions that have reduced the opportunities to connect to floodplains, distributaries, and overflow channels has created flood flows that arrive faster, have higher peaks, have more stream power to erode the channel bed and banks, and deliver more sediment to Sonoma Creek.

Historically the Sonoma alluvial fan channels had sufficient discharge to carry flow to the wetlands and maintain open water bodies. Streambed materials were probably not too coarse historically because the channel was able to incise its streambed and adjust its channel geometry to the lowered base level that was created when the wetlands were ditched and drained. Base level change is one of the major drivers of incision in Sonoma Creek, especially along the lower portion of its alluvial fan. Conversely, Carriger Creek's streambed was too coarse to initiate continuous head cutting from its lowered base level that was created by ditching lower Carriger Creek to Fowler Creek. Much of the cobble and boulder-sized sediment, distributed through the middle and upper portions of the fan move primarily on the larger infrequent floods. Although there is historical incision in Carriger Creek, during recent times during the period of survey it has not been able to substantially incise headward downstream of Arnold Bridge. This is partly because there is insufficient flow through the recharge zone to move the coarse sediment and when there are large floods, the channel is still able to distribute floods through a network of distributaries. The latter is true of Sonoma Creek but it contains relatively more flood flow in its channel than Carriger because of its substantial down cutting and entrenchment.

Both Carriger and Sonoma Creek underwent changes in their upper fan from legacy agricultural land use practices that reduced the number of active distributary channels. This was likely done to inhibit flooding on to the agricultural fields and accomplished by creating berms and levees along the stream banks that would block water from entering overflow and distributary channels. Ultimately, the mainstem channel was forced to contain more flow, which increased local shear stress and caused the channels to adjust their geometry through streambed incision and bank erosion. In both cases, as the channels had more flow forced into them, they became more entrenched, which forced local incision (as opposed to erosion caused by head-cutting from downstream impacts) in the middle and upper portions of the alluvial fans. An initial hypotheses is that the driving mechanisms for incision in the mid fan area of Sonoma Creek was from both the loss of distributaries and subsequent entrenchment and from downstream head-cutting processes, while Carriger Creek mid and upper fan was probably more influenced by loss of its distributaries.

Unlike Carriger Creek, Sonoma Creek's channel is not as coarse-bedded over the length of its fan. The influence of this is that the length of net incision has probably exceeded the length of net deposition over the entire alluvial fan length. Although the section of Sonoma Creek downstream of the highway bridge has not been resurveyed, field observations indicate that it is currently in an incision mode. Although historically incision at the toe of the Sonoma fan was driven by head-cutting associated with ditching, it still seems to be dominated by incision that is likely due in part to its entrenchment, and in part to its gaining discharge along the fan toe, which also increases sediment transport.

Modern land use impacts that have created entrenched and incised channels have also substantially reduced the sediment storage functions of Sonoma Creek. The storage functions on Carriger Creek have been reduced slightly on the lower fan reaches due to the loss of large woody riparian vegetation and the channel geometry that augments the formation of woody debris jams. Without establishment of new riparian trees, its future recruitment and influence on sediment storage and protection of stream banks will be largely diminished.

The Sonoma Creek alluvial fan channel is a gaining reach at the toe of its fan. It does not appear that Carriger gains flow along its lower fan, unless the ground water table becomes fully saturated. Further data would be needed to clarify this. It is likely that local well water withdrawals have influenced where the channels now become gaining and loosing reaches relative to their historical conditions, especially Carriger Creek, which has had historical well withdrawals along its upper and middle fan.

Faulting influences uplift and down dropping along both fans, as well as known horizontal offset in the case of Carriger Creek. Vertical tectonic motion has likely caused the larger changes in stream gradient near the upper portions of the fans and might very well affect where the intermittent reaches function as significant ground water recharge zones.

The Carriger Creek Canyon watershed is smaller, not as steep and probably receives less total rainfall than the Sonoma Creek Canyon. Sonoma Creek has much greater landslide potential in its headwaters and can probably generate and effectively transport more sediment farther. Especially fine sediment because Carriger Creek in its canyon still has the substantial ability to trap and store abundant fine sediment within the interstices of the very coarse bed material. For these reasons, the potential for future large or catastrophic inputs of sediment from headwater sources to the alluvial fans from upstream fluvial transport is likely far greater from Sonoma Creek than Carriger Creek.

Food for Thought about General Alluvial Fan Processes

Questions that are often asked about alluvial fans are commonly focused on what is the relative importance of sediment supply from fluvial contribution versus landslide/catastrophic event contribution? Similarly, are alluvial fans controlled by moderate or extreme events? A question that comes up specifically about the Sonoma and Carriger alluvial fans is about the WY 2006 flood and whether it was a geomorphically catastrophic event thereby altering the fan and transporting/producing more sediment in the fan channel compared to more frequent yet moderate–sized floods? Scott Lecce (Arizona State University) wrote that relatively frequent events of moderate intensity are considered to accomplish the greatest amount of work over the long-term. Catastrophic events of low frequency and high magnitude, such as debris flow events, are on some alluvial fans, a common process contributing to fan formation (Beaty 1974). This is the common case for alluvial fans in Utah for example. Hooke and Rohrer (1979) found that dominant discharge increased with increasing debris size, affirming Wolman and Miller's (1960) observation that catastrophic events become increasingly important as the threshold stress required to move material increases. Wells and Harvey (1987) concluded that on the effects of a storm with a recurrence interval greater than 100 years, high magnitude events of low frequency become equally important in accomplishing geomorphic work as the relatively frequent events of moderate magnitude. In Sonoma the influence of legacy land use practices may have increased the ability of moderate-sized fluvial events to become more geomorphic effective at changing the channel system. Large floods would therefore become even more effective at altering the local surroundings and channels that have undergone substantial alterations in drainage network connectivity.

Lecce further discussed that Rachocki (1981) had suggested a model of fan evolution in which fans develop through time until the source area can no longer provide sediment to the fan. Bull (1977) postulated that a fan increases with time at a decreasing rate until its growth levels off and the depositional landform becomes an erosional surface with decreasing volume. These questions and discussions imply that processes on alluvial fans can change temporally and spatially. If climate change alters the supply of water or sediment, channels on fans could respond by changing from erosional to depositional in some areas, which could result in a change in the sedimentary environment.

Because both Sonoma and Carriger Creeks flood, are capable of producing large amounts of sediment, have stream banks that have become increasingly unstable, have streambeds that have become over-widened and cause sediment deposition, have existing and former stream projects to reduce flooding and improve localized stability, and have homes and agricultural development along their banks, it is prudent to assess the fans as a whole to identify future sites at risk.

VII. RECOMMENDATIONS FOR RESTORATION/FLOODING PROJECTS ON ALUVIAL FANS

General

Anyone working on a project situated on an alluvial fan should accept the notion that channels on these depositional features are situated on inherently unstable landforms. As such, projects proposed on these features could be susceptible to a higher potential for failure.

On active or inactive alluvial fans that have losing and gaining reaches, determining the design parameters that might include the cross sectional area for effective discharge, bankfull flow, 100-year flow, or floodprone width can be a challenge. On active fans this is especially true when sediment load can broadly fluctuate and the channel could be in an unstable state. Indeed, the concept that a predictable flow will maintain channel geometry might not hold true for sections with gaining and losing reaches that are susceptible to temporal and spatial variability in groundwater level, discharge, and sediment supply. In such cases, designing a reliable channel geometry that will persist and transport the supplied sediment load over the long-term can be extremely difficult and very risky.

Any project on an alluvial fan should map the full extent of the alluvial fan, the functioning channel braids, distributaries, and overflow channels. According to the Colorado Floodplain and Stormwater Criteria Manual in their Chapter 12 section on Alluvial Fan Hazards (CWCB 2006), “Alluvial fans should first be characterized as whether and where they are active or inactive”. The active parts of the alluvial fan should be delineated and identifying flood flow pathways should be a critical component of any alluvial fan project. On active alluvial fans, flooding is a primary concern for hazard assessment because of the difficulties in being able to accurately identify and account for flood pathways in an actual flood event. With LIDAR mapping, delineation of flood pathways might be improved compared to using traditional topographic maps.

An analysis of the potential amount and range in sediment load should be conducted through hydrologic analyses. Such efforts can help identify headwater sediment sources and potential risks to people and to the success of proposed projects. Sediment storage sites should also be identified.

Projects on alluvial fans should have the potential loss and gain of discharge along the fan evaluated so that appropriate hydraulic geometry can be designed for expected variations. This might best be accomplished by gaging the discharge at various flow stages along several reaches along the fan, particularly if future stream projects have design objectives to improve stability, manage flooding, or improve aquatic or riparian habitat.

When evaluating how to convey floods and reduce peak flows, consider re-establishing distributary systems, and restoring natural functions such as sediment storage, groundwater recharge and baseflow augmentation. When possible, consider historical confluence configurations. If possible, design areas where natural sedimentation and instability are acceptable.

Sonoma and Carriger Creeks

It is important to note that this project only identifies certain aspects of the main channels of Sonoma and Carriger Creeks. It is not intended for channel design metrics. Rigorous mapping of the full extent, location, and conditions of various braids, overflow channels, and distributaries was <u>not</u> conducted for this report and would exceed the project scope. Therefore for future or existing projects on these alluvial fans, first consider fully mapping the channels to identify channel braids, channel bar forms that indicate impending or existing instability from sediment deposition, distributary and avulsion locations, and sites of excessive bank erosion.

Consider using these fans as opportunities to reduce downstream peak floods by creating reaches intended for groundwater recharge, where flow is purposely forced to spreads and sink, and/or by creating numerous distributary channels that disseminate flows along the extent of the alluvial fan.

Consider using multi-stage channel design concepts that provide inner floodable benches that accommodate different flood frequencies while minimizing the shear stress at any given stage on the streambed and banks. Common design flows for multi-stage channels are for summer base flow or very low winter discharges, bankfull and/or effective flow, 25-year flow, and 100-year flow. The latter can often be effectively designed at the level of the alluvial fan surface by use of set back levees.

Consider reach-specific monitoring of identified sites of instability. This might include resurveying segments of the longitudinal profile that have slugs of sediment that are creating a loss of capacity and could lead to new channel avulsions. This might also include installing cross sections in areas identified to have significant bank erosion. The latter could contribute to developing estimates of rates of localized sediment supply from this source.

Temporary stream gages could be installed near the upstream and downstream ends of these alluvial fans to establish discharge relations and to determine where groundwater recharge or baseflow contributions exist and under what conditions.

Consider mapping the occurrence of riparian vegetation along the channel, both present and past from historical aerial photo and map analyses. Develop an understanding of its influence on stability and potential risks of loss from channel bank erosion or from incision that lowers the ground water table. If needed, consider riparian restoration to promote bank stability, to recruit LWD to the channel in the future, and to add to structural diversity and pool habitat. In entrenched channels this may require developing riparian vegetation on inner benches rather than on the previously occupied alluvial fan surface.

Consider developing a post WY 2006 sediment budget for the two watersheds for the alluvial fan drainage areas. This would require more field analysis that would build on the pre-existing Sediment Source Analysis by the Sonoma Ecology Center (2006) that was conducted for the Regional Water Quality Control Board's Total Maximum Daily Load Analysis (TMDL). The field methods would be those used in the 2006 Sediment Source Analysis that was conducted prior to the

December 2005 storm. Such an analysis would provide a measure of the influence of an extreme event on rates of sediment supply.

Consider delineating channel geometry zones based upon width/depth and entrenchment ratios to identify reaches of potential instability.

Consider the following factors for single lot/structure protection on alluvial fans:

1. Structures can be elevated on armored fill with properly designed foundations;
2. Structures can be elevated and placed on piers;
3. Floodwalls and berms can be used to deflect floodwaters;
4. Berms can be placed to surround structures and accommodate roads or driveways;
5. Upstream walls, windows and doors can be reinforced to protect against flood and debris impact; and
6. Inner floodprone benches and instream rock and woody debris veins can be designed to deflect flow away from eroding banks that are adjacent to structures.

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APPENDIX 1 – USGS Stream Gage Data for Sonoma Creek at Kenwood and near Kenwood.

Sonoma Creek at Kenwood, Station 11458433
Latitude 38°25'08", Longitude 122°33'42" NAD27
Drainage area 14.3 square miles
Gage datum 420 feet above NGVD29

Water Year	Date	Gage Height (feet)	Stream-flow (cfs)
2009	Feb. 22, 2009	7.18	439
2010	Jan. 20, 2010	9.84	1,170
2011	Mar. 20 2011	9.35	1,020
2012	Mar. 14 2012	8.72	835

Sonoma Creek near Kenwood, Station 11458400
Latitude 38°26'32", Longitude 122°32'15" NAD27
Drainage area 6.07 square miles

Water Year	Date	Gage Height (feet)	Stream-flow (cfs)
1958	Feb. 24, 1958	13.25	1,510
1959	Feb. 16, 1959	12.53	640
1960	Feb. 08, 1960	17.10[1]	1,430
1961	Dec. 01, 1960	11.83	395
1962	Feb. 13, 1962	12.62	685
1963	Jan. 31, 1963	13.10	910
1964	Jan. 20, 1964	12.95	850
1965	Jan. 05, 1965	16.35	2,750
1966	Jan. 05, 1966	14.49	1,750
1967	Jan. 21, 1967	14.88	2,020
1968	Jan. 30, 1968	12.51	640
1969	Jan. 26, 1969	13.05	900
1970	Jan. 21, 1970	14.28	1,600
1971	Dec. 03, 1970	14.24	1,570
1972	Dec. 26, 1971	10.90	167
1973	Jan. 16, 1973	14.73	1,900

An estimate of the highest peak flow during WY 2005 at old site near Kenwood is about 3900 cfs and is based on a linear regression with gage data from Sonoma Creek at Agua Caliente.