San Francisco Estuary Institute Regional Watershed Program

Pinole Creek Watershed Sediment Source Assessment

SFEI Contribution 316
January 2005

San Francisco Estuary Institute
in conjunction with
Contra Costa Resource Conservation District
and
USDA Natural Resources Conservation Service

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Prepared by the San Francisco Estuary Institute

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The Regional Watershed Program was founded in 1998 to assist local and regional environmental management and the public to understand, characterize and manage environmental resources in the watersheds of the Bay Area. Our intent is to help develop a regional picture of watershed condition and downstream effects through a solid foundation of literature review and peer-review, and the application of a range of science methodologies, empirical data collection and interpretation in watersheds around the Bay Area.

Over this time period, the Regional Watershed Program has worked with Bay Area local government bodies, universities, government research organizations, Resource Conservation Districts (RCDs) and local community and environmental groups in the Counties of Marin, Sonoma, Napa, Solano, Contra Costa, Alameda, Santa Clara, San Mateo, and San Francisco. We have also fulfilled technical advisory roles for groups doing similar work outside the Bay Area.

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EXECUTIVE SUMMARY

Excess sediment, water quality, water supply, aquatic habitat, and flood conveyance are primary issues facing planners and the public in many watersheds of the Bay Area. Based on these community concerns which were developed by the Pinole Creek Watershed Vision Planning group, the Contra Costa Resource Conservation District (CCRCD) decided to conduct a Sediment Source Analysis and Baseline Water Quality study in the Pinole Creek Watershed. The CCRCD and the Natural Resources Conservation Service (NRCS) jointly assembled a Technical Advisory Committee (TAC) consisting of local land managers and agencies to develop the scope of the study. The RCD and NRCS retained SFEI in October 2003 to gather data on hillslope sediment erosion and storage, road related sediment erosion and storage, stream bed and bank erosion and storage, nutrient concentrations at 11 locations, and water and sediment discharge to the flood control channel. SFEI followed accepted geomorphic and water quality methods and appropriate quality assurance protocols during all stages of data collection, analysis, and interpretation. Periodic presentations were made to the TAC and to the local community at the Friends of Pinole Creek Watershed meetings throughout the project.

Sediment erosion in the watershed is occurring from 3 primary sources. Active landslides are the largest contributor providing approximately 61% of the total annual average sediment supply to the Creek. On average, active gullies and road related sources provide a further 17% and 14% annually. Sediment derived from creek bed and bank erosion are only minor contributors to the overall sediment budget of the watershed. During the study, all 11 sampling locations for water quality exceeded EPA guidelines in Level III Eco-Region 6 for nitrogen and phosphorus on at least one occasion. The guidelines were not met for phosphorous all year round whereas the guidelines were exceeded for nitrogen mainly during the winter months. Generally, it appears that the watershed is nitrogen limited. Suspended sediment concentrations measured at Pinole Valley Road Bridge number 5 ranged between 5.7- 13,238 mg/L. Suspended sediment loads measured during the study were probably a little above average given rainfall was above average. Suspended sediment export was 252 t km^{-2}, approximately 2.5 times greater than the Bay Area average. Virtually all of this sediment passes through the flood control channel annually – presently we believe the flood control channel is largely self-maintaining. The reader is referred to the main body of the document for specific data and interpretations, and rational or implications behind our general recommendations that follow:

1) *Encourage water sensitive planning to increase base flow and decrease storm flow, and install a real-time flow gauge to assist in day-to-day water allocations.*
2) *Encourage land use specific sediment control measures (BMPs), selective conservation in subwatersheds most prone to landsliding, and riparian management strategies that increase riparian width and function.*
3) *Implement projects to stabilize gully head cuts, to control sediment input from active landslides, and to prevent reactivation of dormant landslides.*
4) *Plan creek setbacks in areas where land is publicly owned or where private landowners are willing to allow channel form evolution.*
5) *Encourage maintenance of water quality through reduction of fine sediment supply to the creek in general and BMPs on horse boarding facilities (phosphorus), and maintenance of septic sewage systems (nitrogen).*
6) *Carryout periodic monitoring of the functioning of the flood control channel in relation to redesign and upstream changes in water and sediment supply.*
7) *Encourage collaboration between landowners, agencies, and funding sources so that reasonable solutions are identified and management actions can be successfully implemented.*

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INTRODUCTION

In the highly urbanized and developed San Francisco Bay Area, the Pinole Creek watershed remains one of the last areas that supports a strongly rural lifestyle. The upper watershed contains large areas of open space and managed grazing lands, ranching and agricultural activities, and ranchettes focused upon equestrian activities. The lower watershed contains historic Old Town District of Pinole, and quiet suburban neighborhoods of Pinole, Hercules, and El Sobrante. Because of its uniqueness, the residents, local natural resource managers, and other stakeholders of the Pinole Creek watershed wish to work collaboratively to maintain its assets by enhancing the watershed for flood management, water quality, aquatic habitat, sustainable ranching and agricultural productivity, soil health, water supply, and aesthetic value.

The primary concerns expressed by residents and stakeholders include control of landslides and other large erosion sources, excess sediment in the creek reducing habitat value, sediment in the flood control channel reducing flood conveyance capacities, excess nutrients in the creek, and maintaining surface and ground water supplies. Many physical features relating to these concerns are readily observable to the general public as they travel through the watershed. For example, in the lower reach residents observe very high water levels and brown-colored water while walking along the creek and flood control channel during winter storm events. During the summer months, residents observe bright green algae and lots of aquatic plants growing in these same areas. Compared to years past, residents have noticed a decline in the numbers of fish, especially steelhead trout, in the creek. Further upstream in the watershed, driving along Pinole Valley Road/Alhambra Valley Road, residents can't help but notice massive landslide features on the hillslopes, large gullies forming in some of the fields near the sides of the road, or channel bank erosion threatening the stability of the road. They may also have noticed more people and activity in the watershed year by year, whether it is more houses and development, more ranchettes, more recreational activities, or even increased amounts of illegal dumping of trash and household items at roadside pullouts. The focus of this project, to gain a better understanding of processes occurring in the watershed relating to water and sediment in Pinole Creek, was in part guided by the concerns expressed by residents and stakeholders.

Erosional processes in streams and on hillsides are controlled by factors such as underlying geology, soil development, slope, climate, vegetation cover, land use, road density, and other human landscape modifications such as changes in basin hydrology. Although erosion is a natural process, excess erosion and sediment contribution can cause a creek's equilibrium to change, potentially causing damage to property and ecological functions. Excess sediment can carry nutrients detrimental to aquatic organisms, cause channel aggradation, cause flooding, or negatively affect creek bed conditions for fish spawning and rearing. Excess sedimentation in creeks can be caused by geologic and climatic characteristics, changes in land use, or modifications to the natural flow of water within the basin.

An analysis of sediment sources in the Pinole Creek watershed is necessary to understand the dominant physical processes, and their rates and magnitudes that are contributing sediment to the creek. An understanding of these processes is an important step in the development of management practices and solutions that will address concerns of residents and stakeholders, and can assist in maintaining the beneficial uses of the watershed.

The primary goals of this project are to:

1) Identify the major sources of sediment in the watershed,
2) Determine the relative magnitude and causative mechanisms of sediment production, supply to, and storage in Pinole Creek,
3) Identify physical processes and factors that limit beneficial uses in the watershed that are related to sediment,
4) Develop data on water quality, and
5) Recommend potential areas of management solutions based upon sound science and community and stakeholder input.

The data and observations collected during this project will form the base information needed for the design of landscape-scale erosion prevention and conservation practices, as well as for watershed-scale environmental management and decision-making by the residents and stakeholders of Pinole Creek watershed.

Report guide

This report, which describes the physical processes relating to sediment in the Pinole Creek watershed, is written for the lay-person as well as the natural resource managers and other stakeholders with a greater technical background. The report is comprised of nine major sections, and an appendix. Each section describes key aspects of the physical environment and how it relates to sediment, land use, and management by the landowners, resource managers, and stakeholders. The following bullets detail the report contents:

- The Pinole Creek Watershed Overview section generally describes the location, underlying bedrock geology, soils, topography, climate, land use, political boundaries, vegetation, and other basic components of the watershed.
- The Rainfall and Pinole Creek Flow section describes the sources and analysis of historic and current rainfall and creek flow data. This hydrologic data provides the climatic background for the other sections.
- The Landslides, Gullies, and Surface Processes section describes the methodologies, analysis, and findings of the aerial photograph interpretation and landslide and gully mapping effort. Our assessment of road and land use contributions of sediment to the fluvial system is also discussed.
- The Channel Processes section describes the methodologies, analysis and findings from our channel geomorphology assessment. The in-channel sources, storage, and transport of sediment, as well as channel form and function are discussed.

- The Suspended Sediment Load section describes our 2004 Water Year measurement of suspended sediment concentration, turbidity, and discharge in Pinole Creek. The data is analyzed and compared to other Bay Area creeks.
- The Water Quality section describes the data collection methodologies, analysis, and findings, presenting information on nitrogen, ammonia, and phosphorous at 11 locations throughout the watershed.
- The Synthesis section brings together all of the collected data, and presents a conceptual model of physical processes relating to sediment occurring in the watershed. This section also presents two sediment budgets, one for Pinole Creek upstream of the flood control channel, and the other for the flood control channel portion of the watershed. Additionally, this section generally describes our best understanding of the form and function of the watershed.
- The Environmental and Stakeholder Concerns section addresses concerns raised by residents and stakeholders of the watershed including: aquatic habitat, primarily for steelhead trout; water supply, focusing on surface perennial creek flow; flood management, including the response of the flood control channel; water quality degradation from animal wastes, including sediment and nutrients contributed from confined animal facilities; and water quality degradation from excess sediment, including effects of current and historic land use such as urban areas, agriculture, and grazing.
- The Conclusions and Recommendations section outlines our findings and major recommendations for future opportunities, management, and study.
- The Appendix compiles the raw data that was collected during the project, and other more detailed data and analyses that were not included within the report.

PINOLE CREEK WATERSHED OVERVIEW

The Pinole Creek watershed is located in the East Bay hills in western Contra Costa County, California (Figure 1). The watershed follows the regional geologic northwest-southeast orientation (similar to the orientation of the Berkeley Hills), and is located just northeast of the Sobrante Ridge. The watershed is approximately 39.6 km^2 (15.3 mi^2) in area, extending from Costa and Duarte Peaks (in the Briones Hills) at the headwaters, northwest to the San Pablo Bay just east of Wilson Point. Elevation varies between 378 m (1,240 ft) at Costa Peak, down to mean sea level where Pinole Creek enters San Pablo Bay. The watershed is located on the Briones Valley, Richmond, and Mare Island USGS 7.5′ topographic quadrangles.

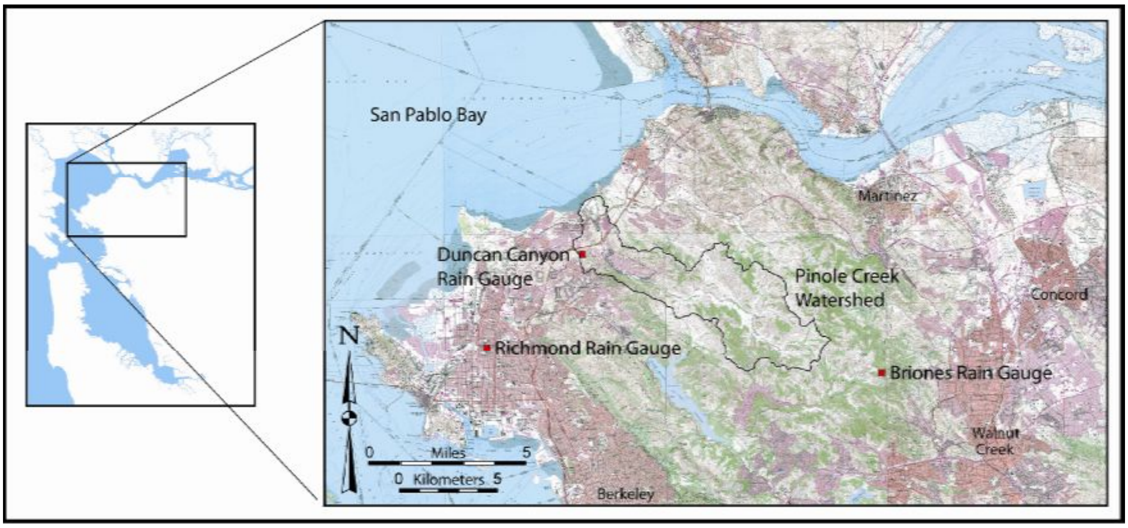


Figure 1. Location map showing the location of the Pinole Creek watershed. Local rain gauges (Briones, Richmond, and Duncan Canyon) are highlighted (see Rainfall and Pinole Creek Flow section).

The complex geologic structure of the East Bay is primarily controlled by strike-slip movement along the major northwest trending faults of the area. Similarly, the geologic units underlying the Pinole Creek watershed are complexly faulted and folded, in association with movement along the Hayward, Pinole, Franklin Canyon, and other unnamed and active strike-slip fault systems (Figure 2). The Pinole and Franklin Canyon Faults control the specific rock formations that are present in the watershed. The rocks present in the watershed are primarily Miocene to Eocene (5.3 to 55 million years old) sandstones, shales and volcanic tuffs. The geologic formations partially control the topography, the soils that develop, the vegetation that is present, and in turn, the natural geologic erosion potential of the watershed.

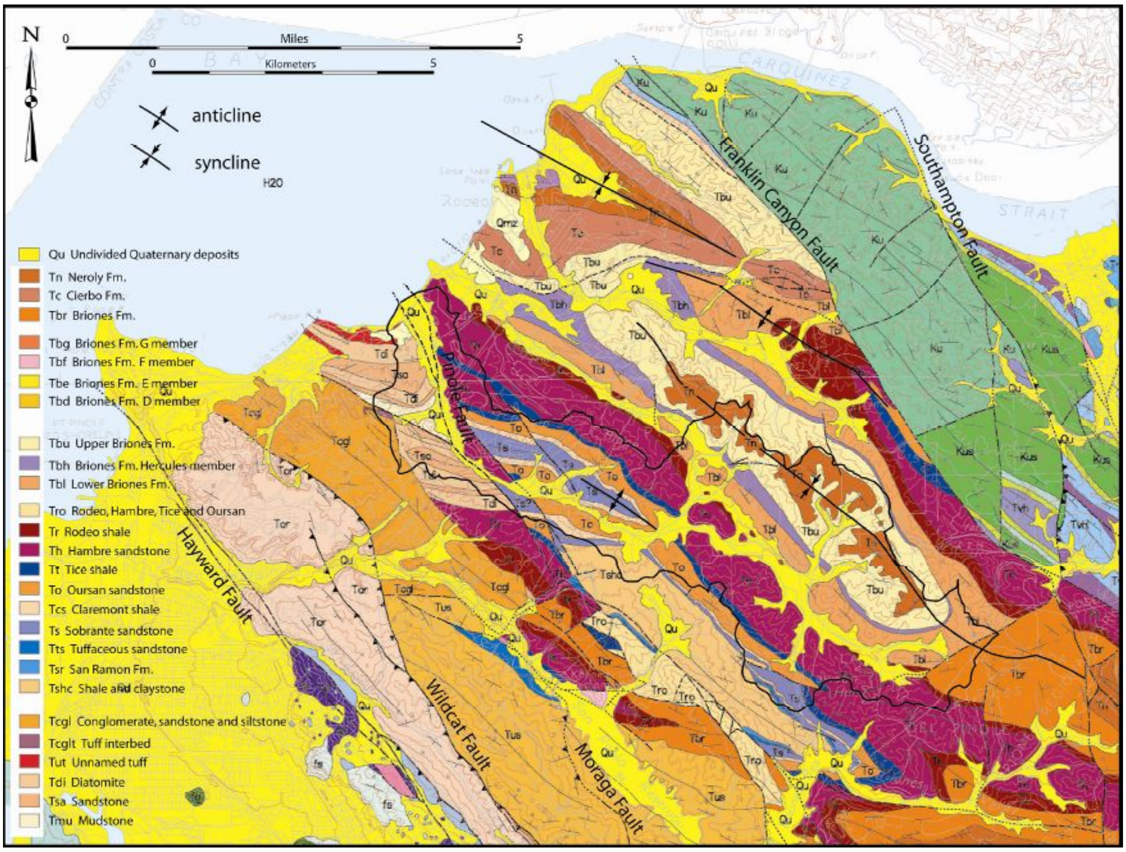


Figure 2. Bedrock geology map of the Pinole Creek watershed and surrounding areas (from Graymer et al, 1994). Major faults and structures are highlighted. See Appendix for full description of rock units.

The watershed contains a variety of different soil types, resultant from the assemblage of parent rock types and other soil forming factors. Along the valley bottom, soils are typically in the Clear Lake-Cropley association, consisting of gently sloping, poorly drained and moderately well drained clays on valley fill and in coastal valley basins (Welch, 1977). On the hillslopes, the soils are typically in the Los Osos-Millsholm-Los Gatos association, consisting of moderately steep to very steep, well-drained clay loams and loams that formed in material weathered from interbedded sedimentary rock on uplands (Welch, 1977). The physical properties of the soils not only determine what kinds of vegetation can be supported and the productivity of agricultural activities, but also the potential for erosion and failure, and the suitability for disposal of septic household waste. The Pinole Creek watershed contains many areas of clay-rich, steep-sloped, thick, low shear strength soils, which are more prone to failure than other soil types. These soil types also display poor to moderate drainage characteristics in septic leach fields.

The San Francisco Bay Area has a Mediterranean climate, with cool, wet winters and warm, dry summers. Average annual air temperatures range from 5.8° C (42.5° F) to 23.3° C (73.9° F) with the warmest temperatures occurring in September (Richmond, CA station 047414, Western Regional Climate Center). In the Bay Area, over 90% of the annual rainfall is received between the months of November to April. The average annual rainfall for the Pinole Creek watershed is 610 mm (24 in).

Pinole Creek is a perennial third-order creek (Strahler, 1957) with an average channel gradient of 1.0% (ranging from 0.1 to 2.2% in the measured reaches). The mainstem channel is approximately 18 km (11 mi) in length from the headwaters to San Pablo Bay, and the watershed as a whole contains over 75 km (46 mi) of channel length (Contra Costa County Watershed Atlas 2003). The majority of this channel length is comprised of the 12 locally named tributaries that flow into the mainstem. During the winter months, Pinole Creek transports large volumes of both water and sediment off of the hillslopes and out to San Pablo Bay. During storm events, the water in the creek is often sediment-laden, and transports logs, branches, trash, and other debris. Compared to pre-European settlement, water quality in the creek has probably decreased, however, the creek still supports and provides habitat for many aquatic and riparian species of plants and animals.

The watershed can be divided into three parts: a lower, middle, and upper portion (Figure 3). This watershed is less developed compared to surrounding watersheds primarily because of historic plans by the East Bay Municipal Utility District (EBMUD) for a drinking water reservoir, which was never built. Currently, the lower portion is urbanized and includes portions of the Cities of Pinole, Hercules, and El Sobrante, and is mostly single-family residential and commercial areas. The middle portion is primarily owned by EBMUD, and is utilized as open space and grazing lands. The upper portion is primarily privately owned land containing small ranchettes, grazing, mixed agriculture, and some publicly-owned open space lands maintained by the East Bay Regional Park District. The four main land uses in the watershed are: public watershed lands (for example, EBMUD land) (39%), agricultural lands (31%), single family residential (16%), and open space and parklands (11%) (Contra Costa County Watershed Atlas, 2003). The total population of the watershed is approximately 15,700, with most people living in the lower portion of the watershed (Contra Costa County Watershed Atlas, 2003).

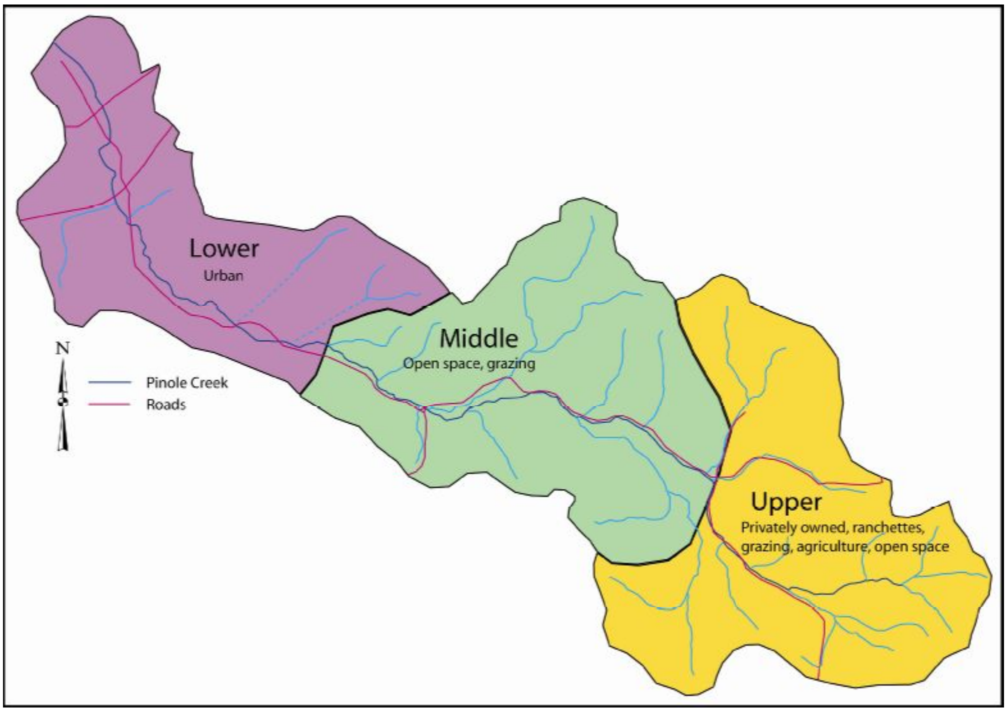


Figure 3. Informal divisions of the Pinole Creek watershed, and primary land uses of each portion.

The non-developed areas of Pinole Creek are host to a variety of vegetation species and communities. A majority of the watershed is dominated by Northern California oak woodlands and grasslands, similar to many other areas of the East Bay. North-facing slopes tend to be more densely wooded, containing oak, California Bay, California Buckeye, eucalyptus, poison oak, and coastal scrub species. South-facing slopes tend to be grasslands or oak savannas, comprised primarily of Eurasian non-native annual grass species, and also star-thistle, poison oak, and pampas grass (Goals Project, 1999). Areas of riparian vegetation along Pinole Creek and its tributaries contain an assemblage of species including willow, California Bay, alder, California Buckeye, maple, blackberry, equisetum, poison oak, sedge, broom, and ivy, among smaller numbers of other species.

RAINFALL AND PINOLE CREEK FLOW

Rainfall data and methods

There are no long-term records of rainfall for either the City of Pinole or the Pinole Creek watershed that are suitable for describing rainfall patterns in relation to the instigation of land sliding and channel bed and bank erosion over multiple decades. Some residents have been diligently collecting climatic information over the more recent times. For example, rainfall data have been collected in the Pinole Creek watershed by resident Tim McDonough at Duncan Canyon (250 ft above sea level) from 1992 to present. These data are compiled within each climatic year on a storm-by-storm basis and, as such, a single data point can represent either one day or several days of accumulated rainfall. The data are high quality, and limited mainly by the length of the record. A short rainfall record has also been collected in Briones Regional Park (gauge location at 1450 ft above sea level) by East Bay Regional Park District Fire-Rescue Services from 1998 to present. These data are recorded every hour and can provide us with insights about rainfall intensity, but again the main limitation is the very short length of record. Daily rainfall summaries for the City of Richmond, 50 ft above sea level and 7.3 miles (11.7 km) southwest of the City of Pinole, are available from 1951 to present. These data are high quality and provide a useful data set for understanding the active soil and sediment movements in the watershed. Monthly summaries of rainfall for the City of San Francisco are also available, and provide 150 years of context for the local data sets and an understanding of the long-term climatic trends for the Bay Area.

Annual rainfall

Rainfall in the Bay Area is predominantly maritime, with regional-scale weather systems moving on shore in response to the position of the Pacific high-pressure zone and westerly winds that bring moist air from the Pacific Ocean. In general, higher rainfall occurs on westerly and southerly facing slopes and on topographically higher areas. Rainfall decreases with distance from the coast and most storm tracks pass further to the north, resulting in a general increase in annual rainfall towards the northern edge of the region. On a regional scale these phenomenon are referred to collectively as the *microclimates of the Bay Area*. At the local scale of the Pinole Creek watershed, annual rainfall also varies from place to place (Table 1) but the variations are less dramatic than for the Bay Area region due to the relative subdued topography, valley aspect, and its position relative to the Golden Gate, the Bay, and local prevailing wind patterns. It appears from the relatively short record that the data collected in the City of Richmond is a reasonable surrogate for the climate of the Pinole Creek watershed over the longer term. Note however, that the period illustrated in Table 1 was wetter than normal (giving a 12-year average of 28.25 inches); based upon the longer-term City of Richmond dataset, the average annual rainfall for Pinole Creek watershed is approximately 24 inches.

Table 1. Annual rainfall at gauging locations in and around Pinole Creek watershed summarized for the Climatic Year (July 1st to June 30th where the year is denoted by the ending date). See Figure 1 for locations.

Climatic Year	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
City of Richmond	26	14	42	31	26	49	23	21	26	26	28	27
Duncan Canyon	29	19	42	31	26	46	24	30	21	25	-	24
Briones	-	-	-	-	-	39	22	27	18	-	24	22

Although the average is a useful statistic for describing the rainfall in Pinole Creek watershed relative to other places around the Bay Area, in fact, rainfall in the Pinole Creek watershed is highly variable from year to year and this variability is one of the contributing factors influencing landsliding, channel erosion and creek water quality and quantity. We estimate that annual total rainfall in the watershed can vary from about 8 to 54 inches (Figure 4).

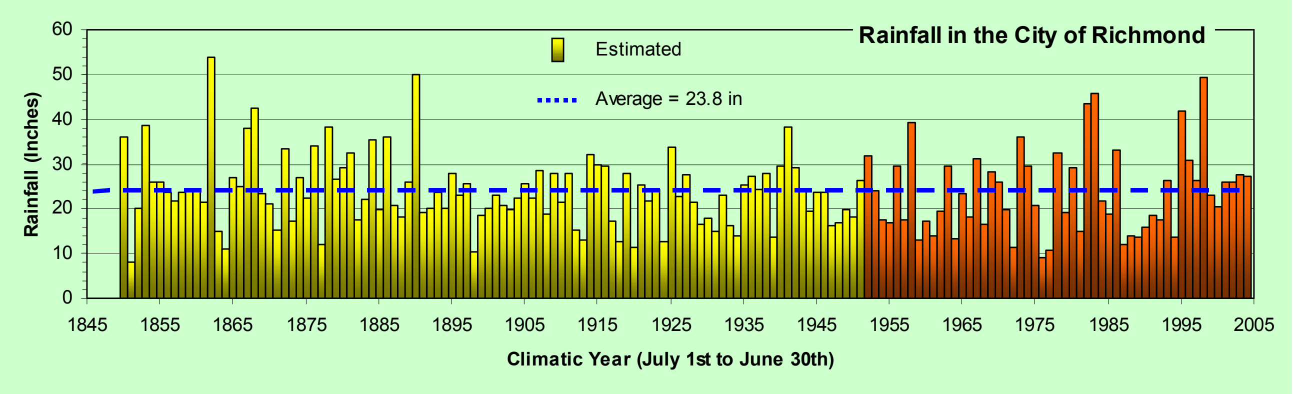


Figure 4. Measured annual rainfall totals in the City of Richmond (red bars), and estimated historic rainfall totals based upon long-term records from San Francisco (yellow bars).

Rainfall distribution within the year

On average 90% of the annual rainfall occurs during the winter season (November 1st – April 30th) on just 54 days (City of Richmond data). Rainfall on these days can be very intense and cause flooding and erosion throughout the watershed. For example, on January 4th 1982, 6.83 inches of rain fell in a 24-hour period. This storm had an estimated return period greater than 200 years. Once every 10 years on average the watershed is likely to receive 2.1 inches in a 6-hour period, 3 inches in a 12-hour period or 4 inches in a 24-hour period (Figure 5).

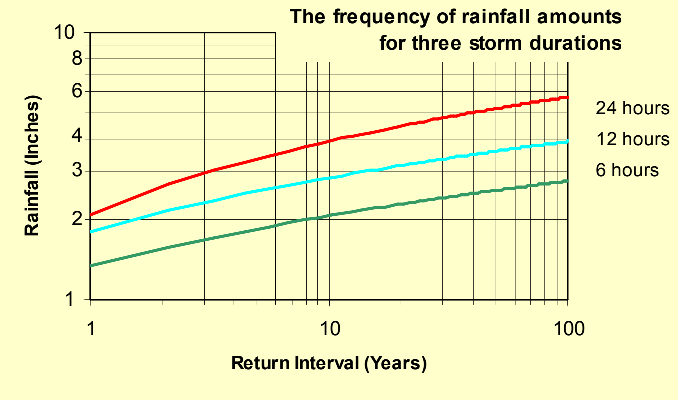


Figure 5. Rainfall frequency for three storm durations.

The US Geological Survey has developed a regional model for the Bay Area to predict the likelihood of landslide activity based on rainfall and the number of rain days (Wilson and Jayko, 1997). The model suggests that significant landslide activity is likely to occur in the Pinole Creek watershed when rainfall in a 6-hour period exceeds 2 inches and in a 24-hour period exceeds 3.3 inches, or approximately once every 10 years. Table 2 shows the years when these conditions were met over the last 50 years. In particular, 1970, 1982 and 1998 sustained intense rainfalls when rainfall for the season-to-date exceeded 20 inches.

Table 2. A summary of the most intense rainstorms over the past 53 years in the Pinole Creek watershed.

	24-hour period			Storm period			Season-to-date	
Climatic year	Date	Rainfall (in)	Rank	Start	End	Rainfall (in)	Rainfall (in)	Rank
1956	12/19/55	3.15	7	12/15/55	12/24/55	9.65	14.59	5
1963	10/12/62	3.29	6	10/10/62	10/14/62	7.37	7.56	7
1970	12/20/69	3.90	3	12/18/69	12/26/69	6.10	10.74	6
	01/21/70	3.03	9	01/08/70	01/24/70	10.32	21.06	3
1982	01/04/82	6.83	1	12/29/81	01/05/82	11.57	26.13	2
1995	11/07/94	5.56	2	11/05/94	11/07/94	5.76	7.17	9
1996	12/12/95	3.10	8	12/11/95	12/15/95	6.68	7.28	8
1998	02/03/98	3.37	5	01/31/98	02/08/98	10.93	35.23	1
2001	01/23/01	3.70	4	01/23/01	01/26/01	4.64	14.87	4

Rainfall during the study period (Climatic Year 2004)

Climatic Year 2004 sustained a rainfall about 14% above average. During the year there was rain on 144 days for a total accumulated rainfall of 27.12 inches in the City of Richmond (Figure 6). The largest storms occurred over the New Year holiday and in February when rainfall intensity exceeded 1.9 inches in a 24-hour period in the City of Richmond. However there were another 8 storms during the year that exceeded 1 inch in the City of Richmond. These storm rainfalls are summarized in Table 3 for rain gauges at the City of Richmond, Duncan Canyon, and Briones.

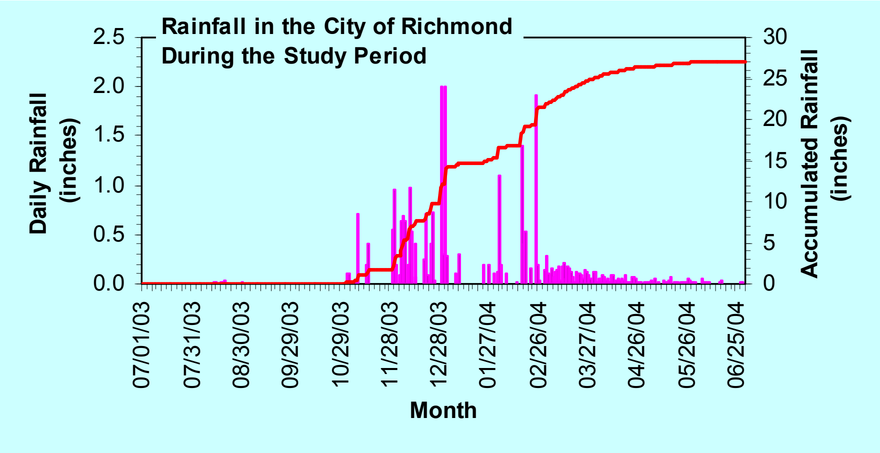


Figure 6. City of Richmond rainfall, Climatic Year 2004. Pink bars show daily rainfall totals, while the red line shows accumulated total rainfall.

Table 3. Storm-by-storm rainfall in inches for Pinole Creek during Climatic Year 2004.

Date		Richmond			Duncan Canyon		Briones			
(Start-End)	Storm	24-hour max	Storm total	Year-to-date	Storm total	Year-to-date	6-hr max	24-hr max	Storm total	Year-to-date
11/30/03-12/02/03	1	0.96	1.71	3.14	1.50	3.00	0.27	0.42	0.71	2.11
12/04/03-12/07/03	2	0.70	2.05	4.75	1.30	4.30	0.62	0.64	0.93	3.04
12/09/03-12/11/03	3	0.98	1.71	6.57	1.50	5.80	0.43	0.7	0.91	3.95
12/19/03-12/21/03	4	0.71	1.04	8.52	0.85	7.25	0.33	0.59	0.69	5.38
12/23/03-12/24/03	5	0.73	1.16	9.74	1.25	8.50	0.49	0.65	1.02	6.4
12/29/03-12/30/03	6	2.00	2.30	11.77	3.00	11.50	0.62	1.46	2.58	8.98
01/01/04-01/02/04	7	2.00	2.59	14.07	2.50	14.00	2.1	2.64	2.72	11.7
02/01/04-02/03/04	8	1.10	1.43	16.50	1.50	16.65	0.96	1.16	1.21	13.71
02/16/04-02/18/04	9	1.40	2.33	18.21	3.15	19.85	1.2	2.27	3.45	17.27
02/25/04-02/27/04	10	1.91	2.14	21.21	2.25	22.55	1.98	2.53	3.02	20.54

Pinole Creek flow methods

There is no long-term continuous record of flow in Pinole Creek or its neighboring creeks. However, flow in Pinole Creek was measured by the US Geological Survey from December 1st, 1938 to September 30th, 1977 about 1.4 miles upstream from Simas Avenue on what is today the property owned by EBMUD. At this point, the creek drains an area of 26 km^2 (10 mi^2). These data were retrieved to provide context for flow and other measurements made during this study. In order to fulfill one of the primary objectives of the study – to measure transport of sediment in the creek – we made measurements of water flow in the creek approximately 0.8 miles downstream of the old USGS flow gauge. Our measurements during the Study Year were made under the Pinole Valley Road Bridge number 5 near Ellerhorst School (Figure 7). At this point on the creek, the watershed area upstream is 30.7 km^2 (11.9 mi^2). The cross-section under the bridge was surveyed and a staff gauge with increments of one-tenth of a foot was installed. During storms and between storms observations were made of the height of water and measurements were made of the speed of water flow using a Marsh McBirney Flowmate 2000 flow meter. The flow meter was passed into the water column by hand, when the creek could be waded, and, using a cable and winch system from the bridge, when the height of the water was greater than 2.0 ft.

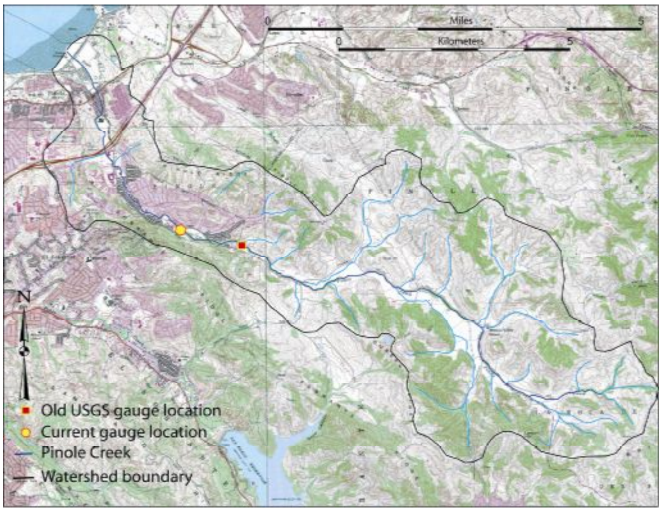


Figure 7. Map of Pinole Creek watershed showing the historic flow gauge location, and the current flow gauge location at Bridge number 5, near Ellerhorst School.

Historic flow records in Pinole Creek

Flow records measured by the US Geological Survey provide us with an understanding of the annual flow variability and maximum flows under a variety of climatic conditions. If we make the assumption that changes in land use over the past 66 years upstream of the gauge have not significantly changed the flow character of the creek, we can use this historic data set to calibrate our study observations and make statements about low flow conditions. Note, however, that neither the historic record nor the data we collected during the study period can tell us anything about flow from the urbanized lower portion of the watershed. The average annual flow in Pinole Creek for 1938 – 1977 was 3.6 cfs or 2,594 acre-feet (3.2 million cubic meters) of water yield per year (Figure 8). The driest Water Year (October 1st – September 30th where the year is designated by the end date) was 1976 with an average flow of 0.08 cfs (57 acre-feet or 0.07 million cubic meters) and the wettest year was 1958 with an average flow of 11.9 cfs (8,594 acre-feet or 10.6 million cubic meters). Based on rainfall, we estimate that the very wet years of 1983 and 1998 had annual average flows in excess of 13.6 cfs (10,000 acre-feet or 12.3 million cubic meters). The largest flood recorded during the historic record period occurred on April 4th, 1958 with a peak instantaneous flow of 1,660 cfs. On average during the historic record period, 93% of the flow occurred during the wet season (November 1st to April 30th).

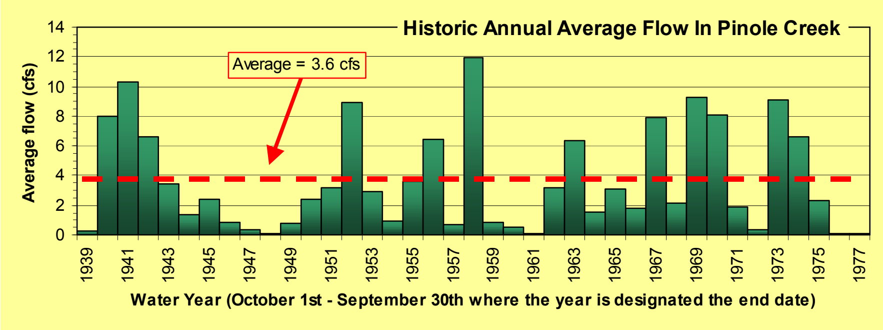
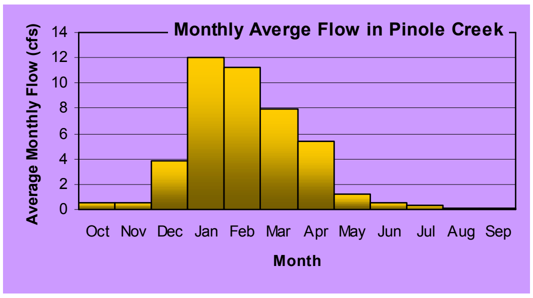


Figure 8. Historic annual average flow in Pinole Creek.



The highest flow month was typically January and lowest flows typically occurred in August and September (Figure 9). During the dry season, there were 14 years (or about 1 in every 3 years) when flow completely ceased for 1 - 5 months.

Figure 9. Monthly average flow in Pinole Creek, 1938-1977.

Flow during the study (Water Year 2004)

We made flow measurements between November 1st 2003 and April 30th 2004. During this period the average flow was 5.1 cfs and the total flow past the gauge was 3,648 acre-feet (4.5 million cubic meters). If we assume that this period accounted for about 93% of the flow for the entire Water Year, our Study period was about 40% above normal. The largest flood occurred on February 25th at 11:30 AM when water under the

Pinole Valley Road Bridge number 5 reached 6.2 feet in depth and flow peaked at 981 cfs (Figure 10). Using the historic flow record as a guide, a flow of this size is likely to occur on average once every 5 years. Although there were 10 storms during the year when rainfall exceeded 1 inch, only 3 of these storms produced a large amount of flow. This was because rainfall for the season needed to accumulate to about 6.5 inches before storms produced even 1 foot of increased flow depth or 60 cfs at peak flow. The historic data suggests that on average it takes about 7 inches of accumulated rainfall before significant flow occurs. The 3 largest storms occurred on January 1st 2004 at 12 inches of accumulated rainfall, February 16th 2004 at 17 inches of accumulated rainfall and February 25th 2004 after 19 inches of accumulated rainfall. These storms accounted for about 30% of the wet season flow. Although dry season flow was not a focus of our work, during the study we observed a flow of 0.1 cfs sustained throughout the summer.

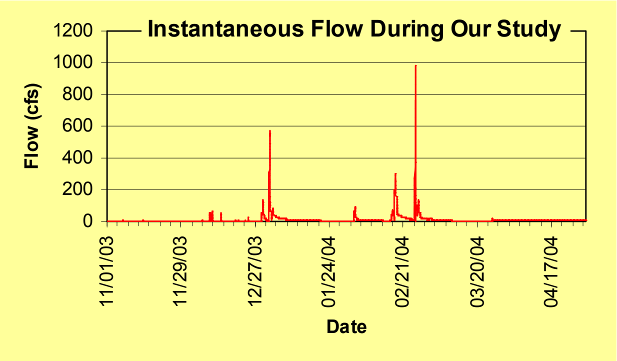


Figure 10. Instantaneous flow measured on Pinole Creek at Pinole Valley Road Bridge number 5.

Synthesis

Rainfall and Pinole Creek flow data were collected and interpreted within the context of the objectives of the study. We estimate that the total annual rainfall in the watershed can vary from about 8 to 54 inches and averages about 24 inches. Rainfall during the study year was about 14% above normal. Most rainfall occurred during a few storms. We estimate that on average, once in every 10 years, 4 inches of rainfall can occur in just 24 hours. The US Geological Survey has predicted that a rainfall of around 3.3 inches in a 24-hour period is likely to cause severe landslide failures somewhere within the Pinole Creek watershed. These conditions have been met about 9 times in the last 53 years, and 3 times when rainfall for the year-to-date exceeded 20 inches. However, these conditions were not met during the Study Year. These observations of the historic record provide us with a means to calibrate our field observations of landsliding and provide some predictions about what might happen during future storms. A review of the historic flow records gathered by the US Geological Survey suggested that the annual average flow in the creek is approximately 3.6 cfs with a likely range of 0.08 – 13.6 cfs between very dry and very wet years. Flow during our study averaged 5.1 cfs and the largest flood reached 6.2 feet of water depth and a flow of 981 cfs with a likely return interval of once in five years. This data set will be ideal for making estimates of suspended sediment loads under typical flow conditions and will make it possible to understand the flushing characteristics of the tidal portion of the flood control channel in Old Town Pinole.

LANDSLIDES, GULLIES, AND SURFACE PROCESSES

General overview

Three of the major objectives of this study are to identify the primary sources of sediment, characterize the physical processes of sediment delivery, and quantify the relative contributions from each source. Within the watershed, the hillslopes are the dominant source of sediment to the creek, including landslides and other types of hillslope mass movements, gullies, and land use related contributions. This section describes the methodologies and results from the hillslope sediment source assessment, including the landslide and gully mapping task and other hillslope sediment sources such as roads and various land uses.

In this document, we use the term "landslide" loosely, as a catch-all term to describe landslides and all other mass-movement types generally following the very simple definition of Cruden (1991): landslides are "the movement of a mass of rock, debris or earth down a slope". Note, however, that in the geological and engineering literature, landslides are more strictly defined, and are broken into elaborate classification schemes based upon the rate of movement, the water content, the type of material involved, and the type of movement of the failing material. Although landslide descriptions can be very complex, we chose to keep the classification relatively simple, making it more useful for the landowners and resource managers of the watershed.

Methods

The first step in identifying hillslope sediment sources was to perform a literature review. Two publications relevant to landslides in the Pinole watershed were found. The first was a publication from 1973 by Tor Nilsen titled "Preliminary photointerpretation map of landslide and other surficial deposits of the Concord 15-minute Quadrangle and the Oakland West, Richmond, and part of the San Quentin 7 1/2-minute Quadrangles, Contra Costa and Alameda Counties, California". This map was useful in determining the location of larger landslides (with a longest dimension longer than 150 m or 500 ft). Smaller landslides, with a longest dimension between 60 and 150 m (200 to 500 ft) are shown as an arrow, without any representation of shape or exact dimensions. Because this interpretation utilized aerial photographs at a scale of 1:20,000, and the map is compiled at a scale of 1:62,500 the resolution was not good enough to accurately map smaller slides. The map only includes slides that occurred before 1968, and Nilsen did not attempt to classify the type or style of landslide.

The second publication is a journal article published in Water Resources Research by Leslie Reid in 1998 titled "Calculation of average landslide frequency using climatic records". This paper uses the Simas Valley sub-basin, a tributary to Pinole Creek, as a field area in which landslides were mapped on aerial photographs from 1939 to 1986. Reid uses the aerial photograph record in combination with precipitation records to calculate the long-term average debris-slide frequency of the area. This publication proved useful as a comparison for slides mapped in the Simas Valley sub-basin, however, it did not cover any portion of the watershed outside of this sub-basin.

The second step in our analysis was aerial photograph interpretation. Landslides in the Pinole Creek watershed were mapped and classified utilizing a set of June 1989, stereo-paired, black and white, 1:1,200 scale photographs obtained from the USDA Natural Resources Conservation Service Concord Service Center. These photographs were observed under a stereoscope, an optical tool that produces a three-dimensional relief image from the stereo photographs. A sheet of clear plastic Mylar was placed over the photographs, and then each individual observable landslide was drawn on the Mylar. During this process, each landslide was classified in terms of activity, certainty, movement type and thickness (modified from Varnes, 1978; Turner and Schuster, 1996). The mapped landslides were then transferred onto a set of 2000 stereo, black and white, 1:400 scale photographs obtained from Contra Costa County Public Works Department. The photos were brought into ArcView (a GIS program) where the landslides were heads-up digitized (digitized on-screen) in ArcView. The results of the literature review and aerial photograph interpretation were combined and compiled on a single set of photographs in ArcView to produce a detailed GIS map of landslides in the watershed.

The third step involved field checking the landslides that were observed on the aerial photographs. Field checking allows a more accurate representation of the shape, depth, style and activity level of the slide to be recorded on the GIS map. Field checking also provides an estimate of error of the photo interpretation, by comparing measures made in the field to those made on the photographs.

Using a large printout of the GIS map and the topographic maps for orientation, the field team visited many hillslopes throughout the watershed. At each potential landslide location, the field team answered a series of questions:

- Is this a landslide?
- How certain are we?
- What type of movement does it display?
- What are its dimensions (length, width and depth)?
- What is its state of activity?
- How much of the disturbed material remains on the hillslope?
- How connected is the landslide to the fluvial system?
- Should we prioritize this location for management actions?
- Is there evidence of a triggering mechanism?

Each location was photographed, notes were taken, and any modifications to the shape or size of landslide were made on the map. Care was taken to measure the dimensions, so that a comparison of disturbed landslide material measured in the field could be made to the area calculated in GIS. It is important to note that field checking of slides only occurred in areas where the field team had access to the property. Because of access limitation, as well as time limitations, only a subset of the total number of mapped slides were field checked. However, an effort was made to visit sites with differing geologic rock types, land uses, and styles of landsliding throughout the watershed area. Lessons learned from visiting each area or style of landsliding were then extrapolated to areas of the watershed that were not visited. About one-third of all mapped landslides were field checked (Table 4).

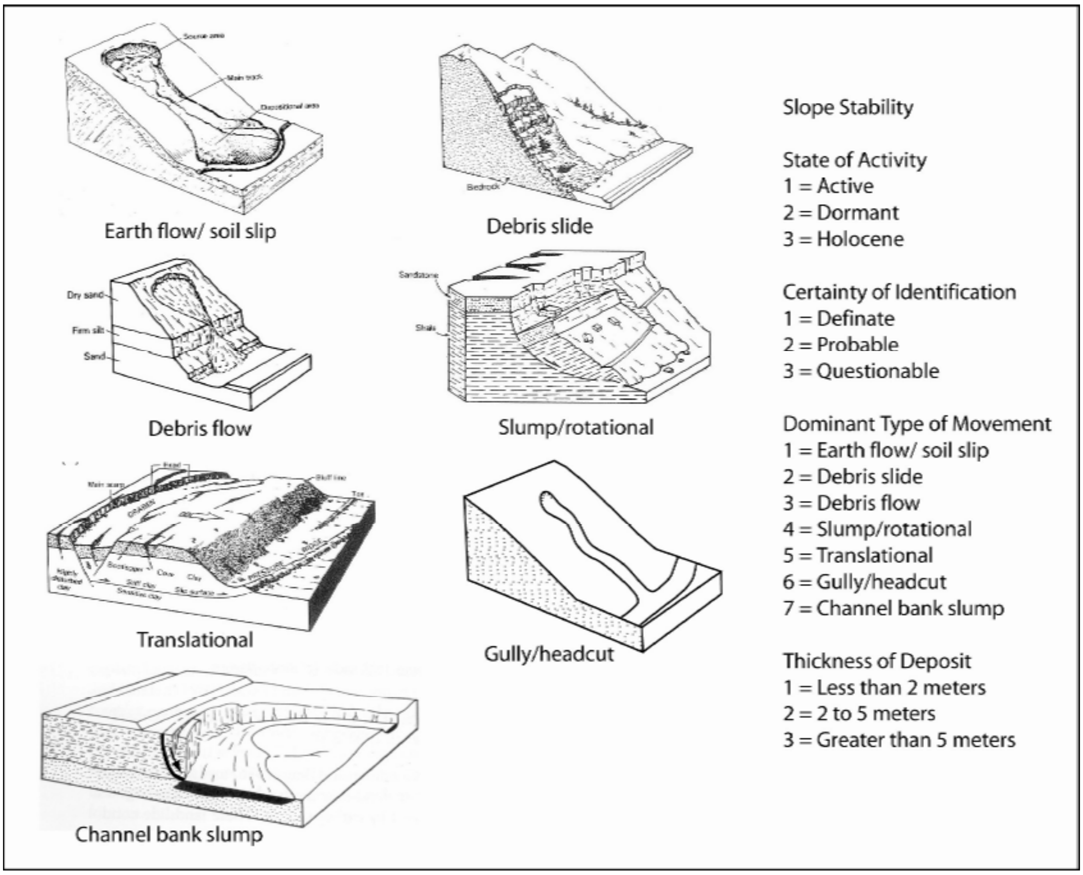
Table 4. Landslide statistics.

Landslide Type	Total number mapped	Number field checked	Percentage field checked
Active Landslides	342	134	39
Dormant Landslides	200	61	30
Holocene Landslides	124	25	20
Active Gullies	91	33	36
TOTALS	757	253	33

Once all field checking was completed, the team returned to the office and made the necessary modifications to the GIS map. Once the GIS map was completed, ArcView was then utilized to create statistics regarding the total area of slides, slide type, effect of underlying geologic rock type, effect of slope and aspect, and slide proximity to a creek. The following sections will discuss the classification scheme, each landslide type, and all of the calculated landslide statistics for the watershed.

Landslide classification scheme

During the aerial photograph interpretation and field checking, an assessment of landslide type and level of activity was made. This assessment utilizes a classification scheme initially proposed by Varnes (1978), which is now widely used. The classification scheme assigns a four-digit code to each slide; the first digit describes the state of activity, the second describes the level of certainty of identification, the third describes the dominant type of movement, and the fourth digit describes the thickness of slide deposit (Figure 11). Although relatively simple, this numeric code can convey a significant amount of information about the slide quickly. See the Appendix for a full description and definition of each term.



Slope Stability

State of Activity
1 = Active
2 = Dormant
3 = Holocene

Certainty of Identification
1 = Definate
2 = Probable
3 = Questionable

Dominant Type of Movement
1 = Earth flow/ soil slip
2 = Debris slide
3 = Debris flow
4 = Slump/rotational
5 = Translational
6 = Gully/headcut
7 = Channel bank slump

Thickness of Deposit
1 = Less than 2 meters
2 = 2 to 5 meters
3 = Greater than 5 meters

Figure 11. Landslide classification scheme used in characterization of landslide types in the Pinole Creek watershed (modified from Varnes, 1978; Turner and Schuster, 1996). Each landslide is assigned a four-digit code, based upon the categories shown on the right.

Landslides and gullies in the Pinole Creek watershed

The following description of landslide types mapped in the Pinole Creek watershed uses the first digit of the code (the state of activity) to divide the mapped landslides into categories. Besides “Active” landslides, “Dormant” landslides, and “Holocene” landslides, we also created a category for “Active gullies” because an initial reconnaissance of the watershed suggested that both gullies and landslides might similarly influence sediment supply to the creek.

Active landslides

An active landslide is one that has evidence of movement in the previous 50 years. Typically, this slide type retains its disturbance features, such as the headscarp, vertical cracks, and its toe. The area of disturbance is still quite visible on the hillslope, displaying bare soil, a distinct vegetation pattern, or a clear topographic expression. Because all of the slides in this class are relatively “fresh”, we relied upon subtle distinctions of the slide’s disturbance features to determine its likely time of initiation. For example, in the field, a slide that was initiated twenty years ago can often be distinguished from a slide that initiated five years ago. However, it is much more difficult to distinguish slides that occurred five versus seven years ago, without any landowner observations or information. In the Pinole Creek watershed, active landslides are typically small features, most ranging in total volume from approximately 200 to 2,000 m^3 (7,063 to 70,630 ft^3). However, a few large active slides do exist, especially in the upper watershed. Most slides show evidence of earth flow type of movement, are generally shallow, and are oval, teardrop, or hourglass shaped. These slides are mostly likely to fail when rainfall intensities reach 3.3 inches in a 24-hour period (see Rainfall and flow section).

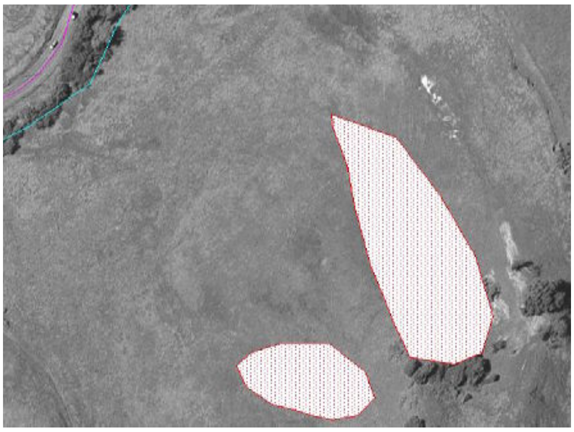
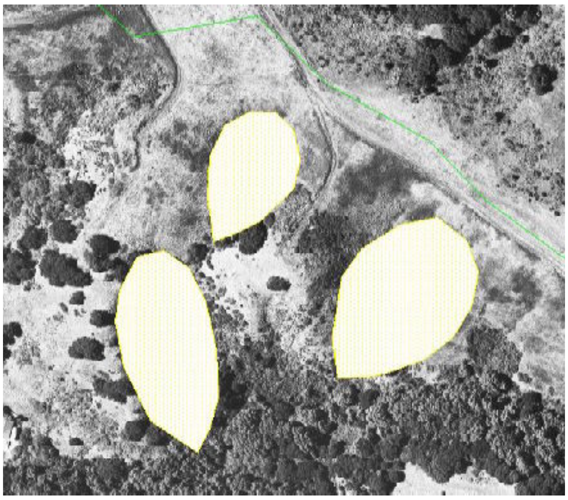


Figure 12. Example of two typical active landslides in the Pinole Creek watershed.

Dormant landslides

A dormant landslide has evidence of movement that occurred between 50 and 100 years ago. Typically this slide type retains some of its disturbance features, such as its headscarp and its toe. However, these features are muted and more difficult to identify due to other surface processes including rainfall-induced erosion, wind erosion, vegetation, or land management impacts. In the Pinole Creek watershed, dormant landslides are generally of a similar shape to active slides, and are either of a similar size, or slightly larger than active landslides, with most volumes ranging from 1,000 to 20,000 m^3 (35,315 to 706,293 ft^3). We hypothesize that a majority of these slides likely occurred from approximately the late 1930s to the mid-1950s. Prior to this time period, land use intensity had significantly increased from pre-European contact intensities, with the expansion of grazing and agriculture in the watershed. Also, a period of reduced total rainfall and lesser intensity rainfall occurred from the early 1890s to the late 1930s (see Rainfall section; Reid, 1998). These two reasons likely lead to the increased “build-up” of material on the hillslopes that is prone to landslide failure. The change in rainfall regime (increase in amount and intensity) starting in the late 1930s provided the driving force to trigger many of these slides, mobilizing the sediment that had been temporarily stored on the hillslopes. This increase in slide frequency was documented by Reid (1998) in the Simas tributary to Pinole Creek. In addition, starting about 1950, the fluvial system likely began a period of incision; as a channel deepens, it provides less lateral support to the toes of the slopes adjacent to the channel. If a landslide is impinging upon the channel, a period of channel incision would likely reduce the lateral support at the slide toe, and could reactivate the slide.

Figure 13. Example of typical dormant landslides in the Pinole Creek watershed.



Holocene landslides

A Holocene landslide is one that shows evidence of movement that occurred more than 100 years ago. However, the characteristics of these slides suggest that they occurred much longer ago, when climatic conditions were much wetter (in the Holocene Period, from 10,000 years before present to present). These landslide types, also referred to as ancient or fossil landslides in the literature, remain visible on the landscape for hundreds to thousands of years after they moved and then stabilized (Cruden and Varnes, 1996). Typically, this slide type covers a large portion of the hillslope, is much thicker than other slide types, and is only evident from its subtle topography and shape. In the Pinole Creek watershed, Holocene landslides are the largest of the four slide classes, typically ranging from 1,000 to 100,000 m^3 (35,315 to 3,531,500 ft^3). These slides cover a much larger area, and are more complex in shape than active or dormant slides probably because they express multiple triggering events that occurred over many years. Often, within a mapped Holocene landslide area, a smaller portion has been reactivated and is thus mapped as either an active or dormant slide. The large area of these Holocene slides will not likely reactivate under today's climatic regime.

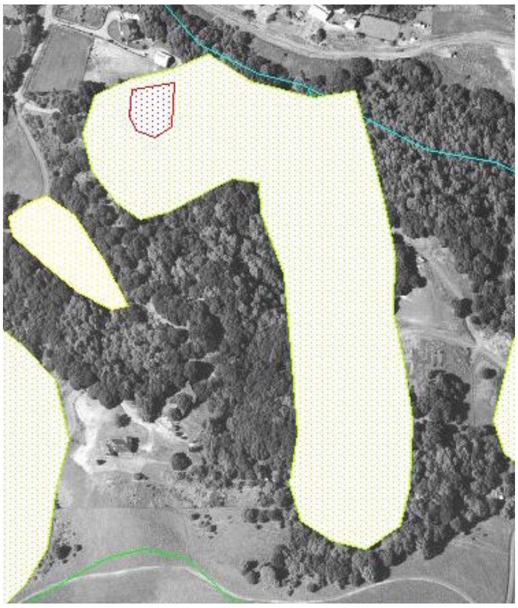


Figure 14. Example of a typical Holocene landslide with a younger active landslide mapped within it.

Active gullies

An active gully has evidence of erosion that has occurred in the past 50 years, but in most cases the erosion is continuing to occur today. Gullies can be associated with a change in grade along the mainstem or tributary channel, associated with culverts or roads, or associated with land use-related changes in runoff from the hillslopes. Gullies typically display bare banks, active incision and headcutting. Most are relatively shallow features, disturbing a sediment volume between 50 and 5,000 m^3 (1,766 to 176,573 ft^3). The large calculated disturbed volumes are primarily due to the length of these features, rather than the width or depth. In contrast to landslides, active gullies in the Pinole Creek watershed likely erode (to varying degrees) under almost the full range of storm rainfall intensities described in the Rainfall and Flow section. The concept of a triggering rainfall intensity is less applicable to gullies than it is to landslides. However, storms of greater magnitudes with greater rainfall intensities have a greater chance of triggering gully erosion either in a pre-existing gully, or in a location without a gully. In addition, because gullies are existing drainage lines, any erosion that occurs has a greater chance of being delivered to the mainstem creek, compared to landslides, which are often not located directly on a creek or gully.

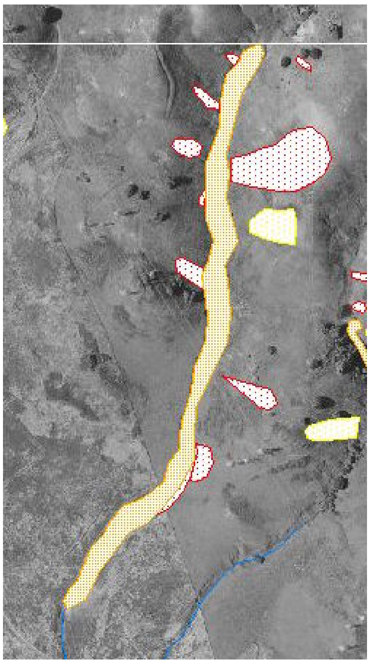


Figure 15. Example of a typical active gully, in this instance with adjacent landslides, in the Pinole Creek watershed.

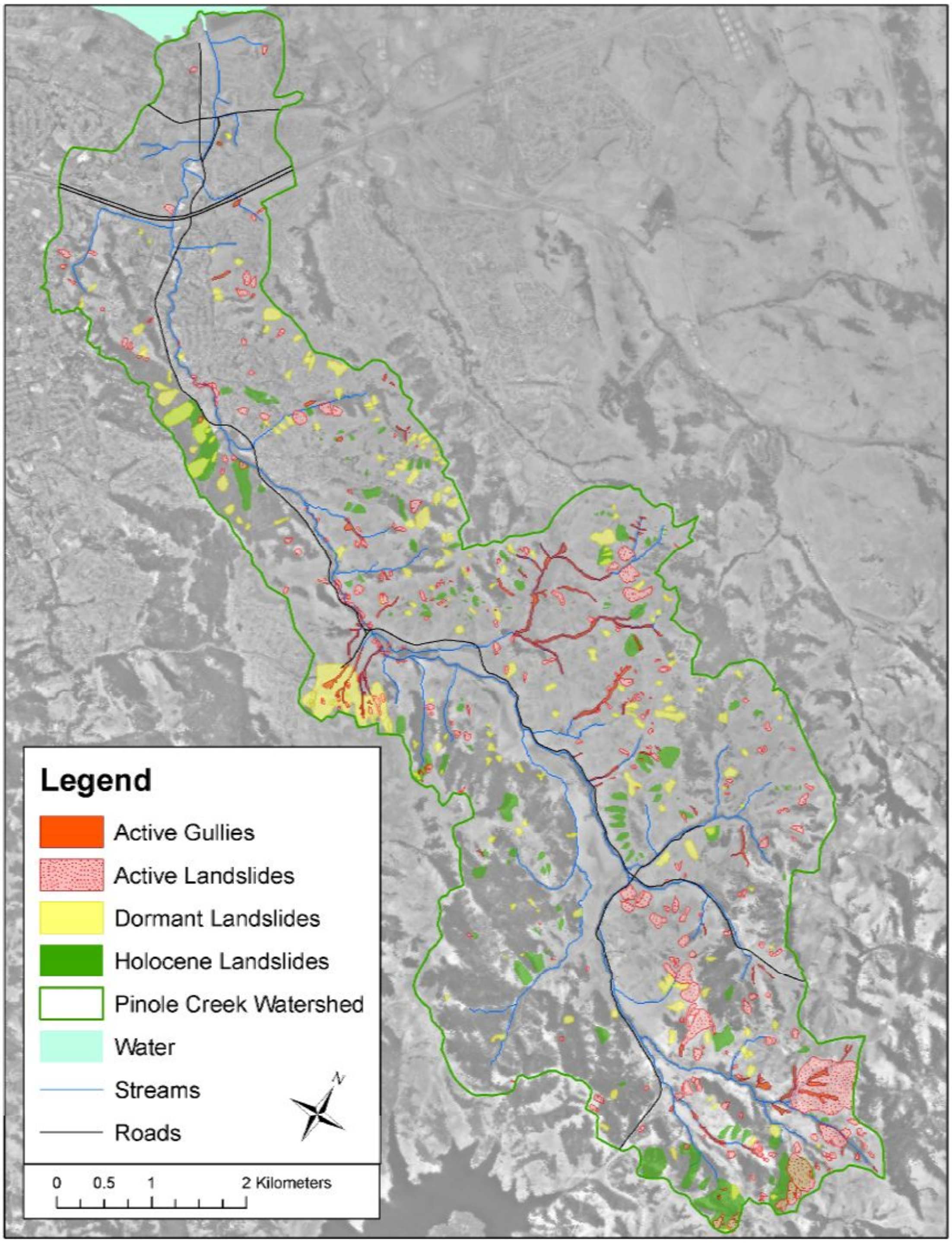


Figure 16. Mapped landslides and gullies (Active landslides, Dormant landslides, Holocene landslides, and Active gullies) in the Pinole Creek watershed.

Landslide statistics

Using the Pinole Creek watershed landslide map and ArcView, relationships and patterns in landslide characteristics can be defined. Utilized in this manner, the GIS landslide map of the watershed is more than just a spatial information tool. Now the map can help predict and prioritize areas where landslides are most prevalent, and areas where applying management efforts would be most effective. Of the 39.6 km^2 (15.3 mi^2) watershed area, 4.58 km^2 (1.77 mi^2) (or 11.6%) is included within one of the four landslide classes. Based solely upon area, the Holocene slide class is most dominant in the watershed at 4.2% of the total watershed area, followed by Active landslides at 3.4%, Dormant landslides at 3.2%, and finally Active gullies at 0.8%. This relationship between landslide classes also holds when comparing total volume of disturbed landslide material in the watershed.

While in the field, measurements of the amount of material that was disturbed during initial slide movement, as well as an estimate of the amount of that disturbed material that still remains on the hillslope as a landslide deposit were made. For instance, when a slide occurs, material is mobilized from the zone of depletion and possibly a portion is delivered directly into a tributary drainage, where it can be transported downstream mainly during wet season floods. But the other portion of the material that was disturbed may not have reached the drainage, and still remains as landslide deposit material on the hillslope (Figure 17). This material is deposited in the zone of accumulation, and because it was previously disturbed, the material is often more easily available for future transport to the fluvial system via rilling, sheetwash or soil creep. However any movement that does occur is dependant upon slope, amount of vegetation, and water content of the deposit, among other factors. After initial slide movement, the zone of depletion remains prone to surface erosion, and often contributes more sediment than the deposit in the zone of accumulation because the scarp is often devoid of vegetation and is steeply sloped.

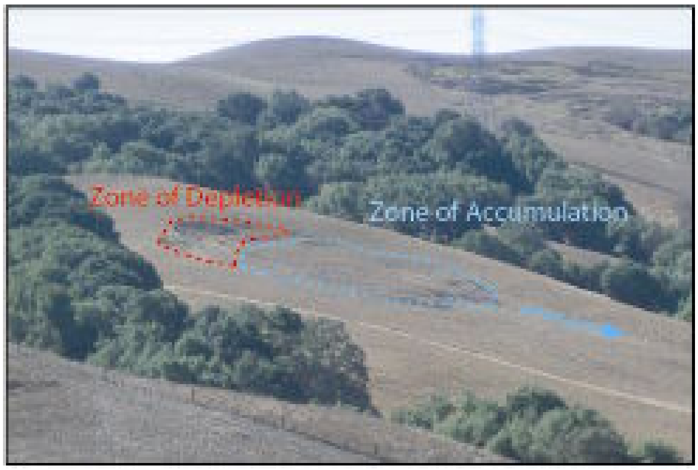


Figure 17. Photograph illustrating an example of the zones of depletion and accumulation. In this location, some material was transported away from the slide (shown with an arrow), however, the majority remains in the zone of accumulation.

Table 5 shows the average percentage of material remaining on the hillslope as a landslide deposit, based upon our field observations. It also includes the total volume of material in all mapped landslides in the watershed. Using the percentage from the second column, the last column reports the calculated total volume of landslide material that remains on the hillslopes across the entire watershed.

Table 5. Statistics of landslide deposits remaining on the hillslopes.

Slide type	**Average percentage of landslide material that remains on the hillslope**	**Total volume of all mapped disturbed landslide material (m^3)**	**Calculated total volume of landslide material remaining on the hillslopes (m^3)**
Active landslide	76	6,426,765	4,733,543
Dormant landslide	75	5,152,387	3,835,057
Holocene landslide	60	9,135,332	5,519,022
Active gully	30	626,285	157,806
Totals		21,340,769	14,245,428

Geology and soils

The underlying geology plays a large role in the soils that form, and the strength of rock and soil materials (its resistance to gravity). Overlaying the different landslide classes onto the mapped bedrock units provides us with a better understanding of which units are the most susceptible to failure. Five mapped bedrock units stand out as having the highest percentage of their total area included in one of the landslide classes. These bedrock units are: Tshc (Shale and Claystone) with 45% of its outcrop area disturbed by a slide, Ts? (Sobrante Sandstone? [note: the mapper was unsure if this was Sobrante Sandstone, or possibly another formation]) with 27%, Tbr (Briones Fm. sandstone and shale) with 21%, Tbl (Lower Briones Fm. sandstone) with 18%, and Tbh (Briones Fm. Hercules Shale) with 17% of its total outcrop area disturbed. A handful of other bedrock units contain between 5 and 10% of their total area in landslide (see Appendix for full data table). This data suggests that bedrock lithology is an important control on the location of landslides within the watershed. This natural control should be considered when determining where to focus management efforts to control sediment supply due to landslides.

A similar analysis was conducted to determine which soil classes were most susceptible to failure. In general, three soil types had a substantial percentage of their total area included within mapped active landslides. These soil types are the Altamont-Fontana complex (30 to 50 percent slopes), the Diablo clay (15 to 30 percent slopes), and the Dibble silty clay loam (15 to 30 percent slopes). In addition, three other soil types also had significant percentages included with other landslide and gully types. These soil types are the Altamont clay (15 to 30 percent slopes), the Los Osos clay loam (15 to 30, and 30 to 50 percent slopes), and the Millsholm loam (15 to 30, 30 to 50, and 50 to 75 percent slopes). See Appendix for the entire data set.

Figure 18. Weathering properties of Tshc and Ts? clasts found in a gully in the Pavon Creeks sub-basin.

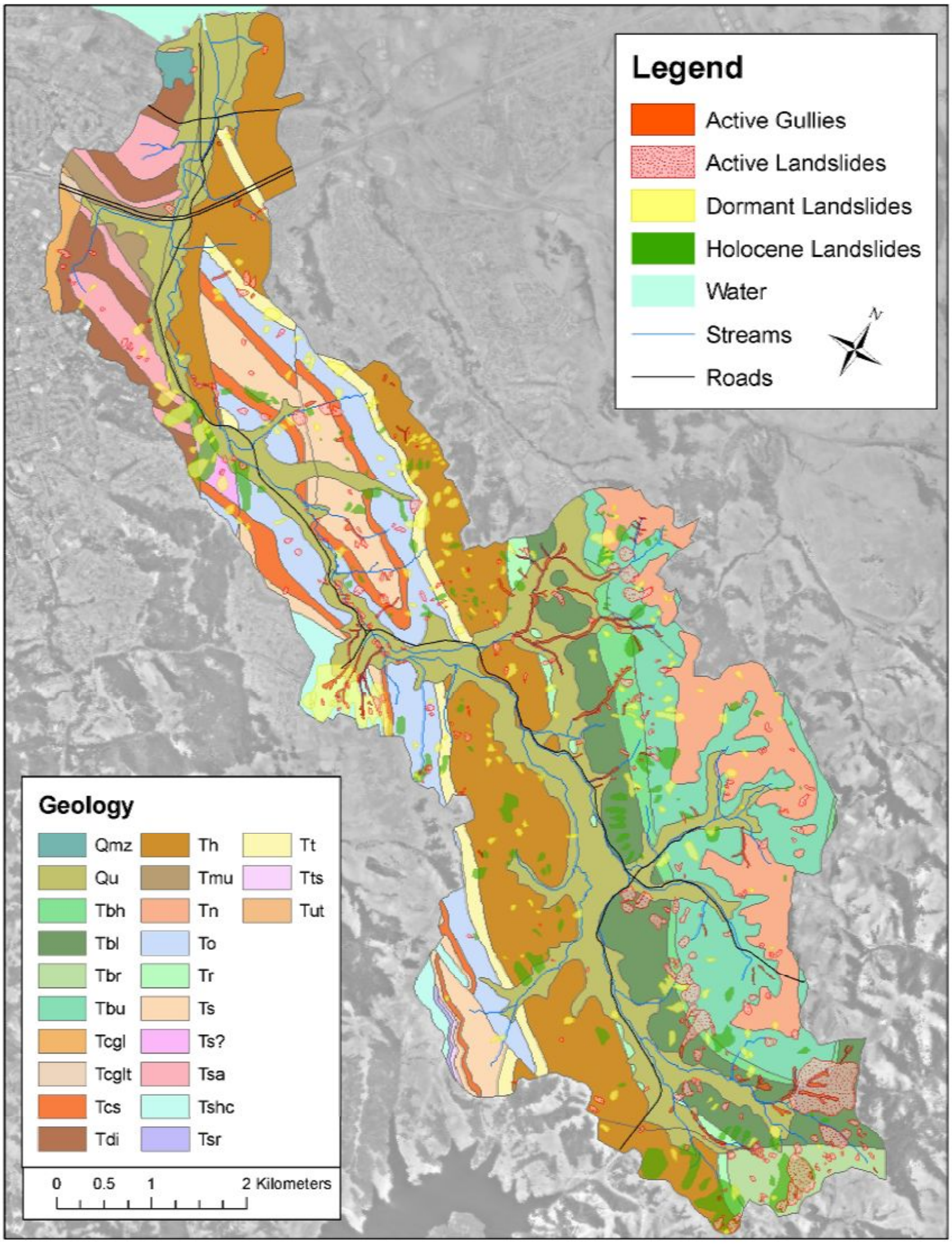


Figure 19. Map of the Pinole Creek watershed, underlying bedrock geology, and mapped landslides. Geology data is from Graymer et al. (1994). Color scheme is different than geology units shown in Figure 2 to make the figure easier to read.

Slope

The average slope, or gradient, of each mapped landslide was calculated using ArcView and US Geological Survey digital elevation models (DEMs). For most of the slides, this calculation gives the average hillslope gradient on which the slide occurred. In general, the average calculated slope of the landslide is similar to the adjacent hillslope gradient. This is because the slides are small, with little gradient change between the head and the toe of the landslide. Only for the largest slides, does the calculated slope actually differ substantially from the adjacent hillslope gradient. These large slides will have a lower gradient because the larger landslides have more flat area at the toe of the slide. Breaking the data into slide classes and type, 75% of earth flows, debris slides, and slump/rotational slide occur on slopes of >15 degrees, or 27% slope. For comparison, in the neighboring Wildcat Creek watershed, earthflows rarely occur on slopes less than 12 degrees (Collins, 2001). The gully/headcut type generally has a lower slope, ranging between 10 and 15 degrees, primarily because these gullies are connected into the fluvial system, and are largely controlled by the gradient of the mainstem channel and the valley gradient. In addition to slope, hillslope shape also contributes to slope stability. Concave slopes tend to concentrate surface runoff, leading to greater slide hazards, whereas convex slopes tend to disperse runoff, decreasing hazards. The water content of the soils and the routing of water go hand-in-hand with slope in determining stability.

Aspect

In addition to slope, the aspect, or average compass direction, of each slide was also calculated. Aspect is given in degrees, with 0° as north, 90° as east, 180° as south, and 270° as west. The data was divided into "bins", with each bin comprising 30 degrees. Data for each slide class was analyzed separately and later combined. When combined, the majority of slides occur on slopes with aspects between 240 and 300°, or generally west-facing. A lesser number of slides occurred on slopes with aspects between 150 and 240°. The general west-southwest aspect of a majority of slides is due to three factors. First, a large portion of the watershed, especially the upper watershed has slopes facing this direction. Secondly, these southwest facing slopes generally receive more and higher intensity rainfall (see Rainfall section). Thirdly, and most importantly, it is these west-southwest facing slopes that are typically grasslands, as opposed to the north-facing slopes that tend to be wooded. These open areas historically and currently are utilized for more intensive land uses, such as grazing and agriculture. Along with underlying geology, it appears that vegetation and land use are important in determining if material on a hillslope will fail in the Pinole Creek watershed.

Proximity to creek channels

The proximity, or distance, of individual landslides to adjacent channels was analyzed to better understand the proportion of landslides that contribute sediment into the fluvial system. Landslides can contribute sediment via two processes: either sediment is directly contributed as the slide is in motion, or through rilling, sheetwash, and soil creep of the landslide deposit over time after initial slide motion. If a slide does not contribute sediment during its initial motion, the slides that are closer to channels have a greater chance of contributing their sediment via the other processes. ArcView calculated the straight-line distance from the proximal edge of a slide to the nearest mainstem or tributary channel (using the USGS blueline channel network). We then sorted the data by distance and slide type. Of the 342 total active landslides mapped, 13% are within 10 m of a channel, 23% are within 50 m, 31% are within 100 m, 81% are within 500 m, and the remainder are located further than 500 m from the nearest channel. Looking at a subset of the data, only at the active earth flow landslide types, we see that 2% are within 10 m, 6% are within 50 m, 7% are within 100 m, and 44% are within 500 m. This data suggests that only a small percentage of landslides actually contribute sediment during initial slide movement. A larger percentage of slides are proximal to channels, and dependant upon rainfall, slope, and vegetation, have a good chance of contributing sediment over time. However, the largest percentage of slides are further than 100 m from a channel. It is likely that a majority of sediment disturbed at these locations will remain on the hillslopes in a landslide deposit, and never enter the fluvial system. This suggests that hillslope storage in the form of landslide deposits is potentially a large contributor of storage in the watershed. In comparison, sediment disturbed and eroded from gullies is less likely to remain in storage because the concentrated flow in the gully that causes the erosion is also able to transport it to the mainstem channel.

Zones

After the landslide mapping and statistics analysis was completed, the watershed was divided into nine zones, each representing an area with a predominant intensity and style of landsliding. Although the delineation of the zones was somewhat arbitrary, the zones do capture and define areas with different intensities of slope failure, perhaps caused by underlying geology, soil characteristics, slope, or land use. Figure 20 illustrates the nine zones, while Table 6 gives relevant statistics for each of those zones.

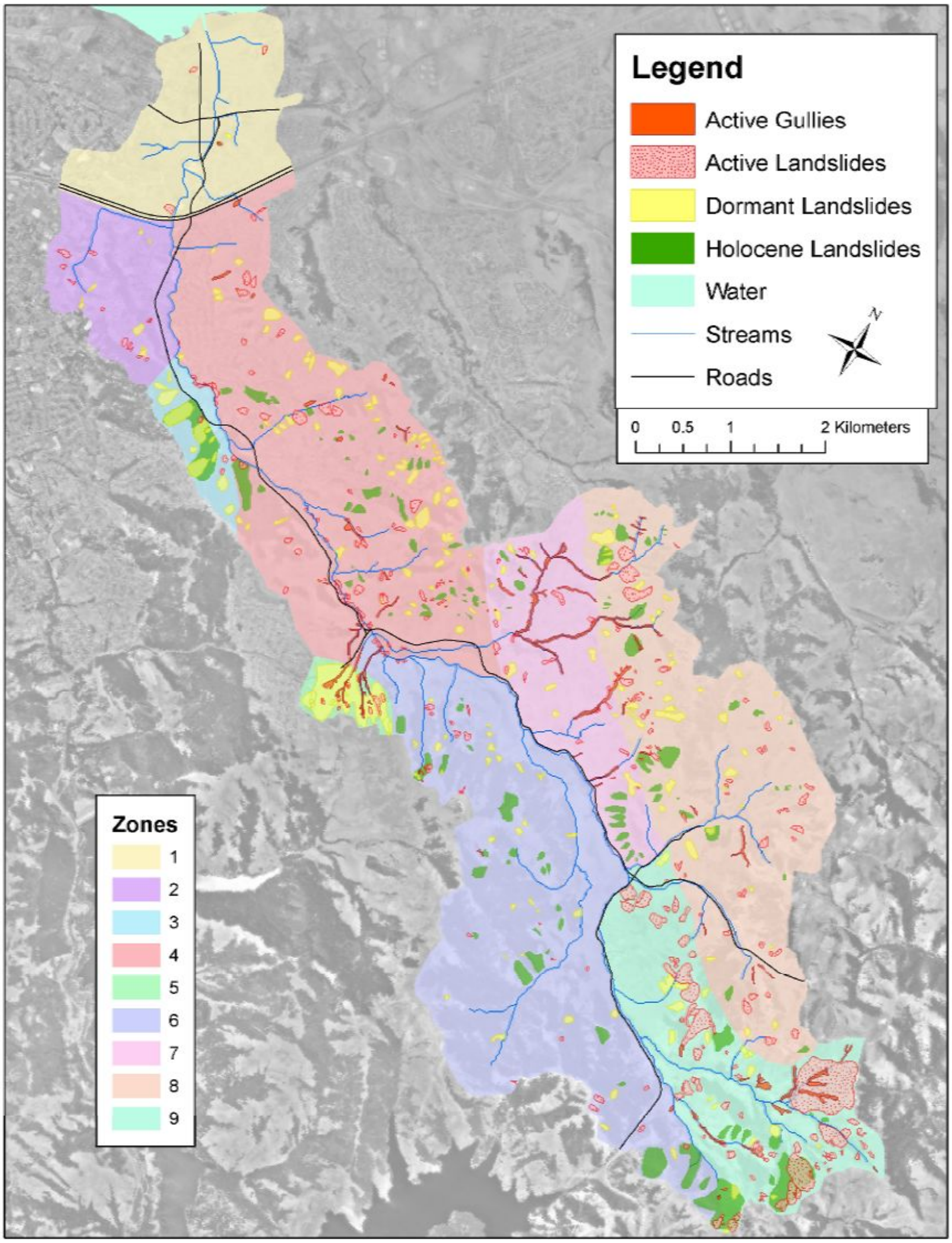


Figure 20. Pinole Creek watershed divided into nine zones representing different styles and intensities of landsliding.

Table 6. Statistics for each of the nine zones within the watershed.

Zone	Zone area (km^2)	Total area in zone comprised of landslide (km^2)	Percentage	Dominant landslide type	Dominant underlying geology	Dominant land use
1	3.245	0.017	0.55	Active landslide	Qu, Th, Tsa, Tdi	Urban
2	1.931	0.041	2.15	Dormant landslide	Tsa, Tdi	Urban
3	0.804	0.378	47.06	Holocene landslide	Ts?, Tdi, Qu	Open space/ Urban
4	8.857	0.748	8.45	Holocene landslide	Ts, To, Th, Tcs, Tt	Urban/ EBMUD
5	0.521	0.399	76.53	Dormant landslide	Tshc, Ts?	EBMUD
6	8.668	0.590	6.82	Holocene landslide	Th, To, Tt, Ts	EBMUD/ Open space/ Mixed ag
7	3.277	0.315	9.61	Active gully	Tbl, Tr, Qu	EBMUD
8	7.522	0.695	9.24	Holocene landslide	Tn, Tbu, Tbh	EBMUD/ mixed ag/ equestrian
9	4.778	1.388	29.07	Active landslide	Tbl, Th, Tr, Tbr	Equestrian /mixed ag/ EBRPD
Totals	39.603	4.571	11.54			

Table 6 shows that Zones 5, 3 and 9 have the highest percentage of their areas mapped as landslides. At the other end of the spectrum, Zones 1 and 2 have a very low percentage of their areas disturbed by landslides. These differences likely reflect the influences of rock type, slope, land use, and current management actions occurring in each zone. For example, Zones 1 and 2 on average have much lower slopes, and a majority of the zone is developed. Thus, it is not surprising that these zones have a lower percentage of their total area that is mapped as landslide compared to Zone 9, which has much higher slopes, a more erosive geology, and a different suite of land uses.

These zones have delineated portions of the watershed that have similar underlying geologic rock types, soil properties, vegetation, and land use characteristics. Because of these factors, management actions taken to control the input of landslide-derived sediment to the creek will likely be different between zones. For example, measures taken in Zone 6 may not be appropriate or adequate to control slides in Zone 5.

Other sediment sources

Roads

Besides landslides and gullies, road erosion, especially in rural watersheds, can often be a significant source of sediment supplied to the fluvial system. Sediment can be sourced through the formation of rills and gullies on the road surface itself, inadequate drainage of the road causing scouring or gullies along the inboard ditches, on the exposed cut (upslope) and fill (downslope) edges alongside the road, or erosion associated with culverts either crossing the road, or draining the road surface.

Lisa Hokholt of the USDA Natural Resources Conservation Service and Sarah Pearce (SFEI) completed a reconnaissance of different road types throughout the watershed, assessing the roads for their current condition, and any observable erosion. Roads were classified into four types: (A) paved roads, (B) highly traveled residential or ranch gravel and dirt roads (ranch roads), (C) rarely traveled dirt fire roads (fire trails), and (D) non-traveled fire breaks. An example location of each type of road classification is shown in Figure 21.

A. Paved road

B. Ranch road

C. Fire trail

D. Fire break

Figure 21. Photos illustrating the four types of road classification. A) Paved road, B) highly traveled gravel or dirt ranch road, C) rarely traveled fire trail, and D) non-traveled fire break.

The total length of roads in each classification were traced (as visible on the 2000 aerial photographs) and calculated in ArcView giving a total of approximately 175 km^2 (109 mi^2) of road surface in the watershed. The total length is comprised of 55% paved road, 9% ranch road, and 36% fire trails. The total length of fire break was not observable on these aerial photographs, but totals approximately 7.2 km (4.5 mi) (Scott Hill, pers. comm.), and is variable year to year. Road widths were either measured in the field, or established via personal communication with maintenance staff. Using observations, photographs, and notes collected during our reconnaissance of road condition, we estimated the total road length in each erosion category. An erosion guide from the USDA was used to assign rates of erosion (in ft/yr) for each of our road lengths (Steffen, 1983). Multiplying road area by erosion rate gave us an estimate of 21,517 m^3/yr of erosion attributable to roads. This estimate is the sum of 15,442 m^3/yr from paved roads, 1,360 m^3/yr from ranch roads, 4,216 m^3/yr from fire trails, and 498 m^3/yr from fire breaks. See Appendix for a description of erosion rates for each road type. However, it is important to note that not all of the eroded sediment is transported to the fluvial system, but instead a portion is stored on the hillslopes adjacent to the roads. Many examples of well managed roads and fewer examples of poorly maintained roads were observed in the Pinole Creek watershed. Figure 22 illustrates a well-maintained gravel ranch road, and also a poorly maintained outboard drainage along a paved road.

Figure 22. Photos illustrating a well-maintained gravel ranch road, and a poorly maintained paved road.

Overall, roads in the Pinole Creek watershed are relatively well maintained, and are not a significant source of sediment supply to the creeks. Of the four categories, paved roads are the largest overall source of sediment because of their greater total length, and a higher percentage of areas that are experiencing severe or very severe erosion. Drainage and concentrated runoff from the impervious paved roads typically causes the erosion, either forming gullies or causing bed incision. For example, the concentrated drainage from Castro Ranch Road has formed gullies in the Pavon Creeks tributary to Pinole Creek. When Castro Ranch Road was relocated in 1985, the drainage from the road surface was funneled via culverts into small existing tributary drainages adjacent to the road. A problem did not exist until the wet season of 1993, when heavy rains caused the formation of the large gully that is still currently observed (R. Hartwell, pers. comm.) (Figures 23 and 24). The eroded material was transported downstream, where a portion deposited on the south side of Pinole Valley Road, and the remainder was input into Pinole Creek. We acknowledge that this particular location is logistically very difficult to maintain a safe and functioning road. The Pavon Creeks sub-basin is underlain by a rock type that is very prone to failure, and an active fault trace has been identified along the southern boundary of the sub-basin (B. Nuzum, pers. comm.). Prior to road relocation, the road was continually damaged by the movement of landslides. The existing road location has also been damaged by a small landslide in 1995 and 1997 (B. Fernandez, pers. comm.). While the existing location is more stable, routing road drainage without causing significant erosion has now become an issue. Additionally, the Simas Creek tributary with the Pinole Creek mainstem is located immediately upstream of the intersection of Pinole Valley Road/Alhambra Valley Road and Castro Ranch Road (locally known as the “Y”), and has caused other erosion related road repairs in this location during the past 10 years.

Figure 23. Photographs of a hanging culvert draining Castro Ranch Road, and of the gully that has developed downstream.

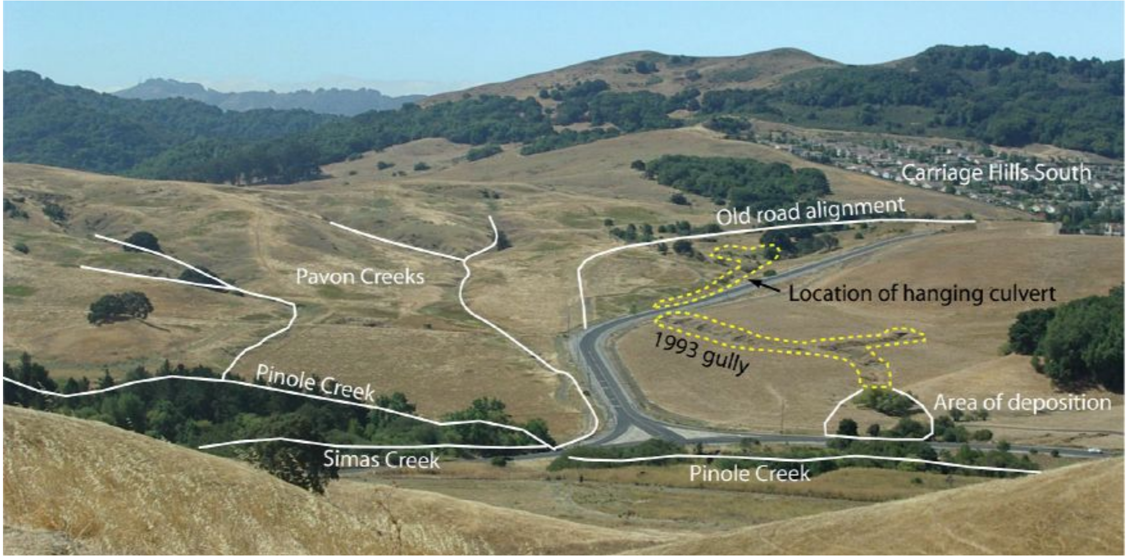


Figure 24. Photograph looking across the valley at Castro Ranch Road and the Pavon Creeks area. Photograph shows the current alignment of the road, past alignment, location of hanging culvert (also shown in Figure 23), gully location (dashed yellow line), and area of sediment deposition.

Another example involves drainage from Bear Creek Road that was routed to the adjacent channel via a culvert when a road washout was replaced in 1987 (B. Fernandez, F. Nunes, pers. comm.). At the location where the culvert discharges, bed incision of approximately 0.5 m (1.6 ft) has occurred. The incision is recorded by the height of a concrete sill that was poured to prevent erosion at this location. Downstream of this location, approximately 1.6 km (1.0 mi) a knickpoint, or abrupt drop in elevation in the creek channel, exists along the Pinole Creek mainstem just downstream of the Bear Creek Road and Hampton Road intersection. This knickpoint shows evidence of advancing upstream over the past 10 years (R. Hartwell, pers. comm.) and if it continues, may threaten the road intersection in the future.

Based upon observations made during our reconnaissance, it appears that only minor areas of the road surfaces are actually eroding. Instead, we observed localized areas of poorly designed and maintained inboard ditches and culverts draining road surface runoff which appear to be responsible for a majority of the road-related erosion (Figure 25). Because these areas are few in number, and relatively small in length, management efforts at these locations would likely be successful in reducing the amount of sediment supply from these locations. The gravel and dirt roads, fire trails, and firebreaks that are in good condition are not a significant source of sediment because they are well managed and maintained. In many locations, we observed features that reduced the erosion potential, such as remnant low vegetation on the road surface, outsloped roads (roads that disperse rather than concentrate runoff), and avoidance of creating roadside berms during annual road grading operations.

Figure 25. An example of a poorly constructed and maintained inboard ditch that is contributing sediment.

Land use

In addition to landslides, gullies, and roads, an analysis of sediment supply from land use-related sources was also completed. High intensity land use has the potential to cause significant amounts of erosion due to activities that modify the natural hydrology and drainage, change or reduce vegetation composition and cover, change soil density by compaction associated with livestock or vehicle use, or actively disturb soil or rock units.

The watershed was divided into six simplified land use types, and multiple areas in each type were visited by the field team (see Appendix for generalized land use map). Observations made during these visits are the basis for this assessment. The six land use types are:

1. Urban and single family residential areas
2. Open space lands managed and maintained for wildfire control and recreation
3. East Bay Municipal Utility District (EBMUD) open space and managed grazing lands
4. Ranchettes and horse boarding facilities
5. Mixed agriculture, including vineyards, hay production, and small areas of grazing in pastures
6. East Bay Regional Park District (EBRPD) open space, managed grazing lands, and recreation

Type 1- In comparison to landslide-derived sources, current land use impacts contribute a smaller volume of sediment to the creek. However, land use-related sediment supply to the creek is still quite substantial, and makes up a much larger component of the sediment that could be reduced through management efforts. The urban and residential land uses likely make a small annual contribution of sediment to the creek from stormwater carrying wind-blown dust particles, erosion from cut slopes and areas of bare soil, sediment fall from vehicles, wear debris and other urban debris. In addition, construction sites, if not managed properly, can supply substantial quantities of sediment if erosion and sediment control measures are absent or fail during rainstorms. Changes in surface hydrology in urban areas can concentrate water in hillslope swales or in oversteepened road cuts that could cause surface erosion or exacerbate landslide activity. In addition, the increased discharge of stormwater from these impervious areas can potentially erode sediment from the channel bed and banks; this is especially obvious where culverts enter the channel. From values obtained in the literature, urban areas are known to supply 140 - 320 kg ha^{-1}yr^{-1} of sediment to receiving waters (Australian Water Resources Council, 1981; Cordery, 1977; Letcher et al., 1999). Given the urban area of the watershed is approximately 709 ha (Contra Costa County Watershed Atlas, 2003), the urban areas likely contribute 99 – 227 metric tonnes of suspended sediment to the creek annually, much of which is manageable via best management practices such as vegetated swales and stormwater detention basins.

Figure 26. Example of minor channel bank erosion where a culvert draining city streets enters the mainstem channel.

Type 2- The areas of open space that are managed and maintained for wildfire control, recreation, watershed land, and wildlife areas appear to only be contributing minor amounts of sediment. In these areas, the potential for sediment sourcing is from fire trails and firebreaks, as well as from any modification of drainage that could cause gully erosion, sheetwash erosion, or trigger or reactivate a landslide. However, our observations of these areas suggest that the current style of maintenance is doing an adequate job of limiting erosion of the road and fire break surfaces as well as limiting hydrologic modifications.

Figure 27. Example of a well-maintained fire trail that is not contributing a significant amount of sediment.

Type 3- EBMUD owns and manages a significant portion of the middle watershed. On these lands potential land use-related erosion sources include fire trails, firebreaks, and areas managed for and grazed by livestock. Despite the potential for measurable erosion from these sources (such as would occur with overgrazing or recurring wildfire impacts), current land use and management effects contributing to sediment sourcing appear to be minor. Fire trails appear to be well maintained and demonstrate the use of many techniques that limit road surface erosion and concentrated runoff. Wide firebreaks are mainly limited to areas adjacent to Pinole Valley Road, and most retain some vegetative material on the soil surface, which reduces raindrop splash erosion and slows runoff water velocity. The areas that are grazed currently have a low stocking rate, and the cattle are often rotated between pastures to reduce the effects of overgrazing. However, one major source of land use-related sediment from these lands is from the gullies that previously formed likely due to historic grazing practices. These gullies were present before 1972 and likely formed due to heavy grazing that occurred between the mid-1850s and the 1920s (B. Nuzum, pers. comm.). Although most of the gullies have significantly stabilized since their initial formation, all of the observed gullies are still actively contributing sediment today.

Figure 28. Example of a firebreak on EBMUD lands.

Type 4- Lands in the upper watershed that are used for ranchettes and horse boarding facilities are showing effects of land use-related erosion. In a few locations, surface drainage from the ranchette building sites and access roads is causing minor gullies. Also, many pastures that are either too small or contain a high density of horses are showing signs of chronic surface erosion, as evidenced by gullies and exposed fence post bases (Figure 29). However, some ranchette owners are making efforts to control the amount of erosion associated with equestrian facilities (Figure 30). Although it is possible to estimate the volume of sediment erosion in specific areas such as that shown in Figure 29, it was not possible with this study to extrapolate such estimates to all equestrian activity and horse boarding facilities. Because most equestrian activity and horse boarding facilities are located in sub-watersheds that have the greatest volumes of sediment supply from landslide sources, it is very difficult to directly link observations made in the creek channels to specific hillslope sources. Because of the coincidence of sediment sources in these sub-basins, a further detailed study would need to be conducted to determine if the local tributary channel is being adversely affected by specific land use impacts associated with ranchettes and horse boarding facilities.

Figure 29. Exposed fence post bases due to surface erosion in a horse pasture.

Figure 30. Erosion control efforts associated with the installation of a new equestrian facility (work in progress).

Type 5- The mixed agriculture land use category is the most diverse of all six categories. It contains vineyards, hay fields, soil mining areas, small pastures used for grazing, and other small-scale agriculture activities. Many of these areas have a long history of agricultural use, including hay, grain, and tomatoes. The potential for erosion from this land use category is primarily from soil disturbance and modification of natural drainage patterns. Some of these areas show evidence of historic erosion, for example, the gullies that formed in a sub-basin due to the historic removal (mining) of topsoil. This action decreased infiltration, and increased runoff, carving two large gullies (Figure 31). However, most agriculture activities, especially historically, are located in the topographically flat areas which do not have high erosion potential. Ranchers and farmers are typically very interested in reducing erosion, because the soil and land represents their livelihood. In addition, the current management of most agricultural lands has significantly reduced the sediment transport that is occurring. For example, agricultural land uses, such as vineyards, have the potential to increase sediment input from surface soil erosion. But many vineyards often employ management actions such as planting parallel to contour, utilizing cover crops to increase soil resistance to erosion, and carefully planning surface drainage and runoff detention strategies, all of which allow sustainable operation, with reduced impact to the watershed.

Figure 31. Gully caused by the resultant increase in runoff due to historic removal of topsoil in a sub-basin.

Type 6- And finally, the East Bay Regional Park District (EBRPD) lands at the headwaters of the watershed (Briones Park) represent a very unique area with a mix of historic and current land uses. Historically this area was likely grazed at rates equivalent to other portions of the watershed. More recently, after purchase of the land by EBRPD, land use has continued to include grazing with low stocking rates, but now also includes actively maintained fire suppression, PG&E right-of-way, and limited public recreational use. The current potential for erosion is limited to the effects of minor grazing and the condition of fire trails and fire breaks. However, in spite of these limited land uses, this portion of the watershed produces large volumes of sediment because it is naturally highly erosive and landslide prone. The sub-basins containing the EBRPD land are two of the three most landslide-prone basins in the watershed (Pavon Creeks sub-basin is the third). It appears that most of the sediment supplied from this land use area is due to the large, naturally occurring landslides. The fire trails appear to be well maintained, and are not contributing measurable amounts of sediment to the fluvial system. However, because of the high landslide-associated erosion potential, it is critical that land managers in this area are aware of the potential negative consequences of land use modifications (such as road building, vegetation removal, excavation, etc.). Current and future management should strive to limit activity that modifies drainage patterns or increases runoff in these sub-basins.

Figure 32. Example of a well-maintained fire trail on the East Bay Regional Park District lands.

Synthesis

The hillslope sediment source assessment revealed that landslides and gullies are the dominant hillslope sources delivering sediment to Pinole Creek. Many of the slides are naturally occurring and are often related to the underlying bedrock units rather than current land use practices. However, we suggest that approximately 50% of the dormant and active landslides and 75% of the active gullies were triggered because of historic or current land uses that caused increases in runoff and changes in vegetation communities (such as the change from perennial to annual grasses). A majority of the mapped slides show evidence of earth flow type of movement, which typically only involves the surface soil material. This, along with erosion from the active gullies and land use-related surface erosion, is likely providing a majority of the fine (< 2 mm) sediment observed in storage in the creek and observed in suspension during floods. Despite these mapped landslides having disturbed millions of cubic meters of material, a significant portion of that material remains on the hillslopes as landslide deposits and has not yet been delivered to the creek. Based upon our mapping and assessment of landslide characteristics, the watershed has been divided into nine separate zones, each with a different landslide type and intensity, underlying bedrock units, and current land use. Each of these zones will likely require different management practices to control further erosion or failure of landslides. In comparison to the landslide sources, the total volume of sediment supply from roads, and other current land uses and land management practices is not as significant. However, we suggest that the proportion of total sediment supply due to human activities, in comparison to natural geomorphic processes, has increased, especially over the past 50 years. During this study, observations of many areas of erosion, and potential erosion related to human activities were made. A number of these locations would benefit from focused management actions, thus reducing land use-related contributions of fine sediment to Pinole Creek.

CHANNEL PROCESSES

General overview

Gaining a better understanding of the current condition and dominant physical processes occurring in Pinole Creek is central to many of the goals of this study, including: identifying sources of sediment, determining sediment storage, and identifying sediment-related limitations of beneficial uses. Currently, Pinole Creek is able to respond and adjust to changes in external controls such as changes in sediment or water input. However, there are issues that might be addressed or controlled through management measures, such as accelerated bed incision and bank erosion in the middle and upper reaches, minor areas of sediment deposition in the lower reaches, a predominantly fine grain size distribution, and high suspended sediment concentrations during times of flood. This section reports data collected during this study regarding the form and function of Pinole Creek, with emphasis on sediment-related processes in the channel.

Methods

A field-based fluvial geomorphic survey of Pinole Creek was conducted to collect data on the condition of the channel banks and bed. The survey’s design and methods are based upon previous work conducted by SFEI in other creeks in the Bay Area. This survey type uses a systematic random sampling approach to collect data within carefully chosen sample reaches, which can then be extrapolated to characterize the entire channel length. First, a longitudinal profile of Pinole Creek was plotted using the Mare Island, Richmond, and Briones Valley USGS 7.5' topographic quadrangle maps. Because channel slope is known to be a good predictor of channel morphology (e.g. Montgomery and Buffington, 1997; Rosgen, 1996), general areas where sample reaches would be selected were chosen to characterize the entire range of channel slopes. However within these general areas, actual locations of sample reaches were selected by consideration of both the longitudinal profile, and access to private property. In the field, the exact location of each reach is randomly chosen, but each is referenced to a fixed, known location to allow future re-occupation of the reach if necessary. The length of each sample reach is 25 times the measured bankfull width, as measured at the downstream end of the sample reach. Within each sample reach, field flagging was placed at intervals of five bankfull widths, to provide a sampling framework to collect in-channel data.

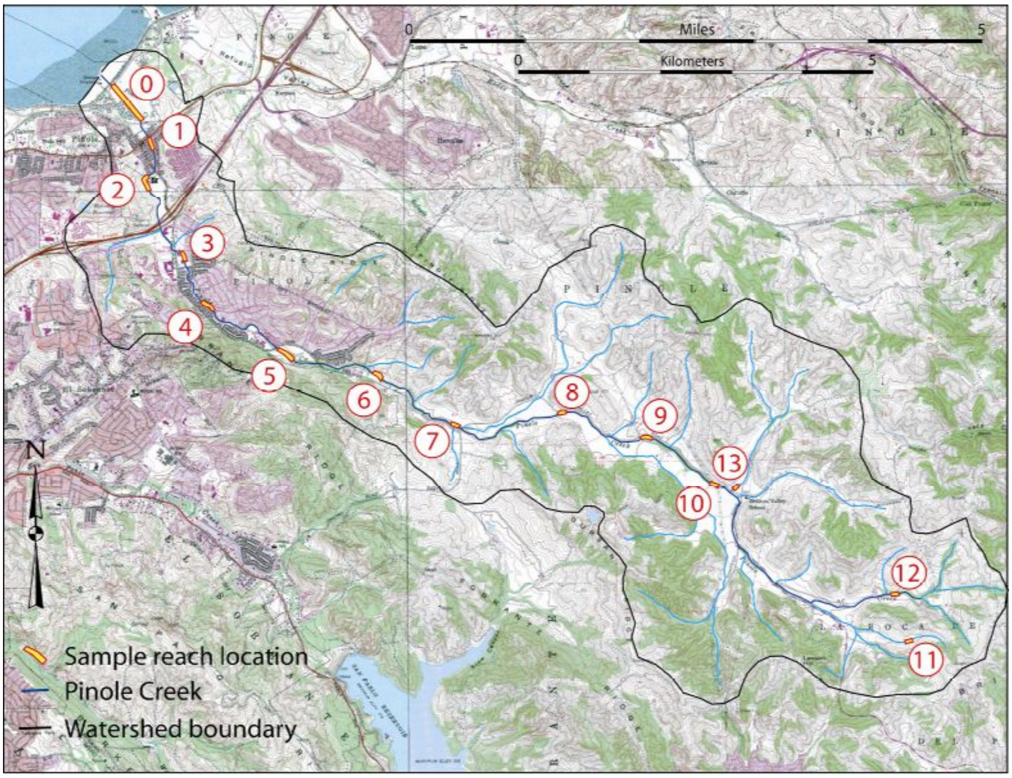


Figure 33. Topographic map of the Pinole Creek watershed highlighting the 14 in-channel sample reaches. Sample reach 0 extends beyond the standard 25-bankfull widths sample reach length, however data collected here were adjusted to allow comparison with the other sample reaches. See Appendix for exact sample reach locations.

This sampling methodology aims to characterize and quantify channel conditions and processes characteristic of the entire channel length. The 14 chosen reaches are intended to represent the entire creek, eliminating the need to collect intensive data for the entire channel length (Figure 33). Data was collected in 1,883 m (6,180 ft) of channel, comprising approximately 10% of the entire mainstem channel length. While data collection focused on the 14 sample reaches, much larger areas of the creek were also observed, allowing sample reach data to be put into context in the entire watershed.

In each sample reach the following data were collected:

- Channel bank and bed erosion data, to determine the volume of sediment supply from in-channel sources
- Sediment deposit data, to determine the volume, grainsize distribution, and stability of sediment stored in each sample reach
- Sediment grain size distribution, to determine the sources and stability of in-channel sediment
- Pool and large woody debris data, to determine the effect of these channel features on the sourcing, transport, and storage of sediment
- Three channel cross-sections, to determine the variability within and between sample reaches

Channel bank and bed erosion

Besides sediment supply from the hillslopes, the incision of a creek's bed and erosion of its banks can also be significant contributors to the total sediment load supplied to the creek. Quantifying the amount of active in-channel erosion allows volumetric comparisons to other sediment sources to be made, as well as the identification of reaches that are less stable. Data collection on channel bank erosion and bed incision included: bank erosion length, height, extent of lateral retreat, and age; bank revetment length (hardening and stabilization efforts), height, type, and condition; and bed incision length, width, depth, and age. In order to be included in this survey, bank erosion must have a lateral retreat greater than 0.1 m (0.3 ft), and bed incision must be greater than 0.1 m (0.3 ft) in depth. Only after meeting this criteria were the areas of erosion measured and included. Areas of erosion were typically averaged over their length. Age estimates of erosion were based upon indicators of erosion, such as exposed tree roots, undercut structures, and hanging fence posts.

In the 14 sample reaches, a total amount of 2,974 m^3 (105,032 ft^3) of bank erosion was measured. Because erosion estimates are based upon present indicators, this methodology typically measures erosion that has occurred over approximately the past 100 years. See the Appendix for further description of bank erosion measures. When erosion is normalized to sample reach length, the middle watershed reaches exhibit greater amounts of measured erosion, with the greatest values observed in sample reaches 10 and 7. Based upon the data collected, banks can be characterized as eroding, revetted, or stable. Figure 34 shows the percentage of bank length in each of these three categories. Generally, most revetment occurs in the downstream reaches (in the urbanized area). The middle reaches typically have between 40 and 60% of their total bank length actively eroding, while two of the three tributary reaches have much greater percentages of active erosion.

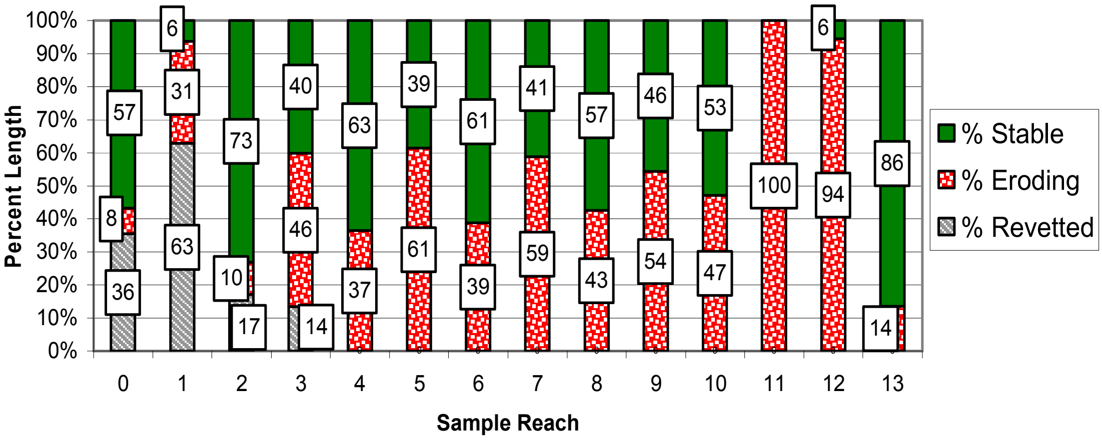


Figure 34. Graph illustrating the percentages of channel bank in each sample reach that are stable, eroding, or revetted.

As the channel continually makes adjustments in its channel planform or cross-sectional geometry, sediment is eroded and provided to the channel to transport and rework. Changes in channel planform, or channel migration from side to side, provides sediment from bank erosion, while changes in cross-sectional geometry, or channel downcutting, provides sediment from bed incision. Because channel incision will occur over much longer channel lengths, the total volume of sediment supplied can be quite substantial. Channel incision can be a response to an increase in runoff, a reduction in sediment load, a response to tectonic uplift, or a change in baselevel (natural or engineered). In this assessment, the cause of incision often cannot be confirmed, but we believe that it is most likely a combination of tectonic uplift (natural), land use related changes in hydrology (increased runoff), and localized changes in baselevel due to landslide inputs. In the 14 sample reaches, a total amount of 945 m^3 (33,372 ft^3) of bed incision was measured during approximately the past 100 years, however most occurred more recently. Measures of bed incision determined that the upper watershed sample reaches displayed the greatest amount of incision, with a maximum value in reach 12. Because a channel tends to create an even gradient, areas of incision will extend beyond our standard sample reach length. Using our field measures, the total amount of sediment contributed from bed incision can be extrapolated between reaches. From the entire 17.8 km (11.1 mi) channel length considered (the mainstem plus Periera and Costa Creek tributaries), approximately 19,835 m^3 (700,466 ft^3) of sediment has been disturbed due to bed incision over the same time period. When combined with bank erosion, a total volume of sediment supplied from in-channel sources in each sample reach is obtained (Figure 35).

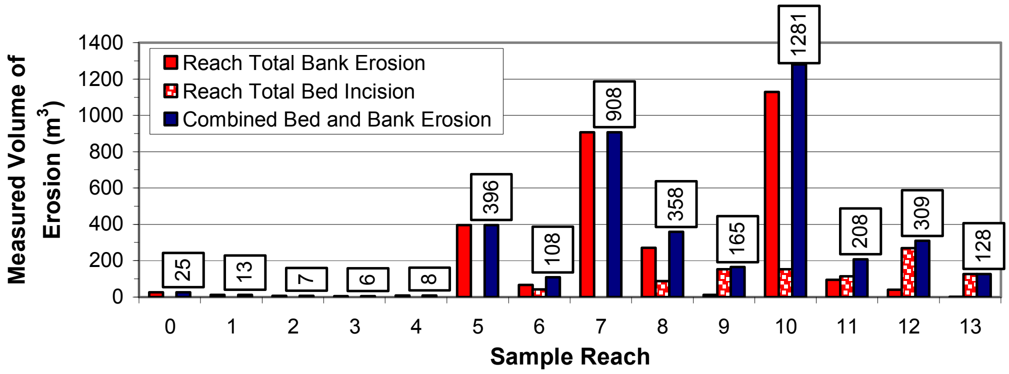


Figure 35. Reach total measured bank erosion, bed incision, and combined erosion and incision in each sample reach.

In the middle watershed, anecdotal evidence suggests that a period of incision occurred in the 1940s/1950s. Near sample reach 9, both cattle and tractors could cross the mainstem in the 1940s, however, by the 1950s the channel had become too incised to cross (F. Nunes, pers. comm.). Other anecdotal evidence suggests that incision near sample reach 10 occurred in response to a landslide triggered in the wet season of 1982/1983. The proportion of incision due to tectonic uplift of the entire watershed is likely minimal; for example, in neighboring Wildcat Creek, incision due to uplift is estimated at 11% of the total calculated incision. Some minor incision could be controlled by local faults, along which any vertical offset that occurs could provide a local baselevel control which could induce incision upstream of the fault. However, we believe that a majority of the incision is due to increased intensity land use, altered vegetation communities that now offer a reduced resistance to erosion, and increased runoff from changes in land use and more impervious areas in the watershed.

In-channel sediment storage

The volume and mobility of active sediment deposits in a creek reflect the volume of sediment supplied from the hillslopes and channel, and the ability of the creek to transport that sediment downstream. Sediment deposits can affect the water height during floods, the stability of banks, the stability of structures built by humans such as bank revetments or bridges, and the quality of aquatic habitat features. However, in-channel sediment storage can be quite substantial and provides a temporal buffer between supply from the hillslopes, and transport to the flood control channel or the Bay.

Data on bars and other sediment deposits in Pinole Creek were collected for the entire length of each sample reach. The following features of each sediment deposit were measured and categorized: length, width, depth, type, forming mechanism or process, and deposit age or stability. To be recorded, each deposit needed to be at least 0.1 m (0.3 ft) in depth, with one dimension greater than 1 m (3.3 ft). Deposit types are based upon those defined by the California Department of Fish and Game (Flosi, et al., 1998) and by previous work by SFEI. Deposit types include: alternate bars, active channel deposits, pool deposits, forced bars, point bars, medial bars, lateral bars, slump block deposits, and fluvial terraces. Deposit age, or stability, is based upon position of deposit within the cross-section, grain size distribution of deposit clasts, and amount and type of vegetation established on the deposit.

The total volume of available stored sediment measured in all 14 sample reaches is 1,860 m^3 (65,685 ft^3). When extrapolated over the entire mainstem and select tributary lengths, approximately an additional 18,126 m^3 (640,122 ft^3) of sediment is stored in the channel. Storage occurred most often in active channel deposits, pool deposits, and forced or lateral bars (Figure 36). Because sample reach length varied (reach length is based upon the measured bankfull width), total sediment storage volume should be normalized to the reach length to allow comparison between reaches. Figure 37 plots the total sediment volume measured in each sample reach (in m^3) per meter of channel. Proportional to the reach length, sample reach 0 stores the greatest amount of sediment, followed by reaches 5, 10, 9, and 2.

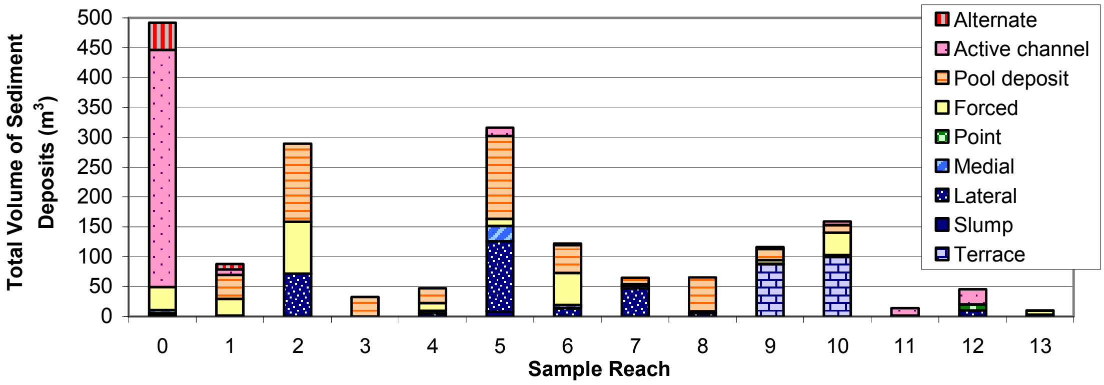


Figure 36. Total volume and type of sediment deposits (in m^3) in each sample reach.

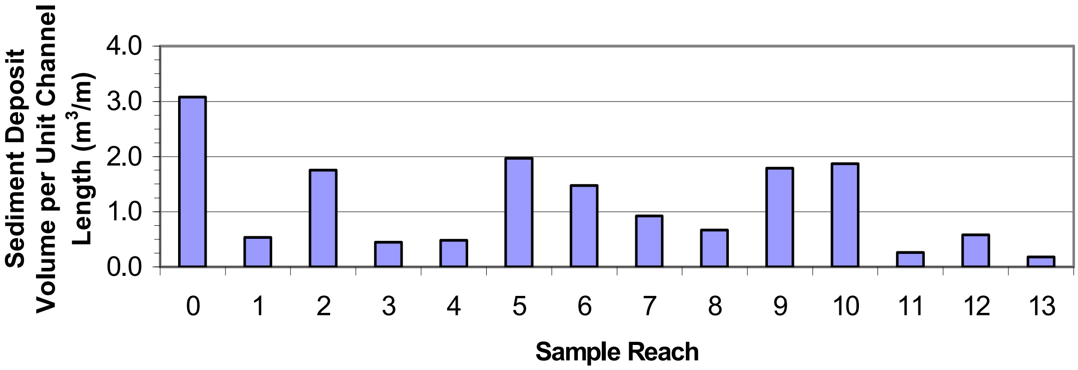


Figure 37. Total volume of sediment storage per unit channel length in each sample reach.

The age, or stability, of each deposit was also estimated. This measure informs us about the amount of supply of sediment to the creek, as well as the stream power available to transport this sediment. Sediment deposits were placed in the following age classes (in years): <1, 1-5, 5-10, 10-20, 20-50, 50-100, and >100 years. A creek that has many young deposits typically has a consistent annual supply of sediment, and has enough stream power to rework deposits annually. Streams with older deposits typically have a lesser annual supply of sediment, and have not had a recent flood event large enough to rework existing deposits. Pinole Creek is dominated by young, or low stability, sediment deposits, most of which have been deposited in the past 10 years (Figure 38). This corresponds well with the high sediment supply from landslide sources, and the relatively recent periods of incision that have occurred on the mainstem, which may have eroded or abandoned any existing older deposits.

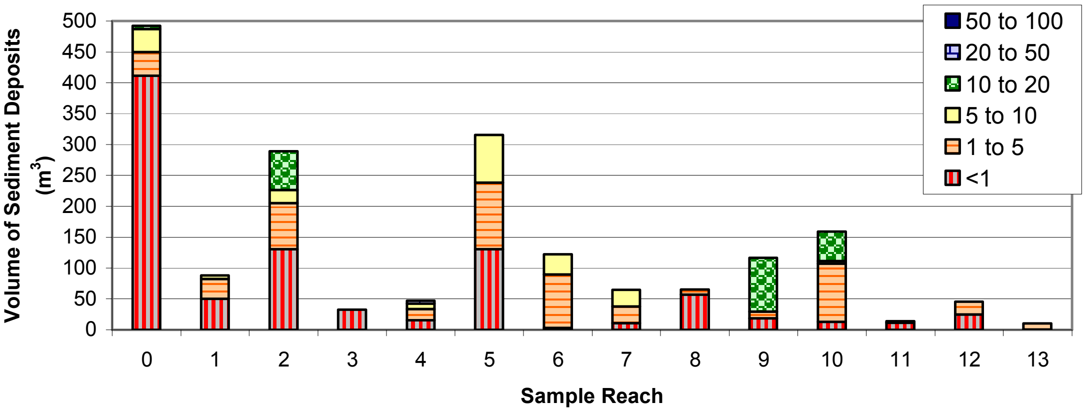


Figure 38. Total volume and age class of sediment deposits in each sample reach.

Sediment grain size distribution

Our understanding of the sources of sediment supplied to the creek, the dominant processes of transport and storage occurring in-channel, and the mobility of in-channel sediment is greatly improved by characterizing the grain size distribution of sediment on the channel bed. For example, a channel bed dominated by sand-sized clasts will have very different sediment sources and transport processes compared to a channel bed that is dominated by cobbles or boulders.

The surface sediment grain size distribution was characterized in each sample reach by performing pebble counts at five locations, corresponding to every fifth bankfull width. Surface sediment is that which is exposed on the top of the bed, rather than that sediment that is buried beneath the surface layer. A total of 500 clasts per sample reach were measured, producing a statistically robust estimate of grain size distribution for each reach. Clasts were measured by hand, and are reported in size classes (in mm).

Generally, Pinole Creek has a relatively fine surface sediment grain size distribution. All of the sample reaches contain at least 40% sand-sized or finer grained sediment (Figure 39). The majority of the grain size distribution is comprised of silts, sands and gravels in all reaches of the creek. The median grain size (D50) ranges from <2 mm in many reaches to 6.5 mm in reach 5 (Table 7).

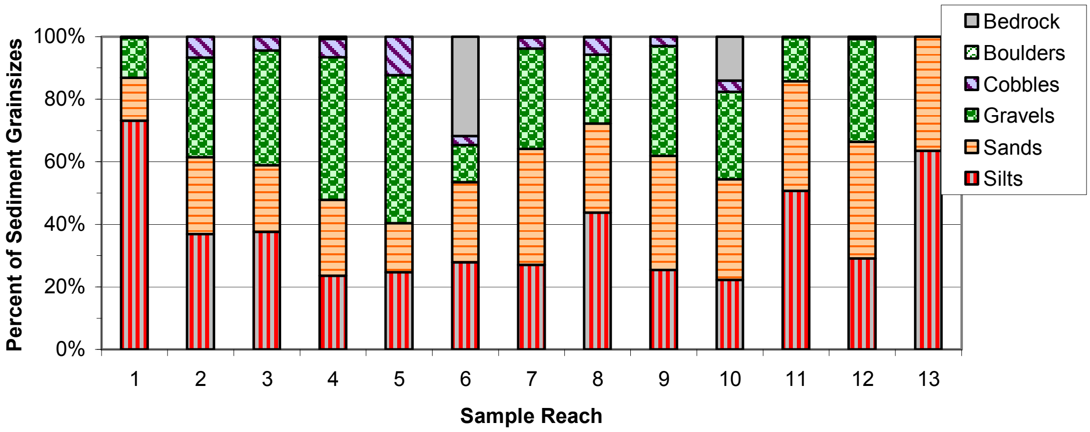


Figure 39. Simplified grain size distribution for each sample reach. Silts are < 0.5 mm, sands are 0.5 mm to 2 mm, gravels are 2 mm to 16 mm, cobbles are 16 mm to 256 mm, and bedrock is > 256 mm.

Table 7. Surface grain size distribution data for each sample reach. *Data for reach 0 is qualitative, and based on observations, not measurements.

Sample reach	% < 2mm	% < 6.35mm	D16	D50	D84
0*	80	90	<2	<2	3
1	85	90	<2	<2	<2
2	55	67	<2	<2	17
3	54	64	<2	<2	19
4	41	55	<2	4.5	24
5	36	49	<2	6.5	36
6	43	57	<2	3.2	7
7	54	69	<2	<2	16
8	68	78	<2	<2	11
9	53	72	<2	<2	11
10	46	61	<2	2.6	12
11	82	88	<2	<2	3
12	45	72	<2	2.4	10
13	99	100	<2	<2	<2

This surface sediment grain size distribution is consistent with many observations made in the watershed. For example, earth flows, the dominant style of landsliding, typically provides only fine-grained sediment, similar to the sizes measured in the channel bed. Gullies and land use related surface erosion are also responsible for providing fine grained sediment. Also, given the abundance of fine-grained sediment on the surface of the channel bed, the high suspended sediment concentrations during floods is not surprising.

Pools and large woody debris

Pools and large woody debris (LWD) are two components of a creek that affect the quality of aquatic habitat available. But more importantly, these two components can have a significant effect upon the sourcing, transport, and storage of sediment in a creek. The formation of most pools requires localized scour of the bed or bank, providing sediment that can be transported by the creek. Also, pools often are the storage sites for pool deposits, or deposits of relatively fine-grained sediment that are deposited as the water level decreases after a flood. These deposits can be quite substantial in volume, providing a large storage “sink”. However, because of their fine-grained size distribution, an individual pool deposit is often mobile every wet-season. Once LWD enters the channel, it may also affect sediment sourcing and storage. For example, a piece of LWD can create a sediment source by causing localized scour of the bed or bank, potentially forming a pool. Alternatively, a piece of LWD, or a group of pieces, may cause a jam that temporarily stores sediment behind the jam.

Data on the location, width, length, depth, type, and volume of sediment storage of pools were collected within each sample reach. This survey required that pools must have a residual depth greater than 0.2 m (0.65 ft), and one dimension greater than 1 m (3.3 ft) for characterization. Data on the location, length, and diameter of LWD were also collected. LWD pieces are defined as those that affected flow within the bankfull channel, and that were larger than 20 cm (8 in) in diameter and 1.8 m (6 ft) in length.

A total of 42 pools, classified by mechanism of formation, were measured in the 14 sample reaches (Figure 40). Of these 42 pools, 33 contained measurable sediment, in the form of a pool deposit, and 6 of these were significant (greater than 30 m^3 (1060 ft^3)). Overall, pool deposits account for approximately 7% of the total volume of sediment storage measured in the 14 sample reaches. However, these deposits are the primary storage location of fine-grained sediment (clays, silts, and sands). The largest pool deposits by volume were measured in sample reaches 2 and 5, due to the long, wide, and low gradient pools found in these locations (Figure 41).

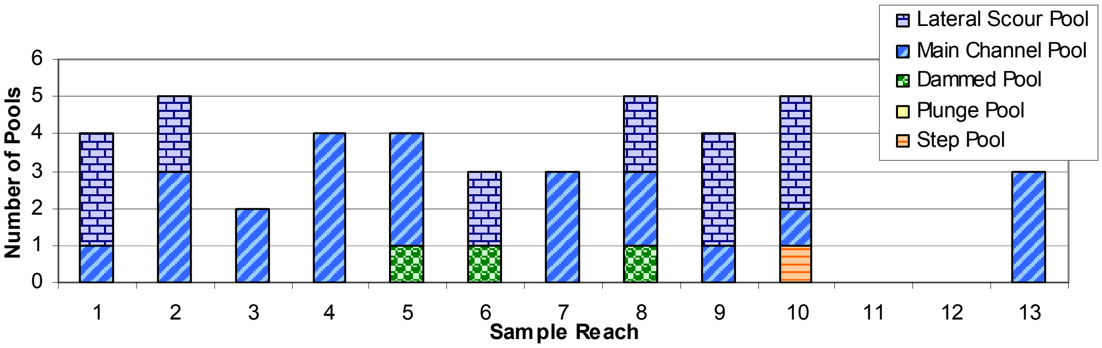


Figure 40. The number of pools, and mechanism of formation, measured in each sample reach.

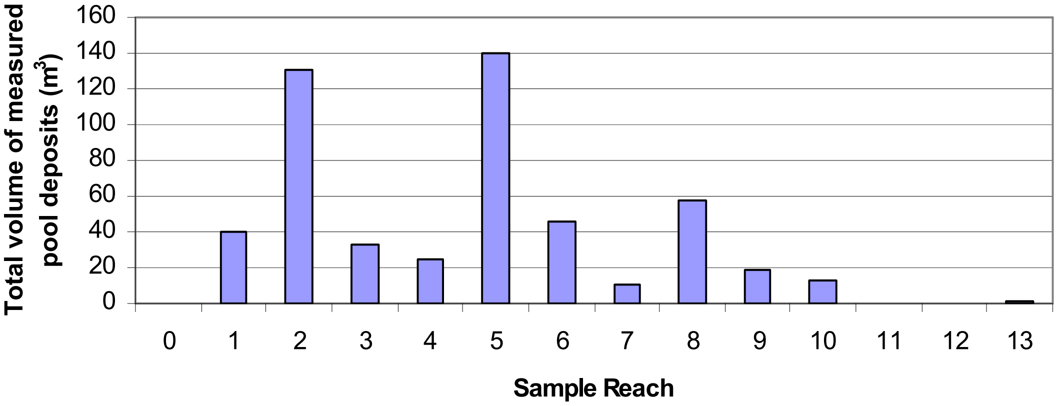


Figure 41. Total volume of measured pool deposits (in m^3) in each sample reach.

A total of 47 pieces of LWD were measured, averaging 3.6 pieces per reach, ranging from zero pieces in reach 2 to nine pieces in reach 8. Overall, the number of in-channel LWD pieces was fairly low, compared to other creeks in the Bay Area. Also, no LWD jams were observed in the creek. In general, LWD only has a minor influence on sediment processes in Pinole Creek. For example, only 44% of all pools measured were either directly formed by, or were associated with a LWD piece, illustrating the minor amounts of sediment sourcing due to scour around LWD pieces. Similarly, sediment storage caused by LWD pieces is minimal; only a few LWD pieces were trapping a measurable volume of sediment behind them.

Channel cross-sections

In each sample reach, three channel cross-sections were surveyed to determine the variability in channel geometry both within the sample reach, and between sample reaches. Surveys were completed using a hand-held level, survey rod, and tape measure. Each cross-section is oriented perpendicular to the channel axis, looking downstream. Figure 42 shows one cross-section from each sample reach. On each cross-section, the brown line represents the ground surface, the dark blue line represents the bankfull water depth (as determined from field indicators), and the light blue line represents the water level on the survey date. See Appendix for the entire set of 42 cross-sections.

Channel geometry varies greatly between the upper and lower reaches. In general, the channel becomes wider and deeper in the lower reaches, as the channel is required to transport a greater volume of water and sediment. A series of distinct channel geometries, or channel shapes, are evident in Figure 42. In reaches 0 through 2, the channel has inherited the constructed design of the engineered flood control channel; these reaches have gently sloped banks, and a wide channel cross-section. After an initial adjustment in slope and cross-sectional geometry since the flood control channel was built (1965), tidal reach 0 now transports all the sediment that is supplied to it, essentially maintaining a stable cross-sectional geometry. However, reaches 1 and 2 are entirely fluvial (no tidal influence), and illustrate more complex adjustments since it was built. This portion of the flood control channel is controlled by the concrete box culverts under I-80, Tennent Avenue, and San Pablo Avenue, as well as the significant riprap chute structures that control the channel grade. Within these external controls, the channel appears to have slightly incised, and is attempting to return to a more natural pool-riffle sequence (Figure 43). Reaches 3 and 4 illustrate the typical cross-section in the urban area; these reaches are entrenched and are fairly narrow, possibly due to areas of bank revetment and the constraints placed on the channel by the adjacent houses. Reaches 5 though 7 illustrate a reach of the creek with a much wider valley cross-section. These reaches may still be entrenched (as in reach 5) but in general, have greater access to their floodplains (as in reaches 6 and 7). In reaches 8 through 10, the creek maintains a fairly narrow and entrenched cross-section. These reaches typically have evidence of both bed incision and sometimes-substantial bank erosion. And finally, in the tributary reaches 11 through 13, a much smaller cross-section is observed, due to their position in the upper watershed. Although all tributary reaches have a small channel width and depth, variation in shape is still evident. For example, reach 11 is quite narrow and deep, whereas reach 12 maintains a wider, flat-bottomed channel, with a more accessible floodplain.

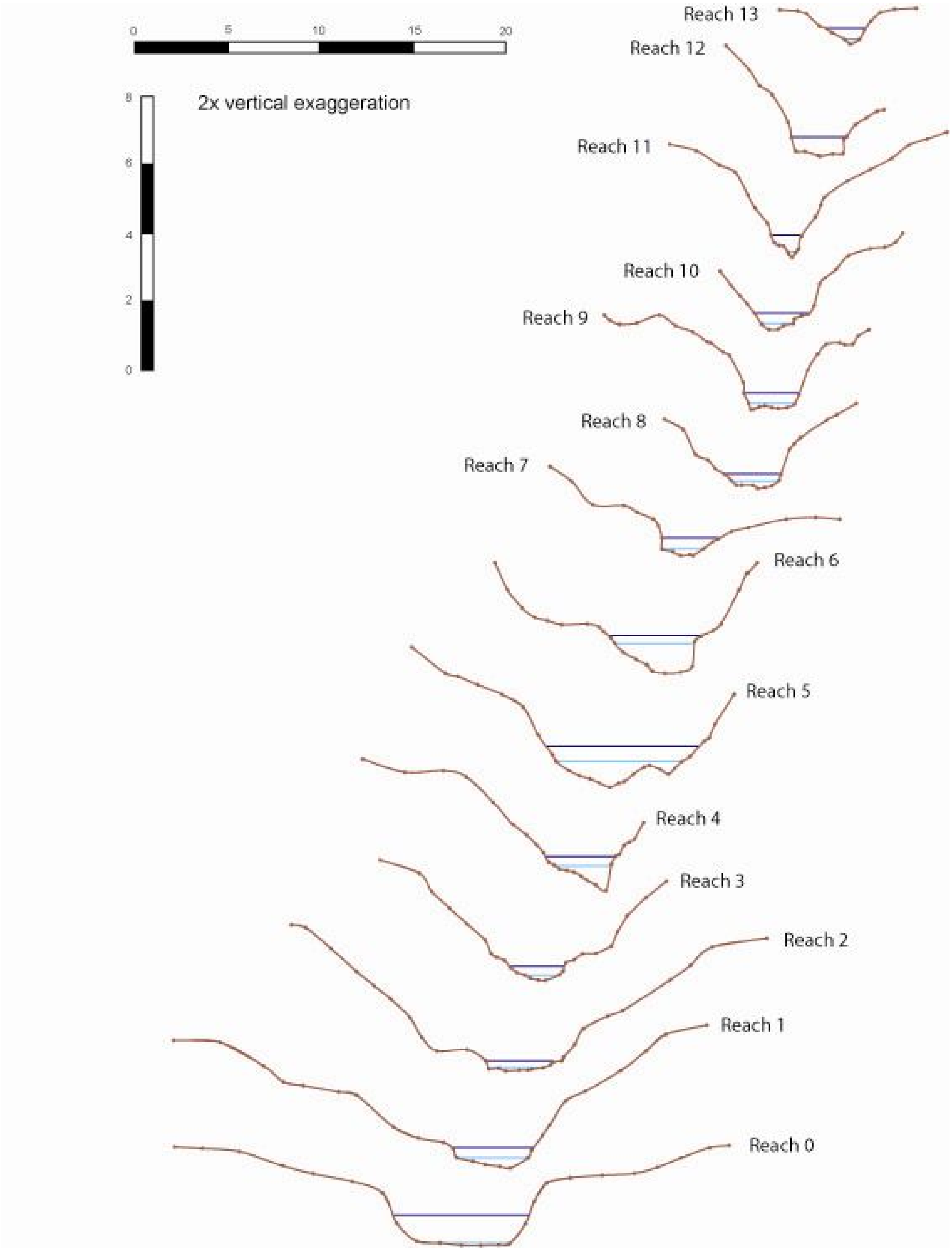


Figure 42. Diagram of a representative channel cross-section from each of the 14 sample reaches. The cross-sections are oriented upstream (Reach 13) to downstream (Reach 0), with sections 11 through 13 representing tributary reaches. Scale in meters. The brown line is the ground surface, the light blue light is the water level on the date surveyed, and the dark blue line is the field indicators of bankfull depth. Cross-sections are plotted with 2x vertical exaggeration.

Figure 43. Photograph illustrating typical cross-sectional geometry in the fluvial portion of the flood control channel reach.

Synthesis

Due to changes in land use, population, vegetation communities, climate and level of channel engineering/modifications that have occurred over the past 180 years, Pinole Creek has been forced to make adjustments in its channel geometry and planform. Today, Pinole Creek is able to transport the water and sediment supplied to it while largely maintaining its form. Based upon data collected in the 14 sample reaches, we found that bank erosion and bed incision are important sources of sediment, particularly in the middle reaches. These two erosion types are linked and are easily observable, especially in reaches 8 through 10. As bed incision occurs, creating a narrow, entrenched channel geometry, the channel banks become oversteepened, encouraging greater bank erosion. We suggest that in these reaches, the channel geometry is currently adjusting; the channel is now responding to the incision that has occurred by laying-back its oversteepened banks through erosional processes. Pinole Creek is currently storing moderate amounts of sediment as in-channel bars and other types of deposits, and a larger volume of sediment in a more stable, older high terrace deposit. Most active storage (typically as pool deposits) occurs in the lower and middle reaches, either where the channel cross-section widens or where channel gradient decreases. Despite the overall high sediment supply to Pinole Creek, the channel is quite capable of transporting the sediment downstream on an annual basis. No reach is observed to be significantly aggrading, including the flood control channel reaches. This balance is likely maintained on the decadal time period; during dryer years minor areas of sediment may accumulate, but are then reworked and transported during wetter years. The active sediment that is currently in storage throughout the entire channel length has been deposited recently, suggesting that the creek erodes and reworks its sediment deposits over a period of years, efficiently moving sediment downstream. We believe that the sediment storage characteristics of Pinole Creek reflect the dominance of the hillslope sediment sources, in both the continuity of supply, as well as in the grain sizes that are supplied. Pinole Creek has a fine grain size distribution, reflecting the dominant sediment supplies including shallow landslides, gullies, and land use sources, rather than other factors such as low channel gradient. These grain sizes are able to be transported in flows occurring annually in the creek, with most of the sediment transported through the flood control channel and to the Bay. And finally, despite the areas of hardwood forests and nearly continuous riparian canopy upstream of I-80, the low numbers of in-channel large woody debris pieces have a low impact on sediment sourcing or storage in the creek. Typically, creeks that have low numbers of LWD have discontinuous or no riparian vegetation. However, we believe that the low number of LWD pieces in Pinole Creek is not unlike other Bay Area creeks that support dominantly hardwood tree species (e.g. Carneros and Soda Creeks, Napa County), rather than redwood and conifer species. Although removal of pieces for flood control may be having an impact (especially in the lower reaches), we find that these creeks simply have low numbers of LWD pieces. Adding LWD pieces in carefully chosen locations may benefit aquatic species by enhancing habitat value and adding channel complexity.

SUSPENDED SEDIMENT LOAD

Throughout the year, the amount of water discharge in a creek can vary significantly, primarily in response to precipitation events. There is a strong relationship between the amount of water discharge and the amount of sediment that is being transported by that discharge. Because most of the annual water discharge occurs during the wet season, efforts to quantify sediment loads focus on the wet season, especially during storms. During storm events significant variation in water discharge and sediment concentration occurs, on the scale of hours or even minutes. This section describes the suspended sediment portion of this study designed to quantify the variability and cumulative amounts of water and sediment passing through the creek.

Methods

There are no past measurements of suspended sediment or turbidity in the Pinole Creek watershed. During this study, all sediment measures were taken at the stream gauge underneath Pinole Valley Road Bridge number 5 near Ellerhorst School (upstream watershed area of 30.7 km^2, 11.9 mi^2) (see Figure 7). Measurements at this location integrate processes occurring in the middle and upper watershed, but only capture a small portion of the processes occurring in the urbanized area of the watershed. Although it was beyond the scope of this project to install a continuous flow gauge or a continuous turbidity probe, the field team was on-call 24 hours a day, 7 days a week during the wet season in order to collect high quality data and capture the significant flood events.

The total weight of sediment carried in suspension in a known volume of water is termed suspended sediment concentration (SSC). Samples were collected during wadable flows using a US DH-48 hand-held depth-integrating sampler (Figure 44). This device allows the collection of a single water sample from the entire depth of flow because the user moves the sampler vertically through the entire water column. Water enters the yellow nozzle in the front, and collects in the glass bottle. The sampler is designed to allow air to escape while sampling so that all water and sediment that enters the nozzle is retained. During wadable flows, samples were collected from the middle of the channel, and the middle of the water column. Water collected in the glass bottle was transferred into a sample bottle and a small amount was retained to measure turbidity. San Francisco State University Romberg Tiburon Laboratories analyzed suspended sediment samples.

Turbidity was measured in the field using a Hach 2100P portable turbidimeter, which is widely considered a standard device for field measurements (Figure 44). Turbidity is measured in nephelometric turbidity units (NTU) and is the measure of the attenuation of light by organic and inorganic particles. In other words, by shooting a beam of light through a water sample, the turbidity is the measure of how much light is scattered off of particles suspended in that water sample. The field turbidity meter has a range of 0 to 1000 NTU; during flood events, turbidity levels in Pinole Creek were often above the limit of the meter.

Figure 44. Photograph of the DH-48 hand-held depth integrating sampler, amber glass suspended sediment sampling bottle, the portable turbidimeter, and clear glass turbidity sample container.

The combination of turbidity and SSC measures were utilized to determine the total load of sediment that has been transported past a single location in the watershed over the water year. Because turbidity can be measured in the field using the portable turbidimeter, the field team can take as many turbidity measurements as they need. However, SSC samples must be analyzed by a laboratory, and thus, has a higher cost than turbidity measurements. Because the two are strongly related, turbidity can be used as a surrogate for SSC, once a relationship has been defined. This allows a fairly accurate estimate of total suspended sediment load based upon many turbidity measures and only a limited of number of SSC samples.

Concentration versus flow and time

The following data analysis describes the events occurring from November 1, 2003 to April 30, 2004 in Pinole Creek. Using direct observations of the flow level in combination with rainfall records, a continuous record of discharge was estimated (see Rainfall and Pinole Creek Flow section). During storm events, multiple measures of turbidity and suspended sediment concentration samples were collected in order to create a continuous record of SSC.

A total of 227 turbidity measures were taken during this time period. Turbidity ranged between 2 and 957 NTU, varying mainly in response to discharge. Many additional samples were above the 1000 NTU turbidimeter limit – during these periods water sampling for suspended sediment analysis was most essential. A total of 67 suspended sediment samples were taken. These samples ranged between 5.7 and 13,238 mg/L. The measurable turbidity and suspended sediment concentration data were plotted and found to have a linear relationship, but with some scatter (primarily based on the data point position on the hydrograph, i.e. rising limb or falling limb) (Figure 45). Based upon this relationship, a calibration equation was generated and was used to estimate time-continuous suspended sediment concentration for the study period. In other words, although the field team was not continually measuring sediment concentrations for the entire study period, we were able to "fill in the gaps" and create a record that is continuous based upon the calibration equation. When the continuous suspended sediment concentration is plotted along with continuous flow for the entire wet season, their tight relationship becomes apparent (Figures 46 and 47).

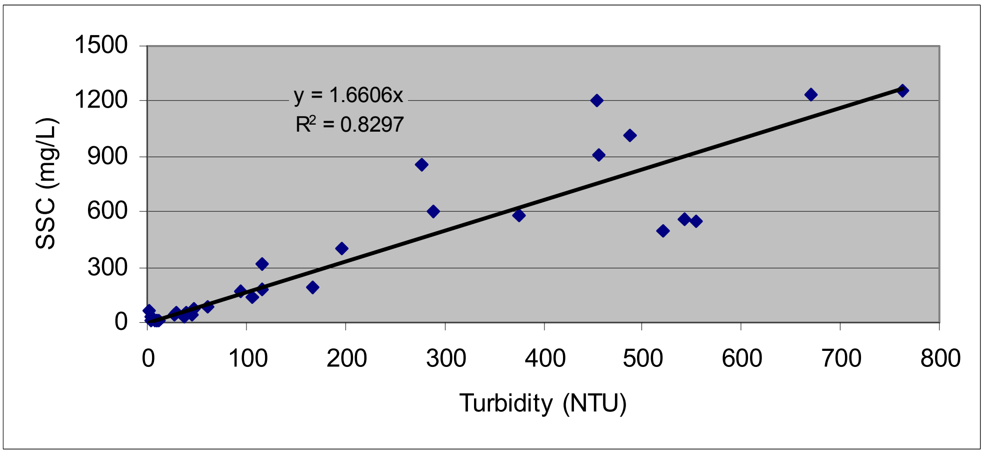


Figure 45. A plot of turbidity versus suspended sediment concentration.

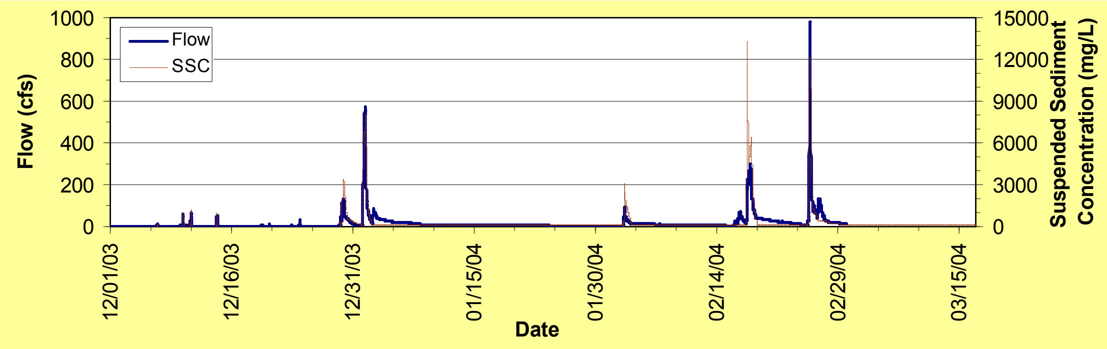


Figure 46. The variation of discharge (flow) and suspended sediment concentration (SSC) during a subset of the study period (December 1, 2003 to March 15, 2004).

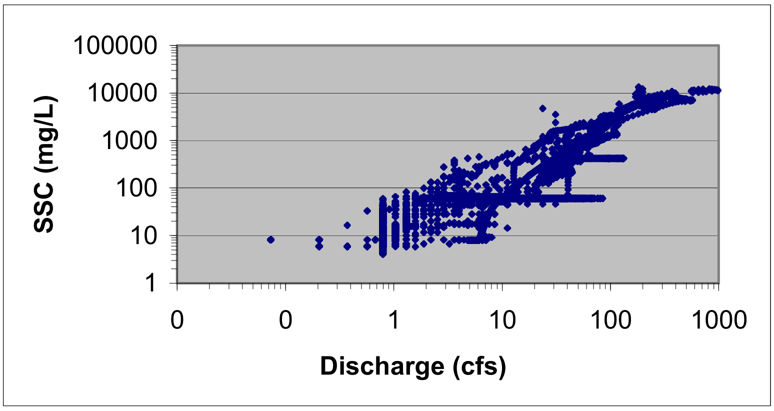


Figure 47. Discharge versus suspended sediment concentrations at the study gauge location, water year 2004.

Loads

From the continuous suspended sediment concentration data set, an analysis of sediment load transported by Pinole Creek can be made. During the period November 1, 2003 to April 30, 2004 a total of 9,964 metric tonnes of suspended sediment was transported past the gauge location (1 metric tonne = 1000 kg, or 1.102 US tons). As in many other creeks in the Bay Area, a majority of sediment transport occurs during only a handful of days. During the 2004 Water Year, the five largest storms occurred on December 29, January 1, February 2, February 17, and February 25. The sediment load reached a maximum of 284.8 metric tonnes transported in 15 minutes during the 11:30 AM to 12:30 PM hour of February 25, 2004. During that hour, 11% of the total load measured during the study was transported past the gauge location. During that day, 42% of the total load was transported past the gauge location. During these five storms, 98% of the total load was transported. An analysis of loads transported each month illustrates the effects of variable rainfall throughout the wet season (Table 8).

Table 8. Suspended sediment loads (in metric tonnes) for the study period.

Date	Nov	Dec	Jan	Feb	Mar	Apr	Total
Load (t)	1.5	333	2558	7029	31.1	11.9	9,964
% of total	0.02	3.3	25.7	70.5	0.3	0.12	100

Comparison

McKee et al (2003) conducted a literature review focusing upon sediment processes in Bay Area creeks. They found that in the nine-county Bay Area, the US Geological Survey has measured SSC in streams over the past 40 years at 26 locations. Six locations recorded peak concentrations greater than 10,000 mg l^{-1}, while another six locations measured concentrations between 5,000 and 9,999 mg l^{-1}.

Sediment transport by Bay Area creeks varies intra-annually, with most sediment transport occurring during the wet season's increased precipitation and runoff. McKee et al (2003) provide evidence that 99% of the sediment transport in Bay Area watersheds occurs during the three or four wettest months. Besides intra-annual variation, sediment transport also varies inter-annually, primarily due to inter-annual variation in precipitation totals. Annual sediment loads can vary in Bay Area watersheds from 2 to 4 orders of magnitude between dry and wet years (McKee et al., 2003). Rainfall in the Pinole Creek watershed was approximately 14% above average annual rainfall during the 2004 water year (see Rainfall section). Although there is not a perfectly predictable relationship between average climatic conditions and average suspended sediment load, as a first order approximation we suggest that the total sediment load calculated in this study is likely slightly higher than the watershed's average sediment load. The collection of only a single year of data does not allow us to make estimates of variability but it seems plausible that annual sediment load in Pinole Creek, like other Bay Area creeks, also varies inter-annually by 2-4 orders of magnitude.

Suspended sediment loads can be normalized to watershed area, to allow comparison between different sized watersheds. Sediment export coefficients (in metric tonnes per square kilometer per year) have been calculated for many watersheds in the Bay Area (McKee et al., 2003). Estimates range between 27 t km^{-2} y^{-1} for Arroyo de la Laguna near Pleasanton (Alameda County) and 1,639 t km^{-2} y^{-1} for Permanente Creek near Monte Vista (Santa Clara County). In comparison, Pinole Creek has an export coefficient of 252 t km^{-2} y^{-1}. Reid (1998) estimated sediment load from the Simas Creek tributary to Pinole Creek as 242 t km^{-2} y^{-1}. These estimates are not dissimilar to Walnut Creek at the City of Walnut Creek (368 t km^{-2} y^{-1}) and Wildcat Creek at Valle Road (in the City of Richmond) (518 t km^{-2} y^{-1}). The average for the Bay Area is approximately 100 t km^{-2} y^{-1}.

Synthesis

During Water Year 2004, a year with approximately 14% higher than average precipitation, the Pinole Creek watershed transported 9,964 metric tonnes of suspended sediment past the study gauge location. Sediment load is highly correlated with water discharge; 42% of the total load occurred on a single day, and 98% of the load occurred during the 5 largest storm events of the season. Pinole Creek has a relatively high suspended sediment concentration, similar to measured maximums found at only six other creeks in the Bay Area. This is likely due to the large inputs of sediment from landslide, gully, and land use sources. It appears that landslide sources dominate in terms of volume supplied, as well as in consistency of supply. However, land use-related sources, including gully formation, have been supplying a steadily increasing proportion of the total supply over the past 180 years. In combination with the current higher intensity land uses, precipitation that falls in years wetter than 2004 will likely trigger more landslides, thus contributing an even greater amount of sediment to the creek. Pinole Creek will likely continue to have high sediment loads in the future because its load is sourced from both the multiple naturally triggered landslides, and the historic and current land uses. However, the total load can be reduced by implementing management actions that control land use-related sources. Without these actions, consequences of an increased fine sediment load include aggradation of the flood control channel (decreasing flood conveyance), or increased pool deposits and increased gravel embeddedness (both decreasing habitat value and likely elevating phosphorus concentrations in the creek).

WATER QUALITY

Introduction

Nitrogen and phosphorus are biostimulatory nutrients. This means that when they occur in the environment in amounts in excess of natural conditions, they are likely to change the rate at which plants grow and the way in which plants compete with each other for space and light. This is a benefit to farmers who use fertilizers to improve crop productivity. However, farming systems typically range in fertilizer efficiency from about 10-30% in animal production systems to 50-70% in cropping systems. It is typical that 10-20% of the total applications of nutrients to agro-ecosystems are lost to the local creek. In addition, nutrients can enter the creek from sources other than the adjacent agricultural land including lawn and garden fertilizer runoff, leach effluent from septic sewage disposal, illegal dumping, sediment erosion, and runoff from confined animal facilities such as horse paddocks and pastures. The forms of nutrients that enter the creek can vary depending on the source. Generally, nitrate, ammonia and phosphate compounds stimulate plant growth the most and that is why they are applied as fertilizers; whereas organic forms such as urea have to mineralize before becoming “bioavailable”. Plants that are present in creeks responds to the larger supply of nutrients just as the crops of the adjacent agricultural systems do – the plants grow faster and compete with one another for space and light. This can lead to higher densities of grasses, reeds and shrubs that can choke up the creek slowing water flow, decreasing dissolved oxygen, increasing sediment deposition, and providing a source of loose vegetation debris that can catch on bridges and other structures during floods. Nutrients can also stimulate the growth of algae, and sometimes the even more undesirable blue-green algae species that can release toxins poisonous to fish, animals, and humans. The excessive stimulation of plant and/or algae communities in aquatic environments is termed eutrophication and is the leading cause of water quality problems in the United States. Residents of Pinole Creek watershed have highlighted nutrient-related water quality as a key concern.

Methods

Our goal was to characterize nutrient concentrations in a number of locations in the watershed over the winter, spring and summer seasons. Water samples for nutrient analysis were collected at 11 locations on Pinole Creek and several tributaries (Figure 48) on January 8th, April 28th, and July 22nd, 2004. These sample locations correspond to the 11 previous benthic macroinvertebrate (BMI) sample locations of the Contra Costa County 2002 Rapid Bioassessment Project (Cressey and Sommers, 2004). Each sample was taken using a sample-rinsed 2-liter bottle that was dipped into the creek in the middle of the channel either within or just downstream from a riffle. Part of the sample was filtered in the field to take out all large particles that would interfere with the laboratory analysis of the dissolved nutrient forms. Quality control included field duplicates and Milli-Q™ purified water field blanks. Samples were kept on ice during the field day and taken to the San Francisco State University Romberg Tiburon Center laboratory on the same afternoon. Samples were analyzed for nitrate, nitrite, ammonia, phosphate, total dissolved nitrogen and total dissolved phosphorus using standard calorimetric methods with appropriate laboratory quality assurances (see Appendix for details).

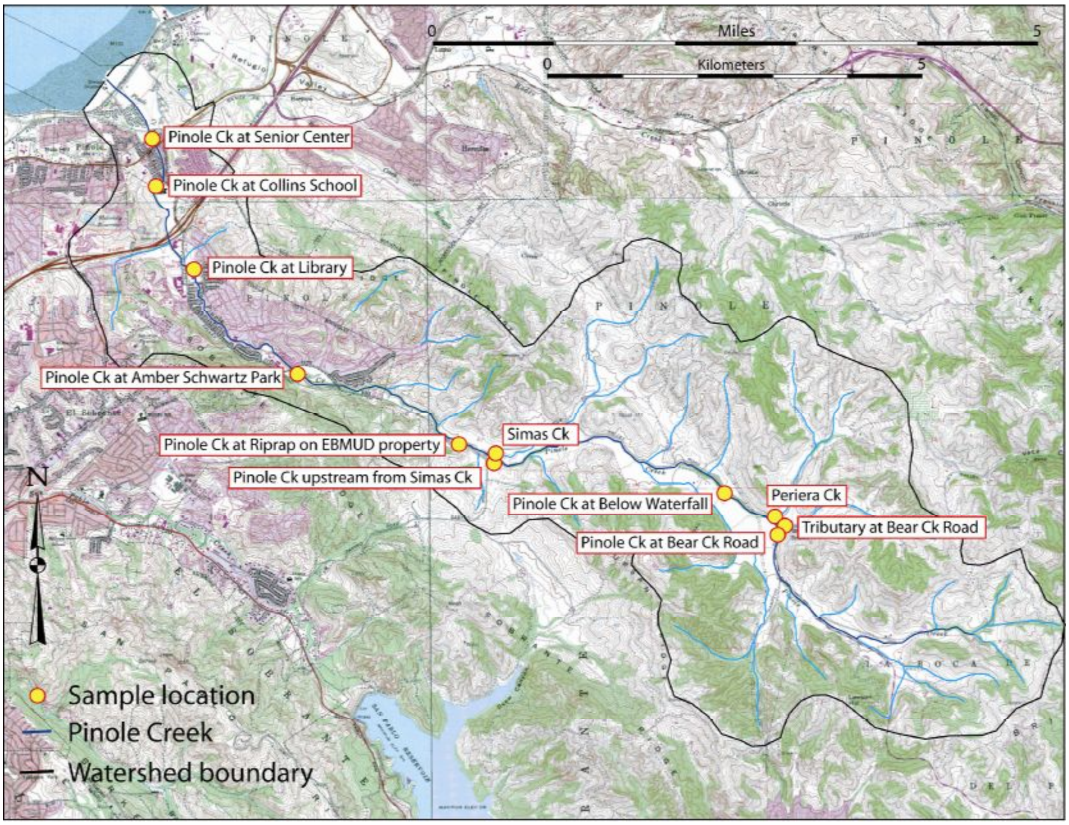


Figure 48. Map illustrating the 11 water quality sample sites in the Pinole Creek watershed.

Nitrate and nitrite concentrations

Comparing among seasons, nitrate concentrations were greatest during January throughout the entire watershed. Nitrate concentrations were greatest in Simas Creek and in Pinole Creek at Bear Creek road. With the exception of Pinole Creek at the library, nitrate concentrations decreased systematically at all locations from January to April to July. Nitrate concentrations were below detection (effectively zero) at Pinole Ck. @ Collins School, Pinole Ck. @ Riprap on EBMUD property, and Pinole Ck. @ Bear Ck. Road during July. Pinole Ck. @ Below Waterfall and Periera Ck. were also near detection limits. Nitrite was generally low in the watershed.

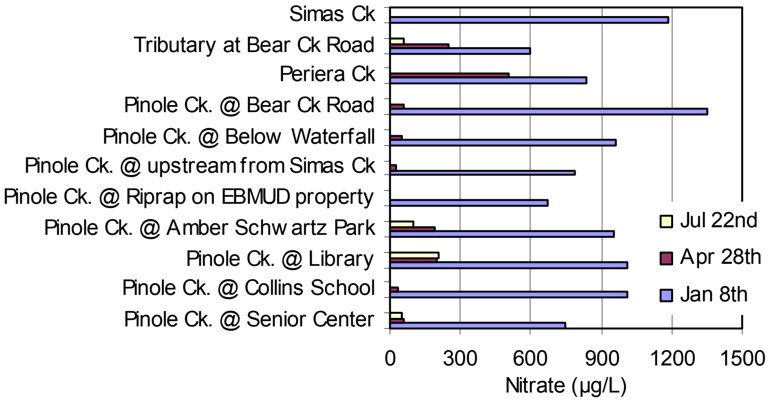


Figure 49. Nitrate concentrations in Pinole Creek, 2004. Samples are organized with the three tributary samples located at the top, and the remaining samples organized upstream to downstream.

In a similar manner to nitrate, nitrite decreased in concentration from January to July, with the exception of the tributary at Bear Creek Road. In general, these observations are consistent with non-point source runoff during the wet season, diminishing contributions from groundwater inputs, and increasing instream plant and algae productivity taking up nitrate and nitrite through the spring and summer. This is further supported by the examination of the proportion of total dissolved nitrogen that is inorganic. In January, on average, 53% of the nitrogen in streams was inorganic mineral nitrogen (nitrate, nitrite, and ammonia). Inorganic nitrogen gradually decreased so that by July only 11% was inorganic or directly bio-available. Dissolved organic nitrogen consists of metabolic waste, cell material, amino acids, proteins, tanic acids, and other dissolved nitrogen compounds associated with the breakdown of organic matter. It is typically not bio-available because it requires an intermediate mineralization step before it can be re-incorporated back into a cellular metabolic process –think of it as good nitrogen in storage.

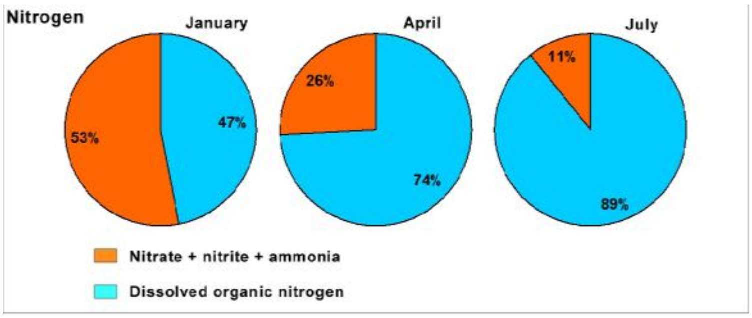


Figure 50. Proportions of inorganic versus organic nitrogen in Pinole Creek.

The nitrogen supply to the creek is likely associated with non-point source surface runoff in the winter, and groundwater discharge during other times of the year. These supplies may be exacerbated by soil erosion, low-level fertilizer use, livestock and manure management, or septic tanks. The soils in Pinole Creek watershed generally have poor properties for septic tank filter fields either because of shallow depth, slow permeability or seasonally high water tables. With care, septic systems can be designed and maintained to deal with these issues. However, poorly maintained septic systems may be exerting some influence at all locations throughout the watershed during the wet season. Elevated nitrate and nitrite concentrations at Bear Creek Road and Periera Creek during the April sampling may also be associated with septic tank runoff. In addition, both of these tributaries have horse boarding facilities that likely supply nutrients.

Ammonia concentrations

In general, ammonia concentrations also decreased from January through July. The patterns, however, were more complex than for nitrate or nitrite. Two locations within Pinole City limits showed a unique pattern. Pinole Creek at the Senior Center exhibited

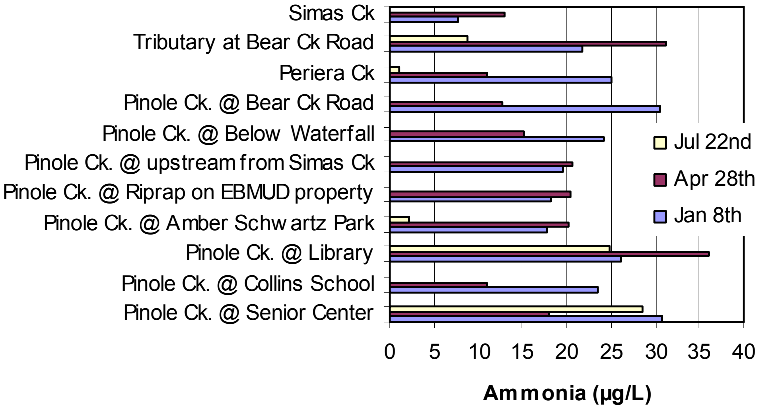


Figure 51. Ammonia concentrations.

a maximum concentration of 31µg/L in January and decreased to 16 µg/L in April before increasing again to 29 µg/L in July. Pinole Creek at the library exhibited a maximum ammonia concentration of 36 µg/L in April and similar concentrations in January and July (~25 µg/L). In a similar pattern to nitrate, ammonia was below detection (effectively zero) at Pinole Ck. @ Collins School, Pinole Ck. @ Riprap on EBMUD property, Pinole Ck. @ upstream from Simas Ck., Pinole Ck. @ Below Waterfall, Pinole Ck. @ Bear Ck. Road, and Pinole Ck. @ Bear Ck Road during July. Concentrations were also near zero at Tributary at Bear Ck. Road. The tributary at Bear Creek Road showed an elevated concentration of both ammonia and nitrite in April.

These patterns suggest several sources of ammonia in the watershed. It is hard to reconcile the specific causes of each observation but the following general statements appear to apply. During the winter, ammonia in the creek and tributaries is likely sourced from diffuse surface runoff associated with livestock, lawn and garden fertilizers, pet manures, and decaying garbage and leaf litter. It is unlikely that ammonia is present in groundwater because nitrification (the conversion of ammonia to nitrite+nitrate) usually occurs in oxygenated shallow ground waters and within the soil profile. During April and July, the unique patterns observed in the town reach may be associated with the use of ammonia-based detergents in commercial businesses and urban areas adjacent to the creek (maybe car washing and lawn and garden irrigation overflows). In addition there might be ammonia associated with the breakdown of plant material that is present in the Creek at these locations. The unique pattern on the tributary at Bear Creek Road is suggestive of an unknown ephemeral point source. At other locations upstream from the city limits, diminishing concentrations through the dry season are probably associated with diminishing supply of ammonia to the creek and uptake by aquatic plants in a similar fashion to nitrate and nitrite.

Phosphorus concentrations

The patterns of phosphorus concentrations differed greatly from those of nitrogen. Phosphate concentrations were greatest at some locations during April and at others during July. In general, locations on Pinole Creek and its tributaries upstream of Simas Creek exhibited greater concentrations during all seasons than downstream of Simas Creek. The exception was Pinole Creek at Bear Creek Road – phosphate concentrations at this location were the least of any location during all seasons.

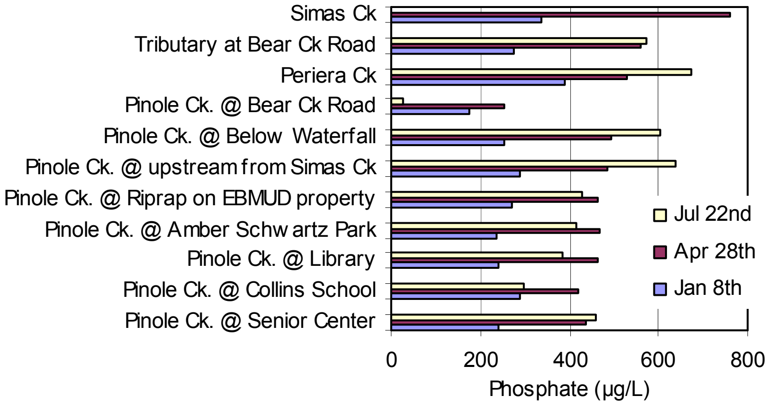


Figure 52. Phosphate concentrations in Pinole Creek.

It is difficult to explain the patterns of phosphate in the Pinole Creek watershed. It is clear that diffuse surface runoff of phosphate during the wet season is not a dominant mechanism of supply. Further evidence of this is gained by examining the proportion of total dissolved phosphorus that is in inorganic mineral form (phosphate). During the wet season phosphate makes up an average of 87% of phosphorus in the creek. This gradually diminishes through spring (73%) and into summer (66%). This tells us that as the concentrations increase in the creek, the biota that live in the creek cannot assimilate all the phosphorus, or putting it simply, plants and algae growth cannot keep pace with the supply.

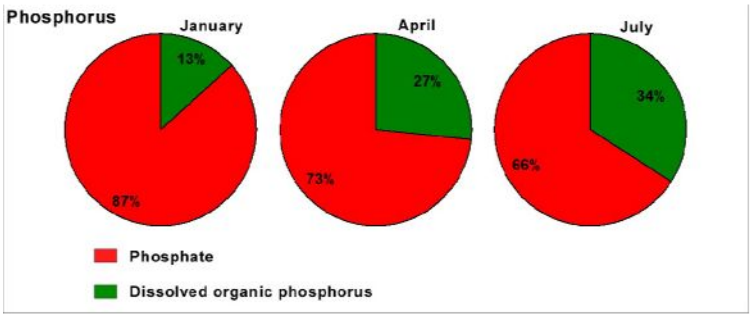


Figure 53. Proportions of inorganic versus organic phosphorus in Pinole Creek.

Although there are undoubtedly unique sources for each location, we propose the following processes of phosphorus supply to the creek and tributaries of Pinole Creek watershed. During the wet season, new soil material is washed into the creek, mainly in areas where landslides have close connection to the creek. Bulk soil is not particularly enriched with phosphorus when in place on the hillslopes. However, when surface runoff and erosion occurs during rainstorms, fine particles that are disproportionately enriched relative to the bulk soil are more easily transported to the creek. This soil material contains organic and adsorbed (particulate) phosphorus. Once in the creek, this soil material gradually releases phosphate through the dry season causing the patterns observed. Patterns of phosphorus adsorption and desorption from creek sediments in Hoxie Gorge Creek, NY, have been explained by changes in pH and changes in anion concentration (in particular, carbonate) (Klotz, 1988) (also see Sharpley and Menzel, 1987). Desorption appears to occur when creek water pH is maintained outside of pH 5.5-7.5. It is possible that groundwater entering Pinole Creek during low flow with low phosphorus concentration and a pH outside of this range, causes desorption of phosphorus from fresh stream sediments. This process maintains elevated phosphate concentrations throughout the dry season and perhaps explains the relatively constant concentrations over time and throughout the stream length. These processes, however, should be treated as a hypothesis for the Pinole Creek watershed that might be proven by a focused study on uptake and release of phosphorus in bottom sediments.

Water quality guidelines

The EPA guideline in Level III Eco-Region 6 for total nitrogen is 500 µg/L and for total phosphorus is 30 µg/L. During our study 100% of our sampling locations exceeded both the nitrogen and phosphorus guidelines on at least one occasion. During the April sampling, 4 out of 11 locations exceeded the EPA nitrogen guideline and during the July sampling only Pinole Creek at the library exceeded the nitrogen guideline. In the case of phosphorus, all samples, no matter which part of the season, exceeded the EPA guideline. Although excedance of a guideline does not necessarily coincide with degraded stream health, these excedances do help to suggest that in-stream productivity in this watershed is generally not nutrient limited for most of the year. It is therefore paradoxical that the most vulnerable reaches in the watershed (areas of slow water and the lower reaches near and within the tidal limit) are not supporting occasional or periodic algal blooms. We did note some areas with increased stream vegetation such as at Pinole Creek at the Senior Center (Figure 54), and to a lesser extent, Pinole Creek behind Collins School. In general however, we do not find any reaches where the extent of eutrophication is excessive or worrisome.

Synthesis

Nitrogen concentrations found in Pinole Creek are not atypical in the Bay Area. For example, average nitrate concentrations in the Sonoma Creek and Napa River watersheds were ~650 and ~620 µg/L respectfully compared to ~380 µg/L under similar flow and sampling conditions in Pinole Creek (McKee and Krottje, 2004). In contrast, phosphate concentrations in Pinole Creek were much greater (compare ~400 µg/L in Pinole Creek to ~60 µg/L and ~45 µg/L for Sonoma and Napa respectfully). Neither the Sonoma Creek nor Napa River watershed streams were limited in their primary productivity by either nitrogen or phosphorus. Pinole Creek in contrast appears to be nitrogen limited (this is not common in freshwater environments). It appears that the maintenance of acceptable water quality is in fact due to relatively low nitrogen concentrations compared to phosphorus concentrations, and seasonal nitrogen limitation. The very high phosphorus concentrations should not be considered a primary concern, whereas maintaining low nitrogen loads to the stream should be considered high priority.

Figure 54. Pinole Creek at the Senior Center, July 22, 2004.

SYNTHESIS

Drawing upon the findings and observations collected during this study, this synthesis section paints a broad picture of our current best understanding of the watershed, its functioning, and dominant processes. First, we begin by presenting a conceptual model for the watershed and its flood control channel. The conceptual model is intended to acknowledge and highlight each of the processes we have identified, and illuminate the relationships between them. It necessarily includes all sediment sources, processes, storage areas, and transport in each part of the watershed, even if we were not able to quantify all of these with field work. Second, we present a sediment budget for Pinole Creek based on our conceptual model. The sediment budget is comprised of two parts, Pinole Creek upstream of I-80, and the flood control channel downstream of I-80. Developing the conceptual model and sediment budgets are prerequisites for formulating management actions and plans.

Sediment budgets are simple mathematical models that provide an understanding of the relative magnitudes of inputs, outputs and storage within defined systems (in this case Pinole Creek and the flood control channel). They are the algebraic versions of our conceptual models, and systematically organize the many disparate elements of our conceptual understanding into a system scale evaluation of the relative influences of humans on watershed processes and functioning. Sediment budgets also organize the magnitude of as many terms as practical or necessary to provide us with answers to our questions. Just like balancing a checking account (Income - Expenditure = Savings), a sediment budget follows a similar equation:

$$\text{Input} - \text{Output} = \text{Storage} \pm \text{Balance} \pm \text{Error} \qquad (1)$$

The Error term is the sum of all the errors of measurement or estimation of each budget term and is the primary reason why it is often difficult to balance a sediment budget. The Balance term accounts for all volume that was not measured or assigned directly, or terms that were estimated, but thought potentially biased high or low.

Sediment budgets can be prepared at a range of scales (e.g. the parcel scale, the sub-watershed scale, or the watershed scale). Each increase in scale usually entails greater assumptions associated with temporal and spatial heterogeneity of the system – a bigger and bigger black box. For example, a sediment particle that erodes from a hillslope far up in the watershed can move down slope under the influence of water and gravity and come to rest (go in to temporary storage) many times before it is either transported out of the system or permanently buried (stored) somewhere in a depositional area (e.g. a fan or terrace deposit). Our black box sediment budget relies on the untrue assumption that in any one year the watershed is completely connected in space and time. We reduce the influence of this assumption by averaging all our budget terms over a period of a decade or more, the time period over which we assume that spatial and temporal connection is more likely. Thus, a budget describes the “average conditions” and average natural and human influences on sediment. It is important to recognize that the black box problem is outweighed by the way a sediment budget forces a reconciliation of errors or unquantified terms. This reconciliation is the most powerful function of a sediment budget. Thus a sediment budget not only provides us answers to our questions but also provides us with questions that might require further study to answer.

Pinole Creek watershed sediment processes conceptual model

The Pinole Creek watershed and its flood control channel contain a large number and variety of sediment sources contributing to the sediment load stored and transported by the creek. Our conceptual understanding of the geomorphology of the Pinole Creek watershed is illustrated in a graphical model (Figure 55). The model is inclusive of all processes that are or might be occurring in the watershed. During field study we did not attempt to quantify some processes that we thought would be minor such as sediment stored in livestock ponds, sediment erosion and runoff from urban areas, sheet and rill erosion, and soil piping. However, floodplain and high terrace deposits, and hillslope alluvial fan sediment storage are potentially major terms that were not quantified in the field. This is the first issue that adds complexity to balancing the budget, and will be discussed later.

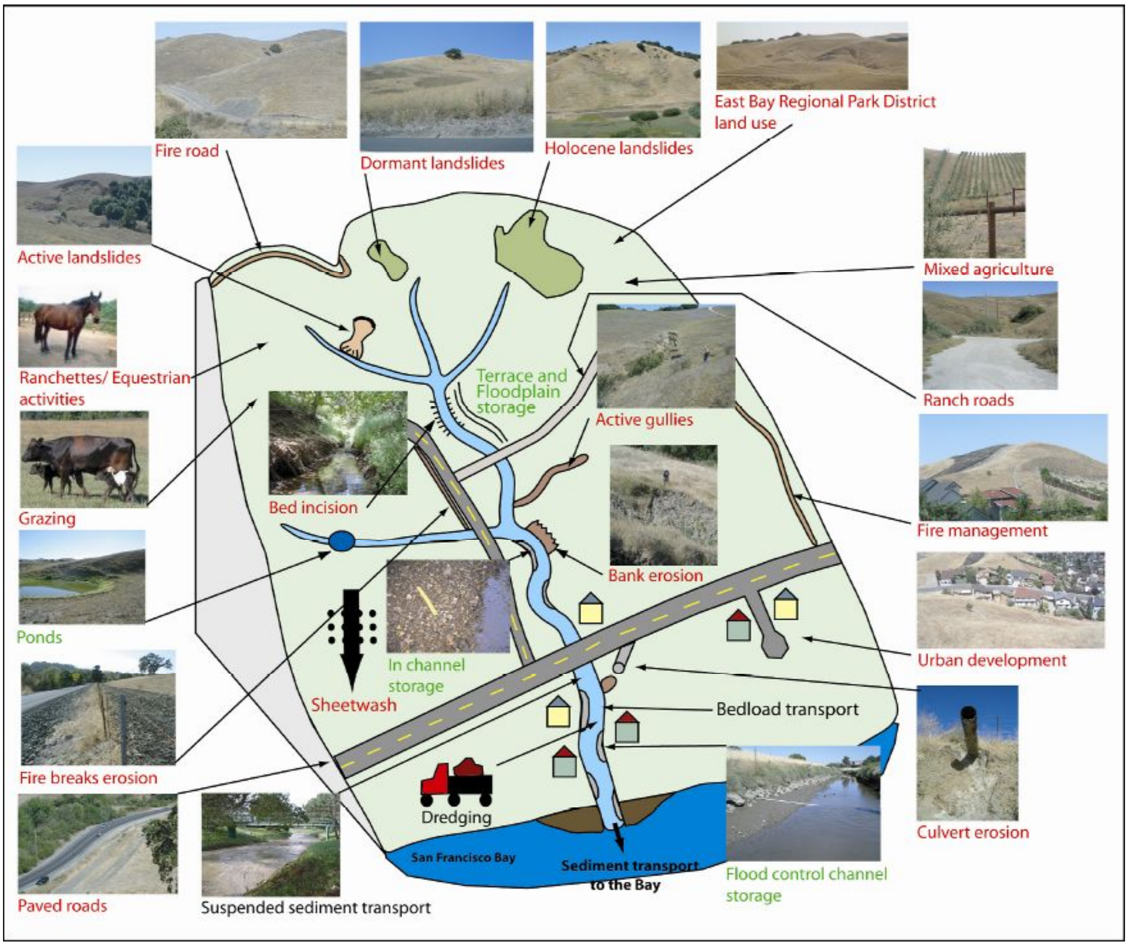


Figure 55. Conceptual model of sediment processes occurring in the Pinole Creek watershed. Red labels represent sediment sources, green labels represent sediment storage sites, and black labels represent sediment transport or removal processes.

A noticeable feature of the model is the number and diversity of sediment sources. These sources can be divided into four main categories: hillslope supply, land use-related supply, road related supply, and in-channel supply. Despite the diversity in location and process, most of these sources are either directly caused by, or are aggravated by, human activities, land use, or land management. Of the total amount of sediment that is supplied, some portion remains in temporary storage (for instance, in fluvial bars, terraces, or livestock ponds) while the remaining portion is transported out of the watershed. The storage locations act as a sediment supply buffer, by capturing the supplied sediment and then releasing it over time or storing it permanently. This illustrates the importance of averaging a sediment budget over a sufficiently long period of time to smooth out the differing temporal and spatial variations in each of the source, transport and storage terms. This is another reason why it is difficult to balance a sediment budget. Sediment that is transported out of the watershed is represented by suspended load, bedload, and dredging, with a majority of the total transported in suspension. Herein lies a third issue that adds complexity when trying to balance our sediment budgets. Sources of sediment supply often supply sediment with different grain size characteristics compared to sediment in storage or sediment in transport. In fact, some sediment is transported out of the system via dissolved mineral salts and in some systems this has been shown to account for a substantial load (Webb and Walling, 1982). We did not directly quantify sediment bed load or solute load with fieldwork in the Pinole Creek watershed.

Quantification of the terms in the sediment budgets

Using our conceptual model of the Pinole Creek watershed sediment processes, we have developed equations (2) and (3) below to constrain our Pinole Creek and flood control channel sediment budgets using a normalization (averaging period of 50 years). Climate in the Bay Area is highly variable year to year and decade to decade (see the Rainfall and Pinole Creek Flow section). The Bay Area goes through successive periods of dryer than normal years and wetter than normal years. The recent climatic record suggests that a minimum period of 30 years is needed for a watershed to experience even 90% of its range of climatic forcing. The influence of climatic forcing on the watershed is supported by our field observations of the age and stability of bars, terraces, landslide deposits, and erosional surfaces. After initial failure, many landslides continue to supply sediment to Pinole Creek or its tributaries for multiple decades. In addition, many of the gullies have formed over periods of decades to 50 years or more. Not discounting land use change as a forcing factor, the time scales of processes inside our budget model demand an averaging period of at least 30 years and more appropriately 50 years. Catastrophic events such as a large landslide failure or a long drought period would bias the model if a shorter time period was chosen.

Pinole Creek (2)

Holocene + Dormant + Active + Gullies + Roads + In-channel + Urban
–
Landslide deposits – Fans – Ponds – Bars – Terraces
=
Supply to flood control channel ± Balance ± Error

Flood Control Channel (3)

Supply to flood control channel ± error
+
Channel erosion and incision
–
Aggradation – Dredging
=
Sediment transport to the Bay ± error

Where:

Holocene = Holocene landslides
Dormant = Dormant landslides
Active = Active landslides
Gullies = Active gullies
Roads = Input from paved roads, ranch roads, fire trails, and fire breaks
In-channel = Input from in-channel sources, including bank erosion and bed incision
Urban = Input from urban (commercial and residential) areas
Landslide deposits = Material disturbed by a slide, but remaining in storage on the hillslope
Fans = Hillslope colluvium stored in alluvial fans
Ponds = Sediment trapped by livestock ponds
Bars = In-channel sediment storage in bars, active channel deposits and pool deposits
Terraces = Storage in larger, older, more stable terrace deposits
Channel erosion and incision = Bank erosion and bed incision occurring in the flood control channel
Aggradation = Channel bed aggradation (build-up) occurring in the flood control channel
Dredging = Removal of sediment via dredging activities in the flood control channel

Landslide sediment sources

Data for determining this term in the budget was gathered during our field studies and described in detail in the Landslides, Gullies, and Surface Processes section of this report. Dormant and Holocene landslide inputs were set to zero on the basis that they did not supply sediment to the Creek over the past 50 years (at least not an amount greater than the errors around our other input terms). Given that in-channel sediment is very dynamic and is cycled over time periods of <<50 years, any sediment supply to the creek channels prior to 50 BP (years before present) would have a minimal influence on the channel storage and transport characteristics of today. To derive the term used in the budget, we subtracted the average volume of material stored in active landslide deposits from the total volume disturbed, giving us the volume of material transported away from each active landslide location. This volume was then averaged over a 50-year time period. Although landslides are highly variable throughout the watershed, we made the assumption that all landslides behave similarly to those that were field checked. For landslides that were not field checked we estimated volumes by assuming a similar average depth and a similar average percentage of material stored. The error associated with mapping landslide area is likely to be about ±20%. The error for depth calculations is likely ±20% due to variability of individual slides. Therefore the error associated with volume estimates is approximately ±40%. There was also an error associated with our estimation of storage in landslide deposits; although errors for smaller slides are greater than that for larger slides, we suggest that overall an error of 51% is appropriate. We estimate 33,864 ± 17,271 m^3/yr of sediment is transported to the creek by active landslides.

Gully sources

Data for gully sources was also collated from the Landslides, Gullies, and Surface Processes section. As with landslides, the average volume remaining in storage within gullies was subtracted from the total volume disturbed. The remainder is the volume of sediment supplied to the fluvial system. We then averaged this value over a period of 50 years. Because of the difficulty of digitizing small irregular features, most of the gully areas are overestimated, likely by 10%. In addition, the amount of material in storage is highly variable, and likely has an error of ±50%. We estimate 9,369 ± 4,778 m^3/yr of sediment is transported to the creek by gully erosion and transport.

Road sources

Data for all road types (paved, ranch, fire trail and fire breaks combined) was collated from the Landslides, Gullies, and Surface Processes section. Because of the methodology used, the erosion was already presented as an amount per year. Thus we did not have to manipulate the data any further. However, three assumptions were made. We assumed that the road portions we observed in the field were a representative subset of all roads in the watershed. In addition, we assumed that all existing road segments were visible on the 2000 photos, and thus were included in the length calculation. We made a third assumption that 50% of the sediment sourced from the roads was supplied to the fluvial system. This final assumption is the source of most of the error and could potentially range from 20 to 80%. This is equivalent to an error of 60% about our estimated volume. Other more minor errors include limited observation of road segments. We estimate 10,758 ± 6,455 m^3/yr of sediment is transported to the creek from roads.

In-channel sediment sources

In-channel sediment sources, including bank erosion and bed incision data were collated from the Channel Processes section of this report. Note that this data describes the sample reaches and not the entire channel length. Using the USGS 7.5′ topographic quadrangle maps, the total channel distance (not included in sample reaches) was measured. Using the field data, we extrapolated the average amount of bank erosion per meter of channel to the adjacent unmeasured channel length. Tributaries not characterized by a sample reach, or those that were mapped as gullies were not included. These extrapolated volumes were then averaged over a 50-year time frame, based upon maximum age estimates of the indicators of erosion. In other words, our field observations of bank erosion activity are based upon indicators such as tree roots, hanging fence posts, etc., producing maximum ages, or the oldest reasonable year that the bank erosion began (in this case, 50 years). Since these erosion processes are episodic through time, we divide our estimated volume by 50 years, to attain a long-term average of sediment contribution to the creek. We also extrapolated measured bed incision between sample reaches that contained indicators of incision. These volumes were also then averaged over a 50-year time frame. This method assumes that data collected in sample reaches is representative of unmeasured reaches – qualitative field observations and experience in other nearby watersheds suggest this is a reasonable assumption. The measurement is likely biased slightly low because channel meander and channel initiation points are not very well represented at the 1:24,000 scale of the US Geological Survey maps; however, we made no adjustment for this bias. In addition, the average amount of erosion measured in the field is likely underestimated because erosion is based only upon still-present indicators of erosion. Overall, we estimate an error of 20% and a possible low bias of 2-5%. Taking into account these factors and methodology, we estimate a volume of 779 ±155 m^3/yr (382 m^3/yr of bank erosion and 397 m^3/yr of bed incision) for in-channel sediment sources.

Urban sediment supply

The supply of sediment from urban sources was not measured in the field, but instead was estimated using values published in the literature. The total urban area in the watershed (709 ha) is obtained from the Contra Costa County Watershed Atlas (2003). Based upon a review of urban literature, sediment supply from urban areas is likely to be approximately 222 kg/ha/yr but could be anywhere between 140 to 320 kg/ha/yr (Cordery, 1977; Australian Water Resources Council, 1981; Letcher et al., 1999). To derive the urban supply, we multiplied the urban area by 222 kg/ha/yr and made a unit conversion from kg to m^3 by dividing by 529 kg/m^3. This estimate makes the assumption that the Bay Area and Pinole urban area is similar to other urban areas. Our experience in the Guadalupe River watershed and the City of San Jose suggests this might be a reasonable assumption. Based upon this methodology, a volume of 298 m^3/yr (with a range of 188 to 429 m^3/yr) of sediment input from the urban areas of the watershed was obtained.

Livestock ponds

Livestock ponds were estimated by tracing the ponds visible on the 2000 aerial photographs, and then calculating the total area in ArcView. A total of 13 ponds were identified, for a total of over 188,000 m^2 (2,023,615 ft^2). Most of these ponds were built in the early 1900s; we assumed the average pond is 80 years old. An average sedimentation rate of 5 mm/yr was estimated. We multiplied the total pond area by sedimentation rate to determine the total sediment trapped in these ponds. This assumes that sedimentation rate is constant over the entire pond surface and through time, and is similar between sub-basins with different land use effects. This also assumes an age for each individual pond, and assumes that storage is permanent, although dam breaches or gullying can liberate sediment from this storage location. The error from area calculation is likely low, most ponds will only vary in age by 10 to 15 years, and sedimentation rates can vary from 20 to 50%. We suggest an overall error of ± 20%. This methodology gives a volume of 940 ± 188 m^3/yr for sediment storage in livestock ponds.

Bars and terraces

In-channel sediment storage data, including bars, active channel deposits, pool deposits and young terraces, was collated from the Channel Processes section. Using the calculated total channel length (used in the estimation of in-channel erosion sources), the data collected in sample reaches was extrapolated to the entire channel length. The total in-channel sediment deposits are the sum of the extrapolated total and the sample reach total. This total is then averaged over a 50-year time period. This assumes that sample reaches are representative of sediment storage throughout the channel length. Based upon our observations of the creek, we believe that sample reach storage is representative. This also assumes that our measurement of storage was correct; in reality it was likely underestimated because we tend to be conservative. The total storage is 399 ± 320 m^3/yr. However, our methodology only quantifies “active” sediment, thus, many of the higher, older, more stable terrace deposits are not included in the total, yet have been deposited in the last 50 years. We assumed a terrace with dimensions of 1 m in thickness and 5 m in width extending along both sides of the channel for the entire channel length. This approximation, based upon qualitative observations, has a low accuracy of ± 80%. This terrace deposit adds a further stored sediment volume of 3,564 m^3 ± 2,851 m^3/yr.

Flood control channel

Analysis of the flood control channel is based upon three sources of data, 1965 “as-built” channel drawings, 2003 Urban Creeks Council channel surveys (both obtained from Drew Goetting, pers. comm.), and our 2004 data collection in sample reaches 0, 1 and 2 (data described in the Channel Processes section). Estimates of dredging activities were collected via personal communication with the County Public Works Department. A series of 31 channel cross-sections originally surveyed in 1965 were re-surveyed in 2003. For each location, the change in cross-sectional area was determined for the 38-year period. These data were multiplied by the distance between the sections to determine the change in net volume in the flood control channel. Note, that some areas of the channel showed net degradation; however, overall there was net sediment accumulation. Average annual volume change was determined by dividing the net change by 38 years. We assume that the cross-sections were correctly surveyed both times, and that the 2003 surveys were in the same locations as the 1965 surveys. We also assume that the channel cross-sections adequately represent the whole channel length. Because the data quality appears high and appropriate survey techniques were utilized, we believe that the error is low, likely ± 10%, primarily due to channel variability. This methodology gives a volume of flood control channel net aggradation of 335 ± 33 m^3/yr and net erosion of 27 ± 3m^3/yr.

Pinole Creek and flood control channel sediment budgets

The volumes associated with each of our terms were combined to form our sediment budget for Pinole Creek and the flood control channel (Figure 56 A and B). The width of each of the arrows and compartments within the budget diagram represents the relative volume supplied or lost for that term. Active landslides are the largest input to the fluvial system. Based on our estimates of the 50-year average, about 61% of the sediment supply to Pinole Creek is associated with active landslides. Gullies and paved roads contribute 17% and 14% respectfully. All the other input terms are less than 5% individually and collectively account for the remainder of the inputs to the Pinole Creek channel (8%). The creek channel presently stores only about 1.5% of the sediment it receives, but we believe a further 13.5% is stored in high terraces that are now largely isolated from floods because of incision. These are only being reworked by the channel in areas were lateral erosion or severe bank collapse is occurring. On average for the last 50 years, we believe that about 82% of the sediment supply from the watershed to the creek channel is transported to the flood control channel.

A budget for the flood control channel is also presented (Figure 56 B). On average, 99.9% of the sediment routed through the flood control channel is supplied from the watershed upstream of the flood control channel. Bank erosion and bed incision in the flood control channel are subordinate. Presently 98.5% of the sediment entering the flood control channel is flushed out of the system on average. These results appear to be consistent with qualitative observations made by the local community.

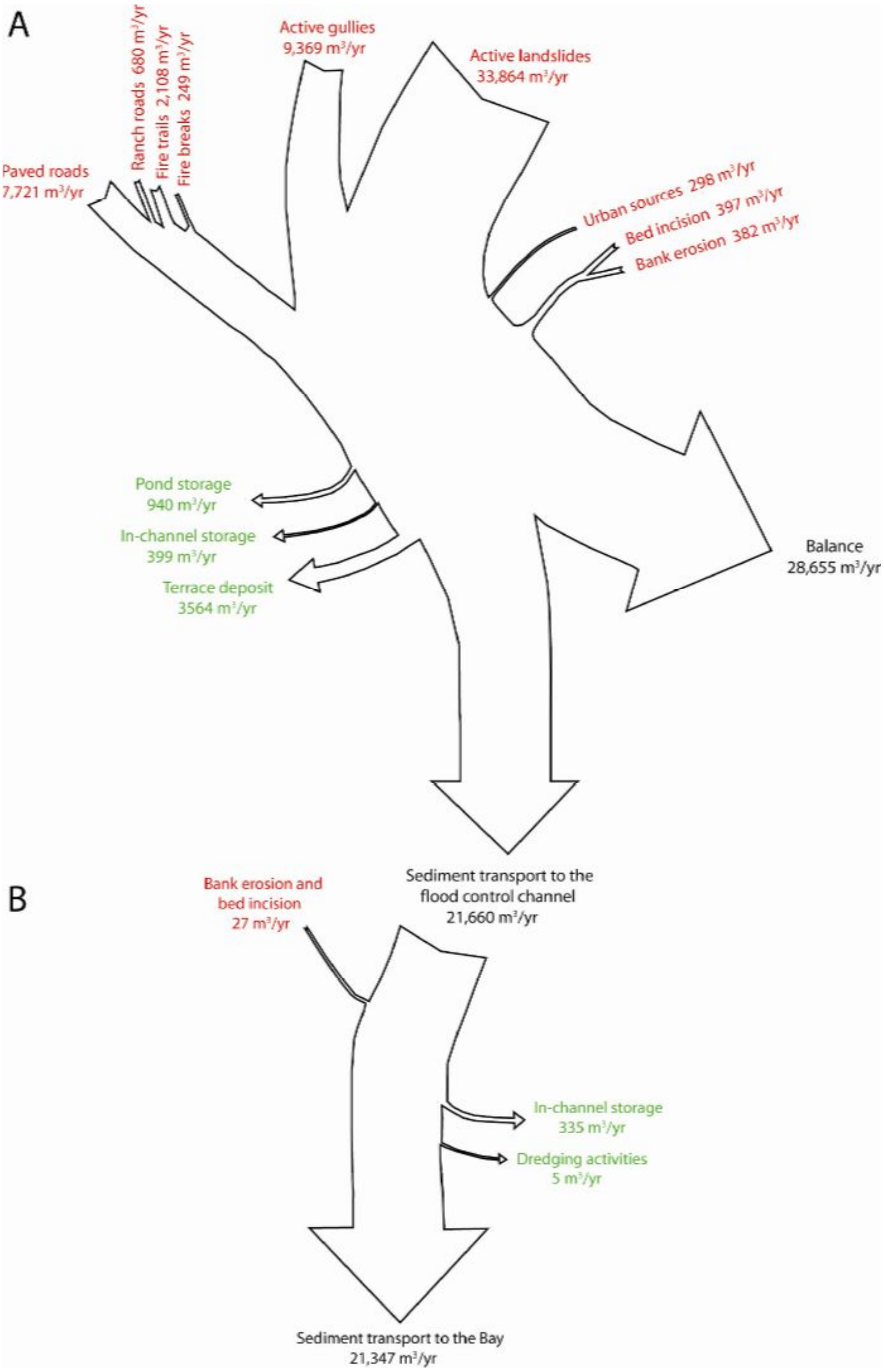


Figure 56. Graphical sediment budgets for Pinole Creek (A), and the flood control channel (B). Sediment sources are labeled in red, and sediment storage is labeled in green.

Discussion and implications for the Pinole Creek sediment budgets

Developing sediment budgets is a tricky exercise at best, partly because of the errors associated with the estimation or measurement of each term and partly because of the differing temporal scales of each process and term. Sediment budgets can be developed with different focuses (Reid and Dunne, 1996). For example, budgets designed to answer questions about topsoil erosion will focus on the erosion, storage and transport of sediment off hillslopes, and only estimate stream loads and net basin yields by difference (e.g. Nolan et al., 1995) In this study we have developed a sediment budget that is channel-centric; the Pinole Creek watershed stakeholder concerns relate to the sources of sediment to the channel and the processes of storage and transport of sediment through the channel and through the flood control channel. Therefore, our fieldwork and lab work were focused upon supply of sediment to the channel and in-channel processes, rather than on the estimation of storage terms associated with hillslope processes. The net sum of these unaccounted processes are represented by the Balance term (discussed below).

Overall the budget for this watershed appears to fall within the norms of other budgets described in the geomorphic literature. For example, if we compare the sediment load delivered to the flood control channel to the total amount of erosion occurring in the watershed and drainage lines, we derive a delivery ratio of 13%. This ratio for the Pinole Creek watershed falls in the range expected (8-35%) for watersheds of this size (Novotnoy and Chesters, 1989). As a local comparison, using data from a budget developed for the 2 km^2 Lone Tree Creek watershed, Marin County (Lehre, 1981), we can post-calculate a long-term average delivery ratio of 17% for that watershed. The delivery ratio lumps the whole watershed and all of the sediment processes into a single black box and is useful for comparisons to other systems but tells us little about how management concerns might be addressed specifically in Pinole Creek watershed. The resource manager is more concerned with the relative volume of sediment supplied to/from a problem area and the reliability of that information. To address this practical endpoint, we carried out a sensitivity analysis (Table 9).

Examination of Table 9 suggests that based on our judgment of errors associated with each of the terms, the most important factors influencing creek function and supply of sediment to the flood control channel are active landslides, active gullies, and paved roads. For example, within the error bounds of each of our terms, regardless of volume estimates chosen, the volume of sediment supplied to the channel from active landslides is between 40-80% of the total sediment supply to the channel. Given the range of error, it is hard to reconcile whether active gullies or paved roads are the next most important factor. However, based upon field observations and our best judgment, we suggest that active gullies are the next most dominant impact on channel function. A multi-faceted management plan could focus on mitigating impacts of active landslides, active gullies, and paved roads, and establishing monitoring of the creek to document channel response.

Table 9. Sensitivity analysis of the relative proportion of sediment volume supplied from each source term in the Pinole Creek sediment budget.

Sediment supply terms	Average %	Min%	Max%
Active landslides	61	40	80
Active gullies	17	8.0	33
Paved roads	14	5.5	29
Fire trails	3.8	1.4	9.2
Ranch roads	1.2	0.4	3.1
Bed incision	0.7	0.4	1.6
Bank erosion	0.7	0.4	1.4
Urban sources	0.5	0.2	1.3
Fire breaks	0.5	0.2	1.2
Total	100		

The Balance term

The Balance term in our sediment budget is primarily a result of study design. Our objective was to understand how sediment and water processes on the hillslopes influence sediment and water processes in the channel and how they influence flood conveyance. Most of the volume of sediment in the Balance term is associated with sediment permanently (on the time scales relevant to management) stored on the hillslopes in the form of fan deposits. Since there is no obvious management outcome associated with the quantification of this term, we did not spend effort collecting data on the extent and thickness of hillslope colluvium stored in alluvial fans. Although the volume of storage in these fan deposits was not quantified, the deposits could be mapped using existing aerial photographs. Other potential storage locations include colluvial deposits, Holocene terraces, or in-channel sediment that is not "active", or readily available under ordinary recurrence interval floods.

The Balance term also includes errors associated with the estimation of some of our budget terms, in addition to any measurements where there could have been a bias. For example, there may have been additional storage of active landslide material that was not quantified and there might have been some bias associated with the measurement of sediment supply from paved roads that was influenced by a handful of areas showing extensive erosion. In addition, sediment storage associated with channel length was likely biased low by the use of 1:24,000 scale US Geological Survey maps which do not adequately depict channel initiation and channel meander. Although each of these areas might be addressed in future study, our sensitivity analysis suggests that better quantification of these terms will have little impact on the interpretation of the results presented and the resulting management initiatives recommended.

Inter-annual variability, channel function, and flood conveyance

The budget and information we developed does not quantify inter-annual variability, but it is worth discussing the likely influences of climatic variation on sediment supply, Pinole Creek function, and the management of the flood control channel. During very dry years most sediment that is eroded on the hillslopes would remain in hillslope colluvial storage. Very few landslides, if any, would occur, and the hillslopes would likely build up an accumulation of sediment. The channel would not make any significant changes in planform or sediment deposit structure during these dry years. Channel bank erosion would be less likely, but minor reworking of the bed would most likely continue to supply the sediment load that passes into the flood control channel. In the flood control channel, successive drier years would likely cause minor net aggradation in the flood control channel.

During wetter years, the watershed would likely respond much differently. More landslides would be likely to occur, liberating much of the sediment that had accumulated. A greater amount of sediment eroded from the hillslopes, gullies and paved roads would reach the channels of Pinole Creek and its tributaries. During major flood events, the channel would experience greater bank erosion and bed incision, and might make significant modifications to its planform or patterns of sediment storage. In the flood control channel, higher flood velocities would scour out the channel, removing sediment accumulated during previous dry years, and might even cause net erosion of the estuarine basin. We suggest that during these wetter years, although the creek would likely be carrying a greater sediment load, the large flood flows would be sufficient to flush the sediment through the flood control channel and into the Bay. Given the capacity of the flood control channel, or the maximum volume of water it can contain, a 2-year return interval flood would completely flush channel water in about 13 minutes (Figure 57). In other words, even relatively small flood events contain a large enough volume of water to flush the flood control channel fairly quickly. This suggests that climate and higher return interval floods (less-frequent floods) are capable of and responsible for maintaining the current flood control channel cross-section. In contrast, if tidal processes are responsible for the relatively stable cross-section we currently observe, climate will have little to no influence on continued flood conveyance capacity. We did not collect sufficient data during this study to determine if fluvial or tidal processes dominate maintenance (continued sediment transport so that significant aggradation or deposition does not limit flood conveyance) of the cross-sections in the flood control channel. However, if sediment load delivered from the watershed were to increase, sedimentation in the flood control channel might be increased if either tidal or fluvial flushing could not keep pace.

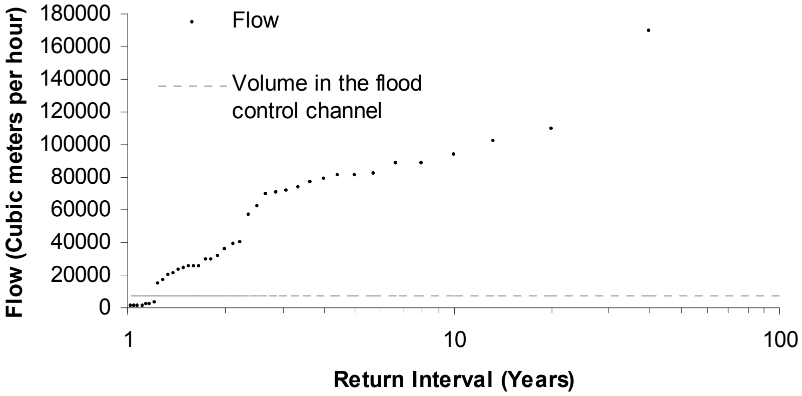


Figure 57. Plot of the return interval (in years) versus the volume of flow (in cubic meters per hour) in Pinole Creek. The volume of the tidal portion of the flood control channel is shown as a horizontal line.

This inter-annual variability has noteworthy implications for management. Managers might observe net improvements in the system over several years, only to see large declines or deterioration during other years. In a system with such a large buffering capacity on the hillslopes, it might take decades for management initiatives to be recognized as observable trends in sediment erosion and supply, or net improvements in channel function at some downstream point in the system.

Pinole Creek watershed form and function related to land use impacts

The Pinole Creek watershed supplies a large amount of sediment, from both natural geologic erosion sources and from sources caused by or exacerbated by land use. Our analysis of landslide occurrence on geologic rock types showed that the physical properties of the prevalent rock types within the watershed (siltstones, shales, claystones, and sandstones) cause these rocks to be prone to mass failure, such as by landsliding (see Figures 18 and 19). In addition to rock types, soil types also control slide occurrence. Many areas of relatively weak bedrock geology and soil types that are sourcing sediment have been highlighted by our landslide and watershed zone analysis, as well as in original descriptions by Graymer et al (1994). Besides natural sediment sources, observations of many specific locations of high-intensity land use that were directly contributing sediment suggest that land use activities have likely augmented the naturally high sediment supply. The specific locations typically are chronic sources of sediment, especially including culvert and road drainage erosion (see Figure 23), surface erosion of confined animal facilities (see Figure 29), rills and gullies forming from ranchette/house drainage, and surface erosion of construction sites. We suggest that approximately 45% of the total sediment load is either directly or indirectly attributable to land use impacts. In neighboring Wildcat Creek, up to 60% of the total sediment load has been attributed to land use (Collins, 2001). Alternatively, the sediment supply could be due solely to the natural geologic composition of the watershed, or due solely to current land uses, rather than a combination of the two. However, based upon our observations in the watershed, we suggest that the combination of both natural geologic erosion and land use activities are providing the large supply of sediment in the Pinole Creek watershed. When inadequately-managed land use is overlain on top of a bedrock geology that is prone to failure and associated with soils prone to erosion, large volumes of sediment supply can occur. For example, in the Pavon Creeks sub-basin, an area underlain by unstable shale and claystone rock types and their associated soil types, an unusually large gully was created by the addition of road drainage to an existing tributary drainage (see Figure 24). Also, many examples of increased runoff or modified drainage patterns from ranchettes and horse boarding facilities were observed to be exacerbating the formation and/or extension of gullies in a sub-basin already destabilized by a large active landslide. We believe that high-intensity land use in conjunction with naturally erosive bedrock and soil materials form a process-linkage that is capable of producing volumes of sediment significantly larger than either source alone.

Substantial differences exist between current and historical land use impacts on the watershed, but the distinction is blurred because the cumulative and inherited history of land use effects cannot be fully divorced from the current landscape. Historic land use in the watershed has been dynamic, but the following five major shifts in land use likely had the largest effects:

- In the 1820s land use began to shift from management by Native Americans to management by European settlers, including introduction of ranchos, grazing and minor crop production.
- In the mid- to late-1800s grazing and crop production increased and intensified as more families settled in the upper watershed and as the town of Pinole became established in the lower watershed.
- In the 1920s EBMUD purchased a major portion of the middle watershed, ultimately causing changes in grazing and agricultural practices.
- In the 1940s/1950s suburbanization occurred, especially in the lower watershed, increasing the area of impervious surfaces and emplacing more constraints on the channel.
- And in the 1980s/1990s to the present increased development of rural housing, ranchettes, and horse boarding facilities in the upper watershed increased the amount of runoff and surface erosion.

Historically, it is likely that high-intensity grazing land use caused widespread alteration of the infiltration and runoff characteristics ultimately accelerating erosion, sediment supply, and transport. We hypothesize that many of the now-dormant landslides, gullies, and mainstem incision were caused by or is related to the increase of runoff associated with high-intensity grazing during the period 1830 to 1920. This is supported by our observations of the age/stability of these erosional features (see landslide database in Appendix), as well as by anecdotal evidence of historic stocking rates, and timing of gully formation and incision (B. Nuzum and F. Nunes, pers. comm.). In contrast to historic land use, current land use is more often associated with localized direct chronic sources of erosion. For instance, we observed many locations of channel bank erosion due to urban storm water discharge from culverts (see Figure 26), locations of surface erosion from confined animal facilities (see Figure 29), and locations of rills and gullies from house, barn, and pasture drainage. Although sometimes it can be difficult to determine if an erosional feature is caused solely by the localized current land use, or if it was caused by a historic land use effect, and is merely overprinted by the current use. Despite the differences in past and current land use impacts, the proportion of the total sediment load supplied from current land use appears to be increasing as development continues and land use intensifies. The integrated and cumulative effects of the current land uses, if continually increased, could result in a substantial sediment supply impact on the watershed. Conversely, it is possible that land use effects on total sediment supply are decreasing, compared to earlier historical times, due to better management techniques and practices such as improved road maintenance, reduction of unnecessary fire breaks, better storm water detention strategies in new developments and urban areas, lower stocking rates, or better erosion control techniques associated with construction. However, based upon our observations and our professional judgment, we believe that the sheer number of high-intensity land uses without adequate management techniques or practices are outweighing the appropriate and successful practices already in use in the watershed. For instance, while we observed some locations of successful bank stabilization, we observed many more locations where poorly placed drainage or poorly implemented bank revetment was contributing to excessive bank erosion and bed incision. These locations are failing primarily because of inadequate design and misunderstanding of fluvial erosion processes. Oftentimes these impacted areas can be fixed with the expertise of an erosion control specialist. We also observed that on lands used for livestock, especially on EBMUD lands, much of the channel length is already fully fenced to manage access by horses and cattle. Typically, only carefully chosen areas are used for channel crossing. Exclusionary fencing, in combination with revegetation efforts, appears to be successfully controlling bank erosion and gully extension in these locations. However, many other areas in the watershed have not been treated with revegetation or fencing efforts, and continue to show evidence of erosion. Although some management techniques are currently in use throughout the watershed, we recommend further efforts to control/reduce the sediment supply associated with current land use. Based upon our findings and observations, we suggest that historic land use contributed to the initial changes in watershed functioning, and the increased sediment supply and transport. Sediment supply is now intensified by current land use effects that are creating new problems, many of which could be controlled by emplacing additional management actions/efforts.

Pinole Creek has been dynamically responding to changes in sediment and water supply as evidenced by incision, widening in response to bed incision, and increased watershed drainage density. Most of the bed incision has occurred in the middle and upper reaches (see Figure 35) coinciding with the reaches with the most intense history of agricultural and grazing land uses. Although additional study would be necessary to determine the exact cause of incision, we believe that some localized incision is in response to landslides impinging on the channel, while greater incision is due to the intense historic grazing history, and incremental increases in runoff due to development in the upper watershed. Much of the measured bank erosion is based upon indicators of erosion; although the exact date of bank erosion often can not be identified, the range of indicator ages suggests that either punctuated or steady bank erosion has occurred over the entire 180 year period (see additional data in Appendix). Most observed bank erosion is associated either with direct land use impacts (culverts, or failing bank revetment) or from channel lay-back as the banks adjust their slopes in response to the incision that has occurred. The formation of gullies evidence the increase in drainage density (total channel network length per basin area) in response to the additional runoff supplied from the basin, likely from historic grazing impacts. Perhaps these channel adjustments merely reflect the channel maintaining dynamic equilibrium in response to climatic, tectonic, or sea level changes. However, we believe that changes in sediment and water supply from increased intensity land use are greater than changes in climate, tectonics, or sea level, and have largely driven the observed channel adjustments. Rainfall has increased in amount and intensity subsequent to the 1930s (see Rainfall section), likely increasing sediment supply through increased landslide intensity (e.g. as found in the Simas sub-basin by Reid, 1998) and increasing overall erosion potential from other sources. Without further study, it is difficult to precisely determine the contributions of sediment due to rainfall versus land use. While tectonic uplift of the entire watershed is likely providing some sediment supply, the expected contribution is small; in neighboring Wildcat Creek, a watershed located on the very active Hayward fault, the influence of tectonics on sediment supply was found to only be minor (Collins, 2001). In addition, over this time period, mean sea level has been slowly rising, yet we observe incision throughout most of the channel length, suggesting that sea level is not exerting a baselevel control on the channel. Based upon our observations, we suggest that since European settlement approximately 180 years ago, Pinole Creek has been dynamically adjusting to changes in sediment and water inputs primarily due to changes in land use.

Pinole Creek, like most watersheds, has a high buffering capacity, or ability to moderate fluctuations in sediment over many years. A perturbation in the system that changes the sediment supply regime probably takes years or even decades to cause an observable change in channel function downstream. Virtually all of this buffering capacity is occurring on the hillslopes. The channel presently has a relatively low buffering capacity mostly because recent incision has caused a low bankfull width-to-depth ratio and has decreased the ability of the channel to access its former floodplain.

Based upon our observations and experience, future trends in the creek form and function can be predicted. Presently the watershed hillslopes and channel network are in a state of disequilibrium associated with the perturbations discussed previously. Currently in the middle and upper watershed, the mainstem is making adjustments to the changes in water and sediment supply. In response to the incision, the channel banks will continue to erode, in an effort to “lay-back” and increase the channel width. This natural, stabilizing process eventually will allow the creek to form a new floodplain at its new elevation. In some instances this widening will occur in areas adjacent to or on high value property, buildings, or roads, and management initiatives will likely try to retard the process by bank protection measures. However, the long term functioning of the creek for both flood conveyance, riparian quality and aquatic habitat would benefit from allowing the channel to widen in areas where widening is acceptable on private properties or where land can be purchased or is already managed by a government authority.

ENVIRONMENTAL AND STAKEHOLDER CONCERNS

This section uses the data and observations collected during this study to focus in upon a set of specific concerns voiced by residents and stakeholders of the watershed. These concerns involve aquatic habitat (specifically for anadromous fish), water supply, flood management, and water quality (animal waste and excess sediment components). The current condition or status, threats to the activity or use, and future management actions to consider for each of these concerns will be discussed.

Aquatic habitat

Historically, Pinole Creek provided habitat for anadromous fish, specifically steelhead trout (UCC, 2004). Evidence suggests that the steelhead trout population in the watershed has severely declined. However, steelhead are still observed in the watershed.

Recently, steelhead have been sighted by Friends of Pinole Creek Watershed members downstream of I-80 (February, 2002), a single dead female was found on EBMUD lands in April 2002 (UCC, 2004), and EBMUD staff observed a 3-year old male Chinook salmon downstream of I-80 in January 2005. The population decline is likely due to a number of physical barriers to migration (including the culvert underneath I-80), a decline in habitat quality, and a decline in water quality and seasonal quantity. This study did not specifically focus upon fish or aquatic habitat, but data on in-channel sediment sources, bank and bed stability, channel bed grain size distributions, pools and large woody debris characteristics, water discharge, and water quality can lend insight into the current condition of habitat available for fish.

In general, the habitat available for rearing in the mainstem upstream of I-80, and especially on EBMUD lands, appears adequate. Good habitat extends from approximately sample reach 5 to sample reach 10, with the best habitat near sample reaches 8 and 9. The habitat most appropriate for spawning coincides with these same reaches, however spawning may be hampered by a relatively fine grain size distribution, a frequently reworked bed, and potentially high levels of fine sediment decreasing gravel permeability and oxygenation of eggs in the redd. Unfortunately, migration barriers in the lower reach may be preventing fish access to these reaches (UCC, 2004). Water quality may also be having a negative effect, including excess nutrients and high levels of water turbidity. Bank erosion and bed incision, especially in the middle and upper reaches, are two of the contributors of sediment to the channel that can reduce the quality of native fish habitat. Erosion is occurring primarily because the channel is adjusting to changes in land uses that have occurred over the past 180 years. The instability in profile and planform over this time period likely reduced the channel complexity and number of habitat elements such as pools, pool tail-out locations, LWD jams, and undercut banks. In addition to reducing channel complexity, bed and bank erosion are in-channel sediment sources that are contributing to high levels of fine sediment in the bed as well as elevated and extended water turbidity levels during flood.

The field team performed pebble counts to describe the grain size distribution of the channel bed surface. We did not collect data on the grain size distribution of sediment below the bed surface; however this would provide further data to assess the suitability of gravels for successful spawning. Grain sizes considered optimal for steelhead spawning range between 18 and 100 mm (Kondolf and Wolman, 1993; Kondolf, 2000; Bjornn and Reiser, 1991). Pinole Creek has a relatively fine grain size distribution throughout all reaches (at least 50% of the grains are finer than 6.5 mm in all measured reaches). While the majority of the bed is fine grained, small patches of more spawning-appropriate sized gravels were observed. These small patches are likely the only locations where spawning may be successful. Based upon the grain size analysis, it is concluded that Pinole Creek is sub-optimal for steelhead spawning. Management initiatives to reduce fine sediment supply to the creek might improve spawning success.

Data on the number, type, and condition of pools and LWD pieces were collected to determine the condition of the channel, however this data is also very applicable to determining the quality of habitat available. An average to low number of pools exist, with each mainstem sample reach containing between 2 and 5 pools. The average pool spacing is one pool every 7.7 bankfull channel widths, ranging between 5 and 12.5 bankfull channel widths apart. Generally pools are spaced every 5 to 7 bankfull channel widths in alluvial sand and gravel bed rivers (Leopold, 1964; Dunne and Leopold, 1978). Pool numbers are slightly lower than expected because many are long mainstem pools that occur over longer lengths than other pool types. A comparison of pool volume per sample reach would likely show that total volume is similar to that measured in other Bay Area streams. In addition to a fairly low number of pools, Pinole Creek does not contain very much LWD. Additional carefully placed LWD pieces would help trap spawning gravels, create more pools, and would increase the channel complexity, providing velocity shelters and hiding locations for fish.

Water discharge was carefully measured at the gauge location mainly during floods in the 2004 water year. However, we made qualitative observations throughout the watershed while in the field for other tasks. During the 2004 water year, mainstem Pinole Creek maintained perennial flow, although it was only estimated at 0.1 cfs (see Rainfall and Pinole Creek Flow section) during the fall months. Observations made between June and October 2004 confirm that flow was still present in the mainstem. However, areas of isolated pools or a completely dry bed were observed in Simas Creek tributary mouth (dry on 7/22/04), Pinole Creek mainstem near Bear Creek/Alhambra Valley road intersection (almost isolated pools on 7/22/04), upper reaches of Costa Creek tributary (dry on 7/23/04), Sample reach 12 (dry on 6/30/04), and the Pavon Creeks tributaries (dry on 9/1/04). Currently, groundwater recharge appears to maintain perennial streamflow in most years (2 of 3 years, see Rainfall and Pinole Creek Flow section). There are a number of factors that could reduce flow in the creek and tributaries. Greater water loss due to evaporation and evapotranspiration can occur when native trees, shrubs and grasses are replaced with annual grass species. Infiltration, watershed storage capacity, and groundwater recharge is decreased when surfaces become impervious during urbanization or in high impact areas where horses or cattle damage the soil structure through excessive trampling. Extraction of groundwater for water supply and irrigation, and surface collection or diversions could further reduce streamflow during the critical summer and fall months. We suggest that the watershed is at a critical juncture; if perennial flow for environmental uses is determined to be a priority for stakeholders, management should focus actions on practices that maintain surface flows and groundwater levels, especially during the fall months.

Water quality, including nutrient concentrations and elevated and extended turbidity levels during flood may also contribute to the decline in anadromous fish. At present, nutrient concentrations in the creek are well below toxicity thresholds for ammonia. If the balance of nutrients were to continue to favor increased nitrate and ammonia concentrations, especially during the dry season, the amount of plant and algal growth might increase, reducing habitat value for fishes by blocking the channel, increasing biological oxygen demand (when plant matter decomposes) or enhancing the growth of toxic species of algae. Turbidity measured during water quality sampling was typically below 10 NTU for each of the three dates, with only four exceptions (17 NTU when the channel was disturbed by ducks, 26 NTU in a nearly stagnant pool, 13 NTU where large amounts of algae were present, and 12 NTU during the January sampling). We measured turbidity in Pinole Creek during floods at the gauge location under Pinole Valley Road Bridge number 5 (see Figure 7). Instantaneous (15 minute) turbidity exceeded 1000 NTU 300 times. Daily average turbidity exceeded 50 NTU on 16 days and exceeded 25 NTU on 100 days. Elevated turbidity can cause physiological effects in fish such as gill trauma, gill flaring, changed blood physiology, impaired reproduction and growth, and behavioral effects such as avoidance, and decreased foraging and predation (Bash et al., 2001). Other effects include reduced feeding ability in juveniles (Newcombe and MacDonald, 1991) and where measured turbidities are as low as 25 NTU growth can be reduced (Sigler et al., 1984). The San Francisco Bay Basin Water Quality Control Plan (RWQCB, 1997) set guidelines for turbidity to protect fish in local waterways. When freshwater fish are present, turbidity may not exceed the established normal [background level] by more than 10% in areas where natural turbidity is >50 NTU. Since background levels are seldom defined, these standards are somewhat ambiguous and hard to enforce (Brady, et al., 2004). The larger juvenile and adult trout appear to be little affected by ephemerally high concentrations of suspended sediment that occur during most storms (Cordone and Kelley, 1961; Sorenson et al., 1977). Based on these guidelines, we suggest turbidity may be a limiting factor for maintaining the creek as a steelhead habitat. Management initiatives that reduce sediment supply to the creek during storm events would likely decrease the amount of time post-flood when turbidity might exceed the guidelines.

Based upon this assessment, it appears that certain actions could improve the condition of Pinole Creek, the aquatic habitat that it provides, and could help in the restoration of a successful population of steelhead in the watershed. For example, a focus on controlling bank erosion and bed incision would increase channel stability and would reduce sediment inputs that are affecting pool volumes, cobble embeddedness, turbidity, and gravel permeability. Other management actions that reduce the supply of fine-grained sediment from landslide, gully, and land use sources would also improve water and spawning gravel quality. Management actions that place an emphasis on maintaining the nearly continuous riparian vegetation corridor that exists upstream of I-80 would decrease bank erosion, decrease water temperatures, provide a supply of woody debris, and increase channel complexity. Also, actions that add riparian vegetation to the flood control channel would provide these same benefits for this lower reach. Related to riparian vegetation, management actions that focus on increasing the number of LWD pieces in appropriate locations in the channel would also increase channel complexity and help trap additional spawning gravels. The LWD pieces could be anchored in place so that they do not move during floods and potentially catch on bridges and other channel structures. Careful management of both groundwater and surface water pumping and surface diversions would help maintain perennial baseflow in the channel. This would most effectively be achieved if these activities were related to a daily stream flow record. In addition, management of some areas of the watershed for groundwater recharge could be improved by reducing impervious surfaces. Proactively establishing or maintaining native perennial grasslands and oak savanna plant communities would reduce evapotranspiration, increase rainfall interception, decrease the rate of overland flow, and increase infiltration. Improvement of the flow rate and the extent of channel with perennial flow would increase the amount of aquatic habitat available, the delivery of food resources for fish, and would help regulate water temperatures throughout the summer and fall. Aquatic animals would benefit from actions that increase water quality, such as hauling horse manure off-site, checking for and repairing leaky septic tanks, reducing roadside dumping, increasing education about dumping in storm drains, reducing or eliminating access to creeks by cattle and horses, and reducing the application of, or applying fertilizers more effectively.

Water supply

As in many watersheds in the Bay Area and across California, the Pinole Creek watershed has a limited supply of water which is used for many different purposes. Perennial surface flows are essential to maintain the creek and its functioning, aquatic habitat, riparian plant species, and wildlife species. Also, a continual water supply (surface or groundwater) is necessary for agriculture, grazing, equestrian activities, and well-water dependant residential areas in the watershed. Although specific data regarding current and historical supplies of water were not collected as a part of this study, some of the data and our observations have implications for the future condition of the watershed if water supplies are decreased.

We observed perennial flow in mainstem Pinole Creek during the 2004 water year (a slightly above average flow year). Historic US Geological Survey gauge data suggest that this condition occurs two out of every three years. Many tributaries were observed by the field team to be dry during the late summer and fall months. It is not known if this was the case historically or if some tributaries were also predominantly perennial. Although many of the tributaries were not observed through the summer and fall months, Pereira Creek tributary and the unnamed tributary following Alhambra Valley road to the drainage divide were observed to be perennial during the entire 2004 period.

There are a range of processes and land management actions that can reduce the perennial flow in Pinole Creek. These include channel incision, changes in land use that enhance surface runoff and decrease infiltration and ground water recharge, capture of some of the annual water budget in agricultural (livestock) ponds, and extraction of water for urban or agriculture irrigation uses (especially during the dry season). Incision of the mainstem creek over the past 180 years has depressed the local water table in the watershed. This, in turn, can lead to changes in riparian structure, or even complete loss of structure, when riparian trees suffer from a lack of water or topple into the creek because of over-steepened banks. Increased and poorly-planned development will likely lead to increased demands on surface and groundwater supplies, decreased amounts of groundwater infiltration, and increased amounts of runoff (with decreased timing of that runoff entering the channel) potentially causing channel adjustment downstream.

There are several useful tools for helping to make future decisions. The development of a watershed-scale water budget would help to dispel arguments about who is getting the most use out of the annually available water and would help to understand maximum allocations and the potential for future impacts to the creek as further water is allocated. In addition, an automated real-time stream gauge or several gauges could be installed on the creek at strategic locations, with the data provided on the internet. A discharge threshold could be decided upon, below which further pumping or diversion would be ill-advised.

Flood management

Flood conveyance is one of the primary concerns of watershed residents. Since European settlement, floods have damaged property along the creek, especially in the downtown area. For example, in 1862 a large flood washed away Bernardo Fernandez's grain warehouse that was located near the mouth of the creek (Emanuels, 1986). In 1916, floods washed the boardwalk sidewalks from downtown out into the Bay (Emanuels, 1986). And again, in 1958, heavy floods damaged many of the downtown buildings. However, the flood control channel is not the only reach that is prone to flooding. Recently flooded locations include: Pinole Creek mainstem at the Library (most recently flooded in early 1998) flooded due to water backup behind the Pinole Valley Road bridge, Pinole Creek mainstem at Ramona Street bridge flooded due to the undersized Ramona Street bridge, and flooding during 1993 at the "Y", or the intersection of Pinole Valley Road/Alhambra Valley Road and Castro Ranch Road from both the Pavon Creeks tributary (flooding occurred just downstream of Castro Ranch Road) and from the Simas Creek tributary (flooding occurred immediately upstream of the "Y"). These areas of flood are typically due to undersized bridges or culverts, or debris catching on these structures and causing a flood backup upstream of the structure.

The increasing flood damages prompted the construction of a flood control channel in the lowest 2.4 km (1.5 mi) of Pinole Creek, built by the US Army Corps of Engineers in 1965. This channel is designed to protect the downtown area from the 50-year flood (UCC, 2004). During construction, the channel planform, gradient, and riparian vegetation community were altered to better convey flood flows. Since it was built, the flood control channel has successfully protected the downtown area from flood hazards. However, potential channel bed aggradation threatens the conveyance capacity of this channel. Other factors indirectly affect flood conveyance, including sediment supply, conversion of land uses, tidal elevations, and even sea level rise. For example, increases in future sediment supply (despite the source) could cause the channel to aggrade or increase sediment storage in the form of bars. These actions would reduce channel cross-sectional area causing elevated water levels, possibly high enough to overtop the banks. In addition, future increases in high intensity land use could modify drainage patterns or increase surface runoff supplied to the creek. This extra volume of water, or the speed in which the water is supplied, can also cause elevated water levels, potentially reaching flood stage. Because a majority of the lower reach of the watershed is already developed in urban land uses, major changes in runoff volumes are not likely for this reach and, even if they were to occur, would likely exit to the Bay before flood waters from the upper watershed would arrive. However, future development in the middle and upper reaches does have the potential to increase flooding hazards.

Cross-sections of the flood control channel, from the "as-built" drawings and surveyed sections collected in 2003 (UCC, 2004) were utilized to determine if fluvial modifications have been made since it was built. Modifications, in the form of sediment deposition, bed aggradation, bank erosion, or bed incision, are evident from comparisons of the channel cross-sections and longitudinal profiles. The as-built and current channel thalweg longitudinal profiles are illustrated in Figure 58. The change in gradient between the two time periods is most apparent in the tidal reach. The channel was constructed with a gradient that was too steep for the tidal processes that occur. Therefore, the channel reduced its overall gradient of this reach by incising in the upper tidal portion, and aggrading in the lower tidal portion. This change likely occurred fairly rapidly after construction (possibly over a period of 10 years) and now is relatively stable. Other adjustments are evident and noteworthy, for instance, a small package of sediment has been deposited between San Pablo Avenue and the Santa Fe Railroad trestle, likely due to the minor constriction caused by the trestle. Areas of incision are found upstream of both the San Pablo and Tennent Avenue concrete culverts. These areas could potentially represent errors in the data, but could also represent real scour associated with the hardscape concrete grade control of the culverts. It also appears that the upper portion of the channel has incised approximately 2 feet. This incision is not readily apparent from standing in the channel, but is apparent from comparison of the longitudinal profiles. Thus, this incision is not included in the in-channel data collection (Figure 35) because the channel is very modified, has no indicators of incision (such as exposed tree roots), and is subject to annual maintenance activities, all of which disguise the incision.

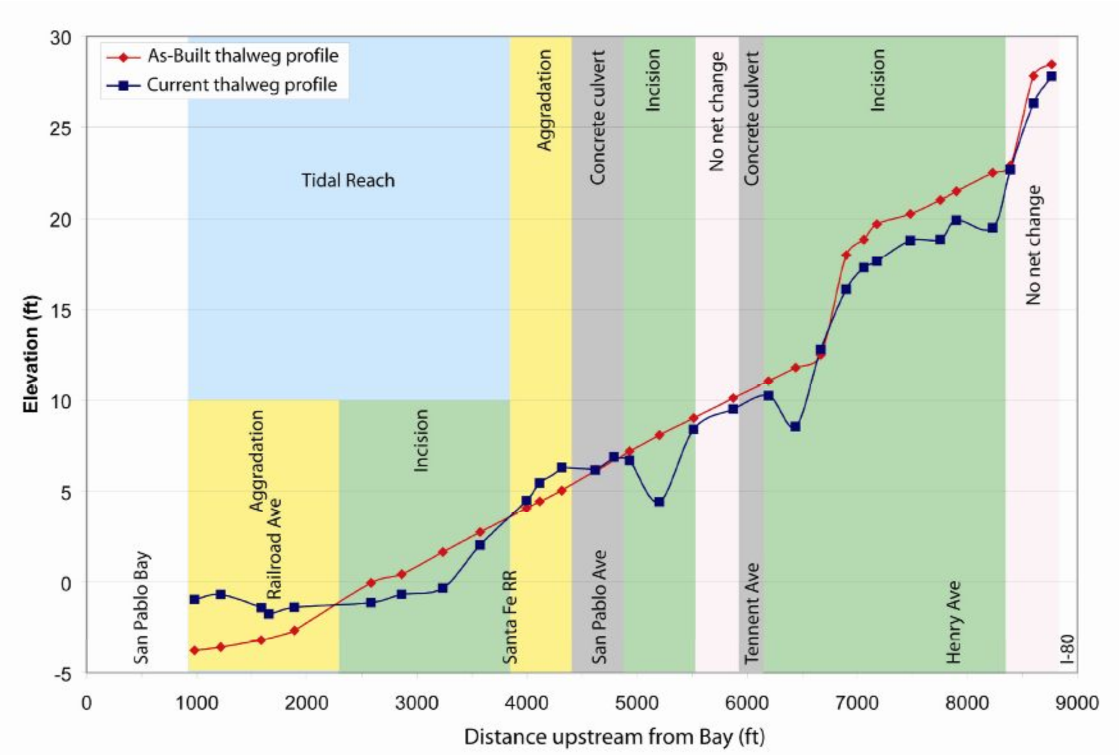


Figure 58. Thalweg longitudinal profile of the flood control channel. Red line is the "as-built" channel profile in 1965, blue line is the channel profile in 2003.

Dredging has likely only occurred since the flood control channel was constructed in 1965. Unfortunately, records of dredging activities were not kept by either the US Army Corps of Engineers (Karen Berresford, pers. comm.) or the Contra Costa County Flood Control District. The Flood Control District does not believe that any major de-silting efforts have occurred for any significant lengths of the flood control channel (R. Taveneir, pers. comm.). In the summer of 2003, the District did a small spot de-silting between San Pablo Avenue and the Santa Fe Railroad, only removing approximately 50 yds^3 (38 m^3). However, watershed residents recall small dredging efforts also occurring in the flood control channel in the 1980s (Dr. J. Mariotti, pers. comm.). These efforts were likely small spot de-silting on the order of the work completed in 2003.

Based upon our observations, data collection, and analysis of the as-built channel plans, we believe that this channel reach is currently working on its channel bed and banks, trying to adjust to a more hydrologically stable profile and planform. The upper reaches that are incising might continue to make minor adjustments, but ultimately the grade of the channel is controlled by sea level and the concrete culverts, thus limiting the amount of adjustment that can be made. Small portions of the channel may continue to aggrade, but wholesale aggradation of the entire channel length does not appear to have occurred since construction. The tidal reach has likely reached equilibrium, now controlled by both fluvial and tidal processes. This reach appears to be able to transport the sediment that is supplied to it, with a majority transported out into the Bay. Decreased flood conveyance due to increased sediment storage is not a significant threat at this time.

We believe hydro-modification (an increased flood volume and increased peak runoff) associated with new development and land management is one of the greatest threats to the watershed. Development or land management activities that include plans to reduce hydro-modification may reduce the costs of maintaining flood conveyance as well as enhance other beneficial uses such as salmonid habitat. Future management should include consideration of conveyance capacity of culvert and bridge locations. Because these are the locations in which the greatest flood hazards exist, replacing any structure that is undersized would reduce the local hazard. Also, management of LWD pieces should also consider the flood hazard that they possess if not fixed in place. LWD is vitally important in maintaining many in-channel functions and supporting many biological functions. However, this benefit must be weighed with the potential to causing flooding. Reaches and individual LWD pieces should be assessed individually.

Management could also encourage projects or policies that allow the channel access to its floodplain. Increasing floodplain access will help slow water velocity, decrease the amount of suspended sediment that is transported, and reduce downstream flooding. However, much of the channel is incised and has lost access to its floodplain. Restoration in the incised reaches would require major efforts to widen the channel's total cross-section and create a new floodplain at a lower elevation. Alternatively, allowing channel "lay-back", or erosion of the steep channel banks, will allow the channel to make adjustments in its cross-sectional geometry, eventually creating its own lower-elevation floodplain. Although major channel widening is impractical in many locations, a restoration opportunity of this type does exist in the flood control channel reach. Restoration of the flood control channel would be beneficial for many reasons. A restored reach would return the channel to a shape that is stable and appropriate for efficient water and sediment transport. It would allow creek flows access to an inner floodplain, and it would increase riparian vegetation, having benefits for aquatic habitat while also decreasing water temperatures.

Water quality degradation from animal wastes

During the Pinole Creek Watershed Vision Plan development (UCC, 2004), residents and stakeholders identified confined animal facilities, especially horse boarding facilities, as a threat to water quality and watershed health. The primary concern involves pollutants such as sediment, nutrients from manure, wood shavings that have absorbed animal wastes, and pesticides entering the channel. Although the field team's access to many of these properties was limited, some specific and some more general observations were made regarding this issue.

The potential negative impacts from confined animal facilities focus mainly on runoff and surface erosion. Runoff can increase due to compaction of the soil from hoof impact, and from the reduction in vegetative cover in pens and pastures. Runoff can also increase due to impervious surfaces associated with these facilities, including roads, barns, arenas, and other buildings. The runoff provides the pathway for transport of nutrients or manure into the creek. Sediment erosion is also a major concern; pens or pastures with confined animals tend to have bare soil and damaged soil structure, which leads to soil erosion from raindrop splash, reduction of infiltration, and the formation of rills and gullies. These processes contribute dominantly fine sediment to the creek. When improperly managed these facilities can adversely influence the water quality in the watershed. Direct inputs of manure into the channel, or runoff carrying animal wastes will significantly contribute to year-round degradation of water quality. These locations are relatively small in area, but are chronic sources of surface soil erosion that impact the overall sediment supply to the mainstem creek and the turbidity levels of the creek water. An increase in the amount of runoff from these facilities will increase downstream flood hazards and in-channel erosion. In addition, the modification of drainage in combination with the reduction in vegetative cover may increase the chances of triggering or reactivating a landslide on the hillslope.

While in the watershed, the field team made observations of specific practices relating to horse boarding and other confined animal facilities. The team observed multiple instances of rills and gullies developing due to concentrated runoff from houses, barns, and roads associated with these facilities. Most pens/pastures had soil completely devoid of vegetation, with some showing evidence of surface erosion of 3 to 4 inches or more over the entire area. Runoff from these areas was observed to be very turbid during a storm event, and was draining directly into a tributary channel. The team observed one location where manure was stored in an old landslide scar which was directly adjacent to a tributary channel. In another location, the team observed manure that had been spread over a mowed vegetated area, however, this area received and collected runoff from the buildings and the road, which then funneled through a culvert into a tributary channel. The team also observed construction of a new equestrian facility that appeared to be incorporating many erosion control methods, including efforts to shape and stabilize the tributary channel that would be draining the facility in the future. However, direct observations were not made on this property.

Based upon our observations we believe that these confined animal facilities are having an impact on the water quality in the watershed. The degradation is in part due to the contribution, either directly or via runoff, of animal wastes and sediment to the channel. Many of the livestock pens and pastures show evidence of surface erosion, suggesting that these are chronic sources of sediment, contributing to elevated fine sediment loads in the creek. Drainage from these facilities leads to gully formation and extension. Modified drainage is also likely exacerbating landslides on the hillslopes. However, we believe that management actions in these facilities would be successful in reducing surface erosion and sediment input, and input of animal wastes to the creek. With additional resources and technical assistance, these facilities can be a sustainable activity within the watershed. Overall, these areas represent challenges to management and careful thought will be required on a site-specific basis if no-net stream degradation associated with nutrients, sediment supply and runoff is desirable.

Water quality degradation from excess sediment

Historically, grazing and agriculture were the primary land uses, with cultivated agriculture occurring primarily on the flats and grazing on the hillslopes. Although a description of the historic stocking rates of cattle in the watershed was not pursued, grazing intensity was likely high, almost that of the neighboring Wildcat Creek watershed (B. Nuzum, pers. comm.). The period 1830 to 1920, from the rise of ranchos to the purchase of land by EBMUD, likely had a significant effect on the modification of hydrology and sediment supply within the watershed. The land uses and management and practices used during this period potentially caused the triggering of many of the processes observable in the watershed today. These include alteration of hillslope infiltration and runoff characteristics and the subsequent triggering of many of the now dormant landslides, initiation of many of the gullies, and likely the initiation of mainstem incision.

Historic cultivated agriculture land uses likely had only minor effects on sediment, water and nutrient contribution to the creek. Because most cultivated agriculture occurred on the flat surfaces within the watershed, the potential for surface erosion due to gravity was low. However, where areas were plowed, the disruption of the soil surface increases the potential for surface erosion and sediment transport into the creek. If any row crops were planted, these areas have increased potential for runoff and sediment delivery because the rows act as pathways for transport. In addition to sediment and water contribution, agricultural areas can also contribute excess nutrients to the creek from fertilizer application. Although the exact impacts from cultivated agriculture, primarily hay and tomato crops, are not known, we suggest that these activities had a low impact. In contrast, an area in the upper watershed where topsoil was removed for sale has had a large impact. The topsoil removal decreased infiltration ability, thus the runoff from the sub-basin was increased, causing two large gullies to be carved on the property.

However, this specific example appears to be an anomaly to the overall impact from historic agricultural activities in the watershed.

Current cropland also appears to be having only minor impacts on sediment contribution in the watershed. The field team observed locations of hay production and orchards (olives) that did not have any noticeable surface erosion or runoff problems. Although the field team did not have access to the sole vineyard in the watershed, observations made from afar did not suggest that significant surface erosion was occurring. However, we suggest that future vineyard developments in the watershed be planted parallel to contour, in areas with less than 10% slope, utilizing cover crops and other modern erosion control practices.

Current ranching and grazing is of a much lesser extent and intensity compared to that of the past. Approximately 500 head of cattle are currently grazed in the watershed during portions of the year, on either a few small family ranching operations, or on lands leased to ranchers by EBMUD (F. Nunes, pers comm.). Currently EBMUD lands represent the largest ranching component, however cattle are only grazed on these lands from October to May. Grazing is a minor source of revenue for EBMUD, but more importantly, grazing is used as a cost-effective tool for fuel reduction and fire protection.

Since the 1920s when EBMUD initially purchased land in the watershed, natural resource protection standards have incrementally been raised. Management objectives have been developed to protect and maintain water quality, biodiversity, rangeland habitat, and resource productivity and are described in two documents, the East Bay Watershed Master Plan (EBMUD, 1999), and the Range Resource Management Plan (EBMUD Natural Resources Department, 2001). For example, site conservation thresholds, or minimum standards of vegetative cover, have been developed that require minimum amounts of residual dry-matter to be maintained on different hill slope classes. Because of the strict standards and practices designed by EBMUD, current grazing does not appear to be having a significant negative impact on sediment supply. On both EBMUD lands and privately owned and operated lands, many examples of well-managed grazing that promote continued rangeland health are currently observed in the Pinole watershed.

Often livestock grazing in general is blamed for causing many detrimental effects within watersheds. These include: conversion of grasslands from perennial to annual species, reductions in water quality, bank trampling and erosion, destruction of riparian areas, compaction of soils, creation of trails and terracettes, and increases in runoff. Frequently the effects of cattle grazing are manifest as increased bed incision which triggers increased bank erosion, and increased gully formation. Also, if higher densities of cattle are supported, localized surface or ground water supplies can be affected. However, all of the above mentioned effects can be minimized, and grazing can be sustained without measurable impacts to a watershed if it is well managed.

Although current grazing practices generally have limited impacts on erosion and are having a low overall impact on the watershed, future sustainable grazing should continue to incorporate management actions that focus on minimizing grazing-related sediment supply from landslide sources, bank erosion sources, gullies, and surface erosion from bare soil. The data collected during this study have shown that these sources are important contributors to the overall sediment supply, and poor grazing management can easily exacerbate all of these processes. For example, this study suggests that many of the landslide locations are primarily controlled by the underlying geology. However, soil compaction, rills and gullies forming along trails, or overgrazing can alter the hydrology of the hillslope enough to potentially cause a slide. These hydrology-altering processes which occurred during historic grazing in the watershed likely caused many of the now dormant landslides, and contributed to the activation of some of the active slides. If practical, careful management of cattle grazing on hillslopes that are prone to sliding, or that have dormant landslides that could be reactivated, could reduce the land use-related sediment contributions. For example, vegetation on slide areas should be maintained for deep root penetration and soil surface stability. Utilizing the geology map and watershed landslide zone map could help in choosing the best locations for grazing based upon the likelihood of that hillslope type to fail.

Bank erosion should continue to be controlled on grazing lands by fully fencing out cattle from sensitive channel areas, and only allowing cattle to cross at carefully chosen locations along the channel’s length. We acknowledge that livestock will have lesser impacts during certain times of the year, and that animal density and frequency of access to the channel also are important in determining the impact upon the channel.

The gullies that have formed in the grazing lands are likely caused by historic grazing impacts, including reduced infiltration (soil compaction) and concentration of runoff from the grazed pastures, as well as from incision of the mainstem creek. It appears that a majority of the gullies could be stabilized utilizing vegetation methods such as willow plantings, or careful grading and shaping of active headcuts, rather than hardscape engineering methods. However, gully erosion control should be carefully planned with the assistance of the NRCS or other erosion control consultants. Bare soil surface erosion is not currently a major issue on the grazed lands, but it should continue to be controlled by regularly rotating cattle between pastures, and minimizing effects of cattle concentration, for example, around watering areas.

In addition to cultivated agriculture and grazing, urban development can have significant impacts on water quality degradation through excess sediment supply. Most contributions from urban areas are due to surface erosion at construction sites, concentration of runoff forming gullies in adjacent undeveloped areas, and urban storm water runoff causing erosion at culvert outlets and overall channel bank erosion and bed incision. While urban areas typically don’t exert a large influence on landslide triggering because the land is graded and paved, and storm water is routed away through storm drains, the field team did find one example of urban development triggering a landslide. In 1903, a water storage tank was placed on the hilltop above the current bowling alley. This tank continually leaked (Dr. J. Mariotti, pers. comm.) eventually triggering the landslide that is now adjacent to the highway near the bowling alley. Because the lower reach is almost fully developed, future increases in sediment contribution from these areas are not likely, with the exception of increased erosion due to storm water runoff. However, it is the middle and upper reaches that have the greatest potential for future sediment contributions due to increased urban development.

The following matrix summarizes the discussion in this section. It serves as a quick reference for understanding which factors or processes are negatively affecting each of the beneficial uses of the watershed that are listed. It is divided into three main sections: factors that are channel-related, water-related, and land use-related.

	Beneficial Use							
Factor or process limiting the beneficial use	Aquatic habitat	Steelhead spawning	Steelhead rearing	Steelhead population	Perennial flow	Acceptable water quality	Healthy riparian corridor	Flood conveyance
Channel-related								
Physical migration barriers		X		X				
Bank erosion	X						X	
Bed incision	X				X		X	
Fine bed grain size distribution		X						
High % fines		X						
Frequently reworked bed		X						
Bed aggradation								X
Decreased channel access to the floodplain	X						X	X
Decreased habitat quality	X			X				
Loss of riparian corridors	X		X	X		X	X	
Decreased number of LWD pieces	X	X	X					
Decreased channel complexity	X		X					
Decreased number of pools	X	X	X					
Debris catching on bridges/culverts								X
The current morphology of the flood control channel	X		X			X	X	
Water-related								
Lack of perennial flow	X	X	X	X	X	X	X	
Decreased water quality	X			X		X		
Decreased water quantity	X			X			X	
Increased evaporation and evapotranspiration					X			

	Beneficial Use							
Factor or process limiting the beneficial use	Aquatic habitat	Steelhead spawning	Steelhead rearing	Steelhead population	Perennial flow	Acceptable water quality	Healthy riparian corridor	Flood conveyance
Increased water extraction	X		X		X		X	
Decreased groundwater recharge					X		X	
Land-use related								
Change in vegetation community					X			
Increased impervious area					X		X	
Increased soil compaction					X	X		
Increased surface runoff					X	X		X
Modified drainage patterns								X
Hydromodification	X							X
Increased sediment supply					X			X
Increased supply of fine-grained sediment	X	X		X		X		
Increased turbidity	X			X		X		
Increased supply of nutrients	X			X		X		
Increased nitrate and ammonia						X		
Improper disposal of manure	X			X		X		
Leaky septic systems	X			X		X		
Roadside dumping	X					X		
Stormdrain dumping	X					X		
Increased fertilizer application	X					X		
Not fencing cattle out of sensitive areas	X			X		X	X	
Inadequate grazing management	X					X		X
Inadequate horse boarding management	X					X		
Agricultural dams					X			
Undersized bridges and culverts								X

CONCLUSIONS AND RECOMMENDATIONS

The primary goals of this project include identifying the major sources of sediment, determining the magnitude and causes of sediment production, supply to, and storage in Pinole Creek, identifying physical processes that limit beneficial uses related to sediment, developing water quality data, and recommending potential management solutions for the watershed. The data collected during this study have met these first four goals; the Synthesis and the Environmental and Stakeholder Concerns sections as well as this section describe our findings, implications of the data, and our recommendations for future management actions to control and reduce sediment inputs.

Based on this sediment source assessment of the Pinole Creek watershed, and given the current climatic, geologic, and anthropogenic setting of the watershed, we outline the following findings and recommendations:

1. Pinole Creek is impaired with fine-grained sediment sourced from the hillslopes of the watershed. Active landslides dominate the supply, followed by active gullies and paved road sources. Urban areas, ranchettes, horse boarding facilities, fire trail and ranch roads, and in-channel sources (bed and bank erosion) are minor sediment sources in the sediment budget.
2. Opportunities to control the continued erosion of existing active landslides, prevent the triggering of new active slides, and prevent the triggering of dormant slides will help control the large volumes of sediment contributed from these sources. Future measurement of the activity of the three largest landslides in the watershed may provide solutions to help control these sources.
3. The watershed has experienced significant changes in land use over the past 180 years. Land use is estimated to be directly or indirectly responsible for 45% of the total sediment supply. Historical grazing likely had the most significant impact upon the watershed, reducing infiltration and increasing runoff, initiating many of the dormant landslides, gullies, and mainstem incision that are observed today. Current erosion is typically more site-specific, chronic surface erosion at horse boarding facilities, and associated with culverts, roads, and urban areas. For instance, management actions that work with horse boarding facilities to control surface erosion will decrease fine sediment inputs. Also, actions focusing on drainage from paved roads, especially those in the middle and upper watershed, could reduce the number of spot locations of poorly designed and maintained inboard ditches and culverts that are causing erosion and contributing sediment. However, any decisions should be based upon further site investigation. Future direct measurement of erosion from specific land use types would help better inform management actions and decisions.
4. Hillslope sediment supply is in part due to the historic and current land uses overprinted upon the naturally highly landslide-prone underlying geology and soil types. Because high intensity land use can exacerbate the natural erosion, future growth and development should be done in context of this high erosion potential. Management practices that insure no net increase in runoff and slope instability are advisable.

5. Pinole Creek has a high suspended sediment load, comparable to only a handful of other Bay Area watersheds. Yet the creek is largely capable of transporting the sediment supplied to it. The channel bed is dominated by fine-grained material, and is often reworked, evidenced by the low stability deposits. Management that targets the fine-grained sediment sources would reduce the suspended sediment concentrations, reduce the volume of pool deposits, and would improve the overall quality of aquatic habitat. Additional data collection at the gauge location could improve the rating curve and SSC/turbidity/discharge relationships. Also, future measurement of subsurface grain size distributions would determine the suitability of spawning gravels for fish species.
6. The channel is currently in a state of disequilibrium; in the middle and upper reaches the channel is beginning to respond to incision by "laying back" its banks, evidenced by spot locations of severe erosion. Although erosion control efforts are not appropriate for many of the reaches with low levels of annual erosion, certain spot locations of major bank erosion that are threatening property would benefit from well-planned restoration efforts. Restoration and stabilization should be based on further site investigations and should be completed in consultation with the NRCS or other erosion control experts. An opportunity exists to encourage selective setback in other locations, by removing buildings or structures from the immediate channel edge, thus, providing room for the channel pattern to evolve. Allowing channel widening in locations where buildings or roads are not threatened will ultimately benefit the creek by allowing it to create a new, lower elevation floodplain. The new floodplain would allow for a healthy, stable riparian area to develop, would encourage deposition of fine sediment during flood, and would decrease flood hazards downstream.
7. Continued channel incision and resultant large-scale bank erosion will negatively impact the quality and quantity of the riparian corridor because many of the existing trees will likely be recruited into the channel. An opportunity exists to encourage new plantings that would increase the riparian width, re-establishing the many benefits of a riparian corridor to the creek after the existing large trees have toppled. Additionally, if the existing corridor is diminished through tree recruitment, installing large, anchored channel complexity elements (e.g. LWD pieces, rootwads, boulders) would provide much of the channel complexity, cover and some shade required by fish species. Again, in-channel work should be based upon further site investigation, and should be completed in consultation with the NRCS or other experts.
8. Focus management actions on stabilizing gullies that are actively eroding and extending. Restoration efforts should understand that these gullies will continue to receive high amounts of runoff from the sub-basins, as well as large pulses of sediment. Seek opportunities to utilize "soft" bioengineering techniques (such as willows and brush layering) to control gully bank erosion. Stabilization efforts should focus on the gully head because most gullies are already at grade with the fluvial system. Stabilization and restoration design and implementation should be completed in consultation with the NRCS or other erosion control experts.
9. A portion of the bank erosion and bed incision in the lower reach is attributable to urban storm water discharges. The larger areas of impervious surfaces and the

greater lengths of storm drains have increased water delivery to the channel, increasing flow depths and velocities which are causing channel erosion due to scour. Opportunities to utilize effective storm water detention and retention should be explored during new urban development.

10. The flood control channel is self-maintaining under the current sediment and water regime. With the exception of minor aggradation likely due to the channel constriction caused by the Santa Fe Railroad trestle, the flood control channel is not experiencing significant aggradation along its entire length. Minor dredging may need to occur in this specific location in response to climatic fluctuations. Overall, this channel reach is able to transport the sediment supplied to it to the Bay.
11. Water quality measurements show impacts from land use related sources. Although elevated concentrations of phosphorus were measured, water quality is maintained because of relatively low nitrogen concentrations (nitrogen limitation). Also, measured nutrient concentrations are well below toxicity thresholds for ammonia. Reducing the sediment supply to the channel will reduce phosphorus concentrations. Management actions that reduce the impact of septic systems and that limit the direct contribution and encourage better disposal of horse and livestock wastes will proactively reduce the nutrient concentrations in the creek.
12. Because perennial creek flow is maintained by groundwater storage and supply, opportunities to maintain or increase groundwater recharge and storage should be explored. For example, installation of a single or multiple real-time stream gauges could help determine the appropriate timing and amounts of diversions. Also, a groundwater well monitoring network could be enacted to better understand groundwater recharge, storage, and movement. Additionally, a watershed-scale water budget could be developed to better understand water usage and storage locations and amounts.
13. Encourage collaboration between landowners, agencies, and funding sources to provide resources and technical assistance to landowners so that reasonable solutions are identified and management actions can be successfully implemented.
14. The conceptual model and the sediment budget will assist land owners and natural resource managers to better understand the dominant processes occurring in the watershed and to better manage the land and resources. These should be utilized as working tools and continually updated as knowledge of the watershed improves.

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GLOSSARY

Aggradation—The geologic process by which stream beds, floodplains, and the bottoms of other water bodies are raised in elevation by the deposition of material eroded and transported from other areas. It is the opposite of degradation. (Flosi, et al., 1998).

Alluvial fan—An outspread, gently sloping mass of alluvium deposited by a stream where a stream issues from a narrow canyon onto a plain or valley floor.

Alluvium—A general term for detrital deposits made by streams on river beds, floodplains, and alluvial fans; stream deposits of recent times.

Anadromous—Fish, such as steelhead and salmon, who hatch and rear in freshwater, migrate to the ocean as a smolt, grow to an adult, and then return to freshwater streams to spawn.

Anticline—A fold, generally convex upward, whose core contains the stratigraphically older rocks.

Aspect—A side or surface facing in a particular direction. The compass direction that a hillslope faces.

Bankfull discharge—The discharge corresponding to the stage at which the flood plain of a particular stream reach begins to be flooded. The point at which bank overflow begins. (Flosi, et al., 1998). The flow that over time maintains the form of the channel by transporting the majority of the sediment load.

Bankfull mean depth—The mean depth of flow at the bankfull stage.

Bankfull stage—Corresponds to the discharge at which channel maintenance is most effective, that is, the discharge at which moving sediment, forming or removing bars, forming or changing bends and meanders, and generally doing work that results in the average morphologic characteristics of channels. The bankfull stage is the most effective or is the dominate channel-forming flow, and has a recurrence interval of 1.5 to 2.3 years. (Dunne and Leopold, 1978; Flosi et al., 1998).

Bankfull width—The surface width of the stream measured at the bankfull stage.

Bar—An elongate ridge, bank, or mound of sediment (typically sand or gravel), built by fluvial processes.

Baseflow—The portion of the stream discharge that is derived from natural storage (i.e. groundwater outflow and the draining of large lakes and swamps or other sources outside the net rainfall that creates surface runoff), discharge sustained in a stream channel, not as a result of direct runoff and without the effects of regulation, diversion, or other works of man. (Flosi, et al., 1998).

Baselevel—The lowest elevation towards which erosion can progress. A channel's baselevel is typically sea level, but may be locally controlled by culverts, or other hardscape elements.

Beneficial uses—The many uses of a particular resource. For example, beneficial uses of a creek may include: recreation, irrigation, aquatic habitat, and environmental flows.

BMP—Best Management Practice. Practical and affordable actions and strategies employed to best manage, conserve, or protect a resource. For example, BMPs may be used by a landowner to control the generation and delivery of sediment or pollutants to surface and ground waters.

Channel geometry—The dimensions of a channel cross-section, including width and depth, but also including channel characteristics such as slope and level of entrenchment.

Clast—A single grain of sediment.

Climatic forcing—Increased or decreased landscape erosion that is driven by changes in climate, i.e., wetter or drier periods.

Climatic year—A continuous 12-month period between July 1 and June 30, with the year denoted by the ending date.

Colluvium—A general term applied to loose and incoherent deposits, usually at the foot of a slope or cliff and brought there chiefly by gravity.

Culvert—An open-ended metal pipe or concrete box that allows water and sediment to pass underneath a road or railway.

D_{16}--16th percentile of a particle-size distribution. The sediment size for which 16% of the sediment sample is finer. In a normal distribution, one standard deviation from the median encompasses all data between the D_{16} and the D_{84}.

D_{50}—Geometric mean particle diameter in a distribution. A measure of the central tendency of particle size composition of substrate materials sometimes used as an index of the quality of spawning gravels. (Flosi, et al., 1998).

D_{84}—84th percentile of a particle-size distribution. The sediment size for which 84% of the sediment sample is finer.

Degradation—The geologic process by which stream beds and floodplains are lowered in elevation by the removal of material. It is the opposite of aggradation. (Flosi, et al., 1998).

Delivery ratio—The percentage of sediment that is delivered at a location in the stream system to the total amount of sediment erosion occurring within the watershed.

Discharge—Volume of water flowing in a given stream at a given place and within a given period of time, usually expressed as cubic feet per second (cfs). (Flosi, et al., 1998).

Dissolved organic nitrogen—The sum of concentrations of dissolved organic substances that contain nitrogen including urea, tanic acids, amino acids, proteins and breakdown products of organic matter.

Dissolved organic phosphorus—The sum of concentrations of dissolved organic substances that contain phosphorus including proteins and breakdown products of organic matter.

Downcutting—The channel process in which the overall bed elevation of a channel is lowered. Synonymous with incision and degradation.

Drainage density—Ratio of the total length of the entire channel network (creeks, tributaries, gullies, etc.) within a watershed to the area of that watershed.

Earth flow—a mass-movement process and landform characterized by downslope sliding of soil and weathered rock over a discrete basal shear surface within well-defined lateral boundaries. Earthflows often terminate in lobelike forms.

Embeddedness—The degree that larger particles (boulders, cobbles, or gravel) are surrounded or covered by fine sediment. Usually measured in classes according to percentage of coverage of larger particle by fine sediments. (Flosi, et al., 1998).

Entrenched—A vertical description of the stream. A stream that flows in a narrow valley cut into a relatively level upland. Often these channels have very limited access to floodplains, and channel morphology is strongly controlled by the confining banks or valley walls.

Erosion—The wearing away of soil and rock by weathering, mass wasting, and the action of streams, glaciers, waves, wind and underground water.

Floodplain—Any flat, or nearly flat lowland that boarders a stream and is covered by its waters at flood stage. (Flosi, et al., 1998). The surface constructed by the river in the modern climate. It is available to the river to accommodate flows greater than the bankfull discharge. (Rosgen, 2001).

Fluvial—Pertaining to streams or produced by stream action. (Flosi, et al., 1998).

Gradient—The general slope, or rate of the change in vertical elevation per unit of horizontal distance, of the water surface of a flowing stream. (Flosi, et al., 1998).

Gully- Incised channels that form on planar slopes where no well-defined channel pre-existed (Schumm, 1984). Gully depth often exceeds twice the height of their maximum discharge (Collins et al, 2001).

Hydromodification—Increases in the volume, frequency, and duration of runoff resulting from urban development. Often leads to channel degradation, increased sediment transport, stream bank erosion and channel bed incision.

Inboard ditch—The area between the roadway and a hillslope that collects water from upslope areas and from the road surface. Often this ditch will drain via a culvert underneath the roadway.

Incision—the process in which a stream channel cuts its channel into the valley surface through degradation.

Inorganic nitrogen—The sum of the concentrations of nitrate, nitrite, and ammonia/ammonium in a water sample.

Inorganic phosphorus—Phosphate and all other (less common) oxidized forms of phosphorus.

Landslide- A general term describing the downslope movement, under gravity, of masses of soil and rock material. There is a broad range of landslide types, rates, pattern of movement and scale.

Large woody debris (LWD)—A large piece of relatively stable woody material having a diameter greater than 20 cm and a length greater than 1.8 m that intrudes into the stream channel. (Flosi, et al., 1998).

Non-point source pollution—Pollution or contaminants that are supplied diffusely from the landscape; the source does not occupy a small area nor has a concentrated output, for example, a single source such as a pipe or culvert does not exist.

NTU—Nephelometric Turbidity Unit, a standard measure of turbidity. Measures the attenuation of light by organic and inorganic particles in suspension in a water column.

Outcrop—That part of a geologic formation or rock type that appears at the surface of the earth. Also, bedrock that is covered by surficial deposits such as alluvium.

Pebble count—a sampling method used to determine the particle-size characteristics of alluvial surface sediment. Pebble counts select and hand-pick a present number of surface particles at evenly-spaced increments along transects that may be parallel and span a relatively large sampling area (about 100 m^2). (Bunte and Abt, 2001).

Planform—The aerial form or pattern of a channel. The planform may be straight, braided, or meandering. Planform is dependant upon the width-to-depth ratio, bank stability, valley gradient, sediment transport rate, and bedload transport, among other factors.

Pool deposit—a package of typically fine (mud, silt and sand sized) sediment deposited in a pool bottom. This deposit may cover the bottom as a thin veneer, or may fill a substantial portion of the pool volume. (Bunte and Abt, 2001).

Pool residual depth—The maximum water depth of a pool minus the water depth at the pool outlet. This method allows pool depth to be consistently measured despite water level on any given day.

Reach—a defined length of the creek channel.

Return interval—The statistical probability of how frequently a flood of a particular discharge will occur. It's the average time (in years) between events. Where discharge data has been collected, return interval is calculated as the (number of years of stream discharge record + 1)/rank of that discharge.

Revetment—Durable materials (usually rock or concrete) used to protect a stream bank from erosion.

Riffle—A bed feature with gravel or larger grain sizes, relatively shallow water depth, swift flows, and a steeper gradient than the average gradient of the channel. Riffles are produced during high flows by the accumulation of large bed materials.

Rill—The smallest natural feature formed by channelized surface runoff (Collins et al, 2001).

Riparian—Pertaining to anything connected with or immediately adjacent to the banks of a stream or other body of water. (Flosi, et al., 1998).

Sensitivity analysis—An analysis of how sensitive outcomes are to changes in the assumptions, data, errors, and uncertainties that are used in the model or budget.

Sheetwash—the removal of thin layers of surface material more or less evenly from an extensive area of gently sloping land, by broad continuous sheets of running water rather than by streams.

Soil piping—erosion of soil material through the development of small conduits, or pipes, within the soil profile.

Staff gauge—A permanently affixed device that measures the water stage (height of water level) above a known datum or reference. Often staff gauges are porcelin-covered metal plates that are divided into tenths of feet, and resemble a large ruler. Allows an observer to record water level versus time.

Stability—the ability of a stream to transport the water and sediment of its watershed in such a manner to maintain its dimension, pattern and profile, over time, without either aggrading nor degrading. (Rosgen, 2001).

Stage—the elevation of a water surface above or below an established datum or reference. (Flosi, et al., 1998).

Suspended sediment concentration (SSC)—The concentration is measured as the total weight of sediment carried in suspension in a known volume of water.

Syncline—A fold of which the core contains the stratigraphically younger rocks; it is generally concave upward.

Terrace—A flat adjacent to the river in alluvial valleys created by the abandonment of the floodplain. Many higher terraces are related to elevations associated with the Holocene period. (Rosgen, 2001).

Thalweg—the line connecting the lowest or deepest points along a stream bed. (Flosi, et al., 1998).

Turbidity—Relative water clarity. A measurement of the extent to which light passing through water is reduced due to suspended materials. Typically measured in Nephelometric Turbidity Units (NTU). (Flosi, et al., 1998).

Water year—A continuous 12-month period during which a complete annual cycle occurs. USGS uses the period October 1 to September 30 in the publication of streamflow records. (Flosi, et al., 1998).