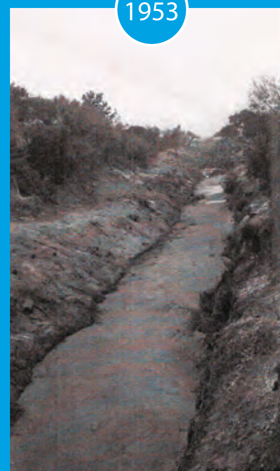


A Sediment Budget for Two Reaches of Alameda Creek

Analysis of natural and land use-related channel erosion and storage in Arroyo De La Laguna and Upper Alameda Creek from their confluence upstream to gage locations near Verona and Welch Creek

by Paul E. Bigelow[1], Sarah Pearce[2], Lester McKee[2] and Alicia Gilbreath[2]

[1]Bigelow Watershed Geomorphology and the [2]San Francisco Estuary Institute

Prepared for the Alameda County Flood Control District

October 2008

bigelow watershed geomorphology

SFEI

Suggested citation:
Bigelow P., S. Pearce, L. McKee, and A. Gilbreath. 2008. A sediment budget for two reaches of Alameda Creek. Prepared by Bigelow Watershed Geomorphology and SFEI for the Alameda County Flood Control District. October. 140 pp.

EXECUTIVE SUMMARY

Since construction of the flood control channel reach on lower Alameda Creek in the 1970s, net sediment deposition has required periodic dredging to maintain "100-year" flood capacity (~1,472 m^3/s). Two upstream reaches of Alameda Creek (the Arroyo De La Laguna tributary and the upper Alameda Creek tributary, from their confluence near Niles Canyon, upstream to USGS gaging stations at Verona and Welch Creek) were identified in previous studies as possible substantial sources of sediment deposited in the flood control channel despite comprising only 0.25% of the total stream length of Alameda Creek. This study provides a detailed sediment budget for these reaches that range in length from 5.8 km (Arroyo De La Laguna) to 7.3 km (Alameda Creek). The objectives were to determine the dominant processes and quantify rates of sediment supply and storage from these reaches over time (1901 - 2006), compare the net erosion from the study reaches to other portions of the watershed, and project future channel evolution with rough estimates of sediment supply based on various land and water management scenarios.

To meet these objectives, a field-based assessment of sediment sources was conducted including field erosion surveys, bed elevation and cross section surveys, and tree coring to estimate floodplain age. In addition, air photo analysis and extrapolation of limited suspended sediment and bed load data at USGS gages were conducted. In the Arroyo De La Laguna tributary, incision was historically the largest component of the sediment supply following anthropogenic breaching of the historic Tulare Lake and other channelization upstream, supplying roughly 14,800 tonnes/yr for the period 1901 - 1958, and 13,500 tonnes/yr for 1959 - 1971 following the massive floods of the 1950s. These changes fundamentally altered the nature of the Arroyo De La Laguna study reach from a sediment sink, which was well connected to the valley floodplain and stored overbank deposits, to a conduit that more effectively transports sediment downstream. For the most recent period, 1994 - 2006, channel incision migrated upstream of the study reach leaving steep banks, and channel adjustment shifted to primarily bank erosion as the dominant process, supplying roughly 13,400 tonnes/yr. This channel erosion is partially offset by sediment storage processes, where floodplain accretion (on a younger inset floodplain) was the largest storage component from 1959 - 1971 (1,800 tonnes/yr), and later (1994 - 2006) storage was dominated by in-channel point bar storage (2,600 tonnes/yr) opposite of eroding bends, as storage in floodplains (1,100 tonnes/yr) and bed aggradation (1,100 tonnes/yr) continued. Given the large uncertainties associated with geomorphic measurements, the Arroyo De La Laguna reach supplied an estimated net average of roughly 9,000 tonnes/yr of sediment to downstream reaches during the most recent period from 1994 - 2006. This is similar to the higher periods of estimated net average erosion from 1901 - 1958 and 1959 - 1971 that ranged from 13,500 - 13,700 tonnes/yr, respectively. Estimated net erosion from 1971 - 1993 was reduced (250 tonnes/yr), presumably due to lower precipitation during this period.

Similar methods were used to complete the budget for the Alameda Creek tributary, although only a subset of the field parameters were evaluated because, in contrast to Arroyo De La Laguna, the Alameda Creek study reach is *generally* well connected to the historical valley floor floodplain with small amounts of bank erosion and little incision. Moreover, much of the flow and sediment supply to the reach is impounded by two reservoirs (70% of the drainage area), substantially reducing channel dynamics in the reach under the current flow regime. Based on this partial sediment budget, historically the dominant sediment supply to the reach was from landslides and gullying (4,400 tonnes/yr) from 1901 - 1958, and later *minor* incision (3,900 tonnes/yr) in 1959 - 1971. Sediment supply during the recent period 1994-2006 is much smaller in comparison (320 tonnes/yr from landslides, 140 tonnes/yr from bank erosion). Sediment storage from channel bars and bed aggradation was historically higher (3,000 tonnes/yr in 1959 - 1971) than recent periods (140 tonnes/yr for 1994 - 2006), most likely due to reduced

flow and sediment supply from reservoirs. Given the uncertainties in geomorphic measurements and that this is a partial budget, net erosion from the Alameda Creek study reach was roughly 320 tonnes/yr during the recent period 1994 - 2006.

To evaluate the significance of net sediment supplied from the study reaches, these field-based estimates were then compared to sediment supply from upstream, as measured at USGS gage station locations at Verona (on Arroyo De La Laguna) and at Welch Creek (on Alameda Creek), and sediment supply transported from the study reach, as measured on Alameda Creek at Niles. For the period 1994 - 2006, 104,000 tonnes/yr at Arroyo De La Laguna near Pleasanton (Verona) and 3,400 tonnes/yr at Alameda Creek below Welch Creek passed into the study reach. In comparison, for the same period, an estimated average of 156,000 tonnes/yr of sediment passed through the Niles gage (below the study reaches). To make a more complete comparison of the watershed, a conservative estimate of 53,000 tonnes/yr was made for the 116 km^2 of ungaged tributary watershed area *between the gages at the top of the study reaches downstream to the Niles gage* (this does not include watershed areas that drain from upstream of the Verona and Welch gages). Based on these budget terms, roughly 6% of the sediment mass passing through the Niles gage during the period 1994 - 2006 was derived from net channel erosion within in the study area, primarily Arroyo De La Laguna. The study reaches comprised roughly 0.25% of the entire watershed stream network length. For the drier period from 1972 - 1993 the study reaches accounted for < 1% of the estimated total sediment load at the Niles gage. During the period 1959 - 1971, the study area accounted for 26% of the total load passing Niles gage, reflecting a period of rapid incision following the 1950s flood events.

The sediment budget accounts for historical sediment supply and storage from 1901 - 2006. However, Arroyo De La Laguna continues to adjust and evolve from past and ongoing alterations in stream flow and sediment supply. This continued channel evolution should be considered in future management decisions. Using descriptive channel evolution models described in the scientific literature, we describe, interpret, and classify the evolutionary stage for each subreach of Arroyo De La Laguna and make projections for continued evolution. We present three coarse *conceptual scenarios* illustrating how changes in land use, climate, and watershed management could affect the continued evolution of Arroyo De La Laguna. Under the most likely scenario (a slight increase in total discharge and decrease in total fine sediment supplied to the study reach), it is estimated that future net sediment yield from the reach will be similar to current rates.

The sediment budget was conducted to provide managers with information on the contribution of sediment from the study reaches to downstream areas, including the flood control channel. As often observed in other Bay Area watersheds, small areas or short channel reaches can provide significant amounts of sediment to the channel network. This suggests that identifying similar reaches within the watershed may be an important next step in making management decisions to reduce the sediment supply to downstream reaches. A series of recommendations are provided for consideration, including further study to better quantify potentially manageable sediment sources within the watershed by accounting for natural and human influenced sediment production on public and private lands, possible restoration approaches that promote sediment storage in the upper watershed, and watershed planning using a stream goals approach.

ACKNOWLEDGEMENTS

Funding for this project was provided by Alameda County Flood Control & Water Conservation District (AFC&WCD) for the total amount of $81,528.40, via a subcontract (number 1825) with Philip Williams and Associates (PWA) agreement number C-2006-90.

We gratefully acknowledge and thank the following organizations and people for their support of this project, invaluable guidance and comment, and sharing of data:

Ralph Johnson, Alameda County Flood Control
Manny DaCosta, Alameda County Flood Control
Hank Ackerman, Alameda County Flood Control
Tim Ramirez, San Francisco Public Utilities Commission
Steve Apperson, San Francisco Public Utilities Commission
Tim Koopman, San Francisco Public Utilities Commission
Christie Beeman, Philip Williams and Associates
Setenay Bozkurt, Philip Williams and Associates
Laurel Collins, Watershed Sciences
Virginia Mahacek, Valley & Mountain Consulting
Dave Martinez, East Bay Regional Park District
Joe Seto, Zone 7 Water Agency
Dexter Yee, Zone 7 Water Agency
Vince Wong, Zone 7 Water Agency
Carol Mahoney, Zone 7 Water Agency
David Lunn, Zone 7 Water Agency
Gerald Gates, Zone 7 Water Agency
Brad Ledesma, West Yost and Associates
Jackie Charbonneau, USDA NRCS
Terry Huff, USDA NRCS
Stuart Hill, USGS Hayward
Tom Haltom, USGS
Katie Bergmann, Livermore Resource Conservation District
Josh Milstein, City of San Francisco Attorney
Nuria Bertran-Ortiz, RMC

TABLE OF CONTENTS

INTRODUCTION

Since completion of the flood control channel on lower Alameda Creek in 1975, Alameda County has periodically removed aggrading sediment deposits to maintain the “100-year” flood capacity (~1,472 m^3/s at the junction with Dry Creek, FEMA 1975). The need for sediment removal is fundamentally due to inherent limitations common to all engineered channels designed to pass flow rather than sediment (e.g. Griggs and Paris 1982). In the case of Alameda Creek, the flood control channel was constructed in an area where massive amounts of sediment were historically deposited (Figure 1), creating an extensive (now disconnected) alluvial fan[1] and floodplain between the mouth of Niles Canyon and the Bay margin (Sowers 1999). Sediment continues to deposit in the flood control channel as Alameda Creek attempts to restore its natural grade or profile, similar to other flood control channels in Northern California (e.g. Griggs and Paris 1982, Mount 1995). The channel maintenance needed can potentially disrupt aquatic habitat and riparian zone wildlife and mobilize sediments and contaminants. Therefore, the County must acquire a permit from the Regional Water Quality Control Board (Regional Board) and other agencies each time channel maintenance is proposed. Moreover, perpetual sediment removal from the flood control channel is financially challenging for Alameda County, and costs may escalate as dredging costs inflate and permit conditions require additional mitigation.

Figure 1. Oblique photo showing the Fremont area (facing southeast looking upstream) during the 1955 flood, prior to construction of the flood control channel (source: Young 1962, Sowers 1999).

[1] The north side of the Niles fan was last inundated with floods in 1958, while the south side of the fan may have last received flood waters in 1939 (Sowers 1997).

As part of the permitting process for sediment removal from the flood control channel, the Regional Board requested that Alameda County investigate potential controllable erosion sources in upper Alameda Creek. Previous studies of the Alameda Creek watershed identified natural and anthropogenic sediment sources throughout the basin (Golder Associates 1999, Ayres Associates 2001, Collins and Leising 2003, Collins 2005, Alameda County 2006). One study in particular (Collins and Leising 2003, Collins 2005) suggested that Alameda Creek and Arroyo De La Laguna (ADLL) immediately upstream of their confluence (Figures 2 and 3) may be significant sources of sediment deposited in the flood control channel.

In this study, we construct a sediment budget for these two reaches of Arroyo De La Laguna and Alameda Creek as the next step in evaluating sediment sources. The ultimate objective of the study is to evaluate whether or not the study reaches may be a major source of sediment deposited in the flood control channel. Accordingly, the specific objectives of the sediment budget were:

1. Estimate the processes and rates of erosion and storage from the study reaches over time.

2. Evaluate the magnitude of net erosion from the study reaches relative to the rest of the watershed.

3. Estimate possible future erosion trends of the study reaches.

Secondary objectives of the study were to perform a historical literature and map review for the upper watershed (primarily areas draining to Arroyo De La Laguna), and characterize the grain size distribution of sediment deposited in the flood control channel (Appendix A).

BACKGROUND

Physical Setting

The Alameda Creek watershed is the largest local watershed draining to the San Francisco Bay, encompassing an area of 1,662 km^2 (642 mi^2) at the head of tide near the Bay margin and 1,639 km^2 (633 mi^2) at the U.S. Geological Survey (USGS) flow gage in Niles Canyon. The headwaters of the 5th-order creek (Strahler 1957) drain a large portion of the East Bay interior hills and valleys, including the Livermore-Amador and Sunol valleys. Alameda Creek then cuts through the East Bay Hills via Niles Canyon before flowing through the large historical alluvial fan and floodplain complex, now disconnected by the engineered flood control channel, ultimately discharging into the southern portion of the San Francisco Bay (Figures 2 and 3). Currently, the lowest 19 km of the creek is constructed flood control channel (Alameda County Flood Control Channel), created by the US Army Corps of Engineers in the 1960s and 1970s. This flood control channel is operated and maintained by the Alameda County Public Works Department.

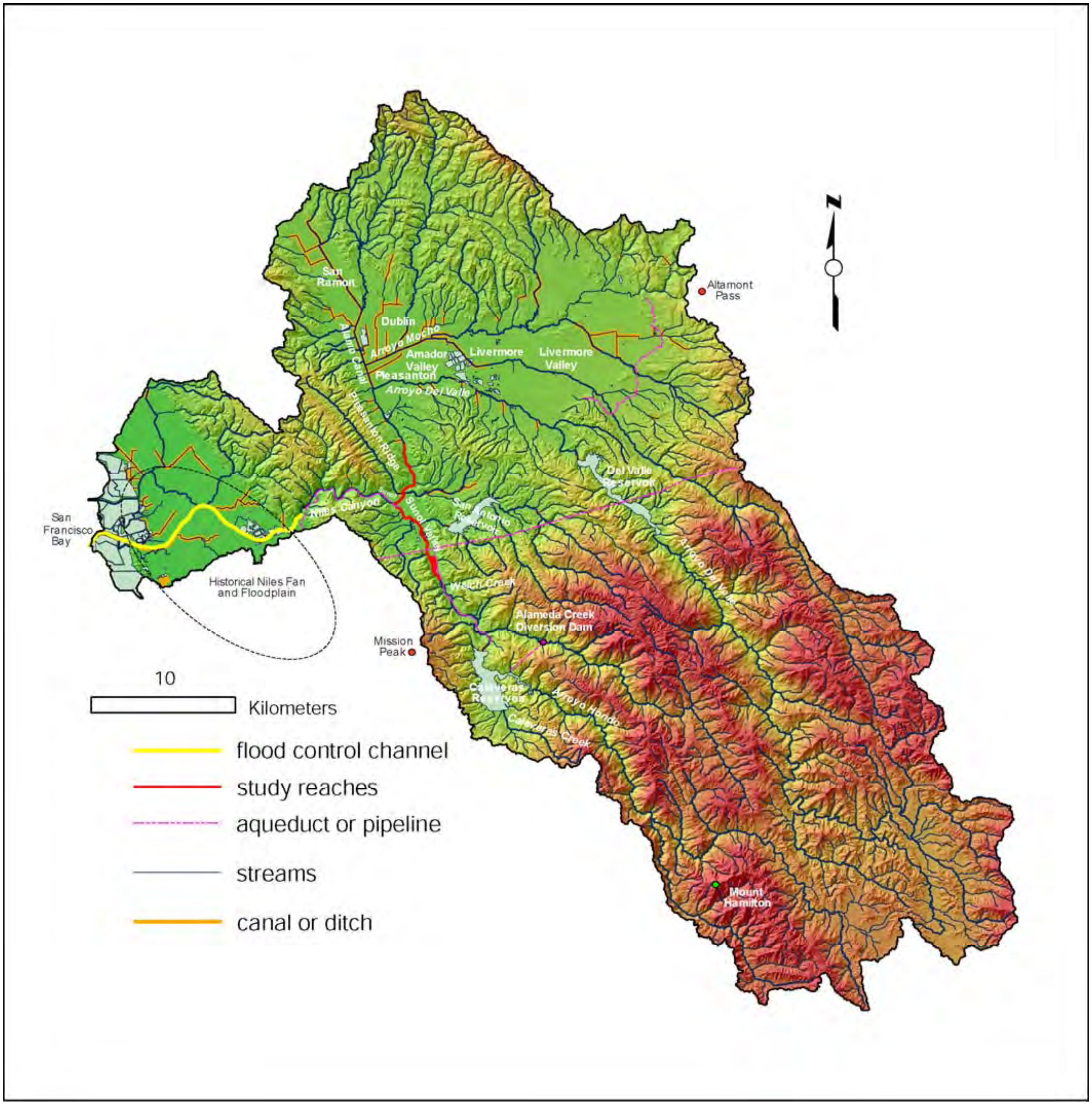


Figure 2. Alameda Creek watershed showing study reaches, and flood control channel. Canal and ditch information is provided by Sowers (1999), Sowers and Richard (2003), and the digital stream layer from USGS (2008). See Figure 3 for close up of the study reaches.

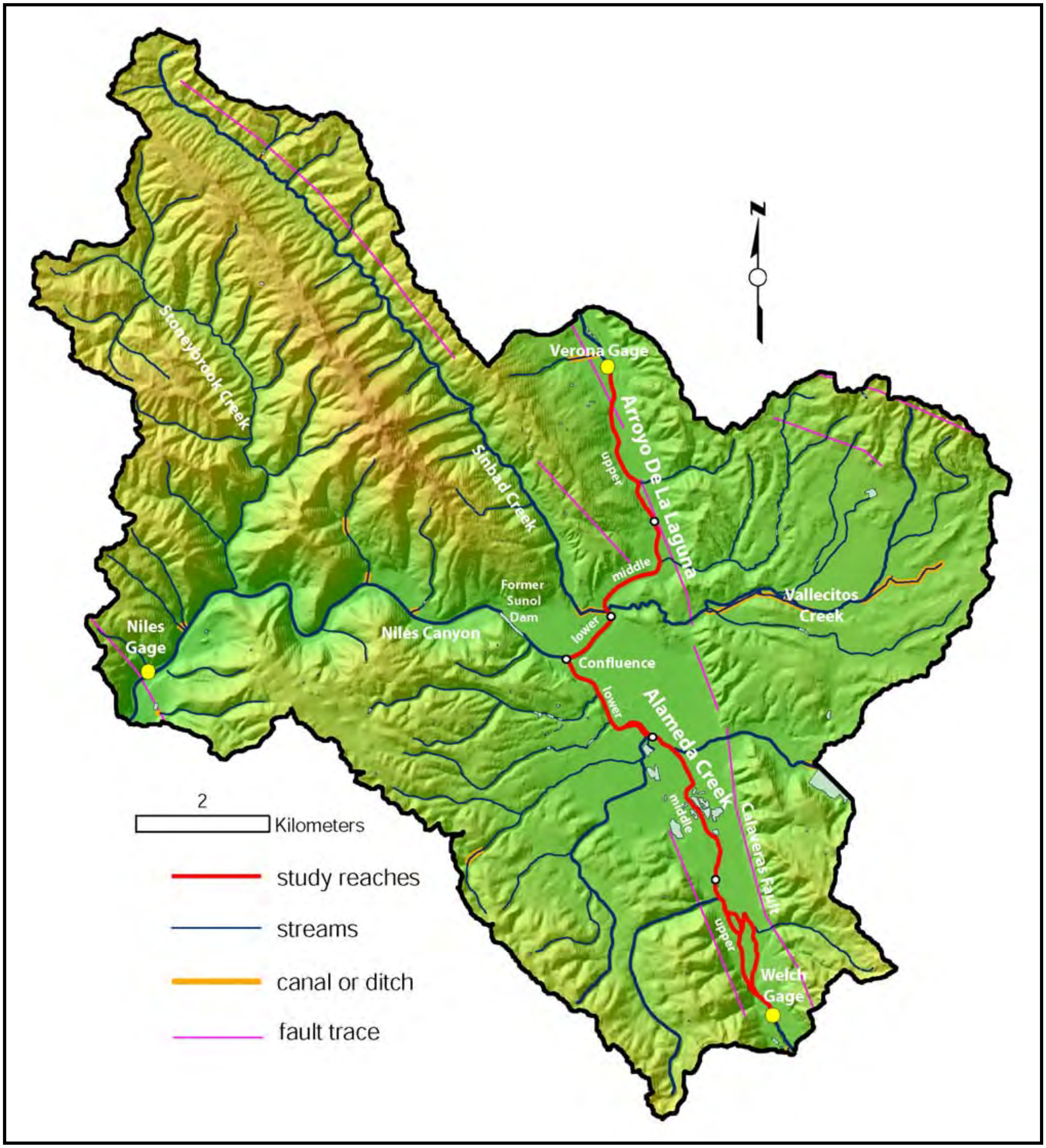


Figure 3. Study area showing study reaches and subreaches, USGS gages, and ungaged tributary basins. Fault trace locations from Jennings (1994). Note that the middle subreach of Alameda Creek contains setback levees where gravel mining occurs (see later).

The watershed ranges in elevation from sea level at San Francisco Bay to 1,341 m at the top of Mt. Hamilton. The Mediterranean climate of the watershed is characterized by dry summers and moderate winter rainfall with a mean annual precipitation of 37 cm/yr measured at Livermore (McKee et al. 2003; Philip Williams and Associates [PWA] 2005), the majority of which falls between October and May. However, precipitation within the watershed varies with elevation and with distance away from the Bay, where higher elevations of the East Bay Hills receive more rainfall, thus the overall watershed average is likely slightly higher than that measured in Livermore. For example, the highest rainfall in the watershed is recorded at Mission Peak (61 cm/yr), while the lowest is recorded near Altamont Pass (28 cm/yr) (Collins and Leising 2003). The watershed is underlain primarily by Quaternary alluvium, Pliocene/Miocene sedimentary lithologies, and the Cretaceous Franciscan Complex (Graymer et al. 2006). The Hayward fault passes through the watershed in Fremont, and the Calaveras fault passes through the watershed near Sunol, with the two faults essentially defining the western and eastern edges of the East Bay Hills. The watershed contains three large reservoirs (Calaveras Reservoir, San Antonio Reservoir, and Del Valle Reservoir) and the Alameda Creek Diversion Dam which store and transfer water and sediment from approximately 728 km^2 or 44% of the watershed area.

Downstream of Niles Canyon, Alameda Creek flows across its alluvial fan through the suburban cities of Fremont, Union City and Newark. Upstream of Niles Canyon, the watershed can be divided into two major portions: the Alameda Creek tributary to the south, and the Arroyo De La Laguna tributary to the north. The Alameda Creek tributary drains the Sunol Valley, Calaveras Creek, Welch Creek, and Arroyo Honda areas. These areas are primarily open space lands comprised of the Sunol-Ohlone Regional Wilderness Preserves and watershed land owned by the San Francisco Public Utilities Commission. A portion of these lands are used for grazing, plant nurseries, and gravel mining. Above the confluence with Alameda Creek, approximately 45% of the Arroyo De La Laguna watershed area is impounded by Del Valle reservoir. The Arroyo De La Laguna tributary drains the Livermore-Amador Valley, including the Arroyo Del Valle, Arroyo Mocho, and Alamo Canal tributaries. This area is much more suburbanized, including the cities of Pleasanton, Dublin, Livermore and San Ramon, however many areas of open space still exist, such as along the Pleasanton Ridge. Above the confluence with Arroyo De La Laguna, approximately 70% of the Upper Alameda Creek watershed area is impounded by San Antonio and Calaveras reservoirs.

Alameda Creek has historically supported an assemblage of native fish species, including resident rainbow trout and anadromous steelhead trout (*Oncorhynchus mykiss*), coho salmon (*Oncorhynchus kisutch*), and possibly chinook salmon (*Oncorhynchus tshawytscha*) (Leidy et al. 2003, 2005; Alameda Creek Alliance 2007). Adult steelhead trout seeking to migrate and spawn upstream are frequently observed in the flood control channel (Alameda Creek Alliance 2007), but successful migration and spawning are severely limited by a number of migration barriers, dams and associated low water flows, and pressures from suburban development (Trush et al. 2007). However, a number of other native fish species are found in the watershed, including California roach (*Lavinia symmetricus*), Sacramento sucker (*Catostomus occidentalis*) and prickly sculpin (*Cottus asper Richardson*), as well as non-native species (e.g. common carp (*Cyprinus carpio*) and golden shiner (*Notemigonus crysoleucas*)) (Leidy 2007; Alameda Creek Alliance 2007).

Alameda Creek and Arroyo De La Laguna currently support a diverse assemblage of riparian plant species. These plants are important to both the quality and quantity of habitat provided, but also to the channel form and resistance to erosion. For example, a number of tree species were observed along the study reach, and were used in our interpretations of bank erosion, floodplain accretion, and channel evolution. The most common species include: California bay (*Umbellularia californica*), sycamore (*Platanus racemosa*), Fremont cottonwood (*Populus fremontii*), willow (*Salix spp.*), valley oak (*Quercus lobata*), coastal live oak (*Quercus agrifolia*), buckeye (*Aesculus californica*), and black walnut (*Juglans hindsii*).

Channel Network History – Alterations in Water and Sediment Supply

Changes in channel planform, cross sectional shape, location, slope, or discharge, whether the changes are a response to a natural cause (e.g. climate, tectonics) or to an anthropogenic alteration (e.g. ditching, dredging), can cause major changes in sediment supply from the reach, storage within the reach, and sediment transport capacity of the reach. Just a single change to one aspect of a creek may set in motion a period of channel adjustment wherein a dramatic range of channel forms and magnitudes of sediment production are observed. These channel adjustments have a profound effect upon the sediment budget, affecting both the sediment supplied from the channel itself, as well as the ability of sediment supplied from upstream portions of the watershed to be transported further downstream.

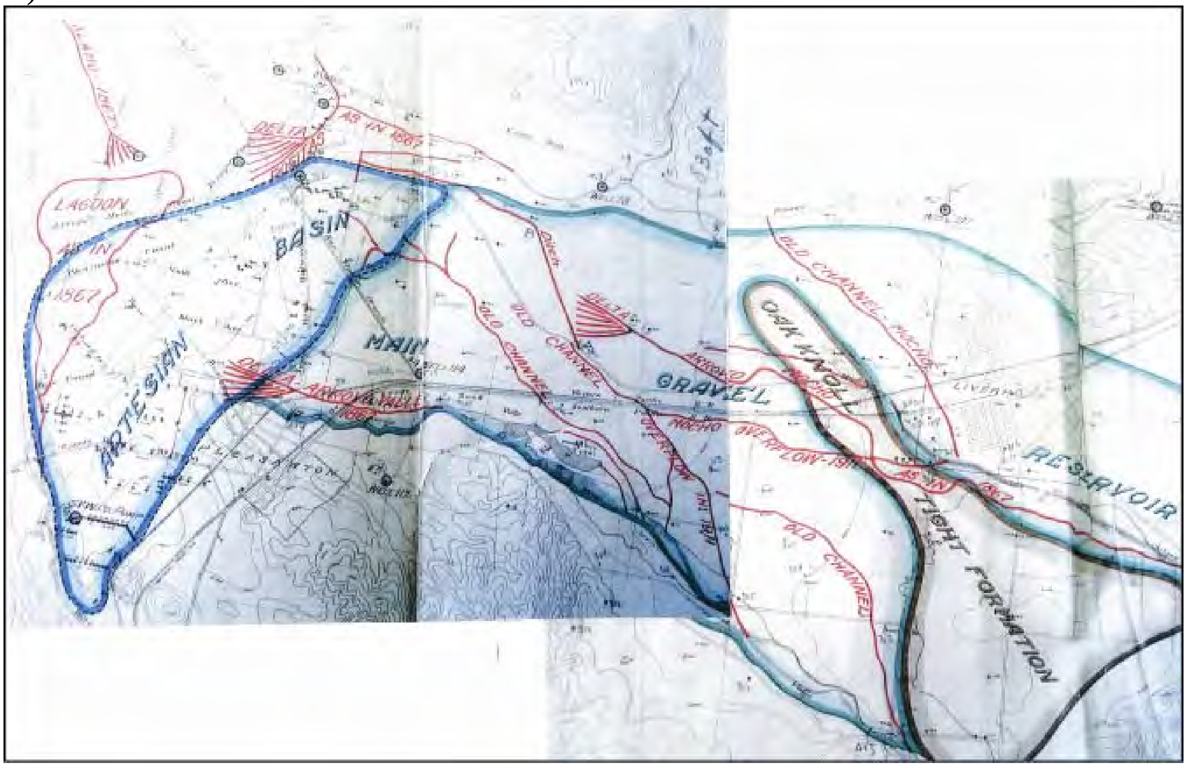
A number of channel network changes have occurred within the Alameda Creek watershed, including major anthropogenic modifications to both the Arroyo De La Laguna reach and the Alameda Creek reach. Specifically in the Arroyo De La Laguna reach, these changes have dramatically affected the sediment budget of the reach, both historically and currently. And because this reach is still adjusting to past and ongoing changes in stream flow and sediment supply, the sediment budget will continue to be affected well into the future. This section aims to document the major anthropogenic alterations to the channel network in order to understand the historic and current channel form and sediment production. The timeline is primarily comprised of information gathered from the multiple documents utilized in the literature review. Collection and analysis of additional site-specific information, such as an historical ecology analysis, would yield a more complete understanding of change within the channel network.

1800 to 1900

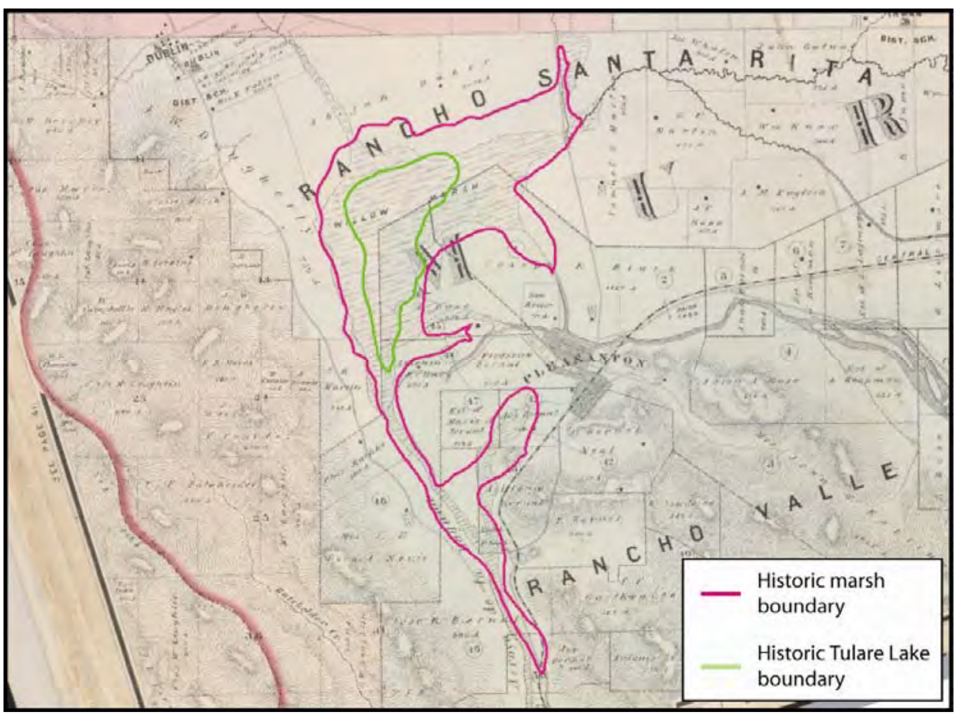
- 1826 Jose Amador and others establish Spanish ranchos in the Livermore-Amador Valley (City of Pleasanton 2007)
- 1841 Construction of stone dam across Alameda Creek, near the mouth of Niles Canyon, by Jose de Jesus Vallejo (Weiss Associates 2004). This is likely the first engineered water diversion/use project constructed in the watershed.
- 1854 Dr. John B. Trusk writes “In the north central part [of the valley] there is a lagoon which is overgrown with tule” (Williams 1912).
- 1864 Alameda Water Company becomes incorporated (Williams 1912).
- 1865 Construction of Niles Dam by Spring Valley Water Company (Collins and Leising 2003; Williams 1912).
- 1866 to 1875 Alameda Water Company purchases parcels of land in the Calaveras Valley (Williams 1912).

1867 The lagoon (Tulare Lake) and surrounding willow marsh is mapped (Figure 4A and B) (Ayres 2001).
1869 The transcontinental railroad is built in the valley (City of Pleasanton 2007). A wooden covered Howe Truss bridge is constructed for the railroad to cross Arroyo De La Laguna (Luna 2005) (Figure 5).
1874 Possible date of ditching of Arroyo Mocho (Collins and Leising 2003).
1875 Spring Valley Water Company purchases some Alameda Creek water rights (Williams, 1912).
1878 Map of the area is published by Thompson and West.
1880s Cattle ranching and grazing is common within the valley.
1887 Construction of Niles Dam atop Vallejo Dam (Weiss Associates, 2004); Construction of a concrete dam 1 mile upstream from Niles (Williams, 1912).
1888 First surface water diversions from Alameda Creek by Spring Valley Water Company (Williams, 1912).
1888 Spring Valley Water Company gaging at Niles Canyon Dam begins in December (Freeman, 1912).
1892 November, A flood with a recurrence interval greater than 15 years occurs (16,200 cfs at the USGS Alameda Creek near Niles gage 11179000).
1898 Groundwater is extracted from gravel beds near Sunol (Williams, 1912).
1898 Spring Valley Water Company taps artesian wells and drills many (56) wells in the Livermore Valley; ditches were cut leading from these wells to the Laguna Creek (Williams, 1912).
1898 The original wooden railroad bridge across Arroyo De La Laguna is replaced with a steel Phoenix Bridge Co. girder design (Luna 2005).
Pre-1900 Ditching of many tributary channels in the Livermore-Amador Valley (Weiss Associates 2004).

A)


LAGOON
ARTESIAN
BASIN
MAIN
GRAVEL
RESERVOIR
TIGHT FORMATION
OAK KNOLL
OLD CHANNEL
DELTA
PLEASANTON

B)


RANCHO SANTA RITA
RANCHO VALLE
PLEASANTON
DUBLIN
Historic marsh boundary
Historic Tulare Lake boundary

C)

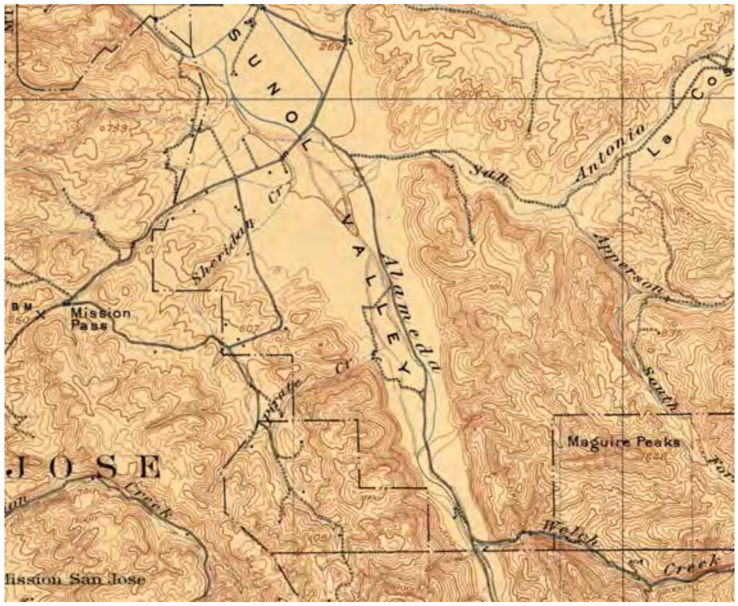


Figure 4. A) Map showing the historic drainage patterns (shown in red) in the Pleasanton and Livermore area (Williams 1912). Note that many of the creeks ended in distributaries before reaching Tulare Lake. B) Map showing the historic boundary of the historic marsh and lagoon (Tulare Lake), as mapped by Sowers and Richard (2003). The downstream (southern) limit of Tulare Lake is located just upstream of Bernal Avenue, upstream of the study area, and the downstream limit of the marsh is located approximately at Verona, the upstream limit of the study area. The map underlay is Thompson and West (1878). C) A portion of the 1906 15' Livermore Topographic Quadrangle showing the Sunol Valley and the braided nature of the Alameda Creek tributary.

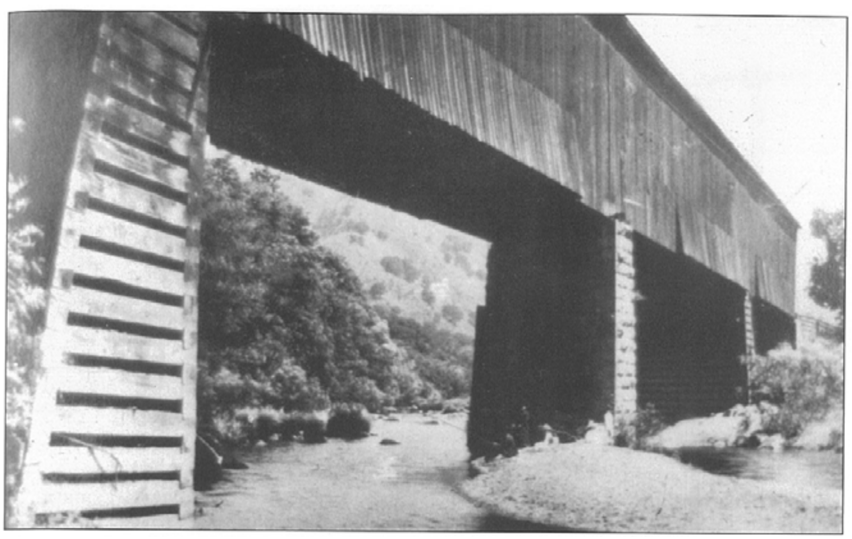


Figure 5. Photograph of the original wooden Howe Truss railroad bridge across Arroyo De La Laguna (Luna 2005). The photograph is undated, but was taken sometime between 1869 and 1898.

1900 to 1950

1900 Assumed date of the ditching and draining of Tulare Lake, and connection of all upstream channels to the Arroyo De La Laguna mainstem (Collins and Leising 2003).

1900 Construction of the Sunol Dam in the upstream portion of Niles Canyon (Weiss Associates 2004).

1900 Gage station moves to the new Sunol Dam location (Freeman 1912).

~1900 Gravel mining (continuing to present) and agriculture begins along Alameda Creek tributary near Sunol (Collins and Leising 2003).

1902 March, Mr. B. Murphy, employee of Spring Valley Water Company, records that "Laguna Creek at the outlet of the "C" line of wells (downstream of Bernal Avenue) is 40 ft wide, 4 ft deep, with a velocity of 50 ft in 15 seconds [533 cfs]. Water raised 8 ft during storm" (Williams 1912).

1906 Publication of the USGS Livermore 15' Topographic Quadrangle Map, showing no remnant of the historic lake or marsh, only straight ditches connecting upstream channels through to the Arroyo De La Laguna mainstem. However, the map does show an aqueduct that removes water from the creek immediately downstream of the railroad bridge, and transports it to the Sunol Valley, presumable to the filter gardens. Also, the Alameda Creek tributary through Sunol Valley is shown as braided (Figure 4C).

1908 to 1910 Pumps are added to the artesian wells to capture additional water (Williams 1912).

1911 March, A flood with a recurrence interval greater than 10 years occurs (14,700 cfs at Niles gage).

1911 November, Williams' observation of a rate of incision of 6 inches/year in Arroyo De La Laguna. Associated photographs of Arroyo De La Laguna (see appendix for historic photographs).

> "In recent years the marsh has been drained by the construction of reclamation ditches and by the deepening and clearing of a portion of the Laguna Creek channel, which allowed the flood waters a free course. The channel, now less obstructed, is greatly cut down, its present bed opposite the Spring Valley Water Company's "C" line of wells being now, November 1911, 5 feet lower than in 1901, the erosion, in other words, being at the rate of 6 inches per year."

1913 Construction of Calaveras Dam begins (Collins 2005).

1916 Photographs taken on the Alameda Creek alluvial fan show heavy siltation and aggradation of creeks (Collins and Leising 2003).

1925 Calaveras Dam completed (FEMA 1997).

1920s Gravel mining in Arroyo Mocho begins. Mining provided gravels for the 1933-1937 construction of the Golden Gate Bridge (David Lunn personal comm.)

1920s Gravel mining in Arroyo Valle begins, and continues through the 1970s (David Lunn, personal comm.)

1929 Construction of the Alameda Creek diversion tunnel to transport water from the upstream reach of Alameda Creek into Calaveras Dam. Construction complete by 1931. (Collins 2005).

1950 to Present

1950s Gravel mining in Arroyo Mocho utilizes Fresno Scrapers which scrape the channel bed, but leave sycamore trees remaining in mounds (David Lunn, personal comm.).
1951 and 1952 The largest two floods since 1922 occur (18,400 and 24,300 cfs at Niles gage).
1953 US Army Corps of Engineers clears a portion of Arroyo De La Laguna near Bernal Avenue for increased flood conveyance (Figure 6). Longitudinal extent is unknown (SFPUC photograph archive).
1955 Largest flood on record (29,000 cfs at Niles gage) occurs on December 23rd. Many areas of the valley are flooded, including the re-emergence of Tulare Lake (Figure 7).
1958 The second-largest flood on record occurs (25,500 cfs at Niles gage).
1960 Channelization of many upstream channel reaches begins (e.g. Arroyo Mocho) (Golder Associates 1999).
1964 San Antonio Dam completed (FEMA 1997). Design discharge of 13,500 cfs.
1965 Portions of the Alameda Creek Flood Control channel complete (Weiss Associates 2004).
1968 Del Valle Dam completed (FEMA 1997). Max spillway peak discharge is 7,000 cfs.
1970s and 1980s Pleasanton, Dublin, and Livermore experience rapid population growth.
1975 Remainder of Alameda Creek Flood Control Channel completed (Weiss Associates 2004).
1975 190,000 yds^3 dredged from the flood control channel (Collins 2005).
1980 Documented gravel mining is still occurring in Arroyo Valle (Golder Associates 1999).
1981 27,000 yds^3 dredged from the flood control channel (Collins 2005).
1982 37,000 yds^3 dredged from the flood control channel (Collins 2005).
1984 158,000 yds^3 dredged from the flood control channel (Collins 2005).
1986 The sixth largest flood on record occurs (16,400 cfs at Niles gage).
1986 43,000 yds^3 dredged from the flood control channel (Collins 2005).
1989 166,000 yds^3 dredged from the flood control channel (Collins 2005).
1998 The fifth largest flood on record occurs (17,900 cfs at Niles gage).
1998 152,000 yds^3 dredged from the flood control channel (Collins 2005).
1998 to 2001 Alameda County spent an average of $780,000 per year removing deposited sediment from the Flood Control Channel (Collins and Leising 2003).
1999 67,000 yds^3 dredged from the flood control channel (Collins 2005).
2000 106,000 yds^3 dredged from the flood control channel (Collins 2005).
2001 Cessation of significant use of the Alameda Diversion Tunnel, because of the seismic retrofit project on Calaveras Dam.
2001 40,000 yds^3 dredged from the flood control channel (Collins 2005).
2005 Nearly the entire area of historic lagoon and marsh is now urbanized (see Appendix B for figure).
2006 Removal of Sunol and Niles Dams.
2006 Construction of a large bank erosion restoration project occurs approximately ½ mile south of Verona on Arroyo De La Laguna.

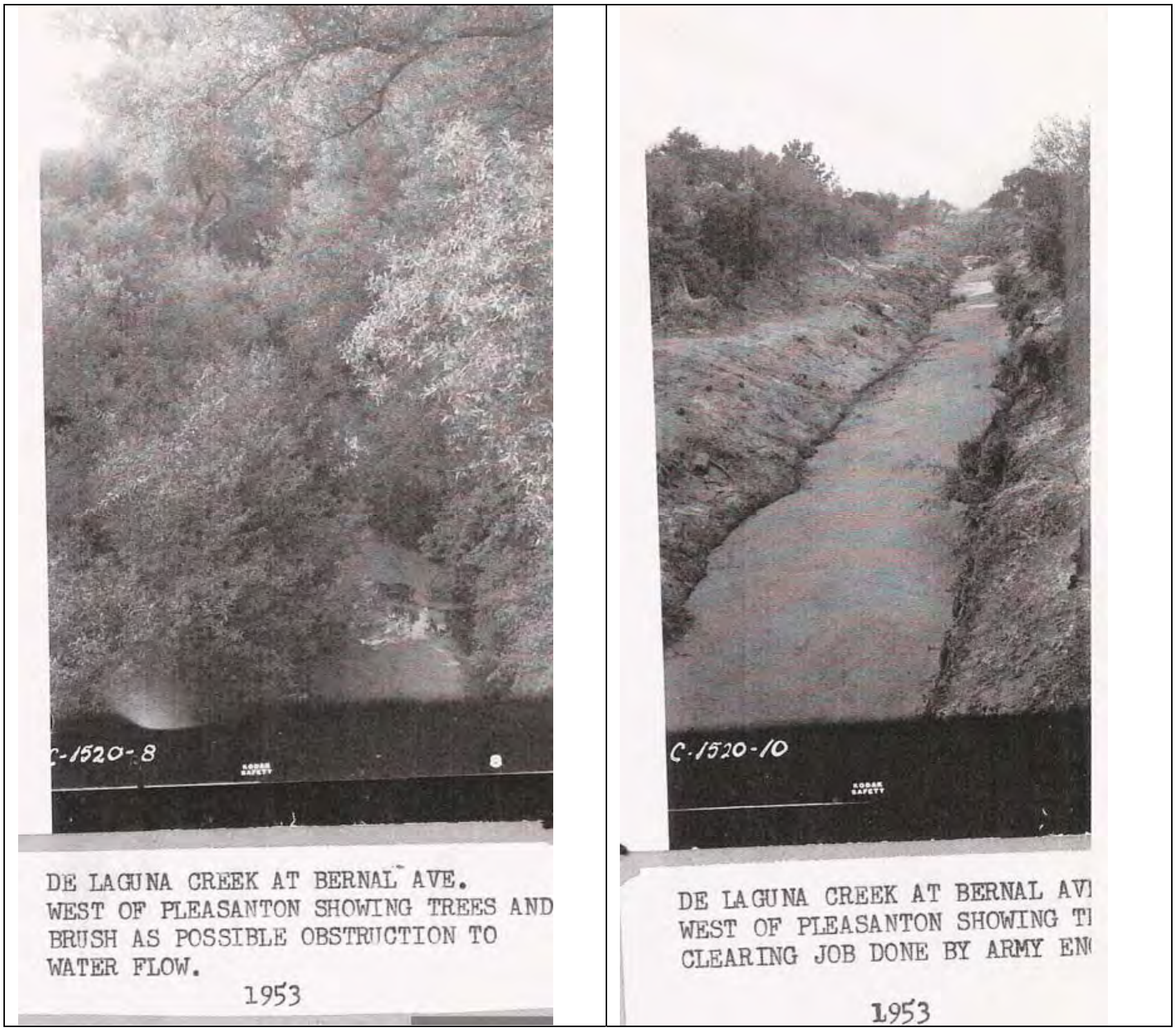


Figure 6. A) Photograph showing Arroyo De La Laguna at Bernal Avenue before riparian vegetation clearing in 1953. B) Photograph showing the same reach after riparian vegetation clearing in 1953 by the Army Corps of Engineers (Source: Alameda County Resource Conservation District). For general comparison to the present day condition (2006), see photograph from Castlewood Bridge on cover of this report (note that Castlewood Bridge is just downstream from Bernal Bridge).

Figure 7. The day after the 1955 flood in Pleasanton area looking west, note flood waters reoccupy the historic lagoon area (Source: Zone 7 Water Agency, Sowers and Richard [2003]).

Supporting Observations for Timeline Development and Watershed Functioning

The timeline was compiled utilizing the number of previous reports and studies on the Alameda Creek watershed. During the document review, a number of observations and hypotheses stood out as valuable in developing our understanding of the watershed's history and current functioning. We have compiled the relevant observations and hypotheses from each study that pertain to the sediment budget and channel evolution analysis and interpretation in Appendix B.

General Characteristics of the Study Reaches

Here we describe the general characteristics of the study reaches to provide context for the methods of the sediment budget. To characterize the general channel morphology of the reaches, we collected the following general channel metrics at roughly 300 meter intervals: (1) bankfull channel widths, floodplain heights, and terrace heights were measured with a laser range finder; (2) average bar heights were measured from the thalweg with a stadia rod; and (3) the dominant particle size of the streambed and channel type (e.g. Montgomery and Buffington 1997) were visually estimated.

Arroyo De La Laguna. The Arroyo De La Laguna reach includes approximately 5.8 km of channel length. The contributing watershed area to the upstream limit of the study reach is 1,044 km^2, 670 km^2 of which is downstream of dams. At the downstream limit of the study reach, the contributing watershed area is 1,087 km^2, 713 km^2 of which is downstream of dams (Table 1). Table 1 summarizes the general reach characteristics, where we divided the reach into 3 subreaches (lower, middle, upper) for descriptive and geomorphic purposes. Representative photos of the subreaches are shown in Figures 8 (air photos) and 9 (photos taken during field work). The reach is highly incised where the former valley floor floodplain is nearly abandoned except during extreme floods, and is now typically 4 - 8 meters above the active channel and is now a terrace (abandoned floodplain) (Figure 10). Inset within the valley terrace, a lower and younger but discontinuous floodplain has formed that is typically 1 - 3 meters above the active channel (Figure 11A). This discontinuous floodplain contains typical flood tolerant riparian vegetation including cottonwoods and willows not found on the valley floor terrace, as well as evidence of floodplain accretion (sand deposits) in wet years, therefore we call it a floodplain. Below this floodplain in some areas with large bars, the bar surface contains young willows with a maximum age of roughly 10 years, dating back to the last El Nino event in 1997 when the bars were last reworked, and we refer to it as an emerging floodplain surface. Figure 11B shows a generalized cross section of these surfaces and the components of the sediment budget they represent (i.e. bar storage, floodplain storage). These surfaces in no way quantify any type of current bankfull condition, but rather reflect evolving conditions. Defining static bankfull conditions in highly disturbed and evolving channels such as Arroyo De La Laguna can be dubious (see Simon et al. 2007). Figure 12 shows a plot of measured terrace and floodplain heights throughout the reach. In the upper subreach, several massive bars are forming on the inside bend of meanders, where extensive bank erosion into valley fill is occurring on the outside bend (Figure 13). Overall, the entire study reach is generally characterized by bar-pool-riffle channel morphology and sand and gravel substrate, with the size of both the bed and bank material abruptly increasing at and below the junction of the Sinbad and Vallecitos Creeks, likely due to the coarse sediment supply from these two large tributaries (Figure 14).

Alameda Creek. The Alameda Creek reach includes nearly 7.3 km of channel length with contributing drainage areas of 376 km^2 to the upper limit of the study area, including 121 km^2 of area below dams. At the lower limit of the study reach, the contributing watershed area is 511 km^2, including 157 km^2 below dams (Table 1). The study reach lies within a wide valley and the channel is often split or braided, indicative of a channel where bedload is a substantial component (e.g. >10%) of the sediment load (Schumm 1977, Knighton 1998). The upper subreach in particular contains repeated division and joining of channels characteristic of braided streams (Knighton 1998) as well as distributary channels connected to the floodplain. Active gravel mining occurs along the valley floor in the middle subreach, and here the floodplain is moderately constrained by levees, reducing the area for floodplain storage and channel migration. Near the bottom of the reach, the channel abuts a high older terrace (Pleistocene or Pliocene era) on the west side of the valley that periodically supplies material to the channel from landslides and gullying. The lower subreach was reportedly moved to the west side of the valley (Tim Ramirez, SFPUC, personal communication 2007), however an extensive floodplain now borders the east side of the channel on the lower reach and there are no levees immediately adjacent to the channel. Table 1 summarizes the general characteristics of the reach (lower, middle, upper) and Figures 15 and 16 show air photos and photos taken during fieldwork of the subreaches, respectively.

Table 1. Summary of study reach characteristics.

	Arroyo De La Laguna Reach		
	Lower	**Middle**	**Upper**
Parameters[a]	**Confluence to Paloma Bridge[b]**	**Paloma Bridge to RR Bridge**	**RR Bridge to Verona Gage**
Survey length (m)	975	1820	3010
Channel type	plane bed, bar-pool-riffle	bar-pool-riffle	bar-pool-riffle
Channel slope[d] (%)	0.42	0.26	0.23
Mean bankfull width (m)	20	21	21.5
Mean bar height (m)	0.9	1.1	1.1
Top of bank height[e] (m)	4.7	5.2	6.5
Dominant Substrate	cobble	Sand	gravel
Subdominant Substrate	gravel	Gravel	sand
Drainage Area[f] (km^2)	1087		1044
Drainage Area Below Dams[g] (km^2)	713		670

	Alameda Creek Reach		
	Lower	**Middle**	**Upper**
Parameters[a]	**Confluence to 680 Bridge**	**680 Bridge to Farm Bridge[c]**	**Farm Bridge to Welch Gage**
Survey length (m)	1980	2485	2800
Channel type	plane bed, split channel	plane bed, split channel	split channel
Overall Channel slope[d] (%)	0.45	0.42	0.34
Mean Bankfull width (m)	24	28	26
Mean Bar height (m)	1	0.8	0.5
Top of bank height[e] (m)	3	1.5	2
Dominant Substrate	cobble and sand	gravel	gravel
Subdominant Substrate	gravel	cobble	cobble
Drainage Area[f] (km^2)	511		376
Drainage Area Below Dams[h] (km^2)	157		121

Notes

a channel parameters collected roughly every 300 m (n = 18 for Arroyo De La Laguna, n = 15 for Alameda Creek), values shown are averages within each subreach.

b subreaches are shown moving upstream (left to right), and were divided at the confluence, bridges, and gages.

c the floodplain of this subreach is moderately constrained by levees as the valley terrace is used for gravel mining here. The upstream end of this subreach and berms end at a wooden bridge that crosses the channel to a private farm/ranch on the west side of the channel.

d channel slopes derived from 2007 auto level survey on Arroyo De La Laguna and 1971 survey for Alameda Creek.

e bank height from channel bed to top of valley terrace (i.e. often not the evolving but discontinuous contemporary floodplain).
f drainage areas are shown for bottom (confluence) and top (gage) of the study reaches.
g Del Valle reservoir impounds 374 km^2
h Calaveras reservoir impounds 255 km^2 and San Antonio reservoir impounds 99 km^2. The Alameda Creek diversion dam (drainage area of 86 km^2) is not included here as an impoundment although flow and associated suspended sediment is subject to diversion to Calaveras reservoir.

Figure 8. Examples of the lower, middle, and upper subreaches of the Arroyo De La Laguna study reach.

Upper subreach looking upstream at Verona bridge and gage.

Upper subreach just above railroad bridges, outside of eroding bend showing exposed roots and some floodplain accretion above root level.

Middle subreach just below railroad bridges looking downstream at erosion around grade control structure.

Middle subreach below railroad bridges looking ustream at erosional bend and bedrock knickpoint at riffle, possibly fault related.

Small tributary junction on middle subreach showing incsion through valley fill that is headcutting upstream.

Lower subreach facing downstream looking at the wedge of sediment built up behind massive bar at the confluence.

Figure 9. Arroyo De La Laguna study reach showing various field photos of subreaches.

Figure 10. Bank erosion into valley fill and channel incision along Arroyo De La Laguna study reach showing the valley terrace approximately 7 meters above the channel bed. Note the valley terrace is an abandoned floodplain now only inundated during extreme flood events.

Figure 11A. Photo showing an example of the younger discontinuous floodplain 1- 3 meters above the active channel and valley terrace 4 - 8 meters above the active channel in Arroyo De La Laguna.

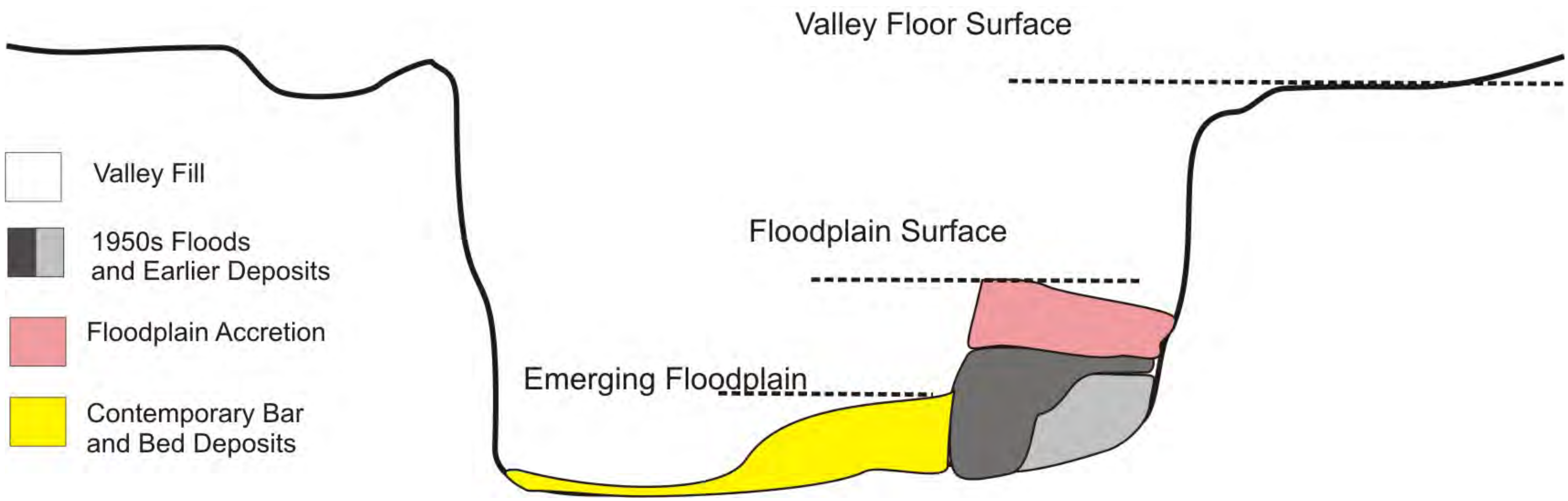


Figure 11B. *Conceptualized* cross section showing the main surfaces in the Arroyo De La Laguna study reach. Note that the floodplain surface (pink) contains cottonwoods and willows, active floodplain accretion in wet years, and is discontinuous throughout the reach; this is not necessarily the current bankfull surface as such distinctions are dubious in disturbed reaches that are evolving rapidly (see Simon et al. 2007). See text for more detailed description of the surfaces.

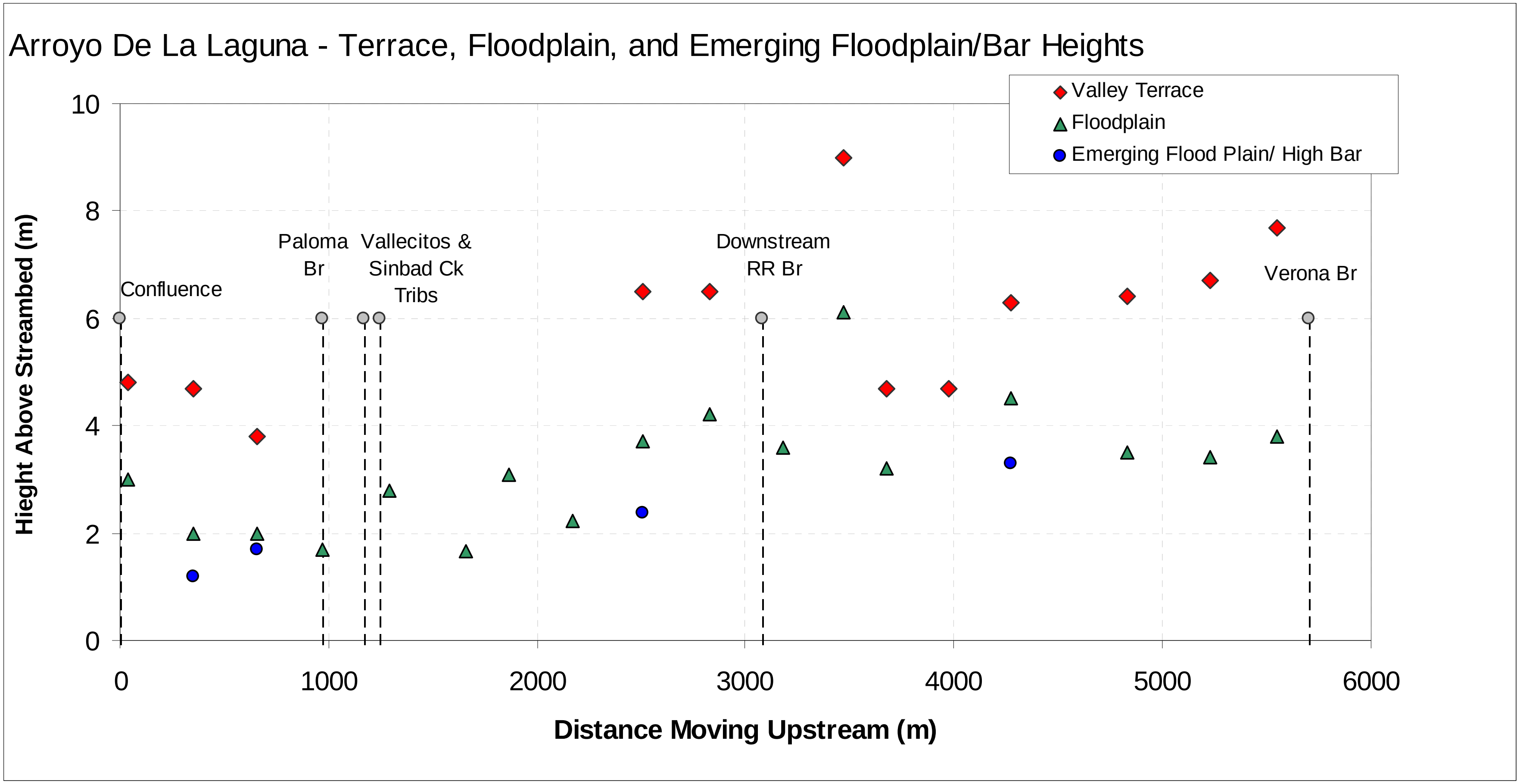


Figure 12. Longitudinal profile of valley terrace, floodplain, and emerging floodplain/high bar heights along Arroyo De La Laguna study reach.

Figure 13. Panoramic photos from opposite sides of a large erosional bend and massive bar in the upper subreach of Arroyo De La Laguna, just upstream of the railroad bridges.

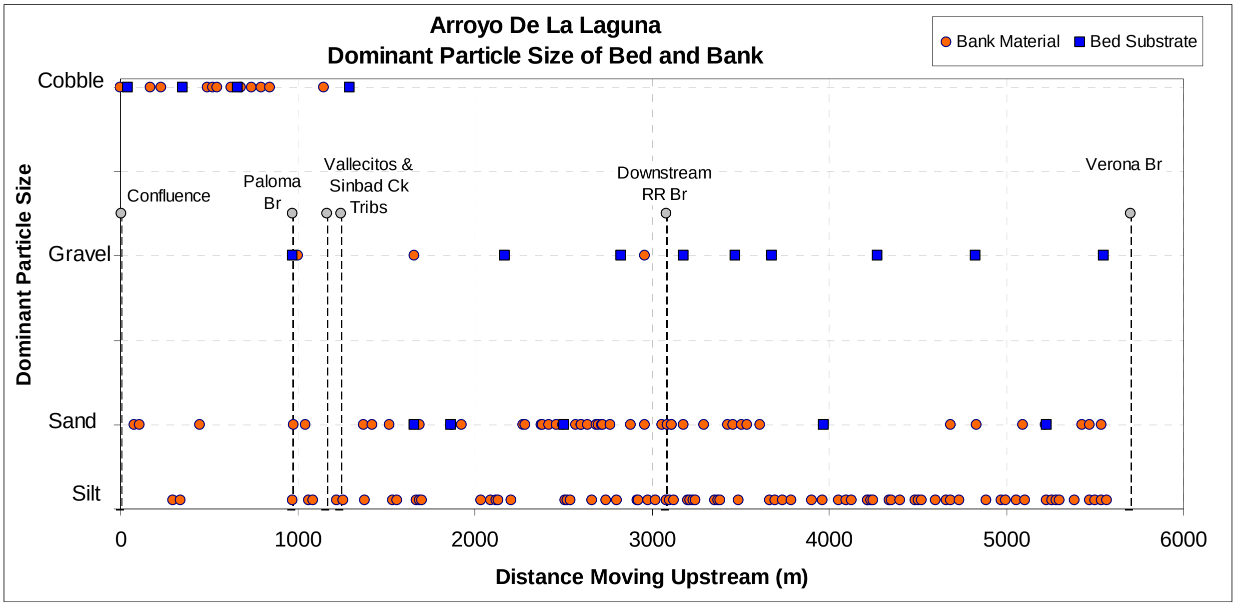


Figure 14. Longitudinal profile of dominant particle size of bed and banks in Arroyo De La Laguna, showing dominant particle size increasing at and downstream from the Sinbad and Vallecitos Creek tributaries.

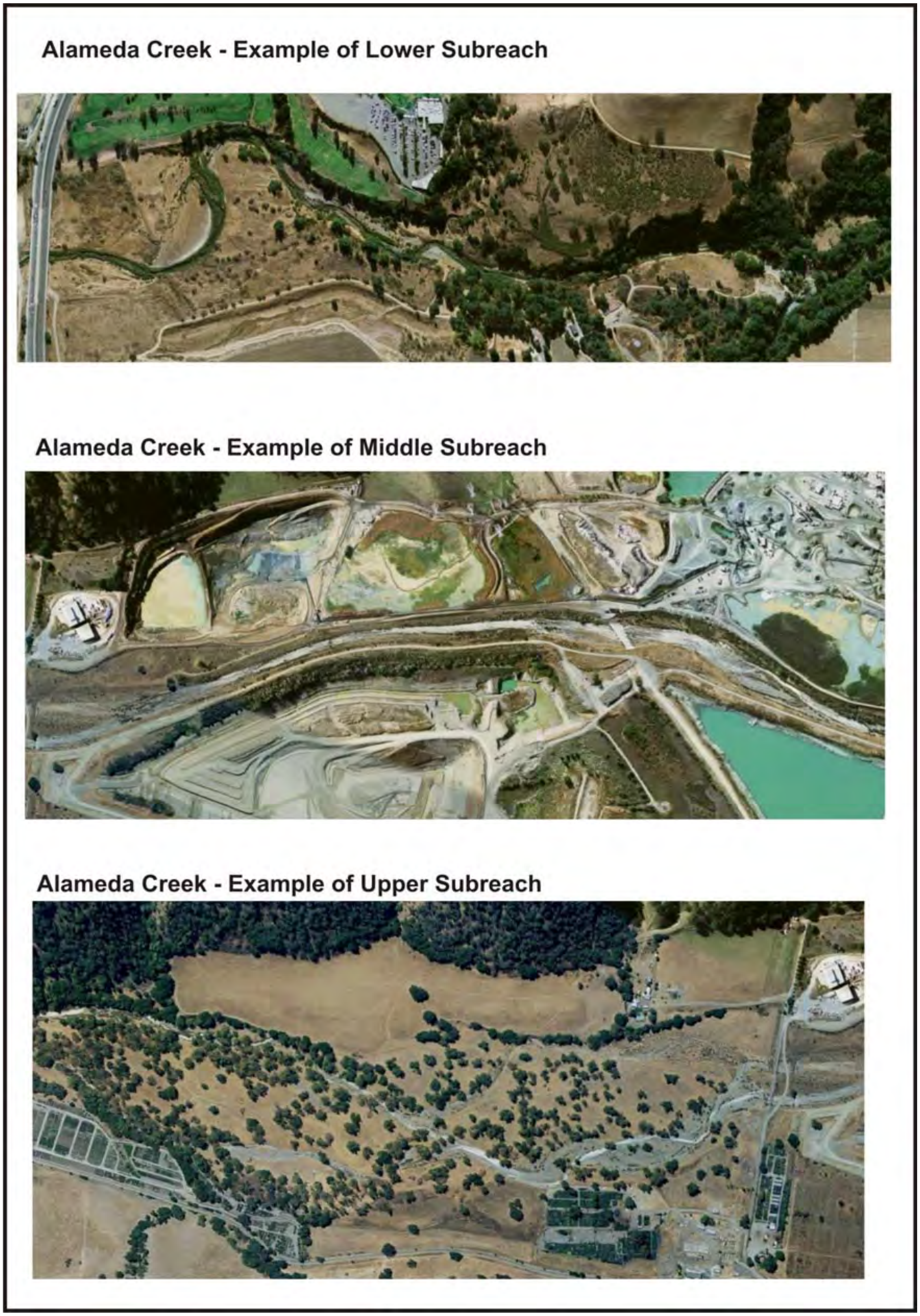
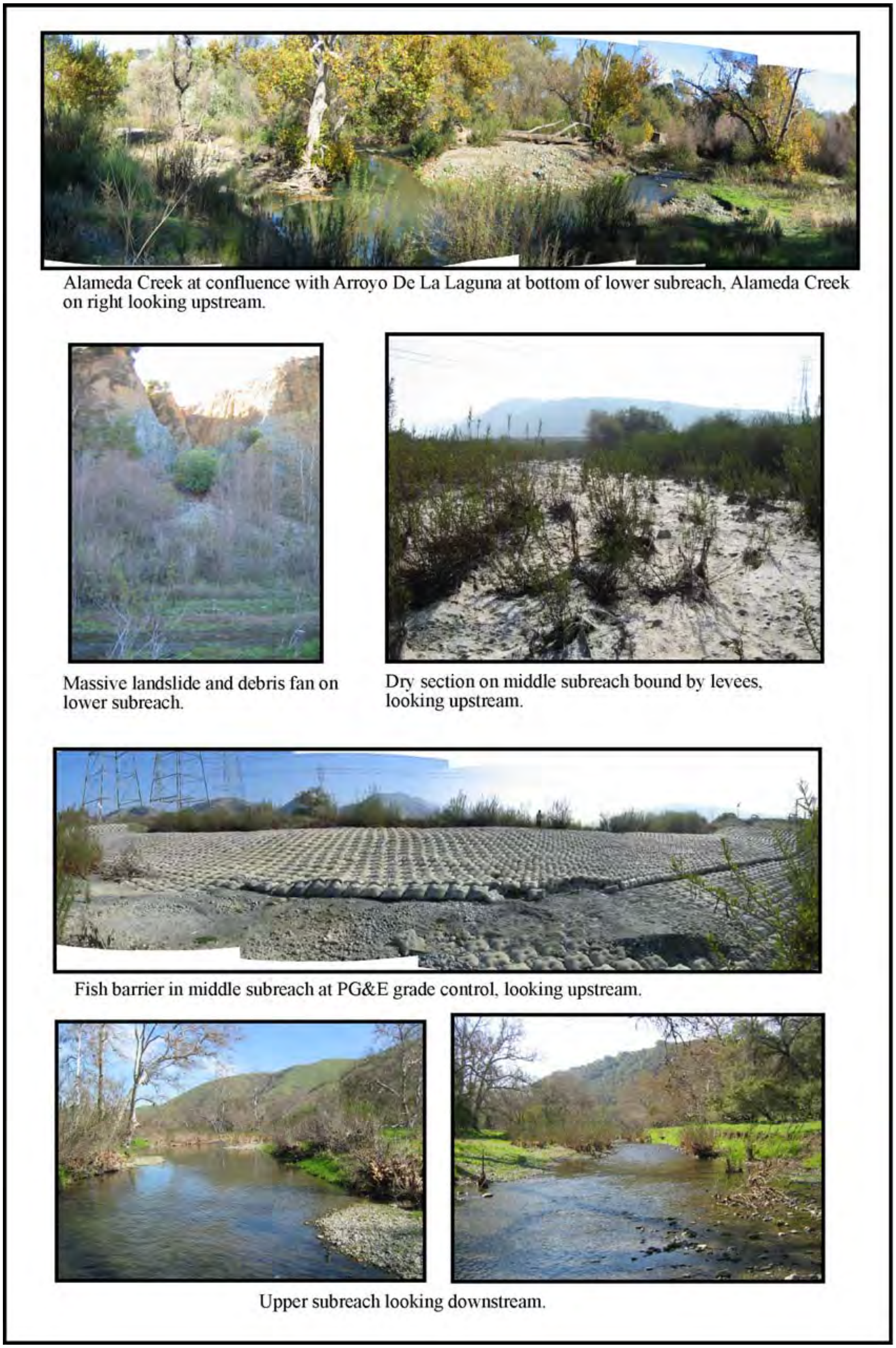


Figure 15. Examples of the lower, middle, and upper subreaches of the Alameda Creek study reach.



Alameda Creek at confluence with Arroyo De La Laguna at bottom of lower subreach, Alameda Creek on right looking upstream.

Massive landslide and debris fan on lower subreach.

Dry section on middle subreach bound by levees, looking upstream.

Fish barrier in middle subreach at PG&E grade control, looking upstream.

Upper subreach looking downstream.

Figure 16. Alameda Creek study reach showing various field photos of subreaches.

METHODS

Time Periods and Components of Sediment Budget

Four time periods were established for analysis of the sediment budget in Arroyo De La Laguna and Alameda Creek based on the flood record (Figure 17), available air photos, and bed elevation surveys. The four budget time frames include:

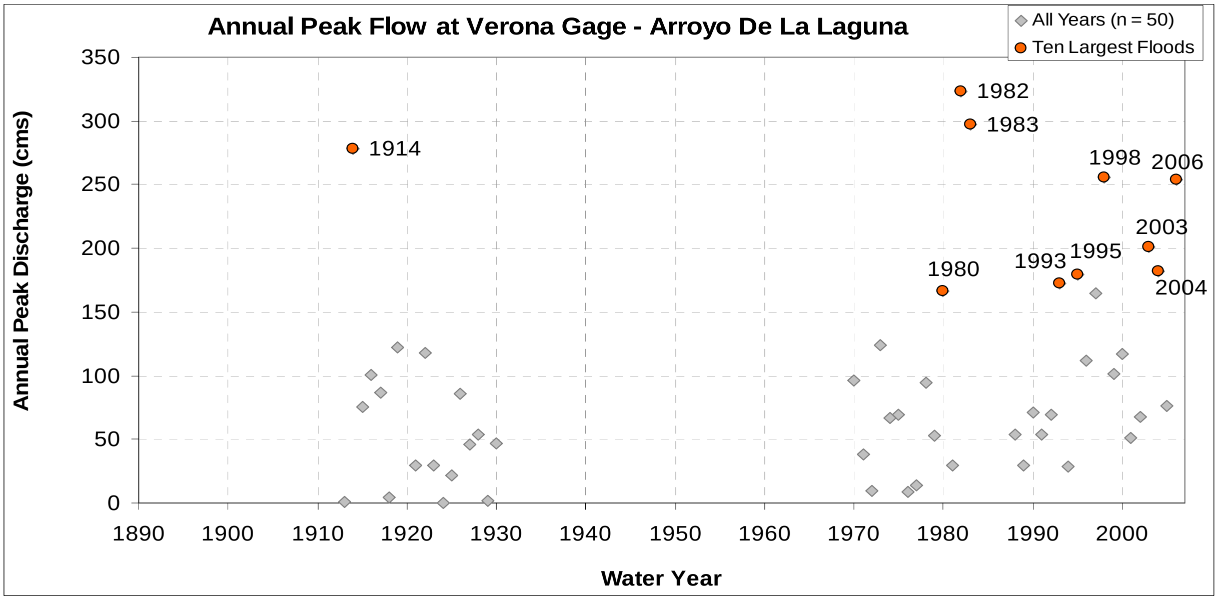
- 1901 - 1958, a period when Arroyo De La Laguna began incising after upstream channelization was completed, includes air photos from 1939 and 1950, a bed elevation survey near the end of the time period (1959), and includes the historic 1950s floods.

- 1959 - 1971, a period that includes bed elevation surveys at the beginning and end of the time period (1959 and 1971), and air photos from 1966.

- 1972 - 1993, this period includes a bed elevation survey near the beginning of the time period (1971) and air photos at the end of the time period in 1993.

- 1994 - 2006, the most recent period that includes field erosion surveys from 2006, a bed elevation survey in 2007, and air photos from 2005.

The recent period (1994 - 2006) provides the most detailed estimate of sediment yield, while the earlier periods are coarse but still useful for context and observing erosion trends over a longer time frame. Figure 18 summarizes the data used in determining the four time periods of the sediment budget, including historic floods, air photo periods, and bed elevation and field surveys.



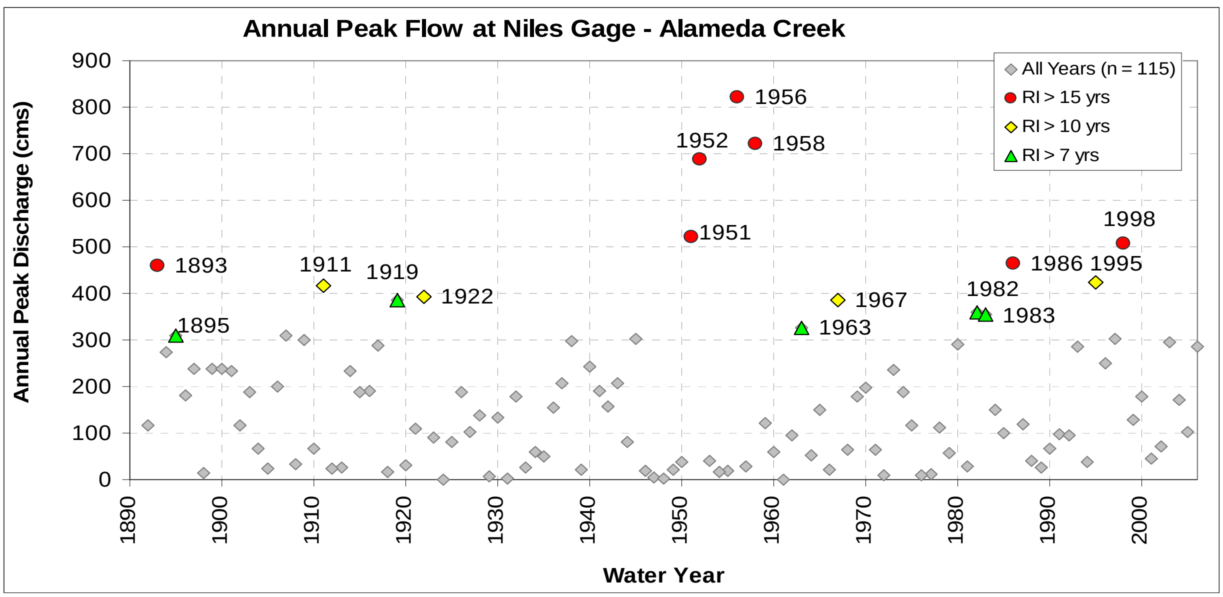


Figure 17. Annual peak flow events at Niles and Verona gages by water year. Recurrence intervals (RI) for peak flows at Niles gage were calculated as described in Dunne and Leopold (1978). The Verona gage on Arroyo De La Laguna moved location in 2004 due to bank erosion and the record is incomplete (no data from 1931-1969). The water year is the 12-month period from October through September, designated by the calendar year in which it ends.

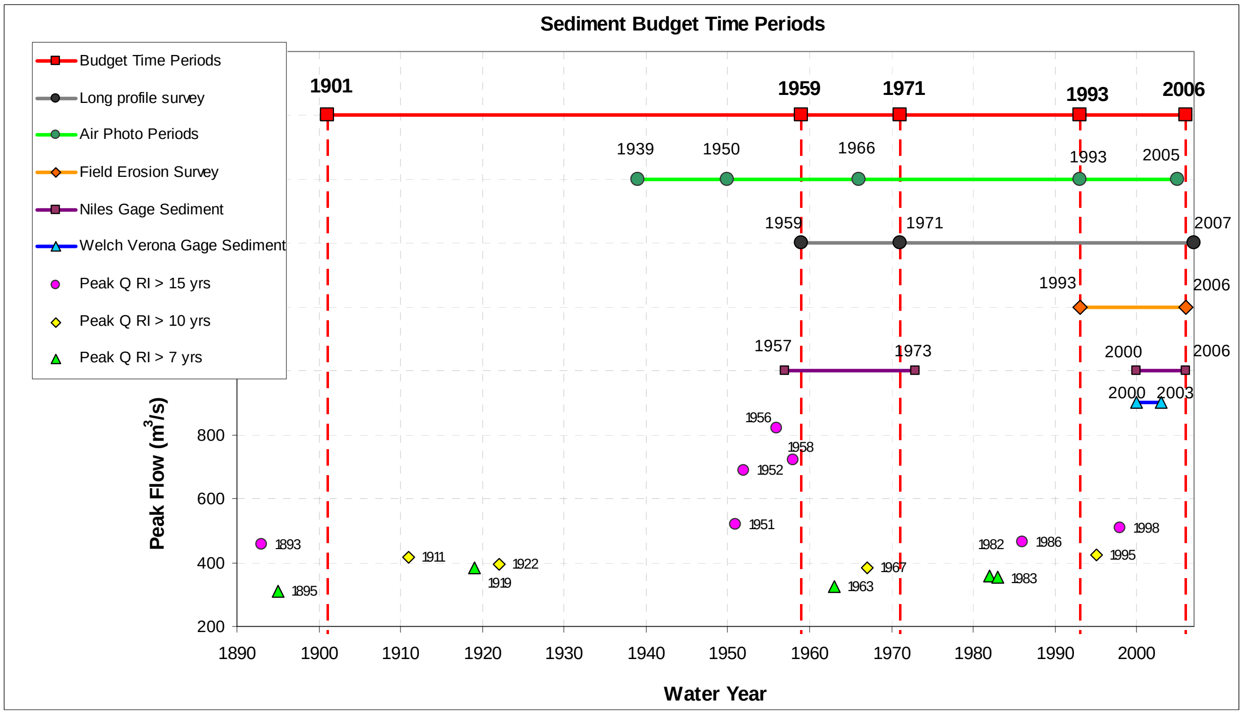


Figure 18. Summary of the four sediment budget periods, data sources used for different periods (long profile surveys, air photo periods, field erosion surveys, suspended sediment data at gages), and the higher peak flows at Niles gage.

Through the development of a sediment budget, we aimed to characterize the major components of sediment supply and storage within the study reaches and their change through time from a combination of field erosion surveys, air photo analysis, bed elevation and cross section surveys, tree coring to age floodplain storage, and extrapolation of limited suspended sediment and bed load data at gages to estimate up and downstream sediment yield for comparison to the study reaches. Methods for each component are explained in the following sections. All of the components were evaluated for Arroyo De La Laguna, but only a subset of the components was evaluated on Alameda Creek. Although high sediment loads pass through and are stored in the generally braided or split channel of the Alameda Creek reach, the reach itself does not appear to be a major source of sediment (e.g. extensive bank erosion, bed incision), with the exception of some landslides that impinge upon the channel in the lower subreach. Consequently, a more detailed sediment budget did not appear necessary for the Alameda Creek study reach. The need for more detailed information in the Alameda Creek study reach may change in the future depending on channel evolution in relation to the nature of gravel extraction, channel restoration to improve the anadromous fishery, climate change, changes in reservoir configuration and management, and other land use and management changes.

Channel Incision and Aggradation – Bed Elevation Surveys

Arroyo De La Laguna. Sediment supply from channel bed incision can be a major component of sediment budgets in urban creeks (Trimble 1997) and is quite apparent in the Arroyo De La Laguna study reach (Golder Associates 1999, Ayres Associates 2001, Collins 2005, Alameda County 2006). Channel incision and aggradation depths were estimated from bed elevation surveys conducted in 1959, 1971, and 2007. The 1959 bed elevation survey was conducted by Alameda County (1959) presumably for flood control planning after the major floods of the 1950s (see flood history in Figure 17). Only the profile of the survey was available, and we were unable to obtain any information on survey methods. Another bed elevation survey was conducted in 1971 as part of a flood insurance study conducted by the Federal Emergency Management Agency (FEMA) (FEMA 1975). While the flood insurance study was completed and published in 1975, the actual surveys were apparently completed in 1971 as indicated on the raw data obtained from FEMA (1971). Only plots of the survey were available and no information was available on survey methods.

We conducted a bed elevation survey of the Arroyo De La Laguna reach in 2007 for comparison with the previous surveys. Because incision is not a major process on the generally braided Alameda Creek reach, a similar bed elevation survey was not necessary. The survey was conducted using an auto level, stadia rod, and measuring tape. Individual survey shots were from riffle crest to riffle crest and were no longer than 50 meters in length. The survey was tied into a Caltrans bench mark (North America Vertical Datum [NAVD 1988]) near Paloma Bridge. The 1971 survey was relative to the National Geodetic Vertical Datum (NGVD 1929), and while the 1959 survey does not list a datum, it appears to be NGVD because the top of bank elevations for 1959 and 1971 generally align, and bed elevations near the grade control structure immediately upstream of Paloma Bridge also generally align. The 1959 and 1971 survey elevations were converted to NAVD using the VERTCON program (Milbert 1999) for comparison to the 2007 surveys and possible future use of the survey data.

Since the initial bed elevation survey in 1959, the sinuosity of the Arroyo De La Laguna study reach has increased over time due to migration of large meander bends. Consequently the channel length of the study reach has increased over time and the lengths of the three surveys did not match up. The change in thalweg location over time also contributes to differences in survey lengths, but is likely minor compared with increased channel sinuosity. To match up the channel lengths and estimate incision and aggradation depths over time, the 1959 survey was adjusted to match the 1971 survey lengths, and the 1971 survey lengths were adjusted to match the 2007 survey. The 1959 survey length was also adjusted to match the 2007 survey length so that all three surveys could be <u>compared visually</u>. This was accomplished by first dividing the Arroyo De La Laguna reach into three sections with match points: (1) the confluence of Alameda Creek and Arroyo De La Laguna upstream to Paloma Bridge, (2) Paloma Bridge upstream to the downstream railroad bridge (the Western Pacific railroad bridge is immediately downstream of the Southern Pacific railroad bridge)[2], and (3) the downstream railroad bridge upstream to the Verona Bridge (USGS gage location). Within each of these three sections, the length of earlier surveys were reduced or increased proportionally along the surveyed section to match the later surveyed channel length. For example, the 1959 surveyed section from the downstream railroad

[2] The downstream Western Pacific railroad bridge and immediately upstream Southern Pacific railroad bridges are now owned by Union Pacific.

bridge upstream to the Verona Bridge was 2621 meters long compared to 2709 meters in 2007 (88 meters difference), therefore each of the individual 1959 survey shot lengths within that section were increased by ~3.3 percent (88/2621*100). Average and maximum changes in subreach lengths between time periods were 11 and 23 percent, respectively. Again, the stretching of surveys to match was done only for visual comparisons, where as actual survey distances were used in volume calculations (see below).

Ultimately sediment supplied from bed incision or stored from aggradation (bed and bar storage) was estimated for three time periods in Arroyo De La Laguna: (1) from 1901 (presumed start of incision) to 1958, where the bed incision depth was estimated as the difference in elevation from the inferred 1901 bed elevation (1959 top of bank elevation minus an estimate of the historic 1901 bankfull depth) to the 1959 bed elevation; (2) from 1959 to 1971 using differences in the two bed elevation surveys; and (3) from 1972 to 2007 using differences in bed elevations from 1971 and 2007, where the distribution of the incised or aggraded mass over the two budget time periods (1972 - 1993, 1994 - 2006) was prorated using peak flow history at Verona gage on Arroyo De La Laguna (Figure 17). For example, the proportion of incision mass attributed to the 1972 - 1993 period was calculated as the sum of the annual peak flows from 1972 to 1993 divided by the sum of annual peak flows from 1972 to 2006. The rate of sediment stored or eroded from the channel bed for discreet sections of either aggradation or incision of the channel was quantified as follows: (change in bed elevation * length of incised or aggraded section * width of section [from field surveys] * sediment bulk density) / number of years between surveys. Note that actual survey distances were used in the mass calculations, specifically, for the period from 1901 to 1958, the 1959 survey length was used; for the period from 1959 to 1971, the 1971 survey length was used; for the period from 1972 to 2007, the 2007 survey length was used.

We are not aware of laboratory measurements of sediment bulk density (bed, bank, or hillslope) for the study area or the watershed. Hence, we use a bulk density of 1.6 tonnes m^{-3} to convert sediment volume to mass. This bulk density conversion is similar to other Coast Range studies (Benda and Dunne 1987, Stillwater Sciences 2004, Pearce et al. 2005) and in the range of typical densities for soil, sand, and gravel (e.g. Simetrics 2007). Moreover, this bulk density appears representative of silt and sand that dominates sediment supply from the Arroyo De La Laguna study reach through bed incision and bank erosion into valley fill (see later).

Alameda Creek. Bed elevation surveys were conducted along the Alameda Creek study reach in 1959 (ACFCWCD 1966) and 1971 (FEMA 1975). Similar to the Arroyo De La Laguna bed elevation data, we used differences in bed elevation surveys and field measurements of bankfull widths to estimate the volumes from incision or aggradation during this period (1959 - 1971). Adjustments to the survey data were not necessary for comparisons because location points (Sunol Dam, Highway 680/Mission Road) matched closely. Because major incision along the Alameda Creek study reach was not observed during field surveys, a contemporary bed elevation survey was not necessary.

Bank Erosion and Landslides - Field Surveys

Field erosion surveys were conducted to quantify volumes and ages of eroded features from recent bank erosion and landslides for the most recent budget period (1994 - 2006). Typically, high order streams and rivers (Strahler 1957) in wide valley bottoms are considered transport and storage reaches in long term (century scale) equilibrium, where alluvial bank material eroded from one side of the channel is accreted downstream on the opposite side often as bars. For example, in meandering rivers of humid regions, maximum bank erosion occurs on the outside of bends while a similar volume from upstream deposits on point bars on the inside edge (e.g. Wolman and Leopold 1957). Consequently, bank erosion in such large alluvial rivers is not counted as sediment production (Reid and Dunne 1996). This is generally the case along the frequently split or braided channel of the Alameda Creek reach, however, the Arroyo De La Laguna reach is highly incised and bank erosion is not only cutting into more recent floodplain deposits, but often cutting into relic valley fills deposited over millennia, where we occasionally observed large pieces of old carbonized wood protruding from eroding banks of valley fill (Figure 19). Alluvial deposits (i.e. floodplain deposits and valley fills) along the narrow valley of Arroyo De La Laguna are mapped as historical (<150 years), latest Holocene Terrace deposits (<1,000 years), and older Holocene deposits (<11,800 years) (Witter et al. 2006). Although the Alameda Creek reach does not typically contain steep banks and associated bank failures, channel erosion surveys were still performed because the creek abuts the valley walls in some areas, including a Pleistocene/Pliocene era terrace prone to landslides and gullying in the lower subreach.

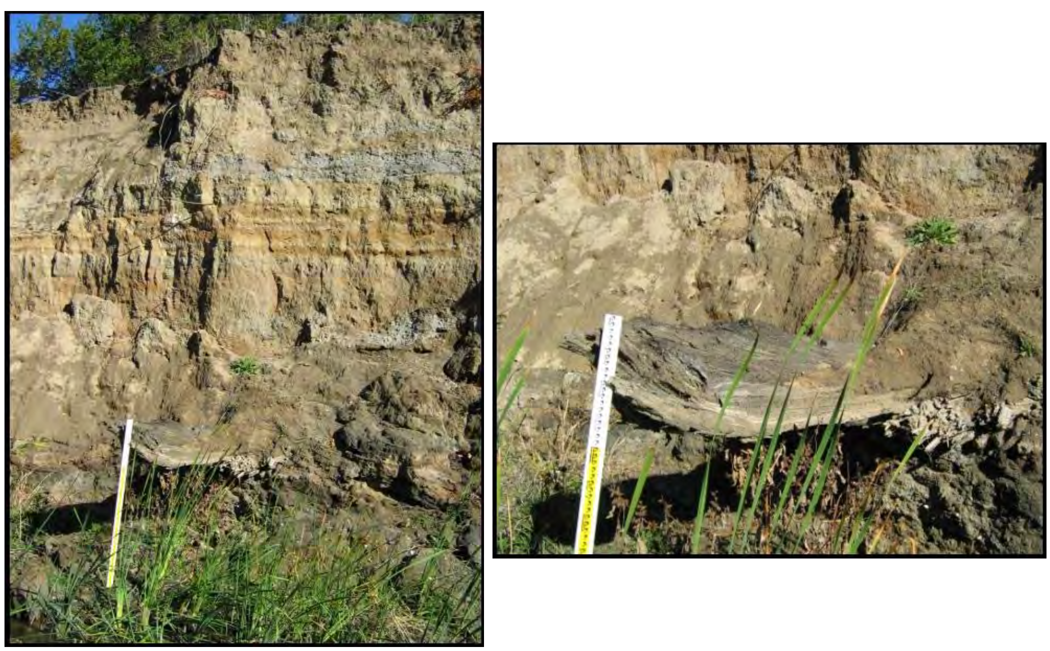


Figure 19. Old carbonized wood protruding from valley fill material exposed by bank erosion in the Arroyo De La Laguna study reach.

Field measurements consisted of estimating the volumes and ages of eroded features (bank erosion scarps, landslide scarps). Channel distances and dimensions of eroded areas (average length, width, height of eroded bank) were measured with a laser range finder (Impulse 200 model) with typical accuracy of 3 - 5 cm (Laser Technology 2008). For bank erosion patches or scarps, eroded areas were often bare, steep, and had exposed roots and had sloughed soil at the base of the bank. Where roots were exposed by erosion, they were used to help estimate the width of bank erosion (lateral recession) at a particular eroded patch (e.g. Lehre 1982, Collins 1998, Stetson Engineers 2000, SFEI 2001, Natural Resource Conservation Service 2003, Stillwater Sciences 2004). In areas where bank erosion was extensive along the outside edge of large channel bends and exceeded the reliability of any field indicators such as exposed tree roots (e.g. grassy areas devoid of trees), estimates of bank retreat (erosion width) were not possible in the field and were estimated from air photos. For landslides, the estimated volume of sediment remaining on the hillslope was subtracted from the volume of the scarp to estimate the volume of sediment delivered to the channel. Where vegetation was growing within erosion scarps, the age of erosion features was estimated by coring trees using an increment bore or cutting vegetation with a hand saw and counting the annual growth rings. Where riparian trees were recruited to the channel by bank erosion (i.e. undercut by bank erosion and fell into the channel but still alive), vertical sprouts (i.e. saplings initiated after the tree fell) growing from such recruited trees were cut and the rings counted to estimate the age of recent bank erosion at such locations (e.g. Benda et al. 2002, Benda and Sias 2003). The dominant particle size of the source material at each landslide scarp or bank erosion patch (boulder, cobble, gravel, sand, silt) was visually estimated. The rate of sediment eroded from channel banks was quantified as follows: (total volume of eroded bank material * sediment bulk density) / maximum age of vegetation encountered in scarps, and sediment supply rate from landslides was calculated in a similar manner. These field-based estimates of bank erosion are used in the most recent period of the sediment budget from 1994 to 2006, based on the maximum age of vegetation in erosion scarps and generally provide a minimum estimate of the eroded volume.

Bank Erosion and Bar Storage - Air Photo Analysis

As described above, the bank erosion data was initially gathered from field surveys using visible indicators. However, it was not possible to estimate the width of bank erosion at four large meander bends in the Arroyo De La Laguna channel. Here the channel had experienced extensive erosion (e.g., in excess of 4 meters in width and 20 meters in length) rendering field estimates of the width of retreat impossible. Therefore, a series of historic aerial photographs were analyzed to quantify the bank erosion that had occurred to complement the field measures of erosion. Historic aerial photographs were gathered from the University of California Berkeley Earth Sciences Library[3] and were scanned at a high resolution for use in ArcGIS (Table 2). Although additional photographs from different years do exist, we chose a subset of years based on photograph scale and quality, photo periods that show channel changes, and photo periods that tie in well with other sources of data (bed elevation surveys) and watershed history used to establish the sediment budget time periods (see Figure 18). Each photograph set was georeferenced, and then important channel features were mapped, including the channel centerline and channel edge (bank), which was typically the edge of the valley terrace. Then the

[3] We also sought historical air photos from the Alameda County Resource Conservation District, but all of the photos of interest were missing from the files.

location of the channel edge was compared between successive photographs, defining an area of erosion that had occurred during that time period. In ArcGIS, a polygon was created representing this area, which was then combined with an average terrace height for that location (as measured in the field) to estimate the volume of bank erosion for the most recent time period; terrace heights for earlier periods were adjusted based on incision depths for the respective period. For these locations, erosion was only calculated using the aerial photograph method, and not using field surveys, so that erosion was not double-counted in these locations. These estimates should be considered minimums because where vegetation in some areas reduced our confidence in accurately locating the bank edge, we were conservative in the creation of the polygons.

Table 2. Aerial photographs used in the analysis of bank erosion areas along Arroyo De La Laguna.

Photograph year	**Scale**	**Source**	**Description**
1939	1:24000	US Agricultural Adjustment Administration	Black and white
1950	1:20000	US Production and Marketing Administration	Black and white
1966	1:20000	US Agricultural Stabilization & Conservation Service	Black and white
1993	1:24000	USGS DOQQ	Black and white
2005	1m pixel resolution	National Agriculture Imagery Program	Color

It was only possible to estimate the mass of small bank erosion patches not visible on air photos from field surveys for the most recent budget time period (1994 - 2006) due to the young age of vegetative indicators. To approximate the mass from smaller bank erosion patches not visible on air photos for earlier budget time periods, we used the ratio of mass from small patches (field based) to large patches (air photo based) from the most recent budget period (1994 - 2006).

To estimate rates of bar storage over time in Arroyo De La Laguna, we approximated the growth of large bars opposite of eroding bends by using the same areas of channel erosion estimated from air photos combined with bar heights measured during field surveys. We also used the ratio of bank erosion mass measured in the field (small patches) to the mass estimated from air photos (large patches) from the most recent budget period (1994-2006) to roughly approximate the mass of small bars not visible on air photos.

Channel Cross Section Change - Historical and Contemporary Surveys

As a potential additional approach to quantifying incision and bank erosion in the Arroyo De La Laguna reach over time, we re-surveyed several historic channel cross sections originally surveyed in 1971 (FEMA 1975). Older historic cross section data along the Arroyo De La Laguna study reach may exist, including at the historic and current USGS gages and the four bridges. We contacted Alameda County, USGS, and Union Pacific in an initial attempt to obtain any cross section data, but with the exception of USGS cross section data from 1991 - 1998 for the Verona gage, we were unsuccessful in gaining any information. In addition to quantifying change through time for a single location, cross sections are also useful for characterizing the hydraulic geometry of a channel, quantifying width to depth and entrenchment ratios, and understanding the spatial relationship of channel features such as bars and terraces. We surveyed selected channel cross sections for comparison to the historic cross sections to help potentially quantify changes in channel geometry over this time period (1971 - 2007).

Of the original 24 cross sections surveyed over the study reach in 1971, we reoccupied six. These six cross sections were selected to sample a range of reach types, particularly those with major incision based on the long profile. For example, there has been minor change in the long profile downstream of Paloma Bridge since 1959, so only a single cross section was surveyed in this lower subreach. Conversely, the upper subreach between the railroad bridges and Verona Bridge has experienced noticeable changes on the longitudinal profile, therefore more cross sections were located in this subreach.

The wide channel width, steep banks, and dense riparian vegetation along Arroyo De La Laguna provided many challenges during the cross section surveys. After an initial attempt, an auto level and measuring tape were deemed unfeasible for this survey due to limitations in visibility. Instead, the surveys were conducted using a standard metric stadia rod, a hand level, and a laser range finder. For each shot along the section, the elevation change was measured using the hand level and the stadia rod. Shots remained short (1 to 20 m in length) so that the error in each reading was +/- 1 cm. The distance for each shot was measured using the laser range finder, bouncing the beam off the stadia rod. The range finder has a typical horizontal distance accuracy of 3 - 5 cm (Laser Technology 2008). The most difficult challenge was locating the historic cross sections. These sections were not monumented, nor was there a map or description of their location. The only information that existed was the distance along the longitudinal profile, in feet upstream from the confluence with Alameda Creek. This made reoccupation difficult because the location of the confluence has likely been dynamic through time, and the length of Arroyo De La Laguna has increased as the meander bends have evolved through time. To overcome these location challenges, we used the channel centerline from the 1966 aerial photographs to approximate the location of the 1971 longitudinal profile survey. We measured distances along this centerline, and plotted the expected location of each of the historic cross sections. While in the field, we used the expected location of the section (plotted both on 1966 and 2005 photographs) and the cross section topography itself to help identify its potential location. Ultimately, our decision on where to place our survey was based upon best professional judgment and matching the landscape forms we observed in the field to those shown in the cross section as accurately as possible.

Each end of our cross section was described in field notes, located on an aerial photograph, and was monumented using a 60 cm length of rebar that was painted orange and pounded into the ground. The rebar was typically placed along a fence line, at a fence post, or other location where the chances of disturbance were minimized. Due to the thick riparian vegetation, weak satellite reception precluded georeferencing of the rebar with a standard handheld GPS and time efficiency precluded the use of a more sophisticated GPS unit. Field flagging was placed intermittently along the section to help maintain a straight line perpendicular to the channel.

The field data was checked for accuracy, entered into spreadsheets, and plotted along with the historic cross section. In general, the alignment of the historic and resurveyed cross sections was difficult, although some sections included the railroad grade and rails which allowed for greater confidence in topographic alignment. However other sections did not have any stable anthropogenic features, so alignment was based upon the elevation of a relatively stable feature, such as the valley terrace.

Floodplain Storage

Floodplain storage in Arroyo De La Laguna was evaluated by estimating the depth, area, and age of accreted floodplain sediment. Note that this floodplain surface contains flood tolerant riparian vegetation including cottonwoods and willows not found on the valley floor, as well as evidence of floodplain accretion (sand deposits) in wet years (see Figure 11B). Floodplain sediment depth was measured at unique locations in the field where bank erosion exposed buried riparian trees. The floodplain area was estimated by (1) identifying the width of the floodplain on 24 cross sections surveyed in 1971 (FEMA 1975) and six cross sections resurveyed in 2007, and (2) estimating the floodplain length over the reach based on the presence of floodplains at cross sections. The age of the floodplain surface was estimated by coring the largest floodplain trees (primarily cottonwoods) spread out over the length of the reach using an increment bore. The cores were mounted on wood boards, sanded, and the annual tree rings were counted. Several years were added on to the tree ages for the unaccounted height below the accreted floodplain sediment. The rate of floodplain storage (accretion) was estimated as follows: (floodplain length * width * depth * sediment bulk density)/ maximum age of floodplain trees. The distribution of the floodplain storage mass over the different sediment budget time periods was prorated using peak flow history at Niles gage, as the ADLL gage was not operating from 1931 - 1969 (Figure 17). This approach appears reasonable based on observations that floodplains along North Coast rivers are primarily constructed by overbank deposits during low frequency high magnitude discharges (Nolan et al. 1987). Unfortunately there is little published research on San Francisco Bay Area streams and floodplain processes at this time. Some floodplain storage on the valley floor was likely occurring during the earliest budget period (1901 - 1958) when the channel was initially incising and still could access the valley floor. With no apparent field based method for estimating floodplain storage during the earliest budget period (1901 - 1958), we use the average of the three later periods (1959 - 2007) of floodplain storage as a proxy.

Relative Sediment Supply – Comparison of Sediment Yields within the Watershed

The supply of sediment from the study reaches was coarsely evaluated relative to the upper watershed and downstream to Niles gage using available USGS gage data and other sources. Gage data was used from Alameda Creek near Niles (downstream most station), Arroyo De La Laguna at Verona (upstream station), and Alameda Creek below Welch Creek (upstream station) (Figure 3). Suspended sediment data collected at the Alameda Creek near Niles gage (USGS station 11179000) is the most extensive of any Bay Area watershed, spanning 25 water years in total[5]. Data were available for water years from 1957 - 1973 and 2000 - 2006. Available bed load sediment data was more limited and available for water years 2000 - 2003 and for 2005 - 2006 (just five years). Suspended sediment and bed load data from the upstream gages at Arroyo De La Laguna near Pleasanton (USGS station 11177000) only <1 km from the current USGS gage at Verona (station 11176900), and Alameda Creek below Welch Creek near Sunol (station 11173575) are limited to recent water years (2000 - 2003)[4]. For the purposes of this analysis we assume the two gages on Arroyo De La Laguna were equivalent in terms of discharge and sediment characteristics (reasonable since there are no tributaries in between). A series of rating curves were developed for Alameda Creek near Niles (Figure 20a), Arroyo De La Laguna at Verona (Figure 20b), and Alameda Creek below Welch Creek near Sunol (Figure 20c) based on annual peak flow and annual total suspended sediment discharge data. Similarly, bed load rating curves were also developed for the three locations (Figure 21). These were used to estimate sediment loads during years when USGS water discharge data were available but when USGS sediment observations were not made. The recent period of the sediment budget (1994 - 2006) was the focus. Individual water year estimates for 1994 - 2006 developed using these rating curves were averaged to generate an estimate of long-term average total (suspended and bed load) sediment yield. In the case of Alameda Creek below Welch Creek, peak discharge prior to water year 2000 was estimated by taking into account reservoir operations – in particular a diversion dam and tunnel that diverts flows from Alameda Creek into Calaveras Reservoir. Prior to 2002, the diversion dam and tunnel were generally operated in the rainy season and captured flows up to approximately 18.4 m^3/s (650 ft^3/s) (the capacity of the tunnel); flows exceeding the tunnel capacity would then pass over the diversion dam (CCSF 2007). This flow on Alameda Creek below Welch Creek near Sunol was estimated prior to 2000 by subtracting 18.4 m^3/s from the observations of peak discharge on Alameda Creek above the Calaveras diversion dam (USGS station 11172945). The resulting discharge was then scaled up to account for discharge from the ungaged area between the two gages using a rating curve for the period of concurrent data (2000 - 2007) between Alameda Creek below Welch Creek near Sunol and Alameda Creek above diversion dam near Sunol. Note that since 2002, diversion dam operations were limited due to the reduced capacity of Calaveras Reservoir for seismic issues (CCSF 2007), further confounding our calculation of flows, but at this time we cannot make any better estimates.

While there is limited flow and suspended sediment data for gage stations at the top of our study reaches, there is no flow or suspended sediment data for any tributaries that enter the study reaches (e.g. Vallecitos and Sinbad Creeks) and Niles Canyon (e.g. Stoneybrook Creek) (Figure 3). To make an overall comparison of the sediment budget for the recent period (1994 - 2006) required estimates of sediment yield for these ungaged tributaries in the study area (116 km^2). An overall comparison of the sediment budget for earlier periods is not reasonable due to the limited suspended sediment data for the upstream gages at Verona and Welch Creek (2000 - 2003), no flow data for the Welch Creek gage prior to 2000 (although it was estimated back to 1994, see paragraph above) and no suspended sediment data prior to construction of the Alameda Creek diversion dam in 1930 and Calaveras Reservoir in 1925.

---

[4] At the time of this analysis, data were not yet published for water year 2007 and water year 2008 data collection is still ongoing.

We extrapolated sediment yield rates for the ungaged tributaries (average drainage area 3.5 km^2, range 0.1 - 18 km^2) using three approaches, including: 1) using individual basin sizes of the ungaged tributaries and the sediment yield rate derived from the regression relationship between basin size and average annual suspended sediment load for San Francisco Bay Area tributaries (PWA 2005), 2) using individual basin sizes of the ungaged tributaries and the sediment yield rate derived from suspended sediment and bedload rating curves and mean daily flows between 1994 and 1996 for Cull Creek gage, a 15 km^2 basin in the East Bay hills (~12 km north of the ungaged tributaries area) with 24 years of suspended sediment data, and 3) using sedimentation rates for San Antonio reservoir (Collins 2005). Each of the approaches has many different merits and drawbacks. For example, the regional relationship provides a large sample but includes data from varying and limited time frames, varying terrain and geology, the Cull Creek rate provides an estimate for the same time period of our budget period (1994 - 2006) but represents only one basin size (15 km^2), and the reservoir sedimentation rate represents similar terrain and geology but for a larger basin size (99 km^2) over a different time period from 1965 - 2004.

In addition to a lack of data for the ungaged tributaries, there is little information on sediment sources within the Niles Canyon reach. Consequently comparisons of sediment yield from the study reaches relative to the rest of the watershed should be considered very coarse due to the severe but not uncommon limitations of the data available.

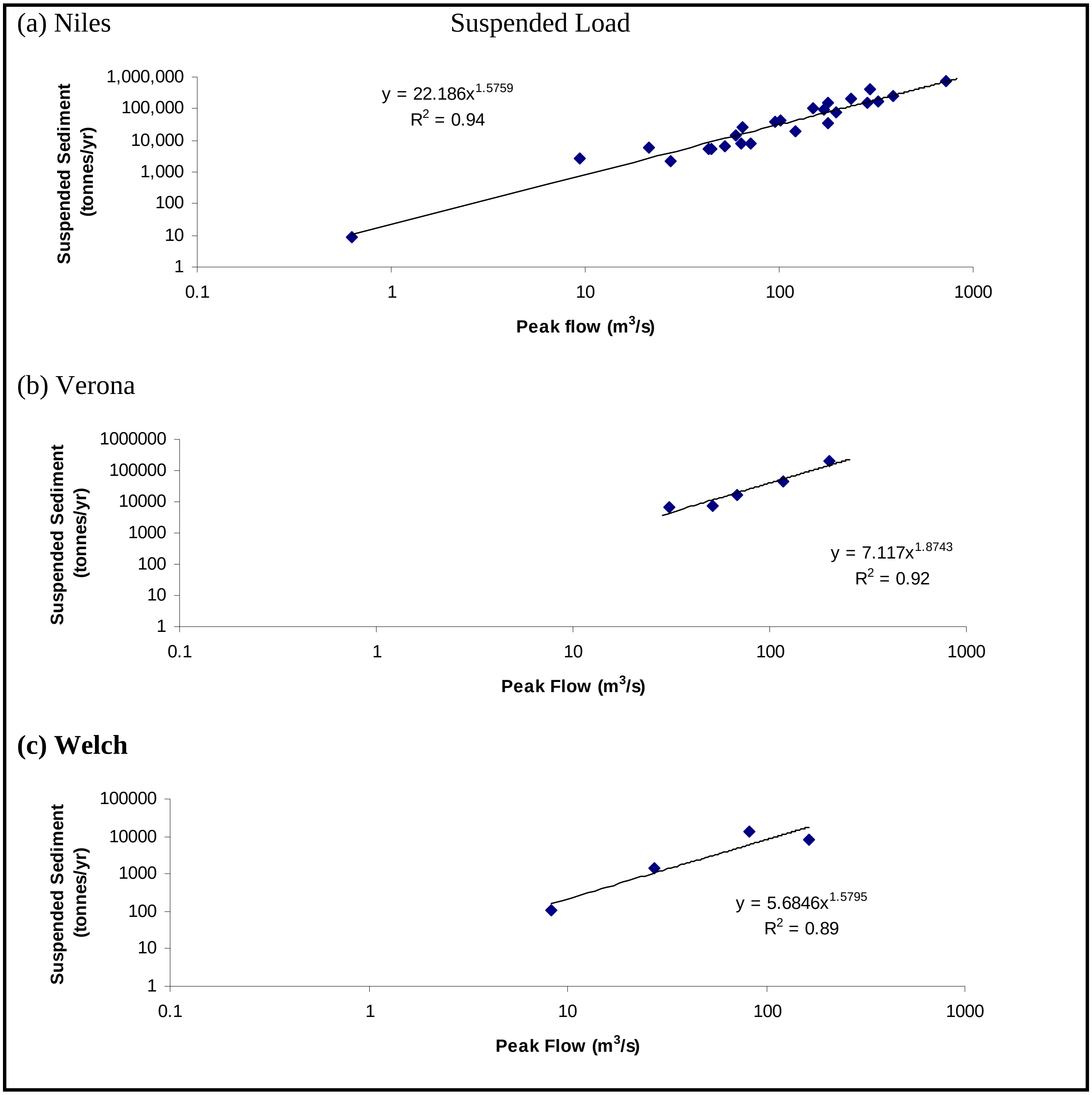


Figure 20. Relation between peak flow and annual suspended sediment loads at USGS gages at (a) Alameda Creek near Niles (station 11179000), (b) Arroyo De La Laguna at Verona (station 11176900), and (c) Alameda Creek below Welch Creek (station 11176900).

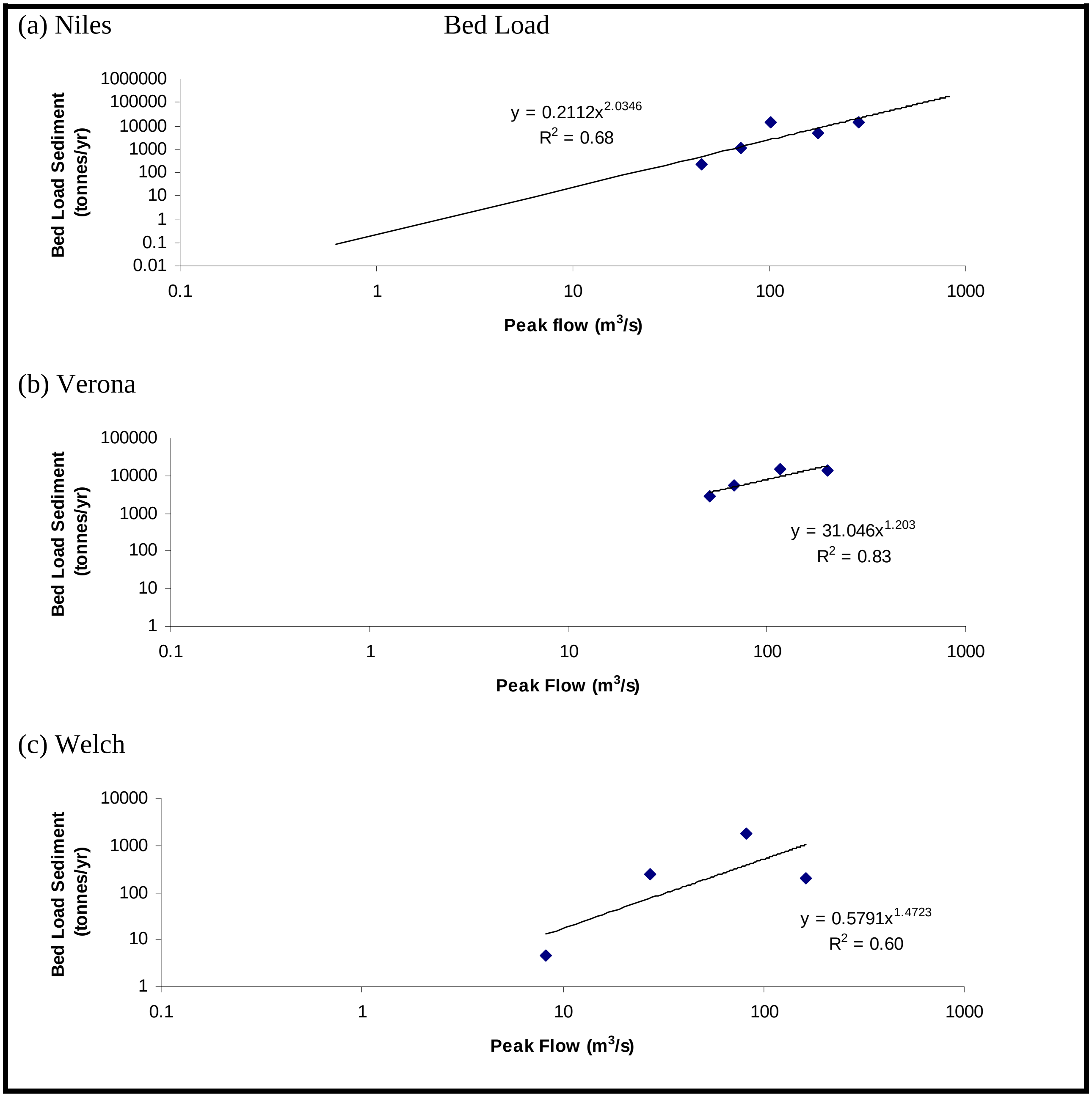


Figure 21. Relation between peak flow and annual bed load at USGS gages at (a) Alameda Creek near Niles (station 11179000), (b) Arroyo De La Laguna at Verona (station 11176900), and (c) Alameda Creek below Welch Creek (station 11176900).

RESULTS

Bed Incision and Aggradation

Arroyo De La Laguna. Here we report the results for each component of the sediment budget, starting with bed incision and aggradation. Interpretation and implications of the results are provided in the Discussion section later. Estimated depths of incision were roughly 4.6, 3.8, and 5.9 m for the lower, middle, and upper subreaches respectively (Figure 22), resulting in average incision rates from 6 to 10 cm/year over the period from 1901 - 1958. Combining the incision depths with the 1959 survey channel lengths, channel widths measured in the field, and a bulk density conversion factor (1.6 tonnes m^{-3}), gives an estimated sediment production rate of 14,800 tonnes/yr from channel incision for this period.

Comparing bed elevation surveys between 1959 and 1971 (Figure 23) shows estimated depths of incision of 1 - 1.5, 1.5 - 2, and 0.9 - 1.5 m for the lower, middle, and upper subreaches, respectively, resulting in average incision rates from 7 to 15 cm/year over this time frame (1959 - 1971). Combining the incision depths with the 1971 survey channel lengths, field measured bank widths, and bulk density, gives and estimated sediment production rate of 13,500 tonnes/yr for this period.

Comparing bed elevation surveys between 1971 and 2007 shows aggradation depths of 1.5 m near the confluence and depths of incision ranging from 0.5 to 0.8 m throughout most of the remainder of the reach (Figure 24). These discreet sections of aggradation and incision depths were combined with bankfull widths measured in the field to estimate the mass of sediment stored in or eroded from the channel bed. We prorated the incised and aggraded mass derived from differences in 1971 and 2007 bed surveys between the two budget periods (1972 - 1993 and 1994 - 2006) based on the Verona gage peak flow record (Figure 17) during this time frame (1972 - 2007). Estimates of bed incision for the 1972 - 1993 period derived from differences in bed elevation surveys and prorating described above were 1 - 3.5 cm/year, resulting in sediment production rates of 820 tonnes/yr. Estimates of bed incision for the 1994 - 2006 period were 2 - 6 cm/year, resulting in sediment production rates of 850 tonnes/yr (Table 3). Reduced rates of incision after 1971 reflect that headward migrating incision was near the top of the study reach (Verona) in 1971 and well upstream of Verona in 1998 (Figure 25). Based on the various bed elevation profiles, the knickpoint migrated headward at an average rate of roughly 190 m/yr between 1959 and 1998 (Figure 25).

The aggradation occurring near the bottom of the reach consists of a massive bar and a wedge of sediment accumulating behind the bar (upstream), visible as a long flat gradient on the 2007 bed elevation survey (Figure 24). Similar confluence effects are well documented at the junction of large alluvial tributaries in many watersheds (Benda et al. 2004). Estimated aggradation rates (bed storage) for the two periods are 625 tonnes/yr (1972 - 1993) and 1,100 tonnes/yr (1994 - 2006) (Table 3).

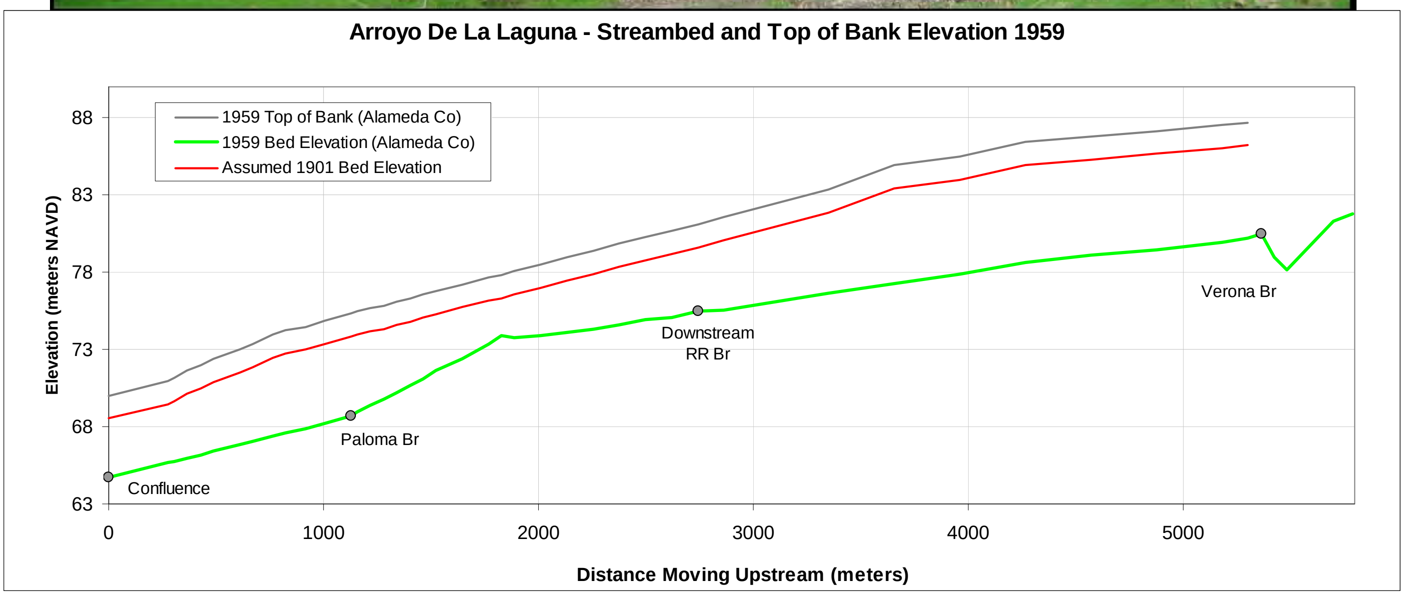


Figure 22. (upper) Photo showing historic (abandoned) Arroyo De La Laguna channel on the valley terrace used to estimate historic bankfull depth of ~1901 channel (~1.5 meters). (lower) Longitudinal profile showing 1959 top of bank (lowest valley floor elevation) and bed elevation surveys with inferred historic ~1901 channel bed elevation.

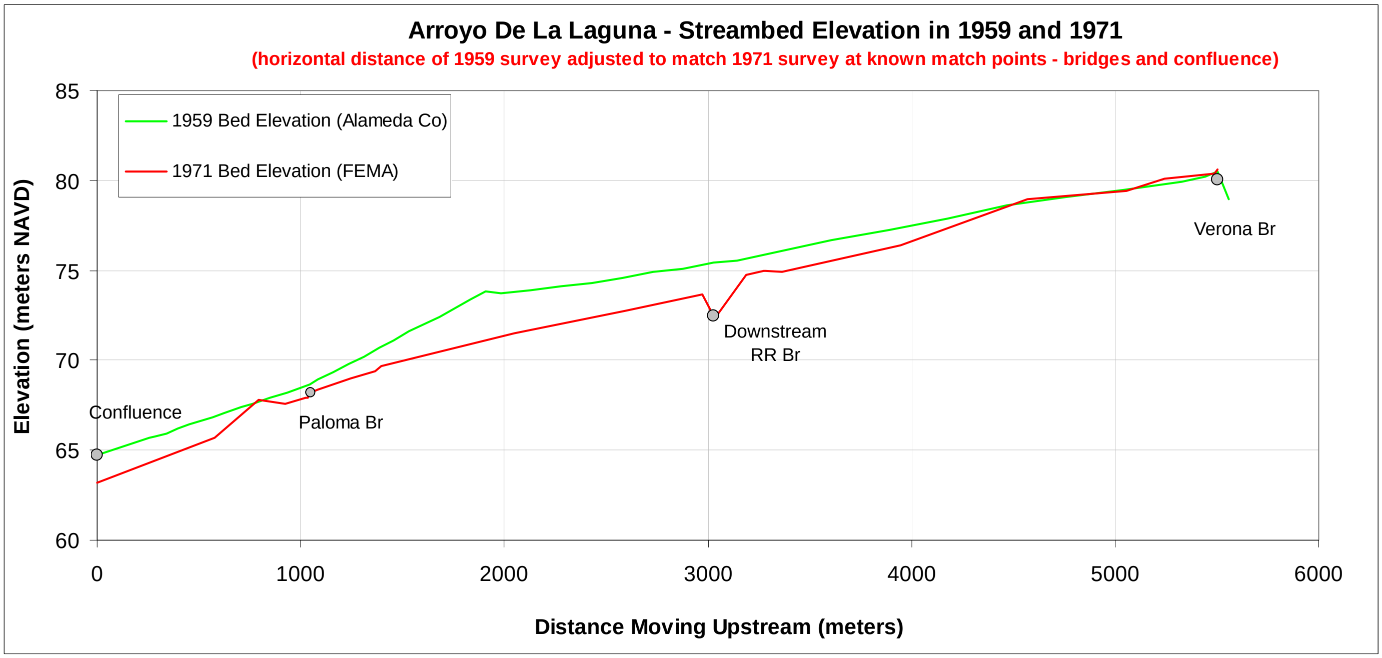


Figure 23. Bed elevation surveys for 1959 and 1971 showing incision throughout the lower and middle subreaches and into the upper subreach. The 1959 survey shown here has been stretched to match the 1971 survey length and match locations at the three bridges (see methods section).

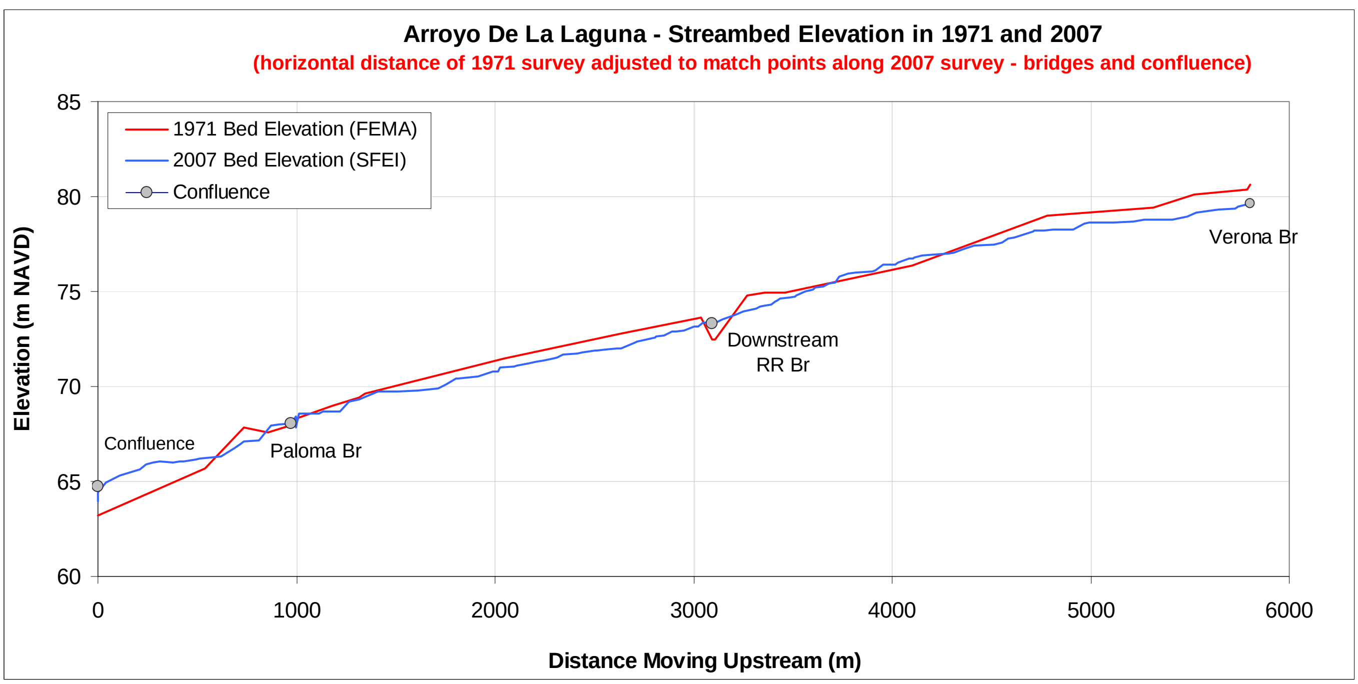
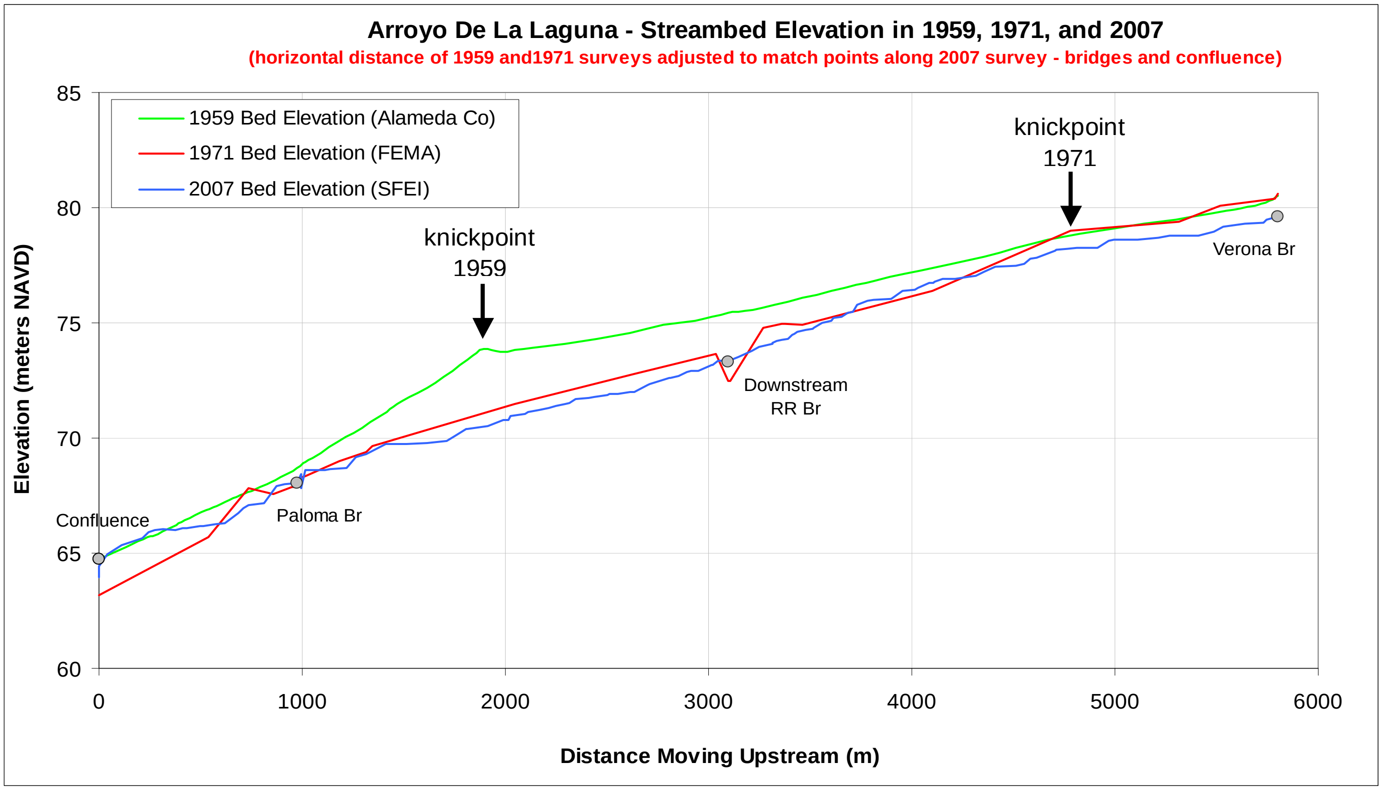


Figure 24. Bed elevation surveys for 1971 and 2007 showing some incision in the middle and upper subreaches and aggradation in the lower subreach. The 1971 survey shown here has been stretched to match the 2007 survey length and match locations at the three bridges (see methods section).



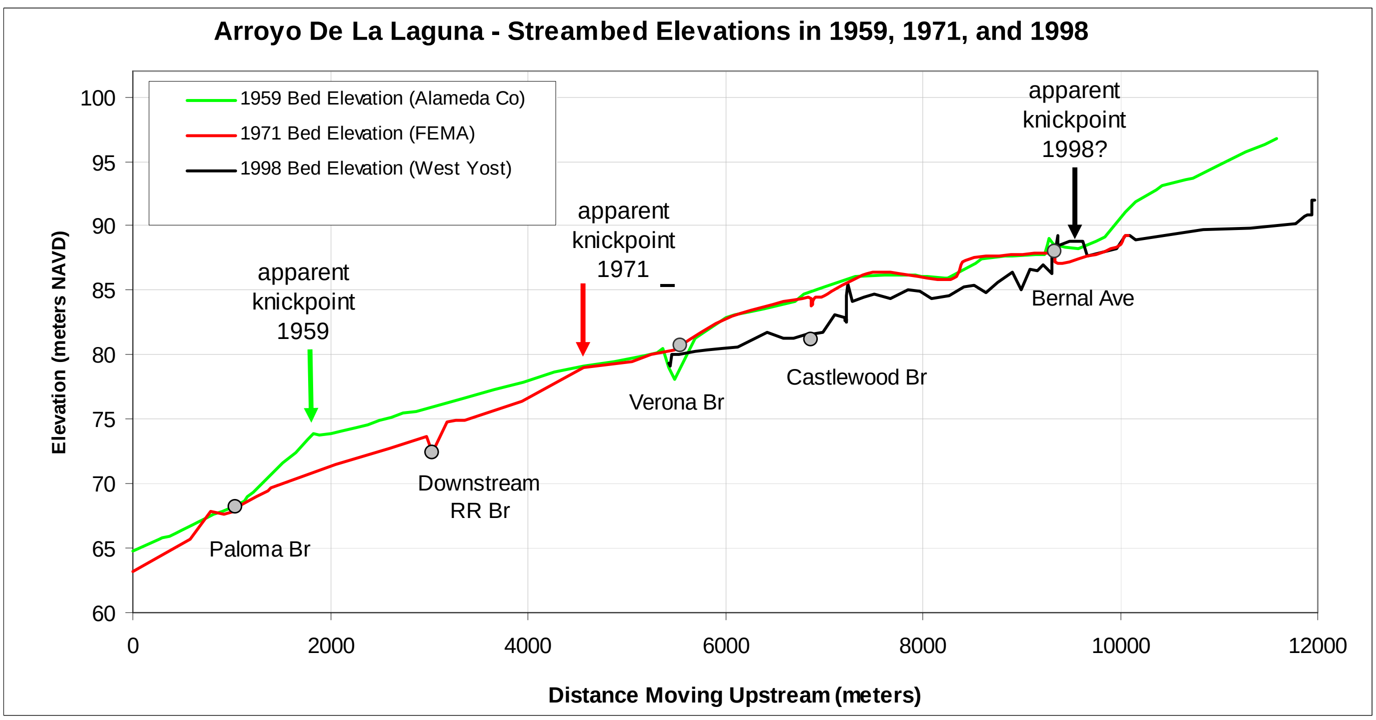


Figure 25. (upper) Bed elevation surveys for 1959, 1971, and 2007 within the study reach showing an apparent knickpoint migrating headward (upstream) over time. (lower) Bed elevation surveys for 1959, 1971, and 1998 for the study reach and upstream showing *apparent* knickpoints over time.

Table 3. Detailed sediment budget rates by process for Arroyo De La Laguna study reach in tonnes/yr. All rates are in tonnes/yr except last column in percentage, all values are rounded for uncertainty.

Arroyo De La Laguna Reach																	
Time Period	Small Bank Erosion[a]	range[b]	Large Bank Erosion	range[c]	Small Bar Storage[d]	range[e]	Large Bar Storage	range[f]	Incision	range[g]	Aggradation	range	Floodplain Storage	range	Net Budget	Net range	% range
1901 - 1958	30	(± 30)	120	(± 140)	-3	(± 3)	-10	(± 15)	14,800	(± 5,900)	0	(± 8,000)[h]	-1,400	(± 1,100)[h]	**13,500**	(± 15,000)	**(± 110%)**
1959 - 1971	500	(± 500)	1,770	(± 520)	-50	(± 50)	-180	(± 100)	13,500	(± 5,400)	0	0	-1,800	(± 1,400)[i]	**13,700**	(± 8,000)	**(± 60%)**
1972 -1993	400	(± 290)	1,400	(± 850)	-110	(± 110)	-390	(± 120)	820	(± 330)	-630	(± 250)[g]	-1,300	(± 1,000)[i]	**250**	(± 3,000)	**(± 1,200%)**
1994 - 2006	2,900	(± 1,450)	10,500	(± 980)	-730	(± 730)	-2,600	(± 170)	850	(± 260)	-1,100	(± 440)[g]	-1,100	(± 800)[i]	**9,000**	(± 5,000)	**(± 60%)**

notes:

a small bank erosion patches estimated in the field for the 1993 - 2006, and extrapolated for earlier periods based on a ratio (0.28) of small patches to large patches (from air photos).

b estimate within 50% based on uncertainty in field bank erosion width for 1993 - 2006, and within 100% based on uncertainty in extrapolation for earlier periods.

c estimate is variable (within 10 - 100%) based on uncertainty in the area of large bank erosion from air photo resolution and within 30% based on uncertainty in bank height.

d small bar storage extrapolated based on ratio of small bank erosion patches to large bank erosion patches (0.28).

e estimate within 100% based on uncertainty on extrapolation of small bar storage.

f estimate is variable (within 10 - 100%) based on uncertainty in area of large bar storage from air photo resolution and estimate within 50% based on uncertainty in bar height.

g estimate within 40% based on uncertainty in changing channel length and width over time and uncertainty in estimating bed elevation differences.

h unknown potential range due to lack of survey data before 1959, possible aggradation from channel recovery prior to 1950s, and unknown aggradation during 1950s floods; here we make approximate estimates of combined range of aggradation and floodplain storage on the order of 75% of the incision rates.

i estimate within 75% based on uncertainty in floodplain storage primarily from extrapolation of floodplain area between cross sections.

Alameda Creek. Comparing bed elevation surveys between 1959 and 1971 for the Alameda Creek study reach shows estimated depths of incision of 0.5 - 1.5 m around the confluence in the lower subreach, and similar aggradation of 0.5 - 1 m around the farm bridge in the middle and upper subreaches (Figure 26), resulting in average incision rates from 4 - 11 cm/year and aggradation rates of 4 - 8 cm over this time frame (1959 - 1971). Combining the incision and aggradation depths with the 1971 survey channel lengths, field measured bank widths, and bulk density, gives and estimated bed erosion rate of 3,900 tonnes/yr, bed storage rate of 3,000 tonnes/yr, and a net sediment production of 900 tonnes/yr for this period (Table 4).

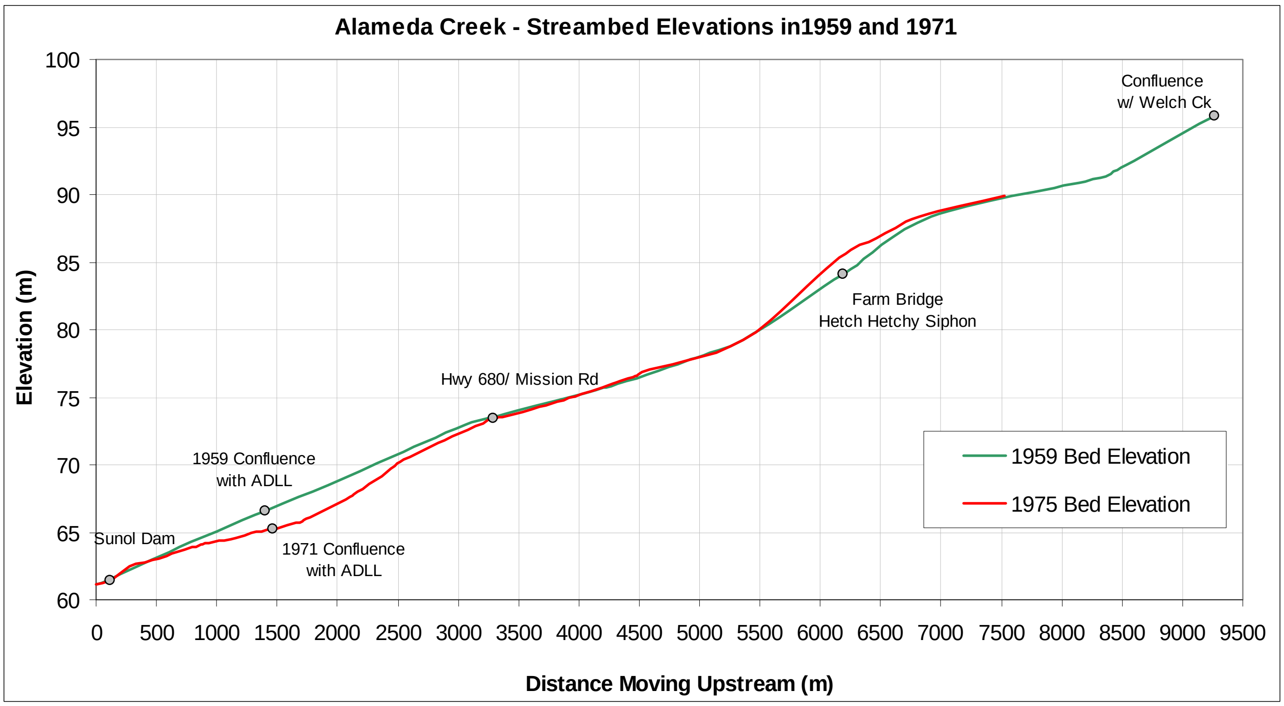


Figure 26. Bed elevation surveys for 1959 and 1971 along the Alameda Creek study reach showing some degradation around the confluence with Arroyo De La Laguna and aggradation upstream around the Farm Bridge. Note that the middle subreach between Highway 680 and the Farmbridge contains setback levees.

Table 4. Partial sediment budget rates by process for Alameda Creek study reach in tonnes/yr. Because the Alameda Creek reach appears to be primarily a transport and storage reach, only a subset of the budget components were evaluated. In addition, San Antonio and Calaveras reservoirs impound 70% of the watershed draining to the reach, limiting both sediment supply and flow to the reach. All values in tonnes/yr except last column in percentage, all values are rounded for uncertainty.

Alameda Creek Reach

Time Period	Bank Erosion	Bed Incision	Bar Storage Aggradation	Landslide[b]	Net Budget[c]	Net Range[d]	% Range
1901 - 1958	--[a]	--	--	4400	**4400**	(± 4400)	**(± 100%)**
1959 - 1971	--	3900	-3000	0	**900**	(± 900)	**(± 100%)**
1972 -1993	--	--	--	0	**610**	(± 900)	**(± 150%)**
1994 - 2006	140	--	-140	320	**320**	(± 900)	**(± 280%)**

Notes:

a because the Alameda Creek reach appears to be primarily a transport and storage reach, this component of the budget was not evaluated.

b only poor quality low resolution historical air photos (prior to 1993) were available to determine initial triggering of landslides in the lower subreach, should higher quality photos become available, this component should be re evaluated.

c no data was available for the 1972 - 1993 budget period, as a surrogate we use an average of the other three budget time periods as the net budget rate for 1972 - 1993.

d net range from uncertainty estimated as the maximum net budget for any of the four budget periods; this estimate should be conservative (i.e. high) because the reach appears to be primarily a transport and storage reach (i.e., no net supply from the reach, with the exception of landslides in the lower subreach).

Bank Erosion

Arroyo De La Laguna. Typically, bank erosion of alluvial sediment in large channels is not counted as sediment production unless the eroding deposits are relics of earlier conditions (Reid and Dunne 1996). We include bank erosion in the budget for Arroyo De La Laguna because the highly incised channel is eroding into historical valley fills that were deposited over millennia. Field measurements of bank erosion patches along Arroyo De La Laguna ranged in mass up to 1,750 tonnes and exhibited a somewhat cyclical pattern, where the magnitude of erosion increases at the outer edge of large bends, particularly in the upper reach (Figure 27). The magnitude of bank erosion decreases substantially in the lower subreach from the Paloma Bridge to the confluence (Figure 27), where the particle size of both the bed and banks increases (Figure 14) creating a higher resistance to bed and bank erosion. This increased caliber of sediment is most likely supplied from the Sinbad and Vallecitos tributaries at the top of the subreach (Figures 3, 12, and 27). Where spalls (blocks of material that break off in layers parallel to a surface, in this case, the vertical bank face) of recent bank erosion from valley fill material were observed, spall thickness (width) ranged from 0.5 to 1 m. Silts and sand were the dominant particle size observed in eroded banks during field surveys (Figure 28). The maximum age of vegetation growing within bank erosion scarps was 13 years, and thus the total mass of bank erosion estimated from field surveys was applied to the most recent budget period from 1994 - 2006.

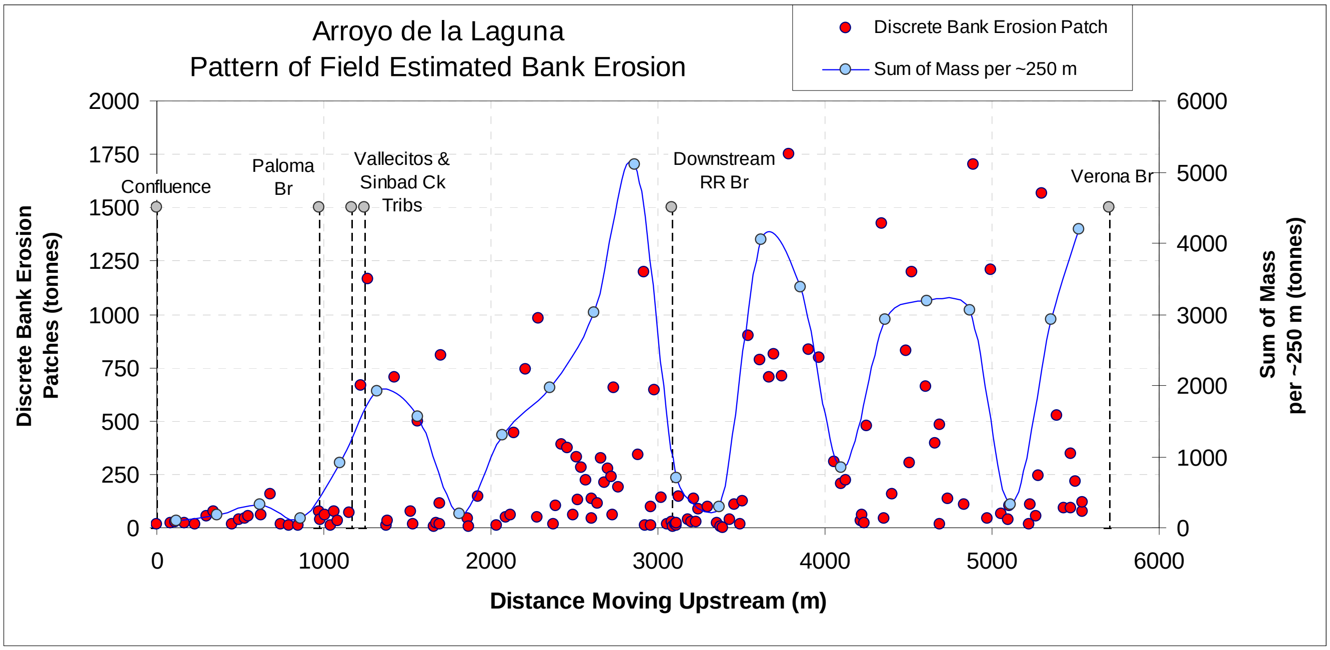


Figure 27. Long profile showing mass of discrete bank erosion patches along Arroyo De La Laguna measured during field surveys and the sum of the bank erosion volumes roughly every 250 meters (with sum plotted at the midpoint) to help show the cyclical pattern on erosion primarily reflective of erosion at large bends. This plot does not include the more substantial mass of bank erosion estimated from air photos.

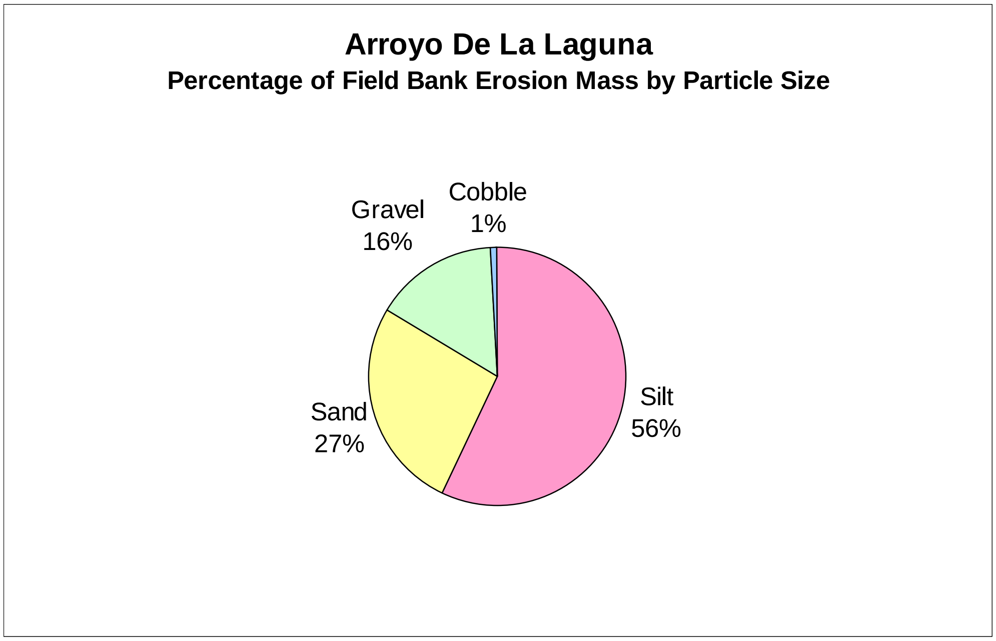


Figure 28. Rough percentage of bank erosion mass by particle size in Arroyo De La Laguna observed during field surveys, based on the sum of bank erosion mass measured in the field where the dominant particle size of bank material at each bank erosion patch/scarp was visually estimated.

It was not possible to estimate the width (lateral recession) of erosion at large bends, consequently air photos were used to estimate the area of bank erosion at these locations and combined with field measurements of bank height to estimate the volume eroded. Estimates of bank erosion are reported for each location and time period (Figure 29, Table 5). Maximum bank retreat rates estimated at the apex of large erosional bends between 1993 and 2005 (from air photos) ranged from 1.6 to 4.5 meters/year. Combining the field (2,900 tonnes/yr) and air photo (10,600) estimates of bank erosion provides an estimated rate of roughly 13,500 tonnes/yr for the most recent budget period (1994 - 2006), with the majority of bank erosion sediment supplied from the large eroding bends (Tables 3 and 5). For example, Figure 30 shows the series of aerial photographs for the meander bend at Location C, where significantly larger changes from bank erosion occur during the most recent time period between 1993 and 2005.

Bank erosion for earlier budget periods in Arroyo De La Laguna were similarly estimated and included an estimate of the small bank erosion patches not visible on air photos (see methods). Tables 3 and 5 summarize the estimated bank erosion rates for the four time periods, with the majority of bank erosion contributed during the most recent period (1994 - 2006). During this most recent period, each of the locations experienced two to four times the amount of erosion than in any other period. For example, Figure 31 shows the erosion polygons for Location A at Verona Bridge; note the significantly larger pink polygon (representing 1993 - 2005) compared to the previous time period polygons. In contrast, the period 1939 - 1950 shows little to no erosion, with only measurable erosion occurring in Location A, possibly due to effects from the Verona Bridge footers.

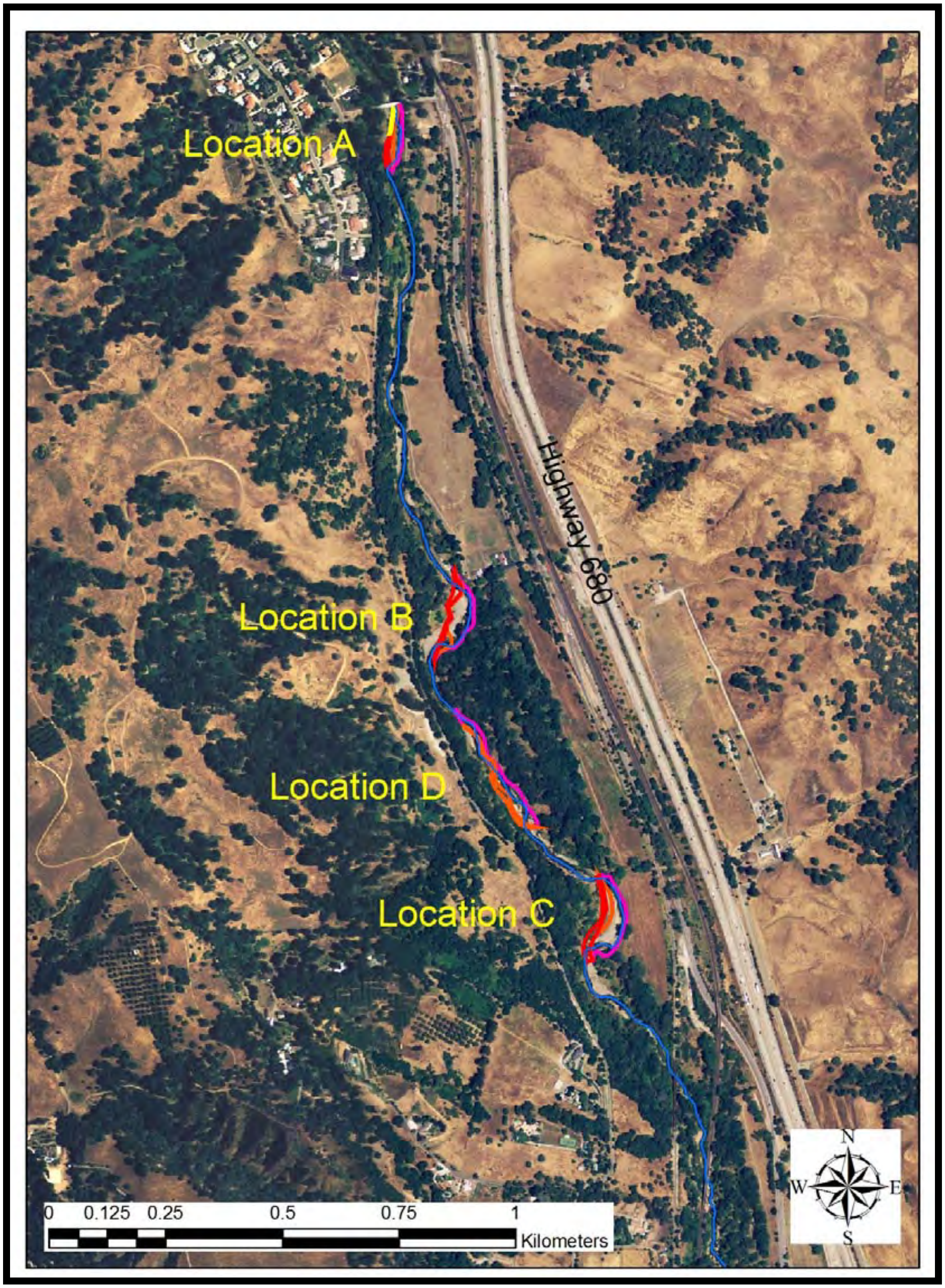


Figure 29. Locations of bank erosion in Arroyo De La Laguna as determined by interpretation of historical aerial photographs. The photograph extends from the railroad bridges (lower right center) to Verona Bridge (upper left center). Yellow polygons represent the time period 1939-1950, red polygons represent 1950-1966, orange polygons represent 1966-1993, and pink polygons represent 1993-2005.

Table 5. Bank erosion (tonnes) estimated from interpretation of historical aerial photographs at four large erosional bends or areas along the Arroyo De La Laguna study reach for each time period (See Figure 29 for locations).

Air Photo Time Period	Erosion Location A	B	C	D
1939-1950	1,300	0	0	0
1950-1966	5,100	9,900	13,300	0
1966-1993	11,200	8,000	10,700	7,800
1993-2005	22,600	38,200	44,800	21,000
Total:	40,300	56,200	68,800	28,800

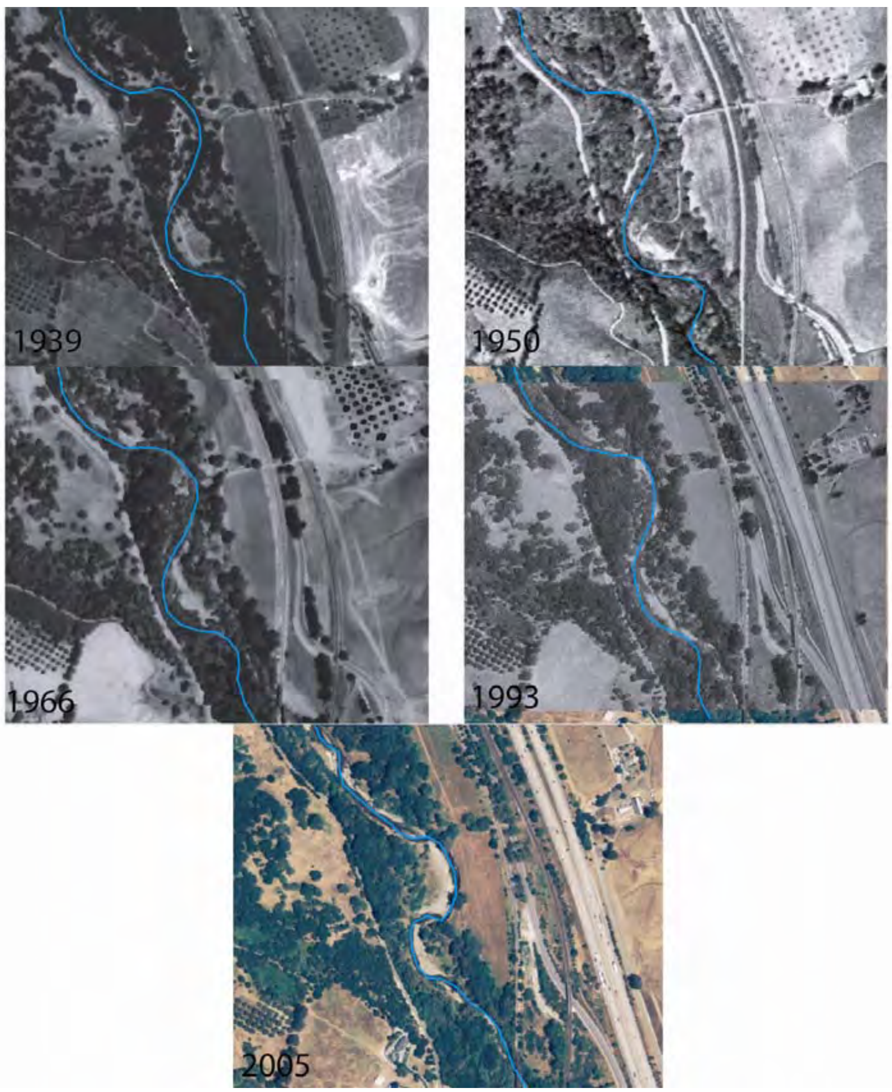


Figure 30. Series of aerial photographs (moving left to right, top to bottom: 1939, 1950, 1966, 1993, and 2005) showing the meander bend at Location C through time. Note the significant channel migration, particularly in the 1993 - 2005 time period.

Figure 31. Erosion polygons at Location A. Polygon colors represent time periods: yellow 1939 - 1950, red 1950 - 1966, orange 1966 - 1993, and pink 1993 - 2005. Channel flows from top to bottom.

Alameda Creek. In contrast to Arroyo De La Laguna, the Alameda Creek study reach is generally well connected to the historical valley floor floodplain with small amounts of bank erosion and little incision. In the middle subreach, the floodplain is constrained by setback levees. While the massive valley fill of the Sunol Valley indicates this reach was historically net aggrading, the Calaveras and San Antonio reservoirs now block 70% of the drainage area to the reach, limiting both sediment supply and flow, and substantially reducing channel dynamics under the current flow regime. In addition, the Alameda Creek diversion dam has diverted flow and associated suspended sediment to Calaveras reservoir. The Alameda Creek study reach is often split or braided, indicative of a channel with more bed load than it can effectively transport. Only small patches of bank erosion were observed along the study reach and the maximum age of vegetation within eroding scarps was 11 years, yielding a sediment production rate of 140 tonnes/yr from bank erosion for the most recent budget time period (1994 - 2006), a relatively minor amount of erosion compared to Arroyo De La Laguna (13,400 tonnes/yr for the same period). These field observations suggest that the Alameda Creek study reach is ***primarily*** a sediment transfer reach (see Schumm 1977) rather than a source. Because many braid bars and point bars were evident throughout the reach, we assume that this minor bank erosion volume is offset by bar storage in the sediment budget. While migration and formation of new braids of Alameda Creek is apparent on historical air photos, estimates of bank erosion for these earlier periods from air photos were not possible because the channel does not appear incised and net bank erosion is not apparent. Should the flow regime to the reach be altered by changes in reservoir releases, increased bank erosion and channel incision are possible and should be considered in future analyses.

Bar Storage

Arroyo De La Laguna. Bar storage represents the temporary channel storage (ranging from weeks to decades) of sediment as alternate point bars, which were substantial in the upper subreach of Arroyo De La Laguna. Estimated bar storage and channel aggradation rates over the four time periods in Arroyo De La Laguna ranged from 13 tonnes/yr in 1901 - 1958, when the channel was primarily incising, to 4,400 tonnes/yr from 1994 - 2006, when the channel was adjusting primarily through bank erosion (Table 3). The tops of most vegetated bars consist of willows that date back to the 1998 El Niño event (Figure 17), indicating the last major bar reworking in the study reach. Note that aggradation for the massive bar at the confluence of Arroyo De La Laguna between 1971 and 2007 was estimated from the bed elevation surveys (Figure 24) and are included in these bar storage rates.

Arroyo De La Laguna Historic and Contemporary Channel Cross Sections

Historic surveyed cross sectional data is invaluable for quantifying channel evolution and sediment supplied from channel bed and banks at discrete locations. Unfortunately quality historic cross section data is rarely available, or is extremely limited in spatial coverage, often for bridges which tend to be located at or create more stable locations in the channel. Arroyo De La Laguna is no exception, with only one 1911 section, a number of 1971 sections, a series of 1991 - 1998 sections at the USGS gage station at Verona, and a number of 2007 Zone 7 Water Agency sections available for the study reach. Despite efforts, we were unsuccessful in obtaining as-built plans for the railroad bridges, Verona Bridge, or Paloma Bridge from Alameda County or Union Pacific.

A single cross section from 1911 (Williams 1912) shows the channel dimensions upstream of the Verona Bridge (upstream of the study area), approximately 1,350 m upstream of Castlewood Drive. Evidence of the channel dimensions that existed following the breaching of Tulare Lake are gathered from a valley cross section designed to show lithologic units through which wells were penetrating (Figure 32) (Williams 1912). Although the intent of this figure was not channel dimensions, we are able to see that the channel was approximately 13 feet (4.0 m) deep, and 150 feet (45.7 m) wide. From this valley profile, the channel dimensions were plotted, and compared to the nearest 1971 cross sections (Figure 33). Although our confidence in this data is decreased because the sections are not from the exact same location, it does illustrate the magnitude of incision that has occurred. Over the course of these 60 years, the channel incised approximately 5 - 6 m, at a rate of 8 - 10 cm/yr. This compares well with the rates of incision calculated from the bed elevation data where an average rate of incision of 6 - 10 cm/yr was calculated for the period 1901 to 1958.

Other historic cross section data available include the USGS gage station Arroyo De La Laguna near Pleasanton (station 11177000) from 1991 - 1998 (Figure 34). This period included multiple flood events (e.g. 1993, 1995, and 1998, see Figure 17), however, none of the survey data correspond to the exact date of peak discharge for the water year. Unfortunately, earlier cross section data for the gaging station was not available. Because this data was collected as a part of the discharge verification, the cross section only extends laterally for the portion of channel that contained water during the survey data collection. Although this limits the usefulness of the sections, we can observe fairly rapid changes in channel geometry, such as the approximately 2 ft (0.6 m) of incision that occurred between 1995 and 1997. Although this incision may be localized scour at bridge footers and rip rap, it does illustrate the ability of even moderate-sized floods to cause significant channel change.

The contemporary cross section data was collected during this study to potentially quantify changes in channel geometry that had occurred between 1971 and 2007 in the Arroyo De La Laguna reach, and to confirm channel incision observed on longitudinal profiles (bed elevation surveys). Our initial intent was to further quantify channel incision or bank erosion by directly comparing the historic 1971 and modern cross sections. However, given the difficulty in accurately locating and re-occupying the historic cross sections, it became apparent that direct comparison was not possible. Despite the many challenges encountered, the current channel cross section data allowed at least qualitative comparisons and some quantitative estimates of historic incision. Cross section locations are shown in Figure 35, while the modern (shown in blue) and historic (shown in red) cross section data for the six re-occupied locations are shown in Figures 36 through 41.

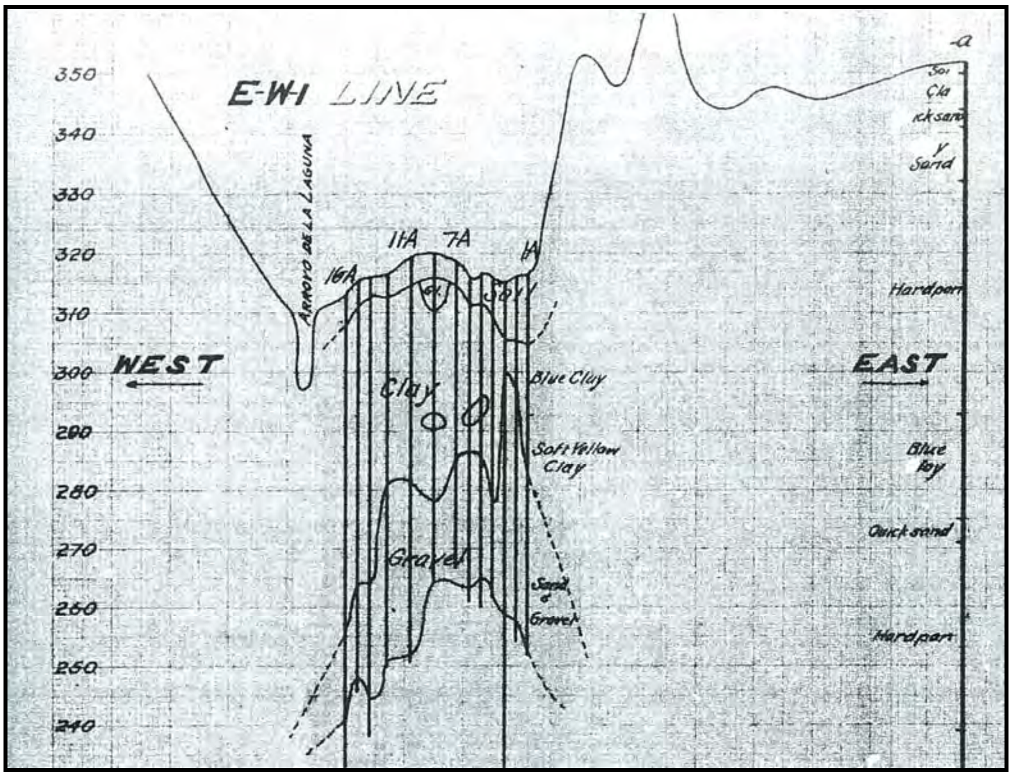


Figure 32. Cross section of Arroyo De La Laguna upstream of Verona Bridge, near Castlewood Drive. Data is from a portion of the geologic section of the Livermore Valley, showing well Line E-W-1 (Williams, 1912). Vertical scale: 1 square = 1 foot; horizontal scale: 1 square = 50 feet.

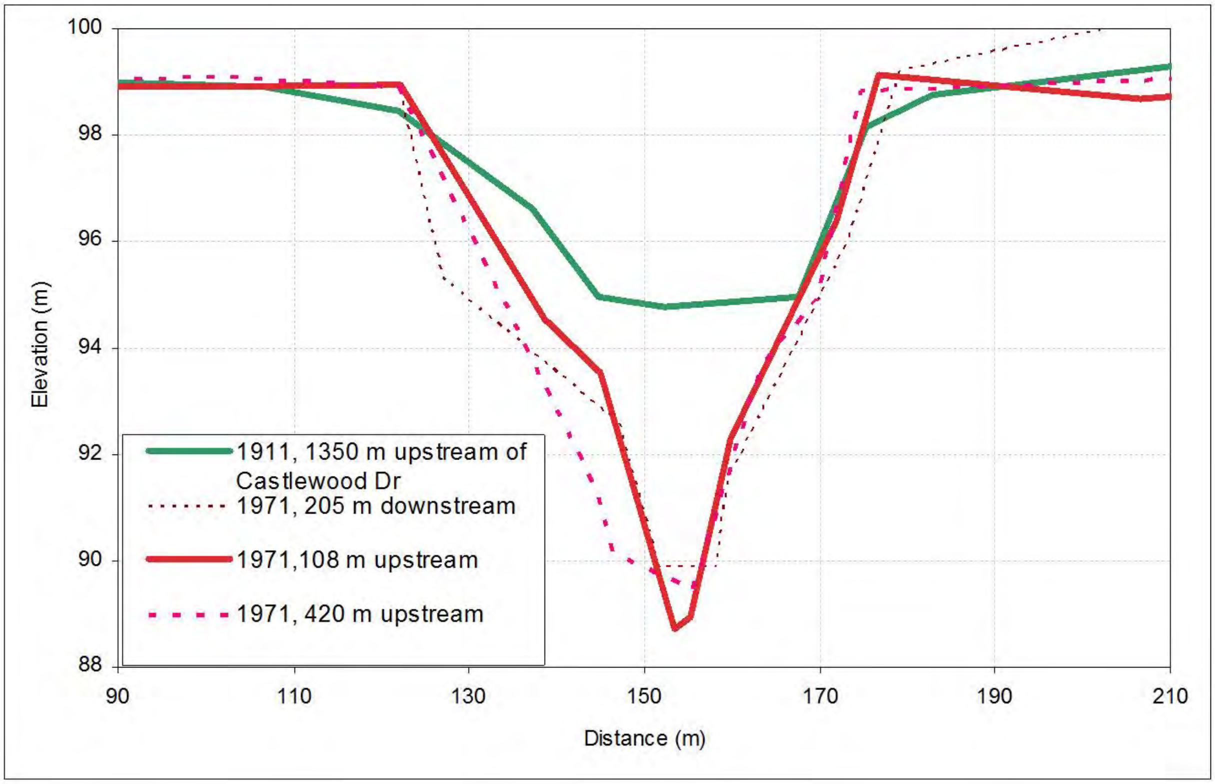


Figure 33. Historic cross sections near Castlewood Drive (upstream of the study reach) illustrating channel incision that occurred between 1911 and 1971. 1971 section distances are relative to the 1911 section location. Although section locations do not exactly correspond, the magnitude of change is still observable.

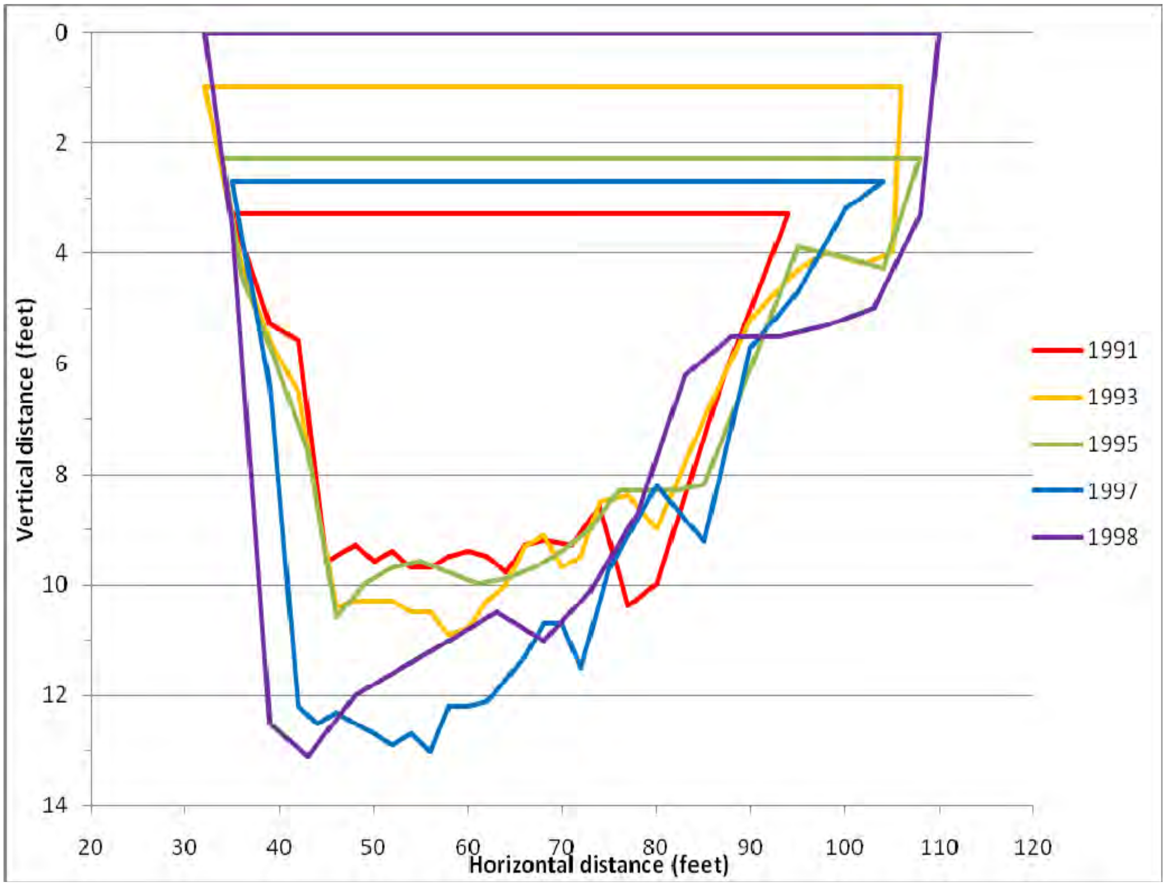


Figure 34. USGS cross sectional bed profiles measured at the USGS Arroyo De La Laguna near Pleasanton gage (station 11177000) (facing downstream). The vertical line at the top of each survey represents the water surface elevation during the time of that survey. Note the apparent bed incision that occurred between the 1995 and 1997 measurements and how the channel again aggraded between 1997 and 1998. Caution must be utilized in this interpretation because of potential effects of time-of-measurement (rising stage or falling stage) upon observed bed elevation. The change in the high right bank between 1997 and 1998 appears to be real, as evidenced by a comment in the original field notes. Note axes are in feet.

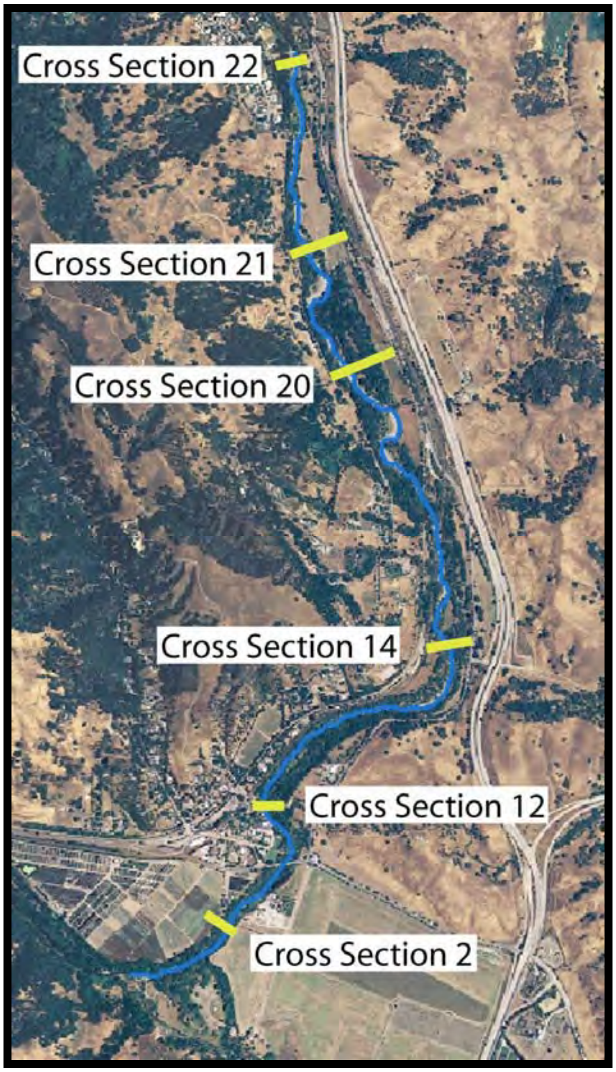


Figure 35. Location of the six re-occupied cross sections on Arroyo De La Laguna. Cross sections 20 - 22 are in the upper subreach, sections 12 and 14 in the middle subreach, and section 2 in the lower subreach (see discussion).

Cross section 2 (Figure 36) is the most difficult section of the six because of the poor alignment of land surfaces on either side of the channel. This cross section does not allow for meaningful comparisons in channel dimension, either width or depth. However, conceptually we see that this section is approximately the same valley width (width between the edges of the valley terrace surface) as historically, suggesting that significant bank erosion has not occurred in this location since 1971.

Similar to section 2, cross section 12 (Figure 37) is not very useful for direct quantitative comparisons. However, it does allow for several interesting qualitative comparisons. First, if the current section is aligned using the elevation of the floodplain, we see that the thalweg is at approximately the same elevation as 1971, which is supported by the longitudinal profile data. Second, the channel width (including low active bars) has increased since 1971, eroding the older floodplain surface in the process. And third, the difference in the section locations is highlighted by the offset in the ditch (farthest left channel) and in the tributary channel (second channel to the left). Because the ditch is likely an old aqueduct, the elevation difference suggests that the 2007 cross section is located slightly south of the 1971 section.

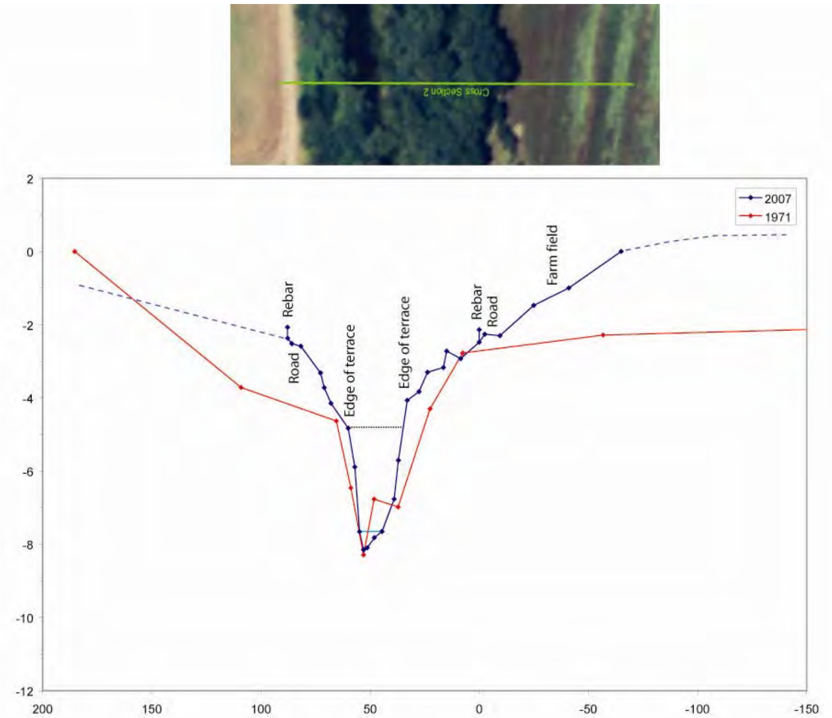


Figure 36. Cross-section 2, facing downstream. Cross section location plotted on 2005 aerial imagery is shown above the graph. Black dashed horizontal line represents the field indicators of bankfull elevation. Axes in meters.

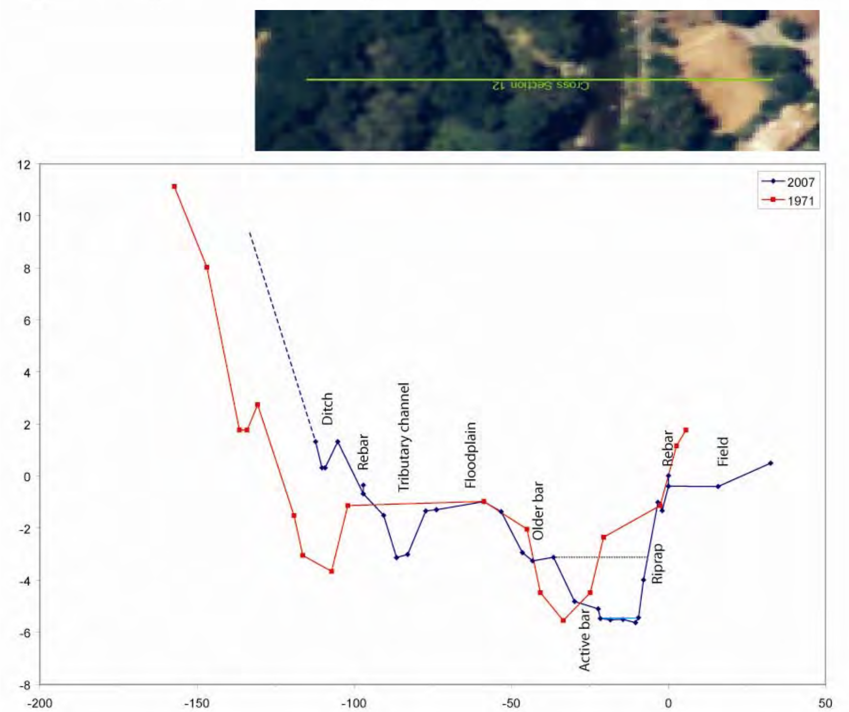


Figure 37. Cross-section 12, facing downstream. Black dashed horizontal line represents the field indicators of bankfull elevation. Axes in meters.

Section 14 (Figure 38) also uses the floodplain surface as a static elevation to compare sections. Making this assumption, the channel incision becomes apparent; approximately 1.7 m of incision appears to have occurred during this time period. This incision is also supported by the longitudinal profile data. And although not captured in the historical section, the modern section does include a channel on the far left side. We hypothesize that this represents either the main, or a secondary channel, to the historic “pre-1900” Arroyo De La Laguna channel (the channel that drained Tulare Lake in the 1800s). A photo of this historical channel is shown in Figure 22. This data helps estimate historical channel dimensions (and possibly discharge), and is useful for understanding the evolution of the channel through time. In terms of incision, the bottom of this historical channel is approximately 4.5 m higher in elevation than the current channel thalweg. Assuming this is the historical channel, and incision occurred continuously between 1901 and 2007, a rate of incision of 4.2 cm/yr is calculated. However, if we assume that the channel was able to incise to the current elevation by 1950 (before the 1950s flood events), the incision rate is calculated as 9.0 cm/yr. These rates are similar to those calculated using the bed elevation data.

Cross section 20 (Figure 39) has the best alignment of the six sections. The valley terrace elevation, the swale in the valley terrace, and the railroad grade all provide greater confidence in the alignment. The channel bed elevation at this location appears stable since 1971, as also shown by the longitudinal profile data. However, this section does show significant bank erosion of the left bank, as the channel has migrated eroding into the valley terrace. This finding is also shown in the aerial photographic analysis at Location D (Figure 29). As with cross section 14, we can calculate rates of incision, assuming that the historic channel was at the same elevation as the possible secondary channel shown in this section. Total incision of approximately 5 m over 50 years, or if spread over 106 years, gives a rate of either 10 or 4.7 cm/yr respectively.

As with section 20, cross section 21 (Figure 40) also aligns very well with the historical section. Again, the valley terrace, swale, and railroad grade are all used for alignment. This reach shows approximately 1.1 m of bed incision (corroborated by the longitudinal profile), and re-working/modification of the active channel geometry. However, unlike any of the other sections, it appears that this section (if properly aligned) captures the deposition of sediment on the floodplain, shown by the 2.2 m increase in elevation on the left side of the channel.

And finally, cross section 22 (Figure 41) had similar alignment issues as sections 2 and 12. Making the assumption that this section can accurately be aligned using the valley terrace elevation and the swale on the right side of the channel, this section shows that the channel has not experienced much incision at this location, but has experienced some bank erosion along the left bank (accounting for an increase in cross sectional area of approximately 40 m^2). Potentially some of the alignment issues on the left bank could be explained by land modification by the owners of this ranch parcel, but generally we have a low degree of confidence in the alignment of this section.

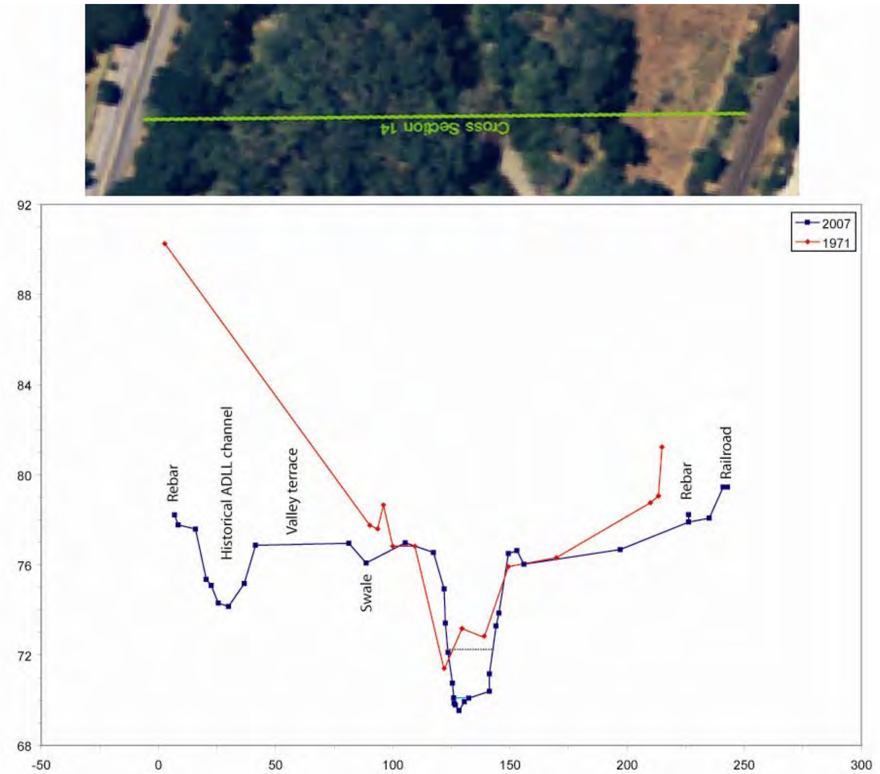


Figure 38. Cross-section 14, facing downstream. Black dashed horizontal line represents the field indicators of bankfull elevation. Axes in meters.

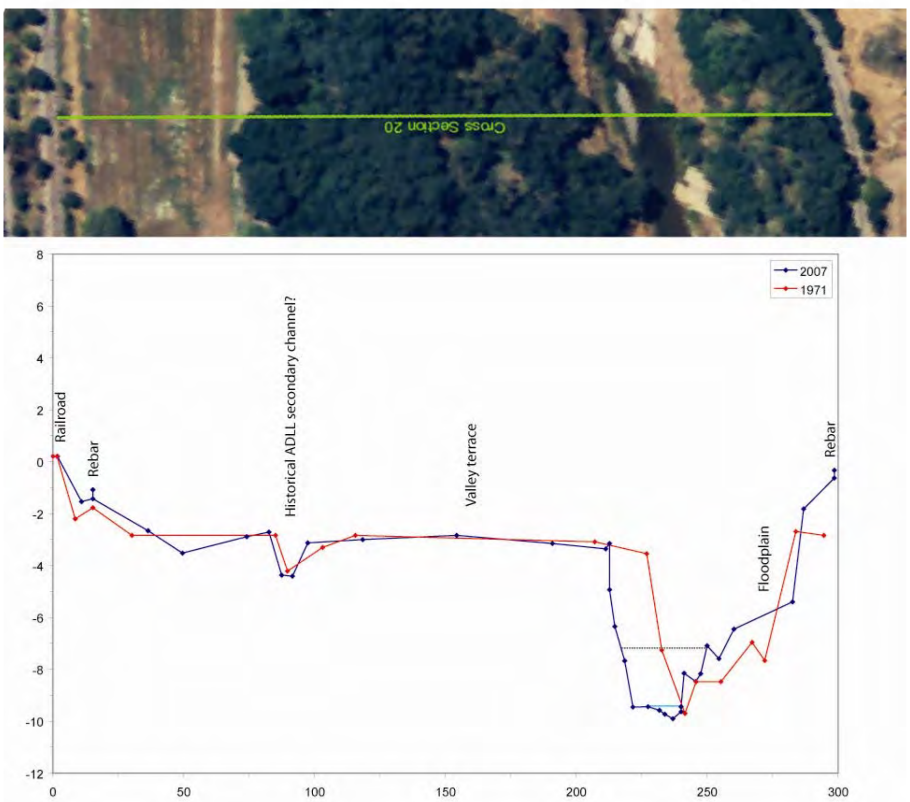


Figure 39. Cross-section 20, facing downstream. Black dashed horizontal line represents the field indicators of bankfull elevation. Axes in meters.

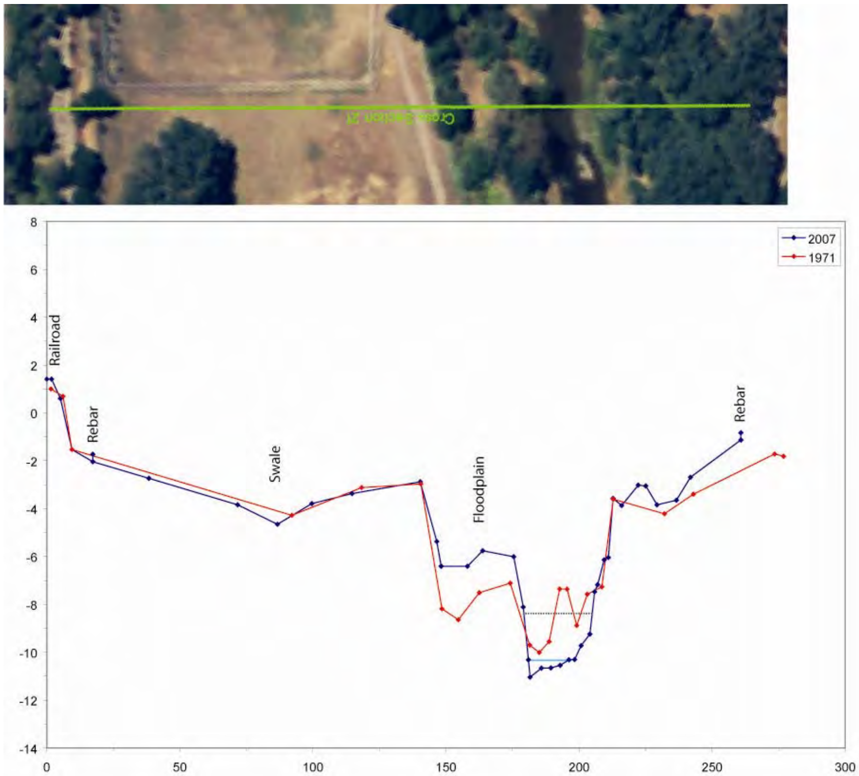


Figure 40. Cross-section 21, facing downstream. Black dashed horizontal line represents the field indicators of bankfull elevation. Axes in meters.

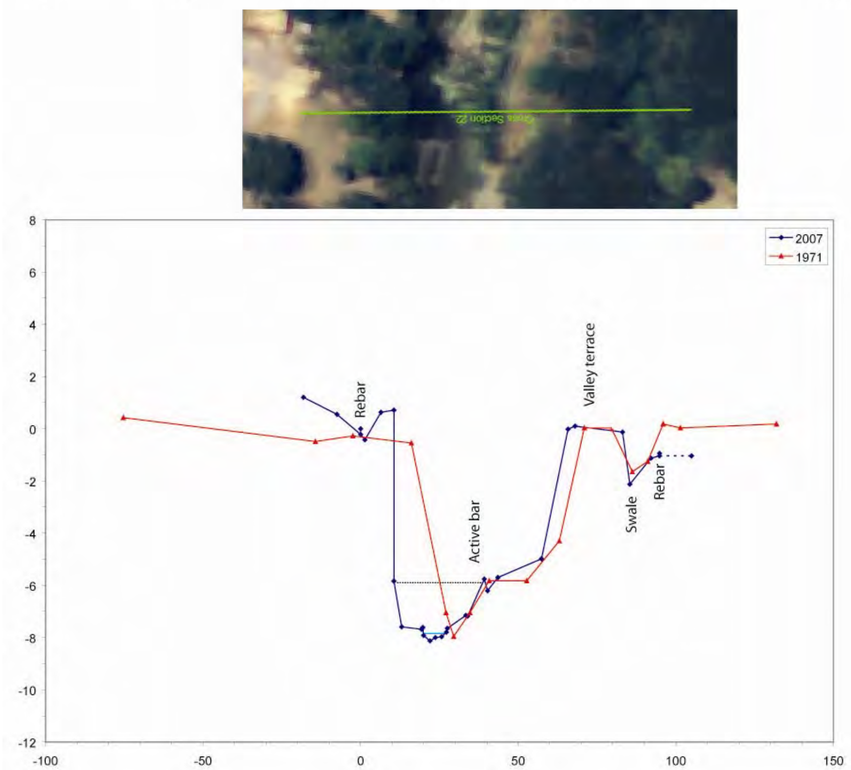


Figure 41. Cross-section 22, facing downstream. Black dashed horizontal line represents the field indicators of bankfull elevation. Axes in meters.

Overall, this series of current cross sections did not provide direct comparison to the historical sections as was initially anticipated, however, many qualitative comparisons and support for the sediment budget findings are provided. For example, the sections corroborate the amount of incision (or lack thereof in certain subreaches) of the channel, an overall increase in channel width caused by either bank erosion or floodplain erosion, and in some cases, likely deposition of sediment on the floodplain. These observations support our findings of substantial historic incision prior to 1971, smaller magnitudes of incision after 1971, channel widening after 1971, and some aggradation after 1971. In addition to these qualitative comparisons, the cross sections become most useful by providing an important baseline for future monitoring and comparison because they are monumented and easily reoccupied.

Another source of contemporary cross section information includes a series of 2007 cross sections completed by West Yost Associates for the Zone 7 Water Agency. These sections were surveyed as a component of a larger data collection effort for a report to the Water Agency. The spatial distribution of sections is shown on Figure 42, and a visual comparison of channel cross sections for each subreach is shown in Figures 43 through 45. Based upon the original survey notes, it appears that each section was surveyed up to the valley terrace elevation.

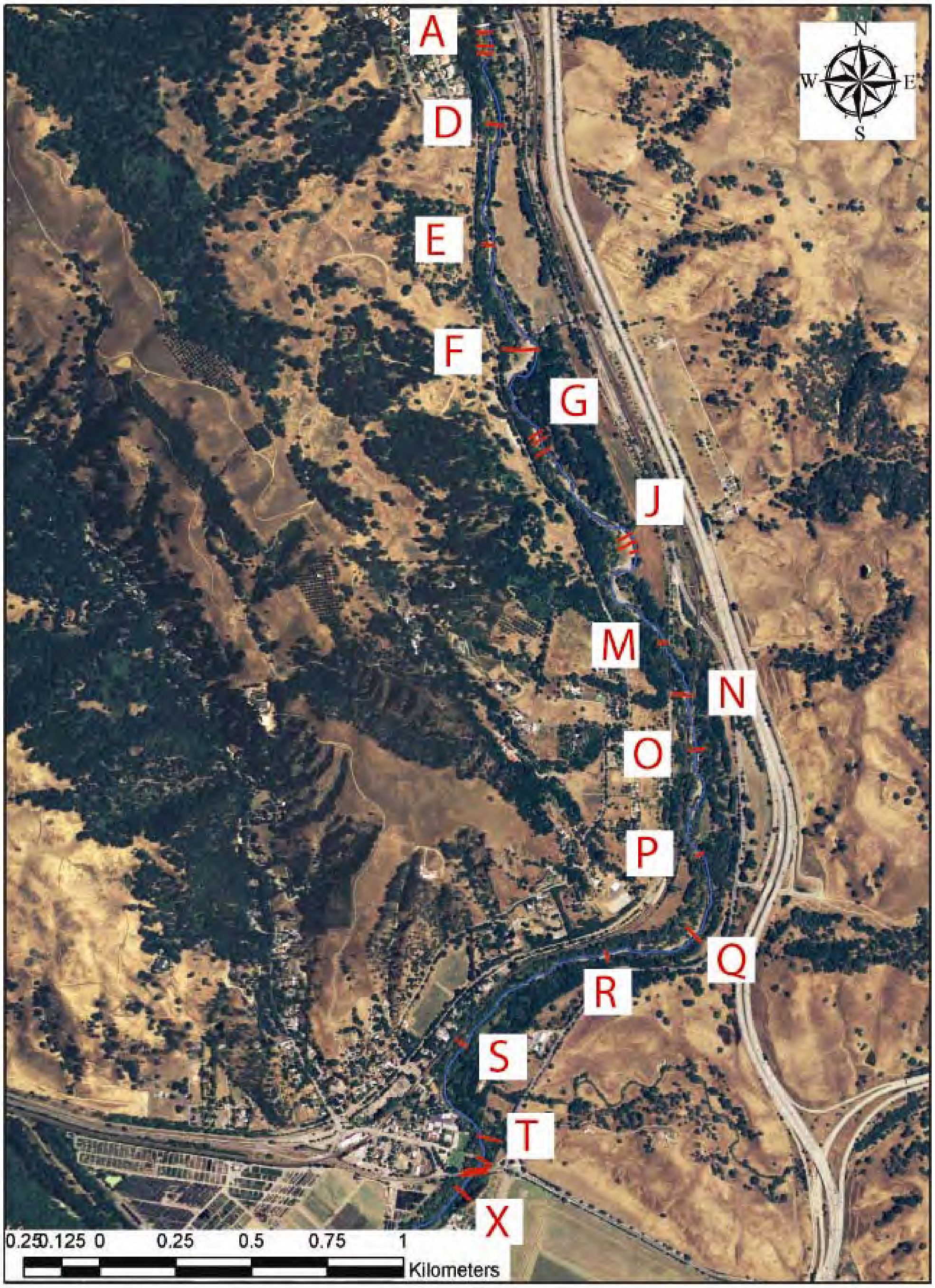


Figure 42. Map showing the locations of cross sections surveyed in 2007 for West Yost Associates.

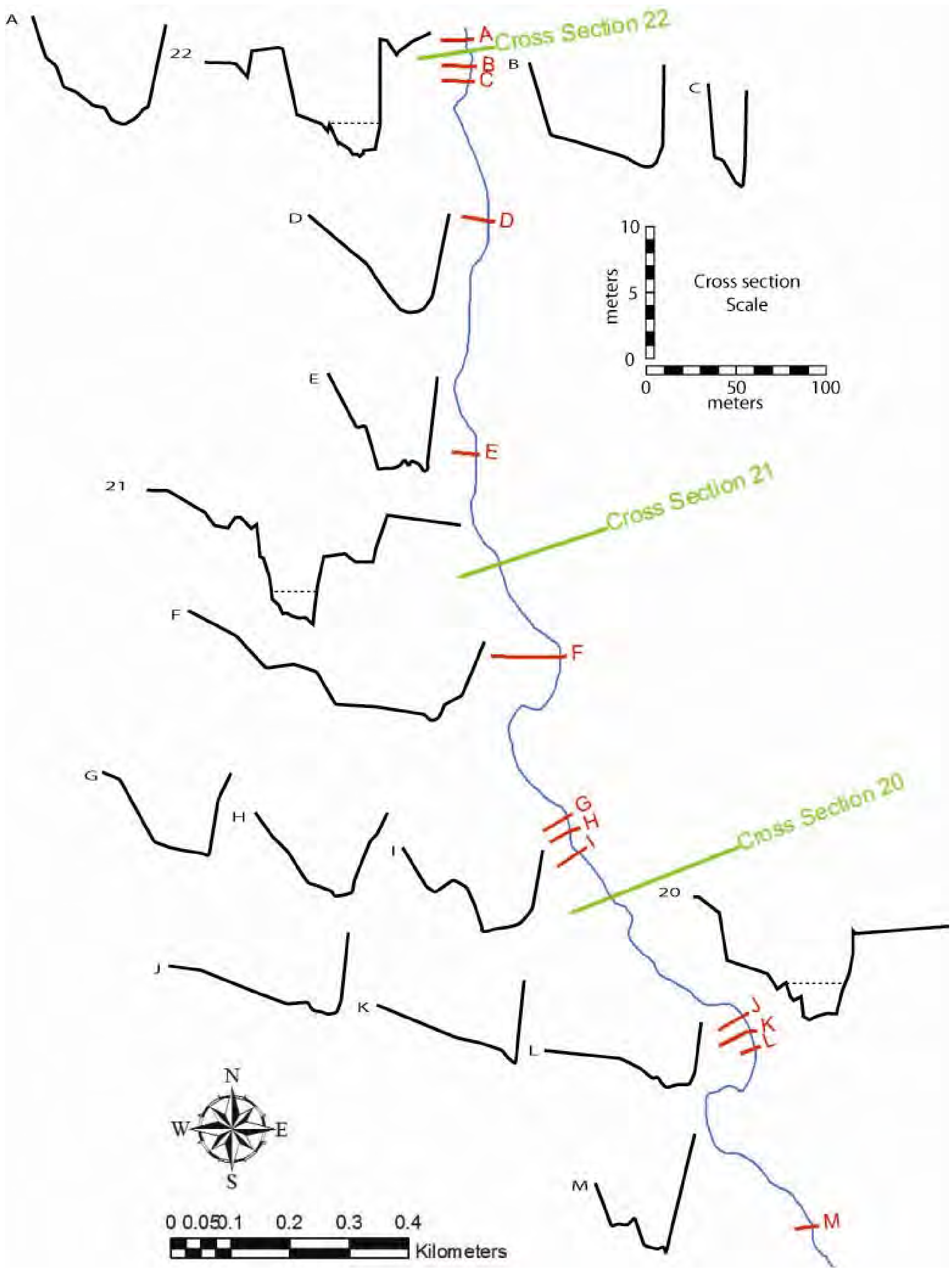


Figure 43. Series of cross sections showing the changes in channel morphology for the upper subreach. Lower scale bar shown is for the along-channel distance. This series shows both the West Yost cross sections and sections surveyed for this study. Note that all sections are plotted looking upstream to match the adjacent plan view map. Black dashed line represents the field identified bankfull elevation.

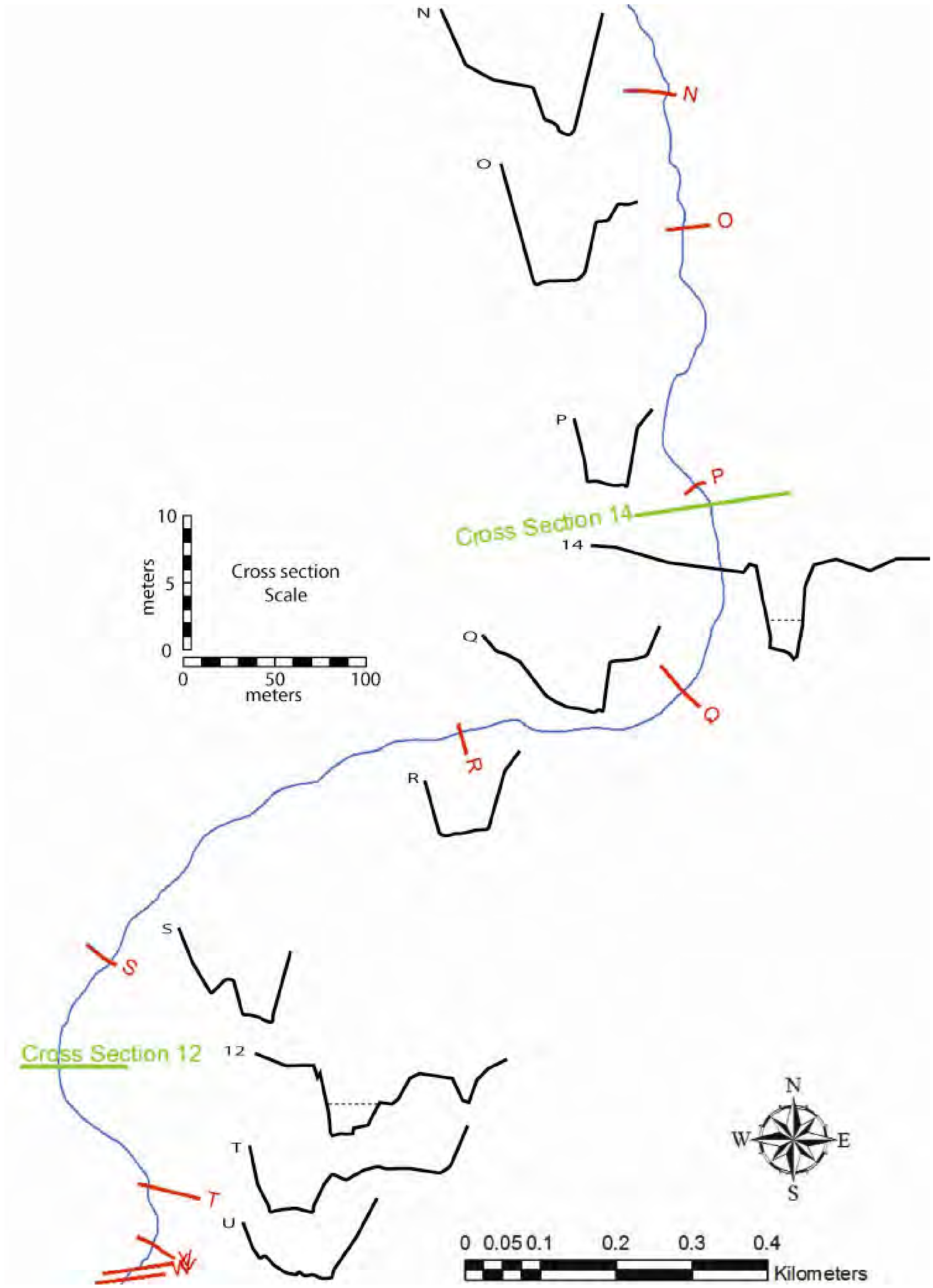


Figure 44. Series of cross sections showing the changes in channel morphology for the middle subreach. Lower scale bar shown is for the along-channel distance. This series shows both the West Yost cross sections and sections surveyed for this study. Note that all sections are plotted looking upstream to match the adjacent plan view map. Black dashed line represents the field identified bankfull elevation.

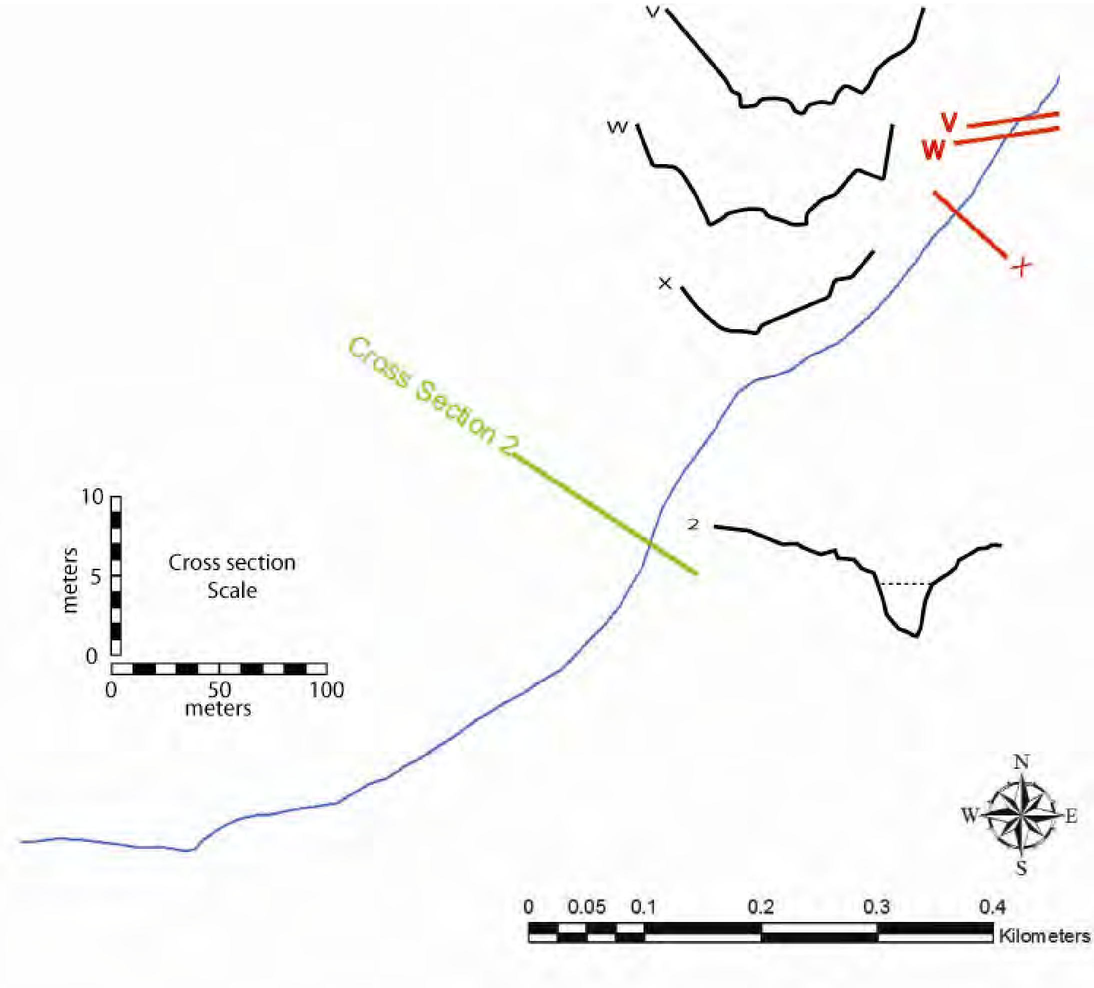


Figure 45. Series of cross sections showing the changes in channel morphology for the lower subreach. Lower scale bar shown is for the along-channel distance. This series shows both the West Yost cross sections and sections surveyed for this study. Note that all sections are plotted looking upstream to match the adjacent plan view map. Black dashed line represents the field identified bankfull elevation.

Floodplain Storage

Floodplain storage can be an important component of sediment budgets in large systems with active or evolving floodplains. We observed three locations in Arroyo De La Laguna where recent bank erosion exposed riparian trees partially buried by floodplain accretion (Figure 46). The base and roots of these trees were typically on coarser material, most likely deposits from the 1950s floods. The depth of the accreted floodplain sediment ranged from 1 - 1.5 m and averaged 1.25 m at the three locations, where trees were exposed in *eroded* banks. This depth was often similar to the depth of fine (accreted) sediments over the coarse sediments observed in eroded floodplain banks. Because floodplain deposits are typically thicker near the channel edge (i.e. natural levee deposit) and thin away from the channel, we reduce the observed depth by one third to roughly an approximate and average depth of the accreted floodplain deposits of 0.88 m. To estimate the floodplain area in Arroyo De La Laguna, we relied on 25 cross sections surveyed over the reach in 1971 as part of the flood insurance study (FEMA 1975) and the 6 cross sections resurveyed in 2007. We identified the floodplain surface on cross sections (Figure 46 shows an example cross section) that generally occurred on one side of the channel and ranged in width from 10 to 30 meters and averaged 20 meters. The floodplain could be identified on 13 of the 25 cross sections, so we roughly approximate that the floodplain extends intermittently over half the middle and upper subreach length (2400 m) (the floodplain in the lower subreach was not extensive or well established).

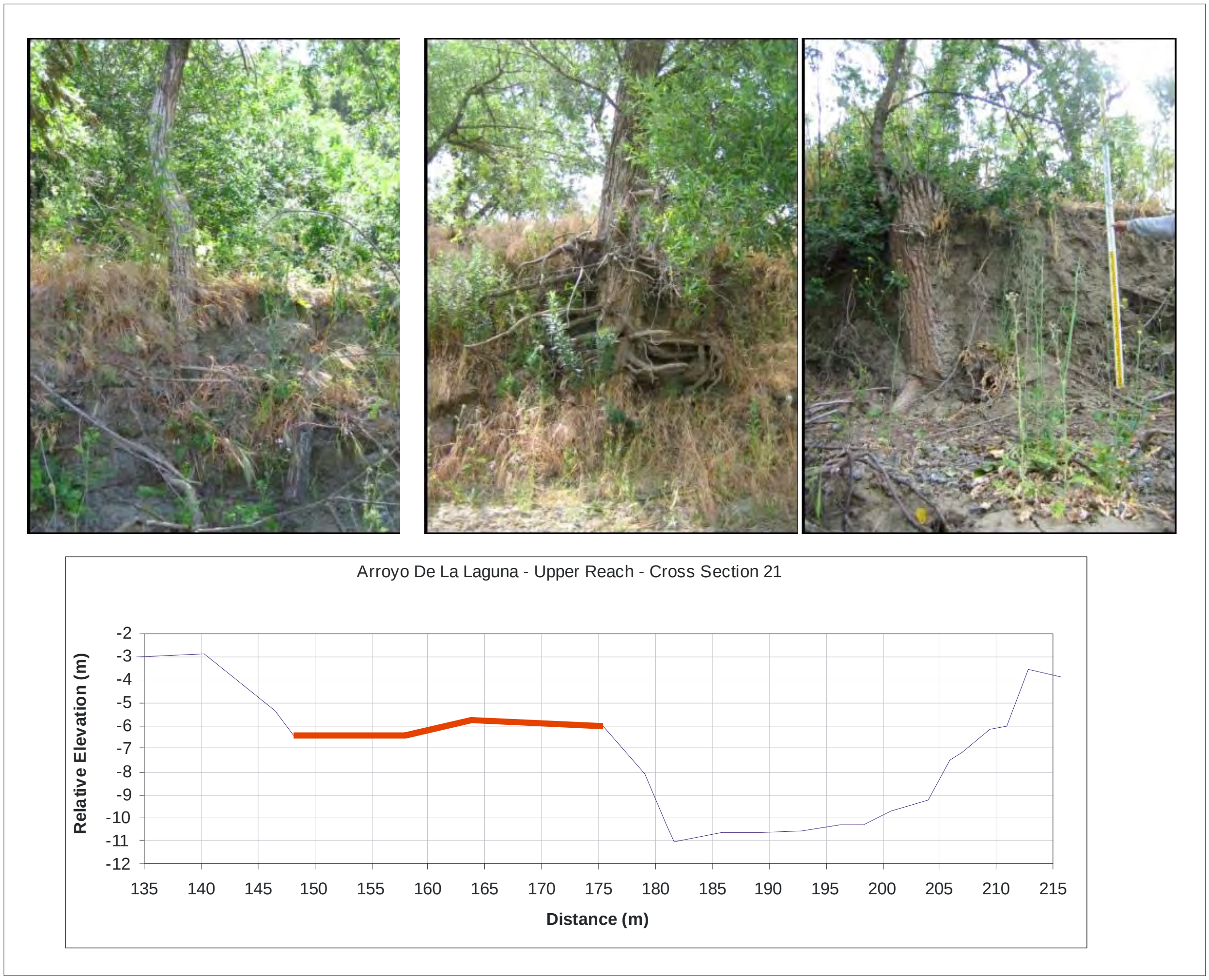


Figure 46. A. (upper) Photos of buried riparian trees on the contemporary floodplain of Arroyo De La Laguna used to estimate accreted floodplain sediment depths. B. (lower) Example of 2007 cross section (facing downstream) in Arroyo De La Laguna with floodplain surface and width identified in red.

To estimate the age of the accreted floodplain deposits described above, we cored the largest floodplain trees spread throughout the upper and middle subreaches of Arroyo De La Laguna. Three of the 12 cores collected did not penetrate the center of the tree and could not be used (12 tree cores total, 9 of which were usable). The floodplain in the lower subreach was not extensive or well established, and therefore we did not core trees in this area. The age of floodplain trees ranged between 30 and 59 years (mean 45 years), dating the last major reworking of the floodplain between 1948 and 1967 (mean 1962) (Table 6). *Based on the flood history (Figure 17) and tree coring results, we infer that much of the floodplain was reworked during the record 1950s floods, and apply the estimated floodplain accretion volume described above to the three sediment budget periods from 1959 - 2006*.[5] We prorate the floodplain mass for each budget period using the annual peak flood record for Niles gage, as the Verona gage on Arroyo De La Laguna was inactive between 1931 and 1969. For example, the proportion of floodplain mass attributed to the 1959 - 1971 period was calculated as: (sum of the annual peak flows from 1959 - 1971) / (sum of annual peak flows from 1959 - 2006). Using this coarse approach, estimated floodplain storage rates over time are 1,800 tonnes/yr (1959 - 1972), 1,300 tonnes/yr (1972 - 1993), and 1,100 tonnes/yr (1994 - 2006) (Table 3). Floodplain accretion on the valley floor for the earliest period (1901 - 1958) was roughly estimated by taking an average of the three later periods (1,400 tonnes/yr) (Table 3).

Table 6. Summary of tree core data used to estimate the age of last major reworking of floodplain along Arroyo De La Laguna study reach.

Sample No.	**Location[a] (m)**	**Floodplain Height[b] (m)**	**Tree Species**	**Tree Ring Count[c, d] (years)**	**Date[d] (year)**
1	5475	4.2	Willow	30	1977
2	4875	4.2	Cottonwood	33	1974
3	4725	4.9	Cottonwood	58	1949
5	3575	4.1	Cottonwood	48	1959
6	3230	3.7	Cottonwood	38	1969
7	2870	4.0	Cottonwood	54	1953
9	2330	4.2	Willow	59	1948
11	1814	2.1	Cottonwood	51	1956
12	1058	2.1	Cottonwood	34	1973
			average:	45	1962
			oldest:	59	1948

notes

a distance upstream from confluence with Alameda Creek.

b floodplain surface height from channel thalweg.

c we estimate the accuracy of tree ring counts are plus or minus 6 years.

d three years are added onto the tree ring count to account for the buried tree height beneath the floodplain sediment.

[5] It should be noted that it was not possible to estimate the bed or floodplain aggradation from the 1950s floods or earlier because there are no apparent bed elevation surveys prior to 1959. However, this aggradation mass is balanced in the budget by estimates of *net incision* from 1901 – 1958 (i.e. bed lowering from incision minus bed aggradation from the 1950s floods).

Landslides and Gullying

Where streams are bordered by hillslopes, sediment supply from mass wasting is often a major component of sediment supply. With the exception of a small section just above the downstream railroad bridge, the Arroyo De La Laguna study reach is generally disconnected from valley hillslopes by the valley floor (terrace), and landslides from valley walls are not delivered directly to the channel. However, in the lower subreach of *Alameda Creek*, the channel abuts a high older (Pleistocene/Pliocene) terrace prone to landslides and gullying. We observed several older massive landslides with subsequent gullying in this area and some smaller recent slides. Figure 47 shows an older landslide scarp with subsequent gullying that also looks apparent on low-resolution (1:24,000) photocopies of 1939 air photos. The steep sheer slope of the cliff walls indicate slope failure (mass wasting), while the v-shaped notch suggest subsequent fluvial erosion from gullying. While this landslide and gully continues to deliver some material to the channel, because the scarp looks apparent on 1939 air photos and the majority of mass from landslides is derived from the initial failure, we include it in the earliest budget period (1901 - 1958) as well as the mass from another massive landslide scarp immediately upstream that is now vegetated with mature oak trees (Figure 47).[6] A recent landslide was also observed in this lower subreach with young vegetation (8 years old) growing within the scarp, and was included in the most recent budget period (1994 - 2006). Based on these observations, sediment production from landslides and subsequent gullying along Alameda Creek ranged from 4,350 tonnes/yr (1901 - 1958 period) to 320 tonnes/yr (1994 - 2006 period) (Table 4) and represents an important stochastic component of sediment supply to the lower subreach of Alameda Creek following major rainstorms that trigger such mass wasting.

[6] Should higher quality historic air photos become available, the age of these slides and gullying should be reevaluated.

Figure 47. (upper) Panoramic streamside view of landslide and gullying observed during field work. (lower) Oblique aerial view of the same landslide and gullying on the lower subreach of Alameda Creek, note the apparent scarp that is now vegetated that continues upstream (left) of the bare scarp. Flow is from left to right on both photos.

Net Budget for the Study Reaches – Patterns of Erosion over Time

Arroyo De La Laguna. Combining the various estimates of sediment supply and storage over the four time periods in Arroyo De La Laguna reveals patterns of erosion and storage by process over time as well as variation of the net budget (Table 3, Figure 48). Although the rates calculated are approximations and contain errors that are difficult to quantify (see later), the rates are likely accurate within an order of magnitude and are most useful in clarifying the relative importance of different processes and observing changes in processes over time (see Reid and Dunne 1996 for discussions on the applications of sediment budget to management questions). The reach sediment budget by process over time (Table 7, Figure 48) reveals a general pattern. Channel erosion was dominated by incision from 1901 - 1959 (90% of the reach budget) apparently triggered by breaching of the historic lagoon and channelization upstream. Another phase of rapid incision then followed from 1959 - 1971 (76% of the reach budget) presumably in response to aggradation from extreme flood events of the 1950s (Table 7, Figure 48). As the incision migrated upstream (head cutting) over time (Figure 25), the channel later began to adjust primarily through bank erosion (channel widening, 68% of the reach budget), accompanied by increased aggradation and bar storage (22% of the reach budget) during the most recent period (1994 - 2006) (Table 7, Figure 48).

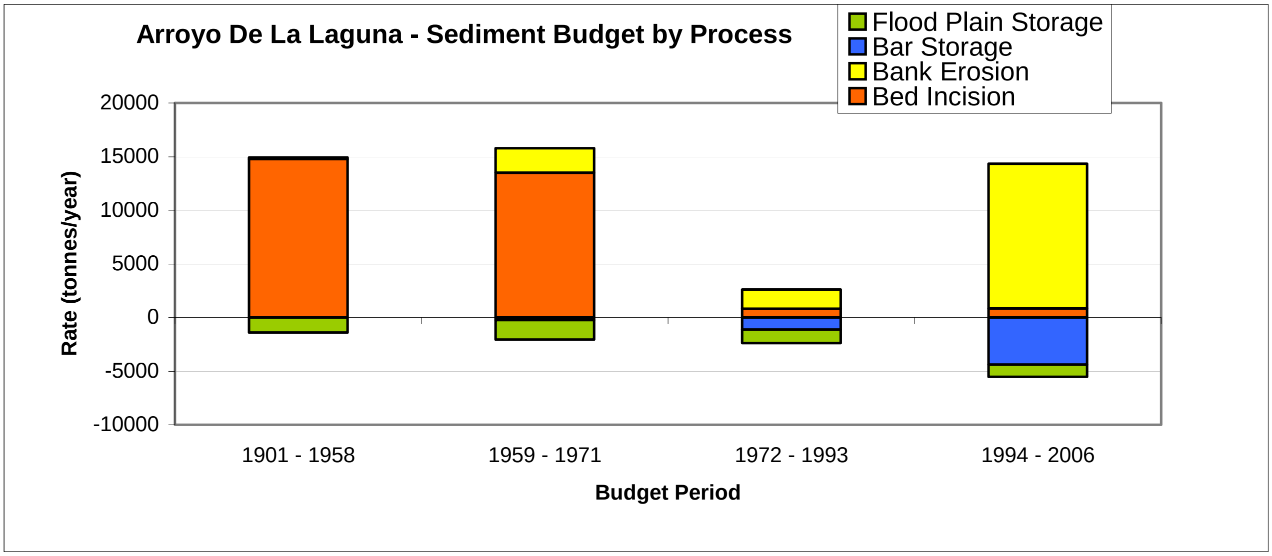
Alameda Creek. While only a partial budget was completed for Alameda Creek, the observed processes suggest that little material is supplied by the reach from bank erosion or bed incision. However, landslides (and subsequent gullying) near the bottom of the reach can episodically supply a large amount of material that may dominate the budget over shorter time frames (Figure 49).

Table 7. Relative percentage of the sediment budget by process for Arroyo De La Laguna over four time periods. All values shown in percent.

Arroyo De La Laguna

Time Period	Bed Incision[a]	Bank Erosion	Aggradation and Bar Storage	Floodplain Storage
1901 - 1958	90	1	< 0.1	9
1959 - 1971	76	13	1	10
1972 - 1993	16	36	22	25
1994 - 2006	4	68	22	6

Note:
a Bed incision represents net erosion of the bed between the bed elevation surveys.



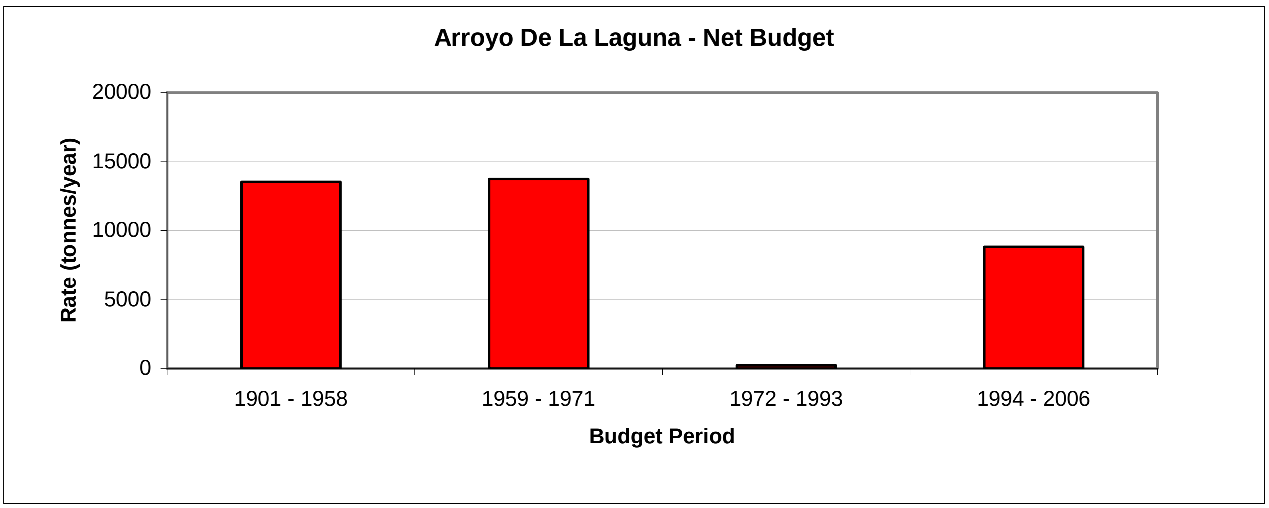
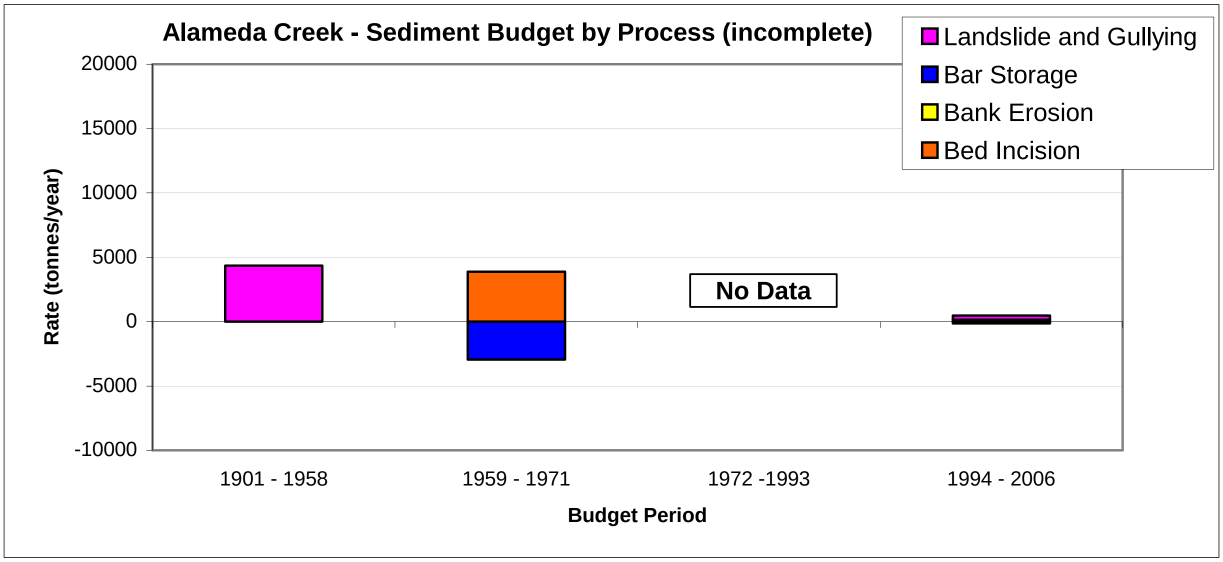


Figure 48. (upper) Arroyo De La Laguna study reach sediment budget by process over the four time frames. (lower) Net sediment budget over the four periods.



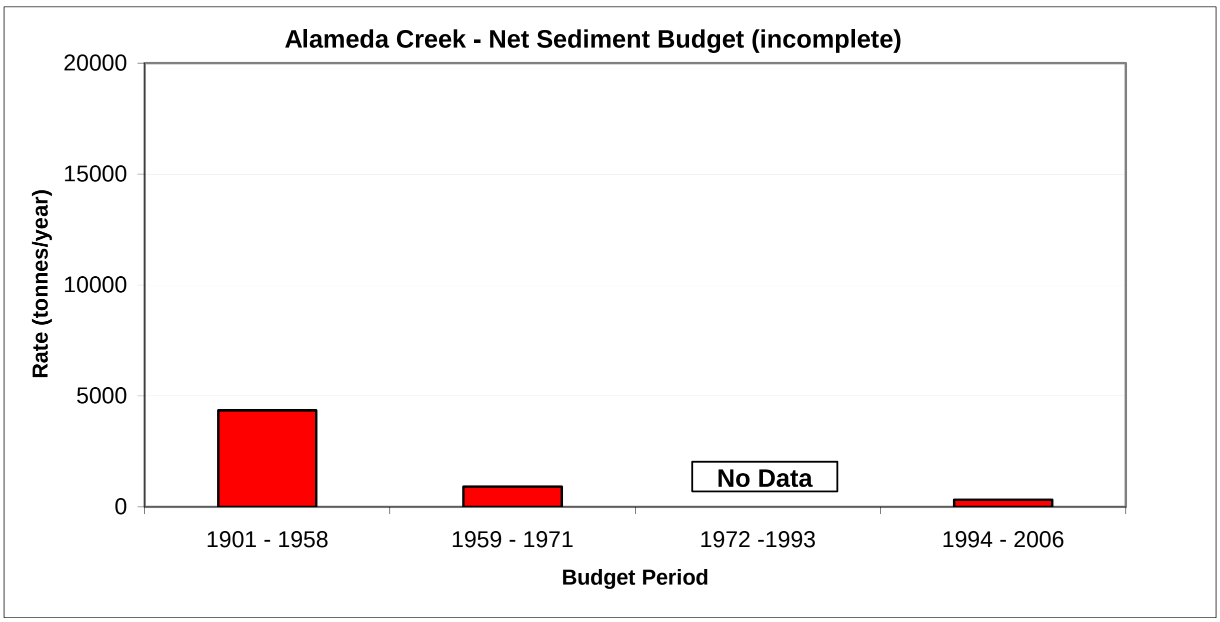


Figure 49. A. (upper) Alameda Creek study reach sediment budget by process over the four time frames. B. (lower) Net sediment budget over the four periods. Y axis is same scale as Arroyo De La Laguna plots (Figure 48) for visual comparison.

Relative Sediment Supply – Comparison of Sediment Yields within the Watershed

From a management perspective, it is important to compare sediment supply from the study reaches relative to other parts of the watershed. This first step provides managers with an initial perspective on possibilities for sediment management, with future steps to better define sediment sources that are feasible to manage. To address this fist step, we compared erosion rates from the study reaches to long term estimates of suspended and bed load at upstream and downstream USGS gages. Annual total loads (suspended sediment plus bed sediment) passing through the gage on Alameda Creek near Niles are estimated to have varied from 9 - 1,048,000 tonnes/yr between 1950 and 2006 (Figure 50). Sediment loads averaged for the 1950s decade with historic floods (328,000 tonnes/yr) were estimated to be six times greater than the 1970s decade (the driest decade) and about twice the average for 1994 - 2006 (the recent period in the sediment budget). The annual variability in total load generally results from differences in rainfall and runoff as well as sediment supply generated during large storm events (1950s floods, El Niño years). This level of variability is often observed at other Bay Area gaging stations and throughout California (e.g. Anderson 1981, Inman and Jenkins 1999). Estimates of total sediment load made for the period 1994 to 2006 for Arroyo De La Laguna near Pleasanton (Verona) also varied in response to climate (5,600 - 256,800 tonnes/yr) as did Alameda Creek near Welch Creek (near zero - 15,600 tonnes/yr). During 2000, 2001, and 2002 when sediment loads were measured at all three gaging stations, a greater mass of sediment flowed into the study area through the upper gaging locations than flowed out through the Niles gage, whereas in 2004 (a much wetter year), the converse was true. Such annual variability observed in the limited measured data suggests that sediment was accumulating in the reach between the Verona and Niles gages in drier years. Average total sediment loads were estimated for each gaging location and compared to our field measurements of net eroded channel sediment derived from the study reaches (Table 8). Although there was much variability from year to year, over the long term (1994 - 2006), it is estimated that an average of 156,000 tonnes/yr of sediment passed out of the study area through the Niles gage, a much greater amount than passed in through the upper gages 104,000 and 7,700 tonnes/yr for Arroyo De La Laguna near Pleasanton and Alameda Creek below Welch Creek respectively.

To make a complete budget comparison of the entire watershed down to Niles gage, we also estimated sediment yield for the ungaged area in the study area (116 km^2, Figure 3). We estimated sediment yield rates for the ungaged areas of the study area for the recent budget period (1994 - 2006) using three approaches, including using the relationship between basin size and average annual suspended sediment load for Bay Area streams (PWA 2005), extrapolating the sediment yield rates from USGS gage data for nearby Cull Creek, and extrapolating sedimentation rates from San Antonio reservoir (Collins 2005). Estimated sediment yield rates ranged from two similar high estimates of 116,000 tonnes/yr (Bay Area streams relationship) and 103,000 tonnes/yr (Cull Creek) to a lower estimated yield of 53,000 tonnes/yr (San Antonio reservoir sedimentation rate). We conservatively use the lowest estimate (San Antonio reservoir rate) for the ungaged areas in our overall comparison of the sediment budget (i.e. using a higher yield from the ungaged areas would lower the relative contribution of sediment from the study reaches to the overall budget).

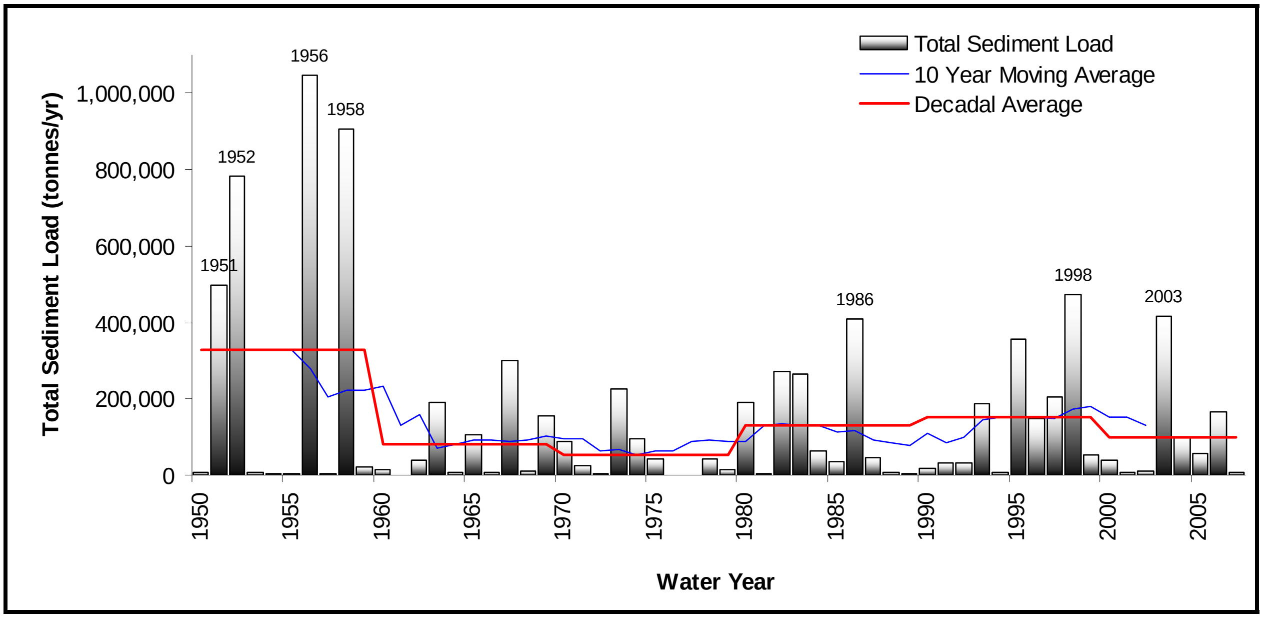


Figure 50 Total estimated sediment discharge (from bedload and suspended sediment rating curves) at the USGS gages in Niles Canyon (station 11179000) for the period 1950 to 2006. The water year is the 12-month period from October through September, designated by the calendar year in which it ends. Decadal and 10-year moving averages are provided to visualize longer term trends only.

Comparing the overall sediment budget of the watershed upstream of Niles gage (sediment yield estimated for Verona and Welch gages, study reaches, and ungaged tributaries), indicates that roughly 5 to 6% of the sediment mass passing through the Niles gage during the period 1994 - 2006 was derived from channel erosion within the study reaches (primarily the Arroyo De La Laguna study reach that comprises roughly 0.25% of the total stream network) (Tables 8 and 9). During the period 1959 - 1971 and 1972 - 1993, the study area accounted for 26% and < 1% of the estimated total sediment load at the Niles gage (Table 9). The higher contribution of sediment from the Arroyo De La Laguna study reach for the 1959 - 1971 likely reflects a period of rapid incision migrating through the reach following the major disturbance of the 1950s floods (Figure 17).

DISCUSSION

Study Reach Sediment Supply to the Flood Control Channel

The primary objective of this study was to evaluate whether erosion from the study reaches may be a major source of sediment deposited in the flood control channel, primarily by estimating the processes and rates of erosion and storage from the study reaches over time and then *comparing the net erosion from the study reaches to the rest of the watershed*. During early periods when Arroyo De La Laguna was adjusting to major disturbances from channelization in the early 1900s and then extreme events of the 1950s floods, the reach contributed a substantial portion of the overall sediment load passing Niles gage down to the flood control channel, roughly 26% from 1959 - 1971 (Table 9). However, as channel incision migrated upstream and channel adjustment in Arroyo De La Laguna transitioned to primarily bank erosion and sediment storage increased, estimated contributions from Arroyo De La Laguna decreased to roughly 6% of the load passing Niles gage to the flood control channel for the most recent period (1994 - 2006), indicating there are much larger sources of sediment to the flood control channel other than the study reaches (Tables 8 and 9). Still, when considering the approximately 2,300 km total channel length in the Alameda Creek watershed using the USGS stream lines (likely a very conservative underestimate that does not include small channels), we see that 0.25% of channel length is supplying 6% of the total sediment load and therefore identifying similar reaches within the watershed may be an important next step in making management decisions to reduce the sediment supply to downstream reaches.

Table 8. Comparison of the total sediment budget for the most recent budget period 1994 - 2006, including study reaches, gages, and ungaged areas.

Comparison of Total Budget for Recent Period 1994 - 2006

Area	**Sediment Yield** **tonnes yr^{-1}**	**± range**	**% range**	**% of Total**	**Drainage Area Below Dams[a] (km^2)**	**Sediment Yield tonnes km^{-2} yr^{-1}**	**Drainage Area total (km^2)**	**Sediment Yield tonnes km^{-2} yr^{-1}**
Arroyo de La Laguna at Verona Gage	104,000	52,000	50%	***62***	670	155	1044	100
Arroyo de La Laguna Study Reach	9,000	5,400	60%	***5*** [b]				
Alameda Creek near Welch Ck Gage	8,000	6,000	75%	5	121	66	376	21
Alameda Creek Study Reach	320	960	300%	0.2				
Ungaged areas[c]	47,908	48,000	100%	28	116	413	116	413
All Areas above Niles Gage	169,000	110,000	65%		907	186	1,639 [d]	103
Alameda Creek at Niles Gage	156,000	39,000	25%		907	172	1639	95

Notes

a Drainage areas above dams: San Antonio 99 km^2, Del Valle 374 km^2, Calaveras 255 km^2; drainage area above Alameda Creek Diversion Dam of 86 km^2 is not included although flow and associated suspended sediment is subject to diversion to Calaveras reservoir (prior to 2002, the dam diverted flows less than 18 m^3 s^{-1} to Calaveras Reservoir).

b The 5% value is calculated by comparison to “All Areas above Niles Gage” (the sum of budget components - 169,000 tonnes yr^{-1}); similar calculation of 6% on Table 9 is by comparison to “Alameda Creek at Niles Gage” (from sediment rating curves – 156,000 tonnes yr^{-1}).

c Estimated using reservoir sedimentation rate for San Antonio of 455 tonnes km^{-2} yr^{-1} (1965 - 2004) (Collins 2005), most conservative (lowest) of three extrapolation methods.

d Includes drainage area of San Antonio of 99 km^2 not reflected in drainage areas above.

Table 9. Comparison of the of the sediment yield at Niles gage to the study reaches for the three budget periods from 1959 - 2006.

Time Period	Niles Gage (tonnes/yr)	Study Reaches Combined (tonnes/yr)	% of Niles
1959-1971	74,000	19,300	26
1972-1993	90,000	320	0.4
1994-2006	156,000	8,700	6

How reliable are these sediment yield estimates? We check the estimates with three basic approaches. First, the overall estimated sediment yield rate of 169,000 tonnes/yr for all areas above Niles gage (1994 - 2006) is very similar to that estimated from the Niles gage data (156,000 tonnes/yr, Table 8), representing a small surplus of 8% of the overall budget and lending credence to the various estimates. Some sediment budgets consider this residual or surplus as the error associated with the budget (Kondolf and Matthews 1991). Second, the overall sediment yield rates (on a per area basis) in this study are similar to rates calculated in other Bay Area studies (Figure 51, Table 10), further indicating the study estimates appear reasonable. Third, the study reach contribution of 6% to the overall budget has an estimated uncertainty of 65% (Tables 3 and 8), but uncertainty associated with sediment budgets can be 100% or more, *when reported* (Kondolf and Matthews 1991, Reid and Dunne 1996). Even with such uncertainty (see more later), the contribution of the study reach could be as much as 15% of the total load passing Niles gage to the flood control channel, still indicating there are likely much larger sources of sediment in the steeper portions of the watershed, including the ungaged tributaries (Figure 3 - all the tributaries draining to the study reaches and between the bottom of the study reaches to the Niles gage). Based on the gage data, the majority of sediment passing the Niles gage is derived from watershed areas above the Verona gage on Arroyo De La Laguna (62% of the total load, Table 9)

Uncertainty of the Sediment Budget and Further Study

Constructing sediment budgets is a common method for characterizing erosion processes and rates across the Pacific Coastal ecoregion, particularly for identifying the relative importance of land use impacts including agriculture, urbanization, forestry, and dams (see Swanson et al. 1982a, Reid and Dunne 1996, Horowitz and Walling 2005). However, the inherent complexities of watershed erosion processes, including their stochastic nature and the difficulty of quantifying processes through field studies, often limits the accuracy of sediment budgets. For example, short-term erosion rates defined in sediment budgets may be in error by at least several hundred percent. Consequently, sediment budgets may be most valuable in defining the relative difference in erosion rates and the general relationships among climate, topography, land use, and erosion. Nevertheless, sediment budgets provide valuable information about watershed processes and the impact of various land uses.

Because sediment budgets are constructed from a variety of sources and assumptions, often including a range of precise to rough estimates, traditional error analysis is rarely possible. Consequently, sediment budget estimates are often evaluated by comparison to other measured rates (as we did earlier), an uncertainty analysis, or assessing the reliability of the methods (Reid and Dunne 2003). To the extent possible, we approximated a conservative uncertainty associated with each budget term (Tables 3 and 4) and the uncertainty associated with the sediment yield estimates from gage data and ungaged areas (Table 8). The evaluation of uncertainty is useful to temper potential management decisions based on the sediment budget and identify which components of the sediment budget may deserve further analysis (Reid and Dunne 2003).

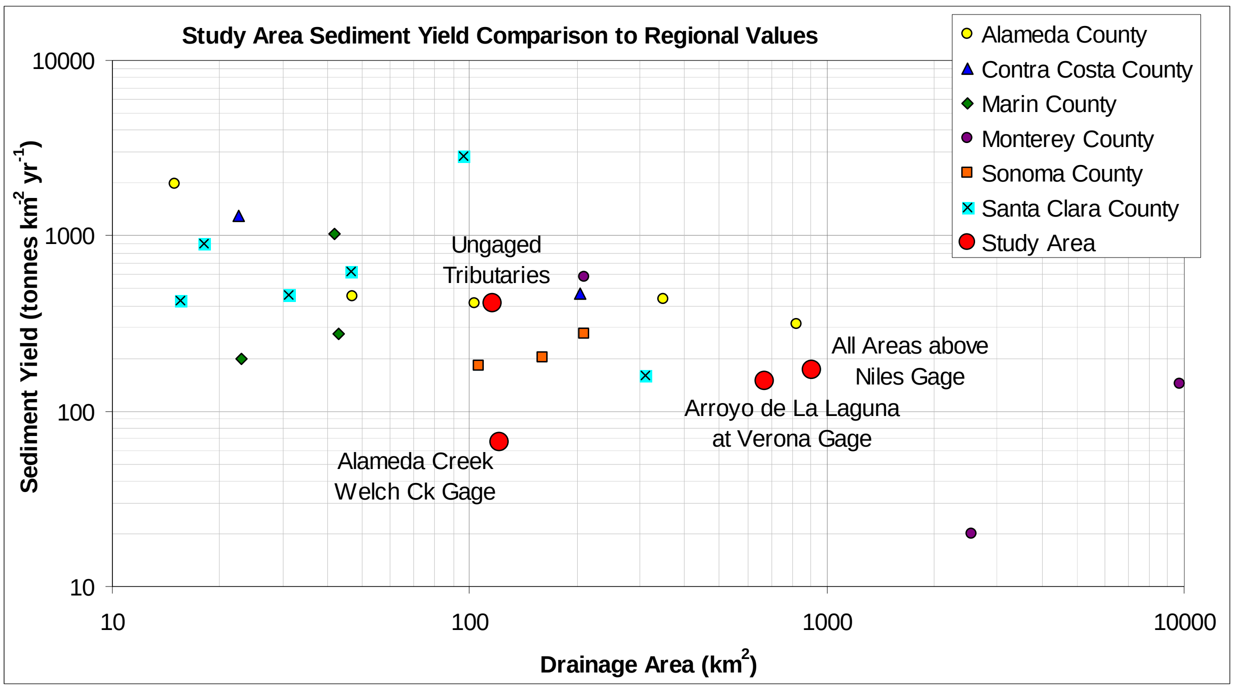


Figure 51. Comparison of sediment yield rates (on a per area basis) between the Alameda Creek watershed (study reaches, gages, and ungaged tributaries) and yields for other watersheds in the region. Sources for regional yields are shown on Table 10. To the best of our knowledge, the drainage areas shown include only areas below reservoirs.

Table 10. Regional estimates of sediment yield on a per area basis.

Basin	County	Drainage Area (km^2)	Sediment Yield (tonnes km^{-2} yr^{-1})	No. Years	time frame	Source
Alameda Creek near Welch Ck Gage	Alameda	121	66	13	1994 - 2006	This study
Ungaged Tributaries	Alameda	116	413	13	1994 - 2006	This study
Arroyo de La Laguna at Verona Gage	Alameda	670	148	13	1994 - 2006	This study
All Areas above Niles Gage	Alameda	907	172	13	1994 - 2006	This study
Cull Creek	Alameda	15	1971[b]	25	1979 - 2003	PWA 2005
San Lorenzo Creek	Alameda	47	452[b]	25	1981 - 2003	PWA 2005
San Antonio Reservoir	Alameda	104	413	80	1925 - 2004	Collins 2005
Alameda Creek	Alameda	821	311[b]	22	1982 - 2003	Weiss and Associates 2004
Calaveras Reservoir	Alameda	350[a]	433	40	1965 - 2004	Collins 2005
Wildcat Creek	Contra Costa	23	1,288	60	1940 - 2000	SFEI 2001
Walnut Creek	Contra Costa	205	464	6	1957 - 1962	Brown and Jackson 1973
Redwood Creek	Marin	23	198	22	1981-2002	Stillwater Sciences 2004
Corta Madera Creek	Marin	42	1,021	25	1976 - 2000	Stetson 2001
Bolinas Watershed	Marin	43	275	51	1950 - 2000	Tetra Tech 2001
Pescadero and Butano Creeks	Monterey	210	585[c]	66	1937 - 2002	ESA 2004
Pajaro River	Monterey	2,550	20[b]	47	1949 - 1995	Inman and Jenkins 1999
Salinas River	Monterey	10,760	143[b]	46	1950 - 1995	Inman and Jenkins 1999
Guadalupe Reservoir	Santa Clara	16	429	69	not reported[d]	Collins 2005
Calero Reservoir	Santa Clara	18	904	68	not reported	Collins 2005
Almaden Reservoir	Santa Clara	31	459	68	not reported	Collins 2005
Stevens Reservoir	Santa Clara	47	628	69	not reported	Collins 2005
Lexington Reservoir	Santa Clara	96	2,846	69	not reported	Collins 2005
Coyote Reservoir	Santa Clara	311	159	68	not reported	Collins 2005
Petaluma Creek	Sonoma	106	181[b]	58	1909 - 1966	Porterfield 1980
Sonoma Creek	Sonoma	161	202[b]	58	1909 - 1966	Porterfield 1980
Napa River	Sonoma	210	274[b]	58	1909 - 1966	Porterfield 1980

Notes:
a includes drainage area of both Calaveras Reservoir and Alameda Creek Diversion Dam
b suspended sediment only
c reported in volume, converted to mass using bulk denisity factor of 1.6 tonnes/m^3
d start and end dates not reported

Estimates of sediment yield within the Arroyo De La Laguna study reach are dominated by incision from 1901 - 1971 and bank erosion from 1994 - 2006 (Figure 48), and consequently also contain the most uncertainty (range of possible values given the possible “error” associated with the estimate) (Table 3). Similarly, estimates of sediment yield for the overall watershed are dominated by sediment loads from the watershed above Verona gage (62%) and the ungaged areas (28%), and therefore have the most uncertainty (Table 8). Because the ungaged areas rely entirely on extrapolated data, confidence in the findings of the overall sediment budget could be improved by quantifying sediment sources and rates from ungaged areas. Similar quantification of sediment sources and rates above Verona gage and possibly Alameda Creek above the Welch Creek gage[7] would also improve confidence in the findings and greatly improve our understanding of the primary processes supplying sediment, including identifying potential controllable sources of sediment. Previous reconnaissance level work has identified various sediment sources and sinks in the watershed above Verona gage (Ayres Associates 2001, Zone 7 Water Agency 2006, Figure 52), however the rates and relative contributions have not yet been quantified nor have they been evaluated from the perspective of potential for future control.

[7] It should be noted that although there are large earthflows upstream of the Welch Creek gage, sediment transport is likely limited by minimal flows from Calaveras reservoir.

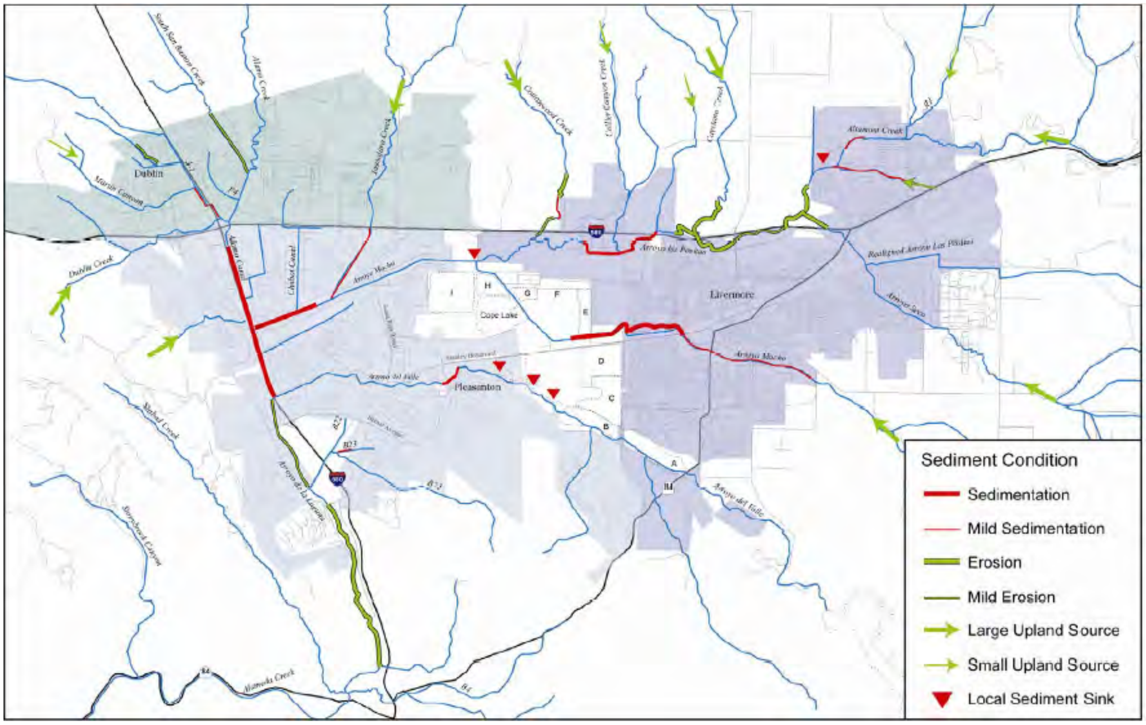


Figure 52. Watershed at and above Arroyo De La Laguna showing sediment sources and sinks identified in reconnaissance level surveys by Ayres Associates (2001) (map source: Zone 7 Water Agency 2006).

While there are many sources of sediment throughout the watershed, steep upland areas may be the largest source and future source analysis and sediment budgets should target these areas. Typically, mass wasting (landslides and debris flows) in low order channels that comprise upwards of 60 - 70 percent of the stream length network (Schumm 1956, Shreve, 1969), dominate most sediment budgets in the Pacific Coastal region (Dietrich and Dunne 1978, Swanson et al. 1982b), including the North Coast (Kelsey 1980) and Bay Area watersheds (Brady et al. 2003, Pearce et al. 2005). Mass wasting is likely a significant source of sediment in the Alameda Creek watershed as well. Although the contribution of mass wasting to sediment yield in Alameda Creek watershed has not been estimated, mass wasting is a well recognized feature in steeper regions of the watershed (Ellen et al. 1997, Wentworth et al. 1998, Coe and Godt 2001). Indeed, headwater basins in the Sunol area are fundamentally carved by debris flows (Alger and Ellen 1987). Accordingly, debris flow sources and runouts triggered by El Niño related storms in 1982 and 1997 show a high density of debris flows sources in the ungaged tributaries of our study (Figure 53). Because small streamside slides can dominate sediment budgets (e.g. Tetra Tech 2001, Lee Benda and Associates 2005), any analysis of sediment sources from mass wasting should include a substantial field component, as landslide inventories based strictly on air photos cannot detect directly connected streamside sliding obscured by tree canopy and hence significantly underestimate the budget (Brardinoni et al. 2003). An analysis of upland sources would also allow a better understanding of how the caliber of sediment supply has been altered over time, where coarse material potentially supplied through mass wasting in steeper regions is cutoff by reservoirs in nearly half the watershed.

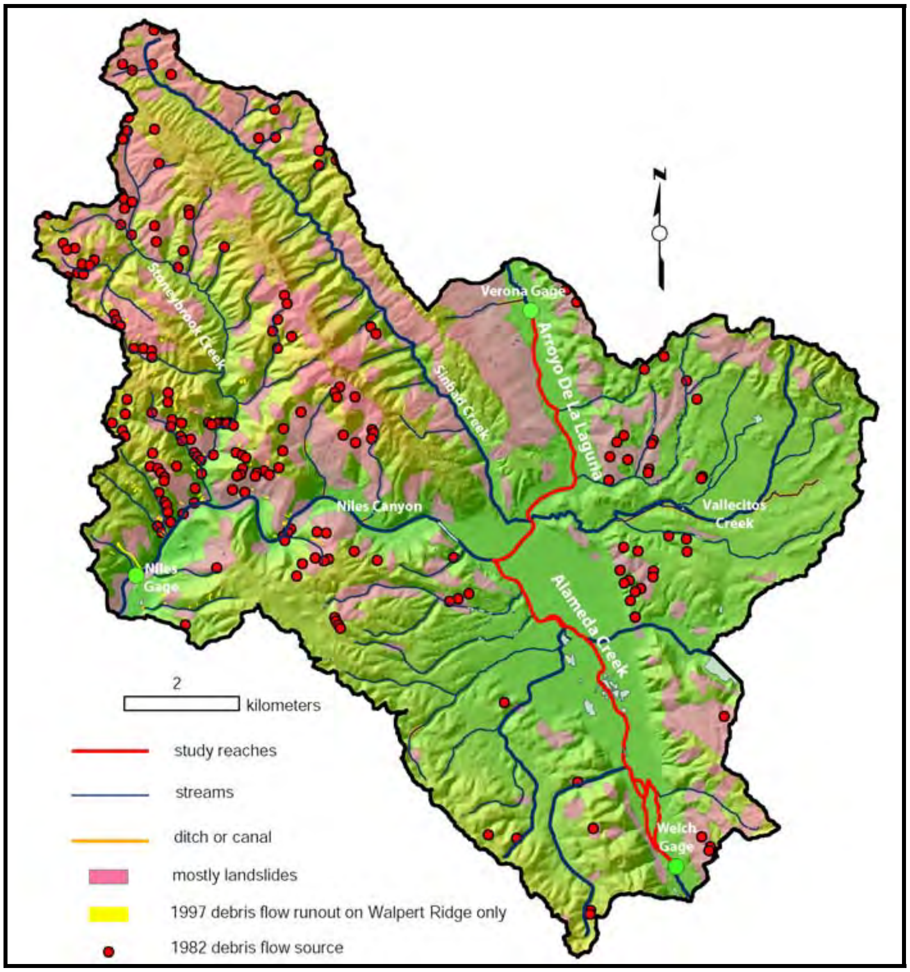


Figure 53. Areas of mass wasting in study area as mapped by USGS, including landslides (Wentworth et al. 1998), and debris flow sources or runouts mapped after El Niño events in 1982 (Ellen et al. 1997) and 1997 (Coe and Godt 2001).

Aggradation in the Flood Control Channel. Driven by Source or Sink Controls?

While this study focused on watershed sediment sources to the flood control channel, here we coarsely consider aggradation in the flood control channel as both a source and sink issue. With the rapid development of water projects in the late 20th century, reservoirs and impoundments rather than alluvial floodplains and colluvial hollows now dominate sediment storage in many watersheds (Vorosmarty et al. 1997, Stallard 1998, Renwick et al. 2005). Typical of most altered watersheds, sediment supply from roughly 44% of the Alameda Creek watershed is now trapped behind reservoirs (Figure 54). Much of this impounded area consists of steeper upper portions of the watershed that typically produce high sediment yields in the Coast Ranges, primarily from mass wasting. Although stream incision and channelization below reservoirs has fundamentally altered the function of many valley streams from sediment storage to sediment supply and sediment conduits, it appears unlikely that the current altered sediment yield is higher than sediment yields prior to reservoir construction, but remains an outstanding question that could be answered in future studies.

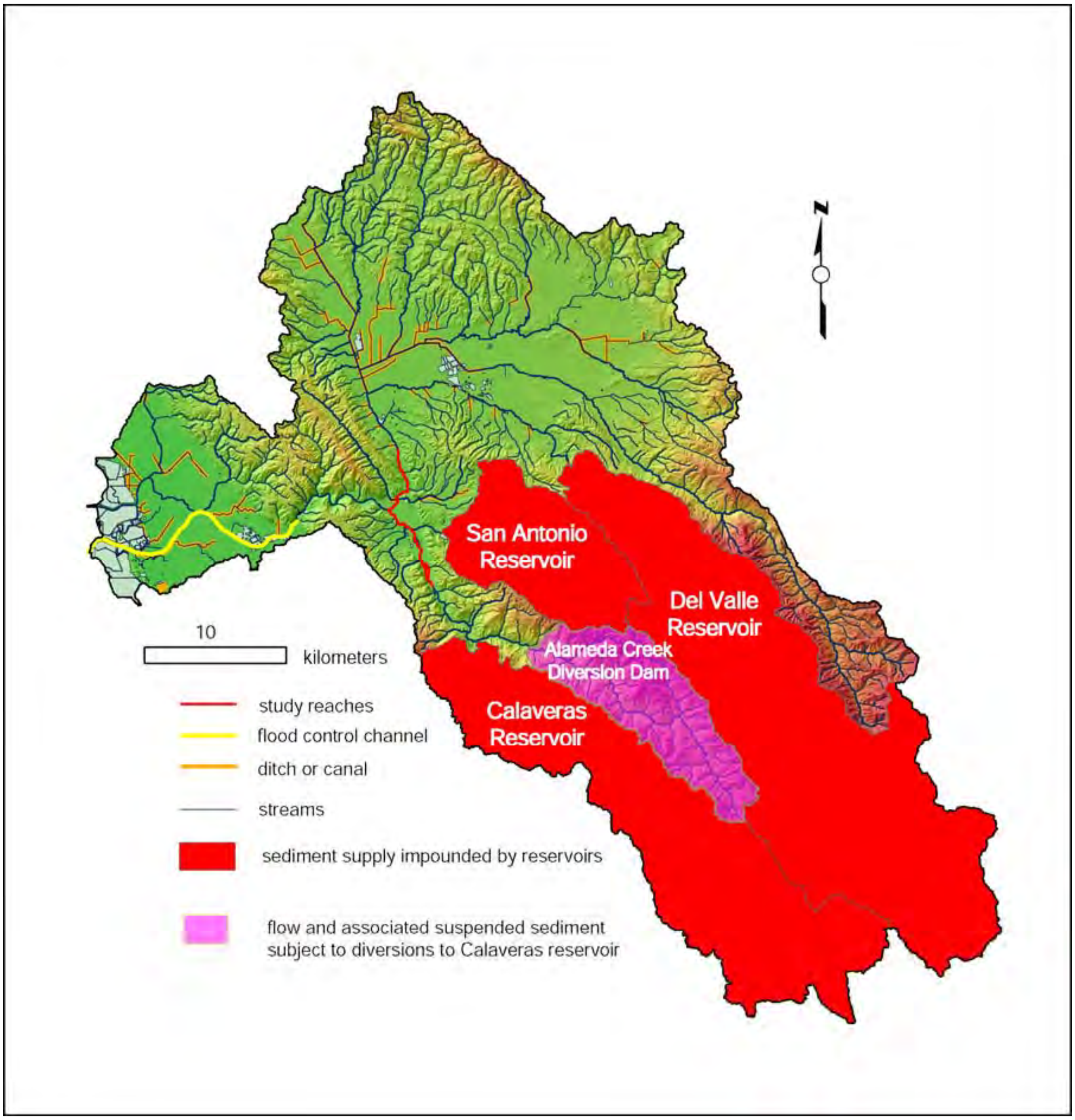


Figure 54. Area of sediment supply impounded by reservoirs.

To very coarsely evaluate such changes in sediment yield at Niles gage over the past century, we apply the suspended sediment and bedload rating curves from 2000 - 2006 to the entire daily discharge record for Niles. This estimate is essentially an evaluation in water discharge changes recorded at Niles over the past century and uses a static relationship between discharge and sediment load, and therefore *the sediment load numbers should not be used quantitatively*. Among other issues, this approach underestimates sediment yield prior to dam construction because a reduction in load at Niles gage is apparent in the sediment rating curves before and after construction on Del Valle Reservoir in 1968 (Figure 55) and similar reductions in the sediment load from the San Antonio, Calaveras, and possibly the Alameda Creek diversion dams are highly probable, as well as other influences on the sediment discharge relationship from land management. Still, this approach provides a very rough but useful estimate of sediment yield flux over time at Niles that may be due to changes in precipitation and land management, including reservoir construction. A century scale comparison of sediment discharge at Niles with mean annual precipitation in the watershed (average of 3 stations at Sunol, Pleasanton, and Livermore, based on records from Goodridge [2007]) shows that sediment yield corresponds closely with precipitation with the exception of two large departures (Figure 56). The first departure occurred when extreme floods of the 1950s supplied massive amounts of sediment to the watershed, elevating sediment yield relative to mean annual precipitation. An opposite departure occurred in the 1980s and 1990s centered around El Nino events in 1982 and 1997, when sediment yield decreases relative to mean annual precipitation, following the first wet periods after construction of San Antonio and Del Valle Reservoirs, in 1965 and 1968 respectively. This departure is most likely due to a reduction in water and sediment supply from impoundment behind San Antonio and Del Valle Reservoirs. The overall trend of sediment yield at Niles gage shows two elevated periods (15 year moving averages of 300,000 - 350,000 tonnes/yr) of sediment yield in the early 1900s, coinciding with higher wet periods, and the 1950s floods, followed by reduced sediment yields in the 1980s and 1990s (15 year moving averages of < 200,000 tonnes/yr), which were roughly 30% lower (Figure 56). In addition to sediment and water impoundment, reservoir releases such as the South Bay Aqueduct Project water transfers (Central Valley water transferred to Del Valle reservoir to the Southbay via Arroyo De La Laguna and Alameda Creek) and other alterations in stream flow from urbanization appear to substantially increase the base flow observed at Niles gage, supplying perennial flow to a system that was formerly ephemeral (Figure 57).

Despite substantial reductions in sediment loads at Niles gage from changes in precipitation and reservoir impoundment, the reduced supply continues to deposit downstream in the flood control channel where sediments historically deposited on distal portions of the Niles fan and floodplain over millennia. This is likely due to the shortsightedness of a flood control channel designed to pass large flows with little consideration of sediment transport, where sediment accumulates in the enlarged trapezoidal channel bound by levees because (1) the creek can no longer deposit sediment on the historical fan and floodplain, and (2) deepening and widening of the channel to accommodate large flows reduced the competence of more frequent intermediate flows to transport sediment. Longitudinal profiles for the flood control channel presented by Collins (2005) indicate most of the aggradation occurs downstream of the major break in slope near Decoto Road Bridge, near the distal end of the Niles Fan, downstream to the Ardenwood Bridge, near the upstream extent of tidal influence (Figures 58 and 59). Moreover, aggradation shown in the profile since construction of the channel (i.e. from design grade profile to the 2003 “top of sediments deposits” profile [presumably the tops of bars], Figures 58 and 59) is approaching the estimated 1915 bed elevation of Old Alameda Creek above Decoto Road (Figure 58), suggesting the flood control channel is returning to a similar elevation of the historic Old Alameda Creek through aggradation. This is a common response in many flood control channels throughout the United States, including California (Griggs and Paris 1982, Mount 1995) and the Bay Area, where active dredging occurs in flood control channels near the bay margin of many watersheds (e.g. Guadalupe River, Coyote Creek, Napa River) to maintain design flood capacity (Dillon 2004, Grossinger et al. 2006). Note that here we just consider watershed sources of sediment to the flood control channel, however, tidal influences and sources are also a major consideration for sediment dynamics and deposition in this area.

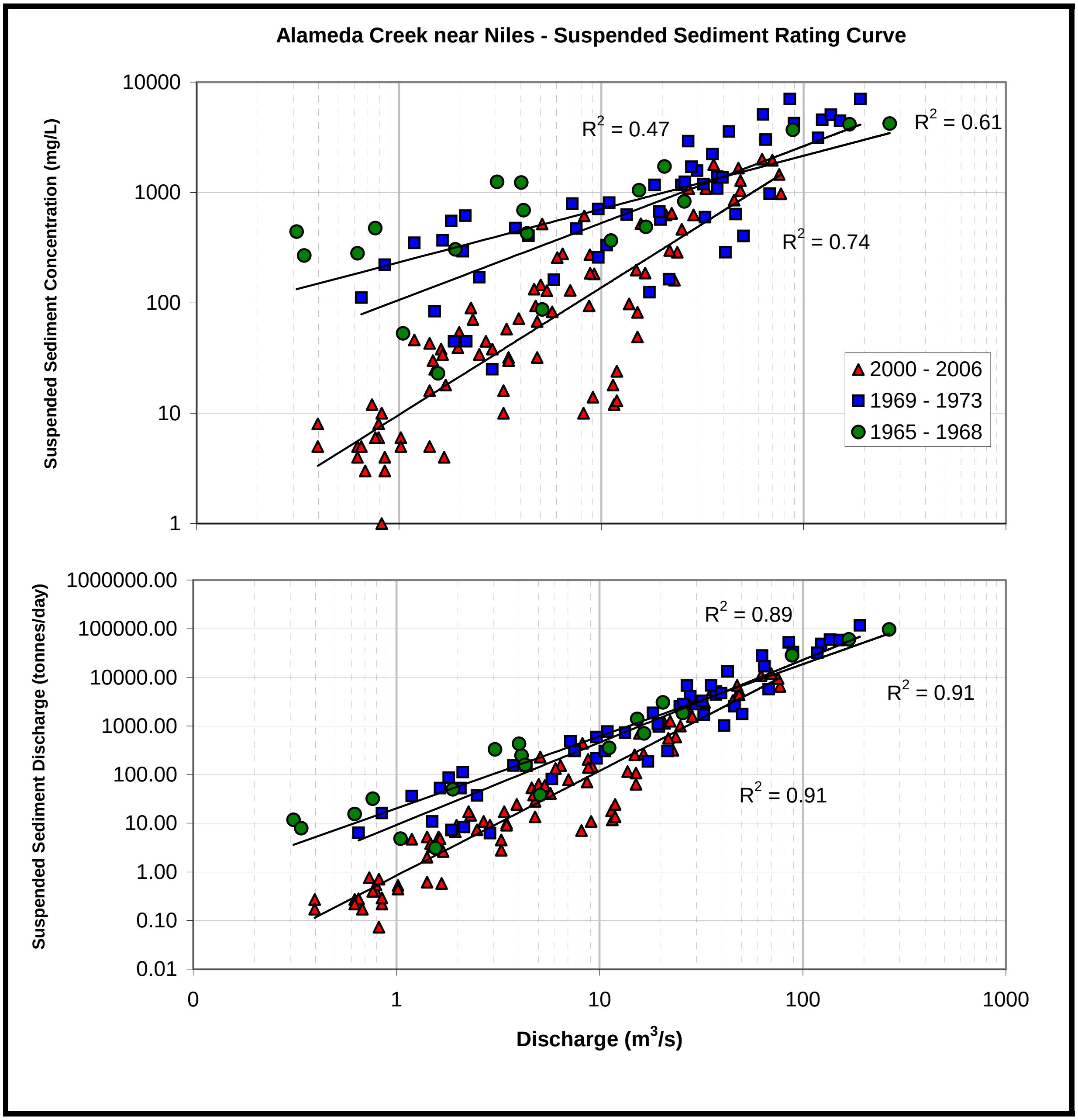


Figure 55. Changes in the suspended rating curve for available time periods at the gage on Alameda Creek near Niles (USGS station 11179000) indicating a reduction in suspended load due to Del Valle Reservoir (constructed 1965 - 1968).

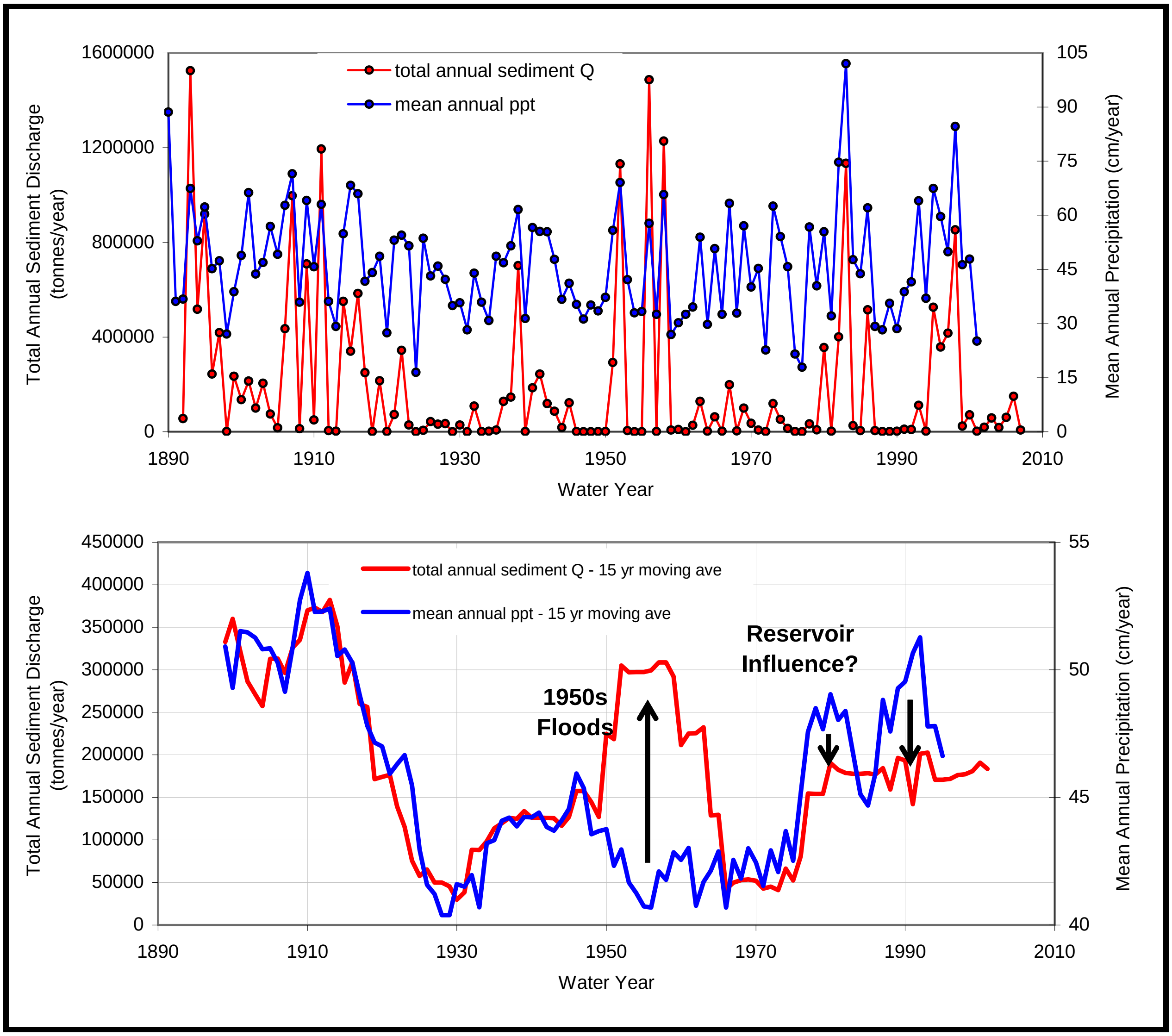


Figure 56. Estimated total annual sediment discharge at Niles gage over the past century and mean annual precipitation averaged from three stations in Sunol, Pleasanton, and Livermore based on data from Goodridge (2007).

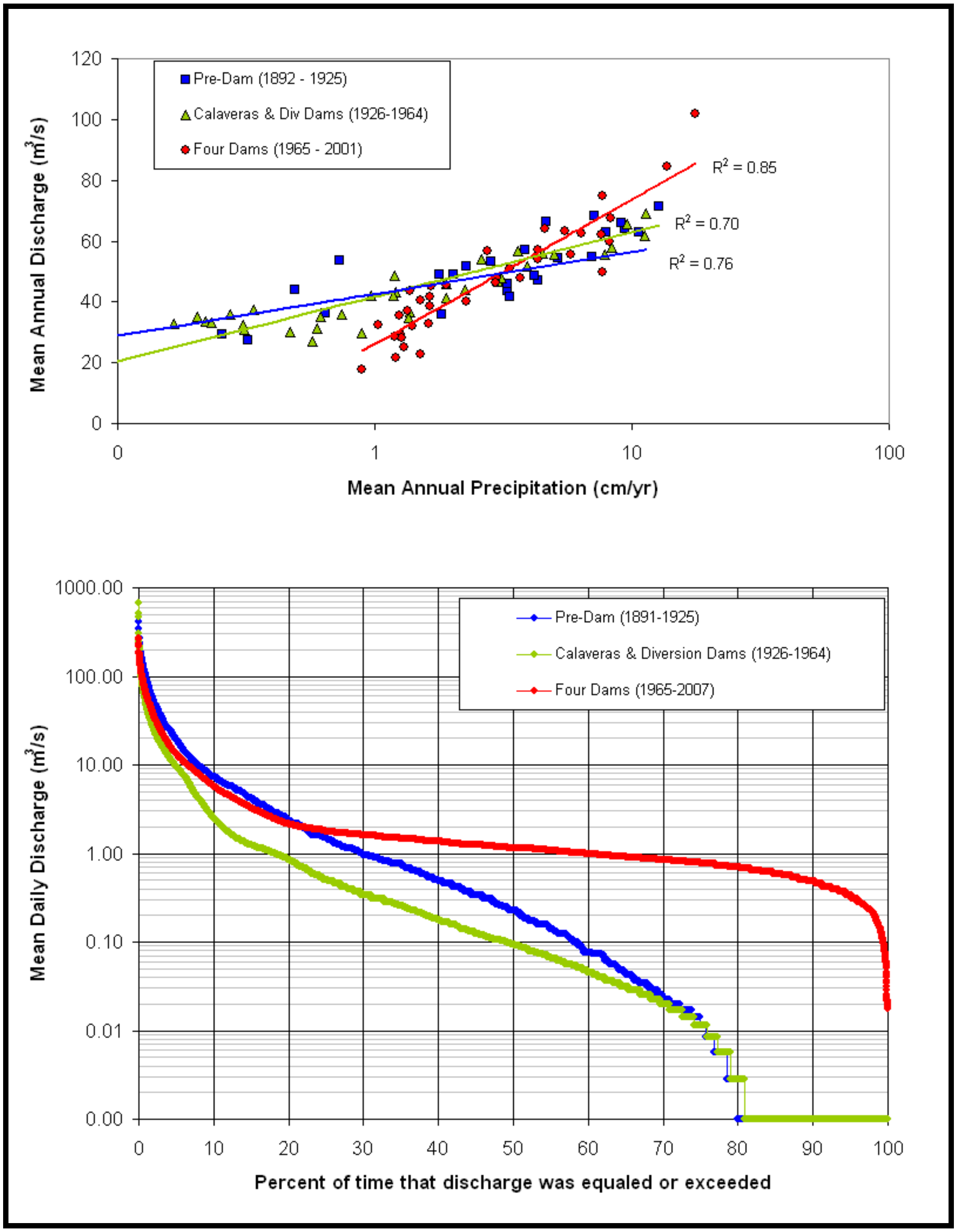


Figure 57. (upper) Relationship between mean annual discharge and mean annual precipitation at Niles gage for three different time periods showing a change after 1965 (that includes the construction of San Antonio and Del Valle reservoirs), where more water is stored in reservoirs in low precipitation years and more water is released in high precipitation years. (lower) Flow duration curves for three time periods at Niles gage showing a substantial increase in base flow after 1965 where water releases from Del Valle Reservoir and associated water transfers (South Bay Aqueduct Project) through the basin now provide perennial flow at Niles.

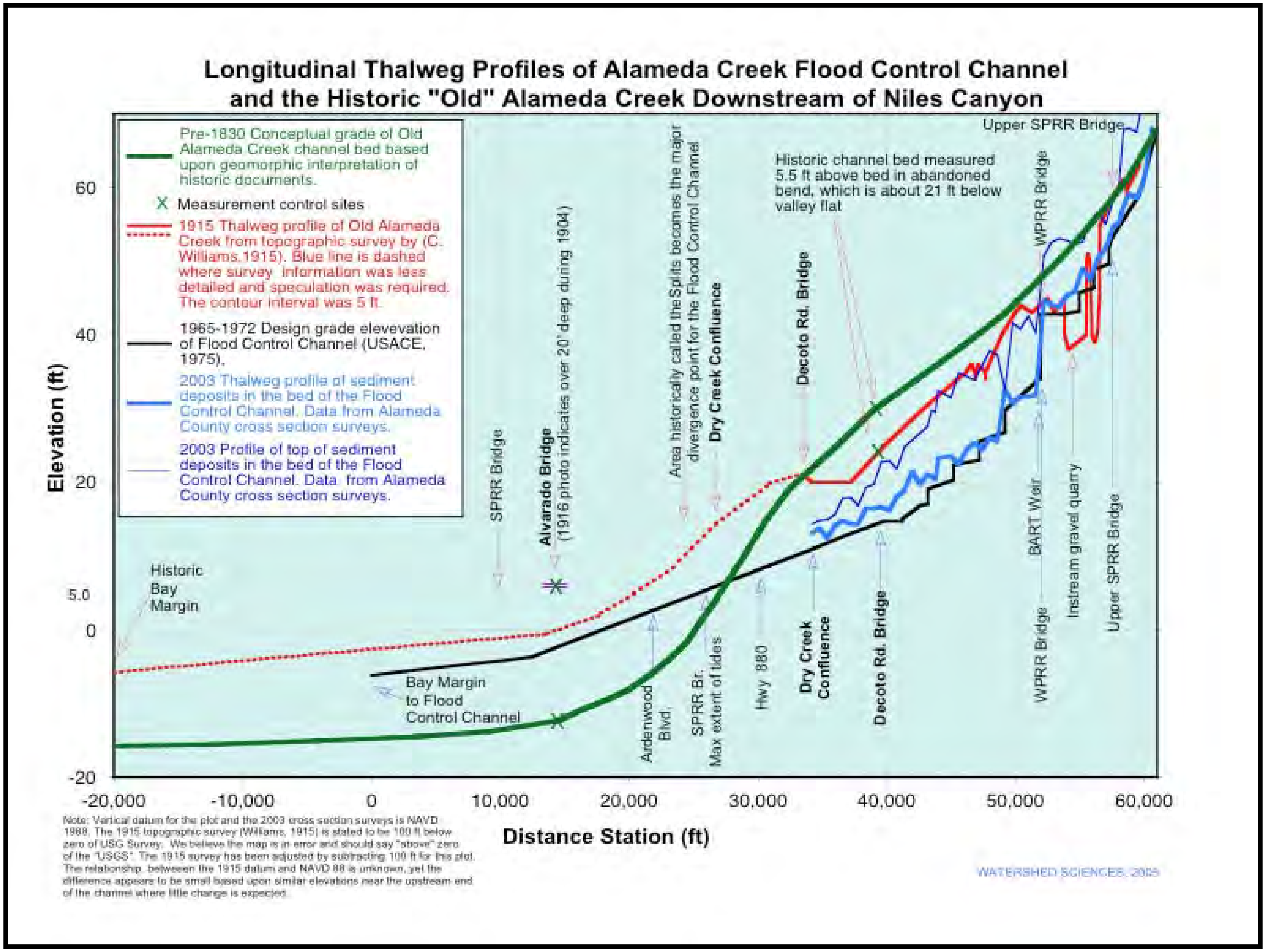


Figure 58. Comparison of longitudinal profiles for various surfaces in the flood control channel and Old Alameda Creek by Collins (2005)

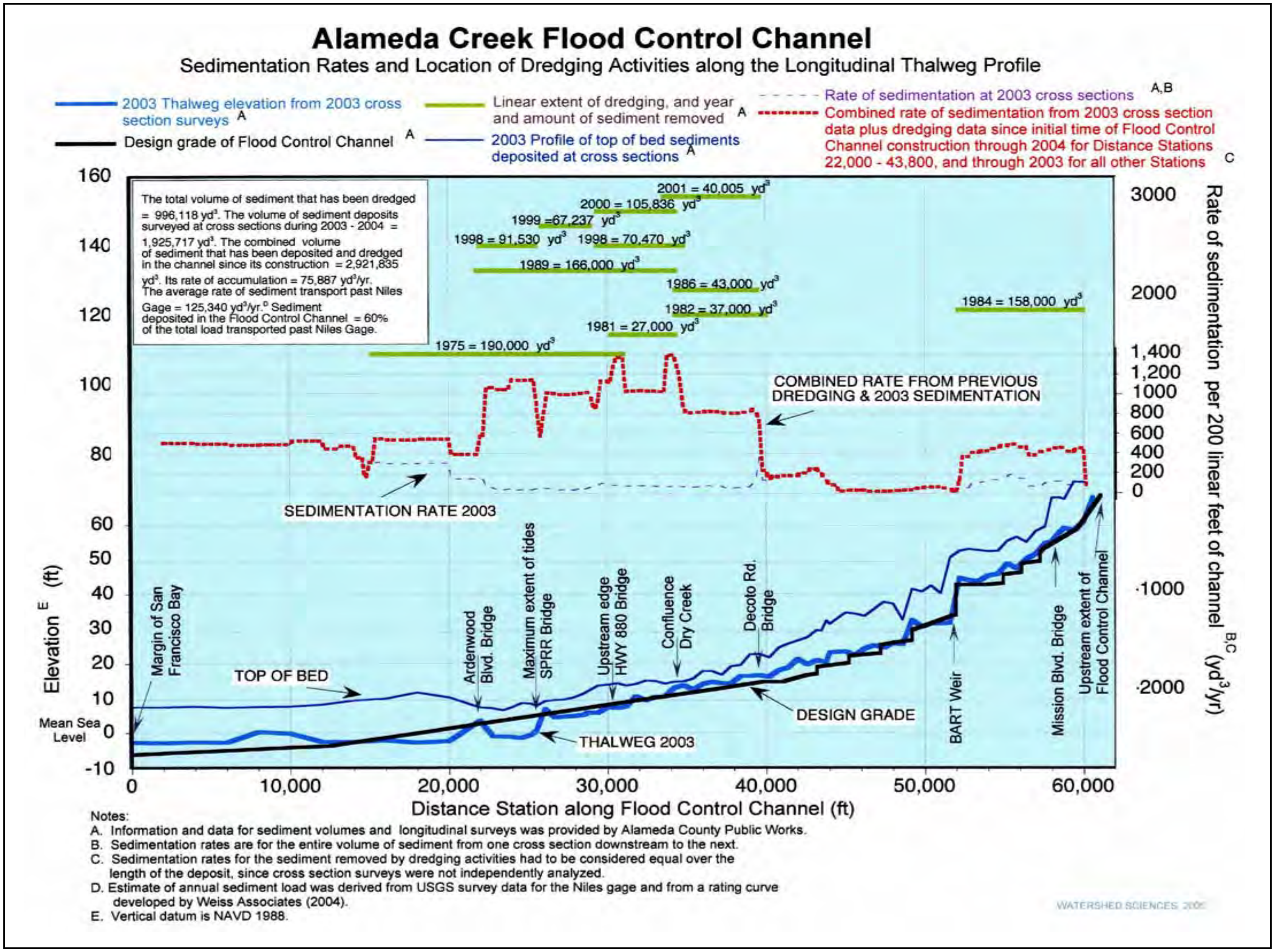


Figure 59. Longitudinal profiles of the flood control channel and estimated sedimentation rates by Collins (2005).

Channel Evolution

Although neither of the study reaches dominate the supply of sediment to the flood control channel when compared to other portions of the watershed, bank erosion in the Arroyo De La Laguna study reach will likely continue, particularly following substantial wet periods and during large floods. In addition, the stakeholders involved in this study (Alameda County Flood Control District, Alameda County Zone 7 Water Agency, San Francisco Public Utilities Commission) have placed high value in evaluating the potential erosion trends of Arroyo De La Laguna, given the continued erosion of banks near residential property immediately upstream of the study reach and future urban development in the upper watershed. Arroyo De La Laguna is continuing to evolve and will continue to supply sediment to downstream reaches until it attains a "stable channel form" or dynamic equilibrium. To this end, we explore possible erosion trends of the Arroyo De La Laguna study reach by:

1. Summarizing the concept of channel evolution models.

2. Summarizing and synthesizing the major historical alterations of flow and sediment supply to Arroyo De La Laguna.

3. Using a channel evolution model and the history of Arroyo De La Laguna to qualitatively interpret and infer past, present, and future erosion trends.

4. Recommend possible future actions to better quantify erosion trends of Arroyo De La Laguna.

It should be noted that Ayres and Associates (2001) evaluated the channel stability of Arroyo De La Laguna and upstream channels that included a brief analysis of channel evolution (see later). Our intention is not to repeat an analysis of channel evolution, but further the analysis for Arroyo De La Laguna using observations made during this study. We did not analyze the channel evolution for the Alameda Creek study reach because: (1) major bank erosion and incision are not apparent in the reach, (2) the reach appears to function primarily as a sediment transfer reach (not supply), and (3) 70% of the watershed draining to the reach is impounded by Calaveras and San Antonio reservoirs, substantially reducing sediment dynamics in the reach under the current flow regime. If flow releases from the reservoirs to the study reach are increased in the future (for example, increased flows to improve fish passage and habitat), sediment supply from the reach by incision and bank erosion are possible and should be considered in future analyses.

Arroyo De La Laguna Channel Evolution

Channel Evolution Model Summary

Channel evolution models (CEMs) are a process-based classification system that conceptually describe the typical sequence of how channel forms observed as channels of large alluvial rivers respond to significant disturbance, primarily anthropogenic disturbance. CEMs illustrate the progression of the channel from "equilibrium", to disequilibrium, and then to a new state of dynamic equilibrium (Bledsoe et al. 2002). Several CEMs have been developed that are generally similar in substance with slight variations between them (e.g. Schumm et al. 1984, Simon and Hupp 1986, Simon 1994; Doyle and Shields 2000). Despite the varied types of channel disturbance and geographic and climatic settings, the conceptual models have widespread applicability because they are based on the adjusting balance between driving and resisting forces (Simon et al. 2007), where channels in many different regions display a similar progression or evolution (Schumm 1999, Bledsoe et al. 2002) including the Pacific Northwest (Simon and Rinaldi 2006). Despite limited published research on San Francisco Bay Area streams, Riley (2003) suggests that such models developed for low gradient streams in the Midwest (Schumm et al. 1984) are not applicable to steeper flashier coastal streams of the Bay Area. However, the Arroyo De La Laguna study reach is indeed a low gradient system (< 1%) that drains a large area (1,044 km^2) (Table 1, Figure 2), similar to those used to develop the CEMs and perhaps not representative of the smaller steeper coastal streams that Riley (2003) references. Moreover, observations in this and two other studies (Ayres and Associates 2001; V. Mahacek of Valley & Mountain Consulting, personal communication 2007) suggest the CEM is indeed useful for interpreting the channel evolution of Arroyo De La Laguna.

Essentially, the CEMs provide a basis to infer past and present channel processes and estimate probable future channel response using a description of systematic temporal adjustments (Simon and Darby 1999). Channel adjustment results from imbalances in driving and resisting forces, where a disturbance alters the balance between sediment supply and sediment-transporting capacity (Simon et al. 2007). In response, the channel will adjust in order to return the balance of sediment transport ability, typically by incising to reduce channel gradient. Once incision has commenced, it is unlikely to cease naturally until the channel has progressed through several stages of evolution (Schumm 1999). As evolution occurs, the channel response is punctuated, not gradual, as several geomorphic thresholds are crossed (Hupp and Simon 1991). In this evaluation of channel evolution for Arroyo De La Laguna, we use a more detailed six stage model described by Doyle and Shields (2000) that was adapted from Simon (1994) (Figure 60). The six stage CEM (Doyle and Shields 2000) with an additional seventh stage from Thorne (1999) is summarized as follows:

Stage I - **Pre-disturbance,** includes the premodified channel, representing a channel that is stable and in dynamic equilibrium.

Stage II - **Disturbance,** represents the time period during and immediately after the disturbance occurs.

Stage III - **Incision**, is where the channel *downcuts* because there is too much sediment-transporting capacity relative to sediment supply (Lane 1955, Simon and Hupp 1986, Simon and Darby 1999). The degradation is initially rapid, but then slows with time, modeled as a non-linear, asymptotic channel response and energy decrease (Simon 1989, Simon and Rinaldi 2006). The downcutting causes increased bank heights that are at the angle of internal friction, but not yet failing. This stage is the most important in determining the magnitude of channel widening that will occur in the future because the amount of incision partly controls the bank-failure threshold (Simon 1989). The length of time that degradation (down cutting) will occur is difficult to predict; Hupp and Simon (1991) suggest that Stage III is short lived, perhaps only 1 to 3 years. However, some studies suggest the bed composition is vital in determining the time frame of response. For example, silt bedded channels may incise for a longer period compared to sand beds. Depths and periods of incision (Stage III and Stage IV combined) observed in various studies include: 6 meters over 10 – 15 years in sand beds (Tennessee; Simon 1989); 2 - 5 meters over 20 years in sand and silt beds (Mississippi; Thorne 1999), 20 – 30 meters over 10 years in beds composed of non-cohesive coarse volcanic material (Washington; Simon and Rinaldi 2006), and incision and widening over 70 years in silt beds (Iowa; Simon and Rinaldi 2006).

Stage IV - **Widening and Incision** marks the switch from purely channel incision to both *widening and incision*. This often sudden change represents an important threshold in the channel's evolution and recovery, because widening reduces flow depth, shear stress and sediment transport capacity (Simon and Darby 1999). At this stage, the critical height of the bank has been exceeded, and the banks begin to fail. Slab, rotational, and pop-out bank failures are observed as the mass-wasting process occurs. Similar to incision, the amount of channel widening is difficult to predict, and a large range of values are found in the literature. However, authors note that the rates of widening primarily vary with bank composition and climatic setting. For example, rates can vary from 0.01 m/yr in bedrock canyons, to 1 m/yr in cohesive materials, and up to 100 m/yr in non-cohesive materials (Simon and Darby 1999, Simon et al. 2000, Simon and Rinaldi 2006). Also, channel width increases of 200-300% have been documented after the passage of a headcut (Thorne 1999). Many of the field studies have shown that the sediment contributed by bank widening can represent 64-90% of the annual sediment yield (Simon et al. 2000, Simon and Rinaldi 2006). For example, channel erosion in an urban creek in Southern California accounted for 66% of the measured sediment yield (Trimble 1997), where banks may be the principle source of coarse material being delivered to the channel (Watson et al. 1986, Doyle and Shields 2000). Stage IV (widening and incision) may last 5 to 15 years (Hupp and Simon 1991), although we suggest that the frequency of flood events is also important in determining the timeframe in incised systems in a Mediterranean climate such as California. The mechanisms of bank failure that occur within this stage are important to understand in order to predict the further evolution of the channel. The five main driving forces controlling bank failures are: increase in soil unit weight (primarily due to water), decrease of matrix suction, positive pore-water pressures, entrainment of bank toe material, and loss of confining pressure during hydrograph recession (Simon and Darby, 1999, Simon et al. 2000). In addition, over-heightening, over-steepening by degradation, undercutting and seepage forces at the toe of the bank were cited as causes of failure in a Tennessee river (Simon 1989). Greatest bank failures are believed to occur during the peak of a large flood, however, Simon et al. (2000) suggests there is often a lag time between peak flow and peak bank failure and that not necessarily the largest floods, but the prolonged wet periods induce the greatest bank failures.

Stage V - **Aggradation** marks an important transition in the channel's evolution, with bed aggradation and the formation of a depositional surface marking the beginning of recovery. Aggradation occurs because of the high sediment supply from upstream incision and widening, and helps to reduce the channel gradient, and thus, stream power. Although aggradation can appear to be dramatic, the bed rarely recovers to predisturbance elevations (Simon and Darby 1999). Rates of aggradation have been measured up to 0.12 m/yr (Simon 1989), and occurring for 20 to 50 years (Hupp and Simon 1991). In addition to bed aggradation, Stage V also includes the formation of a depositional surface on the banks. When the channel becomes so wide that it cannot remove failed bank material, the accumulated material begins to buttress the bank toe, inducing vegetation growth and fine sediment deposition (Thorne 1999). Bank accretion and vegetative regrowth appear to be the most important processes in bank recovery (Hupp and Simon 1991). This stage can be identified by observation of sand deposited on bank surfaces (Simon 1989) and the continued mass wasting of the upper banks, creating a low-angle lower bank surface that is periodically fluvially reworked. In Tennessee, the rates of deposition on this surface were measured as 5.9 cm/yr on inside channel bends and 4.2 cm/yr on straight reaches (Hupp and Simon 1991).

Stage VI - **Dynamic-equilibrium** is marked by significant reduction in overall bank heights due to bed aggradation, fluvial deposition on sloping bank surfaces, and the establishment of woody vegetation on bank surfaces. During this stage, deposition of bars induces thalweg meandering, and further reduction in the channel gradient.

Stage VII - **Floodplain Formation** has been proposed as a late stage of evolution by Thorne (1999). This final stage represents the dynamically stable channel morphology, in which the channel has decreased sediment transport capacity, increased sinuosity, and creation of a proto-floodplain surface (Figure 61).

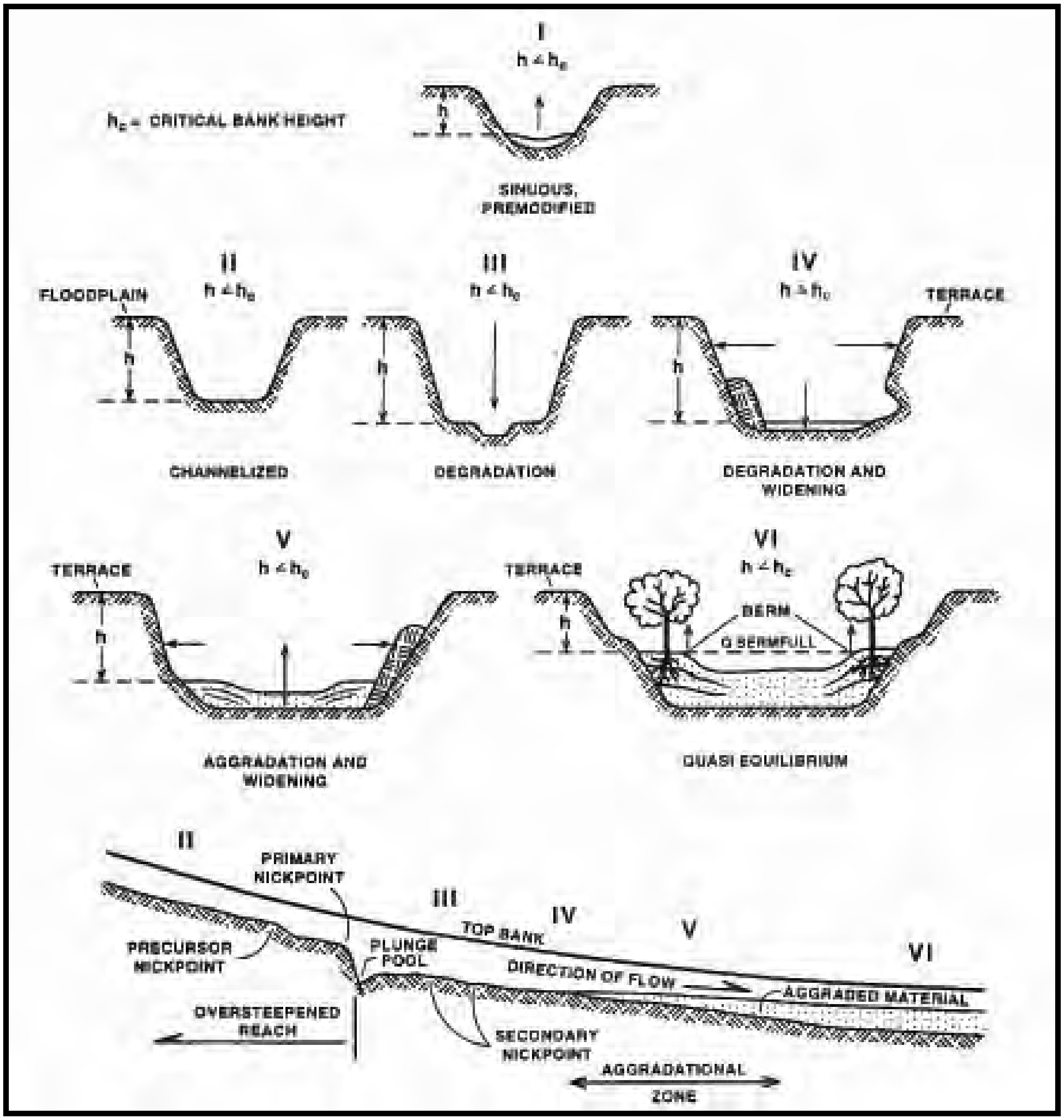


Figure 60. Channel evolution model of Doyle and Shields (2000) modified from Simon (1994).

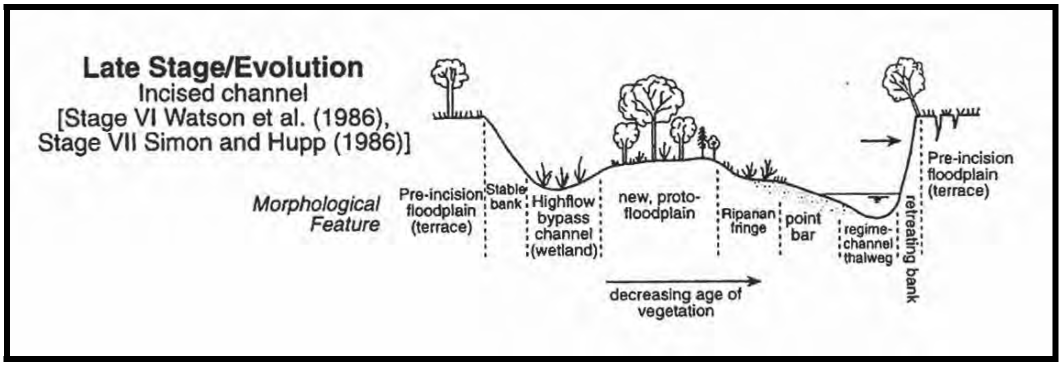


Figure 61. Proposed **Floodplain Formation** Stage VII (Thorne 1999). This stage accounts for the late-stage morphological evolution involving the development of cross sectional asymmetry, establishment of a new floodplain and channel slope adjustment through the growth of meanders as the system approaches a “dynamically stable”, graded condition.

The time scale over which channel evolution occurs until the channel and floodplain size (capacity) are in long-term equilibrium with sediment supply and flow is highly variable. Recall, that evolution is typically punctuated, as many internal geomorphic thresholds are crossed. However, despite the punctuated nature, the entire evolution time frame can range from short to long periods. For example, if the disturbance to the channel is gradual, such as tectonic uplift or climatic change, the adjustment may be very slow. In contrast, anthropogenic alterations and extreme natural events can result in a sudden and significant “shock” to the fluvial system, compressing the total timeframe for channel response (Simon 1989; Simon and Darby 1999). Also, the grain size of bed and bank sediment highly influences the rate and type of channel evolution (Schumm 1999, Simon et al. 2007), where channels with coarse beds and banks might experience faster recovery (e.g. Dolye and Shields 2000). In sand bed channels, incision through aggradation (stages I – V) has been shown to have occurred over a period of 20 - 40 years, whereas stabilization of channel banks and reestablished meanders (stages VI – VII) occurred over a period of 50 to 100 years (Simon 1989), similar to time scales reported by Simon and Darby (1999) primarily in Midwestern U.S. channels. Schumm (1999) suggests that the entire sequence can take 40 to 50 years in channelized streams of the Southeast and over 100 years in the arroyos of the Southwest (many of which are eroding very weakly cohesive lithologies and soils). Despite the channel grain size, instability can persist for decades depending on the watershed size and land use (Bledsoe et al. 2002). For example, channel evolution trends may be disrupted by the effects of urbanization, where urban streams often have highly altered water and sediment flow regimens and are constrained both laterally and longitudinally by infrastructure (Niezgoda and Johnson 2005). Some typical urban effects on channels include significant channel widening downstream of urban areas (Gregory et al. 1992) or major increases in sediment yield from channel erosion (Trimble 1997, Trimble 1999, Nelson and Booth 2002). Given the different causes of disturbance, the dominant channel grain size, and surrounding land use, the timeframe of channel evolution can be highly variable and difficult to quantify.

Major Alterations in Flow and Sediment Load to Arroyo De La Laguna

To provide a basis for interpreting channel evolution in Arroyo De La Laguna, here we summarize the major alterations in flow and sediment load to the study reach. The three primary historical alterations in flow to Arroyo De Laguna include: increased flow following channelization of the Livermore-Amador Valley to drain the historic lagoon (Tulare Lake) in 1901 (Figure 62), increased runoff from suburban development after the 1960s, and the construction of Del Valle Reservoir in 1969. Because flow records did not begin in Arroyo De La Laguna until 1912, well after channelization, it is not possible to quantify the increase in flow to Arroyo De Laguna following channelization. However, because the historic lagoon undoubtedly had some dampening effect on peak flows, qualitatively it seems very likely that peak flows in Arroyo De La Laguna increased substantially following channelization. Coincident with channelization and draining of the lagoon, the Spring Valley Water Company also pumped groundwater from a well field in the near the Arroyo De La Laguna channel (Williams 1912). This water was input into the channel, and then removed further downstream to feed an area of groundwater infiltration galleries near the Arroyo De La Laguna and Alameda Creek confluence (Williams 1912). Although details of the well field operation are vague, if substantial drawdown of the water table occurred, this can also contribute to channel instability as seepage from alluvial banks during floods can substantially attenuate peak flows (e.g. Kondolf and Curry 1986, Kondolf et al. 1987).

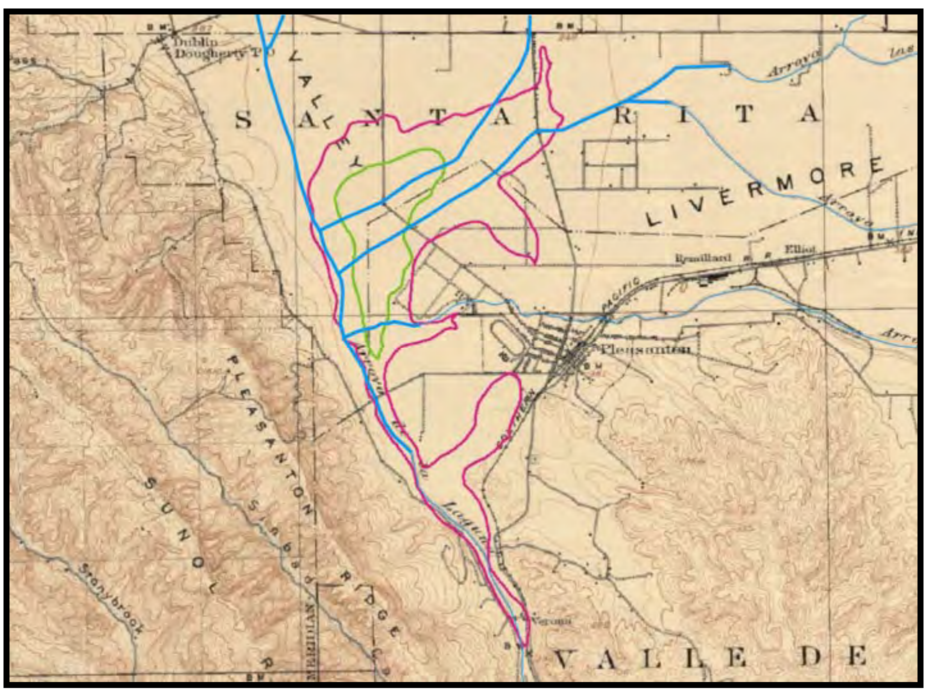


Figure 62. USGS 1906 topographic map showing the historic (pre-1901) boundary of Tulare Lake (in green) and the willow marsh (in pink) through which no obvious channels flowed. Although some ditching likely occurred before 1901, concurrent with the draining of Tulare Lake (1901), the primary ditches were created (highlighted in heavy blue) to drain the lagoon and connect upstream tributaries to Arroyo De La Laguna.

Increased impervious surfaces from suburban development can alter the runoff characteristics of a basin by increasing peak flows, decreasing lag time between rainfall and runoff response, and decreasing groundwater recharge (Dunne and Leopold 1978). However, these effects are difficult to discern in the limited flow records for Arroyo De La Laguna that exclude the period between 1930 and 1969, when such suburban runoff effects would be most apparent in flow records prior to influences from Del Valle Reservoir. Del Valle Reservoir serves as both flood control for downstream areas and storage for the South Bay Aqueduct that imports water from the Sacramento-San Joaquin Delta. The reservoir captures flow and sediment from roughly 35% of the watershed area above the Arroyo De La Laguna study reach (Table 1, Figures 2 and 54). An analysis of the relationship between precipitation and peak flows in Arroyo De La Laguna before (1912 - 1930) and after (1969 - 2007) the construction of Del Valle Reservoir suggests that smaller peak flows have increased for a given wet period (30 days), possibly reflecting increased runoff from suburban development, while effects on larger peak flows are not discernable from the limited data (Figure 63). A more complete gage record exists for Alameda Creek near Niles, but it is too far downstream to detect such effects for Arroyo De La Laguna. Comparing the available mean daily flow records for Arroyo De La Laguna before and after reservoir construction shows substantial increases in flow from the dam, including a 90% increase in mean annual flow (from 1.12 to 2.13 m^3/s) and a 50% reduction in variation (from 6.94 to 3.55 m^3/s coefficient of variation). Flow duration curves and mean annual hydrographs for the two periods also show dramatic increases in base flow, where stream flow was formerly ephemeral, dam releases and water transfers now provide perennial flow to Arroyo De La Laguna (Figure 64). Prior to breaching the historic Tulare Lake, Arroyo De La Laguna may have had perennial flow from the lake, however with no flow data or other information this remains speculative. Such alterations in flows below dams can have substantial effects on downstream sediment transport and channel conditions (Collier et al. 1996) as well as associated aquatic and riparian habitat (Ligon et al. 1995) and are important for trying to assess the potential future response in Arroyo De La Laguna.

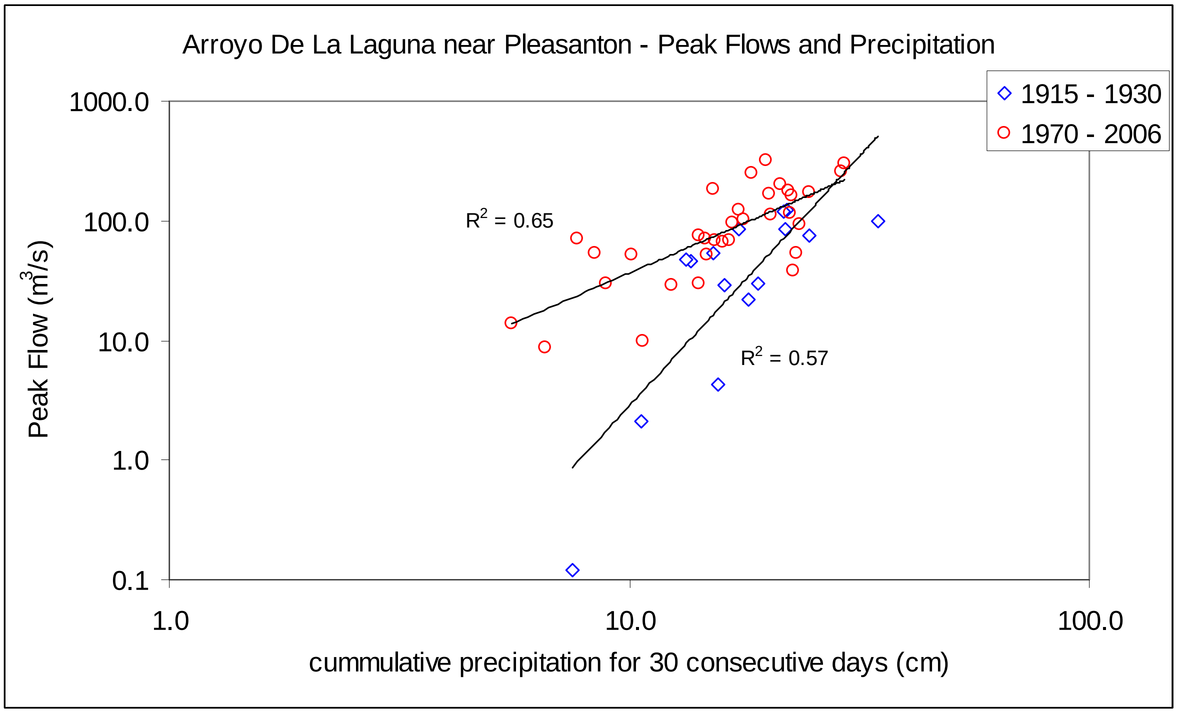


Figure 63. Relationship between peak flows at Arroyo De La Laguna and the highest 30 day cumulative precipitation (averaged from 3 stations at Livermore, Pleasanton, and Sunol based on data from Goodridge [2007]) for the two periods of record. Note that precipitation for specific storm (precipitation) events associated with peak flows was not available, and such data is needed to make more reliable assessments of changes in runoff.

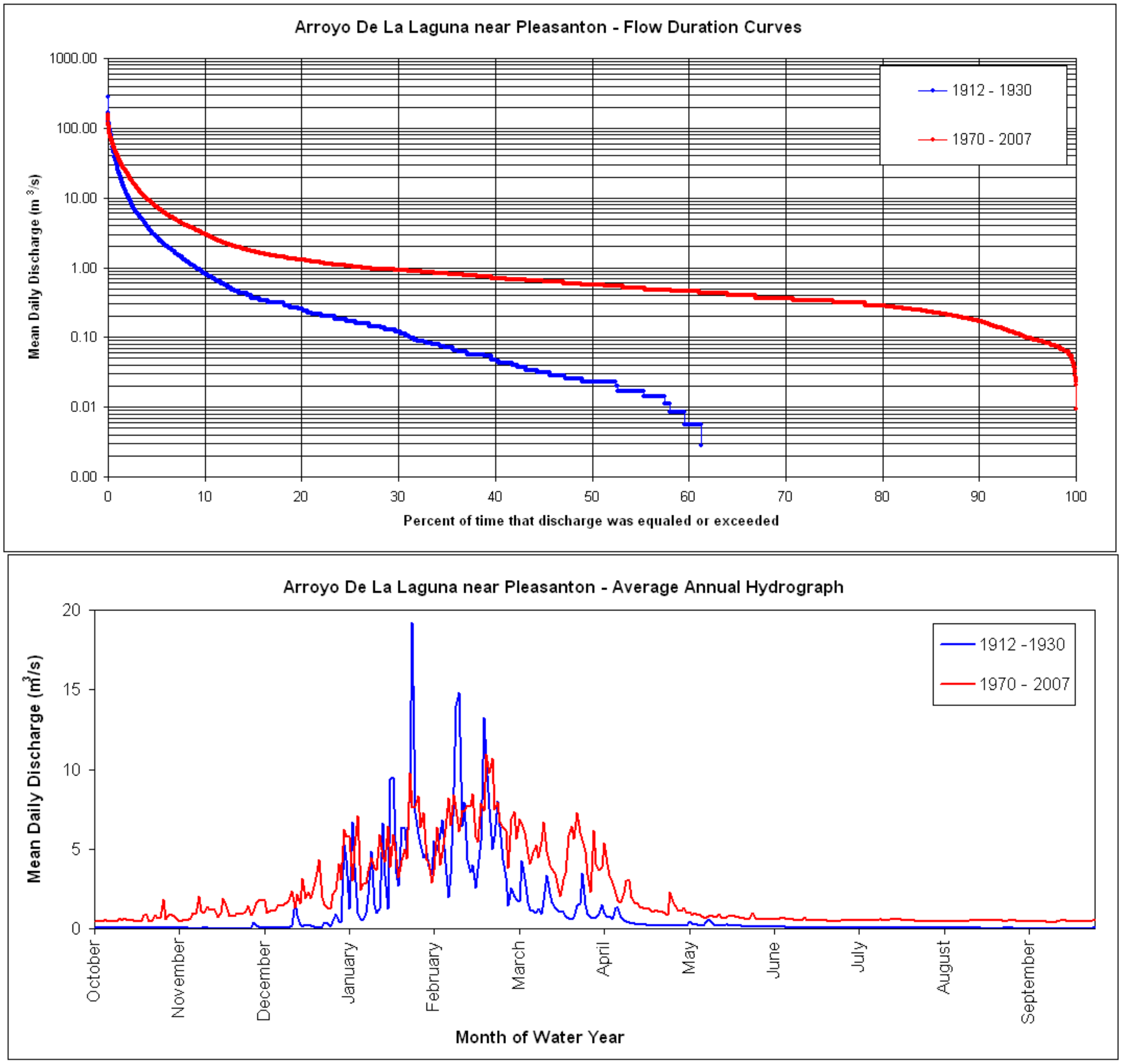


Figure 64. Mean daily flow duration curves and the average annual hydrograph for the gage at Arroyo De La Laguna near Pleasanton (USGS station 11176900) showing increased base flow after 1969, resulting primarily from controlled releases by Del Valle Reservoir and water transfers through the basin.

Arroyo De La Laguna Channel Evolution

Using the CEM as a conceptual basis and the current understanding of major alterations in sediment and flow to Arroyo De La Laguna, here we evaluate past, present, and future erosion trends of the channel. Because Arroyo De La Laguna has experienced several recent dramatic disturbances (channelization in 1901, 1950s floods) and continued chronic disturbance (e.g., suburban growth, gravel mining, water supply routing), the simplified CEMs developed from a single disturbance are not directly comparable. Nevertheless, the CEMs provide a useful basis for qualitatively interpreting and understanding channel response to disturbance over time. CEMs are best applied at a broad watershed scale because they provide a system-wide evaluation of the distribution of channel processes (Simon et al. 2007). In this respect, our analysis is limited because we are focusing primarily on the Arroyo De La Laguna study reach. CEMs are intended for use as a conceptual tool to understand the spatial and temporal patterns observed along a channel network and are not intended for design-level decision-making or management. Additional fieldwork, data collection, monitoring, and analysis are needed to better understand and quantify current and future channel evolution trends.

The discussion that follows is our overall interpretation of the Arroyo De La Laguna channel evolution, much of it based on inference of data, some hypothetical, and in a few cases professional judgment. Figure 65 provides an idealized overview of our interpretation of channel evolution in Arroyo De La Laguna at locations where a contemporary floodplain has formed. Arroyo De La Laguna is currently adjusting to altered flow and sediment supply from both human-induced and natural disturbances. Since channelization occurred in 1901, the channel has been and continues to respond to anthropogenic and natural disturbances by adjusting its width, depth, and channel form, in a progression similar to the CEM described by Doyle and Shields (2000) (Figure 60). This CEM and others are based on empirical observations of response to a single disturbance. However, Arroyo De La Laguna's channel response has been interrupted and retriggered more than once.

Prior to 1900, we hypothesize that the channel dimensions were much smaller based on a lower supply of sediment and water, where the historic lagoon dampened flows and stored sediment from the upper watershed (Figures 4 and 62). Based on observations of abandoned channels of various size on the valley floor (Figures 22A, 38, and 39), the historic channel was well connected to the valley floodplain with multiple or split channels, possibly anastamosing, as are typical for floodplain formation in valleys (Walling and He 1998). At that time, the channel was in the Predisturbance Stage (Stage I) (Figure 66). We hypothesize that the initial disturbance (Stage II) to the channel network occurred in approximately 1901 due to the draining of the historic lagoon and channelizing the creek through what was formerly the lagoon and now upper Arroyo De La Laguna. However, the early mapping and description of water supply in the area is complex, and some modification, including some connections of tributaries and routing of additional flow down the channel likely occurred as early as 1888. This highly channelized and modified section is likely upstream from Verona Bridge, where the historic lagoon was mapped. Although the exact locations of channelization are not known, early photos of the area and the 1906 USGS topographic map shows obviously straight channels or ditches on the valley floor through the area of the historic lagoon (Figure 62). However this historical mapping is rudimentary and the downstream extent of the historical channelization is not definitively known. This major alteration directly connected flow and sediment from the upper watershed to Arroyo De La Laguna (Collins 2005). The increased supply of water to Arroyo De La Laguna likely caused initial rapid channel incision and widening, which corresponds to Stage III (also discussed by Collins

2005). During this period, Williams (1912) reports incision rates of 15 cm/yr (1.5 meters from 1901 - 1911), similar to incision rates estimated from long profiles of 6 - 10 cm/yr between 1900 and 1958 (Figure 22). These early altered channel dimensions are also shown in Figure 33, documented by Williams (1912). We hypothesize that the channel incised rapidly, and then widened (Stage IV), however the widening was not of the magnitude observed today, likely because the upstream land use was not yet highly modified. In terms of function, this first period of incision fundamentally altered the channel from a sediment sink, which was well connected to the valley floodplain and stored overbank deposits, to a conduit that more effectively transports sediment downstream (also see Collins 2005).

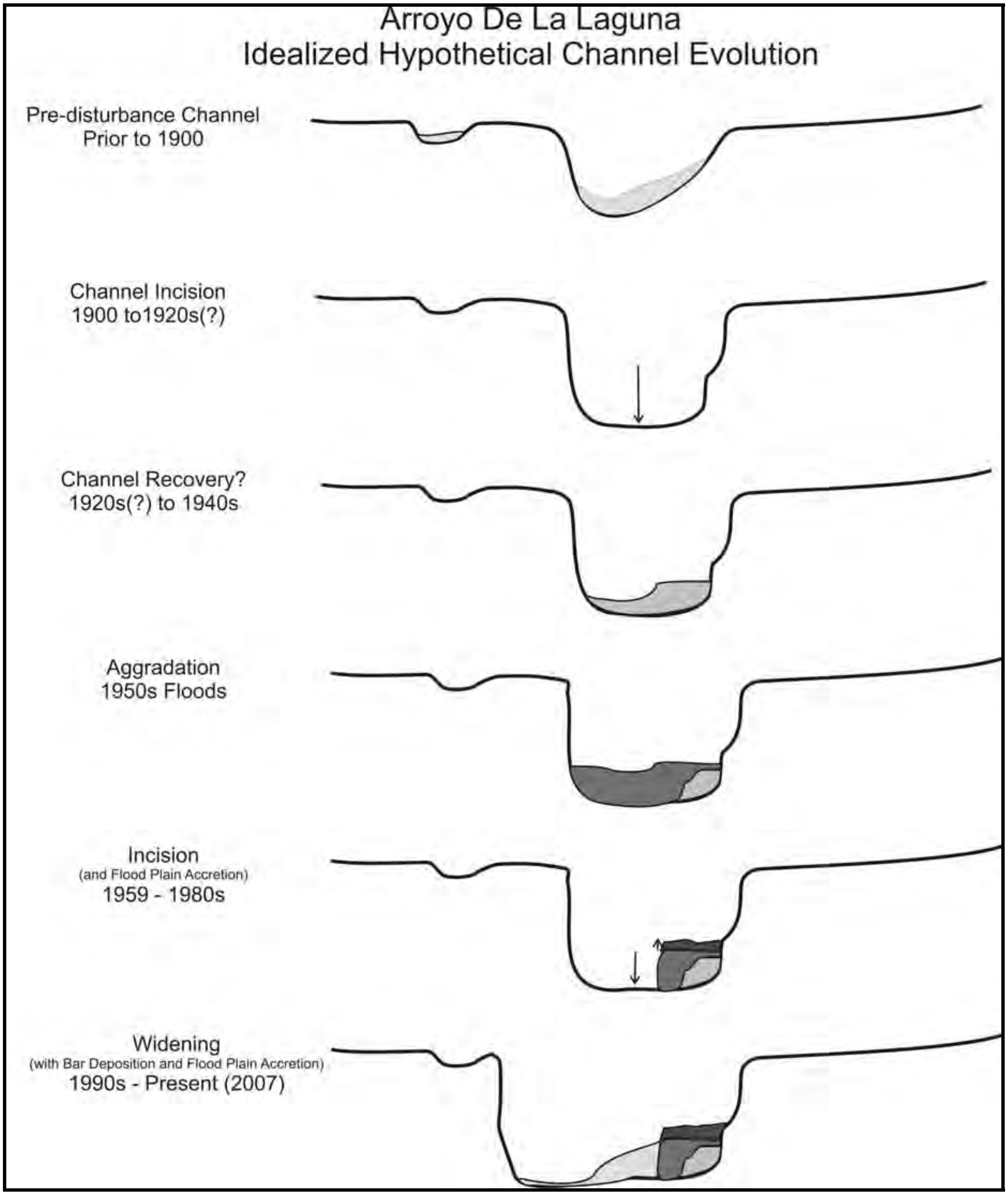


Figure 65. Conceptual interpretation of channel evolution in the portion of Arroyo De La Laguna study reach where a contemporary floodplain has formed. See the following discussion for more detailed sub-reach conceptual evolution.

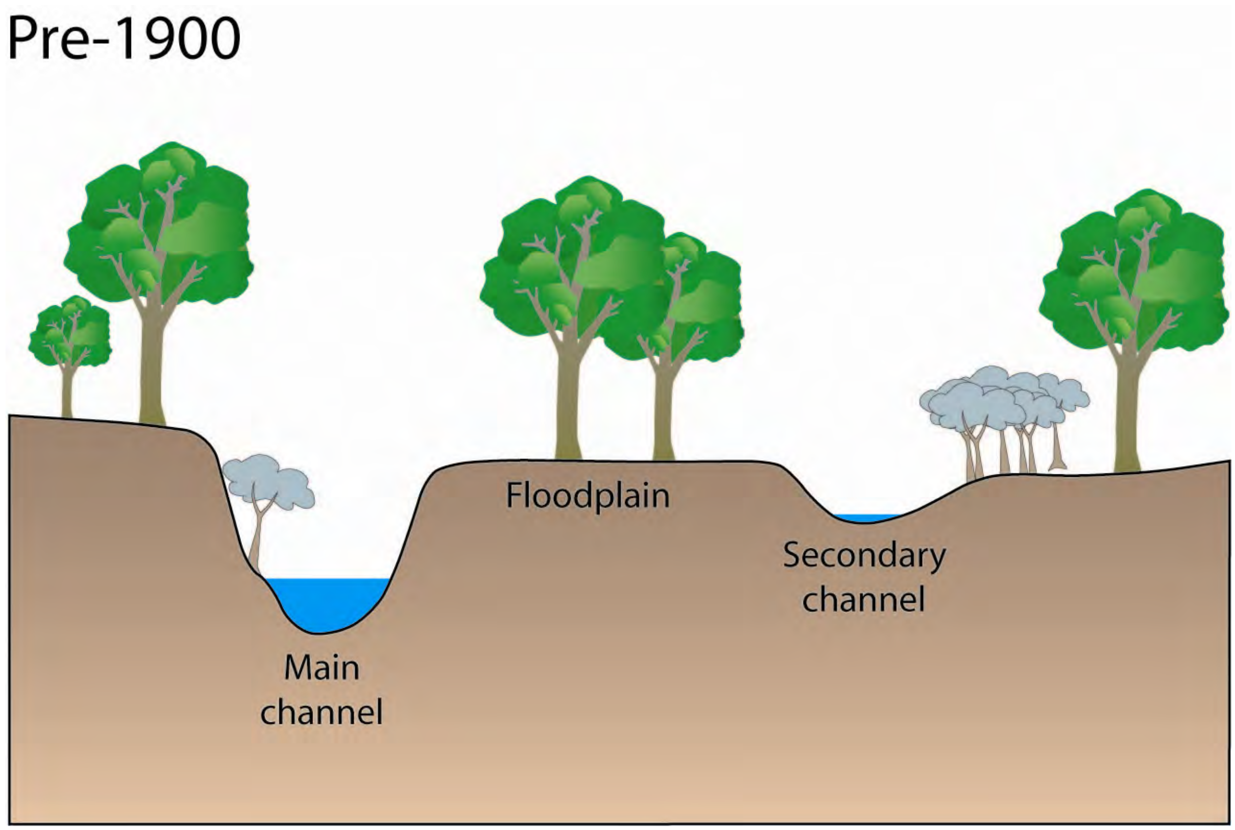


Figure 66. Idealized hypothetical Arroyo De La Laguna cross section depicting the channel prior to 1900. This channel pattern was likely found for most of the study reach length, where the channel is largely unconfined by the valley walls. This cross section is based upon the dimensions of the abandoned channel shown in Figure 38.

The earliest aerial photographs of the creek in 1939 suggest a channel width of approximately 30 to 50 m at the edge of banks. We did not observe significant channel widening on air photos between 1939 and 1950, suggesting that the creek had attained a period of relative stability and recovery (Stage V or VI). In other words, we hypothesize that the channel had already responded to the initial perturbation by incising and slightly widening, and by 1939, it had reached a period of relative stability (see the first three periods of Figure 65). The lack of historical channel cross sections prior to 1959 makes it difficult to infer that aggradation (bar and floodplain formation) had occurred, however the oldest floodplain trees date back to roughly the late 1940s (Table 6) indicating sufficient channel stability and recovery had occurred for establishment of vegetation on an emerging floodplain surface.

The second disturbance to the channel network occurred with the series of extreme floods during the 1950s (Figures 1, 7, and 17). The “Christmas flood” of 1955 was particularly extreme and widespread across the Western Region (Hoffman and Rantz

1963). In North Coast rivers[8], massive erosion occurred in low order channels from landslides and debris flows during massive floods. In response, large order mainstem rivers overwhelmed by sediment from tributaries and adjacent earth flows often aggraded up to 4 meters and reoccupied floodplains and terraces (Kelsey 1980, Lisle 1982, Sloan et al. 2001). These 1950s floods prompted a proliferation of flood control projects throughout the San Francisco Bay Region, including construction of the Alameda flood control channel and Del Valle Reservoir. In Arroyo De La Laguna, coarse unconsolidated fill deposits frequently exposed at the base of the current discontinuous floodplain (Figure 67) and the age of floodplain trees (Table 6) suggests that the channel aggraded and reworked much of the previous emerging floodplain in many areas during the 1950s floods. The channel aggradation (fill terrace) approaches 2 meters in some areas (Figure 67) which corresponds with the general change in bed elevation between 1959 (shortly after the extreme floods) and 2007 (Figure 25). At the outside edge of newly eroded bends, we occasionally observed wood and artifacts imbricated in these flood deposits (Figure 67). During the late 1950s through the 1970s, land use in the valley was substantially altered by the suburban growth of Pleasanton, Dublin, and Livermore. Drainage density increased as storm drains were constructed with the growing urban area, and additional channelization of upstream tributary reaches occurred. These changes contributed even larger supplies of water and sediment to the mainstem Arroyo De La Laguna than previously experienced (also discussed by Collins 2005).

Subsequently, the channel cut back through this aggraded material while accreting fine-grained floodplain sediments, leaving only remnants of the fill terrace that now comprises the base of the contemporary discontinuous floodplain (Figures 67 and 68). This incision is recorded on the three longitudinal profiles (the apparent knickpoint on Figure 25), with estimated incision rates initially rapid, ranging from 7 - 15 cm/yr from 1959 - 1971 and then decreasing to 2 - 4 cm/yr from 1972 - 1993 (see results section). This second period of incision (Stages III and IV) moved upstream through the reach over a period of roughly 30 - 40 years, as the head cutting knickpoint migrated well upstream of Verona Bridge by 1998 (Figure 25). After this wave of incision occurred, the banks began to widen (Stages IV and V), as observed on air photos between 1993 and 2005 (e.g. Figure 31). Presently, the Arroyo De La Laguna study reach is in various stages of channel widening and aggradation, as described by subreach moving downstream (upper, middle, lower, Table 1, Figure 3) in the following sections.

The upper reach of Arroyo De La Laguna (Verona Bridge downstream to the railroad bridges) continues to widen and aggrade in some areas (Stage IV and V) (Figure 69). The channel widening here is dramatic and more developed than the middle and lower subreaches. The majority of bank erosion is most evident on the aerial photographs between 1993 and 2005 (Figures 30 and 31), but substantial bank erosion was observed in field surveys (Figure 27), and can also be observed on some cross sections, for example, on the left bank of cross section number 20 (Figure 39). At some locations, channel sinuosity is increasing where the coupled feedback between bank erosion and bar deposition dominate the channel form creating large meander bends,

[8] With limited published research on Bay Area watersheds, we use North Coast rivers as the nearest analogy.

particularly upstream of the railroad bridges (Figures 13 and 70). Here, sediment eroded from the outside edge of a bank is deposited downstream as a midchannel bar or laterally accreted as a point bar (Figures 13 and 70). Aggradation in this section is shown on the long profile (Figure 71) and might be related to channel constriction from the railroad bridges or valley wall that cause deposition due to backwater flooding (Figures 70 and 71). Similar massive bank erosion and bar development was occurring near the Koopman Ranch further upstream, where a bank stabilization project has been implemented[9] (Figure 71, 72, and 73). Overall, the channel bed in the upper subreach appears to be highly mobile, where much of the bed is composed of deep (0.5 m or greater) loose sand and gravel that is often moving, even at base flows. Some local bed armoring is provided by riprap and concrete blocks from the previous bridge footers at the Verona Bridge (Figure 74). To summarize, the upper subreach appears to currently be in Stage IV and V (some incision and some aggradation, with overall widening), and we hypothesize that widening will continue to occur, as the banks lay back to a more stable slope causing continued aggradation and bar deposition as the channel strives for a new equilibrium.

[9] See http://www.acrcd.org/arroyo.html for details and photos of the bank stabilization project.

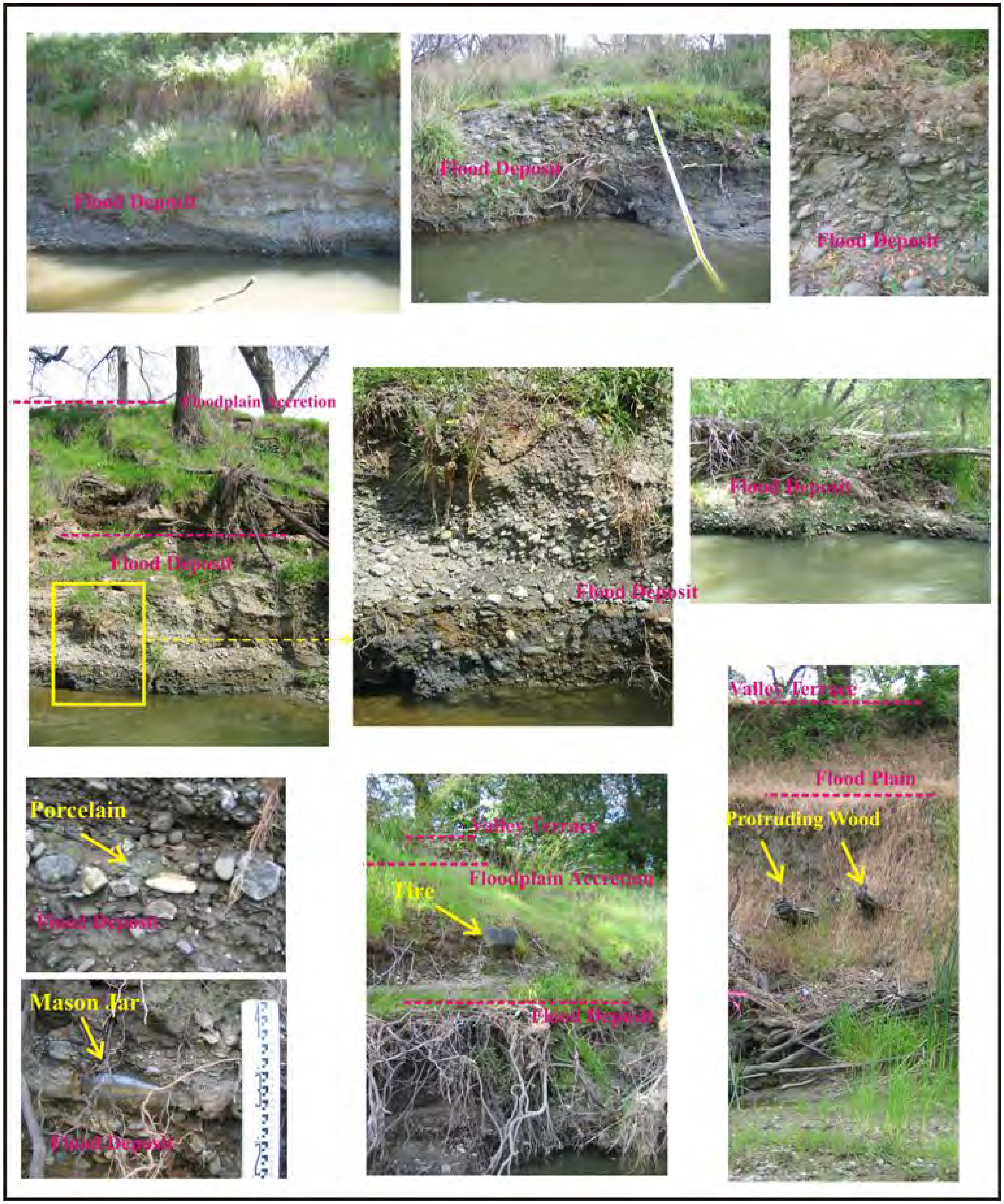


Figure 67. Photos of unconsolidated coarse flood deposits and floodplain accretion that often comprise the discontinuous contemporary floodplain in Arroyo De La Laguna.

Figure 68. Upper subreach example of a remnant of the 1950s package of flood deposit material through which the channel has since incised, similar to examples shown in Figure 67.

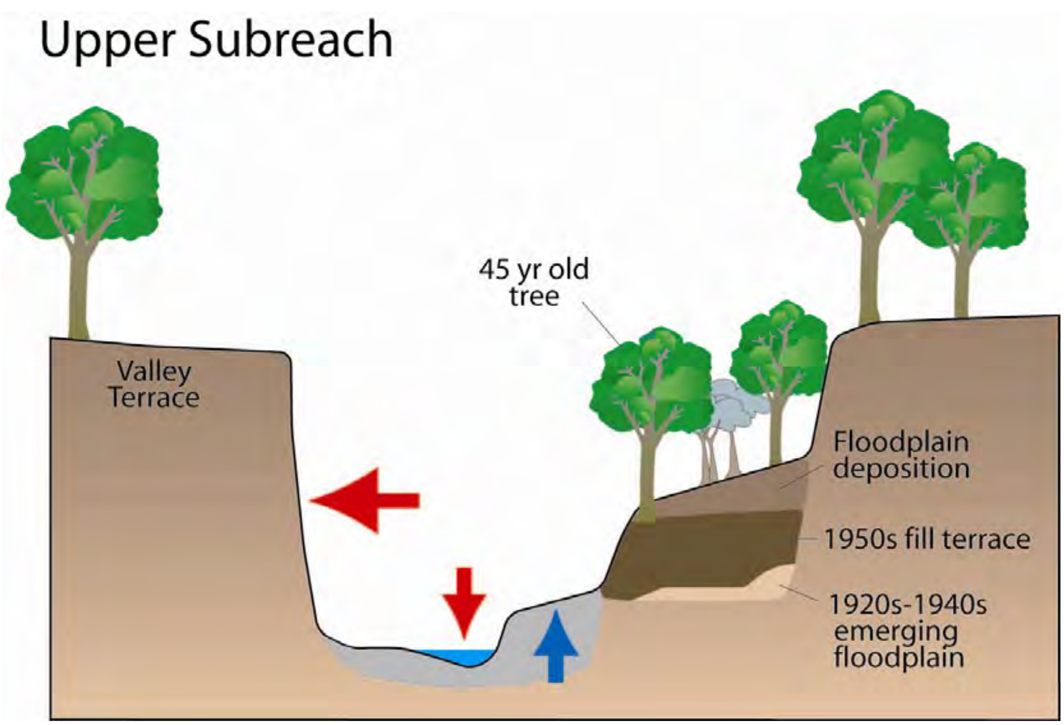


Figure 69. Idealized cross section showing channel form and processes currently occurring in the upper subreach of Arroyo De La Laguna. Red arrows indicate bank and bed erosion, blue arrows indicate deposition.

Figure 70. Aerial photograph showing an example area of increased sinuosity in the upper subreach of Arroyo De La Laguna. Potential constriction of the channel by railroad bridges *may* create a backwater effect that promotes upstream deposition. Also the valley wall on the west side of the channel impinges on the channel here. Flow is from right to left.

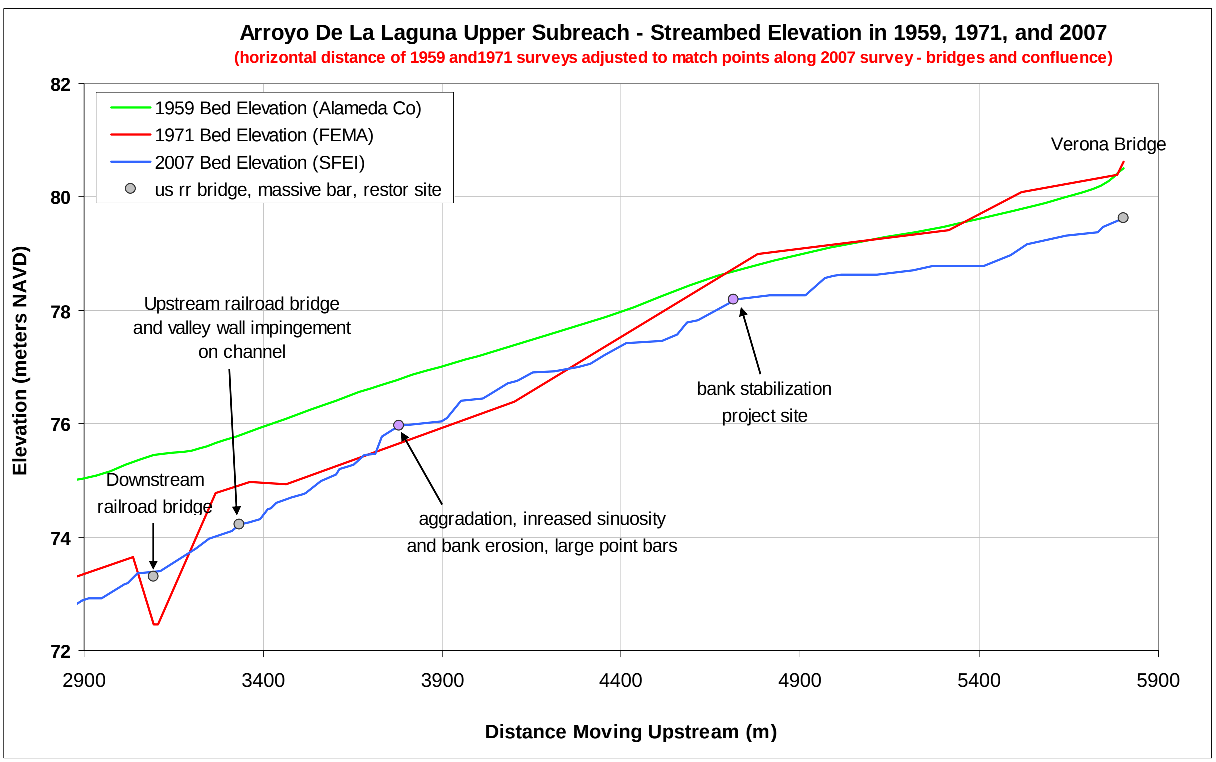


Figure 71. Longitudinal profiles of upper subreach in Arroyo De La Laguna showing incision over time and some recent aggradation.

Figure 72. Panoramic photos showing bank stabilization project in upper subreach of Arroyo De La Laguna (top photo from November 2006, bottom photo from May 2007). Flow is from left to right.

Figure 73. 2005 aerial photograph showing a point bar adjacent to an actively failing erosional bend at bank stabilization project site. Flow is from top to bottom.

Figure 74. Looking upstream at the riprap and old bridge footer debris that is stabilizing the bed elevation at the Verona bridge.

The middle subreach of Arroyo De La Laguna (Paloma Bridge upstream to the railroad bridges) continues to incise and widen moderately, and develop small bars in some areas (Stage IV), although not on the dramatic scale of the upper subreach (Figure 75). Here, channel widening was primarily documented in the field (Figures 27 and 76), however widening from bank erosion is also apparent on aerial photographs (Figure 77). Channel cross sections in the reach also show areas of bank erosion (Figure 37). Channel bed elevation in the middle subreach is locally controlled at four locations, including rip rap at the base of both railroad bridges, a failing concrete grade control structure immediately downstream of the railroad bridges (the channel has currently eroded into the east bank around this structure), a bedrock (weathered mudstone[10]) knickpoint downstream of the lower railroad bridge, and a concrete grade control just upstream of Paloma Bridge (Figure 78). It should be noted that severe bank erosion occurred during the 1998 flood at the junction of Sinbad Creek with Arroyo De La Laguna, requiring major revetment of the bank with riprap (T. Huff, Alameda County Resource Conservation District, personal communication 2006). Long-term bed incision is also documented by the exposure of the railroad bridge pilings; Figure 79 shows the exposed bridge piling, and Figure 80 shows a photographic comparison of the historic channel elevation (in comparison to the grade of the railroad) and the current channel elevation. Although direct comparison is not entirely valid, because the stone pilings were built in 1898 when the wooden bridge was replaced with a steel bridge, these photos do give a general sense of change.

[10] The bedrock here consists of a moderately to poorly indurated silt/mudstone, providing moderate resistance to bed erosion.

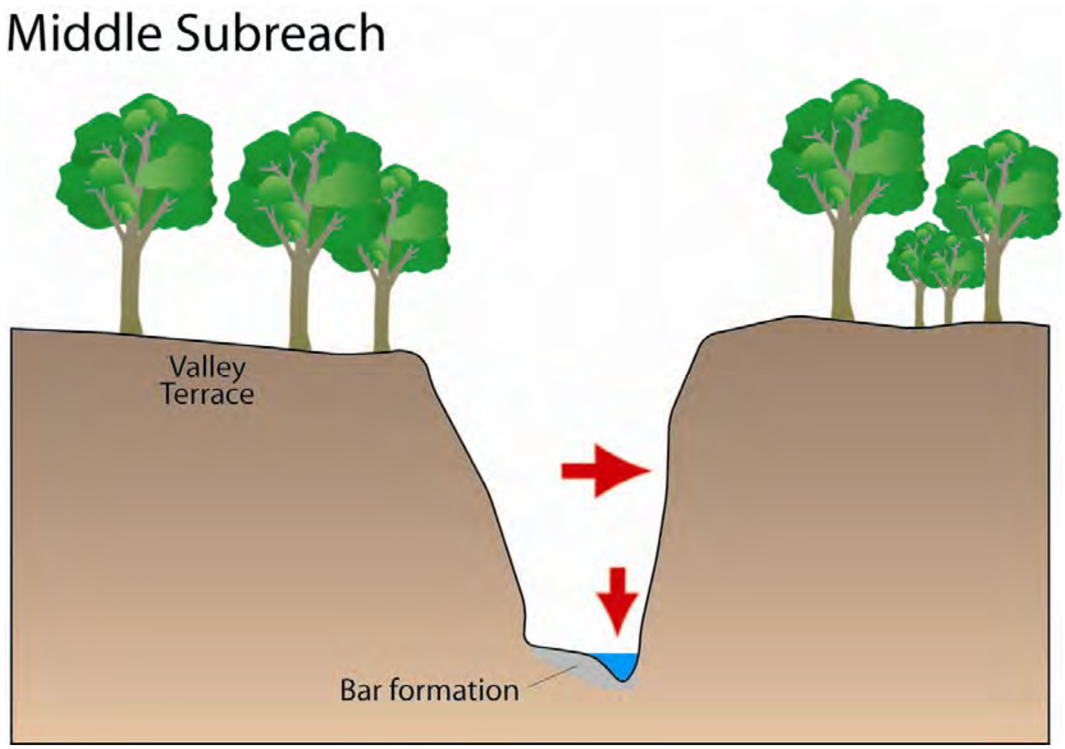


Figure 75. Idealized cross section showing channel form and processes currently occurring in the Arroyo De La Laguna middle subreach. Red arrows indicate bank and bed erosion. Note that there are some sections of floodplain formation in the middle subreach as depicted on Figure 69.

Figure 76. Photo (looking downstream) showing example of coupled bank erosion and emerging bar deposition in the middle subreach of Arroyo De La Laguna.

Figure 77. 2005 aerial photograph showing an example of bank erosion within the middle reach. Flow is from top to bottom.

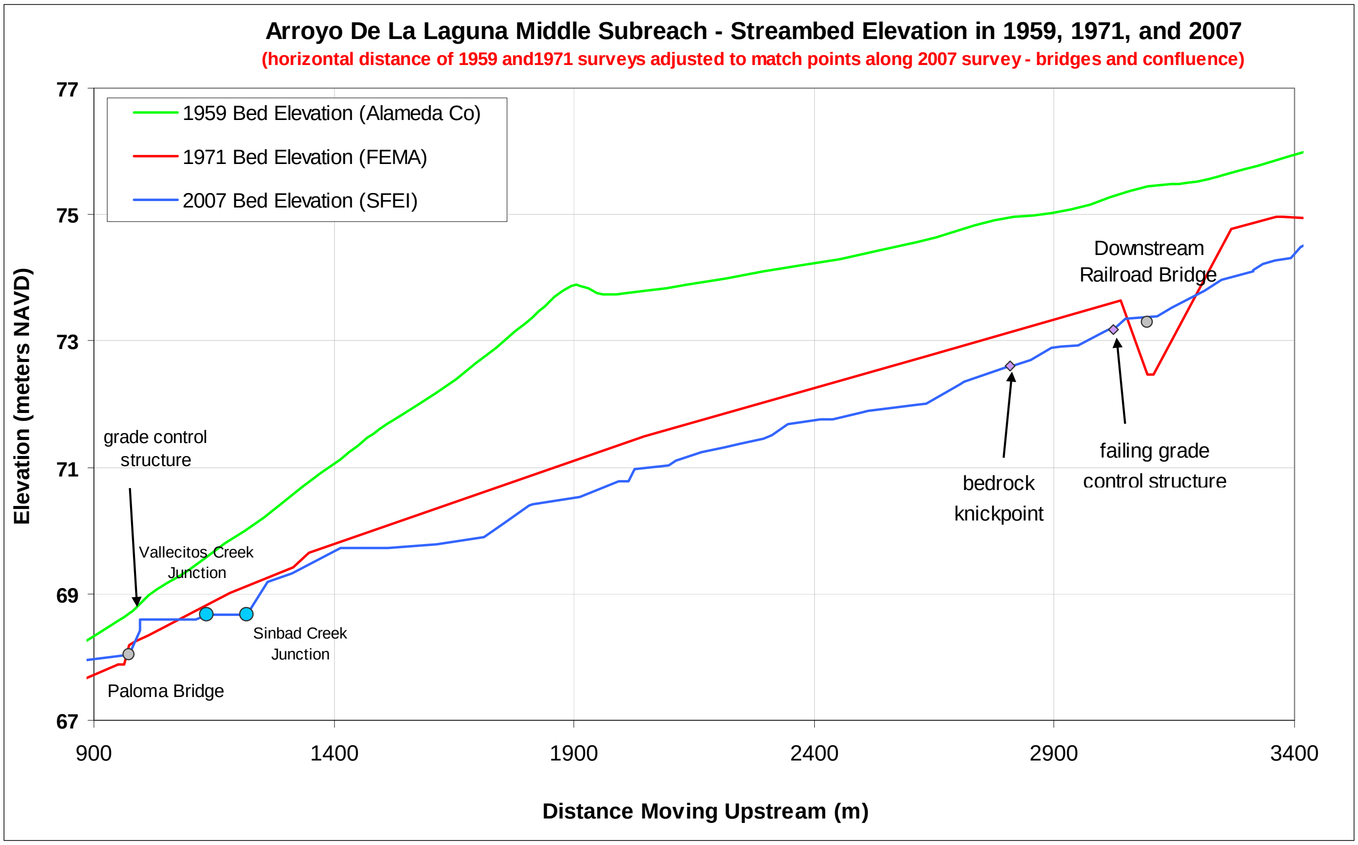


Figure 78. (upper) Longitudinal profiles of middle subreach in Arroyo De La Laguna showing incision over time and local grade controls. Note that the Paloma Bridge likely created a backwater effect influencing deposition during the 1950s floods. (lower) Photograph (looking upstream) at the grade control structure at Paloma Bridge.

Figure 79. Photograph (looking downstream) showing that the bed level is currently approximately 3 m below the stone portion of the abutment for the upper railroad bridge (formerly Southern Pacific, now owned by Union Pacific). Stadia rod is 5 m in total.

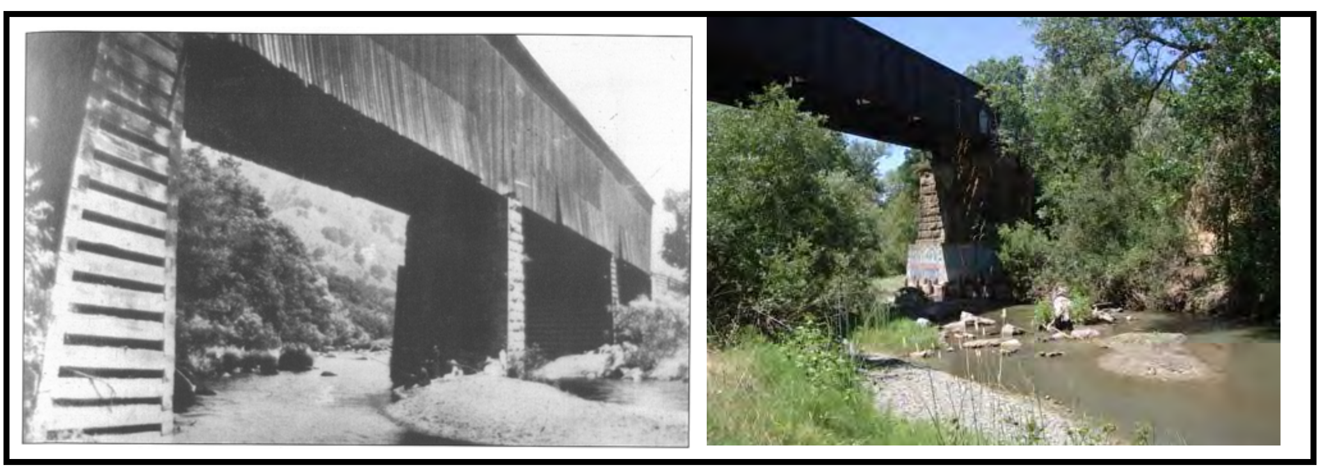


Figure 80. Photographic (looking upstream) comparison of the channel at the upper railroad bridge. On the left is a photo of the historic wooden bridge taken sometime between 1869 and 1898 (Luna 2005), and on the right is the condition in 2007.

The lower subreach of Arroyo De La Laguna (confluence with Alameda Creek upstream to Paloma Bridge) is currently aggrading and widening (Stage V) near the confluence where deposition occurs as a massive bar and upstream wedge of sediment (Figure 81), a common effect observed at many large alluvial tributary junctions (Benda et al. 2004). At the confluence, we also observed a concrete grade control structure exposed only in the thalweg of the Arroyo De La Laguna channel, so the extent of the structure could not be determined. The channel in this reach has a 10 to 20 m wide developing floodplain surface that is currently accumulating sand and silt, and supports established vegetation (Figure 82). The particle size of the bed and bank material also increase substantially in the lower subreach due to supply of coarse material from the Vallecitos and Sinbad Creek tributaries just above Paloma Bridge (e.g. Rice et al. 1998) (Figure 14). Due to the grade control structure immediately upstream of Paloma Bridge, the channel gradient flattens behind the grade and steepens below the bridge (Figure 81). Overall, the lower subreach above the massive confluence bar appears to be the most stable of the three subreaches, due perhaps to several influences including the larger caliber bank and bed material and flow dampening influences of the Paloma Bridge and the grade control structure. This grade control structure was likely installed to stabilize the grade for the current Paloma Bridge or the historical Paloma Bridge that was just upstream of the current bridge. It appears unlikely that the recent removal of Sunol Dam (downstream from the confluence and this subreach) will cause any dramatic changes within this subreach, mainly because (1) the wedge of sediment behind the historic dam only extends 600 to 750 meters upstream (Gragg 2008) from the historic dam, well below the confluence and this lower subreach, and (2) the coarse sediment supply from Sinbad and Vallecitos tributaries appears to reduce bed mobility in this subreach.

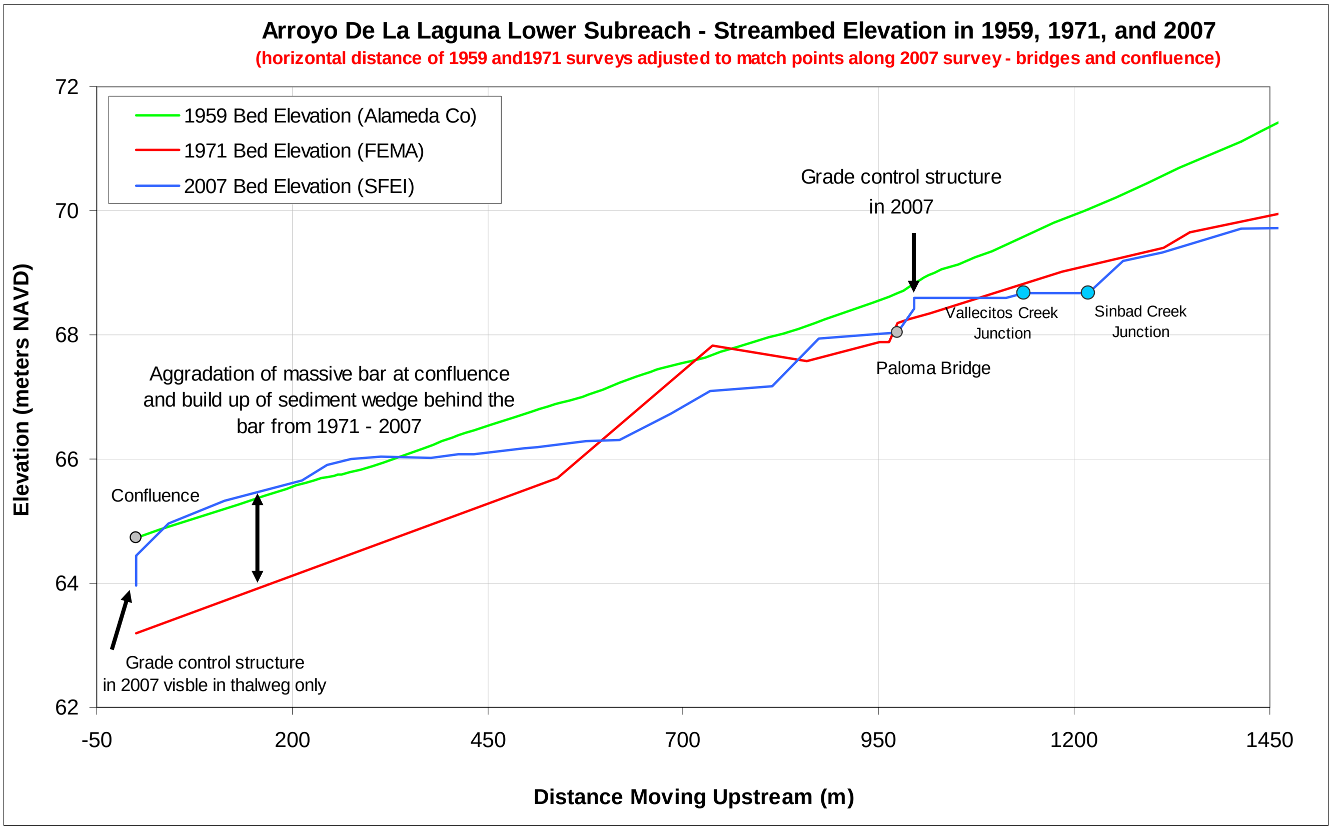


Figure 81. Longitudinal profile of the lower subreach of Arroyo De La Laguna, showing incision from 1959 - 1971 and subsequent aggradation near the confluence from 1971 - 2007.

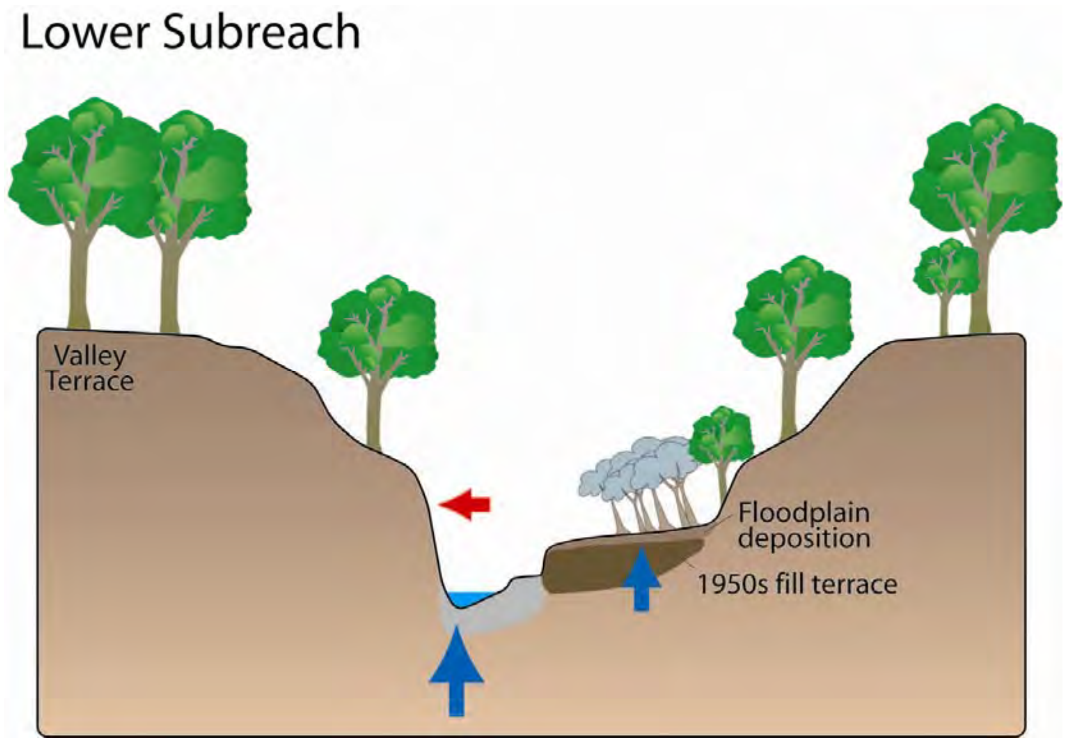


Figure 82. Idealized cross section showing channel form and processes currently occurring in the Arroyo De La Laguna lower reach. Red arrows indicate bank and bed erosion, blue arrows indicate deposition.

Comparison to Previous Analysis of Channel Evolution in Arroyo De La Laguna

In comparison to our evaluation of channel evolution of Arroyo De La Laguna, a previous reconnaissance-level geomorphic survey of portions of Arroyo De La Laguna and other creeks in the valley, including judgments of channel stability using the Incised Channel Evolution Model (ICEM) (Schumm 1984) was conducted by Ayres Associates (2001). In summary, they observed two episodes of incision (< 100 years old), and attributed the incision to: 1) increased sediment transport capacity due to increased runoff from urbanization; 2) decreased sediment supply due to paving urban areas; 3) sediment trapping from dams, detention facilities, and gravel mining ponds; 4) channel straightening (increased slope); 5) breaching of the historic lagoon; and 6) incision of reaches further downstream. They suggest that Arroyo De La Laguna downstream of Verona is in ICEM Stage IV (bed aggradation, reduced rates of bank widening, banks begin to stabilize), but note that the indication of stability could be the result of a number of low flow years prior to their 2001 observation. They also suggest that future flooding could cause additional incision and bank erosion, and that upstream urbanization could also increase instability. The reach upstream of Verona is described as in ICEM Stage II or III (incision and channel widening), and at Bernal Avenue, in-channel riprap is maintaining a 3-foot knickpoint. We generally agree with their reconnaissance-level assessment, but we suggest that the reach downstream of Verona may continue to widen and evolve in the near future (particularly the middle and upper subreaches), rather than reducing rates of widening and stabilizing as suggested above.

Comparison of Current and Regional Channel Dimensions

To provide another perspective on the current state of channel evolution, we compare bankfull dimensions of Arroyo De La Laguna with regional values provided in Dunne and Leopold (1978) and Riley (2003) (Figure 83). This comparison should be considered coarse in part because the streams used to derive the San Francisco Bay Regional curves (Dunne and Leopold 1978) “were from near Leopold’s residence in Berkeley (a listing of sites was not separately maintained)” (Emmet 2004). No information is provided for sites used to derive the East Bay Regional curves (Riley 2003), but are also likely derived from smaller streams in the Berkeley area. Moreover, because Arroyo De La Laguna is still evolving, defining bankfull dimension from such channels is somewhat dubious (Simon et al. 2007). Nevertheless, the comparison still provides another view of potential channel evolution. The bankfull widths and cross sectional areas of Arroyo De La Laguna are generally smaller than “regional values”, while bankfull depths are larger (Figure 83). Loosely interpreted, this suggests the current channel is deeper (incised) but narrower compared to regional channels, and if the current sediment and flow regime and bank materials for Arroyo De La Laguna are similar to those channels used to derive the regional curves (important caveat), the channel may continue to widen to attain a similar “regional” form. This interpretation of current channel evolution using bankfull dimensions is quite similar to the previous interpretations using CEMs.

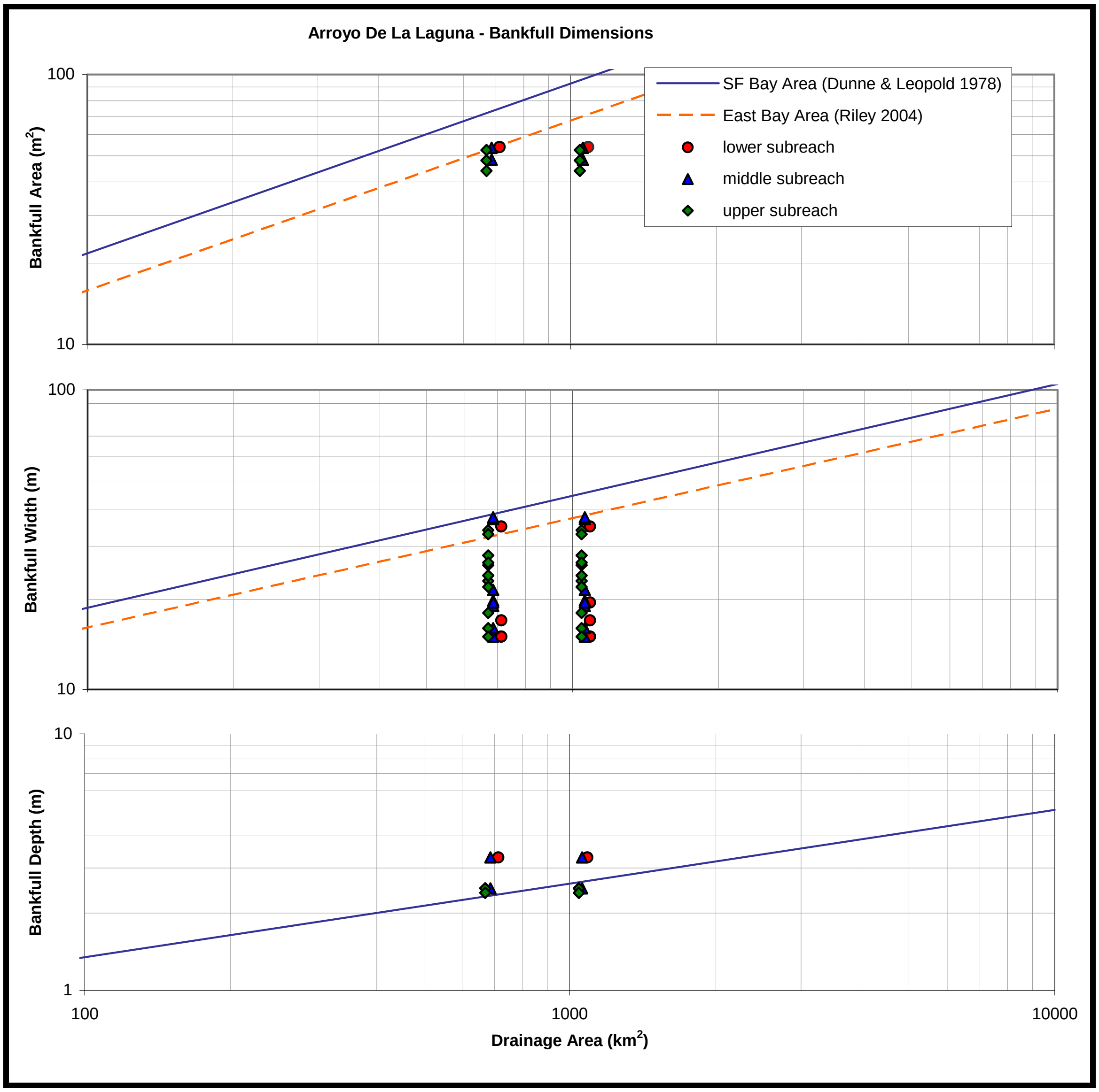


Figure 83. Bankfull dimensions of Arroyo De La Laguna and limited regional bankfull dimension curves. Data is plotted twice for total drainage area and drainage area below Del Valle Reservoir. Bankfull dimensions are from recent cross sections and additional bankfull width measurements from field surveys conducted in this study.

Arroyo De La Laguna Projected Channel Evolution

Predicting the future response of Arroyo De La Laguna requires an understanding of the potential outside influences that could be expected to control or have an impact upon the water and sediment supplied to the channel. For example, because of the density of urban development in the valley, it has been estimated and predicted that between roughly 1968 and 2030 (general plan build-out) peak runoff in the valley will have increased by 50% (Zone 7 Water Agency 2006). However, the numerous influences and controls on water and sediment in a large system like the Alameda Creek watershed make accurate future predictions nearly impossible. Even if we were able to accurately predict future supplies to the channel, the non-linear channel response and stochastic nature of sediment supply makes prediction of the evolution of channel morphology in incised systems both of interest and very difficult (Simon and Darby, 1999). Despite the limitations and difficulties of prediction, here we present three coarse *conceptual scenarios* illustrating how changes in land use, climate, and watershed management could affect the continued evolution of Arroyo De La Laguna. Scenarios A and B are end-member conditions in which each of the individual future sediment and water controls align to create almost certain incision, and almost certain aggradation, respectively. Scenario C represents our best professional judgment about what outside controls on sediment and water supply are most likely to occur, and the resultant channel evolution in each of the three subreaches.

Scenario A (incision):

- Increased flood peak discharge due to increased runoff from full build-out conditions in the valley (increased impervious area and increased drainage density)
- Increased flood peak discharge due to climate change causing more intense rainstorms
- Decreased sediment load supplied from upstream due to channel recovery (cessation of incision, increased stability of channel banks, and aggradation) and maintenance of tributary grades (prevention of further headcutting)
- Decreased sediment load supplied from upstream due to strict maintenance (bank stabilization, grade control, and sediment removal) of canals and engineered channel reaches
- Decreased sediment load supplied from upstream due to increased sediment trapping and removal in sediment basins/traps or gravel mining ponds
- Decreased sediment load supplied from upstream due to better land management reducing erosion from grassland areas
- Decreased large woody debris in the channel due to active removal and reduced rates of recruitment (fewer available mature riparian trees due to current bank erosion and continual flooding of inner floodplain surfaces)
- Failure of one or more grade control structures within the study reach
- Increased bank revetment within the study reach
- *Possible* minor incision in the lower subreach due to the Sunol Dam removal

In this scenario, we would expect Arroyo De La Laguna, from the confluence with Alameda Creek upstream to Verona, to respond to this increased stream power (increased discharge and decreased sediment supply) by beginning a renewed period of incision (reverting to Stage III in our channel evolution model). However, the existing grade control structures (if they remain intact) and the coarse sediment supply from Sinbad and Vallecitos Creek tributaries may help stabilize the channel base level elevation, limiting the amount of incision possibly to as little as 1 m. Incision may be greatest in the reach between the railroad bridges and Verona, as the current slug of sediment (illustrated by the convex longitudinal profile) is transported downstream as the channel tries to smooth its longitudinal profile. But even a small amount of incision would cause the creek to progress through the series of evolutionary stages, causing later additional bank erosion and channel widening. These conditions would increase the amount of sediment that is transported to Niles Canyon, and ultimately to the flood control channel.

Scenario B (aggradation):

- Decreased flood peak discharge due to intense efforts to control urban runoff (detention/retention ponds, increased use of gravel ponds for flood waters, implementation of storm water BMPs by individual homeowners/neighborhoods/developers, construction of new groundwater infiltration ponds, etc)
- Decreased discharge due to alteration of the Del Valle Reservoir operation
- Decreased discharge due to selective disconnection of tributaries from the mainstem, and construction of new in-channel wetland areas
- Increased sediment load due to continued/intensified both within-reach and, upstream incision and bank erosion, possibly due to the failure of grade control structures, or inputs from incising tributaries
- Increased sediment load from upstream channel banks due to the lack of maintenance of canals and engineered channel reaches
- Increased sediment load due to overloading of sediment traps
- Increased sediment load due to landslides and debris flows caused by higher intensity storms
- Increased sediment load due to poor land management
- Increased large woody debris in channel (either through recruitment or placement)
- Maintenance of grade control structures in the study reach

In this scenario, Arroyo De La Laguna would likely respond to this decreased stream power (decreased discharge and increased sediment load) by aggrading, possibly by 2 or 3 m, establishing a lower bank height, increasing access to the currently developing floodplain, and possibly even the valley floor surface. During the peak flows, erosion of outer channel banks and deposition of fine sediment on the floodplain is likely. Because of the decrease in sediment supply and the increase in in-channel sediment storage reflected in these conditions, we suggest that the overall amount of sediment that is transported to Niles Canyon, and ultimately to the flood control channel, would be decreased depending on the overall magnitude of sediment that is supplied from upstream. However, if conditions change again further into the future, this scenario sets the channel up for future incision through this package of aggraded sediment, similarly to what occurred after the 1950s floods.

Scenario C (most probable):

- Slightly increased peak floods due to increased runoff from build-out conditions and higher intensity storms being partially offset by an increased number of effective urban runoff BMPs and better land management of upland grassland areas
- No change in operations of Del Valle Reservoir
- Decreased sediment supply from upstream in-channel sources due to channel recovery and maintenance of tributary grades
- Increased proportion of coarse sediment load due to a greater contribution from landslides and debris flows, and a decreased proportion of fine sediment load due to intensive urban BMP implementation and land management
- Increased load of in-channel large woody debris (LWD) due to cessation of removal activities, continued recruitment from bank erosion within the reach, and placement during restoration projects
- Maintenance of grade control structures within the study reach and upstream
- Allowing the channel to widen at the expense of giving up some current riparian and grazing land

In this scenario, Arroyo De La Laguna would likely respond to this small change in stream power by continuing its current evolution, ultimately reaching Stage VI or VII. We believe that with maintenance of current grade control structures, an increase in stable large woody debris, increased coarse sediment, and allowance of continued bank erosion, the channel will continue to aggrade and reach a new equilibrium. The controlling variables for reaching stability will be the allowance of enough channel widening for the banks to reach a stable angle, and the development of a functioning floodplain and low-flow channel. As the channel makes these adjustments, in-channel sediment storage in this reach will increase. However, because the storage area is smaller than the total volume of sediment supplied to the reach, and because Arroyo De La Laguna remains disconnected from its historical wider valley floor floodplain (except under extreme flood events), ultimately this reach will likely continue to function primarily as a sediment transport reach, merely moving sediment supplied from upstream, down to Niles Canyon.

Making the above assumptions, the upper subreach will likely evolve into a Stage VI over the course of approximately 30 - 50 years. Slight incision (removing the convexity in the longitudinal profile) may occur, along with significant bank erosion, until the channel is able to widen enough to allow bed aggradation (and channel recovery) to occur. The middle subreach will likely remain as a Stage IV, slowly evolving into a Stage V. We hypothesize that the backwater effect of the two railroad bridges and possibly the bedrock knickpoint is contributing to the slower evolution of the middle subreach; during flood events, the bridges cause the flood waters to back up, slowing the velocity, and causing deposition of sediment. When the flood water makes it through the bridges, it now has a decreased sediment load, contributing to the continued incision and bank erosion that we observe today. However, the grade controls (exposed bedrock and weir at Paloma) will ultimately control the amount of incision that occurs, causing the channel to eventually begin to widen as a Stage V. The lower subreach of Arroyo De La Laguna will likely evolve to Stage VI relatively rapidly, possibly over the course of 10 to 20 years. The two grade control structures (concrete weirs at the confluence and immediately upstream of Paloma) and the input of coarse sediment from the Sinbad and Vallecitos Creek tributaries will promote continued stability, unless major modifications occur on these tributaries. The removal of the Sunol Dam in 2006 will likely have minimal impact upon this reach because the wedge of sediment deposited behind the former dam does not extend up to the confluence and the concrete weir and massive bar at the confluence may inhibit incision from progressing upstream.

For each of these scenarios we make our best professional judgment for the amount of sediment involved in each of the processes described above. Each of these values are crude, back of the envelope estimates based upon channel dimensions observed in the field and likely magnitudes of future change, all of which are conservative. We started with the current average channel dimensions for each subreach, and then modified the dimensions for each of the three scenarios, based upon our best professional judgment of the magnitude of likely future change, calibrated to the magnitude of change that we have observed in Alameda Creek and in other Bay Area systems. For each scenario we assume that the magnitude of sediment supplied from upstream is greater than that supplied by, or stored in the reach. In other words, we hypothesize that this reach will likely always be a sediment transport reach, however the magnitude of sediment supplied downstream will change with either sediment storage within, or sediment supply from the reach. Again, we emphasize that these estimates are coarse, and additional numerical modeling would provide better estimates for each scenario (see recommendations) and estimates of channel evolution in general. Our intent is to provide generalized comparisons between each scenario, not highly quantitative data for management-level decision making. Based upon the timeframes of typical management horizons and channel evolution, these estimates of sediment mass (reported below) assume a 20-year evolution time frame, assuming similar flows and flood events as have occurred in the recent past. Table 10 reports conservative estimated future sediment supplied directly from or stored within the Arroyo De La Laguna reach.

Table 10. Estimates of sediment (in tonnes/yr) supplied from (positive numbers) or stored in (negative numbers) the Arroyo De La Laguna reach for each scenario.

Process	**Scenario A**	**Scenario B**	**Scenario C**
Bed incision	6900	0	2500
Bed aggradation	0	-5700	-500
In-channel storage (bars, terraces, etc)	-60	-3400	-250
Bank erosion	8900	1000	7500
Total	15740	-8100	9250

In addition to the processes described in each of the scenarios, other outside influences may affect the continued evolution of the channel. These were not included in the three scenarios, as the effects are difficult to discern and presumably of lower probability.

- Occurrence of extended drought or El Niño periods due to climate change
- Modification or removal of the two railroad bridges or the Paloma weir (grade control)
- Overall fining or coarsening of the bed sediment
- A large earthquake on the Calaveras fault with surface displacement
- The completion of large channel restoration projects
- Alteration of the sediment supply from Sinbad and Vallecitos Creeks
- A change in the volume and timing of water released from dams
- A change in gravel mining operations
- Intensive in-channel vegetation management operations; or the concurrent death of all the cottonwoods and other mature riparian trees on floodplain surface

This analysis of Arroyo De La Laguna downstream of Verona must be placed in context of the larger watershed, especially the upstream reaches because of the importance of water and sediment contributions on further channel evolution. The longitudinal profiles and observations made by Ayres Associates (2001) show that the current area of incision has progressed further upstream than Verona. They also report many areas of instability in the channel network upstream of Verona, including reaches with severe incision and other reaches with severe aggradation (Figure 52). Clearly the creation of the network of canals, channelized reaches, gravel mining reaches, detention basins, Del Valle Reservoir, and other urban disturbances has caused spatial imbalances in the supply and transport capacity of sediment. Future management and control of water and sediment supplies in the Zone 7 Water Agency District will dictate how Arroyo De La Laguna downstream of Verona will evolve. Important questions to consider include:

- To what extent has channel incision migrated upstream (last documented in 1998)? What channel type (canal, natural channel, etc) is the incision currently occurring in? Will Zone 7 actively maintain the channels or canals, preventing further incision or bank erosion?

- Are grade control structures working as intended?

- What is the appropriate balance between sediment transport and sediment removal in upstream reaches?

- How will the findings and recommendations of this study be combined with the ongoing geomorphic analysis within the Zone 7 jurisdictional area?

RECOMMENDATIONS

Based on the findings of this study, we offer the following recommendations for consideration to further the understanding of the Alameda Creek watershed processes and better address various stakeholder concerns. Without a full understanding of potential future projects or management goals, we are presently not in a position to determine which study would best address the County's needs, but we hope to stimulate discussion with the following preliminary suggestions:

- *Sediment Budget* - Conduct a sediment source assessment study and develop a sediment budget for upstream areas to understand the dominant processes and rates of sediment supply to the stream network, focusing on identification of potential controllable sources of sediment. A sediment budget provides the manager with knowledge of relative rates of erosion and supply of eroded material to sensitive downstream areas. The next step is to determine which sources or what percentage of mass eroded from each of the sources are controllable using the reasonable management measures available. There are a number of factors that go into making these decisions, including natural geological versus human-induced erosion sources, private versus public property ownership, erosion management measures and their short- and long-term effectiveness, and relative costs of sediment source control, storage (i.e. increased floodplain storage or detention basins), and downstream (e.g. sediment removal) management measures. Ultimately, further sediment budget assessments need to provide better context for managers to cost effectively manage sediment.

- *Long-term Sediment Erosion and Storage Rates* - Provide a more thorough analysis of the sediment budget over the long term (dating of sediment erosion and storage over thousands of years). Because sediment budgets can only address short term erosion rates, a cosmogenic analysis of stream sediments (e.g. Granger et al. 1996, Granger and Muzikar 2001, Belmont et al. in press) would estimate the long term erosion rate (millennial scale) and provide much needed perspective on contemporary rates. For example, Kirchner et al. (2001) found that short-term budgets can be underestimated by ten fold or more because the short time frame is less likely to include extreme events that can supply most of the sediment over the longer term. Similarly, a North Coast cosmogenic study found that so called background or natural erosion rates estimated by EPA from short term "desktop" sediment budgets were underestimated by approximately 250% (Lee Benda and Associates 2005). The samples for cosmogenic analysis have to be collected upstream of eroding valley fills. Extreme events such as fire, 50 and 100 years storms, or earthquakes occur naturally and human land management can exacerbate the erosion and sediment supply to downstream areas when these events occur. Again the focus of a cosmogenic study would need to be on the human interaction with extreme events and the feasibly controllable sediment associated with such events, if any. In addition to a cosmogenic study to estimate millennial erosion rates, carbonized wood in valley fill deposits could be dated using carbon 14 analysis to ultimately estimate historic sediment storage rates in valley segments of the basin. The two analyses combined would provide an

- *Watershed Terrain Mapping and Analyses Tools (NetMap)* - In support of various watershed analyses and planning activities, consider digital terrain mapping of the watershed combined with computerized watershed analysis tools such as NetMap[11] (Benda et al. 2007). Here, some 26 or more watershed terrain parameters are derived from DEMs, climate and flow data, in conjunction with published mass wasting models and relationships between watershed attributes and aquatic environments. A custom ArcGIS tool kit is then used to automate evaluation of various watershed parameters for analyses of interest from hillslope and erosion process to channel environments, including sediment supply, transport and storage patterns, large scale topographic influences on channels, channel geometry, channel classification, channel disturbance potential, core habitat areas, habitat diversity, and habitat typing, to name a few. For example, this tool could be used to determine best locations for sediment source field studies or monitoring and extrapolation of data across similar terrain, identification of ideal storage areas downstream of large sediment sources, and intrinsic habitat potential for aquatic species of interest, among numerous other potential applications.

- *Channel Evolution Monitoring* - Establish a reach scale monitoring program to collect geomorphic data on channel evolution of Arroyo De La Laguna to better understand the trends and rates of change. Such a program could simply include repeated measurements of channel cross sections. While some cross sections have been monumented in this study, additional monumented cross sections should be added for better spatial scale and understanding, including strategic locations such as large erosional bends. These cross sections could be resurveyed annually if possible, or at least following years with high peak flows, for example after peak flows with recurrence intervals greater than 5 years. In addition, simple longitudinal profiles (i.e. low flow water surface, shots from riffle crest to riffle crest) could be resurveyed after large flood events to document and evaluate bed elevation changes over the reach. This type of data would be useful to the manager charged with the design of reach specific control measures, as data input to physical stream models, and for allocation of restoration resources towards specific reaches.

- *Numerical Modeling of Channel Evolution* - Develop a numerical model to better understand current channel form, discharge, and sediment transport in Arroyo De La Laguna and Alameda Creek through the gravel mining reach under various maintenance, restoration, gravel mining, and reservoir management scenarios. The model could be linked to a transport model that routes sediment downstream through Niles Canyon (incorporating gravel supply from dam removal) and to

[11] See http://www.earthsystems.net/ for details on NetMap.

depositional processes in the flood control channel in Fremont. Such modeling could be used to better predict future channel evolution and sediment deposition under different sediment supply and flow scenarios and most importantly to help inform options for restoration and sediment maintenance (e.g. Langendoen and Carlos in press, Langendoen and Simon in press). Simpler analysis of channel evolution and "stability" in Arroyo De La Laguna is possible, including analysis of various bankfull dimensions and metrics (e.g. bankfull width to depth ratios, floodprone widths, etc), however, such analyses should always be tied to fundamental processes of sediment supply, transport, and bank stability (the balance between driving and resisting forces that control channel adjustment) (Simon et al. 2007).

- *Alternative Restoration Approaches* - As stakeholders consider additional bank stabilization projects in Arroyo De La Laguna, we encourage consideration of more holistic approaches to improving channel stability that account for the larger reach goals and evolutionary stage of the channel. While reveting banks with rip rap is a common approach to bank stabilization, such approaches often preclude development of riparian habitat and concentrate stream power on the channel bed and downstream areas, essentially transferring the erosion to another area of the stream other than the localized bank. One alternative approach might include promoting aggradation in Arroyo De La Laguna through a series of wood jams or structures over time and space (e.g. Benda and Berg 2007, Figure 84). Such an approach could have multiple benefits including reduction of the sediment load to the flood control channel and reduced bank erosion in Arroyo De La Laguna from decreased bank heights and increased access to floodplains. While such an approach is to our knowledge, unprecedented and therefore cutting edge, it certainly merits consideration (possibly a brief feasibility study) given (1) that the massive volumes eroded from Arroyo De La Laguna over the past century are now potential storage volumes with such a restoration approach, (2) the substantial costs of dredging such sediment volumes from the flood control channel, and (3) the potential improvements to channel and floodplain habitat. Among many considerations for feasibility of this restoration approach, modeling of flood routing would be required.

- *Instream Wood Policy* - Currently large wood is periodically removed from Arroyo De La Laguna to reduce localized bank erosion from encroaching on private property. Regardless of restoration approaches for Arroyo De La Laguna, we encourage stream managers to leave large wood in the channel to the extent possible. Such a policy would help retain the many beneficial influences of wood jams on channel and floodplain environments (Gurnell et al. 2002), primarily through the trapping and storage of sediment (Keller and Swanson 1979), whereas removal of wood in floodplain rivers can cause incision (Brummer et al. 2006).

- *Flood Control Channel Sediment Assessment* - To potentially identify major source areas of sediment to the flood control channel, consider sediment fingerprinting physical and chemical properties of geologically distinct regions of the watershed for comparison with similar fingerprints of suspended-sediment or bed sediment from the flood control channel (e.g. Carter et al. 2003). Additionally, to determine long-term sediment deposition rates in undisturbed tidal areas of the flood control channel, consider collecting sediment cores for ^{210}Pb or other isotopic analyses.

- *Watershed Planning* - Presently it is hoped that the sum total of all public policies, programs and projects based on laws, codes, statutes, and ordinances that are spread out or enacted by numerous government agencies and private entities will, independently of each other, maintain ecosystem function. However, a lack of coordination leads to ongoing competition for resources, unintended (or unknown) off site or downstream cumulative effects and ecosystems that continue to degrade. A stream goals project aims to develop a goal-oriented, performance-based approach to planning and management of streams and related habitats to optimize ecosystem function within societal needs. In some streams or reaches, the goals will reflect the societal needs for flood protection or water supply and ecosystem function will reflect an approach to minimize downstream effects. In other streams or reaches where societal demands are minimal, ecosystem function will resemble the full spectrum possible in more natural stream environments. A watershed optimized for ecosystem function within societal pressures will then represent a mosaic of stream “types” ranging between these two conceptual end-members based on goals and achieved through determined effort rather than chance. We recommend that a stream goals project be completed for the Alameda Creek watershed.

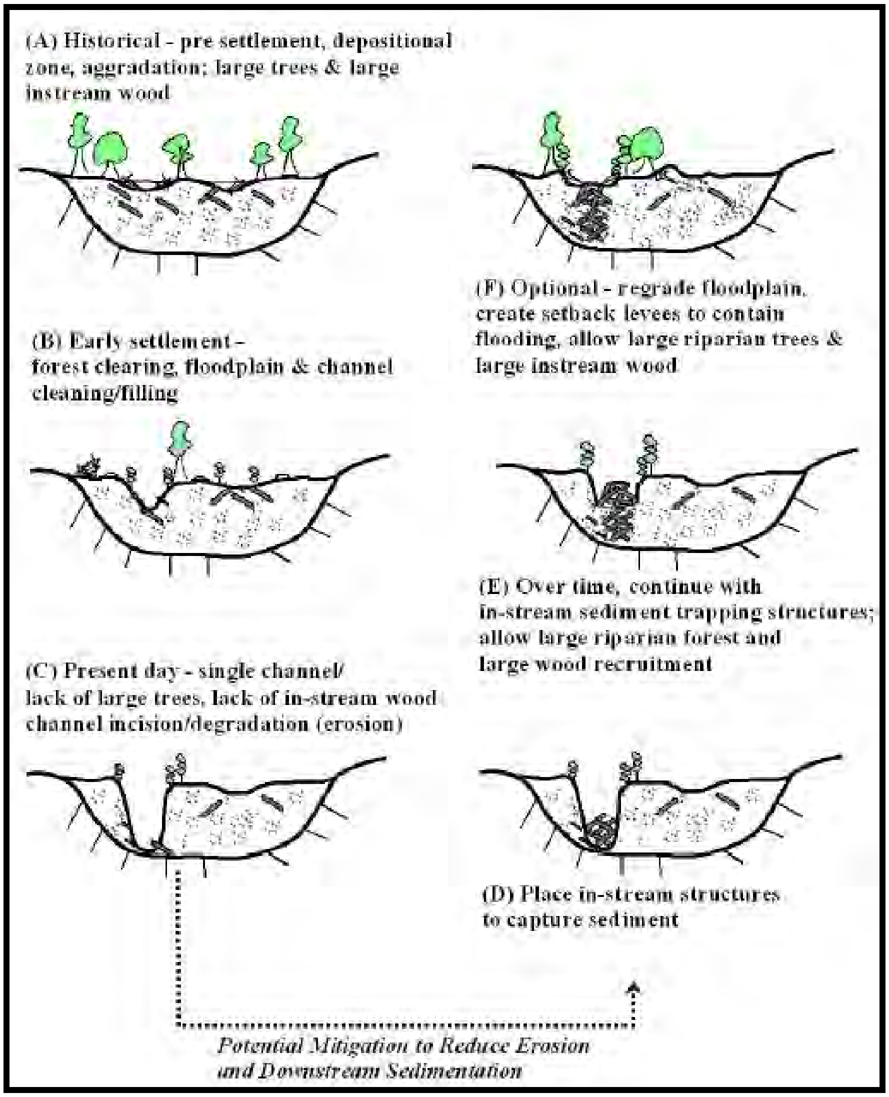


Figure 84. An example from Benda and Berg (2007) shows conceptual incised channel evolution where the channel/floodplain function was altered from sediment deposition to sediment routing (A - C) and a novel approach to restore floodplain function by promoting aggradation (D - F), thereby reducing floodplain erosion and downstream sedimentation, and improving salmonid habitat. Among many considerations for feasibility of this restoration approach, modeling of flood routing would be required.

REFERENCES

Alameda County Flood Control and Water Conservation District (ACFCWCD), 1966. Green Book: Zone 7 Project Line A and Line B general profiles, August, streambed and top of bank elevation survey, file MB52, sheets 1 and 2 of 17, August 1959. Obtained from Zone 7 Water Agency.

Alameda Creek Alliance. 2007. www.alamedacreek.org

Alger, C.S., and S.D. Ellen. 1987. Zero-order basins shaped by debris flows, Sunol, California, USA: In: Erosion and sedimentation in the Pacific Rim, Proceedings of the Corvallis Symposium, International Association of Hydrological Sciences (IAHS), Publication 165: 111-119.

Anderson, H.W., 1981. Sources of sediment-induced reductions in water quality appraised from catchment attributes and land use. Journal of Hydrology 51: 347-358.

Ayres Associates 2001. Technical Memorandum No. 5 Technical Appendix C, Zone 7 Geomorphic and Sediment Transport Evaluation. Unpublished report prepared for West Yost & Associates. September.

Belmont, P., F.J. Pazzaglia, and J.C. Gosse. In press. Cosmogenic 10Be as a tracer for hillslope and channel sediment dynamics: Earth and Planetary Science Letters.

Benda, L., and A. Berg, 2007. Sources, magnitude, and mitigation of erosion and sedimentation in the Salt River Basin, with emphasis on Francis and Williams Creek Basins. Prepared for: Humboldt County Resource Conservation District. 42 pp.

Benda, L., and T. Dunne, 1987. Sediment routing by debris flow. Proceedings, Symposium on Erosion and Sedimentation in the Pacific Rim. IAHS Publ. 165: 213–223.

Benda, L., P. Bigelow, and T. Worsley. 2002. Recruitment of wood to streams in old-growth and second-growth redwood forests, northern California, U.S.A. Canadian Journal of Forest Research 32: 1460-1477.

Benda, L. and J. Sias, 2003. A Quantitative Framework for Evaluating the Wood Budget. Journal of Forest Ecology and Management 172:1-16.

Benda L, K. Andras, D. Miller, and P. Bigelow. 2004. Confluence effects in rivers: interactions of basin scale, network geometry, and disturbance regimes. Water Resources Research 40 W05402, doi:10.1029/2003WR002583.

Benda, L., D. Miller, K. Andras, P. Bigelow, G. Reeves, and D. Michael. 2007. NetMap: A new tool in support of watershed analysis and resource management. Forest Science 53(2):206-219. http://www.earthsystems.net/docs/Benda2007NetMap.pdf

Bledsoe, B.P., C.C. Watson, and D.S. Biedenharn. 2002. Quantification of incised channel evolution and equilibrium. Journal of the American Water Resources Association 38(3): 861-870.

Brady, R.H., S. Pearce, L. McKee, S. Overton, and C. Striplen. 2003. Fluvial geomorphology, hydrology, and riparian habitat of La Honda Creek along the Highway 84 transportation corridor, San Mateo County, California. An unpublished technical report of the Watershed Program, San Francisco Estuary Institute (SFEI), Oakland, CA. SFEI contribution no. 78.

Brardinoni, F., O. Slaymaker, and M. Hassan. 2003. Landslide inventory in a rugged forested watershed: a comparison between air-photo and field survey data. Geomorphology 54 (3-4): 179-196.

Brown, W.M. and L.E. Jackson. 1973. Erosional and depositional provinces and sediment transport in the south and central part of the San Francisco Bay region, California. USGS Interpretive Report 3.

Brummer, C.J., T.B. Abbe, J.R. Sampson, and D.R. Montgomery. 2006. Influence of vertical channel change associated with wood accumulations on delineating channelmigration zones, Washington, USA. Geomorphology 80: 295-309.

Carter, J., P.N. Owens, D.E. Walling, and G.J. Leeks. 2003. Fingerprinting suspended sediment sources in a large urban river system. The Science of the Total Environment. 314-316(1): 513-534

CCSF 2007. SFPUC Water System Improvement Program EIR. For the San Francisco Public Utilities Commission's WATER SYSTEM IMPROVEMENT PROGRAM, San Francisco Planning Department File No. 2005.0159E. City and County of San Francisco, San Francisco Planning Department. Draft PEIR Publication Date: June 29, 2007. http://www.sfgov.org/site/uploadedfiles/planning/vol3_sec5-4_wsip-dpeir.pdf

Church, M.A., D.G. McLean, and J.F. Wolcott. 1987. Riverbed gravels; sampling and analysis. *In*: Sediment transport in gravel-bed rivers, eds., Thorne, C.R., Bathurst, J.C., and Hey, R.D., John Wiley and Sons: 43-78.

City of Pleasanton. 2007. http://www.pleasanton.org/lip_history.html

Coe, J.A., and J.W. Godt. 2001. Debris Flows Triggered by the El Niño Rainstorm of February 2-3, 1998, Walpert Ridge and Vicinity, Alameda County, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-2384.

Collier, M.P., R.H. Webb, and J.C. Schmidt. 1996. Dams and Rivers: A Primer on The Downstream Effects of Dams. U.S. Geological Survey Circular 1126. 94 p

Collins, L. 1998. Sediment sources and fluvial geomorphic processes of Lower Novato Creek Watershed. Unpublished report prepared for the Marin County Flood Control and Water Conservation District.

Collins, L., and K. Leising. 2003. Draft Alameda Creek Sediment Budget and Sediment Source Analysis: 2003 Progress Report. Unpublished report prepared for Alameda County Public Works Department.

Collins, L., 2005. Summary of Watershed Sciences' Progress Report for Alameda Creek Sediment Budget and Sediment Source Analysis (Power Point Presentation).

Dietrich, W.E. and T. Dunne, 1978. Sediment Budget for a Small Catchment in Mountainous Terrain: Zietschrift fur Geomorphologie, Suppl. 29:191-206.

Dillon, R.H., 2004. Napa Valley Heyday. The Book Club of San Francisco.

Doyle, M.W., and F.D. Shields. 2000. Incorporation of bed texture into a channel evolution model. Geomorphology 34: 291-309.

Dunne, T., and L.B. Leopold. 1978. Water in environmental planning. W. H. Freeman & Company. San Francisco. 818 p.

Ellen, S.D., R.K. Mark, G.F. Wieczorek, C.M. Wentworth, D.W. Ramsey, and T.E. May. 1997. San Francisco Bay Region landslide folio part E - map of debris-flow source areas in the San Francisco Bay Region, California. U.S. Geological Survey open-file report 97-745E.

Emmett, W.H. 2004. A Historical Perspective on Regional Channel Geometry Curves. Stream Notes - January. U.S. Forest Service Streams Sytems Technology Center.

ESA. 2004. Pescadera-Butano watershed assessment. Unpublished report prepared for the Monterey Bay National Marine Sanctuary Foundation. March.

Federal Emergency Management Agency (FEMA) 1975. Flood Insurance Study, Alameda County, California: Unincorporated areas. Volume 2 of 2. Federal Emergency Management Agency, Washington, D.C.

Federal Emergency Management Agency (FEMA) 1997. FEMA 1975 Flood Insurance Study, Alameda County, California: Unincorporated areas. Volume 1 of 2. Federal Emergency Management Agency, Washington, D.C. Revised 1997.

Freeman, J.R. 1912. On the proposed use of a portion of the Hetch Hetchy, Eleanor and Cherry Valleys within and near to the boundaries of the Stanislaus U.S. National Forest Reserve and the Yosemite National Park as reservoirs for impounding Tuolumne River flood waters and appurtenant works for the water supply of San Francisco, California and neighboring cities. An unpublished report to James Rolph, Jr., Mayor of San Francisco and Percy Long, city attorney. Published by the Board of Supervisors.

Golder Associates. 1999. Geomorphic Analysis of Arroyo de la Laguna Pleasanton, California. Unpublished report prepared for Schaaf & Wheeler Consulting Civil Engineers. February.

Goodridge, J. 2007. California Weather CD – compilation of various precipitation records for California by the former State climatologist.

Gragg, J. 2008. SFPUC Niles and Sunol dam removal project: channel morphology and fish passage monitoring. Powerpoint presentation by Justin Gragg (Environmental Science Associates) at the April 2008 Alameda Creek Sediment Forum. http://www.sfei.org/alamedacreek/forum.html

Granger, D.E., J.W. Kirchner. and R. Finkel. 1996. Spatially averaged long-term erosion rates measured from in situ–produced cosmogenic nuclides in alluvial sediment: Journal of Geology 104: 249–257.

Granger, D.E., and P.F. Muzikar. 2001. Dating sediment burial with in situ-produced cosmogenic nuclides: theory, techniques, and limitations. Earth and Planetary Science Letters 188(1-2): 269-281.

Graymer, R.W., B.C. Moring, G.J. Saucedo, C.M. Wentworth, E.E. Brabb, and K.L. Knudsen. 2006. Geologic Map of the San Francisco Bay Region. USGS Scientific Investigations Map 2918. 1:275,000.

Gregory, K.J., R.J. Davis, and P.W. Downs. 1992. Identification of river channel change due to urbanization. Applied Geography, 12: 299-318.

Griggs, G.B., and L. Paris. 1982. Flood control failure: San Lorenzo River, California. Environmental Management 6: 407-419.

Grossinger, R., R. Askevold, C. Striplen, E. Brewster, S. Pearce, K. Larned, L. McKee, and J. Collins. 2006. Coyote Creek Historical Ecology Study: Historical conditions and landscape change in the eastern Santa Clara Valley, California. San Francisco Estuary Institute, Oakland CA. Unpublished Contribution no. 426.

Gurnell A.M., H. Piégay, F.J. Swanson, and S.V. Gregory. 2002. Large wood and fluvial processes. Freshwater Biology 47: 601-619.

Hofmann,W., and S.E. Rantz. 1963. Floods of 1955-January 1956 in the far western states, Part 1: Description: U.S. Geological Survey Water-Supply Paper 1650, 156 pp.

Horowitz, A.J. and Walling, D.E. 2005. Sediment Budgets II, IAHS Publ. 292.

Hupp, C.R., and A. Simon. 1991. Bank accretion and the development of vegetated depositional surfaces along modified alluvial channels. Geomorphology 4: 111-124.

Inman, D.L., and S.A. Jenkins. 1999. Climate change and the episodicity of sediment flux of small California rivers. The Journal of Geology 107:. 251-270.

Jennings, C.W., 1994. Fault activity map of California and adjacent areas. California Department of Conservation, Division of Mines and Geology, Geologic Data Map No. 6.

Keller, E.A and F.J. Swanson. 1979. Effects of large organic material on channel form and fluvial processes. Earth Surface Processes and Landforms 4:361-380.

Kelsey, H.M., 1980, A sediment budget and an analysis of geomorphic process in the Van Duzen River basin, north coastal California, 1941-1975; Geological Society of America Bulletin, Part II, 91, 1119-1216.

Knighton, D. 1998. Fluvial forms and processes a new perspective. John Wiley and Sons, Inc. New York. 382 p.

Kirchner, J.W., R.C. Finkel, C.S. Riebe, D.E. Granger, J.L. Clayton, J.G. King, W.F. Megahan. 2001. Mountain erosion over 10 yr, 10 k.y., and 10 m.y. time scales. Geology 29(7): 591-594.

Kondolf, G.M., and R.R. Curry. 1986. Channel erosion along the Carmel River, Monterey County, California. Earth Surface Processes and Landforms 11:307-319.

Kondolf, G.M., L.M. Maloney, and J.G. Williams. 1987. Effect of bank storage, and well pumping on base flow, Carmel River, California. Journal of Hydrology 91:351-369.

Kondolf, G.M., and W.V.G. Matthews. 1991. Unmeasured residuals in sediment budgets: A cautionary note. Water Resources Research 27: 2483-2486.

Lane, E.W, 1955. Design of stable alluvial channels. Transactions American Society of Civil Engineers 120(2776): 1234-1260.

Langendoen, E. and A. Carlos. In press. Modeling evolution of incised streams: I. model formulation and validation of flow and streambed evolution components. Journal of Hydraulic Engineering.

Langendoen, E. and A. Simon. In press. Modeling evolution of incised streams: II. streambank erosion. Journal of Hydraulic Engineering.

Laser Technology 2008. Impulse 200 LR specifications. http://www.lasertech.com/Impulse200LRSpec.pdf

Lee Benda and Associates. 2005. Erosion rates in The Ten Mile River basin, Northern California using cosmogenic isotopes. Unpublished report prepared for Campbell Timberland Management.

Lehre, A.K., 1982. Sediment Budget of a small Coast Range drainage basin in north-central California, in F.J. Swanson, R.J. Janda, T. Dunne, and D.N. Swanston eds., Sediment Budgets and Routing in Forested Drainage Basins: U.S. Forest Service Pacific Northwest Forest and Range Experiment Station General Technical Report PNW;141, p. 67-77.

Leidy, R.A., G.S. Becker, and B.N. Harvey. 2003. Historical distribution and current status of steelhead (*Oncorhynchus mykiss*), coho salmon (*O. kisutch*), and chinook salmon (*O. tshawytscha*) in streams of the San Francisco Estuary, California. Unpublished report prepared by the Center for Ecosystem Management and Restoration, Oakland, California.

Leidy, R.A., G. Becker, and B.N. Harvey. 2005. Historical Status of Coho Salmon in Streams if the Urbanized San Francisco Estuary, California. California Fish and Game 9(14): 1-36.

Leidy, R.A., 2007. Ecology, assemblage structure, distribution, and status of fishes in streams tributary to the San Francisco Estuary, California. San Francisco Estuary Institute, unpublished contribution no. 530.

Ligon, F.K., W.E. Dietrich, and W.J. Trush. 1995. Downstream ecological effects of dams, a geomorphic perspective. Bioscience 45:183-192.

Lisle, T.E. 1982. Effects of Aggradation and degradation on riffle-pool morphology in natural gravel channels, Northwestern California. Water Resources Research 18(6): 1643-1651.

Luna, H., and the Pacific Locomotive Association, 2005. Images of Rail: Niles Canyon Railways

Lunn, David. Employee of Alameda County Zone 7 Water Agency. Personal communication, January, 2007.

McKee, L., J. Leatherbarrow, S. Pearce, and J. Davis. 2003. A review of urban runoff processes in the Bay Area: Existing knowledge, conceptual models, and monitoring recommendations. Unpublished report prepared for the Sources, Pathways and Loading Workgroup of the Regional Monitoring Program for Trace Substances. SFEI Contribution 66. San Francisco Estuary Institute, Oakland, CA.

Milbert, D.G. 1999. National Geodetic Survey height conversion methodology - a process is designed to provide datum shift between the NAVD 88 and NGVD 29 vertical datums at specified geographic position: http://www.ngs.noaa.gov/TOOLS/Vertcon/vert_method.html

Program available at: http://www.ngs.noaa.gov/cgi-bin/VERTCON/vert_con.prl

Montgomery, D.R., and J.M. Buffington. 1997. Channel-reach morphology in mountain drainage basins. Geol. Soc. Am. Bull. 109:596–611.

Mount, J.F., 1995. California rivers and streams; the conflict between fluvial process and land use. University of California Press, London, England. 350 pp.

Natural Resource Conservation Service, 2003. Stream Bank Erosion Field Office Technical Guide. http://www.dnr.state.wi.us/org/water/wm/nps/pdf/mso341_streambank.pdf

Nelson, E.J., and D.B. Booth. 2002. Sediment sources in an urbanizing, mixed land-use watershed. Journal of Hydrology 264: 51-68.

Niezgoda, S.L., and P.A. Johnson. 2005. Improving the urban stream restoration effort: identifying critical form and processes relationships. Environmental Management 35(5): 579-592.

Nolan, K.M., T. E. Lisle, and H.M. Kelsey. 1987. Bankfull discharge and sediment transport in northwestern California. Erosion and Sedimentation in the Pacific Rim (Proceedings of the Corvallis Symposium, August, 1987). IAHS Publ. no. 165.

Pearce, S., L. McKee, and S. Shonkoff. 2005. Pinole Creek Watershed Sediment Source Assessment. An unpublished technical report of the Regional Watershed Program, San Francisco Estuary Institute, Oakland, CA. SFEI Contribution number 316. 102 p.

Philip William and Associates (PWA). 2005. Trends In suspended sediment input to the San Francisco Bay from local tributary watersheds. Unpublished report prepared for the San Francisco Estuary Institute.

Porterfield, G., 1980. Sediment transport of streams tributary to San Francisco, San Pablo, and Suisun Bays, California, 1909-1966. U.S. Geological Survey Water Resources Investigations 80-64.

Reid, L.M. and T. Dunne. 1996. Rapid construction of sediment budgets for drainage basins. Cremlingen, Germany, Catena-Verlag.

Reid, L.M., and T. Dunne. 2003. Sediment budgets as an organizing framework in fluvial geomorphology. *In*: Tools in Fluvial Geomorphology, eds., Kondolf, G.M, and H. Piegay, John Wiley and Sons: 463-500.

Renwick, W.H., S.V. Smith, J.D. Bartley, and R.W. Buddemeier. 2005. The role of impoundments in the sediment budget of the conterminous United States. Geomorphology 71: 99– 111.

Rice, S., 1998. Which tributaries disrupt downstream fining along gravel-bed rivers? Geomorphology 22: 39-56.

Riley, A. 2003. A primer on stream and river protection for the regulator and program manager. Technical Reference Circular. W.D. 02 - #1. Unpublished report prepared by the San Francisco Bay Region California Regional Water Quality Control Board. April.

San Francisco Estuary Institute (SFEI). 2001. Wildcat Creek watershed: a scientific study of physical processes and land use effects. Unpublished report.

Schumm, S.A. 1956. Evolution of drainage systems and slopes in badlands at Perth Amboy, New Jersey. Bulletin of the Geological Society of America 67:597-646.

Schumm, S.A., 1977. The fluvial system: New York, Wiley and Sons, 338 p.

Schumm, S.A., Harvey, M.D., and Watson, C.C., 1984. Incised channels: morphology dynamics and control. Water Resources Pub., Littleton, CO. 200 p.

Schumm, S.A., 1999. Causes and controls of channel incision. *In*: Incised river channels, eds. Darby, S.E., and Simon, A. John Wiley & Sons Ltd.

Shreve, R.W., 1969. Stream lengths and basin areas in topologically random channel networks. Journal of Geology 77:397-414.

Simetrics 2007. Density of materials. http://www.simetric.co.uk/si_materials.htm

Simon, A., 1989. A model of channel response in disturbed alluvial channels. Earth Surface Processes and Landforms 14: 11-26.

Simon, A. 1994. Gradation processes and channel evolution in modified West Tennessee streams: process, response, and form. U.S. Geolgical Survey Professional Paper 1470, 84 p.

Simon, A., and C.R. Hupp. 1986. Channel evolution in modified Tennessee channels. Proceedings of the Fourth Federal Interagency Sedimentation Conference March 24-27, 1986, Las Vegas, Nevada. Volume II. 1986. p 5-71 to 5-82, 5 fig, 3 tab, 11 ref.

Simon, A., and S. Darby. 1999. The nature and significance of incised river channels. In: Incised River Channels, eds. Darby, S.E., and Simon, A. John Wiley & Sons Ltd.

Simon, A., A. Curini, S.E. Darby, and E.J. Langendoen. 2000. Bank and near-bank processes in an incised channel. Geomorphology 35: 193-217.

Simon, A., and M. Rinaldi. 2006. Disturbance, stream incision, and channel evolution: the roles of excess transport capacity and boundary materials in controlling channel response. Geomorphology 79: 361-383.

Simon, A., M. Doyle, M. Kondolf, F.D. Shields Jr., B. Rhoads, and M. McPhillips. 2007. Critical evaluation of how the Rosgen classification and associated "Natural Channel Design" methods fail to integrate and quantify fluvial processes and channel response. Journal of the American Water Resources Association 43(5): 1-15.

Sloan, J., J.R. Miller, and N. Lancaster. 2001. Response and recovery of the Eel River, California, and its tributaries to floods in 1955, 1964, and 1997. Geomorphology 36 (3-4): 129-154.

Sowers, J.M. 1997. Historical Geomorphology of the Alameda Creek Fan, Alameda County, California. EOS Transactions AGU, Fall Mtg. Suppl., Abstract H41B-20.

Sowers, J.M. 1999. Creek and watershed map of Fremont and vicinity. Oakland Museum of California, Oakland, CA.

Sowers, J.M. and Richard. 2003. Creek and watershed map of the Pleasanton and Dublin area. Oakland Museum of California, Oakland, CA.

Stallard, R.F. 1998. Terrestrial sedimentation and the carbon cycle: Coupling weathering and erosion to carbon burial: Global Biogeochemical Cycles 12: 231-257.

Stetson Engineers. 2000. Geomorphic assessment of the Corte Madera Creek watershed. Unpublished report prepared for the Friends of the Corte Madera Creek Watershed and the Marin County Department of Public Works.

Stillwater Sciences 2004. Sediment budget for Redwood Creek watershed, Marin County, California. Unpublished report prepared for the Golden Gate National Recreation Area.

Strahler, A.N. 1957. Quantitative analysis of watershed geomorphology. Tran. Am. Geophys. Union 38:913–920.

Swanson, F.J., R.J. Janda, T. Dunne, and D.N. Swanston. 1982a. Sediment budgets and routing in forested drainage basins. US Forest Service General Technical Report PNW-141, Pacific Northwest Forest and Range Experiment Station, US Forest Service, Portland, Oregon.

Swanson, F.J., R.L. Fredrickson, and F.M. McCorison, 1982b. Material transfer in a Western Oregon forested watershed. *In*: Analysis of coniferous forest ecosystems in the Western United States, R.L. Edmonds (Editor). Hutchinson Ross Publishing Co., Stroudsburg, Pennsylvania, pp.233-266.

Tetra Tech. 2001. Bolinas Lagoon watershed study. Input sediment budget. Unpublished report prepared for the U.S. Army Corps of Engineers.

Thompson and West. 1878. Historical atlas map of Alameda County, California: compiled, drawn and published from personal examinations and surveys. Smith & McKay Printing.

Thorne, C.R., 1999. Bank processes and channel evolution in the incised rivers of north-central Mississippi. In: Incised River Channels, eds. Darby, S.E., and Simon, A. John Wiley & Sons Ltd.

Trimble, S.W. 1997. Contribution of stream channel erosion to sediment yield from an urbanizing watershed. Science 278: 1442-1444.

Trimble, S.W. 1999. Decreased rates of alluvial sediment storage in the Coon Creek Basin, Wisconsin, 1975-93. Science 285 (5431): 1244 – 1246.

Trush, W., S. McBain, and R. Shea. 2007. Alameda Creek instream flow, habitat assessments, and alternative development. Phase 1: Study Development. Unpublished report prepared for Alameda Creek Fisheries Restoration Workgroup. April. 49 p.

USGS 2008. Digital hydrography layer for Alameda, Contra Costa, and Santa Clara Counties downloaded from the National Hydrography Dataset in January 2008. http://nhdgeo.usgs.gov/viewer.htm

Vorosmarty, C.J., M. Meybeck, B, Fekete, K. Sharma. 1997. The potential impact of neo-castorization on sediment transport by the global network of rivers. In Human Impact on Erosion and Sedimentation, IAHS Publ., vol. 245, pp. 261–273.

Vyverberg, K.A., B. Snider, R.G. Titus. 1997. Lower American River Chinook salmon spawning habitat evaluation: An evaluation of attributes used to define the quality of spawning habitat. California Department of Fish and Game, Sacramento, California.

Walling, D.E., and Q. He. 1998. The spatial variability of overbank sedimentation on river floodplains. Geomorphology 24: 209-223.

Watson, C.C., M.D. Harvey, and J. Garbrecht. 1986. Geomorphic-hydraulic simulation of channel evolution. Proceedings of the Fourth Federal Interagency Sedimentation Conference March 24-27, 1986, Las Vegas, Nevada. Volume II. 1986. p 5-21 to 5-30, 5 fig, 1 tab, 19 ref. Soil Conservation Service Contract Nos. SCS-23-MS-80 and SCS-54-MS-83.

Weiss Associates. 2004. Final Report for Channel Geomorphology Study Niles and Sunol Dam Removal Project Alameda County, California. Unpublished report prepared for Project Management Bureau, San Francisco Public Utilities Commission.

Wentworth, C.M., S.E. Graham, R.J. Pike, G.S. Beukelman, D.W. Ramsey, and A.D. Barron. 1998. Summary distribution of slides and earth flows in the San Francisco Bay Region, California San Francisco Bay Region Landslide Folio Part C – USGS Open-File Report 97-745C.

Williams, C., 1912. Report on the Water Supply of the Alameda Creek Watershed with particular reference to Livermore Valley underground supply. Unpublished report prepared for Percy Long, San Francisco City Attorney.

Witter, R.C., K.L. Knudsen, J.M. Sowers, C.M. Wentworth, R.D. Koehler, and C.E. Randolph. 2006. Maps of Quaternary Deposits and Liquefaction Susceptibility in the Central San Francisco Bay Region, California. U.S. Geological Survey Open-File Report 2006-1037.

Wolman, M.G., and L.B. Leopold. 1957. River flood plains: some observations on their formation. U.S. Geological Survey Professional Paper 282-C, 30 p.

Young, L.E. 1962. U.S. Geological Survey Hydrological Atlas HA-54.

Zone 7 Water Agency. 2006. Zone 7 stream management master plan section 3: needs and opportunities. http://www.zone7water.com/images/SMMP_Sec.3-Needs%26Opp.pdf