Pinole Creek Watershed Sediment Source Assessment: Pavon Creeks Sub-Basin

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Prepared by the San Francisco Estuary Institute

for

Contra Costa Resource Conservation District
And
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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 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

This technical data report presents summarized field data collected between November 2005 and May 2006, as well as findings and recommendations for future action in the Pavon Creeks sub-basin, a tributary to Pinole Creek, in western Contra Costa County. This project is designed as a short, small-budget, focused study, and is not intended to provide a comprehensive study of the sub-basin, a world literature review, or a complete sediment budget.

The Pavon Creeks sub-basin currently provides a large supply of fine-grained sediment to the Pinole Creek mainstem, to the detriment of creek function, flood conveyance, bank erosion, habitat for native species, and aesthetic value. This sub-basin displays active landslides and actively eroding, downcutting and extending gully channels. The primary goal of this assessment is to gain a better understanding of the processes and rates occurring within the sub-basin, so that the stakeholders and land managers can make more informed decisions regarding current and future management of the basin. The three objectives within this study are to: identify the dominant processes that contribute to erosion, instability, and downstream sediment delivery from the basin; collect baseline geomorphic data, especially spatial characteristics of sediment supply, erosion rates, and factors contributing to sediment supply; and develop recommendations for future restoration and management of the sub-basin.

The Pavon Creeks sub-basin is composed of four ephemeral channels that drain directly into the Pinole Creek mainstem. The sub-basin is underlain by complexly faulted and folded bedrock geology, and contains many active and dormant landslides that are intimately linked to the drainage network. The sub-basin received 42.5 inches (108 cm) of rainfall during Water Year 2006. However, the wet season only had one major storm (New Years Eve), with a majority of the rain falling as a series of small to medium storms during the months of December and March.

A large and varied set of field-based geomorphic data were collected, including channel cross-sections to determine change over the wet season. Although we observed channel incision, aggradation, bank erosion, and areas with little to no change, the majority of cross-sections increased in cross-sectional area, either through bed incision or bank erosion. In addition, we also observed a zone of deposition in the middle portions of the watershed, where cross-sections consistently display significant aggradation over this wet season. Channel headcuts, or knickpoints, were observed to retreat, extending the drainage network. The headcut with the largest amount of headward extension observed this wet season retreated a total of 16.3 m. Measures of grainsize distribution show that the overall distribution is very fine, with median grainsizes ranging between 1.4 and 2.6 mm (coarse sands and fine gravels), reflecting the erosion of fine-grained sediment, primarily soils and valley alluvium. Most of this fine-grained sediment is transported as suspended sediment, as evidenced by the high values of turbidity measured throughout the season.

The entire sub-basin appears to be rapidly responding, and is in a state of complex response, with channel reaches out of phase (some reaches incising and widening, and others aggrading). The largest storm events of the season appear to cause the greatest instantaneous amounts of change in the basin, but cumulative seasonal rainfall likely plays an important part in determining the total amount and rate of erosion observed. This year's greater than average precipitation total likely drove the relatively high rates of measured erosion, however, these rates do appear to be well within the norm. We suggest that the largest total volume of sediment supply within the sub-basin is currently from landslides and bank erosion (slumps and blocks), followed by bed incision, and

lastly, contributing only minor volumes of sediment is land uses, such as ranch road erosion and pasture surface erosion. We hypothesize that the long history of land use on top of the erosion-prone geology is the most important factor in the behavior and response of the Pavon sub-basin. The underlying geology and structure, especially the Eocene-Oligocene beds and the Capay Shale, appear to be important factors in the behavior and response of the basin, having control on the topography and basin-wide erosion potential. The single period of drainage adjustment and response that we currently observe likely began in the early 1900s in response to land use. Within this long single period, there are likely shorter periods of small-scale rapid aggradation or incision, possibly in response to shorter scale (annual or decadal) climate patterns. The most recent period of incision, beginning in 1993, is probably one of these shorter periods, within the larger long-term response.

Successfully controlling excess sediment erosion and restoring the landscape to a state of quazi-equilibrium will take careful design, and progressive and patient stewardship. We suggest that reducing fine-grained sediment supply to the Pinole Creek mainstem and maximizing land profitability will remain significant challenges for many decades to come. Addressing the contribution of fine-grained sediment from the sub-basin to the mainstem of Pinole Creek could have significant effects upon downstream water quality, aquatic habitat, and quality of potential spawning gravels. The data collected in this study is intended to help land managers focus their attention upon processes and areas of the sub-basin that are providing the most sediment. Our understanding of the sub-basin is continuing to evolve and develop, and continued future observation and data collection will be key in enacting a successful management or restoration plan. In spite of the course of action that is eventually chosen by the stakeholders, we generally recommend that the focus should be on the drivers of basin instability, rather than just addressing the effects of instability. The best solution may be to address the many causes of sub-basin instability, such as concentration of flow, decreased infiltration, and trampling of channel banks, and then enact the fewest number of designed structural elements, such as headcut protection, bank planting and stabilization, and culvert energy dissipaters. A combination of land stewardship and structural controls will likely best provide the basin-wide stability the stakeholders are seeking. Despite the many challenges presented by this sub-basin, we recommend that stakeholders pursue solutions to address the instability, and the supply and delivery of excess sediment from the watershed.

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INTRODUCTION

Creeks and rivers function as conduits to transport water and sediment from the landscape, through the Bay, and ultimately to the ocean. The hillslopes and fluvial system are intimately linked, as processes occurring in one can significantly affect the other. Creek and river channels will adjust through time to the balance of water and sediment supplied to them from the hillslopes and the drainage basin. Drainage basins and their components, slopes and channels, are either adjusting rapidly to altered conditions (instability), or they are in dynamic equilibrium with present conditions (Schumm et al, 1984). These two conceptual end-member drainage basin conditions create quite different land management opportunities and difficulties.

Alluvial channels can take many shapes, or morphologies, based upon subtle differences in geology, tectonics, climate, and land use history. The channel's hydraulic geometry (width, depth, slope, grainsize, and sinuosity) will mutually adjust to most efficiently transport the water and sediment supplied to it, creating a range of different dynamic channel shapes. However, the channel system in the Pavon Creeks sub-basin is not the typical alluvial creek channel, in which the bed and banks are composed of the material it is transporting. Instead, the Pavon Creeks drainage system is incised, and has the morphology of a system of gullies. But, Pavon Creeks, and the larger Pinole Creek watershed, are typical of many other central California creeks, because they have experienced, or are experiencing watershed-scale incision and drainage basin rejuvenation. For example, a study of central coast California streams by Cooke and Reeves (1976) revealed a widespread and significant period of mainstem channel incision and arroyo development as early as 1850 to as late as 1920 in response to increased runoff, greater concentration of flows, and removal/alteration of vegetation communities.

The term gully is somewhat ambiguous because it is commonly used, and often refers to many different landscape features, therefore, we must be clear and explicit in our definition and terminology while discussing the gully system in the Pavon Creeks sub-basin. In this study, the term gully refers to a more specialized meaning, as described by Gregory and Walling (1973):

> "Gullies…often have ephemeral streamflow, they are often incised into unconsolidated materials, and they may have a V-shaped cross-section. In size, they are larger than rills, they are usually bordered by steep sides and heads which often have the appearance of erosional scarps, and they are usually so deep that restoration is impossible with normal tools, and they cannot be crossed by a wheeled vehicle or eliminated by plowing."

Continuing with the explicit definition, Schumm et al (1984) make the distinction between gullies and entrenched streams:

> "A [valley-side] gully is a small, steep-walled, sharply incised, elongate depression on valley sides, that is the result of the expansion of the drainage network. Whereas an entrenched stream flows in a steep-walled trench cut into alluvium, and is the result of deep incision of a pre-existing channel, implying instability and significant alteration of the landform. The gully forms where no channel or only an insignificant channel existed previously, and the entrenched

> stream is the result of a major change or metamorphosis of an existing channel by natural or man-induced causes."

Although we will use the general term gully in this data report, we intend that the mainstem of each of the major Pavon Creeks channels is an entrenched stream (following the description of Schumm et al, 1984) with the characteristics described by Gregory and Walling (1973), and many of the tributaries off the mainstem are actually true valley-side gullies, as described by Schumm et al (1984). All of the channels in the Pavon Creeks sub-basin are ephemeral, unstable, respond to intrinsic and extrinsic thresholds, have some capacity for cyclic response, and are intimately linked to the underlying geology and the land use in the basin.

The gully system in the Pavon Creeks sub-basin currently appears to be in a period of rapid adjustment, as evidenced by the current unstable morphology. The supply and transport of large volumes of sediment to Pinole Creek is a consequence of this adjustment. Although sediment transport is a primary function of a channel, excess sediment supply and transport can decrease the quality and quantity of aquatic habitat, increase flood hazards, reduce water quality, and increase the transport of contaminants within that channel.

Within a basin, land use and land management can cause soil compaction (vehicles and animal trampling), a decrease in permeability, and a change in the vegetation community. These factors usually result in greater runoff and excess sediment supply from hillslopes (landslides and surface soil erosion) and from channels (gully development, bed and bank erosion) as the basin adjusts. However, certain types of bedrock lithologies can also be naturally highly erosive, and can contribute significant pulses of sediment to the channel system. In the case of Pavon Creeks, the precise cause of this period of rapid adjustment, whether it be due to a natural cycle in the long-term basin evolution, or due to historic land use and management can not be conclusively determined. We suggest that the adjustment is likely a result of the long history of intensive land use and management on top of erosion-prone lithologies and soils. One can argue the relative contributions of natural or land use related causes of the physical appearance and processes presently occurring in the Pavon Creeks sub-basin. However, no matter the cause, land management actions that focus upon how the land use and physical features of the watershed interact have great potential to significantly reduce the supply of excess sediment to a creek and increase the viability and profitability of the land for measured agricultural use.

Overarching project questions

Previous studies have found that the Pavon Creeks sub-basin is providing fine sediment to Pinole Creek. We suggest that the drainage network is in a period of rapid adjustment due to a combination of land use/management and the properties of the underlying geology and soil. If this is the case, a number of questions arise regarding the formation and evolution of this basin-wide adjustment. These questions include:

- How is the sub-basin currently responding and adjusting?
- How has the sub-basin responded in the past?

- When did the current response begin? When did the current phase of gully development occur?
- How quickly is the sub-basin responding? What are the rates of the dominant physical processes occurring?
- How much sediment is being supplied to Pinole Creek?
- What caused the gully development?
- How can we expect the sub-basin to continue to evolve?
- How can our knowledge and observation be used to drive future management of the sub-basin?

Because of the limited scope of this project, we can not definitively answer each of these questions. However, this project was designed and executed with this set of questions in mind. These questions are implicit in the project goals and objectives (below), and also help to organize the collection of geomorphic data and the limited collection of historic and current land use information. Overall, the data collected and information gathered in this report provides the stakeholders with a much greater understanding of the basin, and hopefully can be built upon in the future, allowing all of these questions to ultimately be answered.

Project goals

The Pavon Creeks sub-basin currently provides a large supply of sediment to the Pinole Creek mainstem, to the detriment of creek function, flood conveyance, bank erosion, habitat for native species, and aesthetic value. This sub-basin displays active landslides and actively eroding, downcutting and extending gully channels in response to both historic and current land use practices. The excess sediment supply is especially problematic because Federally-listed threatened steelhead/rainbow trout (*Oncorhynchus mykiss*) as well as other endangered or threatened species have been documented in the Pinole Creek mainstem.

The larger Pinole Creek Watershed goals have been established and well-documented in the previous Pinole Creek Watershed Vision Plan document (Urban Creeks Council, 2004). Some of these goals include restoring native habitat, improving water quality, ensuring flood protection, and provision of educational opportunities. This current study strives to be consistent with these larger watershed and ecosystem goals, but because it is focused on a specific sub-basin in the watershed, the study also addresses more specific project goals. This study is focused upon the physical characteristics of the Pavon Creeks sub-basin as it relates to supply and transport of sediment and water downstream. The primary goal of this assessment is to gain a better understanding of the processes and rates occurring within the sub-basin, so that the stakeholders/landowners/land managers can make more informed decisions regarding current and future management of the basin.

Project objectives

In order to meet the primary project goal, we created a series of specific project objectives that would design and drive this study. Our first objective was to identify the dominant processes that contribute to erosion, instability, and downstream sediment delivery from the basin. In order to accomplish this, we chose specific datasets that were quick and inexpensive to employ, and would provide direct measurement of processes we hypothesized to be important, based upon our previous experience in the Pinole Creek watershed, and the previous Pavon documents. For example, previous observation suggested that the gully system was highly unstable, and had the potential to supply large volumes of sediment. Therefore we measured cross-sections and installed bank pins to understand the amount and rate of channel erosion. We also knew that most of the erosion occurs during rain events, so we spent time in the field making observations while it was raining. Our second objective was to collect baseline geomorphic data, especially spatial characteristics of sediment supply, erosion rates, and factors contributing to sediment supply. And finally, using both the data collected, and findings from previous documents, our third objective was to develop recommendations for future restoration and management of the sub-basin. In the future, these recommendations will provide the foundation for the next steps that will be taken by the basin stakeholders.

This technical report presents the field data collected between November 2005 and May 2006, the synthesis of findings, and the recommendations for future action. This current study follows from the previous Pinole Creek Watershed Sediment Source Assessment report (Pearce, et al., 2005). Many of the recommendations in the previous report directly relate to Pavon Creeks, and were helpful in guiding this study, including: focusing management actions on stabilizing actively eroding gullies, employing management actions that reduce sediment supply caused by historic and current land use, limiting high intensity land use on areas of naturally erosion-prone geology, and finally, encouraging collaboration between land owners, agencies and funding sources.

In addition to the Pearce et al (2005) report, a number of other previous documents and reports have been generated for the Pavon Creeks sub-basin. These include a number of short technical reports written by the US Army Corps of Engineers, including: The Section 206 Without Project Conditions Milestone Materials report by USACE Tyson Eckerle (2003), and the USACE Aquatic Ecosystem Restoration Preliminary Restoration Plan (2001), and a single report written by a consulting firm (Levine Fricke Consultants, Erosion Control for Pavon Creek and Other Tributaries of Pinole Creek, 2001). These previous reports were very limited in scope, but often contained important background information, observations, and specifics regarding potential restoration methods. Throughout this report, we build upon the information gathered and created by the previous documents.

Project limitations

The analysis and interpretation of the collected datasets was limited by the timing and funding level of this project. This project was intended to be a short, small-budget, focused study to collect important baseline data on the sub-basin, following from findings and recommendations in the previous Pearce et al (2005) report and other Pavon Creeks documents. This study was not intended to be a comprehensive study of the sub-basin, did not have a large enough scope to complete a literature review on many of the important physical processes, nor was it intended to provide a complete sediment budget for the sub-basin. Instead, in this data report, we provide short summaries of the baseline geomorphic data collected and observations made, and only analyze the data in common and straight-forward methods. Our hypotheses and recommendation reflect the limited data analysis, and would benefit from additional analysis. For example, a complete sediment budget could be developed using a combination of field data and data/rates from the literature. The science of ephemeral channels is rapidly evolving, therefore, a thorough consultation of the world's literature on ephemeral channels and the stabilization of such systems in disequilibrium would also be of great benefit to the project partners, but is also outside the present project scope. The success of solutions that address the styles of bank erosion, downcutting, and headcutting that we observe here would be enhanced by the latest information found in literature describing similar types of systems.

Future studies

In the future, with additional budget, future studies should focus on:

- the timing and details of bank erosion,
- the importance, activity, and sediment generated by landslides,
- the role of groundwater in the basin, including how it affects channel incision and riparian vegetation success,
- the detailed history of land use and its effects on the landscape,
- the age of the fill terrace in the lower reach of Gully A,
- the history of the Pinole mainstem in rejuvenating the channel system (completing a detailed longitudinal profile of the mainstem through this region),
- quantifying the amounts of sediment directly produced from current land use activities,
- re-occupying study sites to observe how the system has progressed and responded.

Any future studies should place the sub-basin in the larger Pinole Creek Watershed setting, and should directly benefit the management or restoration activities deemed appropriate by the stakeholders.

SETTING

The Pavon Creeks sub-basin is a tributary to Pinole Creek, a 39.6 km^2 watershed located in western Contra Costa County, California (Figure 1). Pinole Creek is a perennial third-order creek which flows into San Pablo Bay. The Pinole Creek watershed is underlain primarily by Miocene to Eocene sandstones, shales, and volcanic tuffs which are complexly faulted and folded. Land use in the lower portion is primarily urban residential, whereas the middle and upper areas are varying mixes of grazing, horse ranching and open space. The region has a Mediterranean climate with an average annual precipitation of 610 mm (24 in). On average, over 90% of the annual precipitation and 93% of its annual flow occurs during the wet season. Further details about the Pinole Creek watershed can be found in the previous Pinole Creek report (Pearce et al, 2005). The Pavon Creeks sub-basin is located in the middle third of the Pinole watershed, joining the mainstem from the south. The sub-basin is located entirely on EBMUD land, which is currently leased for grazing. Pavon Creeks has a total watershed area of 1.1 km^2, extending from an elevation of 226 m (740 ft) at the highest drainage divide, to 53 m (175 ft) at the lowest confluence with the Pinole Creek mainstem.

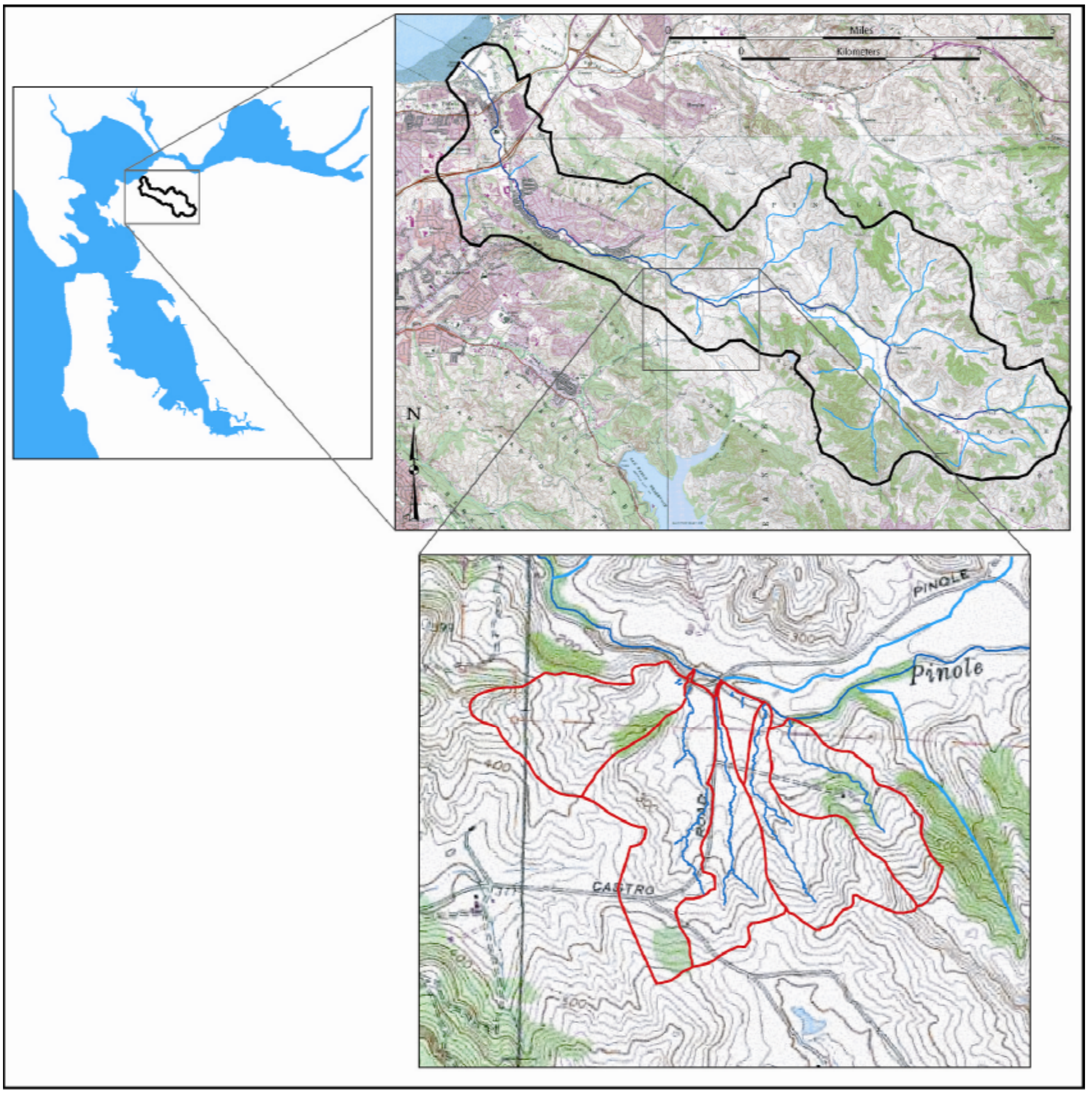


Figure 1. Location map showing the Pinole Creek watershed in black, and the six watersheds of the Pavon Creeks sub-basin in red.

PAVON CREEKS SUB-BASIN SITE DESCRIPTION

The following section describes the physical make-up of the Pavon Creeks sub-basin, and is organized into four major sections: watersheds, underlying geology and structure, soils, and landslides. Each section details how the initial, natural setting of the sub-basin is affecting the basin-wide rapid response that we currently observe.

Watersheds

The Pavon Creeks sub-basin is composed of a total of six sub-watersheds, four of which are major, and contain an ephemeral channel that drains directly into the Pinole Creek mainstem (Figure 2). This study focused on the four major watersheds and the smallest watershed. However, the study excluded watershed Aa, which is actually a tributary of Gully A that joins almost immediately upstream of Pinole Valley Road. The major watersheds are named from west to east: Gully A, Gully C, Watershed BC, Gully B, and Gully D. Watershed BC, the smallest watershed, does not have a channel, but is merely pasture area that drains directly into the Pinole Creek mainstem. The gully naming convention is based on the subjective determination of the potential success and urgency of restoration (A being more successful and urgent than D) described previously (USACE, 2001; USACE, 2003). Although the four main gully watersheds share many similarities (especially compared to other surrounding Pinole Creek tributaries), descriptions throughout this data report illustrate the differences between the four.

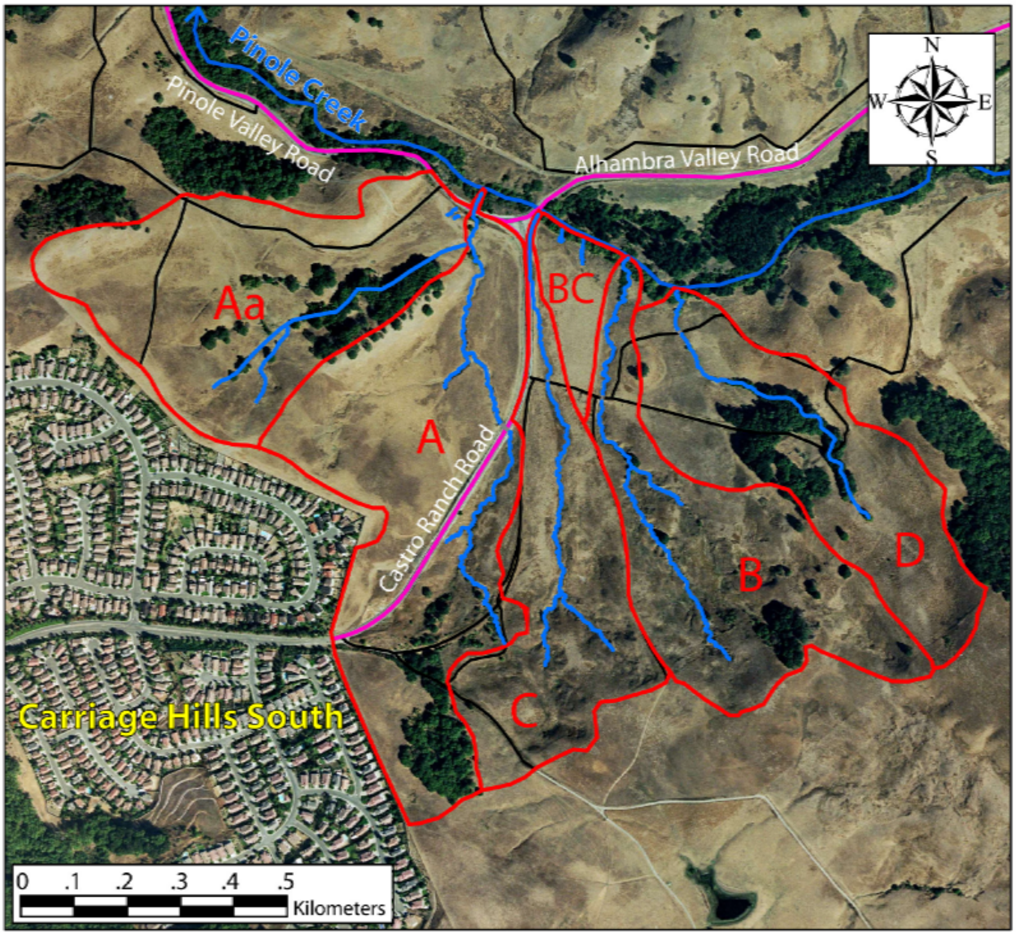


Figure 2. Generalized Pavon Creeks map showing the watershed boundaries (labeled in red), locations of gullies, roads, and the Pinole Creek mainstem. Pinole Creek flows from right to left. Note, the Carriage Hills South development is not within the defined watershed area of Pinole Creek.

Table 1. Characteristics of each of the Pavon Creeks watersheds.

Sub-watershed	Area (km^2)	Area (mi^2)	Area (acres)	Channel length (m)	Overall channel gradient (%)
Aa	0.228	0.088	56.405	-	-
A	0.303	0.117	74.858	1009	3.6
B	0.195	0.075	48.277	982	7.9
BC	0.031	0.012	7.774	36	-
C	0.170	0.066	42.090	918	6.3
D	0.186	0.072	45.983	675	12.7
TOTAL	1.113	0.430	275.028	-	-

Underlying geology and structure

We suggest that the lithology and complex structure of the underlying geology has an influence on the physical processes occurring in the sub-basin, including the erosion-prone hillslopes, and the location and persistence of the drainage system. The bedrock geology in the Pavon Creeks sub-basin and in the larger East Bay Hills region is very complex, dominated by the regional northwest-trending structural and tectonic grain of the Hayward and other major fault systems. This area has been mapped by many different authors during the 20th century, but the most recent, regionally-comprehensive mapping was completed by Graymer et al (1994) of the USGS (see map in Pearce et al, 2005). The Pavon sub-basin is mapped as Tshc (Tertiary shale and claystone), Ts (Sobrante sandstone), Tcs (Claremont Shale), and To (Oursan sandstone). However, other mapping exists, including that by Ron Crane, an independent structural geologist, who also mapped portions of the East Bay in detail, including the Briones Valley Quadrangle, which includes the Pavon sub-basin (Figure 3). Based upon our observations in the field, we conclude that the Crane map is more detailed, and more accurately portrays the underlying lithologic units and complex structure of the sub-basin and is the most appropriate for analysis of geomorphic processes.

The Pavon Creeks sub-basin is underlain primarily by Eocene-Oligocene beds, Capay Shale, Sobrante sandstone, Claremont Formation, and Oursan sand and siltstones (Crane, 1995). These units generally follow the regional northwest trend in the southern portion of the basin, but trend east-west in the northern and western portions of the basin. This change in trend is due to the right-lateral strike-slip fault, mapped near the intersection of Alhambra Valley Road/Pinole Valley Road and Castro Ranch Road. The lowest reaches of the basin are all mapped as Quaternary alluvium, which obscures the exact location of contacts and faults. Three lithologic units play the largest role in determining the topography, soil development, and erosion potential of the basin. First, the Eocene-Oligocene beds underlie the majority of the headwaters of Gully A. Here we observe strongly shrink-swell soils (Altamont clay soils), and large areas of shallow slump and rotational-style landsliding. Large cracks develop in the hillslope soils, allowing surface water to easily infiltrate. Although most of the landslides occur on hillslopes above the drainage lines, some fail directly into drainages, contributing large volumes of sediment directly into the creeks. These landslides locally affect the channel gradient and hydraulics in the channel, providing a driving mechanism for continued incision and gullying, intimately linking the hillslopes to the channel network. Second, the Oursan sandstones and siltstones (underlying large portions of the Gully D watershed), generally hold up much higher topography, and are less prone to large-scale mass wasting. This geology has encouraged a narrow, steep, stepped Gully D channel profile to develop, with much lower sediment production and transport. Primarily Millsholm loam soils develop on this lithology. This basin also has a perennial spring in its headwaters, likely contributing to generally wetter conditions that persist longer throughout the summer and fall. And finally, and most importantly, the Capay Shale lithology underlies large portions of the headwaters of Gullies B and C. This unit is very prone to erosion and large mass-wasting events, typically failing as earthflow and rotational-style landslides. Similarly to the headwaters of Gully A, these gullies also are directly linked to the surrounding landslide and mass-movement processes. The soils that develop are also the shrink-swell Altamont clays, and show the most evidence of compaction and modification from cattle trampling. The channels in this unit have incised very deeply, exposing portions of the very friable and weathered bedrock. The channel slopes fail by slumping, dry ravel, and debris flows, and input large amounts of sediment directly into the channel. Evidence of this lithology's propensity to fail can be observed in the adjacent watershed to the south, as an extremely large, active landslide has developed in this same unit. These two units, the Capay Shale and the Eocene-Oligocene beds (mapped as Tshc by the USGS) do not outcrop elsewhere in the Pinole Creek watershed, making the Pavon Creeks sub-basin unique.

In addition to lithology, the complex structure of the area also strongly controls the sub-basin. In general, rocks that have undergone a history of folding and faulting are weaker and more prone to weathering and erosion. Lithologic contacts often can be zones of weakness, in which mass-wasting failure planes can develop, and can also be zones of preferential groundwater transport. In addition, fault zones (and the associated weaker rocks in the zone) and structural trends can control the location and orientation of drainages. This appears to be true for Pavon Creeks. Many creek segments, especially in the headwaters and along the Pinole Creek mainstem, directly follow either a mapped fault zone, or have the same orientation of the lithology (Figure 4). Because of this structural control, these drainages have likely been in the same general location for hundreds to thousands of years, despite continual changes in morphology related to gully evolution cycles, climate, and land use. And because the drainage lines likely follow routes of preferential groundwater transport, the groundwater can play a larger role in erosion and knickpoint migration. For example, if a fault zone is routing groundwater, and is also controlling the location of a channel, where the groundwater table intersects the ground surface (likely at a knickpoint location), the larger amount of groundwater can contribute to higher rates of erosion via piping (see later results and discussion).

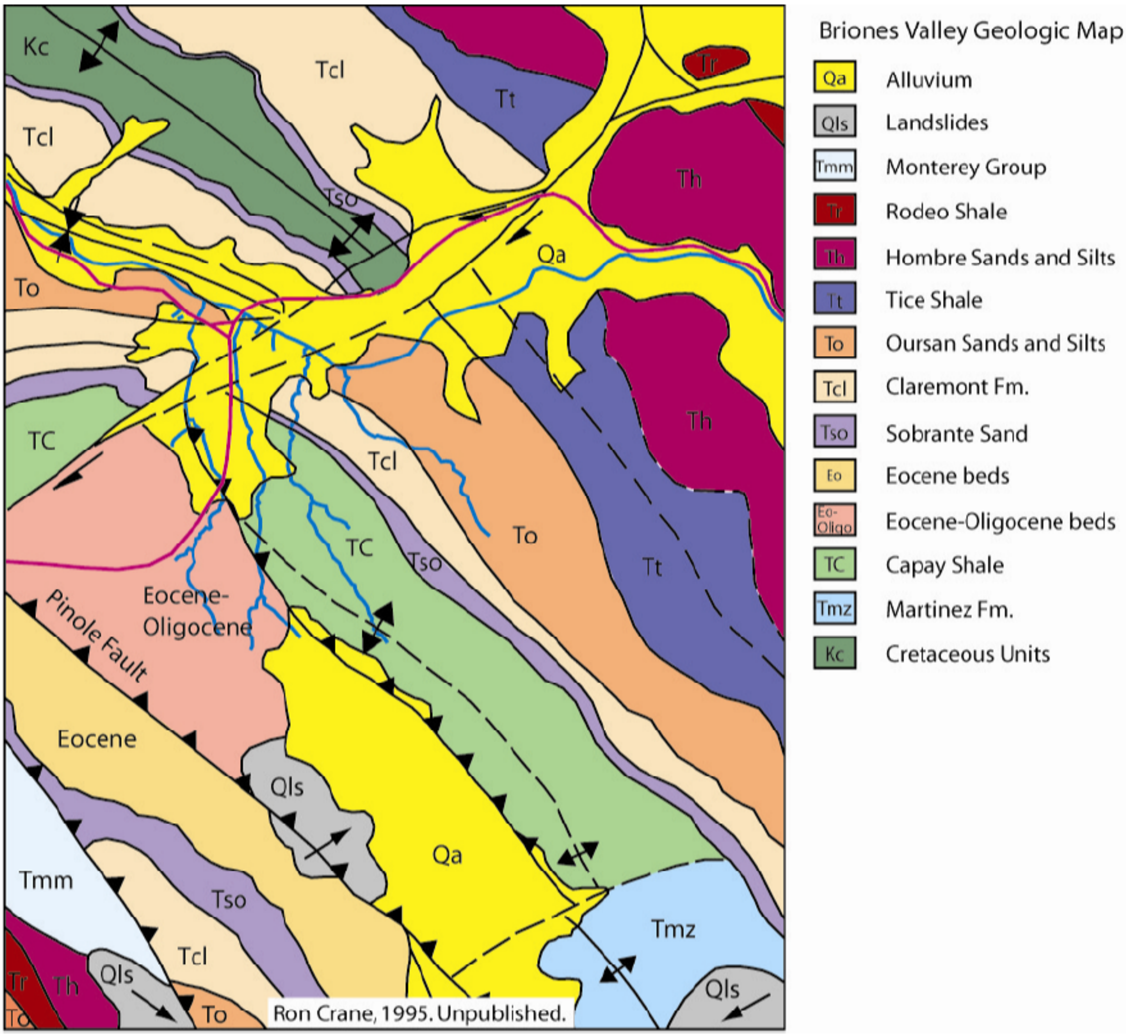


Figure 3. Portion of the bedrock geologic map showing the major lithologic units and structure of the Pavon Creeks region. From Crane, 1995. Pinole Creek and Pavon Creeks are shown in blue (other creeks omitted for simplicity). Alhambra Valley Road/Pinole Valley Road and Castro Ranch Road are shown in pink.

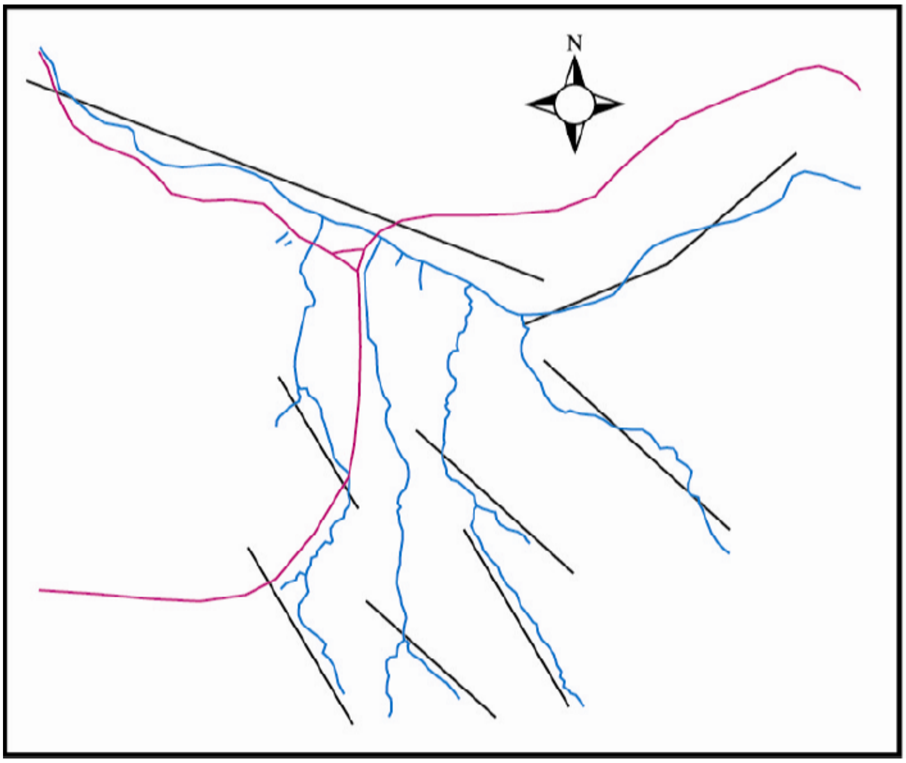


Figure 4. Simplified map illustrating how the regional structural fabric controls the location of drainage patterns. A generalized line (black line segments) representing the adjacent lithologic and structural trend is shown next to selected channel reaches. Channels are shown in blue, and roads in pink.

Soils

Soils also play a role in the magnitude and style of mass wasting that occurs in the Pinole Creek watershed (Pearce et al, 2005). This is particularly true in the Pavon Creeks sub-basin where erosion (channel incision, bank erosion and landslides) are occurring primarily in soil units, rather than bedrock, contributing primarily fine-grained sediment to the drainage network. Soil units include Altamont clay, 15 to 30 percent slopes on the upper watershed (AbE), Cropley clay, 2 to 5 percent slopes on the lower watershed (CkB), and Millsholm loam, 30 to 50 percent slopes in the upper reaches of Gully D (MeF) (Figure 5). These soil units generally have low shear strengths, slow infiltration rates, and high runoff potential (USACE, 2003). A brief field visit with two USDA Natural Resources Conservation Service staff, Ken Oster, Area 2 Resource Soil Scientist, and Lisa Hokholt, District Conservationist for Contra Costa County, provided the following findings (from Oster, 2006 report; see Appendix N). Both the Altamont and Cropley soil units are clayey throughout, with high shrink-swell potential, and often crack deeply when desiccated during the dry season. These cracks provide a preferential flow path for early season rains, until the cracks swell shut with additional precipitation. There is little surface runoff due to the cracks, and also because these units are well-aggregated and vegetated. Many observations of livestock hoof prints suggest that compaction has reduced infiltration rates further. Altamont soils are vulnerable to rotational landslides, even in undisturbed areas, however because they are well vegetated, they often do not contribute sediment directly into the gully systems. Precipitation often exceeds the soil's infiltration rates, causing surface flow across the pasture, pushing grasses over, and providing the source of water to the gullies. The lower portions of Gullies A, B and C typically fail as blocks, because the Cropley soils develop desiccation cracks, causing blocks to be loosened, and then failing when wetted by precipitation and runoff. However, the upper portions of Gullies B and C typically fail by crumbling, due to closer-spaced desiccation cracks, and exposures of highly fractured and friable bedrock material. Also, the soils at Gully D are typically clayey, but are more loamy immediately at the headcut located at DXS2 (see Figure 19 for location).

The fluvial fill terrace in the lower portion of Gully A provides evidence of at least one cycle of cutting and filling. In other words, the terrace in this reach is composed of soils that have been deposited in a void created by an earlier gully of at least the same size as the current gully. The material comprising the inset terrace closely matches that of the Altamont soil found further upstream, and is likely the source of this fill. Although this is the only location where such evidence exists, it suggests that these gullies are capable of cycles of cutting and filling, although probably not at the same magnitude as we observe today.

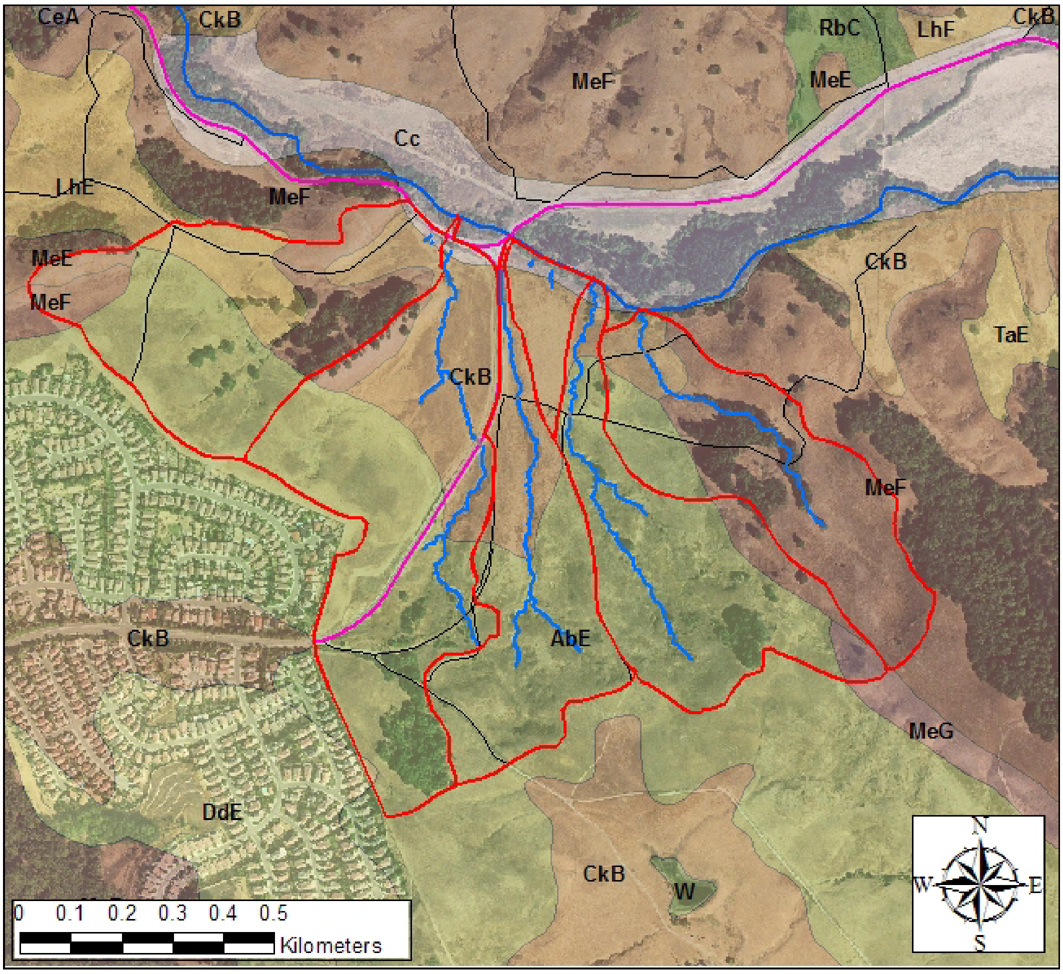


Figure 5. Soils of the Pavon sub-basin. Soil units from the USDA. AbE = Altamont clay. CkB = Cropley clay. MeF = Millsholm loam. Cc = Clear Lake clay. See Appendix N for further soils description.

Landslides

The previous Pinole Creek Sediment Source Assessment (Pearce et al, 2005) concluded that active landslides are the largest source of sediment to the creek system in the watershed. These mass-wasting events are typically episodic, and have the potential to deliver large volumes of loose sediment directly into a channel. The previous mapping shows large areas of the Pavon Creeks sub-basin as containing dormant landslides (Figure 6). In this report, the landslide term is used loosely, as a catch-all term to describe landslides and all other mass-movement types including: Active, or those with evidence of movement in the previous 50 years, Dormant, or those with evidence of movement in the previous 50 to 100 years, and Holocene, or those with evidence of movement more than 100 years ago, and more likely in the Holocene Period 10,000 years before present to present (Pearce et al, 2005).

In the previous Pinole Creek Sediment Source Assessment study (Pearce et al, 2005), landslides were assessed by grouping portions of the watershed into zones. The upper portion of the Pavon sub-basin was classified as a single zone (Zone 5), and then compared to other zones in the watershed. About 76% of Zone 5 was mapped as landslide, with the largest proportion as dormant landslide, with smaller areas of active landslides and gullies. Pearce et al (2005) also looked at lithology and soil type influences on landslide prevalence. The two lithologies present in the Pavon sub-basin mapped by the USGS as Tshc (Tertiary shale and claystone) and Ts? (mapped as likely Tertiary Sobrante sandstone) had the highest percentages of Dormant and Holocene landslides. And related to rock types, the soil types present in the sub-basin also had the highest percentage of area mapped as landslide, including the Altamont clay (largely dormant landslides), Millsholm loam (largely dormant and Holocene landslides), and Cropley clay (largely active gullies). In the previous study, the coarse-scale landslide mapping exercise demonstrated that the Pavon sub-basin is very prone to landslides and gullies, relative to other parts of the Pinole Creek watershed and was the dominant driver for further study in the sub-basin.

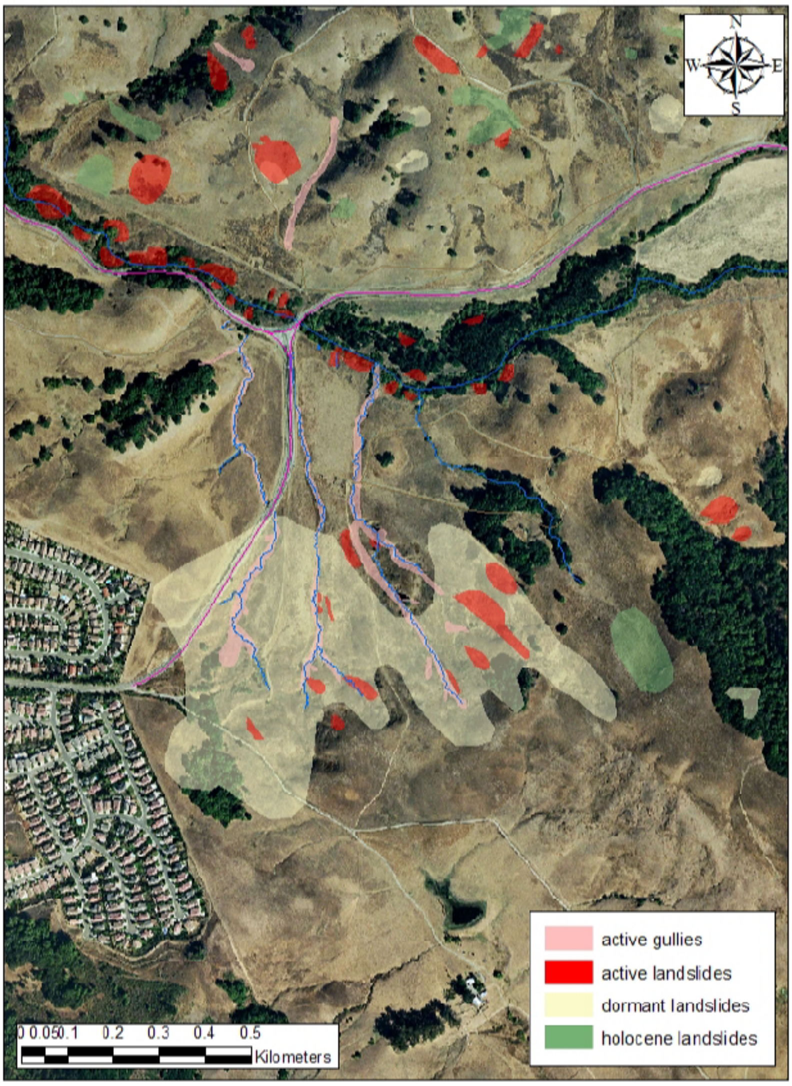


Figure 6. Previously mapped landslides in the Pavon sub-basin and surrounding region. Data from Pearce et al (2005).

During this present study, using the same 1989 aerial photographs, we re-mapped landslides, and used field observations and notes to assist the photograph interpretation. Figure 7 shows the updated mapping of landslides in the Pavon sub-basin, using the same classification as previously. The new mapping improves the previous effort by including more detail of the many smaller slides observable in the sub-basin. Although the new mapping has not been fully field checked, and does not show the large areas of dormant landslides as mapped previously, the increased detail will help future studies or restoration efforts that focus specifically in the Pavon Creeks sub-basin.

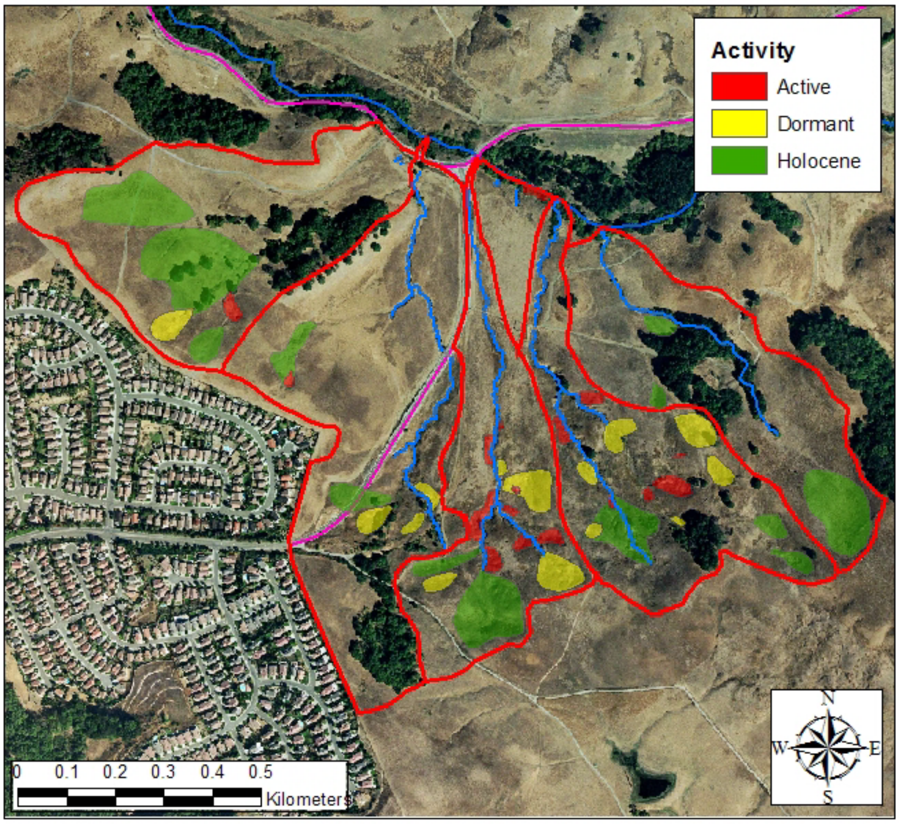


Figure 7. Updated preliminary mapping of landslides in the Pavon sub-basin. Mapping from aerial photograph interpretation of 1989 stereo black and white, 1:1200 scale photographs. Built upon the previous Pearce et al, 2005 study.

It is these many smaller dormant and active landslides that are currently providing a large portion of the total sediment volume to the gullies of Pavon Creeks. Due to the erosion-prone properties of the underlying bedrock, slides in the Pavon Creeks sub-basin have likely been occurring for hundreds to thousands of years. However, we suggest that the recent (in the past 100 years) frequency of landsliding has increased (over background rates) due to a history of changed vegetation, cattle grazing, soil compaction, and increased surface runoff from the hillslopes. In addition, we suggest that the landslides and drainage network are intimately linked. As landslides intermittently occur in the sub-basin, both the gradient and routing of water within the channels is modified. These short reaches of increased slope provide the driver (concentrated fluvial power) for initiation of localized channel incision. This localized incision will affect the sediment transport and gradient of adjacent reaches, necessitating a larger channel response.

PAVON CREEKS SUB-BASIN LAND USE

The following section describes the historic and current land use and land management of the Pavon Creeks sub-basin, and is organized into three major sections: historic land use, current land use, and roads. Each section details how anthropogenic actions can affect the physical response of the basin, regardless of whether the actions cause an immediate response, or accumulate and cause a delayed response.

Historic land use

Detailed history, including historical ecology, land use history, and physical modifications to a watershed can be invaluable in understanding the current form and function of that watershed. The human use of a watershed is linked to the physical features and layout of that watershed, and the watershed form is linked to the history of use within that basin. Many insights into current watershed processes and rates can be developed from a full assessment of the historical ecology of that watershed. For example, our past experience shows that often a watershed can continue to respond for many decades after a change in management such as forest clearing, agriculture or intensive grazing. The direct cause of any increased runoff or sediment erosion may not always be evident or obvious from merely observing the current landscape.

Although this project did not include a detailed assessment of the history of the Pavon Creeks sub-basin, we did gather limited information regarding land use history, and timing of important events from review of previous documents and personal communication with local land managers, including: Roger Hartwell, Rod Tripp, Bob Flasher, Alberta Nunes, and Frank Nunes. By reviewing and summarizing this information, we can gain a better understanding of how some of the land use and land management actions have affected the physical functioning of the sub-basin. The following paragraphs are organized sequentially, and relate back to the implicit overarching project questions described in the Introduction.

Before European contact, portions of the Pinole Creek watershed were likely under Native American management. A USACE report (2001) suggests that the Pavon Creeks sub-basin had an extensive riparian and oak woodland habitat along the channel corridors and upland savannah. While, compared to today, greater riparian vegetation likely did exist, we suggest that the ephemeral nature of these drainages limited the extent of riparian vegetation development. Following European contact, the area was held under Spanish and Mexican land grants, and later by smaller ranchos. The land was later managed by individual families, including the Pavon family. The Pavon family ran a dairy for a few generations (likely 30 to 60 years), with approximately 300 head of cattle grazing in the sub-basin and surrounding Pinole Creek area. This period of grazing was likely quite intense, and probably plays the most significant role in driving the future response of the sub-basin. Throughout its entire history, Pavon Creeks was likely always grazed, and never used for growing hay, wheat, or tomatoes.

The 1939 aerial photographs depicts the drainage network in the same location as today, and shows the channels to be as wide (and possibly nearly as incised) as today. The lowest reach of Gully A appears to have a channel that is wide and flat, with relatively fresh deposition of sediment. This suggests that the current phase of channel response likely began sometime in the early 1900s.

The land was purchased by EBMUD in the 1950s, with the planned development of a drinking water reservoir. However, the reservoir plans never came to fruition, and the land remained in the hands of EBMUD as open space and grazing leases. Until the 1980s, cattle were grazed year-round (USACE, 2003).

An analysis of historic aerial photographs by the USACE (2003) reveals that in 1953 (the date of the earliest photo) that the headwaters of Gully B were already very steep, slumping and unstable. Also, runoff from Castro Ranch Road (in its old location) was causing erosion of Gully A and C channels. In the 1974 photo, Gully B appeared to be aggraded (potentially caused by a plugged culvert) at and above the ranch road. Through time, the photos show evidence that the banks in the lowest reaches of Gully B are laying back. The photos also show the headcut on Gully D (now at DXS2) has propagated headward over 100 m since 1949.

After the Pavon family dairy stopped operations, a single person remained living at a location along the upper ranch road near Gully D. A large amount of trash was accumulated and dumped down the bank into Gully D. Although a majority of the trash has been removed (Bob Flasher, personal communication), significant amounts still remain.

Within the basin, two county roads (Alhambra Valley Road/Pinole Valley Road and Castro Ranch Road) and many smaller ranch roads and fire trails were built and maintained. Just over the southern border of the watershed, the Carriage Hills residential development was built in two phases: the portion on the north side of Castro Ranch Road was built before 1989, and the portion on the south side of the road was built during 1989.

A series of check dams were installed on Gully B (and possibly on Gully C) in the late 1980s. Only one of these dams remains (the grade control structure on Gully B downstream of the ranch road).

By 1991, the base level of Gully A downstream of Castro Ranch Road appeared to be slightly lower than previously (USACE, 2003). After the drought of 1987-1992, the wet season of 1993 brought significant changes to the fluvial system, as Gully A downstream of Castro Ranch Road began to incise, causing significant deposition of material at the mouth of Gully A, and water and sediment to flow over the surface of Pinole Valley Road.

The lowest reach of Gully C was repaired twice between 1995 and 1999, installing riprap along the south bank of Pinole Creek where the Gully C culvert enters, and installing the riprap in the road-side ditch (USACE, 2001). The county continues to maintain this location (clearing the culvert inlet) because water often rises and flows over the road during high flow events (USACE, 2003).

New grazing practices were adopted by EBMUD in 1996 (EBMUD, 1996), reducing the number of cattle grazed, and increasing the amount of residual dry matter remaining on the pasture. Alberta Nunes began to graze her cattle in the parcel east of Castro Ranch Road in 1998.

We suggest that the current channel response has been occurring since 1993, when the climatic events of that year renewed the gully development. However, this incision is a continuation of the response that began in the early 1900s. Between these dates, the system likely had shorter periods of incision and aggradation. We suggest that the current measured rates of erosion have not been occurring continuously since the early 1900s, because the sub-basin does not show evidence of severe erosion, essentially removing all of the topography and transporting it downstream.

Current land use

Currently, the entirety of the Pavon Creeks sub-basin is owned by EBMUD, with Contra Costa County right-of-ways for Alhambra Valley Road/Pinole Valley Road and Castro Ranch Road. Immediately over the drainage divide on the southwest side of the basin, is the Carriage Hills residential development. No evidence of any influence (storm water or sediment inputs) from the development was observed. Aside from the two roads, the sub-basin is entirely open space, which is used for grazing and wildlife habitat. Two separate grazing leases exist in the basin, the Nunes lease (Pavon pasture) on the lands east of Castro Ranch Road, and the Mohring lease (Pinole Y pasture) on the lands west of Castro Ranch Road. Grazing is primarily practiced for fuel management (to prevent or control wildfires), manage for vegetative species diversity and water quality, and to generate revenue for EBMUD.

The basic details of the two grazing leases were provided by EBMUD (Penny Spear, personal communication). On the Mohring parcel, approximately 50 head of cattle are grazed year round (the parcel is larger than the area in the Pavon drainage basin), with about 30 head moved to a different parcel from August to November. The lease does not require rotation between pastures, and no riparian out fencing is in place. The average amount of residual dry matter (RDM) remaining in the pasture (since 1998) is 2223 lbs/acre (with a goal of at least 1120-1600 lbs/acre for moderate utilization on 5 to 35% slopes). Cattle have been grazed here continuously for at least decades.

On the Nunes parcel, approximately 110 head of cattle are grazed from October through March (again, the parcel is larger than the area in the Pavon drainage basin). The lease requires rotation between pastures, ranging from 3 days in smaller fields to 2 weeks in the larger fields. These rotation requirements have been in place since the 1998-99 grazing year, however previously cattle were grazed with no rotation. The RDM goals are the same as for the Mohring parcel. Cattle are fully fenced out of the Pinole Creek mainstem with barbed wire (since 1994), and are fenced out of some areas of the smaller drainages with electric fence (since approximately 1998).

Roads

Roads in the Pavon sub-basin include two major county-maintained roads, and many smaller ranch roads and fire trails maintained by EBMUD. The Contra Costa County Public Works Department maintains Alhambra Valley Road/Pinole Valley Road and Castro Ranch Road. They are responsible for installing and maintaining the roadside drains and culverts to route stormwater from the roads.

Castro Ranch Road has been in two locations. The historic road location was established earlier than 1939 (although likely not paved), based upon the 1939 photos, and was likely present earlier than 1897 based upon the historic USGS topographic quadrangle maps. The road faced chronic stability issues as the surrounding land was continually sliding. During the late 1970s and early 1980s, the road was even completely closed to traffic twice, due to landslide activity (Bob Flasher, personal communication). Because of the increased traffic demands of the Carriage Hills development, it was suggested to re-route the road slightly west to the location of a fire road, further up the slope, and in a more stable location. This relocation occurred in 1986, and included the installation of a large culvert underneath Castro Ranch Road, and a culvert (the now hanging culvert) on the east side of the road, draining runoff from the pavement (Figure 8). This hanging culvert collects drainage from a 280 m length of road surface in two concrete-lined roadside ditches, routing all of the runoff into a single culvert that discharges into a tributary of Gully A (Figure 9). The re-routing resulted in a change in drainage patterns immediately adjacent to the road (USACE, 2001). In the 1989 aerial photographs, the tributary channel appears to be a shallow, grassy swale that has not yet incised. However, major incision has occurred (beginning during the 1993 event) and the culvert is currently hanging approximately 4 m above the channel bed. The discharge has carved a large, deep gully into the hillslope, mobilizing large volumes of soil and bedrock material into Gully A. The gully currently has bedrock exposed in its bed for most of its reach. We suggest that the rate of erosion has slowed significantly, compared to the previous 15 to 20 years, because the majority of erosion likely occurred fairly rapidly over the course of a few wet seasons, and now the channel is beginning to reach a more stable state. However, the side slopes are still quite steep, and receive some road surface runoff, and will likely continue to fail in the future. In particular, the left bank of the gully is in immediate danger of failing (particularly if the Castro Ranch Road ditch drain is plugged), threatening the stability of the road bed surface. Failure might occur during the next large storm event, perhaps with a magnitude of ~50mm (2 in) of rain in a 6-hour period or ~80 mm (3.3 in) in a 24 hour period (see Pearce et al., 2005 for rationale).

The large culvert underneath Castro Ranch Road was installed at the channel bed elevation in 1986. A concrete apron and riprap were placed on the downstream side of the culvert to prevent undercutting and failure. However, during the 1993 wet season, Gully A significantly incised (Figure 10), leaving this culvert elevated approximately 3 m above the current bed elevation (Figure 11). The culvert is currently providing grade control for the gully, and does not appear to be in any immediate danger of failure, but the county should watch and maintain this location to prevent a large failure of the road in the future.

After the 1993 events, the county had to address the culvert at the mouth of Gully A as it crosses underneath Pinole Valley Road. A new culvert (at a higher elevation) was installed after the old one was plugged with sediment, sending water and sediment over the road surface.

Although outside the Pavon Creeks watershed proper, the county also has had to maintain the culvert at the "Y" where the Pinole Creek mainstem flows underneath Alhambra Valley Road/Pinole Valley Road. Since 1986, the county has had to repair this location at least 3 times (USACE, 2001). The creek banks at this location have failed many times when flood events (on the order of the 1:5 year event) send water, sediment and debris onto the road surface at this location.

Figure 8. Photograph of runoff from Castro Ranch Road during a storm event.

Figure 9. Photograph of the hanging culvert.

Figure 10. Photographic comparison of Gully A downstream of Castro Ranch Road from 1992 (upper photograph) and 2006 (lower photograph). 1992 photo courtesy of Jim Dunne (EBMUD).

Figure 11. Photograph of large culvert apron on Gully A downstream of Castro Ranch Road.

The smaller ranch roads and fire trails that are maintained by EBMUD are primarily on the east side of the basin, in the Nunes parcel. The ranch roads are graded and maintained annually by EBMUD staff. However, the single fire trail is not maintained and is used primarily for ranch ATVs. In general, these roads are in very good condition, with evidence of well-planned maintenance, including sloping the road surface in the correct direction, installation of water bars, and removal of any berms. Based upon the field team's observations during storm events of the 2006 Water Year, these roads transport little to no sediment during typical runoff events, and overall compared to other sources, supply relatively little sediment to the channels (Figure 12). A few very short reaches of road are showing minor evidence of erosion, but, targeted maintenance in these few locations would address any future problems. However, one ranch road location had an erosion problem during the 2005-2006 wet season, and should be addressed before the 2006-2007 wet season. Where Gully C crosses the ranch road, the culvert filled with sediment, contributing to sediment deposition both up and downstream on the pasture surface, and causing a late-season washout of the road surface (Figure 13).

Figure 12. Photograph of surface runoff on a small ranch road during a storm event.

Figure 13. Photograph of clogged culvert, road erosion, and surrounding deposition of sediment on Gully C at the ranch road. Flow is from left to right.

Overall, roads do not appear to be causing any large problems for the Pavon sub-basin (see Appendix K for complete ranch road assessment). They do not appear to be significantly contributing to the excess erosion that is observed. However, locations such as the hanging culvert and the small culverts under the ranch road are the exception, and will require attention and modification to prevent further erosion.

Detailed summary map

Using field mapping and GIS photograph interpretation, we have developed a summary map of the Pavon Creeks sub-basin showing many important features that are controlling the sourcing and transport of water and sediment through the basin (Figure 14).

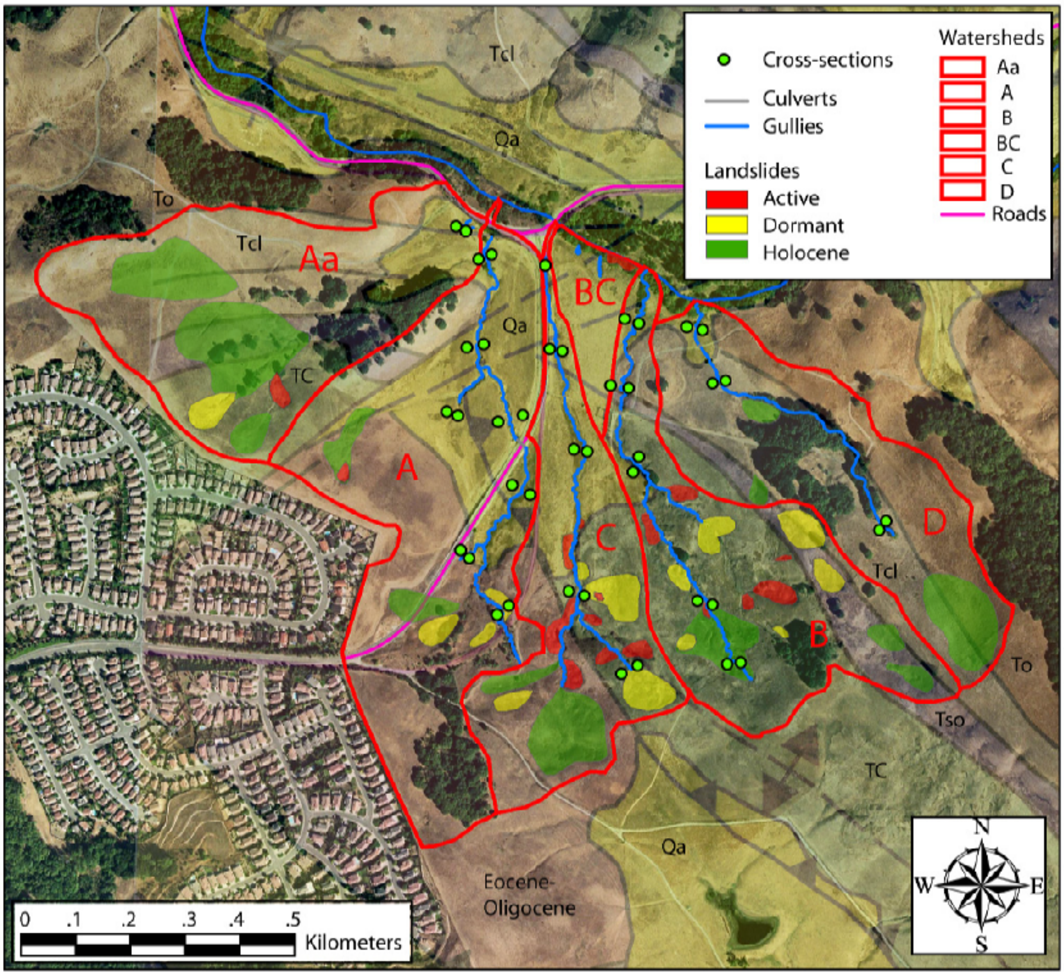


Figure 14. Detailed map of the Pavon Creeks watershed, including the watershed boundaries, gully locations, roads, mapped landslides, cross-section locations, and geologic units (Crane, 1995). See Figure 3 for geologic unit descriptions.

RESULTS

This section discusses the methods and results for each of the types of data that were collected during this study. Each data type is summarized in this section, and in most cases, the complete dataset provided in the appendix.

Rainfall observations

Climate, including rainfall amount, timing, and intensity is one of the most important drivers of geomorphic process. It is rainfall that saturates soils, is converted into runoff and discharge, drives landslides, carves channels, and transports sediment. Any basin assessment must understand short-term (wet year-dry year) and long-term (decadal or greater) climatic variation, as it is a potential cause for basin response and adjustment. Our previous assessment of long-term available climate records (Pearce et al, 2005 Figure 4) provides data to support our basin-evolution hypotheses, and puts the current rainfall observations in perspective.

One component of this project was to observe the sub-basin during rain events, to observe the processes in action. The field team was out during and immediately after 8 separate events, between 12/18/05 and 3/25/06. Unfortunately, the team was not able to be in the field during the large 12/31/05 storm, but was in the field on New Years Day, to observe the results.

This wet season accumulated approximately 42.5 inches (108 cm) of rainfall, compared to 24 inches during the 2004 Water Year. The only wetter season (using the record from Duncan Canyon, 1993 to present) was Water Year 1998, with 46 inches of rain. And using the long-term record (Pearce et al, 2005 Figure 4) we find that since 1850, only 7 years have accumulated equal or greater amounts of rainfall as this year. However, this season only had one major storm (New Years Eve), with a majority of the rain falling as a series of small to medium storms during the months of December and March. Although this wet season was overall quite wet, much of the rainfall occurred as smaller low-intensity storms.

Table 2. Summarized monthly rainfall for the region (in inches). See Appendix Table A-1 for full data. Pinole Creek data provided by Tim McDonough. Briones data from California Data Exchange Center. *Monthly rainfall totals were not available. Richmond data from City of Richmond gage, Western Region Climate Center.

	Pinole Creek watershed	**Briones***	**Richmond**
October 2005	0.60		0.93
November 2005	2.10		0.27 (2 days missing)
December 2005	16.15		8.33
January 2006	3.80		Missing data
February 2006	3.55		1.69
March 2006	10.10		8.45 (2 days missing)
April 2006	5.7		6.27 (5 days missing)
May 2006	0.45		Missing data
TOTAL	42.45	35.77	25.94 (without Jan or May)

During the rain events, the field team made some important observations (see Appendix C for the full description of observations). Although these observations do not provide quantitative data, they lend insight to the processes occurring in the sub-basin. First, we observed that many of the gully banks fail as blocks, with soil cracks and soil piping contributing to the instability of the banks. Second, we observed major changes (both erosion and aggradation) occurring from the largest storm (New Years Eve) of the season. Third, we observed surface runoff on both the ranch roads and the pasture surface, but in neither location was the runoff transporting significant amounts of suspended sediment. Fourth, we observed a rusty piece of metal sticking out of the headcut wall at AXS7 (see appendix Figure A-49), suggesting that sediment in the pasture channel has been deposited since the time of human occupation, supporting the idea of cycles (either large or small) of successive cutting and filling (incision and deposition). And finally, we observed a shift from soil piping to overland flow as the season progressed, providing a future testable hypothesis regarding the dominant process of gully erosion.

Longitudinal profiles

A longitudinal profile is a graph showing the channel distance upstream from a known location plotted against the channel thalweg elevation (deepest point in a cross-section). In other words, it is a graphic representation of the channel gradient throughout the entire length surveyed. Longitudinal profiles are important tools for understanding the history, and potential future of the channels. The field team surveyed the longitudinal profile of each gully using a hand level and stadia rod, following standard surveying techniques. Because the field team was required to cover a large distance, often with channel vegetation and incised reaches, we decided that the hand level would be more logistically feasible compared to the tripod and level. Because of the experience of the field team, this method has an accuracy of +/- 2 cm over 100 m distance, nearly comparable to that of the tripod and level, and well within the needed precision for this type of survey. Each data point represents the channel thalweg, or deepest point, so that the profile is consistent throughout its entire reach.

The longitudinal profile for each of the four gullies is shown in Figures 15-18. The profiles were used to illustrate changes in channel gradient and to determine reaches that may not be in equilibrium, the effects of road crossings, culverts, or grade controls, and to determine areas of aggradation or sediment deposition. It is important to note that none of the channels are at grade with the Pinole Creek mainstem. Each gully drops in elevation immediately at its mouth, whether controlled by culverts (as in Gullies A and C) or by steep, well vegetated, stepped reaches (as in Gullies B and D). Although not conclusive, this observation supports the hypothesis of recent incision of the Pinole Creek mainstem, a potential driver for the Pavon Creeks rejuvenation and instability.

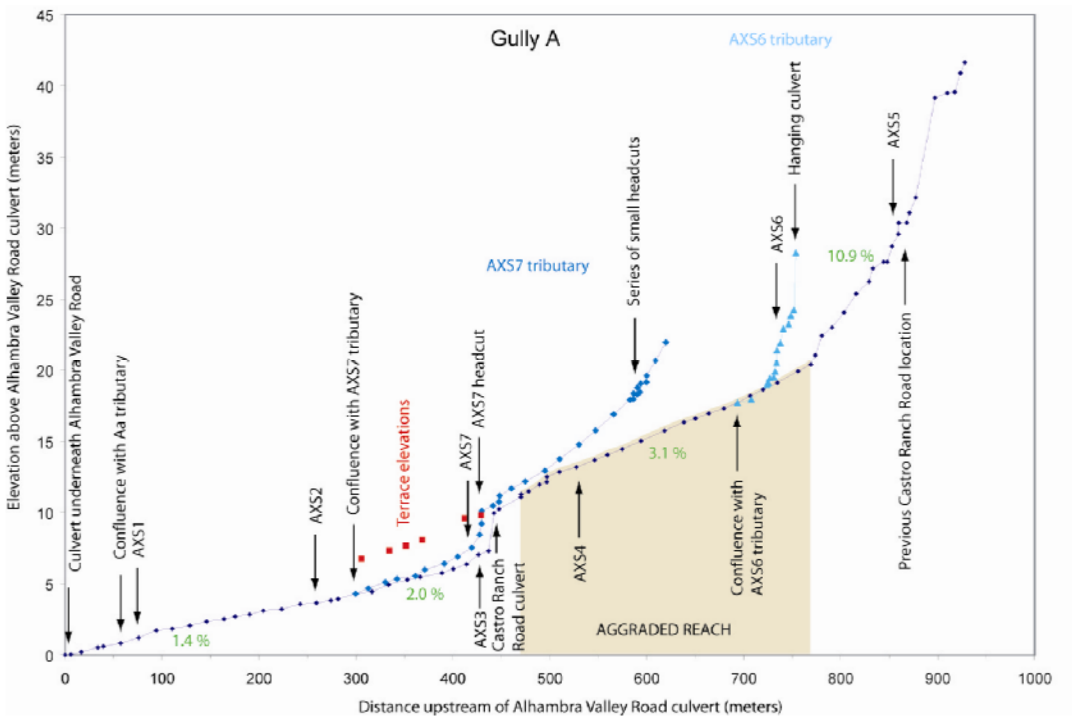


Figure 15. Longitudinal profile of Gully A. Scale in meters. Royal blue is the AXS7 tributary. Light blue is the AXS6 tributary. Red dots are terrace elevations downstream of Castro Ranch Road. Green numbers are the average reach slope (in percent). Note, the profile ends at Pinole Valley Road, not the Pinole Creek thalweg.

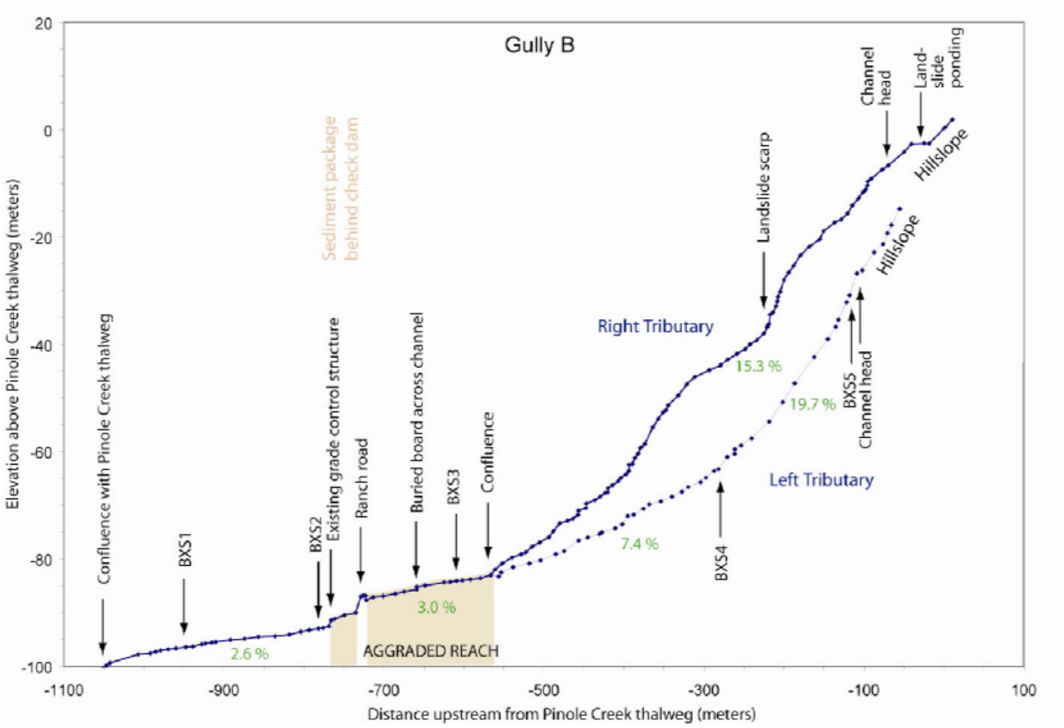


Figure 16. Longitudinal profile of Gully B. Lower profile (left tributary) is the west branch, and the upper profile (right tributary) is the east branch. Green numbers are the average reach slope (in percent).

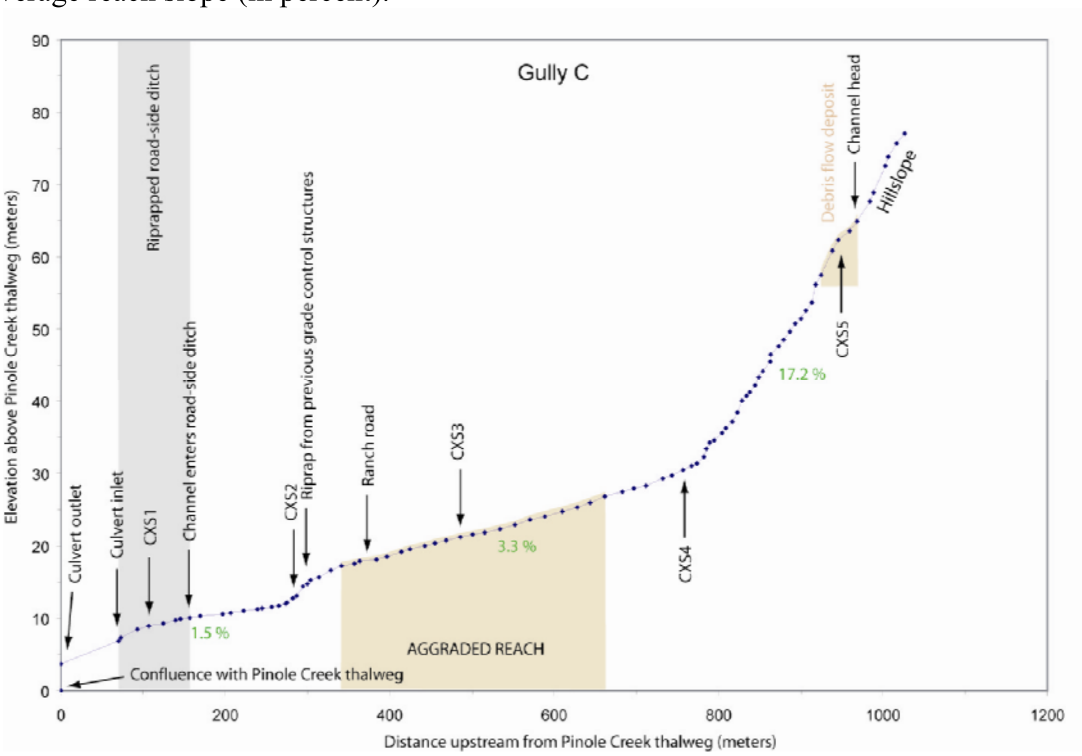


Figure 17. Longitudinal profile of Gully C. Green numbers are the average reach slope (in percent).

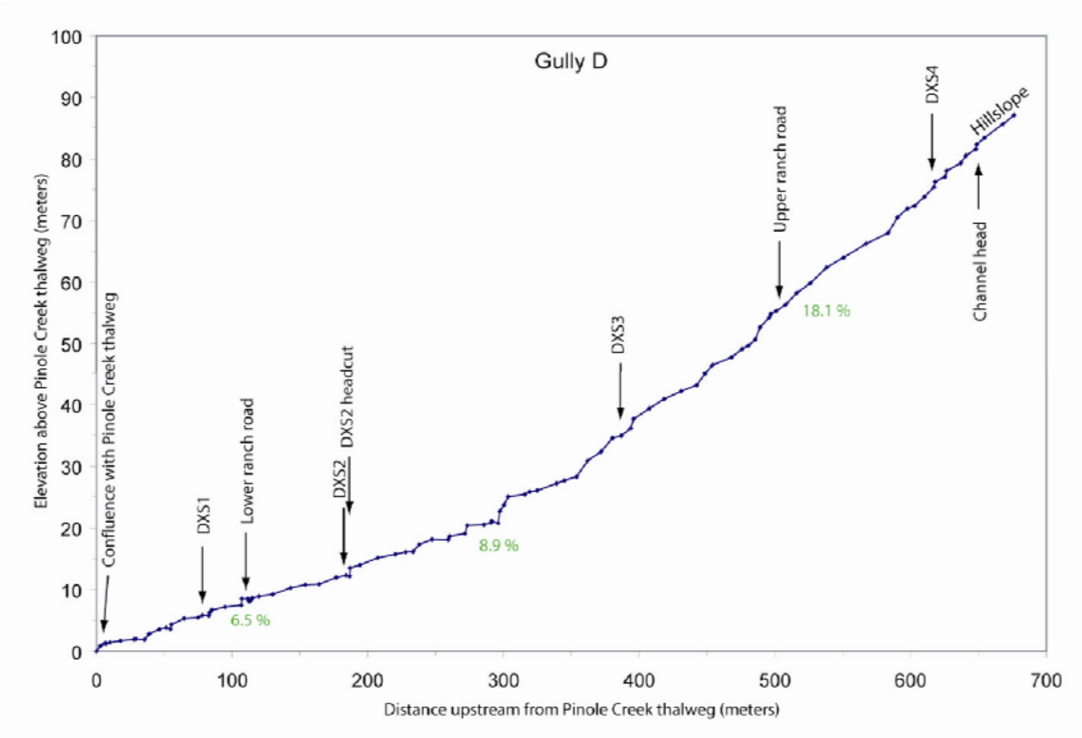


Figure 18. Longitudinal profile of Gully D. Green numbers are the average reach slope (in percent).

Channel cross-sections

The hydraulic geometry of a channel at a single cross-section location reflects the inputs of sediment and water that that channel is required to transport. Channel instability, expressed as incision, erosion, or deposition, results from changes in water or sediment supply from upstream. In the short term, over the course of a single wet season, we can expect to see changes in the cross-sectional shape, especially in dynamic systems such as Pavon Creeks. A cross-section was established on at least four representative locations on each gully, with each location surveyed twice, once before the wet season, and once following the wet season (Figure 19). Our objectives were to quantify the channel variability along the gully length and across different gullies, but more importantly, to accurately quantify channel change (incision, aggradation, erosion) that occurred over the study period (Figure 20). It is important to note that measurements of channel change are short-term measures, reflecting the current climatic conditions, and comprise only a small part of the total channel change and evolution that is occurring over the longer term.

A total of 22 cross-sections were surveyed, with 8 located on Gully A, 5 on Gully B, 5 on Gully C, and 4 on Gully D. Cross-section locations were monumented using a piece of 12” rebar driven into the pasture surface on each side of the channel, typically 10 m beyond the top of the channel bank. Rebar locations were located using GPS, were painted orange, and were described in the survey notes. Surveys were completed using a tripod and level, survey rod, and tape measure. The tape measure was strung between the two pieces of rebar, with zero always on the left bank (looking downstream). Each cross-section is oriented perpendicular to the channel axis, looking downstream.

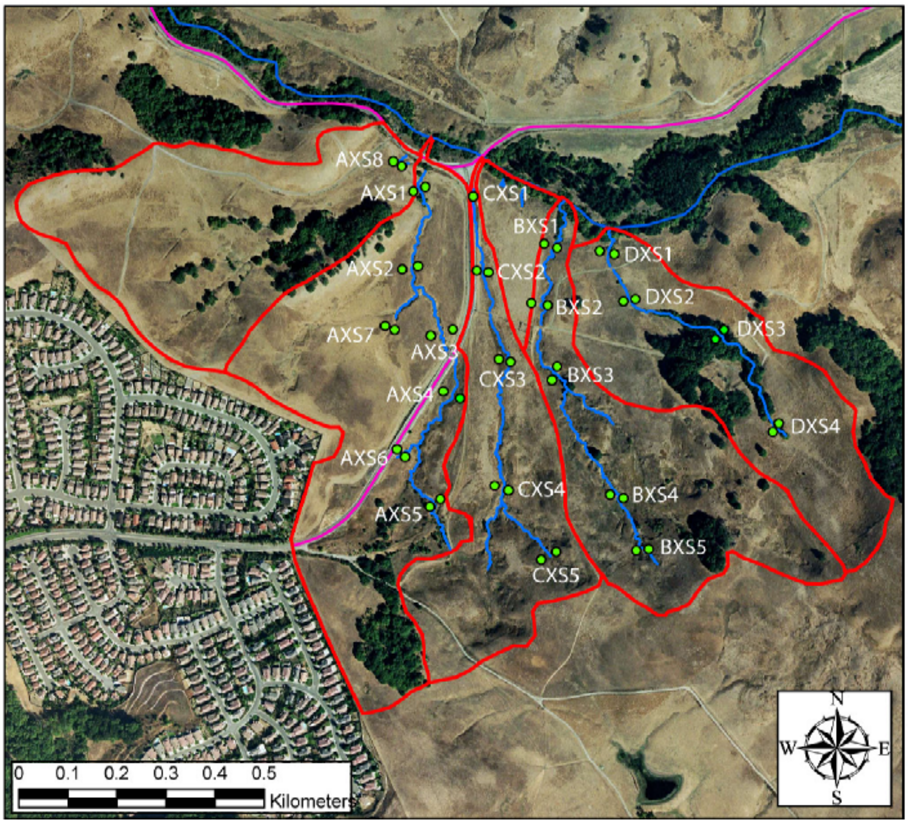
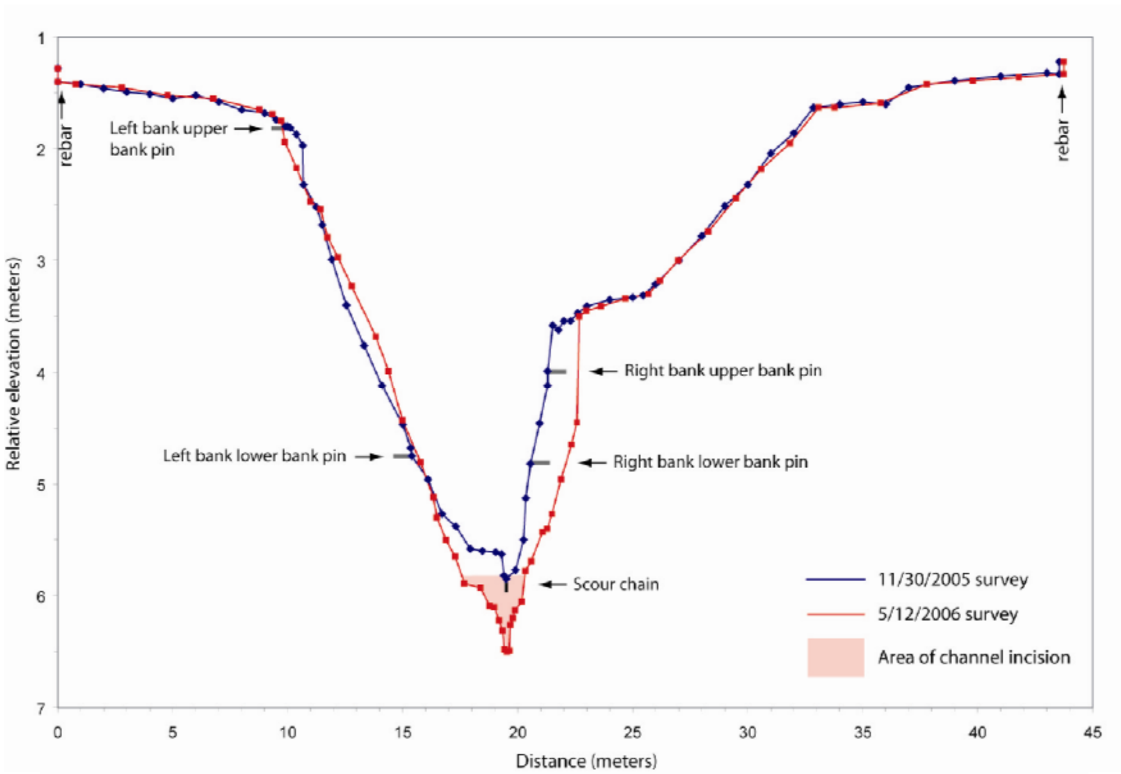
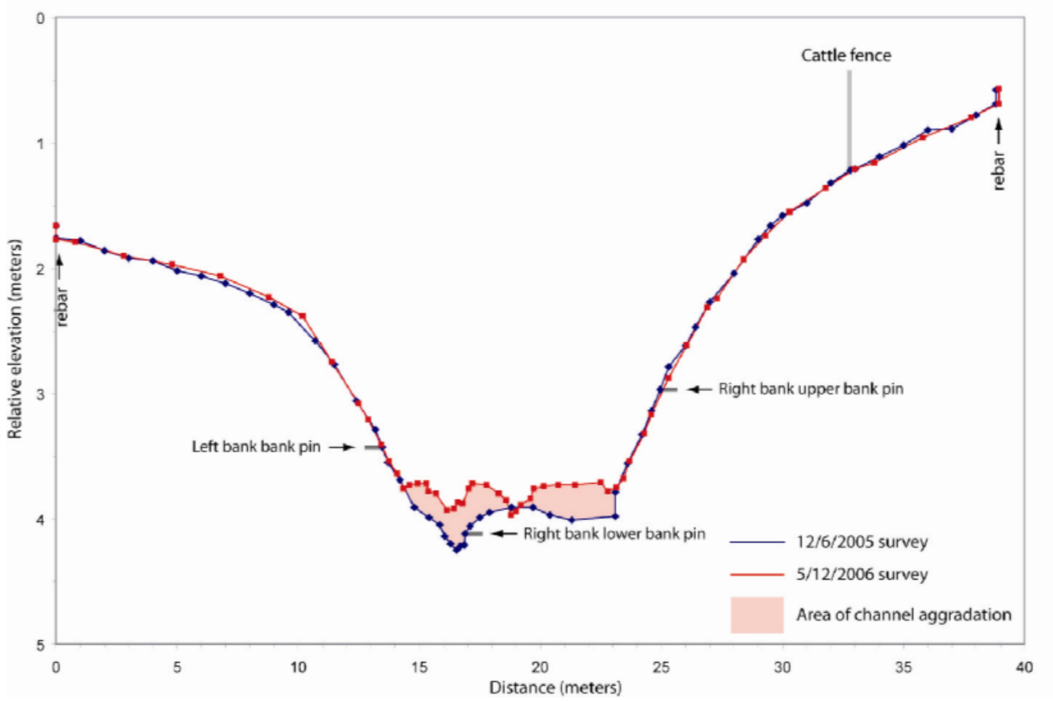


Figure 19. Map showing the locations of surveyed and monumented cross-sections. Green dots represent the monument rebar locations. Note, CXS1 only has one rebar.

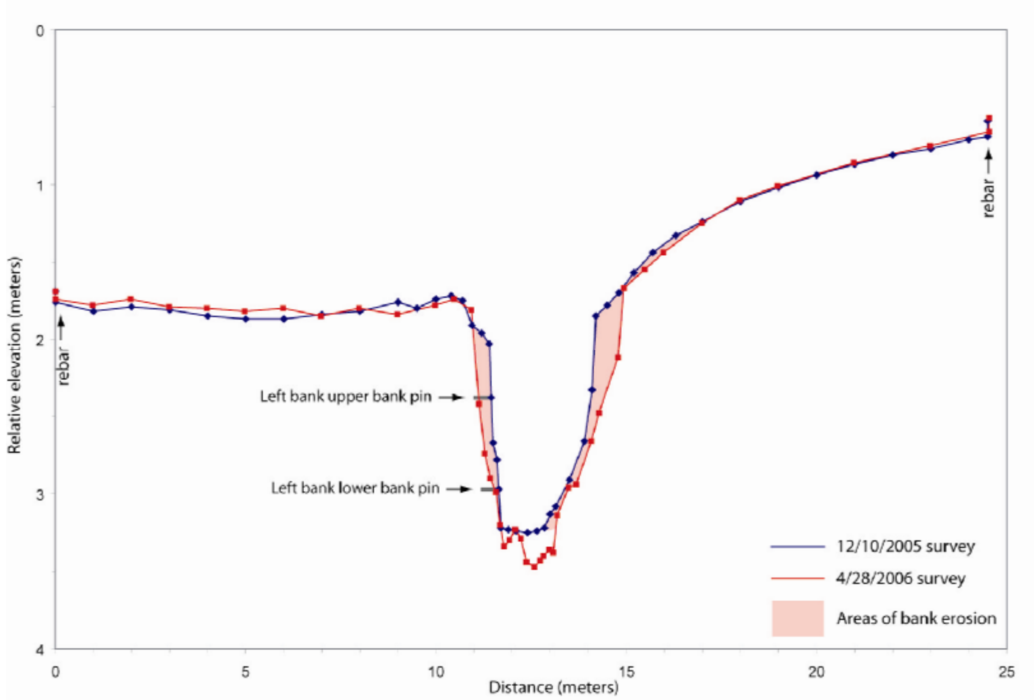
A


Relative elevation (meters)
Distance (meters)
rebar
Left bank upper bank pin
Left bank lower bank pin
Right bank upper bank pin
Right bank lower bank pin
Scour chain
rebar
11/30/2005 survey
5/12/2006 survey
Area of channel incision

B


Relative elevation (meters)
Distance (meters)
Cattle fence
rebar
rebar
Right bank upper bank pin
Left bank bank pin
Right bank lower bank pin
12/6/2005 survey
5/12/2006 survey
Area of channel aggradation

C



D

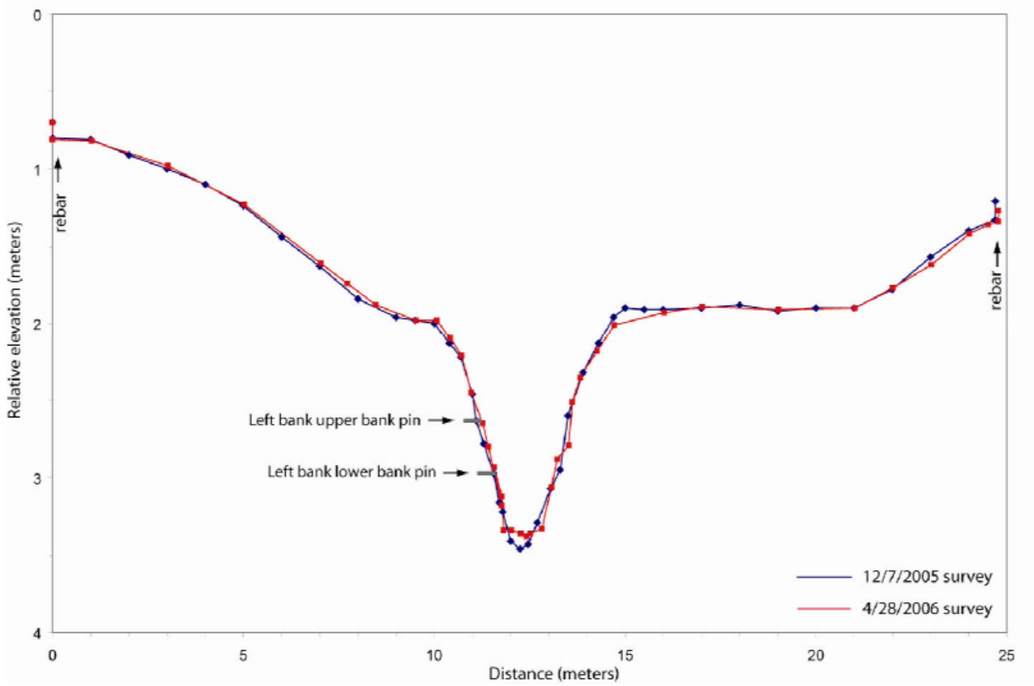


Figure 20. Examples of channel change observed in pre- and post-wet season cross-section surveys. The blue profile is pre-wet season, while the red profile is post-wet season. A) channel incision at AXS3 B) channel aggradation at AXS4 C) bank erosion at DXS2 D) no change at BXS1. Scale in meters, with variable vertical exaggeration, ranging between 6x and 8x exaggeration.

In comparing the pre- and post-wet season surveys from the entire 22 cross-section dataset, we observed many types of change at each of the locations (including channel incision, channel aggradation, bank erosion, and little to no change) (Figure 20 and Table 3). The full dataset of all 22 cross-sections are shown in Appendix E, Figures A-10 through A-31. In general, most cross-sections demonstrated an increase in cross-sectional area (shown by negative numbers in Table 3), whether it be through bed incision or bank erosion. All of the cross-sections on Gully A downstream of Castro Ranch road displayed incision, with AXS3 and AXS7 the most significant. AXS7 incised approximately 75 cm deep as the knickpoint immediately upstream extended headward, and the channel deepened to match the downstream gradient. AXS3 incised 65 cm, creating a narrow notch channel in the hardpan that existed beneath the previous bed elevation (Figure 21). This reach also displayed significant bank erosion, as the banks laid back via large semi-circular slumps. Other reaches with incision include CXS2 (depth of 49 cm) likely due to the large amount of deposition immediately upstream, and direct input of pasture runoff over the bank at the cross-section. And finally, cross-sections DXS1 and DXS3 displayed 17 and 55 cm, respectively, of incision. DXS3 had a large portion of the bank erode, creating a large undercut, and likely de-stabilizing the local bed, causing the removal of sediment stored in one of the many small steps.

Table 3. Summary of channel planform change over the course of the 2005-2006 wet season. Positive numbers indicate aggradation or addition of material, and negative numbers indicate erosion, or removal of material. All measurements in m^3. Note, bank aggradation represents an addition of material, typically from block failures further up the bank slope.

Gully	Incision	Aggradation	Bank erosion	Bank aggradation	Net change (m^3)
AXS1	-0.06		-0.55	+0.64	+0.03
AXS2	-0.33		-1.95		-2.28
AXS3	-1.32		-2.73	+0.66	-3.39
AXS4		+1.60			+1.60
AXS5		+0.35	-0.20	+0.44	+0.59
AXS6			-0.32		-0.32
AXS7	-1.35		-6.96		-8.31
AXS8	-0.88				-0.88
BXS1		+0.03	-0.13	+0.03	-0.07
BXS2			-2.42		-2.42
BXS3		+2.77	-0.89		+1.88
BXS4			-5.93	+7.84	+1.91
BXS5	-0.33		-0.15	+0.09	-0.39
CXS1	-0.02				-0.02
CXS2	-0.77		-0.39	+0.07	-1.07
CXS3		+3.12			+3.12
CXS4		+0.58	-0.69		-0.11
CXS5		+3.95		+1.05	+5.00
DXS1	-0.11		-0.14		-0.25
DXS2	-0.31		-1.81		-2.13
DXS3	-0.54		-1.02		-1.56
DXS4			-0.42	+0.11	-0.31

Figure 21. Photograph showing the newly-formed notch channel at AXS3.

Some cross-sections displayed primarily bank erosion, as oversteepened banks continued to lay back. Cross-section BXS2 experienced erosion on its left bank, as the bank continued to slump, and the toe of the slope was removed, especially during the high flows over New Years (Figure 22). Cross-sections BXS4 and CXS4 eroded as bank slumps occurred, sending entire blocks of material down onto the stream bed. The material from these blocks was slowly removed during the remaining flows of the wet season. Many other cross-sections display bank erosion, but in smaller volumes.

Figure 22. Photograph showing the bank erosion occurring on the left bank of BXS2.

Additionally, a number of cross-sections displayed both bank erosion and bed incision. For example, the change in profile for AXS1 shows channel incision of 15 cm, right bank erosion of 40 to 50 cm, and aggradation on the left bank terrace of 15 cm. This complex change reflects the cross-section's location in the watershed; the channel experienced widening and deepening due to the large flows that occurred this season, while the floodplain surfaces accumulated sediment supplied from the upper watershed, as flows backed up behind the culvert underneath Pinole Valley Road (Figure 23). Other cross-sections, including AXS2 and DXS2 show both incision and bank erosion, as the cross-section integrates water and sediment from the entire upstream watershed.

Figure 23. Silts and muds deposited at AXS1 during the New Years Eve storm.

A zone of deposition is observed in the middle portions of the watershed, where cross-sections consistently display significant aggradation over this wet season. This zone includes cross-sections AXS4, BXS3 and CXS3 (Figure 24). The aggradation is likely due to a combination of both the decrease in valley and channel slope, and the backup caused by culvert constrictions (the culvert under Castro Ranch Road on Gully A, and the culverts under the ranch road on Gullies B and C). Alternatively, this zone may not be consistently experiencing aggradation year after year, but instead, experienced aggradation only this wet season. If this is the case, the aggradation represents a slug of sediment sourced from mass wasting and channel erosion in the upper watersheds. During the next wet season, this slug of sediment would continue to work its way downstream, incising this zone, and possibly depositing at a different location lower in the watershed. Continued observation will illuminate which is the more probable scenario.

Figure 24. Photograph showing the aggradation that occurred at AXS4.

Besides aggradation in the middle zone, cross-section CXS5 also aggraded, but in response to a large mass-wasting event in the headwater bowl of this gully. The mass-wasting transported sediment to the channel bed via a debris flow deposit. This slug of sediment will likely be transported further downstream over the next couple wet seasons, returning the cross-section to a similar shape as the pre-wet season survey.

Some cross-sections demonstrated relative stability over this wet season. For instance, cross-sections AXS6, BXS1, and CXS1 all showed little to no change. CXS1 is the riprapped roadside ditch, so its stability is not surprising. AXS6 is the tributary outlet from the hanging culvert routing water from Castro Ranch Road. This section's stability is also not very surprising, because after the initial rapid downstream adjustment to the culvert installation, this section has likely been fairly stable because the amount of water and sediment supplied from the road does not vary much, and because the channel is controlled by bedrock in its bed. The most surprising stable cross-section is BXS1 because it integrates all inputs from the B watershed, and might be expected to display either aggradation or incision.

An analysis of change was difficult for some cross-sections, either because the rebar was disturbed, or the field team was unable to re-occupy (locate) the rebar location. For instance, the rebar at AXS8 was likely trampled by cattle, but observation suggests that the section displays bank erosion. Cross-sections AXS5, BXS5, and DXS4 were all unable to be re-occupied, however observations suggest that AXS5 aggraded due to an upslope debris flow, BXS5 likely did not change, and DXS4 likely eroded its banks.

Bank pins and scour chains

Bank pins were installed at each cross-section to record the amount of bank erosion that occurred throughout the wet season. The pins, simply 18 inch steel stakes, were driven into the bank using a sledgehammer, ensuring that the stakes remained horizontal. The tips were painted orange for visibility, and the length of stake exposed was accurately measured. Pin placement was based on professional judgment, with locations that were representative, as well as locations that would likely erode chosen. As the wet season progressed, the field team would periodically measure the amount of stake that was exposed. If the pin was exposed more than 10 inches, the field team would pound the stake back into the bank, making careful note of their actions. The total amount of bank retreat, or cumulative length of stake exposed, is shown in Table 4. In some cases, the field team was unable to locate the pin, typically because the bank had eroded more than 18 inches, and the pin had fallen out (noted as 18.0 +), or because the channel had aggraded, and the pin was buried beneath the bed surface. And sometimes the pin just simply could not be located (noted as unknown).

Table 4. Summary bank pin retreat data.

Cross-section	Bank	Upper/Lower	Total Retreat (mm)	Total retreat (inches)
AXS1	RB	Upper	660	26.0
AXS1	RB	Lower	465	18.4
AXS2	LB	Lower	unknown	unknown
AXS2	LB	Upper	unknown	unknown
AXS2	RB	Lower	0	0.0
AXS3	LB	Upper	460+	18.0 +
AXS3	RB	Lower	170	6.7
AXS3	RB	Upper	690+	27.0 +
AXS4	LB	Lower	0	0.0
AXS4	RB	Lower	0	0.0
AXS4	RB	Upper	0	0.0
AXS5	Headcut		460+	18.0 +
AXS5	LB	Lower	460+	18.0 +
AXS5	RB	Lower	460+	18.0 +
AXS5	RB	Upper	unknown	unknown
AXS6	LB	Lower	70	2.8
AXS6	LB	Upper	460+	18.0 +
AXS6	RB	Lower	30	1.2
AXS6	RB	Middle	15	0.6
AXS6	RB	Upper	10	0.4
AXS6	LB	Culvert	unknown	unknown
AXS6	RB	Culvert upper	8	0.3
AXS6	RB	Culvert middle	0	0.0
AXS7	LB	Upper	1,930+	76.0 +
AXS7	LB	Lower	460+	18.0 +
AXS8	Headcut	Center	460+	18.0 +
AXS8	Headcut	Left	460+	18.0 +
AXS8	Headcut	Left B	460+	18.0 +

AXS8	Headcut	Right	460+	18.0 +
BXS1	LB	Upper	0	0.0
BXS1	LB	Lower	0	0.0
BXS2	LB	Upper	460+	18.0 +
BXS2	LB	Lower	460+	18.0 +
BXS2	RB	Lower	335	13.2
BXS3	RB	Lower	unknown, likely buried	unknown, likely buried
BXS3	RB	Middle	unknown, likely 18.0 +	unknown, likely 18.0 +
BXS3	RB	Upper	unknown	unknown
BXS4			no pins installed	no pins installed
BXS5	Headcut		460+	18.0 +
BXS5	LB	Upper	460+	18.0 +
BXS5	LB	Lower	460+	18.0 +
BXS5	RB	Lower	460+	18.0 +
CXS1			no pins installed	no pins installed
CXS2	RB	Upper	unknown	unknown
CXS2	RB	Lower	unknown	unknown
CXS3	LB	Upper	10	0.4
CXS3	LB	Lower	unknown, buried	unknown, buried
CXS4			no pins installed	no pins installed
CXS5	LB	Lower	unknown, buried	unknown, buried
CXS5	RB	Lower	unknown, buried	unknown, buried
CXS5	RB	Middle	unknown	unknown
CXS5	RB	Upper	460+	18.0 +
DXS1	RB	Lower	80	3.1
DXS1	RB	Upper	0	0.0
DXS2	Headcut		460+	18.0 +
DXS2	LB	Lower	140	5.5
DXS2	LB	Upper	305	12.0
DXS3	LB	Lower	460+	18.0 +
DXS3	LB	Upper	15	0.6
DXS4	Headcut		305	12.0
DXS4	RB	Lower	unknown	unknown
DXS4	RB	Upper	375	14.8

In many instances, banks were found to be very unstable, eroding more than 18 inches over the wet season (Figure 25). However, many observations of little to no bank retreat were also made including AXS4, AXS6, and BXS1. As it is no surprise, the aggrading reaches generally had little to no evidence of bank erosion, while the reaches transporting and sourcing sediment had significant and sometimes quite dramatic evidence of bank erosion. In general, Gullies A and B had the highest rates of bank erosion during this wet season. Although this dataset does not speak to the longer-term rates of erosion, the headwaters of each gully likely have very high, episodic rates of erosion, as mass-wasting events occur. Additionally, reaches that are experiencing a wave of incision and rejuvenation will also display very high rates as the wave passes, slowing as the cross-section widens, and returns to a more stable state.

Figure 25. Photograph of exposed bank pin at AXS3, May 2006.

The field team also installed bank pins into some gully headcut walls, with the intention of measuring the amount of headcut retreat, or extension. However, because of the potential for large amounts of retreat, instead of bank pins, a rebar was installed vertically into the pasture surface a known distance upstream from the headcut wall (Figure 26). The distance between the rebar and the headcut was measured periodically, with the total cumulative distance reported in Table 5. The average rate of retreat for all measured headcuts was 3.26 m for the WY 2006 wet season, however, comparison between headcuts is difficult because the measured headcuts are in different locations within the watershed, and are in different bank materials, and have different styles of retreat.

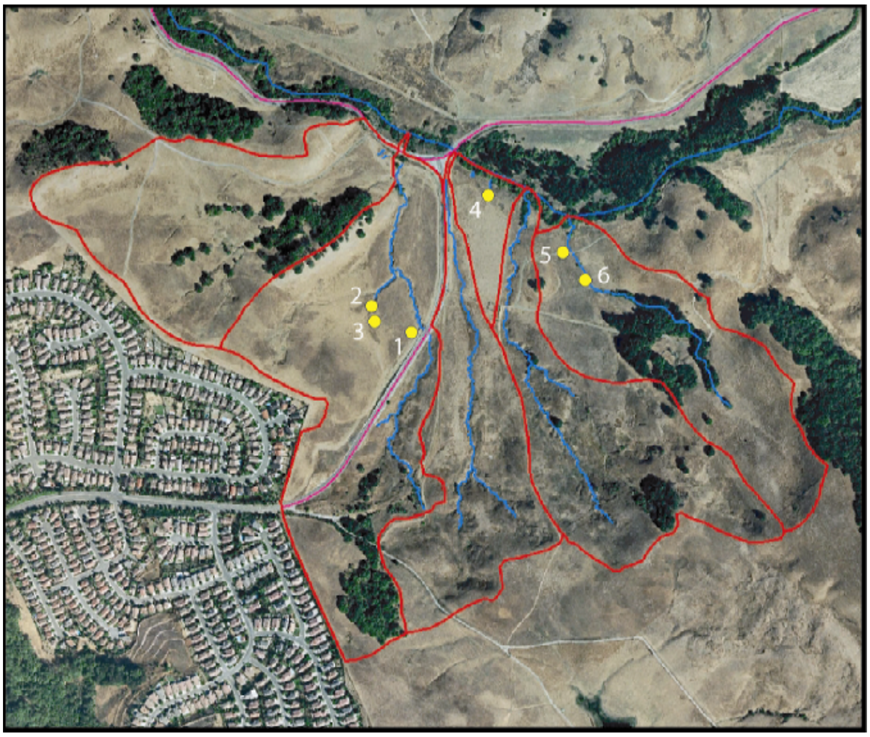


Figure 26. Location map showing measured headcuts. 1) Gully A downstream of Castro Ranch Road 2) AXS7 headcut 3) Small headcut upstream of AXS7 4) Headcut between gullies B and C 5) Gully D and lower ranch road 6) DXS2 headcut.

Table 5. Summary headcut retreat data.

Cross-section	Total retreat distance (m)
Small headcut at Gully A downstream of Castro Ranch Road	0.97
Headcut at AXS7	16.3
Small headcut upstream of AXS7	0.62
Headcut between gullies B and C	0.62
Headcut at Gully D and lower ranch road	0.00
Headcut at DXS2	1.07

The headcut upstream of AXS7 had the largest amount of headward extension observed this wet season, retreating a total of 16.3 m (Figure 27). Throughout the wet season, this small tributary to Gully A was observed to rapidly downcut, to reach the grade of Gully A, and to headwardly extend via headwall failure as a series of blocks that fell from the headwall into the channel bottom. The channel also widened via block failure, and bank slumps, as observed in the cross-section AXS7 (Appendix E Figure A-16) and the photograph series in Figure 28. Using the 2000 aerial photograph, an average rate of headcut retreat of 4.7 m per year can be calculated for the period 2000-2005. The rate of 16.3 m of retreat this season is much larger than the average rate over the past 5 years, however, this rate is likely well within the normal range, with some years experiencing rapid episodic retreat, and others experiencing little to no retreat.

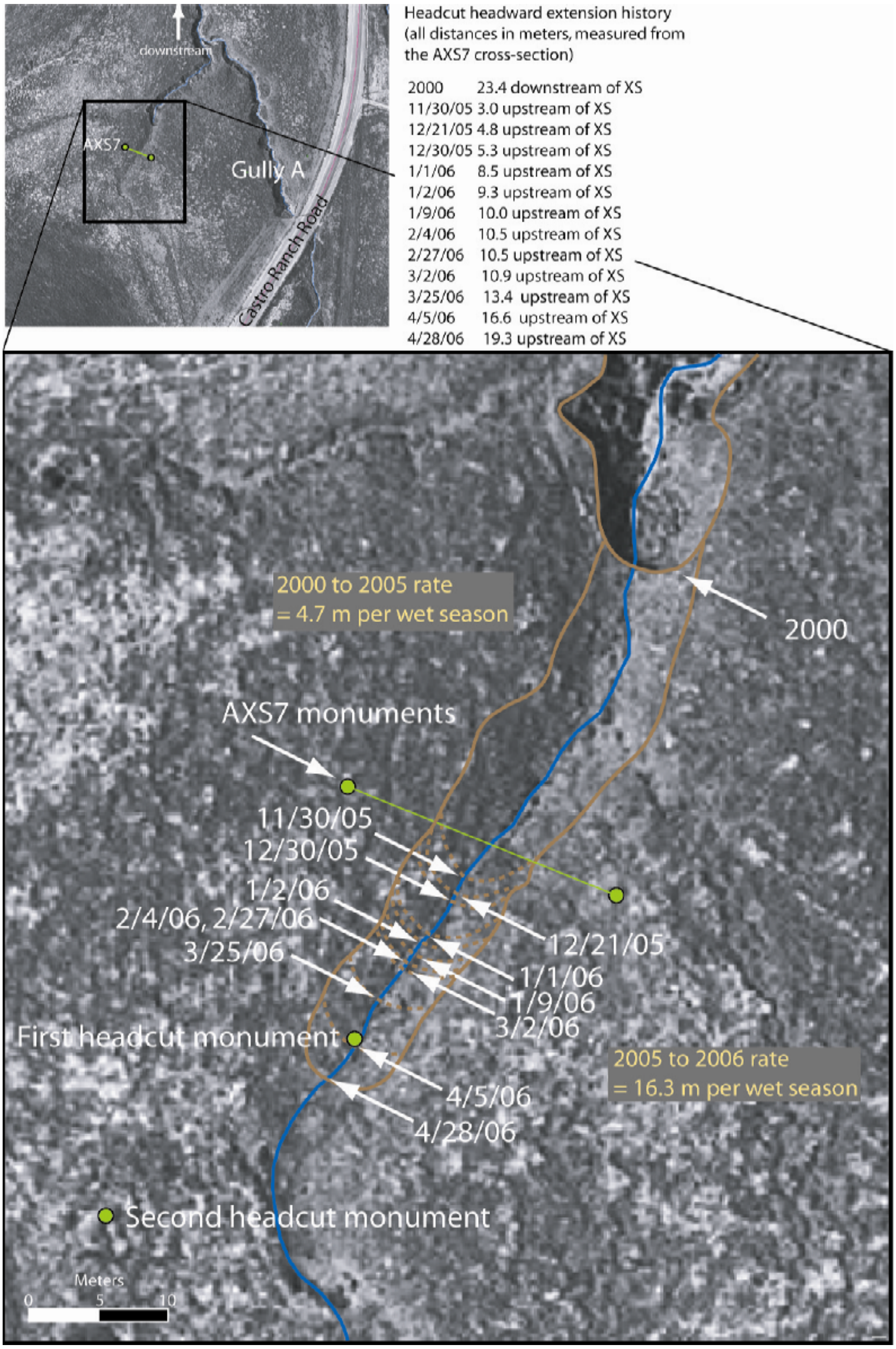


Figure 27. Headcut retreat history at AXS7, showing the date and location of the headcut relative to the two monument rebar that were installed for the cross-section. Locations of the two headcut monument rebar are also shown (green dots).

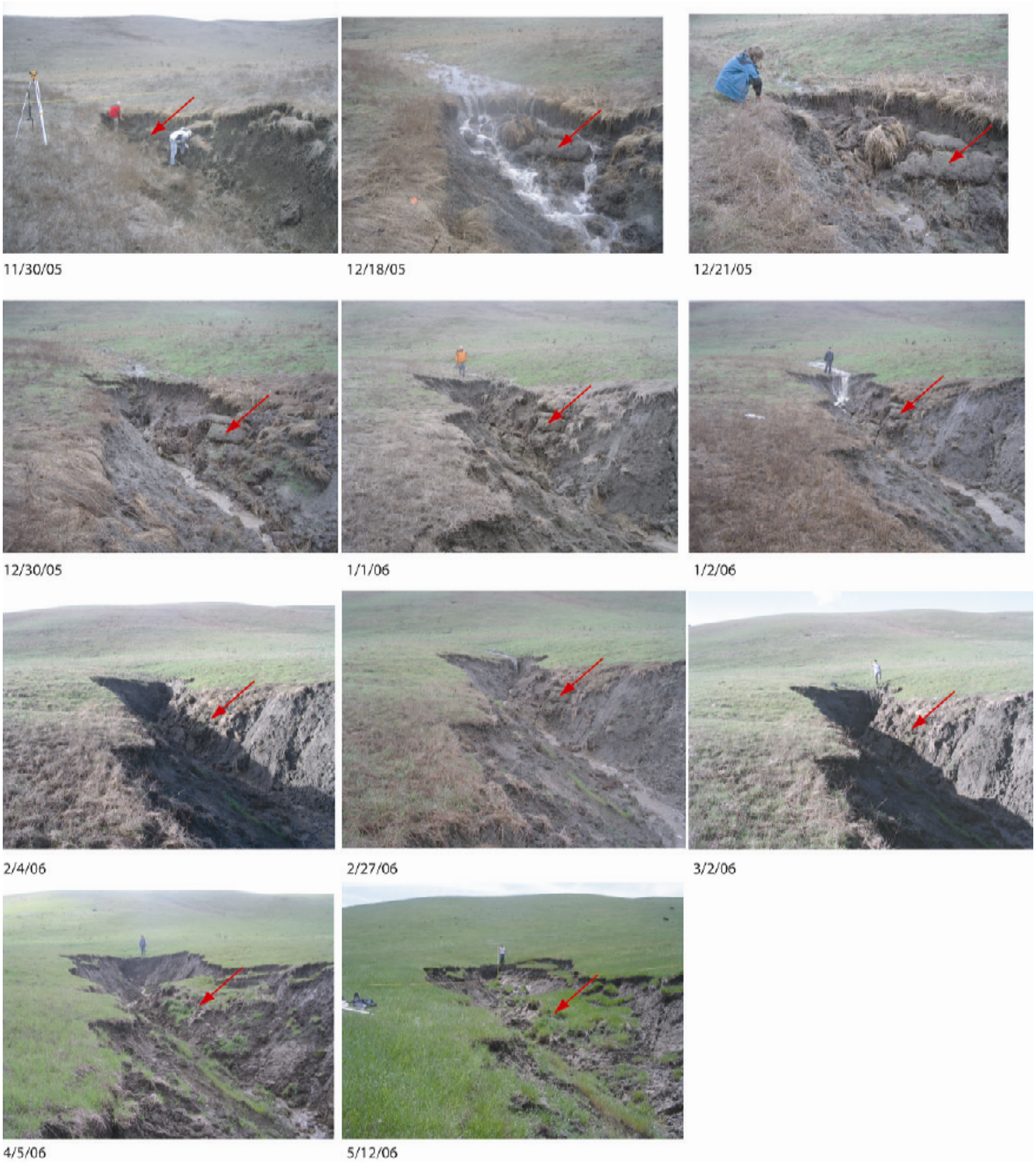


Figure 28. Photograph series of headcut retreat at AXS7 through the 2005-2006 wet season. Red arrow points to the same block of soil in each photograph.

The headward extension at AXS7 is likely caused by a combination of factors including: the channel striving to maintain grade with the downstream gully, early season subsurface pipe flow as the groundwater table intersects the gully headcut, and later season concentration of surface flow that gains energy as it flows over the 1m+ waterfall of the headcut. Figure 29 shows the relationship of retreat to daily rainfall throughout the season. The first storms of the season cause the headcut to slowly retreat (average rate of 0.7 m/day), but the large storm on New Year's Eve caused the most rapid extension observed during the entire season. Through January and February, the storms were relatively small, causing little change in the headcut. However, in March and April, the series of successive medium-sized storms caused the headcut to retreat again, and at a rate twice as fast as that measured at the beginning of the season (average rate of 0.14 m/day). This suggests that the most significant headcut retreat in Pavon Creeks is driven by the amount of cumulative season-to-date rainfall, rather than rainfall intensity. However, additional observations and data would need to be collected to fully test this hypothesis.

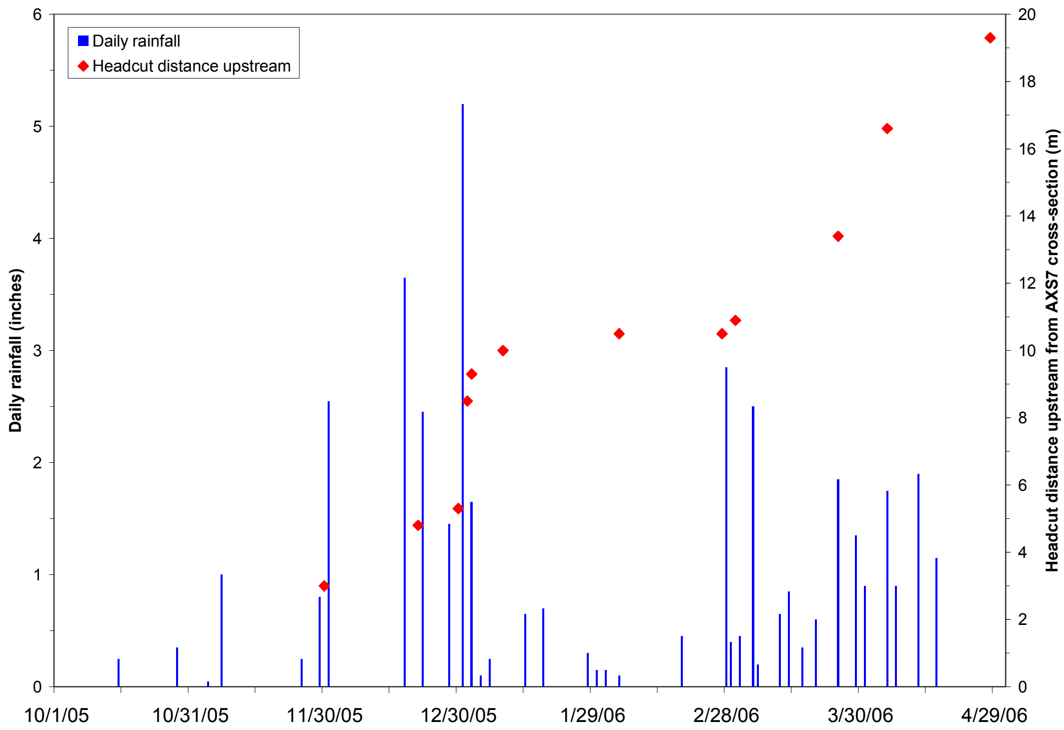


Figure 29. Amount of the AXS7 headcut extension, and local rainfall as measured in the Pinole Creek watershed (Duncan Canyon, data from Tim McDonough, see Appendix Table A-1).

The field team also installed scour chains at three cross-sections: AXS1, CXS3, and DXS1. Scour chains are 0.6m long pieces of fine-gauge chain with an anchor at the bottom, that are installed in the channel bed to measure the amount of bed scour, and subsequent deposition that occurs. A hole is dug in the channel bed, the chain is installed, and then the hole is filled in taking care to insure that the chain remains vertical, with only a small amount of chain exposed above bed level. Over the course of the wet season, runoff events may mobilize the top portion of the bed, scouring the sediment and transporting it downstream. At this point, a greater length of chain would be exposed, and would lie flat on the new bed level. If any subsequent deposition occurs, this can be

measured by the depth of the horizontal chain compared to the new bed level. This method measures the greatest depth of scour that occurred during the wet season.
This method only had limited success in these gullies. At AXS1, the bed scoured to a depth greater than 0.6m, washing the chain downstream. At CXS3, the bed significantly aggraded, burying the chain underneath 0.5m of sediment. And at DXS1, the chain could not be located, despite careful field notes. Based upon the cross-section and observations during rain events, this channel likely did not scour to any appreciable depth because of the cohesiveness (clayey) of the channel sediment. Because of the lack of success using scour chains, we suggest that monumented cross-sections provide the best data set for measuring bed scour.

Summary of sediment volumes

Using the cross-section and bank pin data sets, we were able to estimate the volume of sediment that has been eroded (via incision, bank erosion, and headcut retreat) and the volume of sediment aggraded over the course of the wet season. However, because we are applying a single measurement (one cross-section location) to a larger reach of channel, these values should be used as “back of the envelope” estimates. Our best estimate of sediment volumes for specific reaches within the sub-basin are shown in Table 6. It is important to note the uncertainty in erosion volumes generated in the headwaters of gullies A and C. These two headwater areas are actively eroding via landslides, channel incision, and bank slumps, and likely contribute nearly half of the total sediment supply from the Pavon Creeks sub-basin. However, due to the level of activity, the four cross-section locations established in these areas were compromised, preventing accurate measurement of channel change, and thus, sediment supply. But, from our observations, we know that these areas are quite significant, and therefore we provide our best professional judgment for the volume of sediment supplied over this wet season.

Table 6. First-order estimates of volume of sediment (m^3) associated with erosion or aggradation in specific reaches of the Pavon Creeks sub-basin. Note, many more control points would be needed to provide accurate estimates.

Location	Volume eroded from bed and bank erosion	Volume eroded from headcut extension	Volume aggraded
GULLY A			
Aggradation at the mouth of Gully A			730
Gully A downstream of Castro Ranch Road	2130		
AXS7 headcut		130	
Gully A aggradation upstream of Castro Ranch Road			< 490
AXS6 tributary (this season)	19		
AXS6 tributary (since culvert installation, 1986)	700		
Gully A headwaters	? (big, likely >2000)		
GULLY B			
Gully B downstream of the grade control structure	280		
Gully B between the ranch road and grade control structure (total package stored)*			160
Gully B between the tributary confluence and the ranch road			440
Headwaters of Gully B	>>1760		
BC headcut (total volume since incision)**		1390	
GULLY C			
Gully C downstream of the ranch road	130		
Gully C surrounding the ranch road			< 1210
Gully C upstream of the ranch road			610
Gully C headwaters	? (big, likely >2000)		
Gully C headwater debris flow deposit			220
GULLY D			
Gully D downstream of the DXS2 headcut	< 100		
DXS2 headcut		2	
Gully D headwaters	<< 390		

* The volume calculated for the Gully B grade control structure represents the total volume of material stored behind the check dam. This volume of material did not accumulate entirely during this wet season.
** The volume calculated for the BC headcut represents the total volume that has been eroded since the beginning of the incision and extension of this headcut, and does not reflect erosion that has occurred only during this wet season.

Sediment grainsize distributions

Measurement of channel bed surface grainsize distributions allow us to better understand the sources of sediment, the sizes that are stored in-channel, and the sizes that are being transported downstream. In-channel sediment plays an important role in determining the channel planform, stability, and gradient. At each cross-section location, the channel bed surface sediment grainsize distribution was measured utilizing methods outlined in Bunte and Abt (2001). A systematic random sampling approach was used wherein at each location, a grid pattern scaled to the local bankfull channel width, extending one meter upstream and one meter downstream from the cross-section, was used to measure the clasts. Using the grid nodes to determine where a clast was sampled, the grainsize (along the b-axis) of 100 clasts was measured by hand. Clasts are reported as the size sieve mesh on which the particle would be caught (2, 4, 5.6, 8, 11, 16, 22, 32, 45, 64, 90, 128, and 180 mm). Clasts finer than 2 mm were reported as <2 mm. Care was taken to ensure accurate measurement of each clast, that a single clast was not counted twice, and that no bias towards any particular grainsize was present. Analysis of this dataset allows the grainsize distribution to be determined, including the median grainsize (D50, or grainsize for which 50% of the clasts are finer), D16 (or grainsize for which 16% of the clasts are finer) and D84 (or grainsize for which 84% of the clasts are finer) (Table 7 and Figure 30). See Appendix Table A-11 for the complete grainsize dataset.

Table 7. Summary grainsize distribution statistics for each gully (in mm).

	Minimum	D16	D50	D84	Maximum
Gully A	<2	<2	2.6	11.1	180
Gully B	<2	<2	1.6	6.9	45
Gully C	<2	<2	1.4	7.3	128
Gully D	<2	<2	1.5	5.5	45
Average	<2	<2	1.8	7.7	100

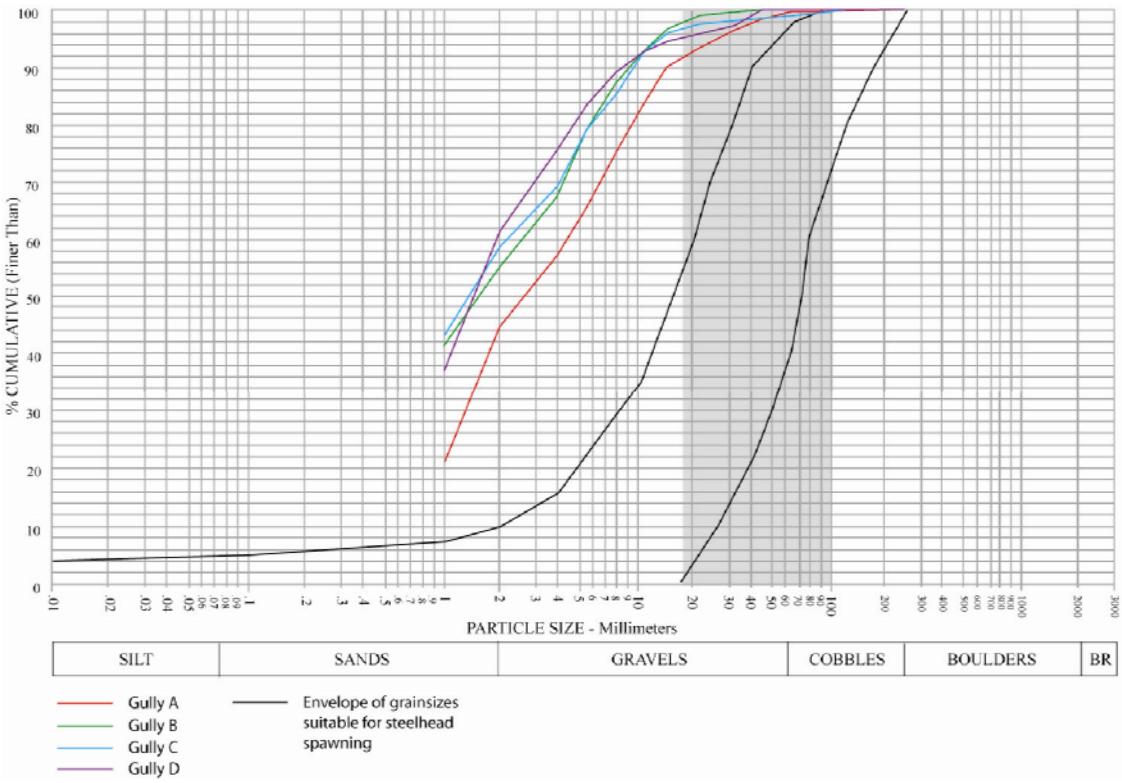


Figure 30. Surface particle size distribution curves for each gully. Envelope and shaded are highlights framework grain sizes utilized by steelhead for spawning (Kondolf and Wolman, 1993). Note, we are not suggesting that these gullies could be managed as steelhead habitat, but rather that these are a significant source of fine sediment to the mainstem of Pinole Creek.

Overall, the grainsize distribution in the Pavon Creeks sub-basin is very fine, with median grainsizes ranging between 1.4 and 2.6 mm (coarse sands and fine gravels), reflecting the underlying geologic and soil units. The sub-basin is somewhat unique because a majority of erosion is sourcing fine-grained sediment, primarily soils and valley alluvium. Most of this fine-grained sediment is transported as suspended sediment (as evidenced by turbidity measures), but this fine-grained distribution is also evident in the sediment that remains in-channel. Throughout the entire length of each gully, the bed and bars are primarily composed of silts, sands, and muds, with only limited larger grainsize particles present. The larger particles are sourced from either landslides or reworking of previous deposits, typically debris flow deposits. Most of these larger clasts are not mobile during events equivalent in size to those observed this wet season. However, these clasts are important because they are typically very friable (fractured) and weather quite easily, breaking down into smaller clasts, either sands or even into silt and clay sized particles. These smaller grainsizes are then able to be transported downstream into Pinole Creek.

Sediment in the bed of Gully A typically has a matrix of silts and fine sands, sourced from both slumping soil banks and from the breakdown of larger sized clasts, with gravel-sized clasts of the very friable sand and siltstone. The slightly larger grainsize distribution likely reflects the fact that the headwaters of this gully are located within the Eocene-Oligocene beds, rather than the Capay Shale. Gullies B and C are also dominated by a matrix of silty-mud, with some fine sands and gravel-sized clasts. The upper reaches of these gullies directly source bedrock during mass-wasting events, but because the bedrock is so fractured, friable, and weathered, the clasts easily break down into smaller pieces either during transport under storm flow conditions or in response to wetting and drying between transport events. Although Gully D has a similar grainsize distribution to Gullies B and C, its sediment composition is different to the other gullies, and is dominated by dark brown silts and clays, with some larger clasts, transported from the steeper gradient reaches of this channel. In general, the sediment in Gully D appears to be less weathered and more cohesive (less friable). Clasts in Gully D are less likely to break apart during transport from their sources to mainstem Pinole. Because the median grainsize in each of these gullies is less than 3 mm, sediment is easily transported downstream in runoff events. Even small events are able to suspend these fine grainsizes, causing the high levels of turbidity we observed. During many runoff events, if one were to place one's hand into the water and touch the bed, sands and fine to medium gravels (2 to 32 mm) clasts can be felt saltating along the bed surface as bedload. The suspended sediment load is likely supply limited, that is the system is currently able to transport all sediment that is supplied, whereas the bedload component appears to be transport-limited, as evidenced by small lags of coarser material remaining on the channel bed. We suggest that a very large storm event in the future has the potential to deliver an extremely large pulse of primarily fine and secondarily coarse grained sediment downstream into the mainstem of Pinole Creek.

Turbidity

Turbidity is the measure of relative water clarity, or a measure of the extent to which light passing through water is reduced due to suspended materials, and is typically measured in Nephelometric Turbidity Units (NTU). Turbidity samples from each of the four gullies, as well as from a number of other locations in the sub-basin were taken throughout the wet season to help qualify amounts of suspended sediment being transported during runoff events. Suspended sediment concentration (SSC) samples were not taken because it was beyond the scope of this project. However a nearly linear relationship exists between turbidity and SSC, as developed for the Pinole mainstem during the previous SFEI study (see Pearce et al, 2005, Appendix C-4). Please note however, that turbidity-SSC relationships are unique for each sampling point so the previous relation cannot be used to convert the Pavon Creeks data to SSC.

In general, there is a strong relationship between the amount of discharge and the amount of sediment being transported. In other words, larger runoff events typically transport more sediment, and thus, have higher turbidity. Variability in measures is due to both the physical characteristics of the watershed (geology, soils, type of mass-wasting, gradient, etc), and also the timing of each sample (during the storm peak, during the falling limb, the following day, etc).

The turbidity samples taken were often beyond the range of the Hach 2100P portable turbidimeter. Therefore, samples were taken back to the SFEI lab, and diluted with distilled water until the sample was within the range of the turbidimeter. Table 8 reports the calculated turbidity of each sample (see Appendix Table A-12 for full data table). A total of 46 turbidity measures were taken between 12/18/2005 and 3/25/2006. Turbidity ranged between 6 and 23,000 NTU, with the highest values measured in Gully B (Figure 31). Although this dataset was collected merely to illustrate the general range of turbidities that can be expected, a few interesting findings were observed. First, surface runoff from the roads (paved and ranch) and the pastures has very low turbidity (6 to 46 NTU) compared to runoff in the gullies. Secondly, apparent dilution effects of adding road runoff are observed in two instances. On January 2nd in Gully A, adding road runoff from the hanging culvert reduced the turbidity from 13,000 to 12,000 NTU. Also, on March 2nd, adding road runoff (unmeasured) to flow in Gully C reduced turbidity from 6,300 to 4,800 NTU. And finally, the gullies have a large amount of variation, with Gullies B and C typically more turbid that Gully A, and an order of magnitude more turbid than Gully D.

Table 8. Summary of turbidity (NTU) for sampled storm events. Note, all data beyond 999 NTU are reported to 2 significant figures (a reflection of our perception of the relative accuracy of the data).

DATE	Gully A upstream of hanging culvert	Hanging culvert tributary	Gully A at Castro Ranch Road culvert	Gully A at mouth	Gully B at mouth	Gully C at ranch road	Gully C at mouth	Gully D at ranch road	Gully D at mouth	Pinole Creek mainstem
12/18/05			5,400		3,300	6,900		1,000		
12/30/05			95	3,400			1,239			
1/2/06	13,000	455	12,000	7,700	23,000				48	
2/4/06							1,253	38		
2/27/06			1,200	4,700	9,100		9,000		150	896
3/2/06			283	1,500	7,800	6,300	4,800		75	647
3/6/06				6,000	23,000		16,000		150	1,400
3/14/06							9,447			
3/25/06			6,300	7,200	19,000		13,000		107	

Figure 31. Photograph of storm event discharge in Gully B, 3/25/2006.

DISCUSSION

The purpose of this assessment is to gain a better understanding of the processes and rates occurring within the sub-basin, so that the stakeholders/landowners/land managers can make more informed decisions regarding current and future management of the basin. To accomplish the stated objectives, this study collected a large and varied dataset, and provided many important observations and hypotheses regarding the current functioning of the fluvial system, impacts of land use, and potential future scenarios for the basin. Below we provide discussion on the basin-wide response, the likely causes of response, other important processes controlling erosion rates, and finally, details of the individual channel response.

Basin-wide channel response

The entire sub-basin appears to be in a state of complex response, with channel reaches out of phase (some reaches incising and widening, and others aggrading). The largest storm events of the season appear to cause the greatest instantaneous amounts of change in the basin, but cumulative seasonal rainfall likely plays an important part in determining the total amount and rate of erosion observed. We suggest that this year's greater than average precipitation total drove the relatively high rates of measured erosion. However, these rates do appear to be well within the norm, and are likely much lower than those that might occur during a water year with a high cumulative rainfall total and a series of high intensity storms.

In the headwaters of Gullies A, B, and C we currently observe large areas of landsliding, providing episodic inputs of sediment directly to the channel. The strongly shrink-swell soils contribute to the instability of the hillslopes and channel banks because of the deep cracks that develop during successive wetting and drying. We suggest that the largest total volume of sediment supply within the sub-basin is currently from landslides and bank erosion (slumps and blocks), followed by bed incision, and lastly, contributing only minor volumes of sediment is land uses, such as ranch road erosion and pasture surface erosion. Although a dataset to confirm the total volume of sediment contributed by landslides was not collected, our observations and best professional judgment lead us to believe that this process is equivalent in magnitude to the bank erosion that was measured.

The drainages appear to be persistent features in the landscape, have likely been in their present location for many hundreds to thousands of years. Their location is strongly controlled by the underlying geologic structure, following the regional trend and orientation of the underlying geology. However, while the channel location appears to be static, the channel morphology may be quite dynamic. The drainages likely have the ability to undergo periods of incision and aggradation in response to outside factors such as climate, tectonics, or land use. Over the long-term, climate and tectonics typically control the rhythm of incision and aggradation, by providing episodic drivers, but in contrast, land use and management likely does not control the rhythm, but merely speeds it up or slows it down. Although we only have limited evidence of such periods of incision and aggradation in the sub-basin, evidence of at least one such cycle does exist. The fill terrace in Gully A downstream of Castro Ranch Road was deposited in a previously carved channel, nearly filling the channel to the same elevation as the adjacent pasture surface.

Causes of response

Past geomorphic literature has documented many of the causes of channel incision and gully development, but the specific reason for a certain gully's instability may not always be ascertained. Incision occurs when the channel crosses a geomorphic threshold, whether it be extrinsic (a change in climate, a change in land use, a change in hillslope vegetation, or an alteration to the channel network) or intrinsic (steepening of the valley floor, channel shift, channel pattern change). Typically a change will occur when the amount of water or sediment supplied to the channel is altered. Incision can be a long-term process, which is discontinuous, with periods of rapid downcutting, followed by periods of aggradation, as pulses of sediment are moved through the system. This will cause large annual and decadal variations in sediment output from the basin. Episodic behavior in steep, high-sediment-producing watersheds should be expected, that is, periods of high sediment production and rapid channel incision may be followed by low sediment production and sediment storage (Schumm et al, 1984).

Although we can not be certain of the cause of the current wave of incision and stability, we can hypothesize multiple reasons, including:

- This is one of many, natural, geologically driven cycles of erosion, which may have been sped-up by land use
- The local base level (the grade of the Pinole Creek mainstem) has been lowered, and has rejuvenated the basin
- A geomorphic threshold (either intrinsic or extrinsic) has been crossed. Potential causes could be a period of slightly wetter climate or the long-term dairy and cattle grazing land uses.

At this point in time we do not have any evidence of a long-term record of continual cyclical response of the basin, nor a significant shift in recent climate. But, we do have limited evidence of incision along the Pinole Creek mainstem. But more importantly, based upon our cumulative set of data, and our current understanding of the sub-basin, we hypothesize that the long history of land use on top of the erosion-prone geology is the most important factor in the behavior and response of the Pavon sub-basin. The single period of drainage adjustment and response that we currently observe likely began in the early 1900s in response to land use. In addition, the slightly wetter period between 1914 and 1925 may have provided enough climatic perturbation on top of the land use stresses to trigger this phase of gullying. However, a more intensive investigation of historical ecology and climatic patterns could confirm or reject this hypothesis. Within this long single period, there are likely shorter periods of small-scale rapid aggradation or incision, possibly in response to shorter scale (annual or decadal) climate patterns. The most recent period of incision, beginning in 1993, is probably one of these shorter periods, within the larger long-term response.

The long history of grazing in this basin has likely changed the vegetation community, including the dominant grass species, as well as removing any vegetation that may have existed along drainage lines. Grazing also has compacted the soils, channelizing and creating more runoff from the hillslopes, as well as contributing to the instability in the headwaters and along channel banks. Previous reports cite bank trampling by cattle as one of the main reasons for instability and supply of sediment to the channels (Levine and Fricke, 2001, and USACE, 2003). Recent land use, including the paved county roads has increased the volume and the timing of runoff, contributing to incision of some channel reaches. Also, the many culverts underneath both paved and ranch roads are providing an additional control of the channel gradient and the transport of sediment. All of these land use and land management actions play an important part in the general instability of the sub-basin, and have likely increased the rates of landsliding and channel erosion over background rates.

Other processes controlling erosion rates

The underlying geology and structure appear to be an important factor in the behavior and response of the entire Pavon sub-basin. The three dominant rock types in the basin, especially the Eocene-Oligocene beds and the Capay Shale, have the most control on the topography and basin-wide erosion potential. These rock units have been shown to fail as large-scale landslides, episodically inputting large volumes of sediment into the channels. The longer-term (hundreds to thousands of years) drainage network development is controlled by the input of this sediment, thus controlling the valley slope in which the channel is maintained, and by providing concentration of runoff and increased stream power to drive localized incision. This process of landslide sediment supply had a major control upon the basin before human modification/management, and will likely continue, although rates of landsliding have been increased by land use.

We hypothesize that gully erosion occurs in a two-part process, with groundwater playing an important role in the instability of the gullies. At the beginning of the season, we observe soil piping, or routing of groundwater into the gully via small pipes (generally 2 cm in diameter) that have formed in the soil profile. Because these soils are strongly shrink-swell, surface runoff is able to easily infiltrate soil cracks during the first portion of the wet season. But as the season progresses, these cracks and pipes primarily swell shut, but also become clogged with soil particles, essentially arresting this process. In the second part of the wet season, after the pipes have largely been closed, the overland flow, or surface runoff from the pasture surface plays a dominant role in the continued erosion of gullies. Flow is typically concentrated, and routed into gullies at specific locations, causing increased rates of headcut erosion, or development of smaller sidewall gullies along existing channels.

Individual channel response

While we have discussed causes and processes for the sub-basin as a whole, it is also important to understand how each individual gully is currently responding. The discussion below focuses upon our direct observations and understanding-to-date of each gully.

Gully A is controlled by the culverts underneath Pinole Valley Road and Castro Ranch Road. In the reach between these two roads, the channel has recently incised (beginning during the 1993 wet season), and is now beginning to lay back its banks. The tributaries are rapidly extending, to maintain the gradient of the downstream channel. The headcut at AXS7 was measured as having the greatest rate of retreat, likely in response to the local lowering of base level (incision of the Gully A mainstem). Investment in bank/headcut stabilization, channel bank vegetation (with appropriate irrigation), and cow fencing may prove successful in reducing the total volume of sediment delivered downstream. This reach also has evidence of a period of previous cutting and filling (incision followed by aggradation) as evidenced by the fluvial fill terrace (of unknown age, potentially as young as 20 years, but more likely 50-300 years old or greater) which is now being dissected. Upstream of Castro Ranch Road, the channel is aggrading, controlled by the elevation of the culvert. The headwaters are still very unstable, with large areas of landslides continuing to contribute sediment to the channel.

The lowest reach of Gully B appears to be at grade, with only short reaches of bank erosion, where the banks are beginning to lay back. The only remaining check dam (grade control structure) is within this reach. The check dam is retaining a significant volume of sediment. This dam presents an area of potential future danger, because if the channel erodes around the dam, the entire package of sediment will eventually be transported downstream, and the ranch road culvert and road prism will be in danger of failing. The reach upstream of the ranch road is aggrading, controlled by the elevation of the culvert. The headwaters of this gully also display large areas of landsliding, creating a right-hand tributary that is convex in profile, and will likely see periods of rapid incision and gullying as the channel attempts to remove the convexity from the profile. The left-hand branch is more at-grade, however, has a very steep and deep "canyon" reach, exposing the friable bedrock. In this reach, the banks will likely continue to lay back, contributing some of the largest volumes of sediment in the basin. We should recognize that efforts to stabilize a channel reach that is still undergoing incision and widening may not be as successful as efforts in reaches where the wave of incision has already passed, and the rate of widening has slowed. The headwaters also have some of the largest active landslides mapped in the basin.

Gully C is controlled by a culvert and the riprapped road-side ditch in its lowest reach. However, parallel to, and continuing upstream of the ditch, the channel is deepening, as a wave of incision appears to be working its way headward, potentially related to the past failed check dams or to the gradient of the road-side ditch. Further upstream, a large area of aggradation is present, both up and downstream of the ranch road, likely partially caused by the undersized and now plugged culvert. If no action is taken, the downstream incision will likely eventually remove this entire package of aggradation. Similarly to Gullies A and B, the middle reach of this channel is currently aggraded, displaying a strongly braided pattern, and storing a significant package of sediment. The headwaters are very similar to Gully B, with large areas of landslides. The channel in this reach is narrow, incising, and experiencing bank failures and debris flows. Large volumes of sediment are being supplied from this reach, but at least a portion is currently being stored as in-channel bars and terraces, and in the pasture surface aggradation near the ranch road.

And finally, Gully D is the most unique of the four gullies, because it is underlain by the Oursan sand and siltstones. Its gradient is quite steep immediately adjacent to the Pinole mainstem, but appears to be somewhat stable due to the established mature vegetation along the banks. Overall, the banks and sediment in this gully are more cohesive and less sandy. The channel tends to be narrower and less incised comparatively. This gully has a culvert underneath both ranch road segments, but neither appears to have a significant effect upon the gradient. The headcut at DXS2 did retreat over the wet season, but at a rate much slower than other measured headcuts. The channel profile is quite stepped, with many small headcuts observed throughout its length. The middle and upper reaches are dominated by the underlying geology, forming a very steep, narrow channel within the dense forested hillslope. This gully also has a perennial spring near the headwaters, contributing to a longer period of flow through the summer and fall.

RECOMMENDATIONS AND IMPLICATIONS FOR FUTURE MANAGEMENT

The three main objectives of this sub-basin assessment include identifying the dominant physical processes, collecting data on sediment supply and erosion rates, and making recommendations for future management and restoration. By focusing on the supply and transport of sediment and water, we have documented many of the important characteristics of the Pavon Creeks sub-basin, and provided information on the timing and rates of the current physical processes.

We find that Pavon Creeks is currently in a state of rapid adjustment, and is unstable due to its long history of land use overprinted upon its erosion-prone underlying geology and soils. Successfully controlling excess sediment erosion and restoring the landscape to a state of quazi-equilibrium will take careful design, and progressive and patient stewardship. We suggest that reducing fine-grained sediment supply to the Pinole Creek mainstem and maximizing land profitability will remain significant challenges for many decades to come. Easy solutions are not evident, given the likelihood of punctuated large-scale morphometric changes in response to future large rainstorms. It is important to realize, that during this study, the field team only observed the sub-basin during relatively low energy conditions. Future wet-seasons have the potential to cause significantly more change and adjustment. We suggest that an important factor in successful land management will be the avoidance of exacerbating current trends in the system, such as the current cycle of incision and associated slug of sediment that is being transported downstream.

By combining the knowledge and data collected by this and previous reports, we can begin to gain a better understanding of the role of the Pavon Creeks sub-basin in the overall sediment budget for the Pinole Creek Watershed. In terms of watershed area, the Pavon sub-basin (1.1 km^2) comprises only 3% of the total area of the Pinole Creek watershed (39.6 km^2). In the previous study by Pearce et al (2005) the total annual sediment load for the Pinole Creek Watershed was calculated by directly measuring discharge and suspended sediment. For Water Year 2004, the total sediment load was 9,964 metric tonnes. In this current study, in Water Year 2006, we directly measured approximately 1,200 m^3 of sediment erosion. However, this is an underestimate of sediment supply because the headwaters of Gullies A and C were unmeasured, and likely contributed significant amounts of sediment (Table 6). The more likely total sediment supply from Pavon Creeks is 5,000 m^3 or more. Using an average soil bulk density value of 1.7 g/cm^3 from the literature for slightly compacted soils, we can convert the volume of erosion into a mass of sediment. This conversion gives a total of approximately 2,000 metric tonnes of sediment, or 8,500 metric tonnes if the larger value of erosion is used. Unfortunately Water Year 2004 is the only measure of total sediment load for the Pinole Creek Watershed, and our measures of erosion are only for Water Year 2006. But, if we assume that these two water years are fairly similar, we can compare the two sources of data. In making this comparison, we find that the Pavon Creeks sub-basin is providing at least 20% and more likely closer to 85% of the total annual sediment load of Pinole Creek. This suggests that addressing the contribution of fine-grained sediment from the sub-basin to the mainstem of Pinole Creek could have significant effects upon downstream water quality, aquatic habitat, and quality of potential spawning gravels.

Future management and restoration

Future restoration should consider the entire Pavon Creeks basin as a whole, and should place the basin into context of the larger Pinole Creek watershed. Careful consideration of both the location and timing of restoration efforts can prevent additional future problems. Stakeholders should learn from previous stabilization efforts in other watersheds in the Bay Area, and should take the opportunity to develop partnerships with others in the region.

Our data collection during this study illustrates the importance of bank erosion, channel incision, headcut retreat, and landslides to the overall sediment supply from the sub-basin. The relatively rapid rates of measured bank erosion and headcut retreat illustrate that these processes are currently occurring and will likely continue into the future, until the channel network is able to reach a state of quazi-equilibrium. However, past experience shows that this may be somewhat theoretical, and in practice, may take years to decades to achieve. Although not directly measured, our observations also show that sediment generation in the basin headwaters via large-scale landslides and bank slumps are also an important contributor of sediment. We suggest that the data collected in this study can help land managers focus their attention upon processes and areas of the sub-basin that are providing the most sediment. The data also suggests that along with the drainage network, our understanding of the sub-basin is continuing to evolve and develop, and continued future observation and data collection will be key in enacting a successful management or restoration plan.

The options for potential basin-wide solutions range from complete physical engineering control of the entire Pavon Creeks sub-basin, to doing absolutely nothing and letting the system evolve on its own to a to quazi-equilibrium dictated by its underlying geology and soils, and its history of land use. But because of the land value, and on-going negative downstream effects of continued instability in the sub-basin, we suggest that the unique solutions for each gully and each gully reach are somewhere in the middle.

Although not exhaustive, some examples of potential management options include:

1) Enact a few specific, targeted physical restoration features (with the greatest likelihood of success, and that are cost-effective) to stabilize certain reaches. Test specific methods and effectiveness in this basin. These features should focus upon: stabilizing areas of active headcutting, vegetating (and irrigating) specific bare bank reaches, and laying back bank slopes in specific reaches to prevent continued bank slumping to reduce the total volume of sediment supplied. Levine Fricke (2001) believes that channel grading, headcut treatments, and bioengineering can be successful, and they recommend many specific restoration techniques.
2) Modify existing land use features that are exacerbating hillslope and channel instability, or concentration of runoff. These include culverts, road-side drains and

ditches, and short lengths of less-stable ranch road. Levine Fricke (2001) recommend energy dissipaters and culvert extenders be installed to reduce further erosion.

3) Modify existing land management practices by reducing the areas available to cattle, specifically fencing cows out of all channels. Also consider fencing cows out of the gully headwaters (the area of greatest landslide initiation). Previous reports also recommend fencing cattle out of the channels and restoration areas (Levine Fricke, 2001; USACE, 2001; USACE, 2003).
4) Enact large-scale engineered restoration (basin-wide use of built physical structures and wholesale grading of hillslope areas), to try and stabilize certain areas such as landslides or highly incised channel reaches. This approach will be very costly, and may only have limited success.
5) Encourage all the stakeholders to take a bigger, long-term look at the root of the issue. Pavon Creeks sub-basin is currently a unique unstable basin, with a long history of land use overprinted on the erosion-prone underlying geology. Land use and management should be well-planned so that they do not aggravate the basin and adjusting drainage network. It appears that there is not a cost-effective solution to completely stabilizing the geology of the entire basin. Therefore, reducing the land use intensity (possibly removing cattle completely) and accepting that this basin will episodically supply large pulses of sediment to Pinole Creek may be the best long-term solution.

In spite of the course of action that is eventually chosen by the stakeholders, we generally recommend that the focus should be on the drivers of basin instability, rather than just addressing the effects of instability. In other words, the best solution may be to address the many causes of sub-basin instability, such as concentration of flow, decreased infiltration, and trampling of channel banks, and then enact the fewest number of designed structural elements, such as headcut protection, bank planting and stabilization, and culvert energy dissipaters, that will provide the basin-wide stability the stakeholders are seeking. The costs (dollars needed for structural elements, reduced land for grazing) should be weighed against the benefits (reduced fine-grained sediment delivery to Pinole Creek, greater basin stability) to reach the best solution.

We recommend that vegetation and bioengineering treatments be used instead of purely structural elements wherever possible. Previous reports all suggest willow plantings as the main method of bioengineering (Levine Fricke, 2001; USACE, 2001; USACE, 2003), but we suggest that other species should be considered as well, to increase biodiversity, and that may have a greater chance of success of surviving or stabilizing the deeper landslides. However, the water requirements of the vegetation, and the suite of species planted should be considered, as annual summer and fall drying may limit the success of these methods. We also caution the use of check dams to control incision because the properties of the underlying geology and soils lead to a high risk of failure. This sentiment is echoed by the Levine Fricke report (2001). Restoration should take advantage of the many years of direct experience of EBMUD staff and rangers in planting and restoring reaches within this sub-basin. In addition, further study or longer-term observation of the sub-basin may reveal additional important processes, and may confirm or reject the hypotheses presented here in this data report. Additional site-specific data or monitoring will likely be necessary before any future restoration activities can begin.

Restoration of this sub-basin presents a unique opportunity to improve downstream aquatic habitat conditions, test many scientific hypotheses, build capacity of local land managers and stakeholders, balance the needs of both the stakeholders and the environment, and involve many school-age children in restoration efforts providing a hands-on lesson in watershed science. Despite the many challenges presented by this sub-basin, we recommend that stakeholders pursue solutions to address the instability, and the supply and delivery of excess sediment from the watershed.

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