Santa Rosa Creek
Watershed Geomorphology Assessment,
San Luis Obispo County, CA

FINAL TECHNICAL REPORT
May 2010

Prepared for
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Cover photography (from top to bottom):

1. Westward (downstream-facing) view of the Santa Rosa Creek watershed, July 2009. Photograph by R. Hawley/Greenspace – The Cambria Land Trust.
2. Eroding hillslopes in the Curti Creek subwatershed of Santa Rosa Creek watershed, July 2009. Photograph by Stillwater Sciences.
3. Santa Rosa Creek channel, view east (upstream), July 2009. Photograph by Stillwater Sciences.
4. Santa Rosa Creek lagoon at Moonstone Beach, view west (downstream), June 2009. Photograph by Stillwater Sciences.

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Table of Contents

List of Tables

List of Figures

List of Appendices

1 INTRODUCTION

1.1 Project Overview

Santa Rosa Creek in northern San Luis Obispo County once supported one of the largest populations of southern steelhead trout (*Oncorhynchus mykiss*) along the central California coast south of San Francisco (Titus et al. 2006). Perennial flow, suitable instream habitat conditions (e.g., riparian cover and spawning substrate), and few physical barriers contributed to the success of this species in the watershed. However, recent fish studies have determined that the population has dropped significantly below historic levels, driven by a number of probable factors including land uses, road building, and groundwater pumping (e.g., Nelson 1994, D. W. Alley & Associates 2007, Nelson et al. 2009). In response to the concerns over the existing habitat conditions of the threatened steelhead trout, several state and local advocacy groups have begun to identify limiting factors for steelhead trout habitat in the watershed (D. W. Alley & Associates 2008; TLCSLOC 2008), although these limiting factors have not been prioritized. These studies have focused on many of the geomorphic controls on habitat at the reach scale of Santa Rosa Creek, but prioritization requires a more comprehensive assessment of geomorphic factors at the watershed scale. Therefore, a watershed-wide evaluation of geomorphic conditions and processes that potentially contribute to aquatic habitat quantity and quality must be considered to successfully identify appropriate management solutions for Santa Rosa Creek.

An assessment of the geomorphic controls on steelhead trout habitat requires a study of hillslope and channel processes in the watershed from a historic and present-day perspective. Greenspace – The Cambria Land Trust (Greenspace) received grant funding from the California Department of Fish and Game (CDFG) to investigate the watershed's geomorphology—the scientific study of landforms and the processes that shape them—and synthesize the study's findings with existing steelhead trout habitat and other pertinent stream ecology information into a watershed management plan. Stillwater Sciences was tasked to conduct the watershed geomorphic assessment of Santa Rosa Creek, which entails the following:

- Compile and review existing information relating to hillslope and channel geomorphic processes
- Characterize hillslope geomorphic processes in the watershed and resulting sediment delivery into the mainstem Santa Rosa Creek
- Characterize sediment transport and channel dynamics in the mainstem of Santa Rosa Creek to understand how these processes affect channel morphology

This technical report examines geomorphic processes across the Santa Rosa Creek watershed at scales ranging from the site to the entire watershed. At the hillslope scale, field observations (including air viewpoints and accessible ground locations) combined with information contained in published literature were utilized to understand sediment production and delivery to the channel network. This approach integrates the effects of climate, precipitation, topography, tectonic activity, underlying rock types and geologic structure, vegetation coverage, and land uses throughout the watershed. Within the mainstem channel, contemporary conditions were assessed using reconnaissance surveys of channel morphology and data collected at accessible field locations including sediment-size distributions and observed sediment delivery from eroding banks and tributaries. Sediment transport characteristics were evaluated using these field data coupled with historical flow frequency and duration data. Evolution of the channel over the past 70 years was assessed using historic and current aerial photography and topography.

The results of these studies have been synthesized to produce a baseline geomorphic assessment, and characterization of geomorphic processes in the watershed that affect aquatic habitat conditions, particularly those for steelhead trout. In support of the watershed management plan, this technical report presents the following:

- Summary of historical changes
- Prediction of hillslope and tributary sediment production and identification of production zone locations and delivery pathways
- Estimation of reach-scale differences in channel form and processes, and sediment transport dynamics within Santa Rosa Creek
- Categorization of the channel network into zones of sediment production, transfer, and storage.

1.2 Regional Setting

The morphology of the central California coast, and in turn the Santa Rosa Creek watershed and its supported aquatic habitats, is controlled by both natural and anthropogenic (human-induced) forces. This section briefly introduces these forces to the extent they relate to the subject area.

1.2.1 Watershed characteristics

Santa Rosa Creek watershed lies within the southern portion of the California Coast Range—a northwest-trending series of mountains and basins along the coast from Santa Barbara north to the Oregon border (Figure 1-1). The 123 km^2 (48 mi^2) watershed is bounded to the east by the Santa Lucia Mountains and the west by the Pacific Ocean. Bordering the watershed are the similarly sized watersheds of San Simeon Creek to the north, Adelaida Creek to the northeast, Paso Robles Creek to the east, and Villa Creek to the south. Santa Rosa Creek and its tributaries flow mostly unobstructed down steep hillslopes mantled with shallow soils and sparse shrub vegetation, and through agricultural areas and the small town of Cambria before reaching the Pacific Ocean. Santa Rosa Creek travels 25 km (16 mi) from its headwaters, following a sinuous course to the west through a confined canyon that opens up into a relatively long, broad valley floor. The town of Cambria sits near the mouth of Santa Rosa Creek, below the confluence with Perry Creek—the largest tributary in the watershed. Only four creeks have been named on topographic maps of the U.S. Geological Survey (USGS)—Santa Rosa, Perry, Green Valley, and Fiscalini creeks (USGS 1979a, 1979b)—while an additional 6 streams have been unofficially designated as derived from past or current property owner names (e.g., D. W. Alley & Associates 2008). These tributaries are referenced throughout this report, as summarized below in Table 1-1 and shown in Figure 1-2.

The watershed exhibits an unusual drainage pattern as it is effectively split in two primary halves: Santa Rosa Creek represents the northern half and Perry Creek, along with Green Valley Creek, represents the southern half. In effect, the watershed supports two main stream branches. Both subwatersheds exhibit similar drainage patterns with longer tributaries flowing from the north and down south-facing slopes to their individual confluences. This pattern gives the valleys of Santa Rosa, Green Valley, and upper Perry Creek an asymmetrical form when viewed looking downstream. This form is clearly exhibited by the position of the three mainstem channels flowing much closer to the southern divide of their respective subwatersheds. The two primary streams and their tributaries flow across various geologic rock units, including shales, sandstones, and volcanics, but they primarily cross rocks of the tectonically sheared Franciscan Complex (see Section 1.2.2). The topographic relief is typical of the southern Coast Range terrain, with steep upland areas and low-gradient valley bottoms bordering the lower reaches of Santa Rosa, Green Valley, and Perry creeks (Figure 1-2). Relatively higher elevations are present in the Santa Rosa Creek subwatershed, which peaks at Cypress Mountain with an elevation of 894 m (2,933 ft). In comparison, the highest point in the Perry Creek subwatershed (NE corner of the Green Valley subwatershed) reaches an elevation of 433 m (1,419 ft). At its lowest elevation, Santa Rosa Creek flows through a lagoon contained by an annually formed sandbar at Moonstone Beach that re-opens when streamflow begins to rise in late fall (see Section 4.5 – Lagoon Morphology and Dynamics).

Table 1-1. Santa Rosa Creek watershed and subwatershed areas, stream lengths, and maximum relief.

Subwatershed	**Area** [A]		**Stream length** [B]		**Maximum relief** [C]	
	km^2	**mi^2**	**km**	**mi**	**m**	**ft**
Total Santa Rosa Creek Watershed [D]	**123**	**47.5**	**25.4**	**15.8**	**894**	**2,933**
Santa Rosa Creek [D, E, F]	63.6	24.6	25.4	15.8	894	2,933
Taylor Creek [G]	*3.8*	*2.4*	*3.8*	*2.4*	*200*	*658*
Curti Creek [G]	*5.5*	*2.1*	*3.5*	*2.2*	*596*	*1,957*
Lehman Creek [G]	*6.5*	*2.5*	*4.1*	*2.6*	*774*	*2540*
East Fork Santa Rosa Creek [G]	*4.9*	*1.9*	*4.7*	*2.9*	*527*	*1,730*
North Fork Santa Rosa Creek [G]	*5.6*	*2.2*	*4.2*	*2.6*	*534*	*1,752*
Mora Creek [G]	*6.8*	*2.6*	*4.8*	*3.0*	*680*	*2,230*
Perry Creek [E]	59.3	22.9	15.6	9.7	245	804
Fiscalini Creek [E]	6.7	2.6	2.3	1.4	188	617
Green Valley Creek [E]	31.5	12.2	12.8	7.9	405	1,330

[A] Subwatershed area derived in a GIS using a USGS 10m Digital Elevation Model (DEM).

[B] Stream length derived in a GIS using a USGS 10m DEM-generated stream network with a contributing area threshold of 0.04 km^2.

[C] Minimum and maximum elevations of subwatershed derived in a GIS using a USGS 10m DEM

[D] Santa Rosa Creek mainstem continues along "East Fork Santa Rosa Creek" per the USGS name designation (USGS 1979b)

[E] USGS stream name designation (USGS 1979a, 1979b)

[F] Excludes Perry Creek subwatershed

[G] Unofficial tributary name (D. W. Alley & Associates 2008)

SANTA ROSA CREEK WATERSHED

Data Sources:
Hillshade: USGS 10m DEM;
Roads, Streams, Cities, and Urban Areas: ESRI
Watersheds: Stillwater Sciences - Calwater

February, 2010

Figure 1-1. Santa Rosa Creek watershed and vicinity map.

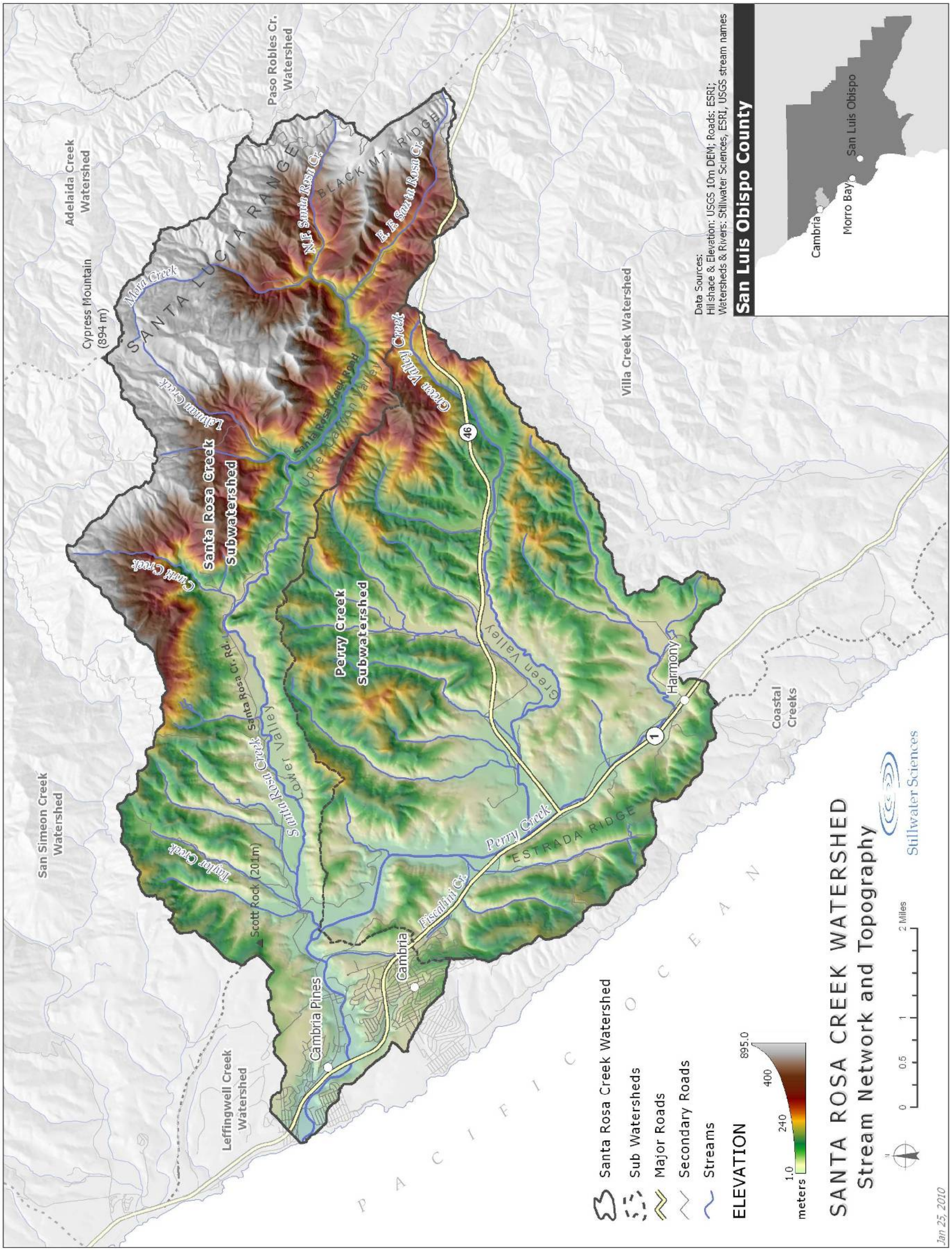


Figure 1-2. Santa Rosa Creek watershed stream network and topography.

1.2.2 Geology

The Santa Rosa Creek watershed lies along the Santa Lucia Mountain range near the southern end of the geologically distinctive Coast Range geomorphic province. Orientated with the overall NW–SE trending grain of the California topography, the Santa Lucia range follows the southern Coast Range for 150 km (93 mi) between Monterey Bay to the north and the San Rafael Mountains to the south near Santa Barbara. The province resides within a tectonically active zone composed primarily of right-lateral strike-slip (horizontal sliding motion) faults separating the Pacific and North American plates. At the axis of this zone is the 1,000-km-long (600-mile-long) San Andreas Fault, which lies 60 km (37 mi) to the east of the Santa Rosa Creek watershed. Overall, this tectonically and geomorphically active province exhibits intermittent seismicity and asymmetrical drainages offset by faulting. Geologic mapping utilized for this study and presented in Figure 1-3 were based primarily on maps produced by Dibblee (2007a, 2007b), with supplemental information drawn from maps produced by Hall et al. (1979) and Lettis et al. (2004).

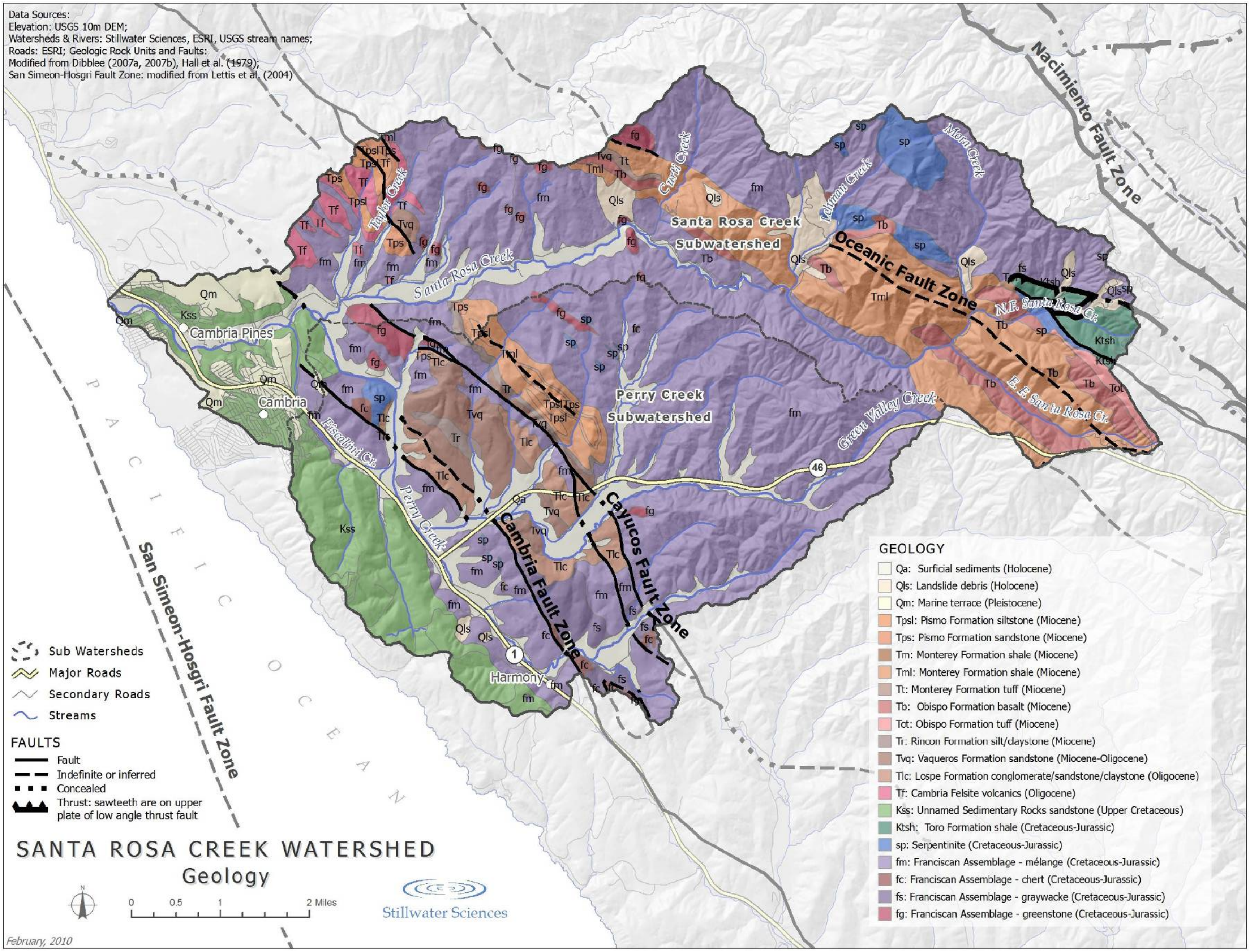
The geologic history of the Coast Range province formation that is relevant to this geomorphic study begins about 150 million years ago (Ma), before the formation of the San Andreas Fault and during a period when the dense oceanic Farallon Plate moved east and slid beneath the less dense continental North American Plate. This process, referred to as subduction, formed a deep, marine trench along the ancestral California coastline at the western base of the Sierras. A portion of the sediments and volcanic flows composing the eastward-moving seafloor were scraped off during the subduction process and, along with sediments transported downstream from the Sierras, accumulated within the trench. These accreted materials are preserved today as the Mesozoic (200 to 100 Ma) rocks of the Franciscan Complex and early Cenozoic (65 to 25 Ma) sedimentary rocks that together make up much of the Coast Range province (Chipping 1987, Dibblee 2007a, 2007b). Rock types contained within the Franciscan include chert, graywacke (argillaceous sandstone), greenstone (altered basalt), and serpentinite—the state rock of California. Non-marine rock units formed during the early Cenozoic era include the Lospe Formation sandstones. Today, the majority of the Santa Rosa Creek watershed is predominately composed of Franciscan mélange: a mix of hard graywacke (sandstone) and sheared argillite (silt/claystone). Sandstones of the Lospe Formation are exposed along the hilltops near lower Perry and Green Valley creeks.

Following the complete subduction of the Farallon Plate, the eventual transition to a transform (strike-slip) plate boundary began about 25 Ma with the gradual contact between the northwest-moving Pacific Plate and the southeast-moving North American Plate (Atwater and Molnar 1973). This transition marked a geologically brief period of coastal volcanism which locally produced the Cambria Felsite rocks of Oligocene age (27 Ma), as seen today at Scott Rock located east of Cambria near Taylor Creek (Dibblee 2007a). Sedimentary rocks subsequently formed in offshore basins developed during early San Andreas Fault activity, which included Vaqueros Formation sandstones and Rincon Formation shales. Both of these units presently occur adjacent to the Lopse Formation sandstones in the uplands of the lower watershed. A second brief period of volcanism occurred underwater along the proto-coastline about 16 Ma (early Miocene) and locally created the basalts and tuffs of the Obispo Formation (Hall 2007). These now highly weathered basalts and hardened tuffs (solidified volcanic ash) lie unconformably upon the Franciscan mélange rocks along a northwest-trending band in the upper watershed. Erosion-resistant Obispo tuffs are presently exposed at the Black Mountain ridge near the headwaters of Santa Rosa Creek. The submarine volcanic activity was followed in the upper Miocene and lower Pliocene epochs (12 to 3 Ma) by continued offshore sediment deposition resulting in the Monterey Formation—one of the thickest and most widespread sedimentary units in the Coast Range—and the Pismo Formation. In the Santa Rosa Creek watershed, both of these units are dominated by thin-bedded, silica-rich shales, siltstones, and claystones, with some sandstones present in the lower Pismo Formation member (Chipping 1987).

The Coast Range orogeny, or mountain-building process, began during the late Pliocene and Pleistocene epochs ($\leq$4 Ma) and continues today. Regional uplift has been driven by crustal convergence that occurs where subtle NW–SE trending bends along the active transform fault zones force earth materials in between the larger faults to "pile up", thereby creating the upland areas of the watershed. Obvious evidence of geologically recent uplift activity is the existence of Pleistocene marine terraces situated along the coastline and the lower watershed. Tectonic movement here may explain the watershed's unusual drainage pattern of being split in two primary halves—Santa Rosa Creek and Perry Creek subwatersheds—where Perry and Green Valley creeks may have once flowed directly to the coast but were eventually "captured" by Santa Rosa Creek as uplift and transverse migration of the elevated landscape re-directed Perry and Green Valley creeks northward. Additional evidence of this event is the presence of a broad, flat expanse along lower Perry Creek where, prior to European settlement, flow and sediment conveyed by Perry Creek collected in the basin to form a perennial lagoon. Additional details on the lagoon are discussed in Chapter 4.

Since the last 10,000 years, active faults traversing and/or bordering the watershed exhibit a general stick-slip motion, whereby movement is episodic and expressed as earthquakes. The largest of these faults in the vicinity of the watershed is the San Simeon-Hosgi Fault Zone located offshore and estimated to have a late Quaternary (since 1.8 Ma) slip rate of 1–3 mm a^{-1} (Lettis et al. 2004). In December 2003, a 6.5-magnitude earthquake occurred about 17 km (10 mi) north of Cambria near the Oceanic Fault, which also traverses the headwaters of Santa Rosa Creek (USGS 2004). Properties in both Cambria and Paso Robles were damaged during this event, as were Highway 46 and Santa Rosa Creek Road.

Coincident with the Coast Range uplift period, the valley floors along Santa Rosa, Perry, and Green Valley creeks have accumulated unconsolidated alluvial and stream-terrace deposits. It is within these sediments that the watershed's groundwater basins have developed, which currently serve as a primary water supply source to urban areas and land use activities in the watershed (see Section 1.2.4 below). The bulk of the water-bearing units are along the lower valley reach of Santa Rosa Creek, below a geologic constriction composed of hard Franciscan greenstone called Mammoth Rock (see Figure 1-5 in Section 1.2.3 below). The groundwater storage capacity in the basin has been estimated at 24,700 acre-feet (CDWR 1975).



Data Sources:
Elevation: USGS 10m DEM;
Watersheds & Rivers: Stillwater Sciences, ESRI, USGS stream names;
Roads: ESRI; Geologic Rock Units and Faults:
Modified from Dibblee (2007a, 2007b), Hall et al. (1979);
San Simeon-Hosgri Fault Zone: modified from Lettis et al. (2004)

February, 2010

Figure 1-3. Santa Rosa Creek watershed geology.

1.2.3 Climate and hydrology

Coastal watersheds along the west side of the Coast Range province experience a two-season Mediterranean-type climate, with wet cool winters and dry warm summers. The regional climate is controlled by the North Pacific High, a high pressure system resting over cold upwelling waters of the eastern Pacific, while the local climate is controlled by the watershed's topography and proximity to the ocean (Carle 2006). The Pacific High system deflects storms from reaching the California coast during summer months, resulting in dry westerly winds blowing over cold ocean water and often producing fog. In the Santa Rosa Creek watershed, this fog belt typically extends inland just past Cambria. During winter, the Pacific High retreats to the south resulting in high rainfall in California concentrated between November and April. Overall, the California coast experiences highly variable annual rainfall depending on each storm's frequency and magnitude and on the landscape relief. Mean annual rainfall across the watershed varies between 53 and 94 cm (21 and 37 in), as reported by the U.S. Department of Agriculture (1971–2000) and San Luis Obispo County Division of Public Works (1954–2008) (Figure 1-4). A clear pattern of increased rainfall with elevation is expressed across the watershed, as the lowlands near Cambria, including much of Perry and Green Valley creeks, receive nearly half the rainfall received in the headwaters of Santa Rosa Creek.

Periodicity in the pattern of the wet/dry years in California is correlated to the El Niño–Southern Oscillation (ENSO) climatic phenomenon. ENSO is characterized by warming and cooling cycles (oscillations) in the waters of the eastern equatorial Pacific Ocean. Specifically, El Niño episodes are initially driven by abnormally low atmospheric pressures in the eastern Pacific, resulting in lower upwelling rates of cold ocean waters and, therefore, a persistence of warmer surface water temperatures (Kousky and Bell 2000). Ultimately, the warmer waters lead to increased precipitation along the eastern Pacific, extending up to California. ENSO cycles typically have a 1–1.5 year duration and 3–8 year recurrence interval. ENSO-induced climate change occurs on a multi-decadal time scale that is consistent with the recent shift from a relatively drier climate (averaged over the period 1944–1968) to a relatively wetter climate (averaged over the period 1969–1995) in North American's Pacific region (Inman and Jenkins 1999). The most recent El Niño event (although weak) occurred in water year 2007, and another event is underway in water year 2010 (NOAA 2009a).

The climatic and hydrologic characteristics of the watershed produce a perennial flow regime along the majority of Santa Rosa Creek, while most tributaries, including Perry and Green Valley creeks, experience intermittent flows (Figure 1-5). Similar to other Coast Range basins, flood flows in Santa Rosa Creek typically increase, peak, and subside rapidly in response to high intensity rainfall. This hydrologic attribute is characteristic of a "flashy" hydrograph, whereby a rapid increase in discharge occurs over a relatively short time period with a quickly developed peak discharge in relation to normal baseflow (Ward 1978). Since 1958, large flood events have occurred in 1967, 1969, 1973, 1978, 1986, 1993, 1995, and 2005, frequently (but not always) corresponding with ENSO years (NOAA 2009b), which is consistent with an understanding that ENSO years in the Coast Ranges, especially south of 35ºN, are characterized by relatively high rainfall intensities, with rivers and streams exhibiting higher annual peak flows than they do in non-ENSO years (Cayan et al. 1999, Andrews et al. 2004). Additional details on the discharge dynamics in the watershed are presented below in Chapter 4.

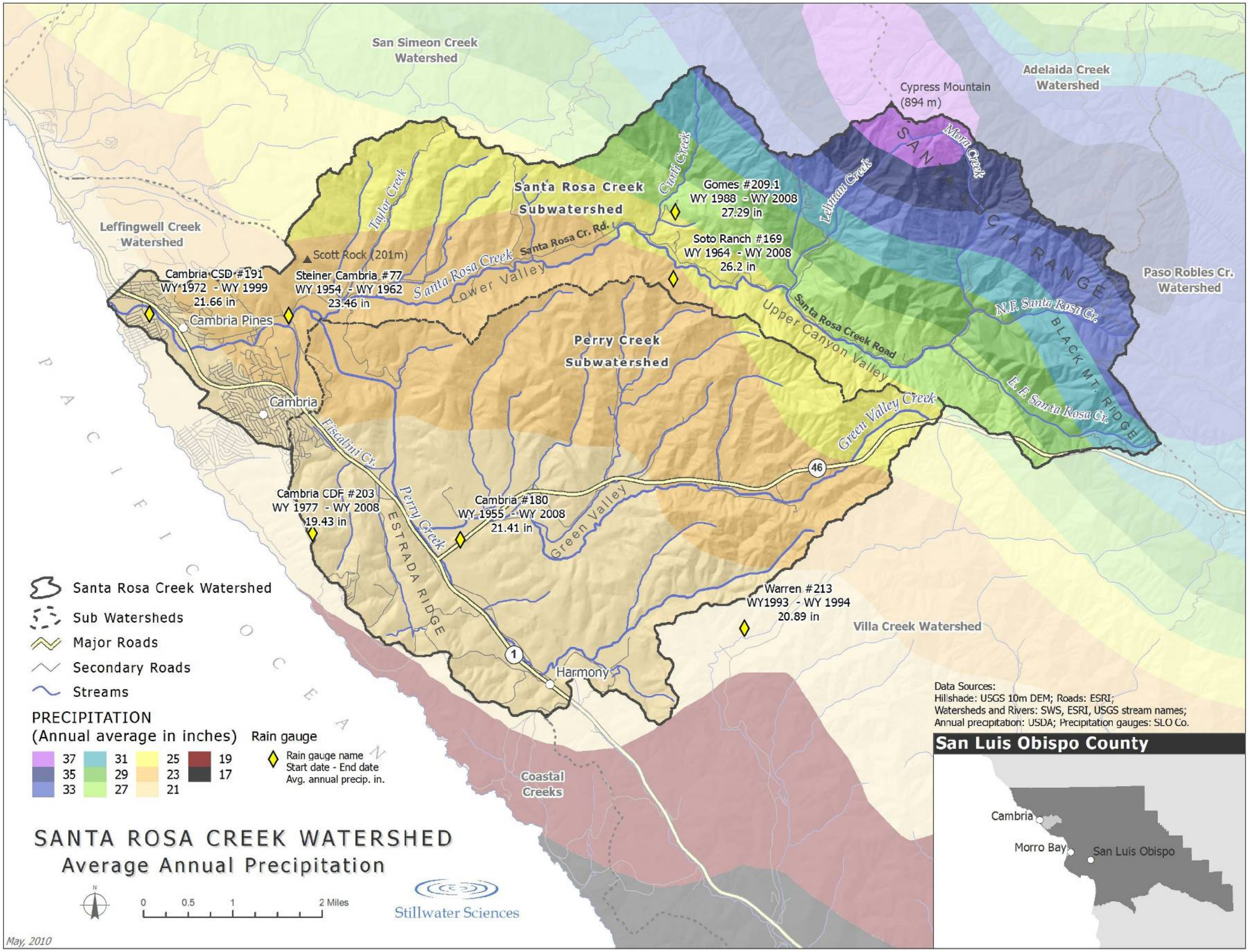
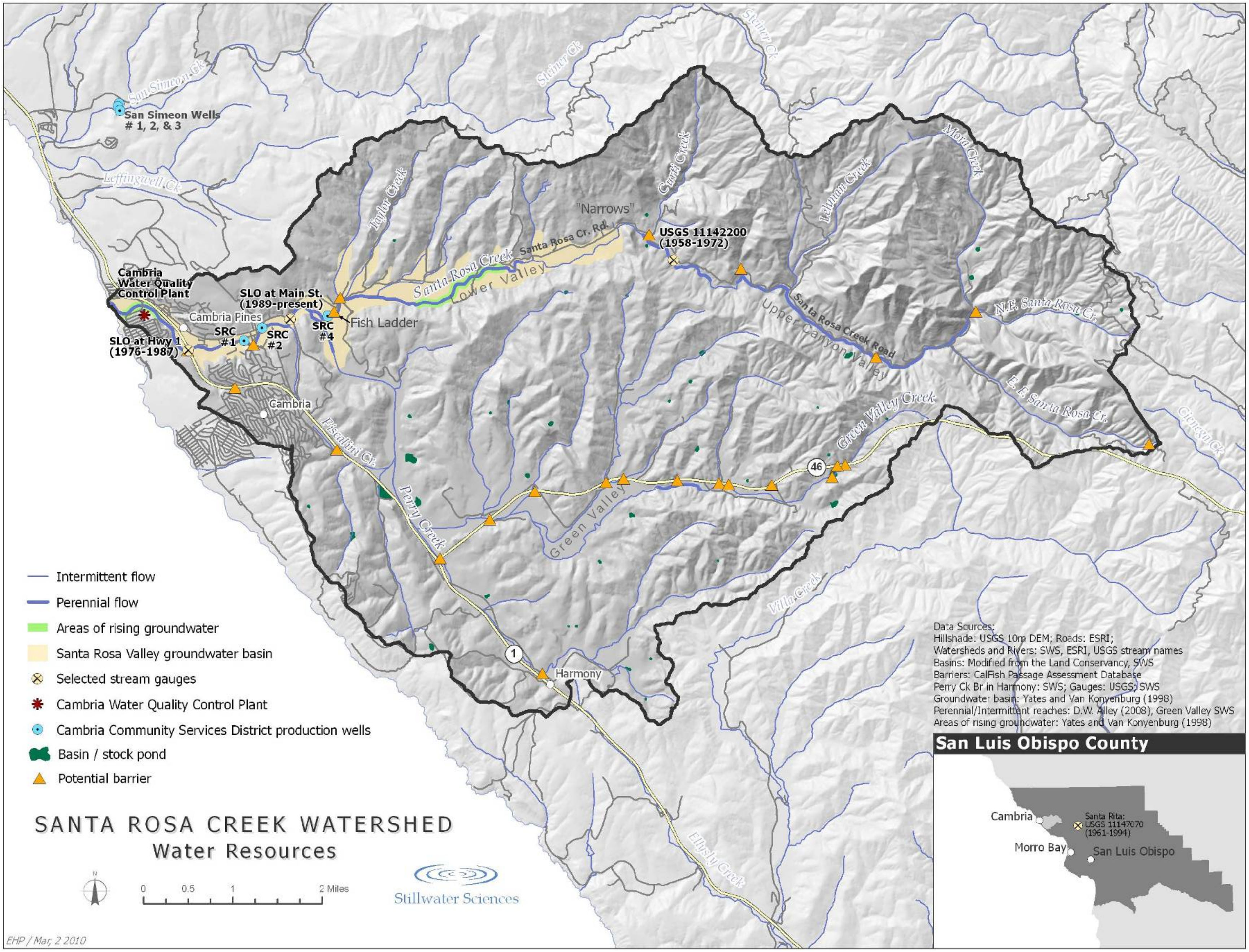


Figure 1-4. Distribution of average annual precipitation in the Santa Rosa Creek watershed. Precipitation contours represent the period of 1960 – 2001. Rain gauge stations representing various years of data shown for reference.



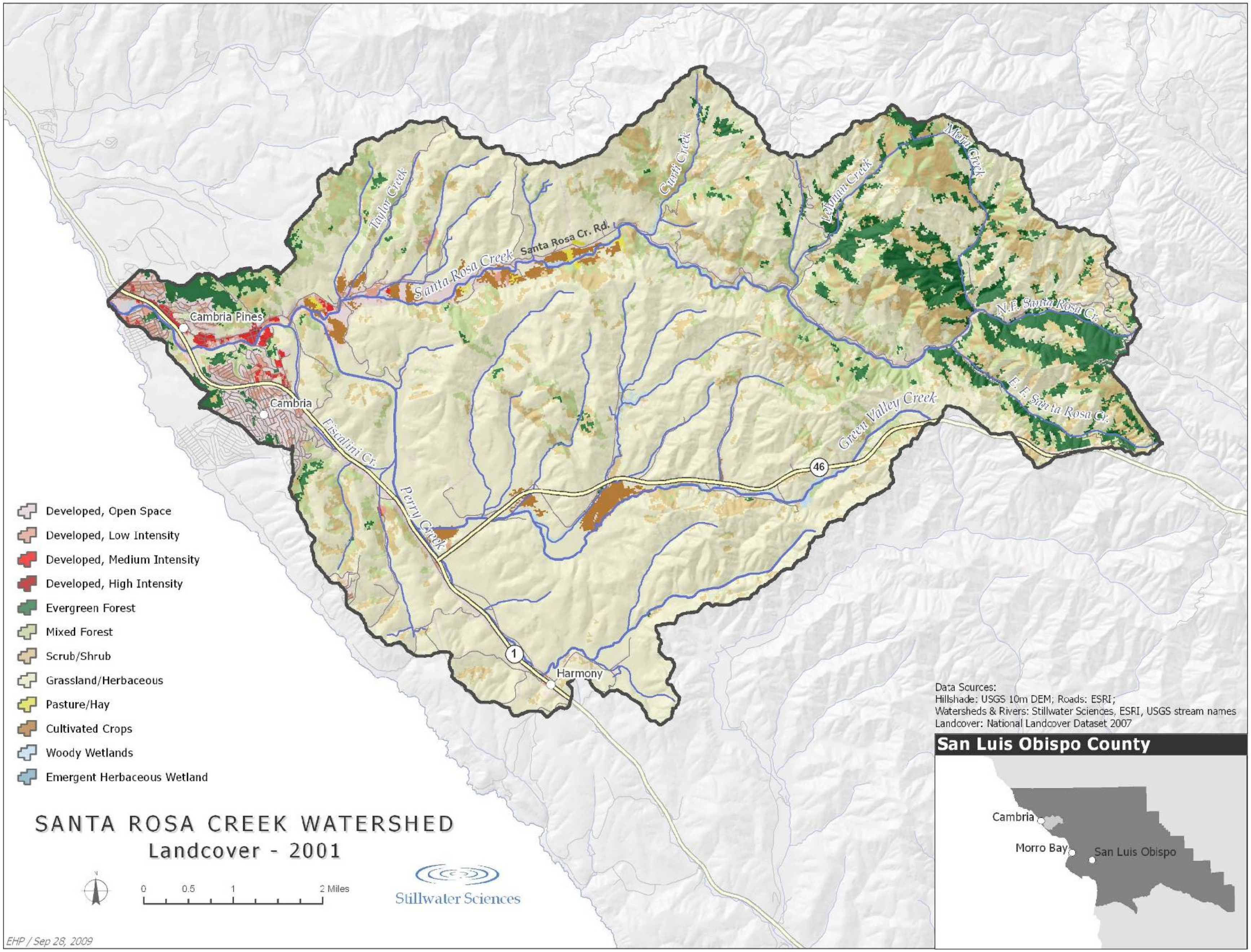
Data Sources:
Hillshade: USGS 10m DEM; Roads: ESRI;
Watersheds and Rivers: SWS, ESRI, USGS stream names
Basins: Modified from the Land Conservancy, SWS
Barriers: CalFish Passage Assessment Database
Perry Ck Br in Harmony: SWS; Gauges: USGS; SWS
Groundwater basin: Yates and Van Konyenburg (1998)
Perennial/Intermittent reaches: D.W. Alley (2008), Green Valley SWS
Areas of rising groundwater: Yates and Van Konyenburg (1998)

Figure 1-5. Water resources in the Santa Rosa Creek watershed. Perennial and intermittent streams, groundwater basin, and stream gauge locations are shown.

1.2.4 Land use/Land cover

The majority of Santa Rosa Creek watershed is sparsely populated, with urban development concentrated downstream at the town of Cambria (Figure 1-6). As of 2009, the town supported a population of 6,624 (Cambria Chamber of Commerce, pers. comm., 2009). The remainder of the watershed is almost entirely under agriculture, with primary activities consisting of cattle ranching, dairying, and crop cultivation, all of which require some level of irrigation, primarily obtained via groundwater pumping. In Cambria, developments consist of a business district, which closely borders the lower 4.5 km (2.8 mi) of Santa Rosa Creek from Main Street bridge to the lagoon area, and residential neighborhoods that extend to the north and south upon the adjacent hillsides. Tourism, primarily catered towards visitors traveling to Hearst Castle in nearby San Simeon, is the chief industry of Cambria. As of 2001, developed areas in total account for approximately 8% of the watershed area according to data contained within the National Land Cover Database (Homer et al. 2004). Besides the town of Cambria, the only other significant elements of infrastructure in the watershed include three roadways: Highway 1, Highway 46, and Santa Rosa Creek Road. The roadways closely follow and occasionally cross, via bridge or culvert, portions of Santa Rosa, Perry, and Green Valley creeks (see Figure 1-5).

Land cover in the remainder of the watershed is dominated (63% of watershed total) by grassland/herbaceous cover related to lands used for cattle ranching and dairy cattle pasture (Homer et al. 2004) (see Figure 1-6). Valley bottoms along Santa Rosa and Green Valley creeks support the majority of cultivated crops grown in the watershed. The steeper uplands support scrub/scrub, or chaparral, cover with some forest cover. Higher density vegetation cover and larger trees generally concentrate on north-facing slopes, higher elevations, and/or adjacent to perennial streams, particularly near the headwaters of Santa Rosa Creek. Native vegetation community types typically include mixed-hardwood forest (e.g., California bay tree [*Umbellularia californica*]) in riparian areas, chaparral (e.g., chamise [*Adenostoma fasciculatum*]) and oak woodland (e.g., coast live oak [*Quercus agrifolia*]) upon ungrazed hillslopes farther up in the watershed, and some remnant stands of conifers (e.g., Monterey pine [*Pinus radiata*]) near Cambria. Aquatic vegetation communities present in the watershed are limited to the lagoon. In the areas of denser vegetation cover (i.e., chaparral and forest), surface erosion is effectively hindered as the vegetation provides: (1) a continuous surface cover that intercepts rainfall and prevents rainsplash erosion, and (2) roughness to the landscape surface that divide and slow sheetflow upon the land surface. Changes to these land cover types over time are discussed in greater detail below in Chapter 2.



Data Sources:
Hillshade: USGS 10m DEM; Roads: ESRI;
Watersheds & Rivers: Stillwater Sciences, ESRI, USGS stream names
Landcover: National Landcover Dataset 2007

Figure 1-6. Land cover present in 2001 within the Santa Rosa Creek watershed (after Homer et al. 2004).

2 IMPACT OF HISTORICAL WATERSHED CHANGES ON GEOMORPHIC PROCESSES

Understanding the historical conditions of the Santa Rosa Creek watershed relative to present-day conditions is necessary in order to answer the following questions: (1) “what did the watershed look like in the past?”; (2) “what geomorphic processes were active?”; (3) “how has the watershed changed over time?”; and (4) “what were the factors that contributed to those changes?” In effect, looking at the watershed’s past provides insight into the natural geomorphic trends in addition to the identification of any human-induced changes over time. An informed forecast of future watershed conditions can therefore be made when synthesizing our understanding of past and present conditions. The information presented here summarizes general historical conditions in the watershed dating back to pre-European settlement in an attempt to answer the questions posed above. A synthesis of this information with the results of contemporary hillslope and fluvial processes (see Chapters 3 and 4, respectively) are presented in Chapter 5.

2.1 Chronology of Watershed Changes

The history of development and land use changes in the Santa Rosa Creek watershed has been documented by several authors (e.g., Angel 1883, Hamilton 1974), whose main focus has been on the town of Cambria and other nearby coastal settlements rather than on the watershed or stream channels. Specific details on the geomorphic conditions of the watershed have been interpreted from maps, aerial photographs, and reports, such as those published by the CDFG and USGS. Overall, very little historical information has been published on the geomorphic or ecologic conditions of Santa Rosa Creek or its watershed. The primary sources of historical information used in this study are listed in Table 2-1. Information from these sources has been distilled here as a narrative summary to illuminate the historical (both natural and human-induced) events that may have had an effect on water and sediment discharge in the watershed, and so have influenced geomorphic processes and channel morphological responses within the mainstem stream corridor (Figure 2-1). Figure 2-1 and Appendix A present more detailed information chronicling the history of potential watershed impacts.

Table 2-1. Primary historical information sources for the Santa Rosa Creek watershed.

Data	Source	Dates	Notes
Aerial photography	UC Santa Barbara (UCSB), USGS, others	1937 to present	Watershed-wide coverage, with variable resolution depending on year
Geography / Topography	Map: R. R. Harris. 1874. Map of the County of San Luis Obispo.	1874	County-wide coverage of geographical elements: cities/towns, land ownership, stream/rivers, and roads. Oldest map of the County. Includes inset map of Cambria.
	Map: USGS. 1919. Topographic map of the San Simeon quadrangle. Scale 1:62,500.	1919	Detailed geographic and elevation maps (50-ft contours)
	Map: USGS. 1932. Topographic map of the Adalaida quadrangle. Scale 1:62,500.	1932	

Data	Source	Dates	Notes
Geography / Topography (cont.)	Map: USGS. Topographic map of the Cambria quadrangle. Scale 1:24,000.	1959, 1989	Detailed geographic and elevation maps (40-ft contours)
	Map: USGS. Topographic map of the Cypress Mountain quadrangle. Scale 1:24,000.	1948, 1979	Detailed geographic and elevation maps (20-ft contours)
Hydrology: Precipitation	San Luis Obispo (SLO) County	1870 to present	Long-term rainfall record from City of San Luis Obispo rain gauge.
	SLO County	1950s to present	Various local rainfall data from Santa Rosa Creek watershed rain gauges.
	U.S. Department of Agriculture (USDA)	1960 to 2001	Spatially averaged rainfall data for SLO County.
Hydrology: Stream flow	USGS	1957 to 1972	Daily stream flow data (upstream of Mammoth Rock)
	SLO County	1976 to 1992	Daily stream flow data (at Highway 1)
	SLO County	1989 to present	Daily stream flow data (at Main Street)
Land cover	Vegetation Type Mapping (VTM) project and NLCD	1930 to 2001	Detailed land cover (i.e., vegetation types) maps for whole watershed
Land use	California Department of Water Resources (CDWR)	1959 to 1996	Land use maps for watershed, primarily focused in urban and valley areas
Panoramic ground-based illustrations and imagery	Book: Myron Angel. 1883. History of San Luis Obispo County.	Late 1800s	Illustrations of farms in the watershed; also showing valleys and hillslopes
	VTM project http://vtm.berkeley.edu/	1930	Panoramic photos of hillslopes in the Santa Rosa and San Simeon watersheds
Population	San Luis Obispo County Historical Society (SLOCHS)	1860s to 1960s	Population estimates for Cambria as reported in document sources archived by the SLOCHS
Roads	California Highways http://www.cahighways.org/	1930s to present	Maps and summary accounts of the history of Santa Rosa Creek Road and Highways 1 and 46 through the watershed.
Textural accounts	Book: Myron Angel. 1883. History of San Luis Obispo County.	1700s to 1880s	Summaries of the history of the Cambria area. Includes some accounts of the watershed's historical condition.
	Book: Geneva Hamilton. 1974. Where the highway ends – Cambria, San Simeon and the Ranchos.	1700s to 1970s	
Verbal accounts	Personal communications: Dawn Dunlap, Santa Rosa Creek watershed resident and amateur historian	1800s to present	Source of additional information related to populations, flood damage, and land use changes, etc.

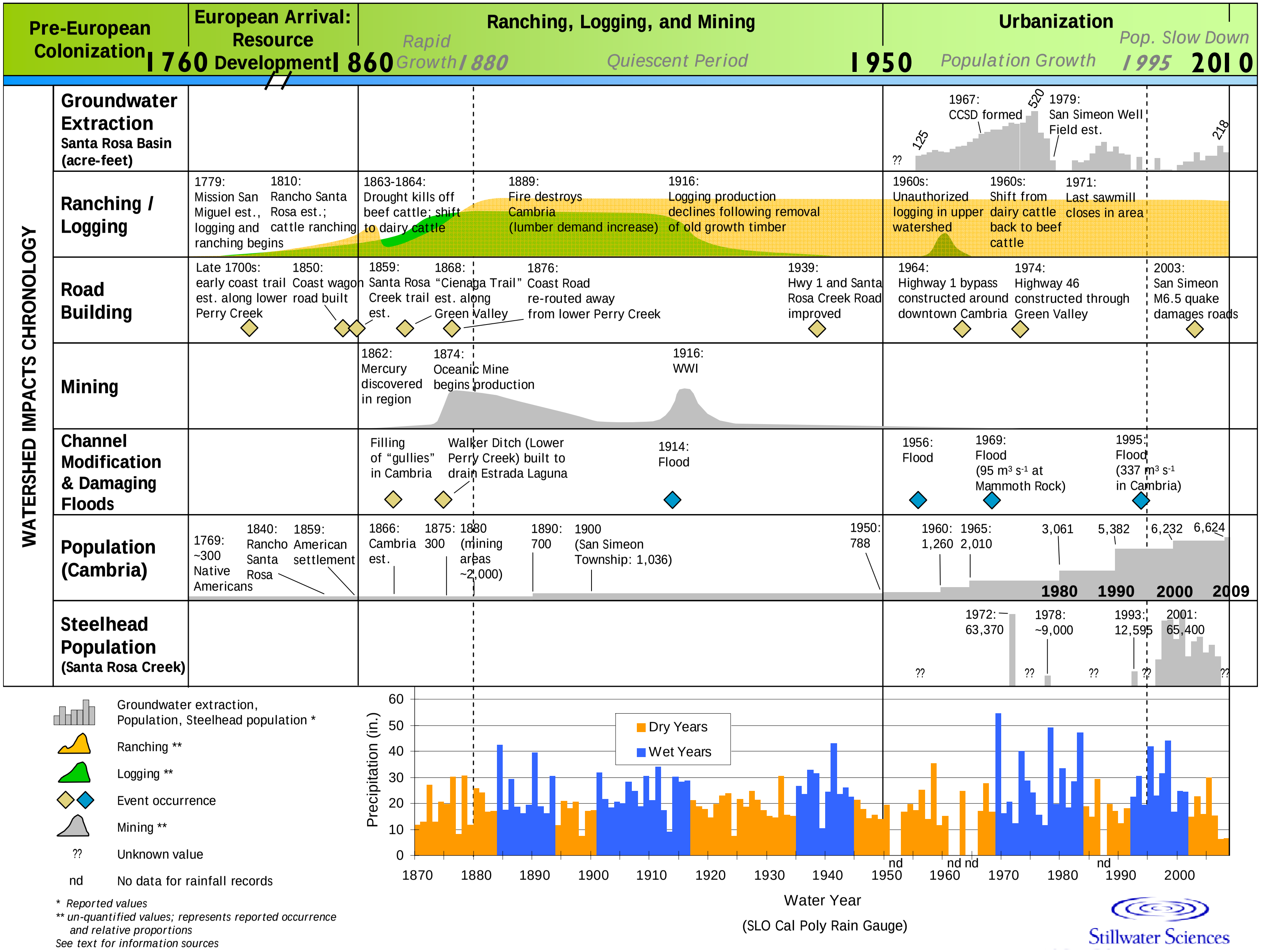


Figure 2-1. Chronology of potential watershed impacts and events. Precipitation records indicate periods of cumulatively wetter (blue) and drier (orange) periods in the watershed. Most very wet years in the watershed are also years with large floods.

Prior to European settlement along the California coast, the watershed is assumed to have been in a relatively undisturbed condition, responding only to fluctuating flood, drought, earthquake, and fire sequences, and with relatively minor impacts associated with the agricultural practices of the local indigenous peoples. The first recorded accounts of Santa Rosa Creek valley are those made during the Portola Expedition where, in September 1769, the party encountered a "canyon… and arroyo surrounded with hills of pine" (Hamilton 1974). The Spanish word of "arroyo", as used in this account, translates to mean a small creek and not one that is necessarily incised, which is unlike the contemporary use of the word in the English language to mean an incised creek, typically those found in the American southwest. On numerous instances, the expedition party noted observing flowing streams, both along what is now known as the mainstem Santa Rosa Creek and from many of its "springs", or tributaries (Hamilton 1974). Few other records of this area's natural resources were made for several decades despite the establishment of Mission San Miguel (1779) near present-day Paso Robles and the growing use of the Santa Rosa and San Simeon watershed areas for timber and wild game to support the growing Spanish population throughout the southern Coast Range region.

In 1841, Don Julian Estrada was granted possession of Rancho Santa Rosa—a 13,200 acre (53 km^2) land holding encompassing much of the western half of the watershed (Angel 1883, Hamilton 1974) (Figure A-1). Estrada drafted an illustration of his land in that year that depicts several notable features of the historical landscape, including Santa Rosa and San Simeon creeks draining to the ocean from steep upland areas, continuous pine forests upon hillsides surrounding lower Santa Rosa Creek near the area of present-day Cambria, a coastal trail parallel to the coastline, and, perhaps most interestingly, a "laguna", or lagoon along the narrow valley of lower Perry Creek (Figure A-2). This inland lagoon is further described in Hamilton (1974) as a "shallow, broad lake… clogged with tules" fed by both Perry and Green Valley creeks, and bordered along its eastern shore by a coastal trail linking San Luis Obispo with San Simeon. The exact location of this lagoon is not precisely known, but it has been estimated to have formerly extended from the Perry and Green Valley creeks confluence north towards Santa Rosa Creek (Hamilton 1974, D. Dunlap, pers. comm., 2009). The lagoon was eventually drained by "Walker Ditch" in the early 1870s under the order of property owner George Hearst for the purpose of converting the wetland area to agricultural land (Hamilton 1974, D. Dunlap, pers. comm., 2009). The first official survey map of San Luis Obispo County published in 1874 does not depict the lagoon, indicating that it had been drained already when the survey was conducted, and instead shows a stream channel that generally follows the present-day stream course of lower Perry Creek (Harris 1874) (Figure A-1). Today, this artificial stream course of lower Perry Creek stands out from all other stream courses in the watershed as it follows long, straight segments connected by right-angle turns along the valley floor and north towards its confluence with Santa Rosa Creek. The lake likely functioned as a settling basin for sediment delivered by tributaries of Perry Creek, and effectively served historically to separate the Perry Creek subwatershed from the Santa Rosa Creek subwatershed in terms of sediment delivery, especially of coarse sediments.

Starting in the late 1700s, clearing of the land in support of agricultural activities—cattle ranching, crop cultivation, and logging—likely caused significant changes to rainfall-runoff relationships as trees, shrubs, and deep-rooted native perennial grasses in the valleys and hillslopes were degraded and replaced by shallow-rooted, non-native annual grass species that less effectively protect soil against erosion. Initially, cattle herds from Mission San Miguel were occasionally moved into the Santa Rosa Creek watershed because of ample sources of water and foraging vegetation even during the dry seasons (Hamilton 1974). Following California statehood in 1850, Americans quickly settled the watershed and greatly increased the pace of land clearing, which was reportedly achieved by cutting and/or burning the native vegetation (Coffman 1995, D. Dunlap, pers. comm., 2009). Historical accounts from across the coastal region tell of coordinated efforts by land owners to clear valley-bottom forests along major rivers (Boughton et al. 2006), which was likely practiced along Santa Rosa, Perry, and Green Valley creek valleys as very little forest cover remains but for some riparian stands closely bordering the stream channels (see Section 2.2). Overall, these land uses coupled with episodic storm events resulted in several significant changes in the watershed, namely: (1) greater volumes of hillslope runoff generated per unit rainfall, with far greater volumes of fine sediment production throughout the watershed and increased gullying and shallow landslide potential on the steeper hillslopes; and (2) incision of the mainstem stream channels due to decreased stream bank stability and increased stream power allowing high flows to entrench the channel. Prior to incision, the Santa Rosa, Perry, and Green Valley creek channels would have supported higher groundwater elevations and more frequent inundation under lower flows, which supported the valley forests.

Between 1860 and 1880 marked a period of unprecedented population growth and land development as the watershed became more settled. Despite a die-off of beef cattle during the intense 1863–1864 drought, a shift to dairy farming, continued logging, and mining of mercury in the region maintained a steady rate of landscape alteration over the next two decades. Urban development and road building began the process of filling in small stream channels, especially those situated where Cambria was to be established (Hamilton 1974). By 1880, the landscape had been radically changed from its pre-European settlement condition and appeared very similar to present-day conditions, as represented in several illuminating sketches made during the 1870s (Angel 1883) that show grass-covered hillslopes and valley floors used for pasture with some relict patches of native riparian vegetation remaining near stream channels (Figures A-3, A-4, and A-5). Another notable feature depicted in two of these illustrations (Figures A-3 and A-5) is active hillslope erosion in the form of gullies, which remains a ubiquitous feature of the present-day landscape (see Figure 3-1 in Section 3). As discussed in further detail in Section 3, gullies and shallow landslides form between ridges in concave depressions, or swales, that are filled with sediment, or colluvium, over time and become the primary focus of erosion when changes to the rainfall-runoff relationship (i.e., vegetation clearing) has occurred (Reneau et al. 1990).

Specific impacts to hillslope and stream morphology from the Oceanic Mine operations situated in the middle of the Curti Creek subwatershed are not well known. Available information, however, both from this mine and others located in neighboring watersheds (e.g., Klau/Buena Vista mines) suggest that land clearing and road building were conducted to access the numerous mine adits while excavation and processing of rock materials led to runoff of toxic water and an increase of fine sediment delivery into the stream channel (CCRWQCB 1999 as cited in CCRWQCB 1998, CDPH 2009). The mining production slowly declined over time but experienced a second peak around 1916 in support of World War I efforts (Hamilton 1974, Baker 2003).

Between the 1880s and 1950s, the rate of new land development leveled off as mining and logging operations declined, along with the transient population that supported those industries. These trends were driven, respectively, by falling mercury prices and by the near-depleted stock of old growth pine trees (Hamilton 1974). Through this period, dairy farming and crop cultivation continued, but likely did not increase in areal extent. In general, the landscape condition present during this period appeared very similar to the present-day condition, as is clearly represented in photographs taken in similar (yet not exact) locations of lower Santa Rosa Creek valley in 1930 and 2009 (Figure A-6). Visible in both photographs are south-facing, pine tree-rimmed hillslopes mostly covered with a mix of scrub/shrub and grass vegetation, and farms situated at the base of the hillslopes upon the valley floor. However, despite these seemingly unchanged conditions in many areas of the watershed, significant changes to specific areas did occur after this relatively quiescent period in the watershed's post-settlement history.

Starting in 1950 and extending through to the mid-1990s, the town of Cambria experienced a steady increase in population and, correspondingly, an increase in urban development in the form of new housing, commercial, and some industrial developments as driven by their tourism industry (see land use / land cover comparisons over time in Section 2.2). According to County and US Census data, Cambria's population (excluding the remainder of the watershed) increased from 788 to 5,382 between 1950 and 1990, representing 6.8-fold increase, while California as a whole experienced only a 2.8-fold increase. Recent population growth in Cambria since 2000, however, dropped considerably to only a 1.1-fold increase, which is below the state growth rate during the past decade (A. Ochs, pers. comm., 2009, US Census Bureau 2003, US Census Bureau 2009). This population growth slowdown period signifies stabilization not only of the Cambria population but also of future development activity that may act to expand the town's urban footprint in the watershed.

The urbanization time period between 1950 and the 1990s also represents an expansion of groundwater pumping to irrigate crops and provide drinking water to Cambria, which has reduced base flows in Santa Rosa Creek. The amount of groundwater and surface water extracted by private entities for agricultural purposes is not well known but was estimated by Yates and Van Konyenburg (1998) in 1988–1989 to total approximately 3.5 times the amount pumped by the Cambria Community Services District (CCSD) for municipal uses. The present-day amounts of urban and agricultural groundwater extraction are approximately equal (815 acre-feet per year [AFY] for urban, 830 AFY for agricultural) in the Cambria Water Planning Area, which includes Santa Rosa Creek, San Simeon Creek, Leffingwell Creek, and Villa Creek watersheds (ESA 2010). Until the San Simeon well field was established to supplement municipal water demands in Cambria, the peak of groundwater extraction by CCSD in the Santa Rosa Creek watershed occurred in 1976 and totaled 520 acre-feet (CCSD 2009), or 3.6 times the total annual streamflow measured at the Highway 1 bridge stream gauge (annual flow in 1976= 144 acre feet).

The likely impact of groundwater extraction has been an overall reduction in baseflow within Santa Rosa Creek, and potentially within Perry and Green Valley creeks, depending on the amount of groundwater pumped by private wells in those basins. A lowered groundwater table has led to subsidence in areas of the lower Santa Rosa Creek valley, which was observed in Cambria during 1976—the year with the highest municipal groundwater extraction (Yates and Van Konyenburg 1998). Groundwater lowering may have led to further degradation of mature riparian vegetation (in areas where riparian vegetation was not replaced by crops), which is reliant primarily on groundwater during summer dry season. Large floodplain areas with extensive riparian vegetation may have attenuated floods within Santa Rosa Creek; the removal and degradation of large riparian stands would have therefore increased the "flashy" nature of the stream to flood events. Indeed, large floods in 1914, 1956, 1969, and 1995 have damaged properties situated upon floodplain areas (Hamilton 1974, D. Dunlap, pers. comm., 2009). As a result, bank revetments, or riprap, were subsequently installed along some reaches of Santa Rosa Creek near Cambria to protect floodplain developments from future flood-induced bank erosion. To date, however, no levees have been constructed along the creek or its tributaries, with the exception of Highway 1, which serves as a low-lying berm to the west of downtown Cambria.

A final and potentially very significant impact to the watershed from 1950 to the 1990s is the construction of roads, namely Highways 1 and 46, and Santa Rosa Creek Road, because each of these have altered runoff patterns as they traverse the landscape. The first trails and roads in the watershed closely followed the contours of the natural terrain as large-scale excavations of hillsides and bridge building were infeasible. Their impact was likely limited only to vegetation removal and fine-sediment run-off. The present-day path of Santa Rosa Creek Road mostly follows the original trail path from Cambria and east towards Paso Robles (Harris 1874, Hamilton 1974) and has since been paved, thereby limiting fine-sediment runoff from road surfaces. Further, a comparison of aerial photographs taken in 1937 and 2009 reveals that the road exactly follows the same path in both time periods. The route taken today by Highway 1 differs slightly from that traced by the original "coast road" (Harris 1874, Hamilton 1974) and, similar to Santa Rosa Creek Road, the current route of Highway 1 was cut into hillslopes and laid across small streams channels with culverts.

Completed in 1974, Highway 46 travels through Green Valley and is the most recent and substantial roadway constructed in the watershed, involving relatively large cut and fill sections that allow for a nearly straight path through the varied topography. As a result, upper Green Valley Creek and numerous small streams have been virtually cut-off from the reaches of lower Green Valley Creek, but for the presence of some culverts. Figure 1-5 shows potential barriers throughout the watershed that are mostly road culverts (CalFish 2009). Under normal circumstances, water may be conveyed completely through these culverts, but coarse sediment and large woody debris deposited at the culvert entrance during high flows causes blockages that deny the replenishment of gravel and cobble substrates and woody debris in the lower reaches. This adversely affects not only the channel morphology of Santa Rosa Creek but also the availability and complexity of steelhead trout habitat (D. W. Alley & Associates 2007, Nelson et al. 2009). An additional negative of all three major roadways in the watershed has been their effect on erosion associated with concentrating runoff towards the downslope side of the roads (see Figure 3-1 in Section 3.2 – Hillslope Processes).

As stated above, the most recent time period between the mid-1990s and present day is generally characterized by a population growth slowdown and, accordingly, a reduction in additional urban developments that would act to further alter the landscape and the rainfall-runoff relationship in the watershed. This period also marks the initiation of several endeavors to restore ecologic and geomorphic function in Santa Rosa Creek, including the removal of certain fish barriers: a former channel weir beneath Burton Bridge and the planned removal of the Ferrasci Road fish ladder. Also, bank-repair projects recently implemented along Santa Rosa Creek have attempted to minimize their impacts to geomorphic and ecologic conditions through implementation of flood storage features (e.g., setback bank protection) and biotechnical elements (riparian plantings).

2.2 Measurements of Watershed-wide Changes in Land Use and Land Cover

During the recent population boom in the watershed since 1950, improvements to infrastructure have been made to support the growing tourism industry, namely more homes, commercial and industrial buildings, roads, and groundwater extraction. Overall, Cambria's urban footprint within the watershed has grown significantly, as is apparent when comparing acreages of land uses presented in 1959 and 1996 maps compiled by the California Department of Water Resources (CDWR) (Figures A-7 and A-8). It is important to note that these maps primarily focused on agricultural and urban areas situated in the valley lowlands, and they do not delineate land uses or native vegetation cover in non-valley areas (e.g., open grazing upon hillslopes) as they typically have not required a significant irrigation supply and therefore are not a primary concern of CDWR. Values presented in Table 2-2 reveal that agricultural types have changed over the 37-year time period with a general decrease in non-ranching agricultural land uses, while the urban footprint of Cambria has increased by almost 4-fold.

Table 2-2. Land use coverage and relative changes in the Santa Rosa Creek watershed between 1959 and 1996. [A]

Land use type [B]	1959 (acres)	1996 (acres)	% Change
Pasture	547	66	-88%
Grain and hay crops; rice crops	531	320	-40%
Field crops; truck, nursery, and berry crops	19	596	3,079%
Semi-agricultural and incidental to agriculture	123	19	-84%
Citrus and subtropical; deciduous fruits and nuts	0	130	+
Total agricultural-related land use (non-grazing)	***1,220***	***1,131***	***-7%***
Barren and wasteland	16	15	-6%
Urban	411	1,553	278%

[A] Source: CDWR 1959, 1996

[B] Remainder of watershed was depicted in CDWR maps as blank areas, which included “riparian vegetation”, “native vegetation”, “unimproved grazing land”, or “unclassified” (see Figures A-7 and A-8).

Changes to land cover throughout the entire watershed between 1930 and 2001 were also evaluated here to illustrate how primary vegetation cover types have changed over time (Figures A-9 and 1-6). Results presented in Table 2-3 reveal several changes to the dominant land cover types over the evaluated time period; specifically, evergreen forest (e.g., pine trees) and scrub/shrub (e.g., chamise) acreages have increased while mixed forest (e.g., oaks and manzanita) acreage has decreased. It is important to note that because the land cover mapping efforts of 1930 and 2001 followed slightly different cover identification methodologies, an unquantifiable degree of error exists and therefore the values presented in Table 2-3 are useful only in demonstrating trends of land cover changes, not definitive values. Furthermore, the absence of a “developed”, or urban, land cover category in the 1930 maps is slightly erroneous as the town of Cambria did exist during this time.

Table 2-3. Land cover and relative changes in the Santa Rosa Creek watershed between 1930 and 2001. [A]

Land cover type	1930 (acres)	2001 (acres)	% Change
Pasture/hay [B]	0	34	+
Cultivated crops	2,571	362	-86%
Total agricultural-related land use (non-grazing)	***2,571***	***396***	***-85%***
Grassland/herbaceous (grazing)	19,640	19,156	-2%
Evergreen forest	1,414	1,954	38%
Mixed forest	4,152	2,930	-29%
Scrub/shrub	2,597	3,290	27%
Woody wetlands [B]	0	157	+
Emergent herbaceous wetlands [B]	0	4	+
Barren/beaches [C]	14	0	-
Developed [B]	0	2,505	+

[A] Source: Weislander 1930a, 1930b, Homer et al. 2004. Land cover categories used in the 1930 maps were converted to those categories used in the 2001 land cover map.

[B] Categories not distinctly represented in the 1930 land cover maps. Developed category also not represented in 1930 land cover maps, however, the town of Cambria, Santa Rosa Creek Road, and coastal road were present during this time (see Figures A-9 and 1-6).

[C] Barren category in 1930 land cover maps represented Moonstone Beach, which still remained in 2001 but was not distinctly represented in the 2001 land cover map.

Overall, information gleaned from the land use maps of 1956 and 1996 and the land cover maps of 1930 and 2001 indicate the following trends that are relevant to evaluating impacts to the watershed morphology: (1) the amount of developed/urban areas has increased with the growth of Cambria and construction of new roads (e.g., Highway 46); (2) the total amount of evergreen and mixed forest has decreased, likely as a result of continued logging and/or some additional land clearing by ranchers in the early half of the last century; (3) the amount of scrub/shrub cover has increased, suggesting either a re-establishment of vegetation at this stage of plant succession upon formerly cleared areas or the conversion of forested terrain to scrub/shrub-covered terrain due to logging; (4) the amount of agricultural land not used for grazing (i.e., cropland) has decreased, either due to urban encroachment or a return to scrub/shrub vegetation cover; and (5) the amount of grassland, which is primarily used for cattle grazing, has remained nearly unchanged.

2.3 Summary of Watershed Changes

Returning to the questions posed at the start of this chapter, the following draws upon the above summary of the watershed's history to briefly answer those questions. Prior to European settlement, the watershed supported a widespread vegetation cover throughout the valleys and hillslopes that acted to stabilize land surfaces, dampen floods, maintain perennial streamflow, and enable a near-equilibrium exchange of sediment through the watershed (i.e., sediment delivery to Santa Rosa Creek more closely equaled the sediment yield at the creek's mouth). Processes occurring during this period would have been the same as those occurring today (see Chapters 3 and 4); however, the frequency and magnitude of those processes would likely have been significantly lower, such as streambank erosion, channel incision, gullying, and landslides, due to the lack of human-induced perturbations.

Overall, the greatest impact to the watershed over the past 150 years has been the alteration of land cover, primarily during the relatively intense change periods of 1860 to 1880 and 1950 to the 1990s, which resulted in the modification of the rainfall-runoff relationship and has, accordingly, led to a flashier system with higher fine sediment production. Lesser but still significant impacts also include reduced baseflows due to groundwater pumping and channel modifications in lowland areas (e.g., draining of Estrada lagoon on lower Perry Creek and riprapping Santa Rosa Creek streambanks near Cambria).

The remaining chapters in this report further investigate the geomorphic understanding of the Santa Rosa Creek watershed following almost two centuries of land use changes and direct modification of water flow, sediment discharges, and channel morphology in the watershed. Note that overall change is cumulative over time and so difficult to quantify: we therefore draw on numerous sources both quantitative and qualitative, and from within the watershed and from the local region where appropriate, to understand the evolutionary trajectory of Santa Rosa Creek and its watershed. Also, sediment transport and morphological changes in Santa Rosa Creek occur only in brief periods during flood events, and frequently when flood events follow large land cover changes (e.g., fires, logging, or conversion of forest to grazing land). As such, there are both natural components and human aspects to channel morphology changes: disentangling human impacts from natural events is one of the most challenging arenas in geomorphology.

3 HILLSLOPE PROCESSES AND THE PRODUCTION AND DELIVERY OF SEDIMENT

3.1 Overview

This section evaluates the hillslope processes that control the production of sediment across the watershed and the subsequent delivery of that sediment into the channel network. Overall, rates of hillslope sediment production in the Santa Rosa Creek watershed are driven by tectonics, geology, climate, and land uses. At a finer scale, sediment is released from hillsides via several discrete processes, including soil creep, gullying, and landsliding. Methods used here to evaluate the active processes occurring in the watershed included field observations, analysis of aerial photographs, and literature review of applicable studies. Quantification of sediment production and delivery rates was beyond the scope of this project due to the lack of available watershed-specific data that could enable such a calculation (e.g., hillslope erosion studies or sediment discharge records at the Santa Rosa Creek stream gauge). However, an attempt has been made here to estimate sediment production and delivery rates using values calculated in similar watersheds in the southern Coast Range region.

3.2 Hillslope Processes

Evaluation of active hillslope processes in the watershed was accomplished by conducting field surveys and analyzing aerial photographs. For the field approach, viewpoints of the watershed hillslopes were made from both the ground (foot and road surveys) and the air (low-elevation airplane flight). This approach was used to identify and characterize active geomorphic processes in viewable and/or accessible areas, with a focus on areas representative of general landscape types (e.g., consisting of distinct combinations of geology, land cover, and hillslope gradient) (see Section 3.4). Ground-based reconnaissance surveys in accessible locations were supplemented with aerial reconnaissance in order to view the majority of the watershed, albeit at a coarser scale. Another benefit of the airplane flight was to view the landscape from an oblique angle, whereby discrete hillslope processes could be seen more directly upon steep slopes, a benefit not afforded by a standard aerial photograph analysis that can only view the landscape at a fixed angle directly overhead.

Active hillslope processes in the watershed, as identified during the field surveys, airplane flight, and/or the airphoto analysis, are summarized in Table 3-1.

Table 3-1. Active hillslope processes in the Santa Rosa Creek watershed.

Category [A]	Hillslope process	Process description [B]
Natural processes		
Sediment production	Conversion of bedrock to soil mantle	Physical, chemical, and biotic-breakdown of bedrock material into friable weathered rock and then physically disrupted into soil. [a]
	Rockfall	Mass failure of mostly rock that has separated from its parent bedrock surface (typically along vertical cliff). [a]

Category [A]	**Hillslope process**	**Process description** [B]
Mass-wasting processes	Soil creep	Slow, often un-observable down-slope movement of surface soils or rock debris. [a]
	Biogenic transport	Exhumation and down-slope transport of soil and rock fragments by biological forces, including tree-throw and burrowing animals. [a]
	Dry ravel	Downslope transport of individual particles under power of gravity (or bioturbation) rather than water; mostly occurring where vegetation cover is non-existent. [b]
	Shallow landsliding	Mass failures that have a composition mostly of colluvial sediments, a failure plane above the soil-bedrock interface, and a relatively long travel distance through the low order channel network. [c]
	Deep-seated landsliding	Mass failures that have a composition mostly of bedrock (parent material), a failure plane below the soil-bedrock interface, and a surface area >0.1 km^2. [d]
Overland flow erosion	Sheetwash	Downslope transport of fine particles (<2 mm) driven by concentrated surface runoff. [a]
	Rilling	Formation of generally discontinuous, small channels less than several cm deep and wide that develop on slopes composed of fine-grained sediments where surface runoff has concentrated. Typically occurs in areas of land disturbance and/or vegetation clearing. [a]
Tributary connection with hillslope processes	Gullying	Formation often driven by the coalescence of several rills into an enlarged master rill, which can further extend the drainage network upslope. Often occurs in areas of land disturbance and/or vegetation clearing. [a]
	Channel head advance	Upslope migration of a stream channel into hillslope colluvium, usually due to gully incision and/or channel head-cutting. [a]
Human disturbances		
Agriculture and rangeland	Surface wash, rilling, and gullying	(see description above)
	Shallow landsliding	(see description above)
Road-related	Cut and fill failures	Erosion by sheetwash, rilling, gullying, or shallow landslides into road cuts or road fill material. [e]
	Surface erosion	Erosion of fine sediments from unpaved road surfaces. [e]
	Gully formation associated with inboard ditch relief	Occurs when road runoff concentrates into an inboard ditch that then incises the ditch and/or adjacent surfaces where the routed flows have been discharged. [e]
	Gully formation and mass failure on the outboard side	Occurs when road runoff concentrates on the outboard side of the road and erodes/destabilizes road fill material and/or hillside soils. [e]
Urban	Construction phase sediment pulse	Release of fine sediment downslope and into the drainage network during the disturbance of the landscape.
	Slope destabilization	Surface erosion and mass failures can occur on slopes that have been over steepened and/or undercut.

[A] With the exception of road-related erosion, human disturbances affect the geomorphic processes already identified as natural and, therefore, require efforts to separate the relative influence of natural and human factors.

[B] Sources: [a] Selby 1993 ; [b] Gabet 2003; [c] Roering et al. 2003 ; [d] Roering et al. 2005 ; [e] Reid and Dunne 1984

The analysis of aerial photographs performed for this study enabled the evaluation and measurement (area) of active erosion processes throughout the majority of the watershed area. The analysis consisted of digitally analyzing recent aerial photographs taken for the National Agriculture Imagery Program (NAIP) in 2005 and 2007 at a constant elevation over the watershed. An inventory of several erosion feature types using the 2007 aerial photographs had been previously created by The Land Conservancy of San Luis Obispo County (TLCSLOC 2008) and was reviewed and subsequently updated through consolidation of some categories and addition of new feature categories (e.g., landslides) identified during a review of the aerial photographs. Some features identified during our field survey and airplane flight were also added to the inventory, provided that they could also be viewed in the aerial photographs taken during either 2005 or 2007. The inventory, however, does not fully identify all erosion processes active in the watershed, nor does it chronicle every erosion feature in the watershed for two reasons: (1) the resolution of the aerial photographs generally prevents the identification of discrete features less than 1–2 m in width, thereby overlooking small-scale erosion processes such as rilling, soil creep, and dry ravel; and (2) obfuscation of the ground surface caused by vegetation severely restricts the identification of erosion features under tree cover. Therefore, these aerial photograph-identified features are considered herein as “macro-scale” erosion features, whereas features too small to be viewed in the aerial photographs, such as soil creep, dry ravel, and rilling, are considered as “micro-scale” erosion features.

The erosion feature inventory, as updated for this study, considered four feature types that all may potentially contribute sediment to the stream network (Figure 3-1). These features include gullies, landslides, and road-related erosion. An additional feature type considered, referred to as “other erosion”, includes those erosion processes that were not identified as either a gully, landslide, or road-related erosion but still exhibited signs of surface erosion. For example, one such feature identified in the aerial photographs and subsequently confirmed in the field exhibited a widespread and deeply incised rilling pattern typical of a badlands terrain. A separate “rilling” category was not created to accommodate this specific feature because the majority of rill features in the watershed, as observed in the field, were too numerous to completely record and were too fine to be identified in the aerial photograph analysis and, thus, could not be easily included in the inventory. Overall, the feature having the greatest number of occurrences and, accordingly, the greatest area represented in the watershed are gullies, accounting for two-thirds of the total area of erosion features contained in the inventory (Table 3-2). Road erosion features accounted for 21% of the total area of erosion-related features, while landslides accounted for only 3%.

An estimate of the volumetric contribution of sediment from each hillslope erosion-related feature was made based on general field observations and select field measurements of feature depths (Table 3-2). The total amount of sediment eroded from gullies, landslides, road-related erosion features, and “other” erosion features is estimated to be approximately 2.5 Mt. If we assume that initial destabilization of the hillslopes initiated approximately at the time of Euro-American settlement of the watershed (i.e., ~150 years ago: 1860–2010), then an annual average sediment-production rate estimate of 17,000 tonnes per annum (t a^{-1}) for these “macro-scale” hillslope erosion features can be made. The sediment-production rate per unit area would equate to 140 t km^{-2} a^{-1} across the hillslopes of the watershed. It is important to note that these coarse estimates do not account for sediment produced from “micro-scale” hillslope erosion features (e.g., soil creep, dry ravel, and rilling) or channel-related erosion features (e.g., bank and bed erosion).

Estimated sediment yields for the watershed as inferred from other studies in the region are presented below in Section 3.3. A comparison of the sediment-production rate estimated for these “macro-scale” hillslope erosion features and sediment production estimates from other studies is presented below in Section 3.4.3.

Table 3-2. Erosion-related feature types and estimated amount of eroded sediment in the Santa Rosa Creek watershed identified using recent aerial photographs. [A]

Erosion-related feature	Number of features	% of total area of erosion-related features	Estimated amount of sediment eroded [B]	
			volume (m^3)	mass (tonnes)
Gully	1,068	72%	1,306,000	2,089,600
Landslide	17	3%	61,000	97,600
Road erosion	253	22%	199,000	318,400
Other erosion	6	3%	24,000	38,400
Total	**1,344**	**100%**	**1,590,000**	**2,544,000**

[A] Source: updated from TLCSLOC (2008) erosion inventory using aerial photograph and field data.
[B] Based on general field observations and select field measurements, the assumed average depth of gully and landslide features was 1 m while the assumed average depth of road and other erosion features was 0.5 m. Assumed bulk density of eroded sediment was 1.6 t m^{-3}.

Water basins were also identified in the aerial photograph analysis; however, these features are considered to promote sediment deposition rather than erosion. The basin feature included mostly cattle stock ponds along with some water supply ponds for crop irrigation. A total of 41 basins were identified to be present throughout the watershed (Table 3-3). Less than five basins identified related to depressions in lowland areas where rain waters collect (visible in the 2005 aerial photographs), specifically near the former Estrada lagoon along lower Perry Creek. Most basins are situated in small first-order tributaries; no basins are present on the mainstem Santa Rosa or Perry creeks, but two relatively large basins, or reservoirs, are present on the upper reach of Green Valley Creek (Figure 3-2). In total, the area of the landscape that drains to these basins was found to equal 10.1 km^2 (2,500 acres), or 8.1% of the total watershed area. Consideration of these basins is important as large basins have the potential to trap sediment transporting down-gradient before reaching the larger stream channels. The trap efficiency of these basins is difficult to estimate, but based on the relatively small storage capacity of each basin (500–5,000 m^3 [0.5–3.5 acre-feet]) it is likely that only the coarse fraction of the sediment load—gravel-size or bigger (>2 mm in diameter)—gets trapped in the basins, while the fine sediment load transporting as suspended or wash load likely flows over the basin retaining wall. Occasional maintenance of the basins by their owners may involve the removal of accumulated sediment in order to maintain storage capacity of the basins over time. Overall, these basins likely represent a coarse-sediment sink within the watershed—a potentially adverse effect on mainstem morphology as coarse sediment serves to stabilize the channel bed elevation (i.e., more stream power is needed to scour down into coarser bed material) and offer suitable steelhead spawning conditions for the construction of their redds.

Table 3-3. Deposition-related feature types in the Santa Rosa Creek watershed identified using 2005 and 2007 aerial photographs. [A]

Deposition-related feature	Number of features	Total area of landscape contributing to the features (km^2) [B]	% of the total contributing area in watershed
Basin	41	10.1	8.1%

[A] Source: updated from TLCSLOC (2008) erosion inventory using aerial photograph and field data.
[B] All precipitation falling upstream of the feature drains down to the basin.

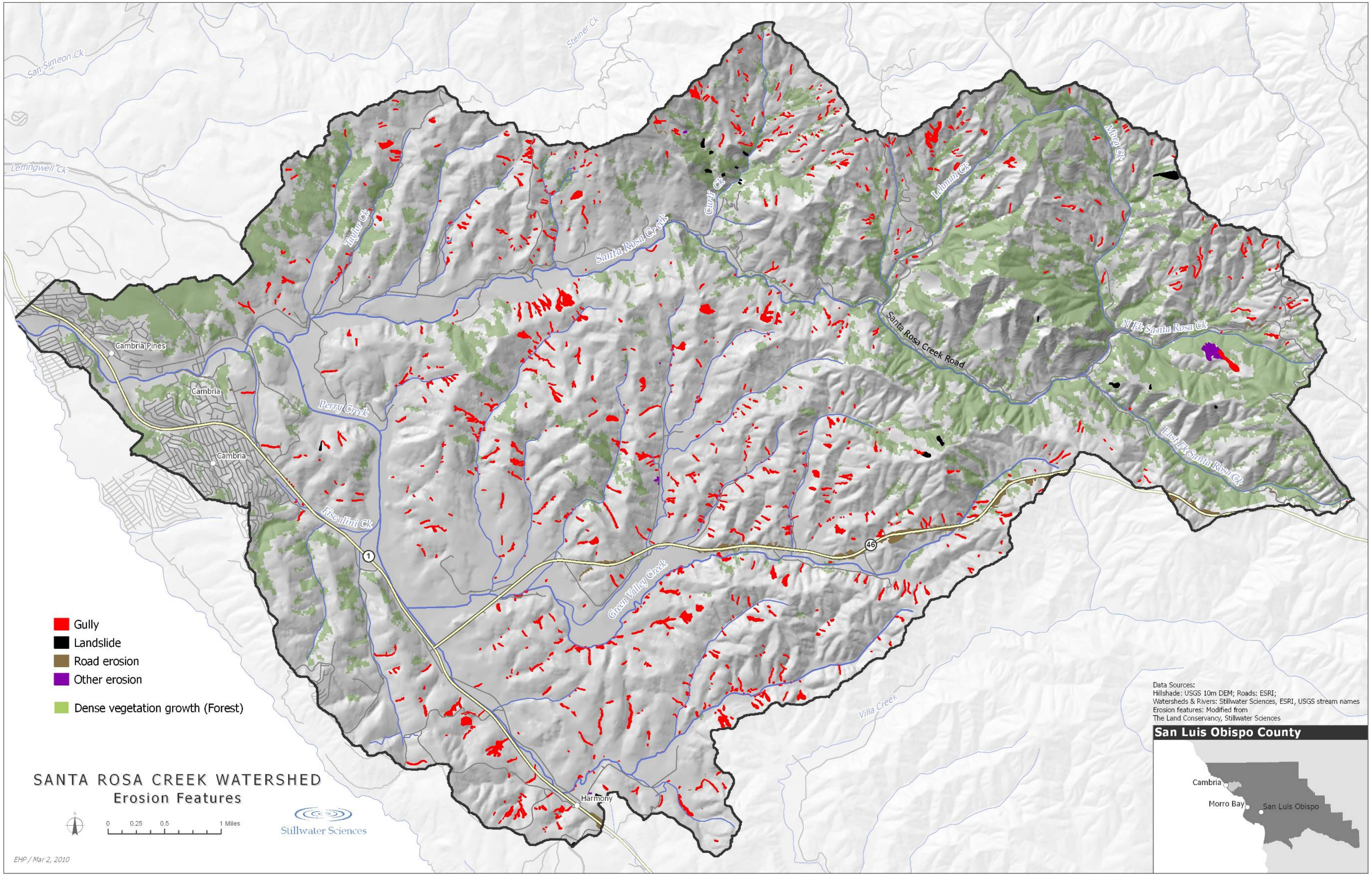


Figure 3-1. Hillslope erosion inventory (2005 and 2007) of the Santa Rosa Creek watershed. Updated from TLCSLOC (2008). Dense vegetation (forest land cover) shown to highlight areas not clearly visible in analysis of aerial photographs.

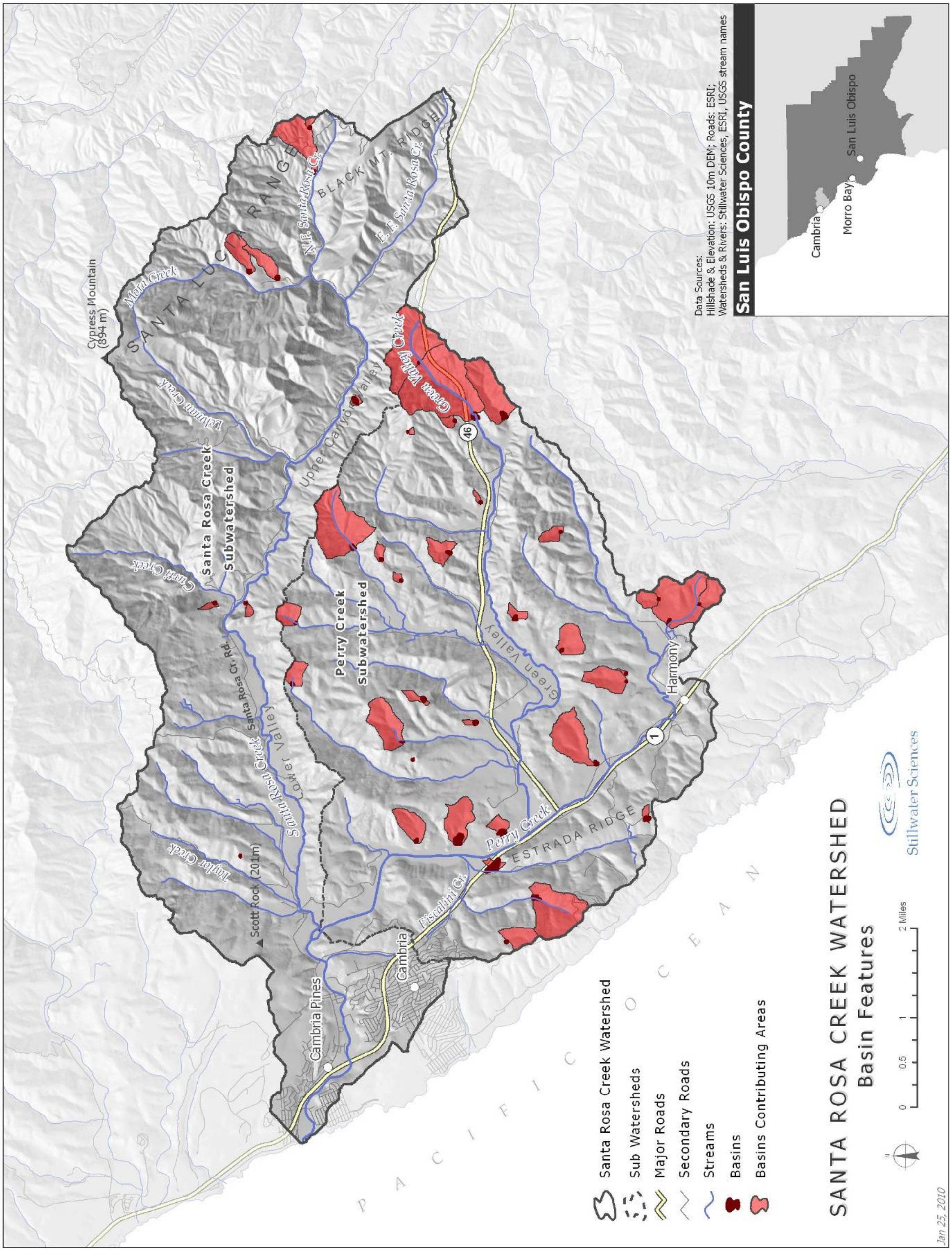


Figure 3-2. Basin features and their upstream contributing areas within the Santa Rosa Creek watershed.

As described in greater detail below in Section 3.3 – Sediment Production, a landscape's erosion potential can be defined by its combination of geology, land cover (e.g., vegetation), and hillslope gradient. Understanding the occurrence of the mapped erosion features with these landscape elements, or units, is necessary in order to estimate relative rates of sediment production and to identify those areas with the potential for future erosion. An overlay of the mapped gullies, landslides, road erosion, and "other erosion" features onto the underlying geology, land cover, and hillslope gradient produced the results presented in Table 3-4.

The vast number of erosion features was found to occur in landscapes that are underlain by rock composed of the highly sheared and fractured Franciscan mélange, covered with herbaceous vegetation, and characterized by moderately steep slopes (10-40%). This relationship is mostly related to the fact that the watershed is predominately composed of these three landscape units and, therefore, erosion features are more likely to occur there. After normalizing the occurrence of the erosion features in a given landscape unit by the proportion of the unit within the entire watershed, we find a slightly different relationship between the total area of an erosion feature within a given landscape unit (Table 3-4). All erosion features were found to be primarily concentrated in terrains underlain by either Monterey Formation shale or Franciscan mélange. Gullies are primarily concentrated in areas underlain by four geologic units: Quaternary landslide debris, Lopse Formation sandstone, Franciscan mélange (graywacke and argillite), and Franciscan graywacke. Landslides occur more upon surfaces underlain by Monterey Formation shales, weathered Obispo Formation basalts, and Franciscan mélange. "Other erosion" features are predominantly underlain by Obispo Formation tuff and serpentinite. Road-related erosion features were found to occur mostly in areas underlain by Monterey Formation tuff; however, this result is likely incorrect as the road-related erosion mostly occurred within imported road fill material based on field and aerial photographic evidence.

Gullies are concentrated within grassland/herbaceous areas, which typically represents those areas used for grazing. Landslides and "other erosion" occur more often in mixed forest and scrub/shrub land cover types. Road erosion is concentrated in developed areas, which is an obvious outcome because roadway areas were categorized as developed areas in the National Land Cover Database (Homer et al. 2004) used in this analysis. In the evaluation of hillslope gradient, the slope distribution was generalized into three classes (see Section 3.4) and it was found that the greatest concentration of erosion features occurred upon hillslopes steeper than 10%. Gullies and road-related erosion features occur more within moderately steep slopes (10–40%), while landslides and "other erosion" features occur more within the steepest landscapes (>40%). For landslides, this is an expected outcome as they develop as a function of the hillslope gradient, soil properties (i.e., cohesiveness), mass of material, and degree of saturation.

Table 3-4. Proportion of erosion features within distinct landscape units of the Santa Rosa Creek watershed.

Landscape unit	**Erosion feature (% of feature area within landscape unit, normalized by the proportion of the unit in the total watershed area)**			
	Gully ($1.3\ km^2$)	**Landslide ($0.06\ km^2$)**	**Road erosion ($0.4\ km^2$)**	**Other erosion ($0.05\ km^2$)**
Geology (mapping symbol)				
Alluvial sediments (Qa)	3	0	8	<1
Landslide debris (Qls)	11	0	4	0
Marine terrace (Qm)	<1	0	2	0

Landscape unit	**Erosion feature (% of feature area within landscape unit, normalized by the proportion of the unit in the total watershed area)**			
	Gully (1.3 km^2)	**Landslide (0.06 km^2)**	**Road erosion (0.4 km^2)**	**Other erosion (0.05 km^2)**
Pismo Fm. siltstone (Tpsl)	1	0	0	0
Pismo Fm. sandstone (Tps)	6	0	1	0
Monterey Fm. shale (Tm)	0	0	0	0
Monterey Fm. shale (Tml)	2	44	6	<1
Monterey Fm. tuff (Tt)	1	0	35	0
Obispo Fm. basalt (Tb)	<1	32	2	0
Obispo Fm. tuff (Tot)	<1	0	<1	38
Rincon Fm. siltstone (Tr)	1	0	0	0
Vaqueros Fm. sandstone (Tvq)	6	0	1	0
Lospe Fm. sandstone (Tlc)	17	0	19	0
Cambria felsite (volcanic) (Tf)	6	0	0	0
Unnamed sandstone (Kss)	3	0	1	0
Toro Fm. shale (Ktsh)	4	0	6	0
Serpentinite (sp)	6	0	0	61
Franciscan mélange (fm)	10	24	10	<1
Franciscan chert (fc)	7	0	5	0
Franciscan graywacke (fs)	11	0	<1	0
Franciscan greenstone (fg)	5	0	<1	0
Land cover				
Developed, open space	8	<1	63	<1
Developed, low intensity	<1	0	20	0
Developed, medium intensity	0	0	1	0
Developed, high intensity	0	0	0	0
Evergreen forest	<1	2	<1	10
Mixed forest	3	52	<1	12
Scrub/shrub	19	41	8	77
Grassland/herbaceous	47	5	3	1
Pasture/hay	5	0	0	0
Cultivated crops	8	0	0	0
Woody wetlands	9	0	3	0
Emergent herbaceous wetland	0	0	0	0
Hillslope gradient (generalized)				
0–10%	25	<1	28	1
10–40%	47	31	45	36
>40%	28	69	27	63

3.3 Sediment Production and Delivery

At a watershed scale, soil production and hillslope sediment transport are difficult to quantify because they are driven by the episodic and commonly transient effects of rainstorms, windstorms, fires, earthquakes, and human and other disturbances (Benda and Dunne 1997, Gabet and Dunne 2003). The inherently episodic nature of erosional processes results in substantial year-to-year variability and makes any assessment of sediment-transport rates sensitive to the timescales over which they are averaged (Kirchner et al. 2001). Although long-term averages cannot predict the sediment load for any given year, they nevertheless can be useful in assessing the long-term consequences of alternative management actions, especially those concerned with impacts to aquatic habitats. To understand and estimate the magnitude of sediment flux down Santa Rosa Creek, we evaluate the production and delivery of hillslope sediment using a combination of field observations, available data specific to the watershed, and estimated values from similar watershed in the southern Coast Range region. Using a combination of methods is important because cross-comparison provides the basis for a more robust and reliable estimate than from any single method.

3.3.1 Lithology, erosion, and channel sediment

With continuous landscape uplift to drive hillslope processes and large areas of highly sheared metamorphic and sedimentary rock units now hundreds of meters above the valley bottoms, the Santa Rosa Creek watershed has geologic characteristics commonly associated with high rates of erosion. The eroded sediment is derived from three distinctly different sources (Figure 3-3), which are categorized as follows:

1. Fine-grained, weak – Easily eroded siltstone and mudstone of the Pismo (shale member), Monterey, Rincon, and Toro formations, found traversing the watershed close to the two primary fault traces (Figure 1-3);
2. Coarse-grained, weak – Moderately erodible and highly sheared/fractured rocks that erode into abundant sand and gravel-sized clasts, primarily the Franciscan mélange unit that is found throughout the majority of the watershed; and
3. Coarse-grained, competent – Relatively durable and moderately fractured sandstone and volcanics of the Pismo, Obispo (volcanic member), Vaqueros, Lospe, Cambria, and Franciscan greenstone units, found traversing the lower watershed paralleling the Cambria and Cayucos faults.

This three-part division into relative grain size and erodibility components is central in understanding the present behavior, and predicting the future behavior, of stream channels such as Santa Rosa Creek. By analogy to other rivers world-wide, the fine-grained load (<2 mm) represents the majority of sediment that is delivered by hillslopes into the channel, and that is subsequently transported by the channel to the ocean. Field observations indicate that areas displaying relatively high hillslope erosion are chiefly underlain by siltstone and shale (e.g., Monterey Formation [Tml]) and fractured graywacke/argillite (i.e., Franciscan mélange) (see Table 3-4).

Delivery of coarse-grained sandstones, weathered basalts, and volcanic tuffs from hillslopes to channels is also important. The clasts from these units are generally more resistant to mechanical breakdown during fluvial transport; although they become rounded within a short distance from their initial entry into the channel network, they persist throughout their passage down the network, which in many cases requires many tens of kilometers of transport. Schmidt and Reid (2007) found wide variability in the relative strength of dominant rock types present in the southern Coast Range. Specifically, they found that serpentine and argillite-dominant Franciscan complex rocks were the weakest rocks, while Pismo Formation sandstones and Franciscan greenstone and graywacke were the stronger rocks. Their findings extended to include a positive correlation between the occurrence of weak rocks and landslide density along their study area of the Monterey County coast, which concurs with our findings that landslides were associated with the weaker rocks of the watershed (Franciscan mélange and Monterey shale) (see Table 3-4). Persistence and dominance of sandstone-derived gravel and boulders in the coarse fraction of bedload sediment in Santa Rosa Creek indicates that the channel morphology is largely determined by the delivery, transport, and floodplain deposition of these erosion-resistant (typically sandstone) clasts. The presence or absence of this sediment in the channel also determines whether any given reach will be alluvial (i.e., flowing over loose bed sediment) or non-alluvial with a scoured channel bottom that exposes the underlying bedrock.

Consequently, the processes and rates by which sediment is eroded off of hillslopes, and subsequently delivered to the channel network, vary substantially across the watershed. Given the profound differences in mechanical properties of the shale, sandstone, and volcanic bedrock, the processes affecting each must be considered distinctly.

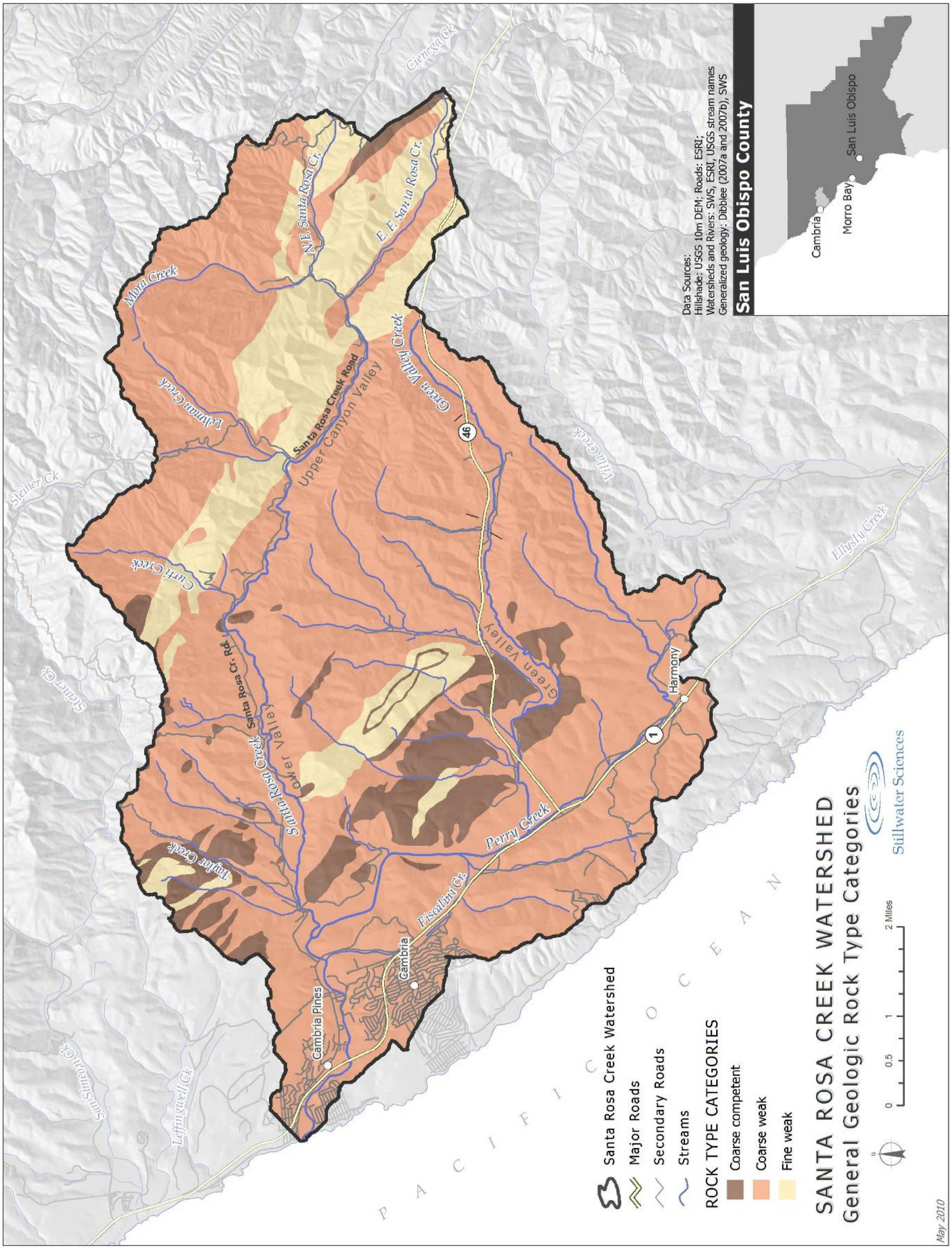


Figure 3-3. Generalized geologic rock unit categories used for the GLU analysis.

3.3.1.1 Fine sediment

The most highly erosive rocks and, therefore, the largest contributors of fine sediment (less than sand, <0.0625 mm) in the watershed are assumed here to comprise siltstone/claystone and thin-bedded shaley rock units, particularly in the Pismo (siltstone member), Monterey, Rincon, and Toro formations (Figure 3-4). In total, these “weak” rock units make up 14% of the watershed area and lie entirely adjacent to the two main fault traces that cross the watershed near the headwaters of Santa Rosa Creek (Oceanic Fault) and near the lower portions of Santa Rosa, Perry, and Green Valley creeks (Cambria-Cayucos faults) (Figure 1-3). These rocks either interbed or occur adjacent to coarser and/or more competent rocks in the watershed, namely the coarser Franciscan mélange graywacke, which structurally support them and, thus, effectively mute their otherwise high erosion rates. In other words, these weaker, fine-grained rocks would likely erode faster as a whole if they occurred across a broader and more continuous area without structural support from harder or coarser rock units. An example of such a terrain is exhibited clearly in the Santa Clara River watershed of southern California where entire mountain ranges composed of weak rock units exhibit active, widespread erosion (Stillwater Sciences 2007a).

It is important to note that all rock units in the watershed produce some fraction of fine-grained sediments, although their relative proportion of fine to coarse particle sizes depend on the specific material properties and the local conditions (e.g., vegetation cover, land uses, and hillslope gradient). Coarse-bearing bedrock can produce fine-grained sediments when the rock already contains a fine matrix component or when biotic (e.g., tree throw or gopher burrowing) or abiotic (e.g., bedrock dissolution or abrasion during transport) processes occur. Fine sediment production from predominately coarse-bearing bedrock is evident by the presence of a mixed-size soil mantle throughout the watershed, not just in those areas underlain by fine-grained rock units. The relatively erodible, yet mostly coarse-bearing Franciscan mélange graywacke unit that accounts for the majority of the total watershed area likely produces a significant portion of fine sediment, which is viewable where gullies have eroded through accumulated colluvium comprised of mixed sediment sizes.

Overall, the fine-grained rocks are generally very susceptible to erosion, especially in the absence of vegetation. By analogy to other studies, rates of fine sediment delivery from these rocks should vary most directly with hillslope gradient and vegetation cover (Reid and Dunne 1996). Observations throughout the Santa Rosa Creek watershed affirm this principle, recognizing that vegetation cover is both a cause and an effect of relative hillslope stability. Lack of vegetation cover enhances the rate of sediment delivery; but where the ground is unstable or eroding rapidly, vegetation does not grow well. Gradients in the watershed are generally moderate to high in areas underlain by these rocks, which is due to two factors: (1) continued uplift of the region does not allow for an equilibrium condition whereby weaker rocks should erode to lower slopes over time (e.g., Gilbert 1877, Schmidt and Montgomery 1995); and (2) the rocks are closely interbedded, underlain, and/or bordered by harder or coarser rocks that structurally support them.

Figure 3-4. An exposure of fine-grained, weak shale of the Monterey Formation in the Curti Creek subwatershed (note person in foreground for scale).

3.3.1.2 Coarse sediment

The most widely occurring rock unit is graywacke (sandstone and argillite) of the Mesozoic-age Franciscan mélange, underlying almost half of the watershed area. In total, all coarse-sediment bearing rocks account for 86% of the watershed. These units include sandstone, volcanic rocks, and young alluvium that are the primary source of coarse-grained sediments to Santa Rosa Creek and its tributaries. Areas underlain by these lithologies display characteristic modes of hillslope erosion and channel delivery that are very different from those of the fine-grained deposits. These rocks are more resistant to surface erosion due the degree of particle cementation (or welding for tuffs); however, many of these units are moderately to severely sheared and/or fractured which decreases their overall net strength. Therefore, two categories of coarse-sediment bearing rock units have been used here to distinguish those units that are more or less erosion-resistant—"coarse weak" and "coarse competent". Examples of a coarse weak rock unit is the highly sheared/fractured Franciscan mélange (Figure 3-5) and a coarse competent rock unit is the volcanic tuff of the Obispo Formation, which forms the backbone of Black Mountain in the headwaters of Santa Rosa Creek (Figure 3-6). Steep bluffs of all coarse-bearing units are prone to rockfalls. Accumulations of talus at the base of these slopes are susceptible to mass transport or gulling; the nearby stream channels are often chocked with coarse, subangular blocks. These coarse-grained rock fragments eventual transport downstream, abrading into cobbles, gravels, and eventually sands and silts. The delivery of these coarse-grained sediments is particularly important to stabilizing channel bed morphology and, thus, supporting steelhead habitat conditions.

Figure 3-5. An exposure of coarse-grained, weak graywacke of the Franciscan mélange along Santa Rosa Creek Road. Large fractured blocks of the rock unit lie upon the top of the outcrop.

Figure 3-6. An exposure of coarse-grained, competent volcanic tuff of the Obispo Formation along Black Mountain.

3.3.2 Relative rates of sediment production - geomorphic landscape units

Relative rates of sediment production and delivery are controlled by vegetation cover, rainfall, and the physical properties of the landscape itself. These conditions, however, can be relatively steady through time, or they can be highly variable. As a result, some delivery processes have fairly constant rates (such as soil creep), but many are unpredictably episodic (such as debris flows or rockfalls). In this section, we discuss estimates of sediment production for the watershed using several approaches to estimate the watershed sediment yield—that is, the amount of sediment per unit area removed from a watershed by flowing water during a given time period.

Although the conditions and events that affect hillslope sediment production and subsequent delivery to the channel network vary greatly over time, different parts of the landscape can be readily identified as to their relative sediment production and delivery potential. Based on available landscape data (both previously available landcover data and recently collected field observations), we can estimate relative production rates for the watershed. We divided these identified factors into discrete categories to define "geomorphic landscape units" (GLUs) across the watershed that, together, influence sediment yields from a particular unit (Reid and Dunne 1996, Montgomery 1999). We assigned relative, qualitative rates of sediment production to each of these GLUs ("High", "Medium", and "Low", commonly abbreviated H, M, and L throughout this report) based on field observations and the inventory of erosion features presented in Figure 3-1. This approach ultimately aids in the identification of these portions of the watershed having relatively high, medium, or low sediment production potential, which can be used to guide future management options. Based in part on field observations in this watershed and on prior studies in southern California (e.g., Stillwater Sciences 2007b, 2008) we have assumed here that sediment-production rates for each category vary by *up to* an order of magnitude. Despite the lack of sediment accumulation and sediment discharge data in the watershed, we can apply estimated sediment yield values from other watersheds in the vicinity to the Santa Rosa Creek watershed and apportion out these yield estimates to each GLU category on an annual unit-area basis (see Section 3.5.2).

Recognizing that many factors can determine sediment-production rates from hillslopes, this study focused on three that were judged to impose the greatest range of variability over the Santa Rosa Creek watershed: rock type, vegetation cover, and hillslope gradient. Overall, those areas of the watershed displaying a combination of erosion-resistant bedrock, dense vegetation cover, and low slopes and correlated with a near absence of observed erosion features (both macro- and micro-scale) were assumed to have a low sediment production potential. In contrast, those areas displaying a combination of weak lithology, minimal vegetation cover, and steep slopes and correlated with numerous observed erosion features were assumed to have a high sediment production potential. Data sources for each landscape category were compiled in a GIS for the entire watershed at a resolution determined by the coarsest dataset (i.e., 30 m). The following describes the methods used in our analysis; tables and figures presenting more detailed information in support of the GLU analysis are presented in Appendix B.

Rock types were derived from the 1:24,000-scale geologic maps of Dibblee (2007a, 2007b; Figure 1-3). Mapped units were grouped into categories of fine weak (siltstone/claystone and shale units), coarse weak (highly fractured coarse sandstone/graywacke and basalt), and coarse competent (less fractured/sheared sandstone, conglomerate, volcanics, and greenstone) (Figure 3-3). Unconsolidated Quaternary deposits, exclusively modern river gravels, paleo-landslides, and uplifted marine terraces were considered "coarse weak" for purposes of this division, reflecting observed abundance of gravels and cobbles in these poorly lithified units. Qualitatively, those units identified as "fine weak" displayed greater erosivity than those identified as "coarse weak", and in turn the "coarse weak" units displayed greater erosivity than those identified as "coarse competent". The relative proportions of the geology GLU categories are summarized in Table 3-5.

Table 3-5. Geology GLU categories within the Santa Rosa Creek watershed.

GLU category [A]	% of Watershed area [B]
Coarse competent	8.2%
Coarse weak	77.8%
Fine weak	14.0%

[A] GLU category based on literature information and field observations.
[B] Proportion of geology GLU category within the total watershed area determined in GIS.

Land cover was based on a data contained within the National Land Cover Database of 2001 (Homer et al. 2004) at 30-m resolution (Figure 1-6). By an automated classification system, four grouped categories were identified; they largely correspond to vegetation covers of forest, scrub/shrub, agriculture/grassland, and developed land (Figure 3-7). The relative proportions of the land cover GLU categories are summarized in Tables 3-6. For this analysis, areas having greater vegetation cover (i.e., forest) are assumed to have lower sediment-production rates, while those areas having lower cover (i.e., agriculture/grassland) have higher sediment-production rates for the following reasons: (1) plant roots physically hold soils in place; (2) organic barriers (e.g., tree trunks, stems, downed branches, and litter) diffuse the erosive force of overland flow and trap sediments transporting down-gradient towards stream channels by acting as physical barriers; and (3) vegetation canopy mutes the otherwise erosive effects of rain splash erosion by intercepting precipitation.

Table 3-6. Land cover GLU categories within the Santa Rosa Creek watershed.

GLU category [A]	% of Watershed area [B]
Forest	16.0%
Scrub/shrub	11.1%
Agriculture/grassland	64.7%
Developed	8.2%

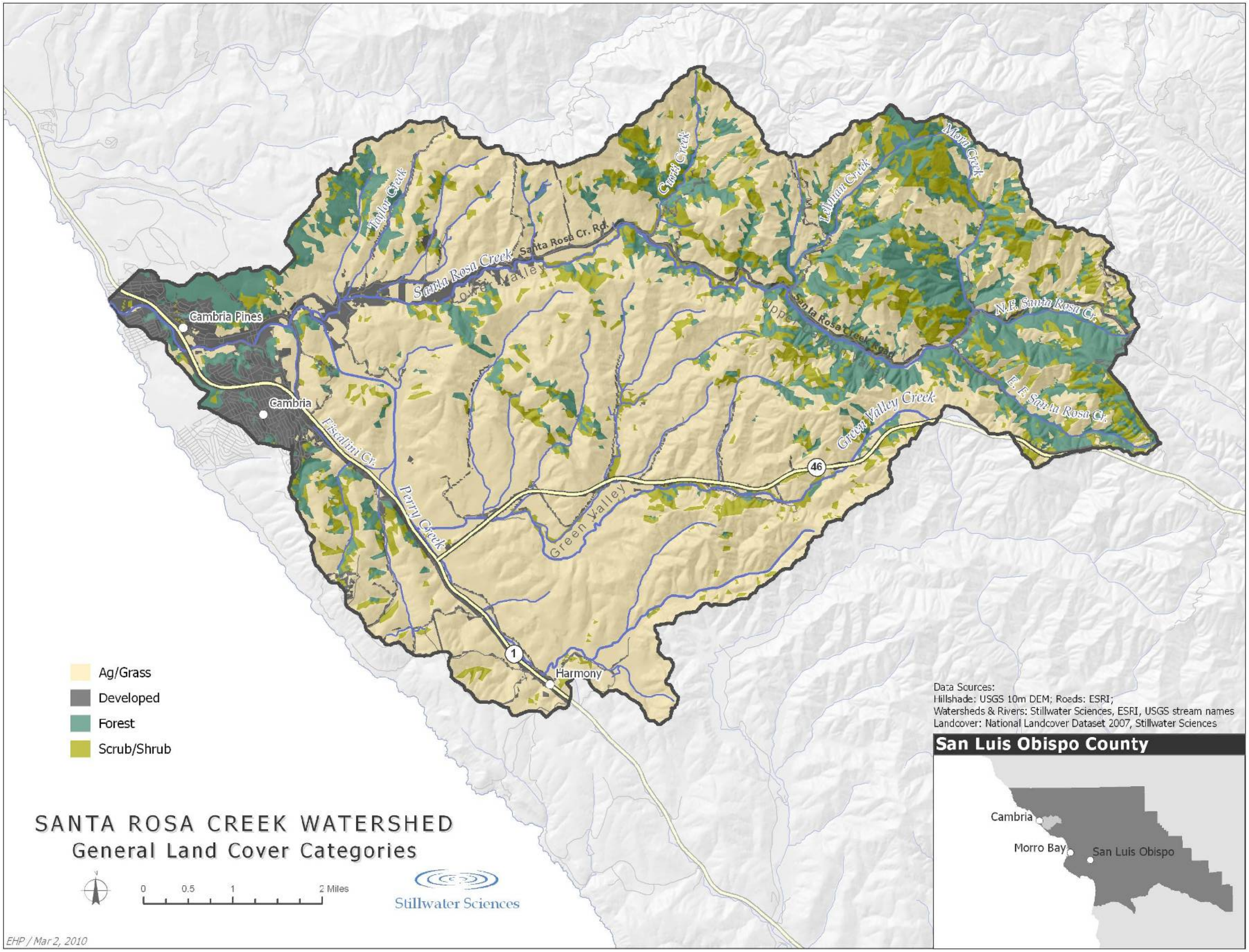
[A] GLU category based on literature information and field observations.
[B] Proportion of land cover GLU category within the total watershed area determined in GIS.

Lastly, hillslope gradients were generated directly from the digital elevation model (DEM), which in turn was based on a USGS 10m DEM. Based on the distribution of slopes and on observed ranges of relative erosion and slope instability, the continuous range of hillslope gradients was categorized into three groups: 0–10%, 10–40%, and steeper than 40% (Figure 3-8). The majority of hillslope gradients fall within the "moderately steep" category of 10–40% (Table 3-7). Greater hillslope gradients have a greater erosion potential and are more likely to deliver eroded sediment downslope towards a stream channel.

Table 3-7. Hillslope gradient GLU categories within the Santa Rosa Creek watershed.

GLU category [A]	% of Watershed area [B]
0–10%	15.3%
10–40%	60.1%
>40%	24.6%

[A] GLU category based on distribution histogram statistics and field observations.
[B] Proportion of hillslope gradient GLU category within the total watershed area determined in GIS.



Data Sources:
Hillshade: USGS 10m DEM; Roads: ESRI;
Watersheds & Rivers: Stillwater Sciences, ESRI, USGS stream names
Landcover: National Landcover Dataset 2007, Stillwater Sciences

Figure 3-7. Generalized land cover categories used for the GLU analysis.

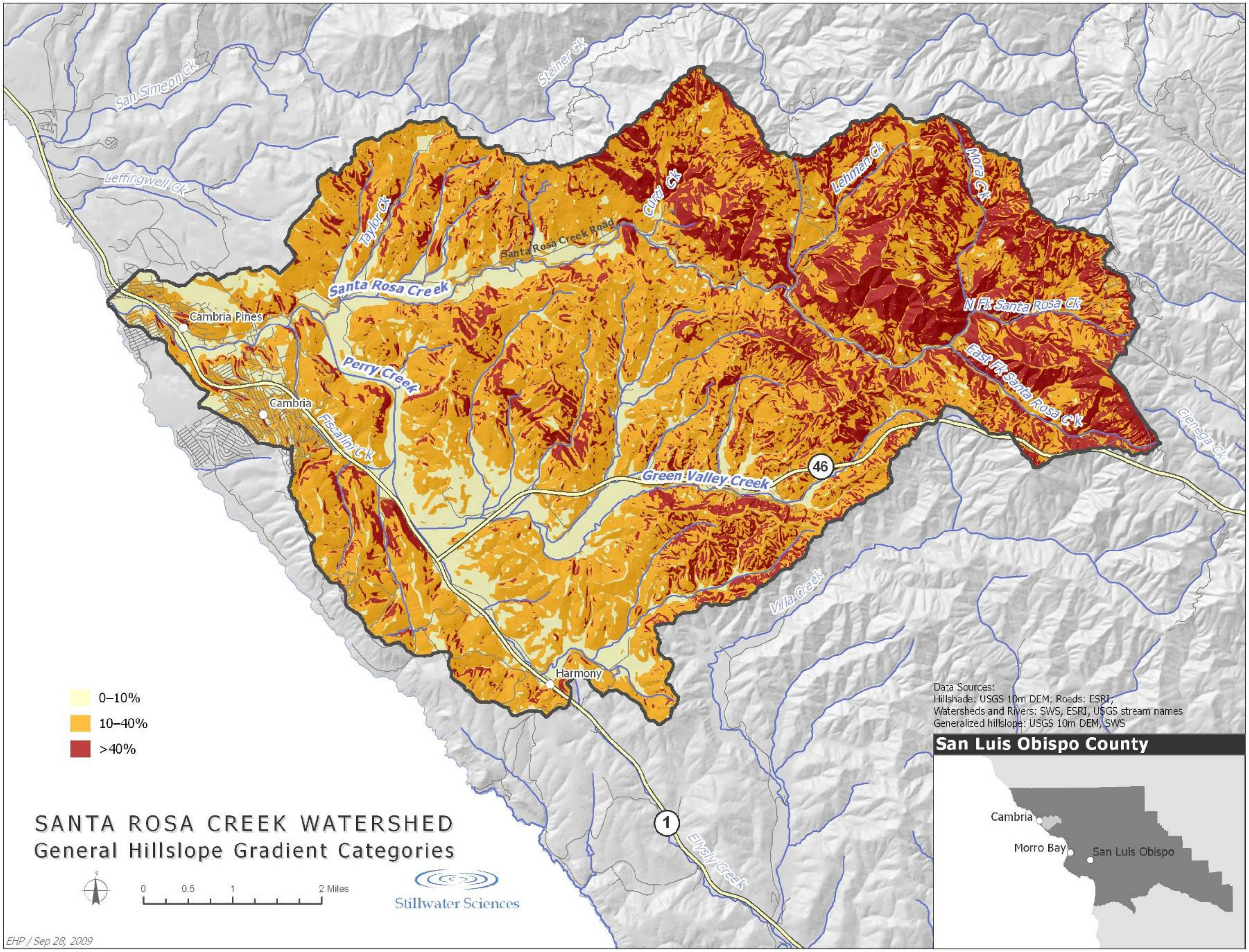


Figure 3-8. Generalized hillslope gradient categories used for the GLU analysis.

The discrete categories defined for these three factors (geology, land cover, and slope) could theoretically overlap into 36 possible geomorphic landscape units—that is, areas that each have a unique combination of these factors that are judged to be the major determinants of hillslope sediment production and, ultimately, sediment yield from the watershed as a whole. In fact, nearly every combination of these factors was represented in the watershed, but one category (geology = "coarse weak", land cover = "ag/grass", slope = 10–40%) represented one-third of the watershed area, which reflects moderately steep grazing lands underlain by Franciscan mélange bedrock. Only 16 of the possible combinations cover more than one percent of the total watershed area, and in total these 16 GLUs account for 94% of the watershed area (Table 3-8).

Table 3-8. Geomorphic landscape units (GLUs) as a percent of total watershed area (representation = 94.1% of the watershed).

Geomorphic landscape units	% of watershed area
Coarse weak; Ag/Grass; 10–40%	35.8%
Coarse weak; Ag/Grass; 0–10%	8.9%
Coarse weak; Ag/Grass; >40%	7.6%
Coarse weak; Forest; 10–40%	5.0%
Coarse competent; Ag/Grass; 10–40%	4.7%
Coarse weak; Scrub/Shrub; >40%	3.9%
Coarse weak; Developed; 10–40%	3.9%
Coarse weak; Forest; >40%	3.8%
Coarse weak; Scrub/Shrub; 10–40%	3.5%
Fine weak; Ag/Grass; 10–40%	3.4%
Coarse weak; Developed; 0–10%	3.3%
Fine weak; Forest; >40%	3.0%
Fine weak; Ag/Grass; >40%	2.5%
Fine weak; Forest; 10–40%	2.1%
Fine weak; Scrub/Shrub; >40%	1.8%
Coarse competent; Ag/Grass; 0–10%	1.0%

For this study, representative areas in each of the major categories were visited in the field and categorized into three relative sediment-production rates, based on observed indications of erosion and mass-wasting processes. Relative differences between many of the different GLUs were dramatic, lending confidence to this three-fold division of relative rates. Figure 3-9 illustrates some of these differences in relative sediment production processes. The assignments of relative sediment production, and in turn of sediment yield, by type of GLU are listed in Table 3-9.

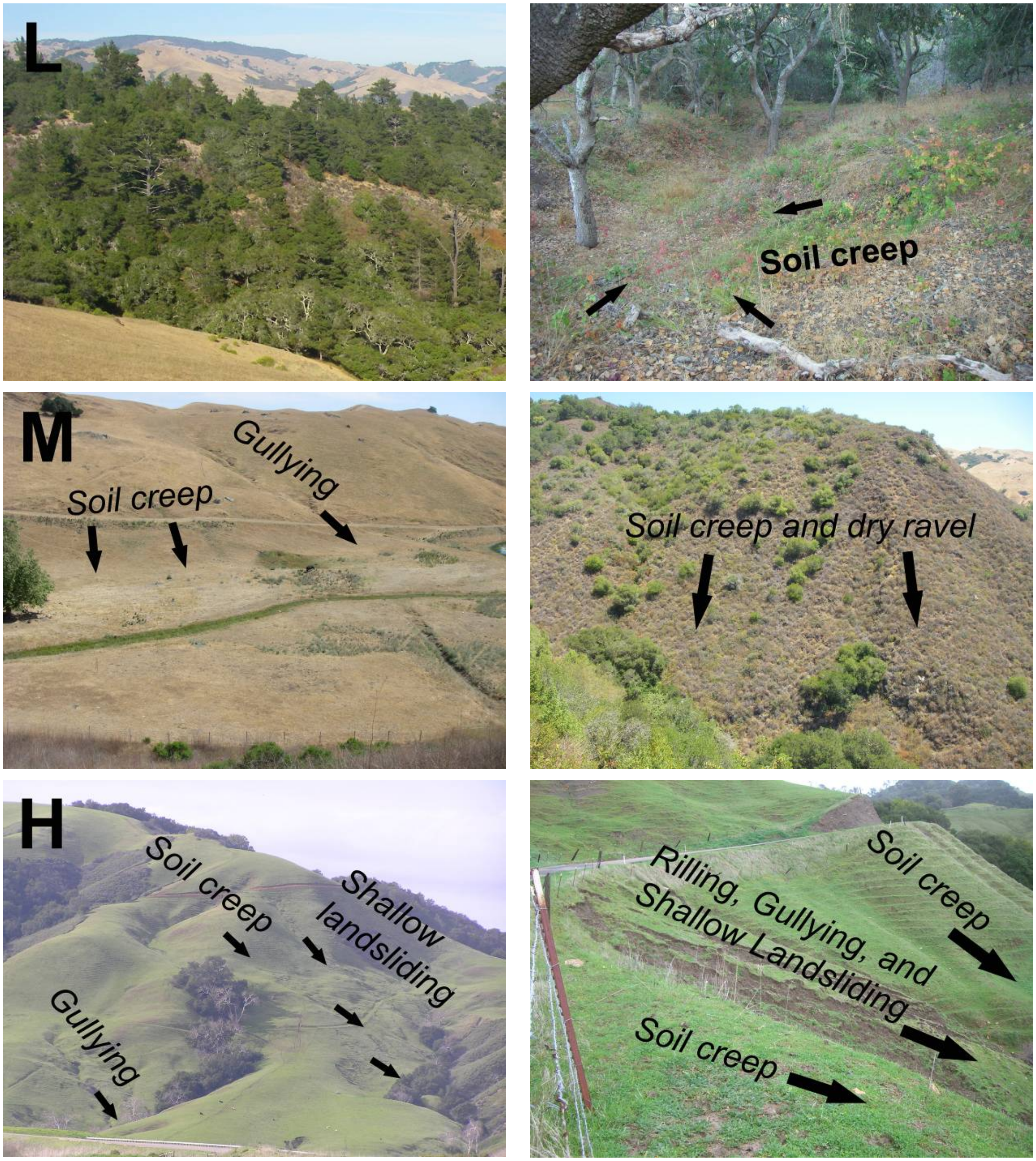


Figure 3-9. Examples of different geomorphic landscape units (GLUs) and their relative levels of sediment production. Top left, low production: coarse competent forest 10–40%; top right, low production: fine weak forest 10–40%; middle left, medium production: coarse weak ag/grass 10–40%; middle right, medium production: fine weak scrub >40%; bottom left, high production: coarse weak ag/grass >40%; bottom right, high production: fine weak ag/grass >40%. Arrows indicate approximate direction of sediment transport from identified erosion process.

Table 3-9. Relative sediment production by Geomorphic Landscape Unit (GLU) (n = 36).

Geomorphic landscape unit	Relative sediment production
Fine weak, Ag/Grass, >40%	High
Fine weak, Ag/Grass, 10–40%	High
Coarse weak, Ag/Grass, >40%	High
Fine weak, Ag/Grass, 0–10%	Med
Fine weak, Developed, >40%	Med
Fine weak, Developed, 10–40%	Med
Fine weak, Developed, 0–10%	Med
Fine weak, Scrub/Shrub, >40%	Med
Fine weak, Scrub/Shrub, 10–40%	Med
Fine weak, Scrub/Shrub, 0–10%	Med
Fine weak, Forest, >40%	Med
Fine weak, Forest, 10–40%	Med
Coarse weak, Ag/Grass, 10–40%	Med
Coarse weak, Ag/Grass, 0–10%	Med
Coarse weak, Developed, >40%	Med
Coarse weak, Developed, 10–40%	Med
Coarse weak, Developed, 0–10%	Med
Coarse weak, Scrub/Shrub, >40%	Med
Coarse weak, Scrub/Shrub, 10–40%	Med
Coarse weak, Scrub/Shrub, 0–10%	Med
Coarse weak, Forest, >40%	Med
Coarse weak, Forest, 10–40%	Med
Coarse competent, Ag/Grass, >40%	Med
Coarse competent, Ag/Grass, 10–40%	Med
Coarse competent, Ag/Grass, 0–10%	Med
Coarse competent, Developed, >40%	Med
Coarse competent, Developed, 10–40%	Med
Coarse competent, Developed, 0–10%	Med
Fine weak, Forest, 0–10%	Low
Coarse weak, Forest, 0–10%	Low
Coarse competent, Scrub/Shrub, >40%	Low
Coarse competent, Scrub/Shrub, 10–40%	Low
Coarse competent, Scrub/Shrub, 0–10%	Low
Coarse competent, Forest, >40%	Low
Coarse competent, Forest, 10–40%	Low
Coarse competent, Forest, 0–10%	Low

A map showing the distribution of the 36 GLU categories across the entire watershed is displayed in Figure 3-10; their distribution by relative sediment production category from Table 3-9 is shown in Figure 3-11.

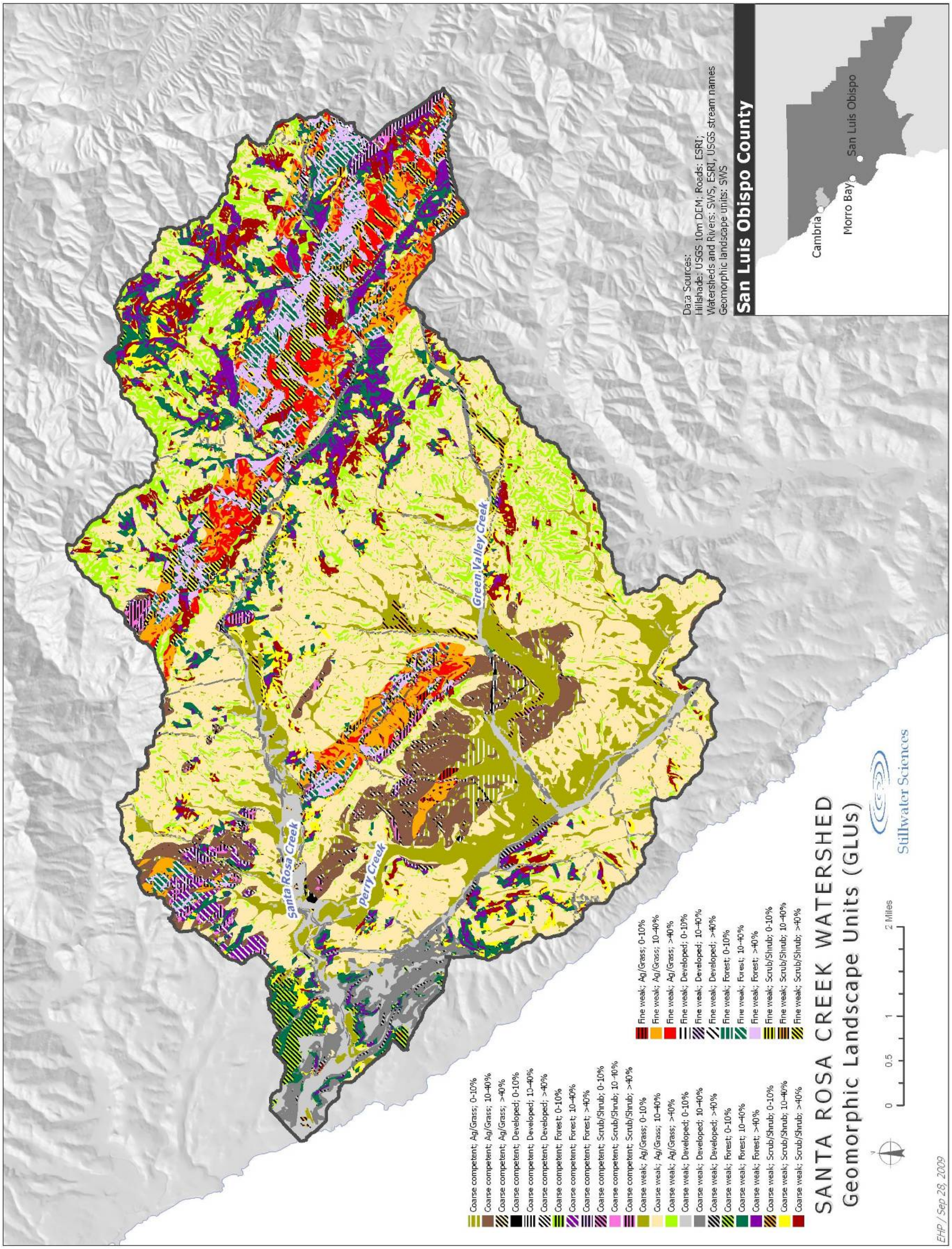


Figure 3-10. Geomorphic Landscape Units (GLUs) in the Santa Rosa Creek watershed.

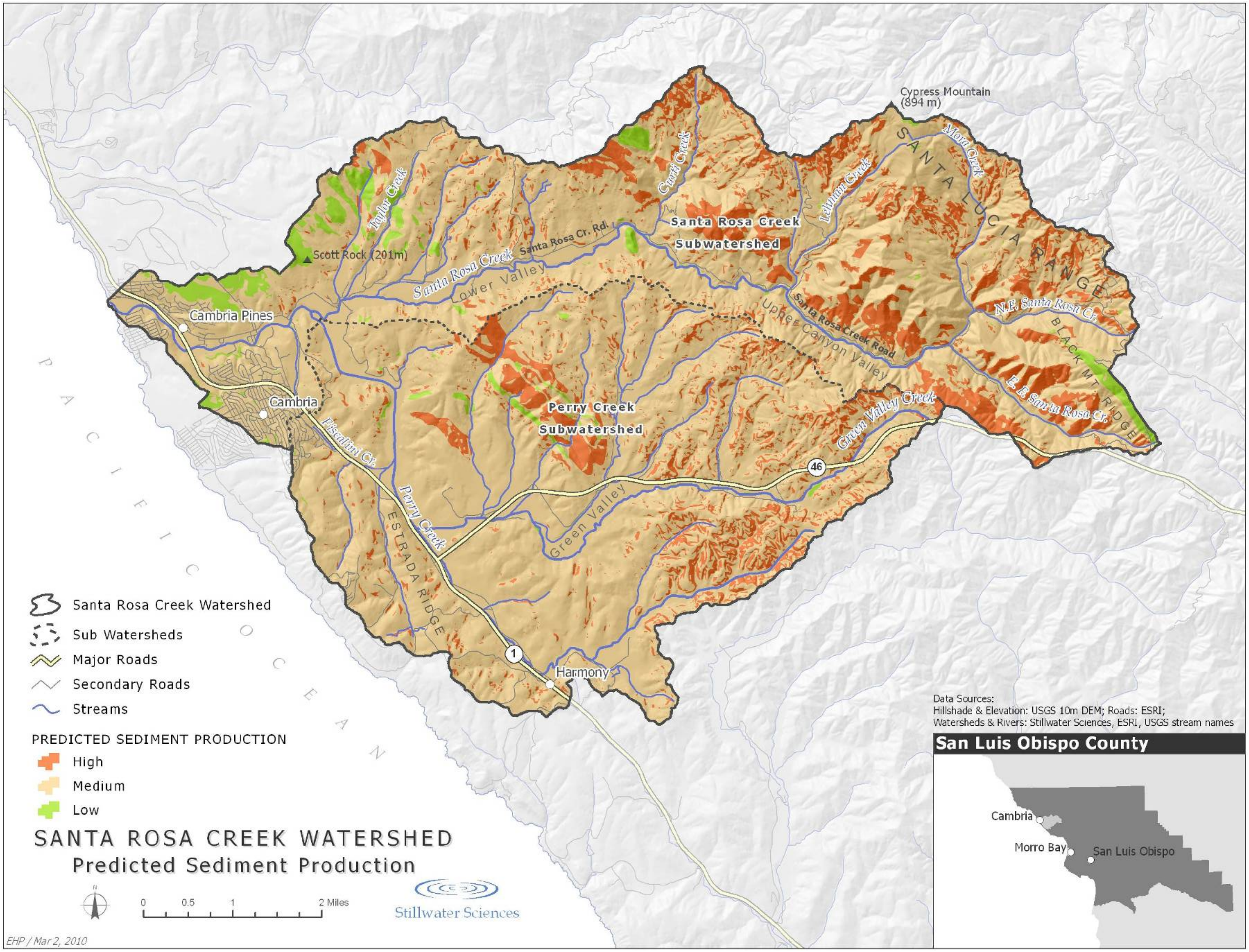


Figure 3-11. Predicted relative rates of sediment production in the Santa Rosa Creek watershed.

The map shown in Figure 3-11 effectively represents a prediction of the relative production of sediment from every part of the watershed. The most striking attribute of this map is the spatial uniformity of sediment generation across the watershed. This reflects the underlying combination of geology, land cover, and slope that place over three-quarters of the watershed areas into our assigned sediment production category of "Medium" (Table 3-10). Less than 15% registers "High", with these areas predominantly on steep bare or grass-covered hillsides concentrated mostly in the headwaters of Santa Rosa Creek and some others clusters concentrated in the headwaters of Perry Creek and long tributaries of Green Valley Creek. Less than 3% registers as "Low", signifying that there are few places in the watershed other than north of Cambria and Scott Rock that are composed of coarse competent rock with forested low- to moderate-gradient slopes.

Table 3-10. Relative total sediment production category as a percent of total watershed area.

Relative Total Sediment Production	% of Watershed Area
Low	2%
Medium	84%
High	14%

This spatial prediction is lacking in one significant respect: the GLU analysis does not account for any routing or storage of sediment within the channel network. This makes it difficult to equate estimated sediment production with actual delivery to the stream channels. However, it can be reasonably assumed in the upland areas of the watershed that sediment production roughly equals sediment delivery to the tributary channels as a function of the steep slopes and minimal storage potential occurring here, with the exception of the stream bed itself. Also, subwatersheds hosting a high proportion of "High" sediment producing GLUs are considered to have relatively high sediment delivery ratios based on the high occurrence of steep, poorly vegetated slopes (see Section 3.5 for discussion of relative sediment yields from the subwatersheds). In the valley reaches of the watershed where storage capacities are greater because of lower gradients and the presence of floodplain areas (i.e., downstream of Mammoth Rock), most sediment produced on adjacent hillslopes with minimal tributary density would simply deposit at the base of the hillside and/or the floodplain, especially in those areas where tributary channels have been filled in for agricultural purposes.

Although the GLU analysis does not explicitly account for discrete erosion processes, a comparison of our High, Medium, and Low sediment producing areas in the watershed against the erosion features shown in Figure 3-1 can be made to identify any apparent connections. Overlying the erosion features with the GLU categories (geology, land cover, and hillslope gradient) reveals that, overall, gullies—the most numerous and voluminous "macro-scale" erosion feature—are predominantly concentrated in the coarse competent and coarse weak (i.e., Franciscan mélange), ag/grass, and moderate slope (10–40%) landscape units (Table 3-11). The corresponding relative sediment-production rate for this GLU was estimated to be in the Medium range (see Table 3-9), which appears somewhat contradictory given that the occurrence of gullies could be indicative of a High yielding terrain. However, as is discussed further in Section 3.4.3 below, the estimated sediment-production rates from gullies is sufficiently lower than from micro-scale erosion features which are assumed here to occur with greater effect in the High GLU areas.

Table 3-11. Proportion of erosion features within GLU categories of the Santa Rosa Creek watershed.

GLU categories	Erosion feature (% of feature area within landscape unit, normalized by the proportion of the unit in the total watershed area)			
	Gully ($1.3\ km^2$)	Landslide ($0.06\ km^2$)	Road erosion ($0.4\ km^2$)	Other erosion ($0.05\ km^2$)
Generalized Geology				
Coarse competent	47	0	29	44
Coarse weak	43	31	39	49
Fine weak	10	69	32	6
Generalized Land cover				
Forest	3	42	<1	13
Scrub/shrub	25	51	13	85
Ag/grass	63	7	5	1
Developed	9	<1	82	<1
Generalized Hillslope gradient				
0–10%	25	<1	28	1
10–40%	47	31	45	36
>40%	28	69	27	63

3.4 Regional Estimates of Sediment Production

The above sections describe active erosion processes and relative sediment-production rates in the watershed using available data. This section takes the next step of presenting quantitative estimates on sediment yields from similar landscapes in the southern Coast Range and then scaling those estimates to the Santa Rosa Creek watershed for the purposes of providing an approximate total sediment yield. This is accomplished by utilizing information published in studies on tectonic uplift rates in the Santa Lucia Mountains and on sediment yield rates in nearby watersheds. Application of these regional estimates to the Santa Rosa Creek watershed is subsequently presented, in addition to GLU-derived sediment yield estimates.

3.4.1 Inference from geological evidence

Watershed topography reflects the interplay between uplift (if any) due to tectonic processes, and the sculpting and wearing away of slopes by erosion. In general, high steep mountains occur in areas that have been subjected to sustained rapid uplift, whereas gently sloping terrain is found where uplift is slow or has been followed by long periods of denudation. The linkages between uplift, slope steepness, and erosion imply that slopes should tend to contribute sediment in proportion to their uplift rates over the long term (Burbank et al. 1996)—that is, rapid uplift rates usually result in high rates of sediment production. Uplift rates, in turn, are directly related to the tectonic setting and deformation history of the landscape.

Late Cenozoic uplift (less than 3 million years ago) in the southern Coast Range is evident based on the following landscape features, which are also present in the Santa Rosa Creek watershed: uplifted and deformed marine strata (e.g., Monterey Formation), elevated marine terraces, and Quaternary faults and folds (Montgomery 1993). Christensen (1965, as cited in Montgomery

1993) estimated surface uplift along the Coast Range to vary between approximately 300 to 600 meters during this recent geologic period, with lower values near the coast and higher values in the Santa Lucia Mountains. The geomorphic response to this Coast Range orogeny is surface erosion, or denudation, of the sub-aerial landscape over time. Based on a comprehensive review of rock uplift and plate convergence rates in the region, Montgomery (1993) estimated erosion rates in the central Coast Range watersheds to range between 0.02 and 0.20 mm/yr (Table 3-12). The section below examines specific estimates of fluvially driven sediment yields from nearby watersheds which more closely match the denudation rates estimated by Montgomery (1993).

In contrast, Ducea et al. (2003) estimated a higher denudation rate of 0.9 mm/yr for the Santa Lucia Mountains over the past 2 million years. Ducea et al. (2003) acknowledged that their denudation estimates are likely one order of magnitude greater than fluvial erosion rates in the region, which they attribute to landslide activity that serve to denude landscapes yet store their sediments for significant time periods (~100 to 1,000 years). This offers a plausible, yet untested explanation for the difference between uplift, denudation, and fluvial erosion rates in the region.

Table 3-12. Long-term sediment yield from the Santa Rosa Creek watershed based on regional estimates of denudation rates.

Study	Denudation rate (mm a^{-1})	Time period [A]	Applied to the Santa Rosa Creek watershed	
			Long-term average annual sediment yield (t a^{-1}) [B]	Long-term average annual sediment yield per unit area (t km^{-2} a^{-1})
Montgomery (1993) – low estimate	0.02	<3 Ma	3,900	32
Montgomery (1993) – high estimate	0.2		39,000	320
Ducea et al. (2003) – low estimate “fluvial”	0.09	<2 Ma	17,700	144
Ducea et al. (2003) – high estimate “landslides and fluvial” [C]	(0.9)		(177,000)	(1,440)

[A] Ma = million years.
[B] Sediment yield calculated using an assumed sediment bulk density of 1.6 tonnes per cubic meter (t m^{-3}).
[C] Expected to overestimate sediment delivery into channels (see text).

3.4.2 Inference from sediment studies in nearby watersheds

Although there has been no direct measurement of sediment discharge or accumulation in the Santa Rosa Creek watershed, sediment yields can be estimated from yields in neighboring watersheds with similar landscape characteristics. Table 3-13 summarizes sediment-yield estimates from other watersheds in the southern Coast Range derived from studies, focusing on either measured sediment discharge at a point of a stream channel or measured sedimentation within a reservoir. The average annual sediment yields from these other watersheds vary between 229 and 1,171 metric tonnes per square kilometer (t km^{-2} a^{-1}), with a median value of nearly 400 t km^{-2} a^{-1}. In developing this tabular summary, we have generally assumed that the fine sediment fraction represents the suspended load fraction—those sand-size or smaller particles (<2 mm) transporting in suspension during high flow events—which likely accounts for approximately 90% of the total load as reported by several other studies in the region (e.g., Walling and Webb 1981, Hadley et al. 1985, both as cited in Farnsworth and Warrick 2007). These data include one study conducted in the nearby Pismo Creek watershed (Hecht 2006). The median denudation rate of 0.3 mm/yr, based on these results, closely matches the long-term (<3 Ma) rate estimated by Montgomery (1993). We therefore judge this rate to be the best available estimate to apply to the Santa Rosa Creek watershed for its long-term sediment yield.

Table 3-13. Estimated sediment yields from watersheds in the southern Coast Range region.

Study	**Watershed**	**Years evaluated**	**Watershed area (km^2)**	**Total sediment yield per unit area ($t\ km^{-2}\ a^{-1}$)**	**Coarse (>2 mm) load fraction of the total load** [A]	**Equivalent denudation rates based on the total sediment yield ($mm\ a^{-1}$)** [B]
Sediment Discharge Study						
Knott (1976) [C]	Santa Rita Creek	1943–1972	53	393	20%	0.2
	Arroyo Grande Creek		175	274	8%	0.2
Farnsworth and Warrick (2007) [D, E]	Pescadero Creek	1952–2005	120	398	10%	0.2
	San Lorenzo River	1937–2005	270	1,171		0.7
	Salinas River	1930–2005	10,760	229		0.1
	Carmel River	1963–2005	640	684		0.4
	San Jose Creek [F]	1972–1997	20	800		0.5
Reservoir Sedimentation Study						
Brown (1973)	Loch Lomond (Newell Ck.)	1961–1971	132	385	10%	0.2
Minear and Kondolf (2009) [G]	Los Padres (Carmel R.)	1949–1984	116	364		0.4
	Atascadero (Atascadero Ck.)	1918–1975	2.3	235		0.2
	Santa Margarita (Salinas R.)	1942–1975	287	349		0.4

[A] Coarse load fraction assumed to be 10% of the total load, unless otherwise stated by the study author.

[B] Sediment bulk density assumed to be 1.6 tonnes per cubic meter ($t\ m^{-3}$), unless otherwise stated (e.g., see note number G).

[C] Study included direct measurements of the size fraction of transported sediment.

[D] Study estimated total suspended sediment yield, which we have assumed represents sand size particles and finer (<2 mm).

[E] All watersheds except for San Jose Creek are located in the southern Coast Range region, which includes San Mateo, Santa Cruz, and San Luis Obispo counties.

[F] Located in the Transverse Mountains of Santa Barbara County and used here to exemplify a nearby drainage in southern California, yet with a relatively greater sediment yield potential due to weaker lithologies and higher tectonic uplift rates.

[G] This study assumed a bulk density of reservoir sediments = 0.96 $t\ m^{-3}$.

Plotting the average annual sediment yield (t a^{-1}) data against drainage area from these other southern Coast Range watersheds shows a strong correlation—the coefficient of determination (R^2) of 94% indicates that this model explains the variation well (Figure 3-12). This correlation is not surprising, since, generally, more sediment is produced from a larger watershed. Using the linear regression of the plotted data in Figure 3-12 with the drainage area of the Santa Rosa Creek watershed (123 km^2), we can derive an estimated total sediment yield that amounts to approximately 52,000 t a^{-1}, or a yield per unit area of 420 t km^{-2} a^{-1}. This estimate corresponds to a uniform, watershed-wide denudation rate (i.e., landscape lowering rate) of 0.3 mm/yr.

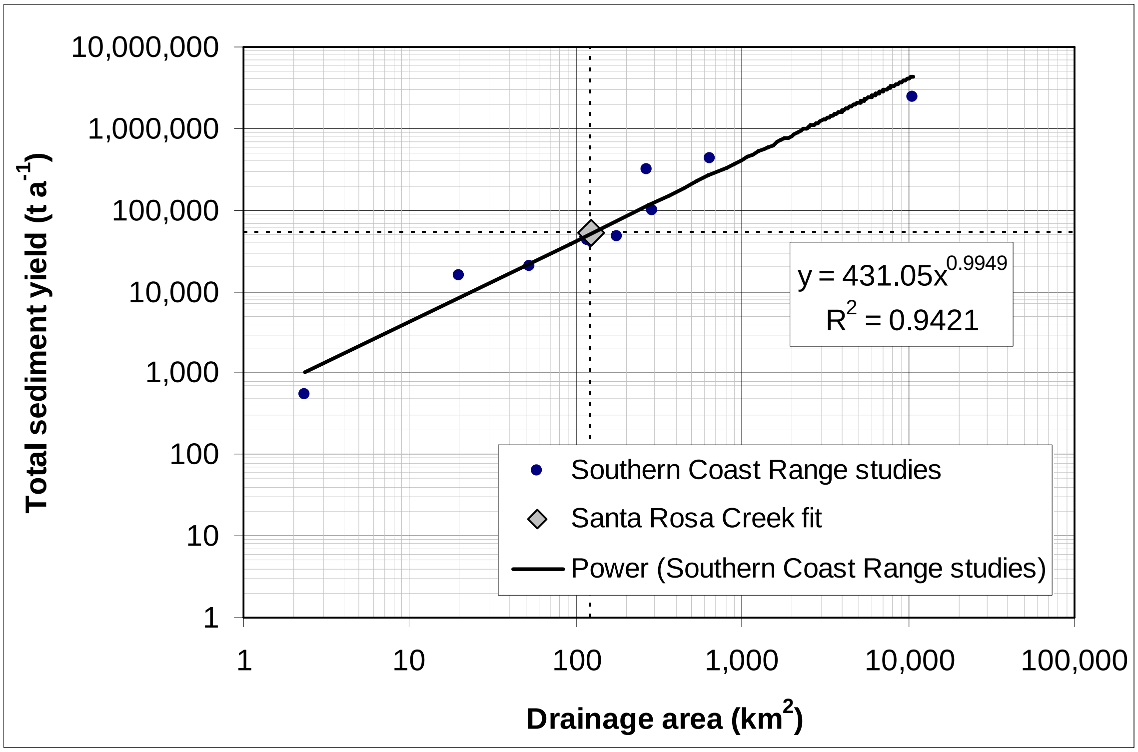


Figure 3-12. Correlation of estimated sediment yields from other watersheds in the southern Coast Range region with their drainage areas. Santa Rosa Creek watershed (123 km^2) is shown by the gray diamond.

3.4.3 Comparison of sediment yield estimates from hillslope erosion features and regional studies

The estimates of sediment yields from other studies throughout the southern Coast Range were used to derive an average annual estimate for the entire Santa Rosa Creek watershed: 52,000 t a^{-1}, or a sediment yield per unit area estimate of 420 t km^{-2} a^{-1}. This value exceeds the sediment-production rate of 17,000 t a^{-1} (140 t km^{-2} a^{-1}) estimated for the "macro-scale" hillslope erosion features located in the watershed, of which the majority (82%) is accounted for by gullies (Section 3.2). This result is expected because the macro-scale erosion rate does not include sediment production from other sources in the watershed, namely "micro-scale" hillslope erosion sources (e.g., soil creep, dry ravel, and rilling) and channel erosion sources (e.g., bank and bed erosion). The remaining two-thirds of the total sediment delivery to the channel network are likely accounted for by these other sources. This supports our previously stated assertion that other hillslope processes such as soil creep, dry ravel, and rilling, which were observed to be prevalent and highly effective in delivering sediment to the channel network in those High units, cooperatively lead to a relatively higher sediment-production rate as compared to the production rate specifically from gullies.

3.5 Sediment Yield Analysis Using Geomorphic Landscape Units

Use of our GLU methodology with the watershed sediment yield estimated from regional studies enables the allocation of the total yield to each identified GLU throughout the watershed based on its relative “High”, “Medium”, or “Low” sediment production potential. Following our previously stated assumption that sediment-production rates vary approximately by up to an order of magnitude (but perhaps less) between GLU categories, we have determined the relative sediment yield potential for each subwatershed for the purpose of ranking them in order from highest to lowest (Table 3-14). Absolute values are not reported here because an unknown degree of error likely exists in our predictions due to the lack of actual sediment yield measurements in the watershed. Varying the sediment yield differences between the High, Medium, and Low categories between a factor of 2 and 10 (i.e., up to an order of magnitude) results in the same ranking order. The tributaries draining to Santa Rosa Creek estimated to have the highest sediment yields are East Fork Santa Rosa and Curti creeks. Two of the other highest sediment producing subwatersheds host unnamed tributaries that drain to Green Valley Creek. All four of these subwatersheds are characterized by their high relief (i.e., large proportion of steep areas), low vegetation cover density, and weak lithologies which drive the relatively high sediment-production rates and, in turn, the high delivery rates to the channel network. Figure 3-13 shows the subwatersheds considered in this analysis; the figure also highlights those subwatersheds predicted to have the highest and lowest sediment yields.

Table 3-14. Relative sediment yield potential in subwatersheds in the Santa Rosa Creek watershed. [A]

Subwatershed			% of subwatershed area			Rank of sediment production rate [C]
ID	Stream Name [B]	Area (km^2)	High	Medium	Low	
1	Curti Creek	5.5	23	73	4	4
2	Mora Creek	6.8	15	84	1	10
3	Taylor Creek	2.2	4	84	12	20
4	*Santa Rosa Creek tributary*	2.7	8	64	28	17
5	Lehman Creek	6.5	20	79	1	6
6	North Fork Santa Rosa Creek	5.6	20	78	2	5
7	*lower Santa Rosa Creek*	5.3	1	85	14	25
8	*Green Valley Creek tributary*	4.4	17	80	3	8
9	*Santa Rosa Creek tributary*	1.4	<1	92	7	24
10	*Green Valley Creek tributary*	8.1	9	90	<1	15
11	*Green Valley Creek tributary*	2.7	15	84	<1	9
12	East Fork Santa Rosa Creek	4.8	33	60	7	1
13	Green Valley Creek	12.3	12	88	<1	12
14	*Green Valley Creek tributary*	2.3	24	73	3	2
15	*Green Valley Creek tributary*	1.7	24	70	6	3

Subwatershed			**% of subwatershed area**			**Rank of sediment production rate** [C]
ID	**Stream Name** [B]	**Area (km^2)**	**High**	**Medium**	**Low**	
16	Fiscalini Creek	3.7	1	98	<1	22
17	*lower Perry Creek*	6.3	4	95	1	19
18	*upper Perry Creek*	11.9	11	88	<1	13
19	*Perry Creek tributary*	1.6	15	85	0	11
20	*Perry Creek tributary*	1.3	3	97	0	21
21	*Santa Rosa Creek tributary*	3.6	6	91	3	16
22	*Fiscalini Creek tributary*	3.0	5	95	<1	18
23	*Santa Rosa Creek tributary*	1.0	<1	99	<1	23
24	Santa Rosa Creek	17.1	18	81	1	7
25	*Santa Rosa Creek tributary*	1.1	10	90	<1	14

[A] Location of subwatersheds are shown in Figure 3-13.
[B] Names in italics are descriptive only for those tributaries without official names (see Table 1-1).
[C] Listed in order of highest to lowest sediment producing subwatersheds.

Numerous water storage basins located throughout the watershed (Section 3.2) have the potential to trap sediment, particularly coarse-grained materials, which further alters sediment-routing processes in the watershed (see Figure 3-2). Determination of a sediment yield for the contributing areas above each basin feature (or point) was determined in GIS using our GLU methodology and was then used to estimate the total sediment yield contributing to these basins. The results suggest that the amount of sediment "trapped" in the basins is relatively low, accounting for a watershed-wide reduction of approximately 5 to 10% of the previously estimated total sediment yield of 52,000 t km-2 a-1 (see Section 3.4.3). Not surprisingly, the greater number of basins present in the Perry Creek subwatershed (including Green Valley and Fiscalini creeks) contributes to a greater reduction in the total sediment yield from that subwatershed. Considering the low trap efficiencies of these basins and that coarse sediment probably accounts for approximately 10% of the total load, the basins likely trap only 40–50 tonnes of coarse sediment annually in the entire watershed. Although this trapping may be locally significant to downstream habitat formation, the watershed-wide amount is only about one percent of the approximately 5,000 t a^{-1} of coarse sediment yield estimated for the watershed as a whole (Table 3-9).

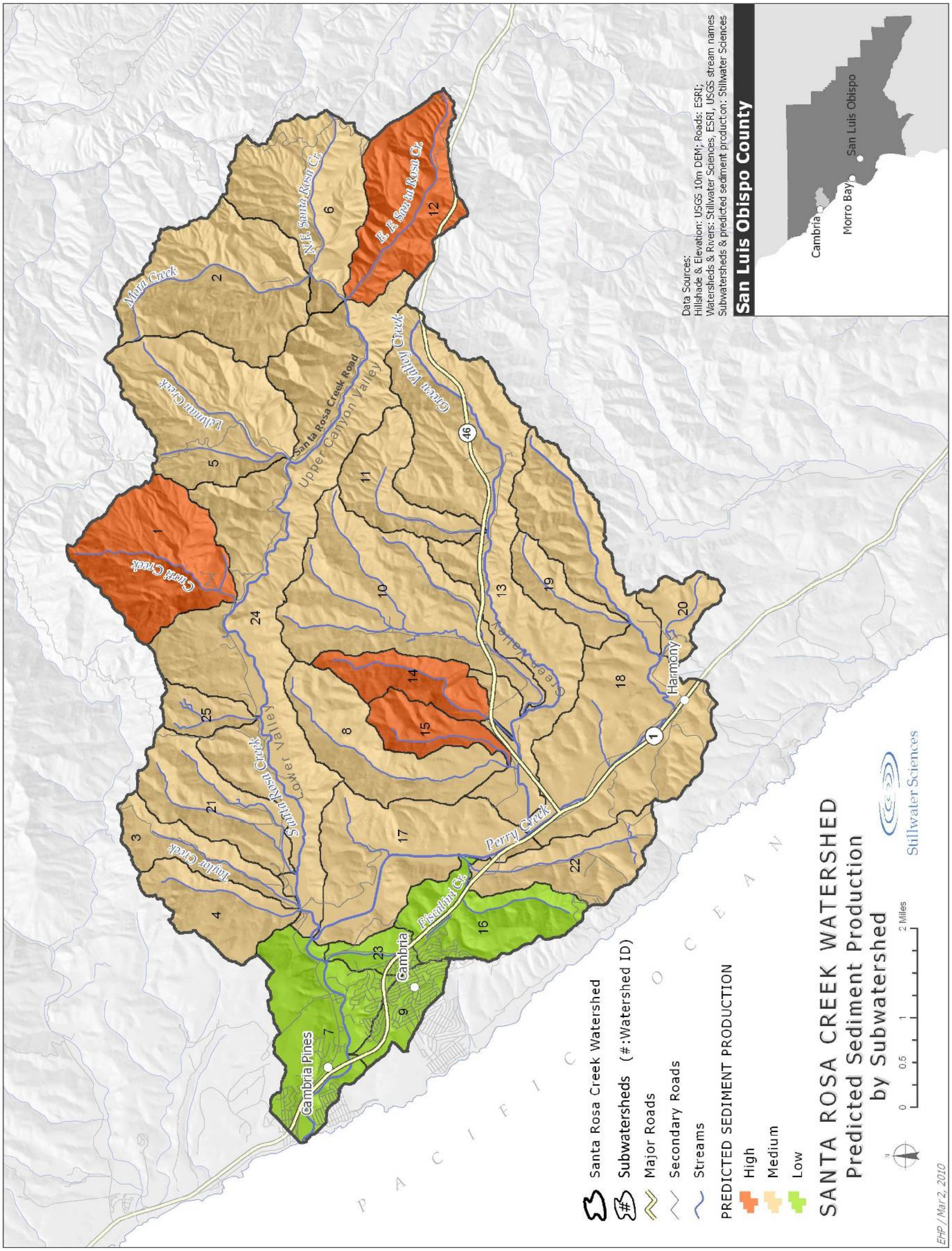


Figure 3-13. Predicted sediment production potential by subwatershed in the Santa Rosa Creek watershed.

4 FLUVIAL GEOMORPHIC PROCESSES OF SEDIMENT TRANSPORT AND MORPHOLOGICAL CHANGE

4.1 Overview

This section assesses fluvial geomorphic processes and morphology of the channel network of Santa Rosa Creek watershed as the basis for understanding the potential implications for, and impacts of, management decisions related to steelhead trout or other aspects of watershed management. We begin by assessing data related to the frequency and magnitude of high flows which are the fundamental control on fluvial geomorphic processes (Section 4.2). We then characterize the morphology and sediments of the channel network to the extent permitted by time, access, and available data: this information is one of the building blocks for determining aquatic habitat quality and the probably extent of impacts to the channel network (Section 4.3). Third, we examine the morphological dynamics of the creek network using historical data, measures of the potential for sediment transport, and our understanding of the history of direct and indirect human impacts on the creek to determine how the creek has changed in the recent past (Section 4.4). Finally, we provide a brief narrative related to available information on the morphology and dynamics of the barrier lagoon at the mouth of Santa Rosa Creek: the lagoon potentially plays an important role in aquatic life cycle for steelhead trout (Section 4.5).

4.2 Frequency and Magnitude of Flows

The magnitude of flow in Santa Rosa Creek ultimately determines the magnitude of sediment transport and the nature and rate of geomorphic change. As a consequence of its Mediterranean climate and historical changes to land uses in the watershed, discharge within Santa Rosa Creek is characterized by long durations of low flow, punctuated by high-flow events that travel relatively quickly through the watershed. Over the past 50 years, a variety of notable floods have occurred in the watershed (e.g., in Water Year [WY] 1969, 1973, 1986, 1995, and 2005; see below). These high-flow events are instrumental in transferring sediment from the hillslopes to the channel, downstream river mouth lagoon, and near-shore waters, and they are integral in controlling changes in the geomorphic character of the creek channel and floodplain over time. The specific short- and long-term impacts of these high-flow events on channel morphology and geomorphic processes are a function of a variety of factors, including both natural and anthropogenic influences.

Discharge has been measured over the past 50 years in both the upper (i.e., above Mammoth Rock) and lower watershed (i.e., below the Perry Creek confluence) by three gauges operating at different time periods (Table 4-1; see Figure 1-5). Flows recorded in the upper Santa Rosa Creek are indicative of the flows entering the alluvial section of the Santa Rosa Creek valley whereas flows recorded by the lower gauges represent the magnitude of flow passing through the town of Cambria and through the lagoon to the Pacific Ocean. From WY 1958 through 1972, the USGS recorded both daily mean and annual instantaneous maximum flow in upper Santa Rosa Creek at a gauge located approximately 0.7 km upstream of the Curti Creek confluence (USGS 11142200). The gauge was designed to assess flow for a potential dam to be build in the upper watershed but never constructed. Following the decommissioning of the USGS gauge, SLO County recorded daily mean and annual instantaneous maximum flow in lower Santa Rosa Creek at a gauge located just upstream of the Highway 1 bridge (SLO County Station 16) from WY 1976 through 1992. The Highway 1 bridge gauge was replaced by another gauge installed in lower Santa Rosa Creek approximately 2.2 km upstream at the Main Street bridge (SLO County Station 21) which has been recording daily mean and annual instantaneous maximum discharge since WY 1989. Summary details are provided in Table 4-1.

Table 4-1. Stream gauges of Santa Rosa Creek. [A]

Stream gauge ID	Stream gauge operator [B]	Stream gauge location	Period of record (water years)	Drainage area above stream gauge (km^2)
USGS 11142200	USGS	Upper gauge: 0.7 km upstream from Curti Creek	1958 – 1972	32.4
SLO County Station 16	SLOCWR	Lower gauge: Highway 1 bridge	1976 – 1992	121.5
SLO County Station 21	SLOCWR	Lower gauge: Main Street bridge	1989 – present	116.6

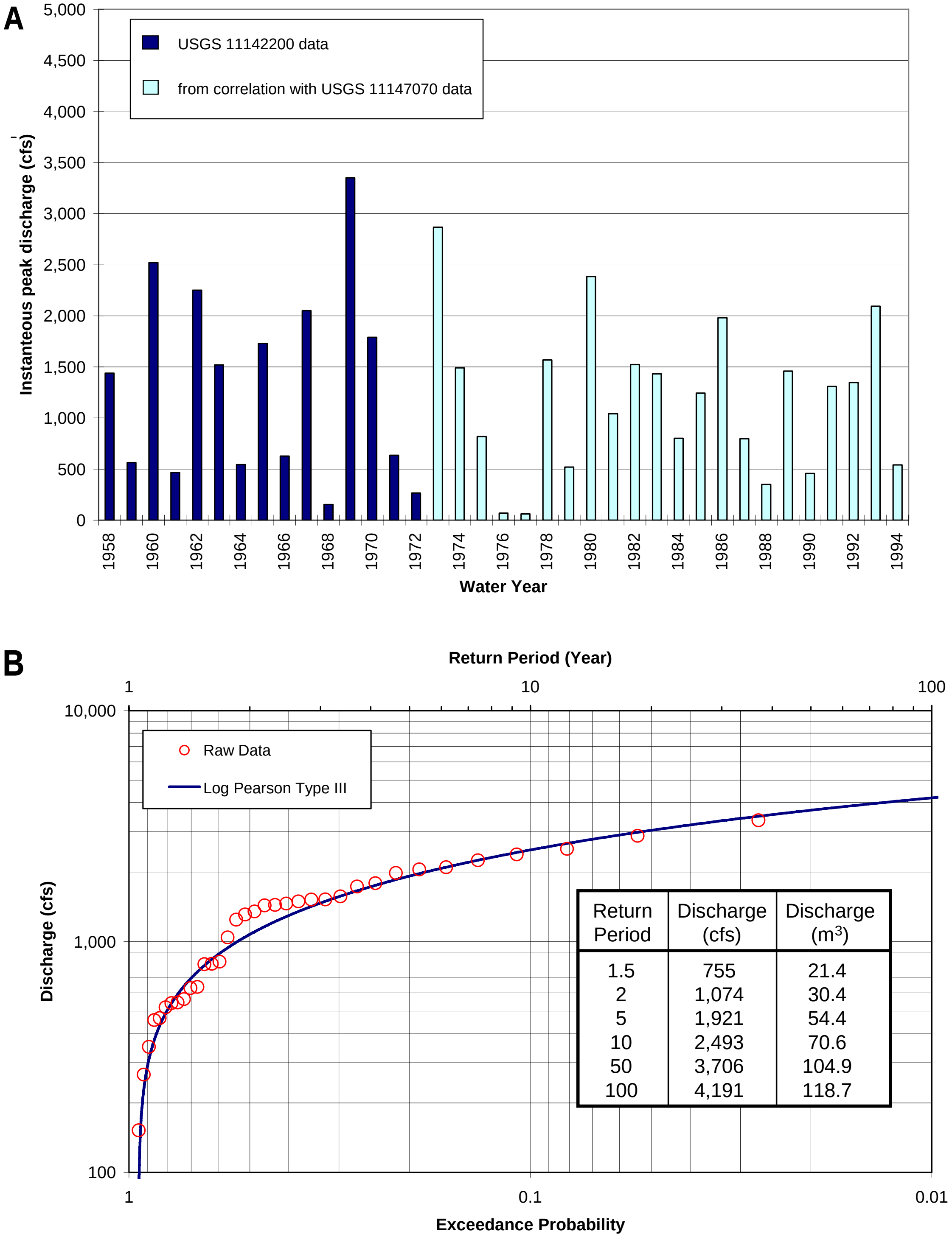
[A] See Figure 1-5 for locations of stream gauge locations on Santa Rosa Creek.
[B] USGS=United States Geological Survey; SLOCWR = San Luis Obispo County Water Resources, Division of Public Works.

In addition to the different operating periods for each gauge, the quality of flow information varies. Flow data from the lower gauges has not been subject to USGS operating protocols and so are not well calibrated restricting confidence in the data; calibration is the process of taking actual measurements of flow taken at a range of low to high flows to develop a reliable relationship between flow depth and flow discharge that allows the operators to infer discharge from depth in unmeasured events. There are large variations in reported annual maximum discharge at SLO County Stations 16 and 21 during the period where both gauges were operating (WY 1989–1992) despite their close physical proximity. At Station 21, calibration of the rating curve has occurred only during very moderate flows (below 9 $m^3 s^{-1}$, 320 cfs) and yet has been used to predict annual instantaneous maximum discharges over 35 times higher. Conversely, flows at Station 16 were deemed sufficiently accurate to use as part of a recent USGS groundwater recharge study conducted in the watershed (Yates and Van Konyenburg 1998). As such, we concentrate our analysis of stream flow dynamics on the USGS gauge 11142200 and SLO County Station 16, and include data from SLO County Station 21 sparingly and with caveats regarding flow magnitude. Also to provide consistency with the study of Yates and Van Konyenburg (1998), gaps in the records of annual maximum flow were filled using correlation with the annual maximum flow record from the neighboring Santa Rita Creek tributary gauge at Templeton, CA (USGS gauge 11147070; flow record from WY 1958-1992). However, without additional calibration of the Station 21 gauge, there are no particularly reliable measurements of high flows in the watershed since WY 1992, including the high flow events in WY 1995 and 2005.

Within these limitations, the compiled data were used to illustrate inter- and intra-annual flow variability within the Santa Rosa Creek watershed since WY 1958. Annual maximum flow has ranged by a factor of ~50 (1.7 to 95 $m^3 s^{-1}$; 60 to 3,350 cfs) in the upper watershed, and even more widely (<0.03 to 340 $m^3 s^{-1}$; <1 to <12,000 cfs) in the lower watershed between WY 1962–1994, with the largest flow recorded at both locations occurring in WY 1969 (Figure 4-1 and Figure 4-2). From the extended annual maximum flow data, the annual maximum discharge expected to be equaled or exceeded approximately once every 1.5 to 2 years (the statistical "bankfull" flow event) during this time period is approximately 21–30 $m^3 s^{-1}$ (760–1,100 cfs) in the upper watershed and 50–78 $m^3 s^{-1}$ (1,800–2,700 cfs) in the lower watershed. For low flows, discharge data from the upper watershed indicates that, on average, the daily mean flow was less than 0.03 m^3s^{-1} (1 cfs) for the period the gauge was in operation (WY 1958–1972) and approximately 99% of the daily mean flow values were at or below 4.5 $m^3 s^{-1}$ (160 cfs) (Figure 4-3). In the lower watershed, mean daily discharge also averaged less than 0.03 $m^3 s^{-1}$ (1 cfs) over the period of record (WY 1976–1992), with most of the daily mean flow values at or below 13.6 $m^3 s^{-1}$ (480 cfs) (Figure 4-4).

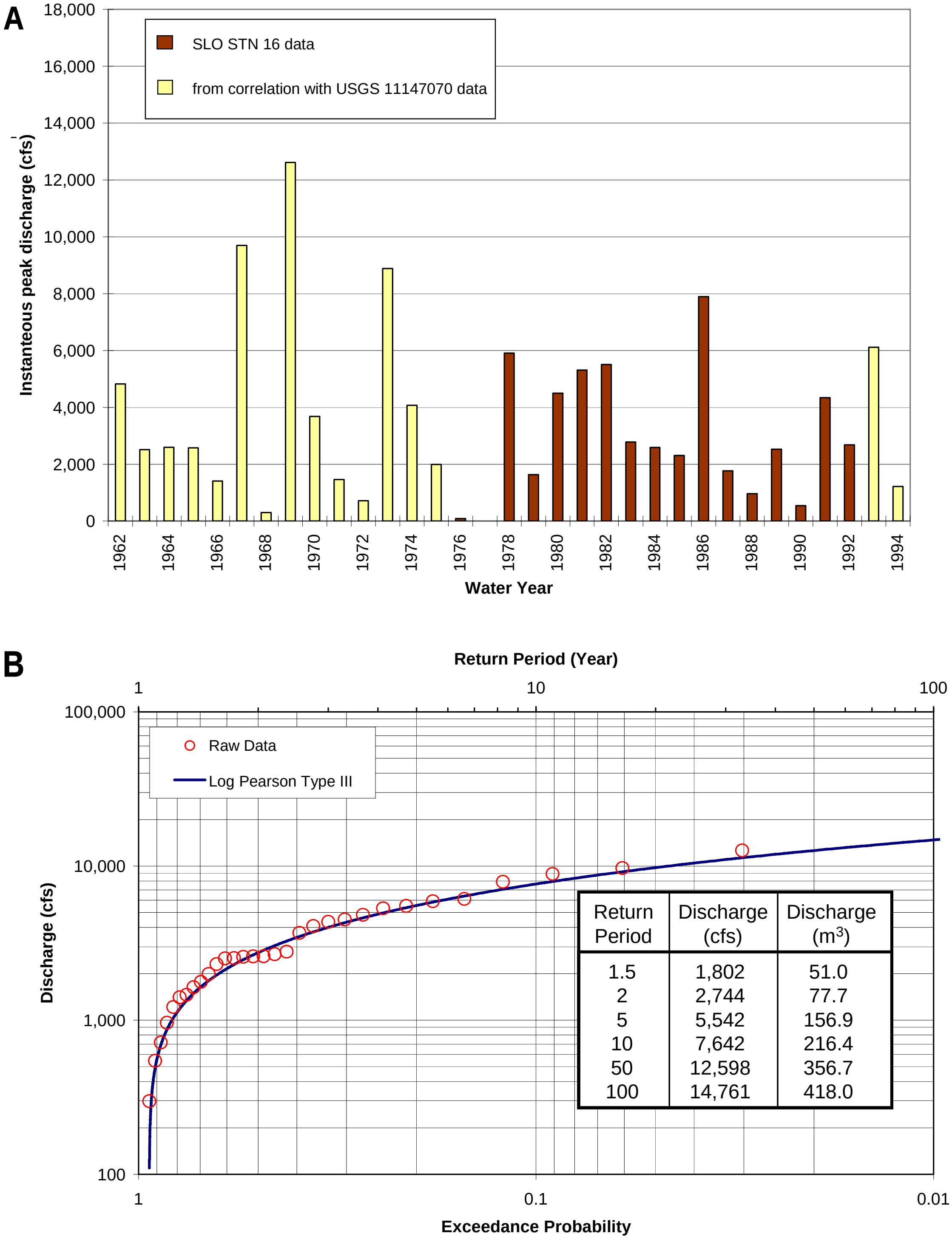
Flood flows within the Santa Rosa Creek watershed are "flashy", meaning that there is a rapid increase in discharge over a short time period with a quickly developed peak discharge in relation to normal baseflow (Ward 1978). Flashiness represents the combined expression of both natural features (e.g., local storm intensity, topographic relief, geology, and soil development) and factors related to human activities (e.g., watershed land use, vegetation cover, extent of impervious surfaces). A measurement of "flashiness" is the ratio of the annual maximum instantaneous discharge to the associated daily mean discharge for that day. For those periods with adequate flow data, this ratio averaged 4.8 (range = 2.6 to 11.1) within the upper watershed (WY 1958–1972), and averaged 7.2 (range = 2.1 to 32.0) within the lower watershed (WY 1976–1992). For comparison, the unregulated and relatively undeveloped Big Sur River watershed (Monterey County, CA) to the north has an average "flashiness" ratio of 2.4 near the mouth (USGS gauge 11143000).

The three largest *recorded* floods in the watershed (i.e., using the SLO County Station data) occurred in WY 1978 (167 $m^3 s^{-1}$ [5,910 cfs]), WY 1982 (156 m^3s^{-1} [5,510 cfs]), and WY 1986 (224 $m^3 s^{-1}$ [7,890 cfs]). With the inclusion of extrapolated data to cover the full flow record from WY 1962 to WY 1994 (Figure 4-1A, Figure 4-2A), the four largest floods during this period may have actually occurred in WY 1969 (by correlation, and also recorded as the highest event in the upper USGS gauge), WY 1967 (by correlation), 1973 (correlation, and also the second highest flow at the upper gauge), and 1986 (recorded), respectively. The floods in WY 1969, 1973, and 1978 are correlated with the El Niño–Southern Oscillation (ENSO) climatic phenomenon (see section 1.2.3). ENSO years in Southern California are generally characterized by relatively high rainfall intensities, with rivers and streams exhibiting higher annual peak flow magnitudes than they do in non-ENSO years (Cayan et al. 1999, Andrews et al. 2004). Andrews et al. (2004) describe the statistically positive occurrence of high floods with ENSO years using data from 20 rivers south of 35ºN. Santa Rosa Creek occurs just to the north of the sample set of rivers used to prove this relationship (the latitude of Cambria is 35ºN) so the ENSO influence exists but is statistically less certain than for rivers to its south. As evidence, in the upper watershed, the annual maximum flow record from WY 1958 to 1994 indicates that there is a 4% chance that flow will exceed the 10-year recurrence interval flow event (Q_{10}: ~70 $m^3 s^{-1}$; 2,500 cfs) during non-ENSO years but a four times greater likelihood (16%) during ENSO years (Figure 4-5a). In the lower watershed, the annual maximum flow record from WY 1962 to 1994 indicates that there is a 10% chance that flow will exceed the Q_{10} (~216 $m^3 s^{-1}$; 7,600 cfs) during non-ENSO years but double that during ENSO years (Figure 4-5b). Overall, there is reason to believe that flood events are likely to be greater during the El Niño years in the watershed, so correlating fluvial process activity (and the potential implications for management) with the ENSO cycle.



Return Period	Discharge (cfs)	Discharge (m^3)
1.5	755	21.4
2	1,074	30.4
5	1,921	54.4
10	2,493	70.6
50	3,706	104.9
100	4,191	118.7

Figure 4-1. Annual maximum discharge and flood frequency for Santa Rosa Creek at Cambria (USGS gauge 11142200). Discharge values reported in the units in which they were measured.



Return Period	Discharge (cfs)	Discharge (m^3)
1.5	1,802	51.0
2	2,744	77.7
5	5,542	156.9
10	7,642	216.4
50	12,598	356.7
100	14,761	418.0

Figure 4-2. Annual maximum discharge and flood frequency curve for Santa Rosa Creek at Highway 1 bridge (SLO County Station 16). Discharge values reported in the units in which they were measured.

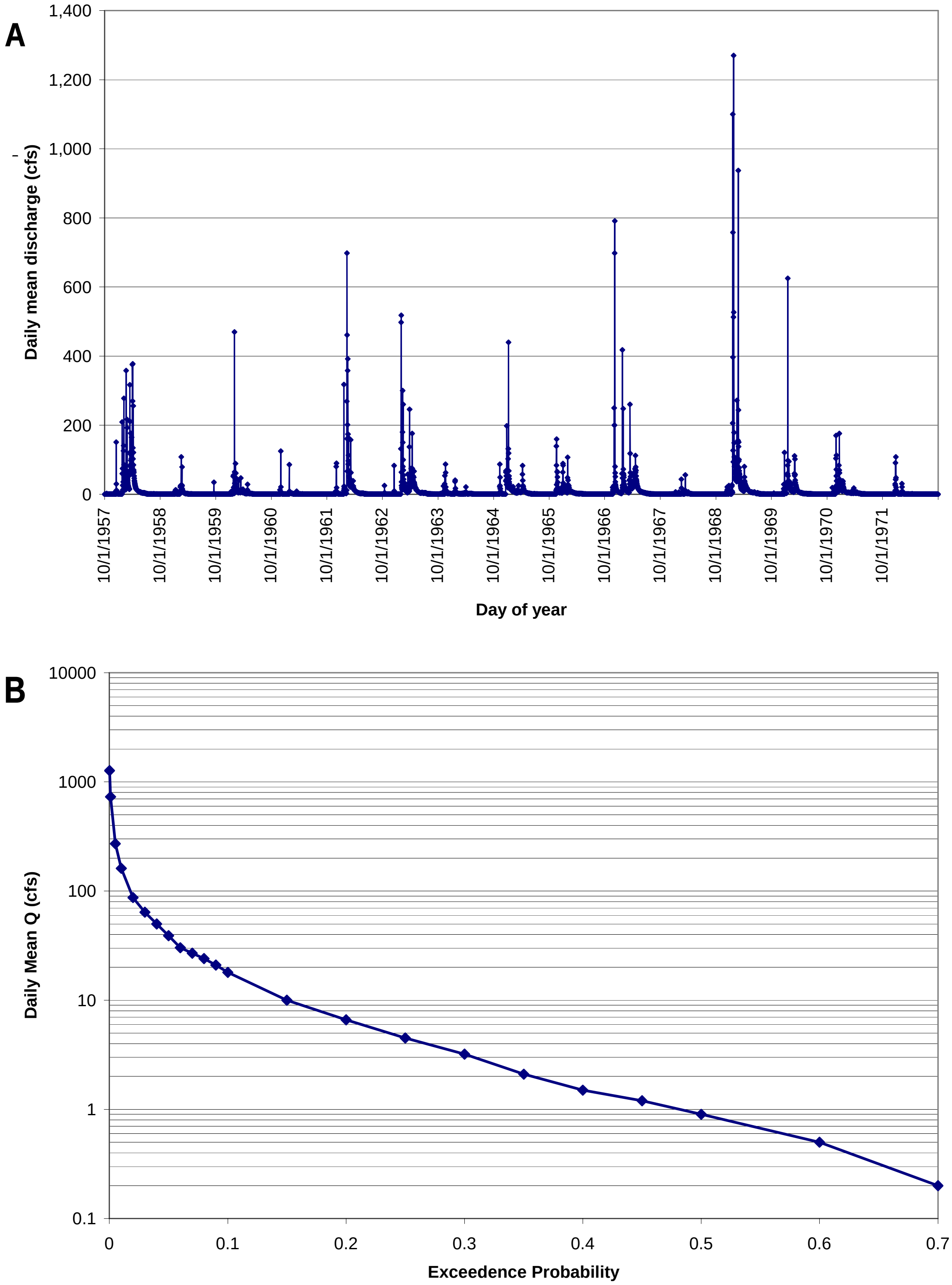


Figure 4-3. Daily mean discharge and flow duration curve for Santa Rosa Creek at Cambria, CA (USGS gauge 11142200).

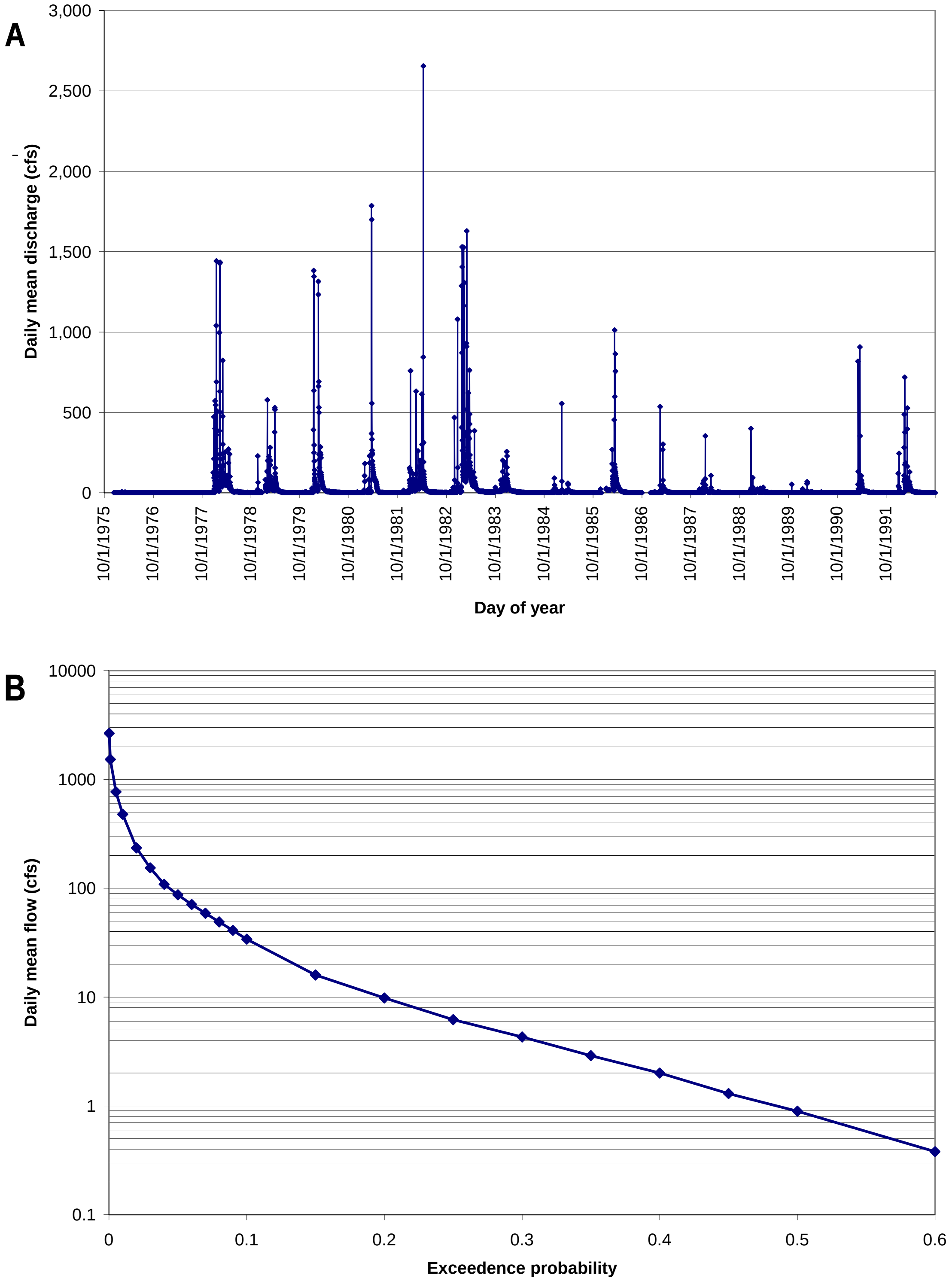


Figure 4-4. Daily mean discharge and flow duration curve for Santa Rosa Creek at Highway 1 bridge (SLO County Station 16).

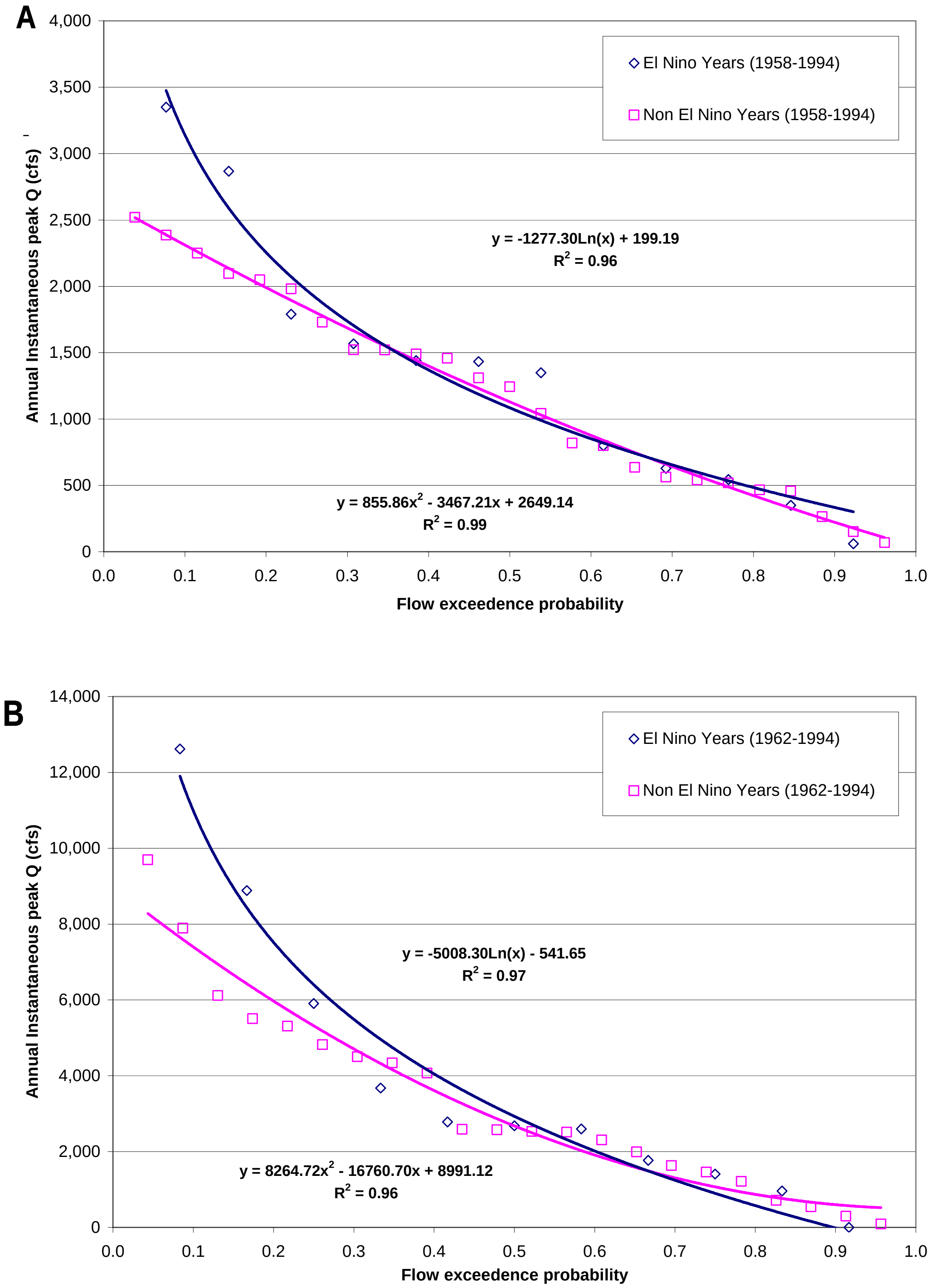


Figure 4-5. Flow exceedance in El Niño/non-El Niño years at (a) Santa Rosa Creek at Cambria (USGS gauge 11142200: WY 1958–1994) and (b) Santa Rosa Creek at Highway 1 bridge (SLO County Station 16: WY 1962–1994).

4.3 Creek Morphology and Sediment Character

Understanding the character of the creek morphology and its sediment is a fundamental component in understanding how fluvial processes will affect the creek, the likely extent and availability of aquatic habitat for native fish, the extent of human impacts on the creek, and should be used to condition appropriate management actions into the future (e.g., Downs and Gregory 2004). Below, we summarize conditions in mainstem Santa Rosa Creek, and in the Perry Creek subwatershed, based on available data and field reconnaissance of Santa Rosa Creek conducted during summer 2009. Time and access constraints prevented a comprehensive survey of Perry and Green Valley creeks and so our results focus on the Santa Rosa Creek mainstem, as the primary fish-bearing creek in the watershed. The field investigation entailed traversing the channel, interpreting channel conditions, assessing bed sediment facies (i.e., areas of similar sediment sizes), taking field measurements at representative channel locations within each reach, and using the field evidence to evaluate the relative input of fine and coarse sediment from tributaries. Measurements included median bed surface particle size counts (Wolman pebble-count method [1954]) at select locations and estimates of bankfull channel dimensions, channel gradient, bank and channel substrate, and channel erosion dynamics. Particle-size distribution data were used to corroborate sediment facies delineation. The channel erosion assessment included estimates of both bank and bed erosion, where the extent of recent bank erosion was determined by considering bank retreat relative to estimated tree age for exposed roots on the adjacent floodplain, and the amount of recent bed erosion, or channel incision, was estimated relative to the age of bank and in-channel vegetation. A full description of the geomorphic character of various reaches of Santa Rosa Creek is provided in Appendix C, with a summary provided below.

4.3.1 Santa Rosa Creek

Mainstem Santa Rosa Creek flows for approximately 25.4 km (15.8 mi) from its headwaters in the Santa Lucia Range, through the town of Cambria, to the creek mouth at the Pacific Ocean. The upper reaches are characteristic of a mountain river, with a steep gradient channel and strong bedrock control on channel form; while the middle and lower reaches display the features of a classic alluvial channel, with a lower gradient channel that meanders through deposited alluvium. The watershed is asymmetrical, with all of its major tributaries draining from the north into the creek and the valley floor set to the southern boundary of the watershed. Throughout the mainstem channel, morphology and geomorphic character are strongly impacted by the degree of channel confinement—that is, the ratio of channel width to the overall valley floor width (Montgomery and Buffington 1997). The mainstem channel transitions from a moderate to highly confined channel in the watershed upstream of Mammoth Rock to a low to moderately confined channel in the middle reaches (Mammoth Rock to the Perry Creek confluence) to a moderately confined channel in the lower watershed from the Perry Creek confluence to the river mouth (Figure 4-6). In long profile, the channel is gently concave on average, with local gradients ranging from approximately 0.0320 (3.2%) near the creek's headwaters to 0.0030 (0.3%) near the river mouth (Figure 4-6). The average gradient is approximately 0.0090 (0.9%). The creek transports a mixed sediment load ranging in size from silt/fine sand to boulders, with the dominant sediment bed particle size ranging from very coarse cobble in the upper reaches to fine gravel in the lower reaches. Bed texture and sediment transport dynamics within the mainstem Santa Rosa Creek are strongly influenced by the size and amount of sediment delivered from several tributaries, including Lehman, Curti, and Perry creeks. Processes in the creek vary according to a combination of local and regional factors. Locally, hydraulic controls exert influence on the dynamics of erosion and deposition according to features such as bedrock exposures, the presence of large woody debris (LWD) and in-channel infrastructure. Regionally, processes are influenced by factors such as the degree to which the valley is confined by bedrock control and the extent to which the channel is incised into its alluvial floodplain.

Based on the field data, the Santa Rosa Creek mainstem was delineated into nine reaches that are relatively homogenous with regard to their morphology and dominant geomorphic processes (Figure 4-6). Delineation provides an effect means of collapsing the complexity of real world differences in reach character into a manageable set of discrete occurrences. The reaches range from 1.8–3.3 km in centerline length and were divided where there was evidence for a distinct break in reach character. Delimiting criteria include tributary junctions where the tributary provides considerable flow and sediment input, abrupt changes in channel gradient, changes in the degree of valley confinement or channel incision, and influence of human influences such as roads that impinge on the active channel meander zone or part channel management activities. Key geomorphic attributes of the reaches determined from the field effort are summarized in Table 4-2.

Table 4-2. Mainstem Santa Rosa Creek reach attributes.

Zone	Reach	Channel length (km) [A]	Degree of confinement [B]	Channel gradient [C]	Bankfull width estimate (m)	Bankfull depth estimate (m)	Dominant sediment facies [D]
Upper	U1	2.5	High	2.29%	8–10	0.75–1.0	BGC
	U2	2.1	High	1.17%	12–14	0.75–1.0	CG
	U3	3.3	Moderate	1.16%	11–15	1.0–1.25	CG
	U4	1.8	Moderate	1.20%	11–12	1.0–1.25	CG
Middle	M1	2.0	Low	0.80%	Unknown [E]	Unknown [E]	CG [F]
	M2	2.4	Moderate	0.62%	12–14	0.75–1.0	CG
	M3	2.4	Moderate	0.75%	9–11	1–1.25	CG
Lower	L1	2.9	Moderate	0.33%	12–19	1.0–1.25	CG SG
	L2	2.1	Moderate	0.29%	20–22	1.25–1.5	SG

[A] Channel length measured from the centerline derived from the USGS 10-m DEM of the watershed.

[B] Confinement estimated from a combination of field observations and the USGS 10-m DEM of the watershed.

[C] Channel gradient derived from the USGS 10-m DEM-derived channel centerline.

[D] Facies designation from the approach developed by Buffington and Montgomery (1999). The dominant sediment size is listed last and the subdominant sediment sizes are listed first. BGC = boulder-cobble-gravel (gravel constitutes >50% of the sediment and boulder and cobble each constitute ≥5%), CG = cobble-gravel (gravel constitutes >50% of the sediment and cobble constitutes ≥10%).

[E] Measurements not taken due to restricted channel access.

[F] Estimated from Santa Rosa Creek Road.

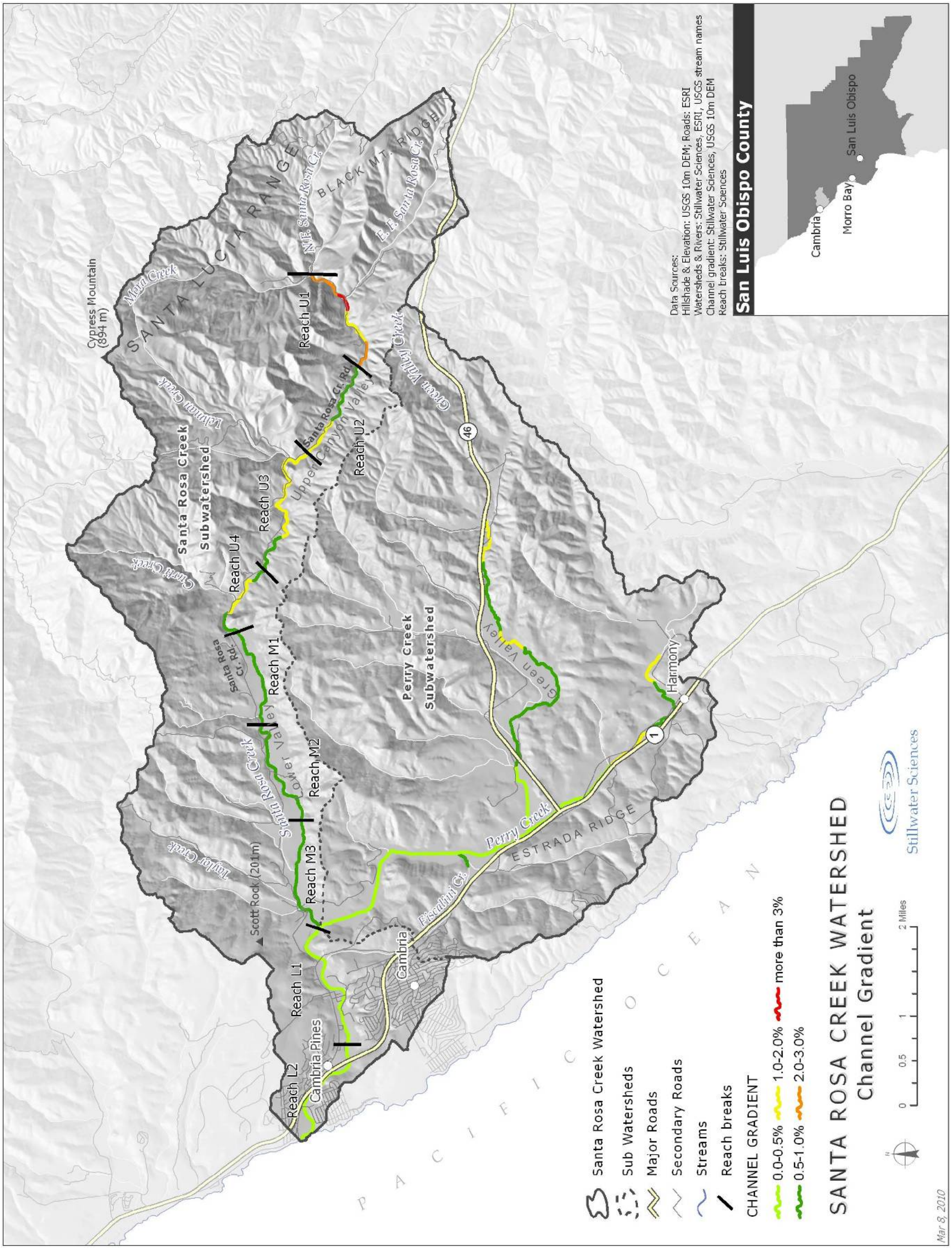


Figure 4-6. Channel gradients of Santa Rosa, Perry, and Green Valley creeks. Study reaches of Santa Rosa Creek are also shown.

Within the upper reaches, the channel transitions from a plane-bed morphology in the steeper, more confined reach U1 to a pool-riffle morphology in the lower gradient, less confined reaches U2—U4 (Figure 4-7a). Bedrock exerts a strong control on channel morphology throughout all reaches within this zone. The channel bed within these upper reaches is interpreted as being from quasi-stable to somewhat subject to deposition, due to a combination of bedrock control on depositional dynamics and relatively high tributary sediment inputs, particularly from Lehman Creek (entering U3) and Curti Creek (U4). The middle reaches transition from a highly incised reach with active bank erosion and high sediment input (M1) to a moderately incised and apparently less dynamic reach M3) as the degree of channel confinement increases and bedrock control once again becomes an influence near the confluence with Perry Creek (Figure 4-7b). The channel bed possesses a pool-riffle morphology and has several reaches showing evidence of sediment stored following recent flood events. In the lower reaches, both channel gradient and the degree of incision decrease and the channel becomes part of a more depositional zone with a channel gradient ultimately controlled by mean tidal elevation in the lower parts of reach L2. Sediment delivered to the lower subreaches from upstream Santa Rosa Creek, the Perry Creek subwatershed, and from local tributaries has resulted in a large amount of stored sediment in the reach which reduces the occurrence of channel bedforms (Figure 4-7c). Banks are relatively stable, not least where extensive riprap protection exists in reach L1. A recent channel erosion inventory conducted by the CDFG (Nelson et al. 2009) shows that bank erosion is most prevalent in the lower gradient (i.e., local channel slope ≤1%) upper and middle reaches (Figure 4-8).

Bed sediments along the mainstem Santa Rosa Creek ranges from boulder-cobble-gravel (BGC) with a median particle size (D_{50}) of 64–128 mm in the upper reaches to sand-gravel (SG: D_{50} of 4–8 mm) in the lower reaches. The bed is predominantly composed of cobble-gravel (CG: D_{50} of 16–32 mm) in the Middle reaches (Table 4-2; Figure 4-9). From our limited sampling, the measured median grain size, D_{50}, in mm, decreases downstream in almost direct proportionality with the drainage area, Ad, as $D_{50} = 1510\ Ad^{-1.0}$ ($r^2 = 0.69$). The size difference between channel bed and adjacent bar sediment as well as the degree of sediment sorting (or, range of sediment sizes) varies considerably along the length of the mainstem channel due in part to local hydraulic controls on sediment transport and deposition dynamics and the size of sediment derived from local and upstream sediment sources. Coarse sediment (gravel and larger) delivered to the mainstem Santa Rosa Creek appears to be delivered primarily from Lehman and Curti creeks in the upper reaches, and from the tributary that runs adjacent to Main Street (Unnamed Tributary SRC-6) in the lower reach (see Figure C-1 in Appendix C – Channel Reach Descriptions). Fine sediment (sand and silt) appears to be predominantly derived from both tributary sources such as Curti Creek that delivers sediment to the upper reach and Perry Creek that delivers sediment to the lower reach, and local in-channel sources such as bank erosion of the high bluffs at the upstream end of the middle reaches.

Figure 4-7a. Views of reaches U1, U2, U3, and U4 along upper Santa Rosa Creek**.**

Figure 4-7b. Views of reaches M1, M2, and M3 along middle Santa Rosa Creek.

Figure 4-7c. Views of reaches L1 and L2 along lower Santa Rosa Creek.

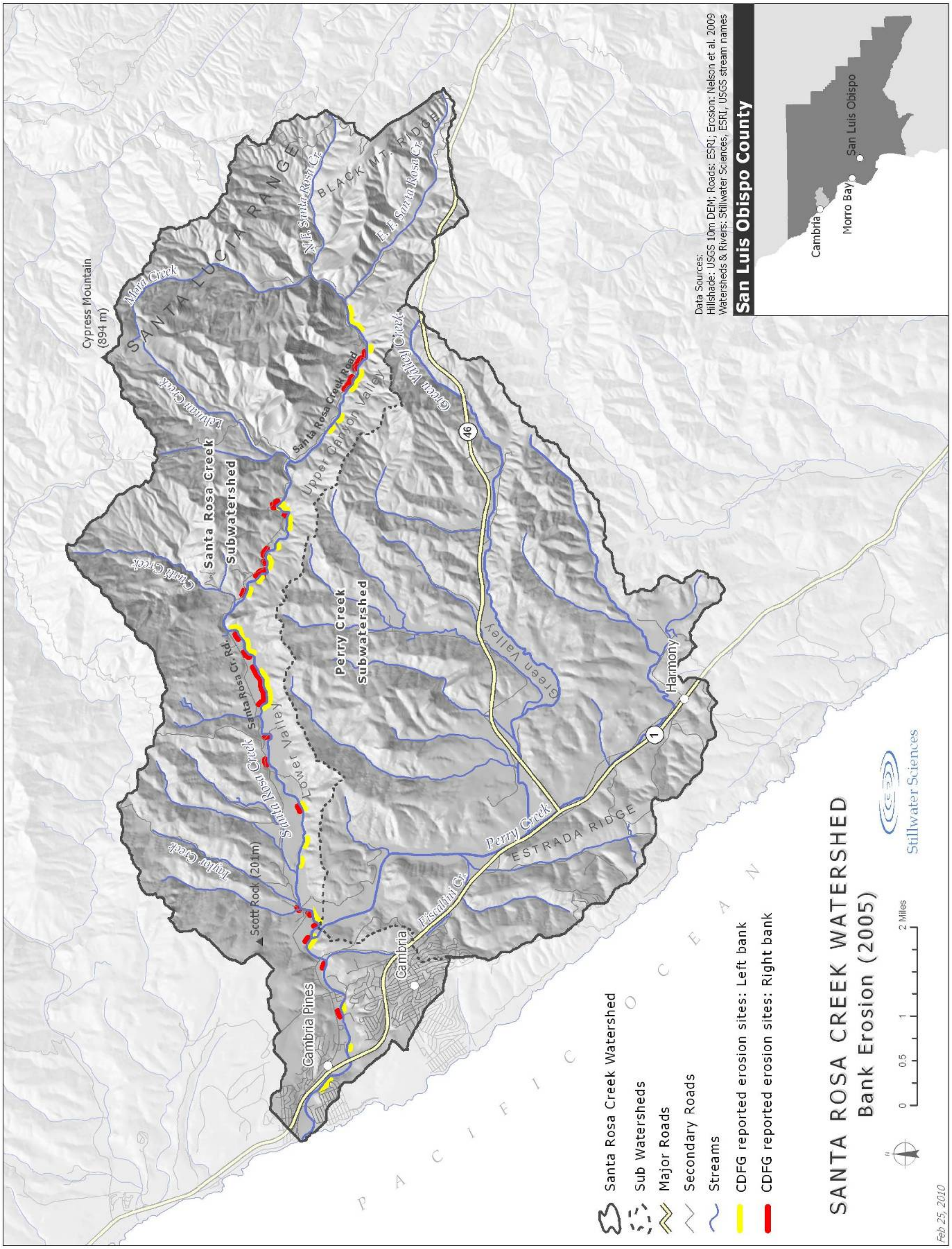


Figure 4-8. Bank erosion along Santa Rosa Creek observed by CDFG in 2005 (after Nelson et al. 2009).

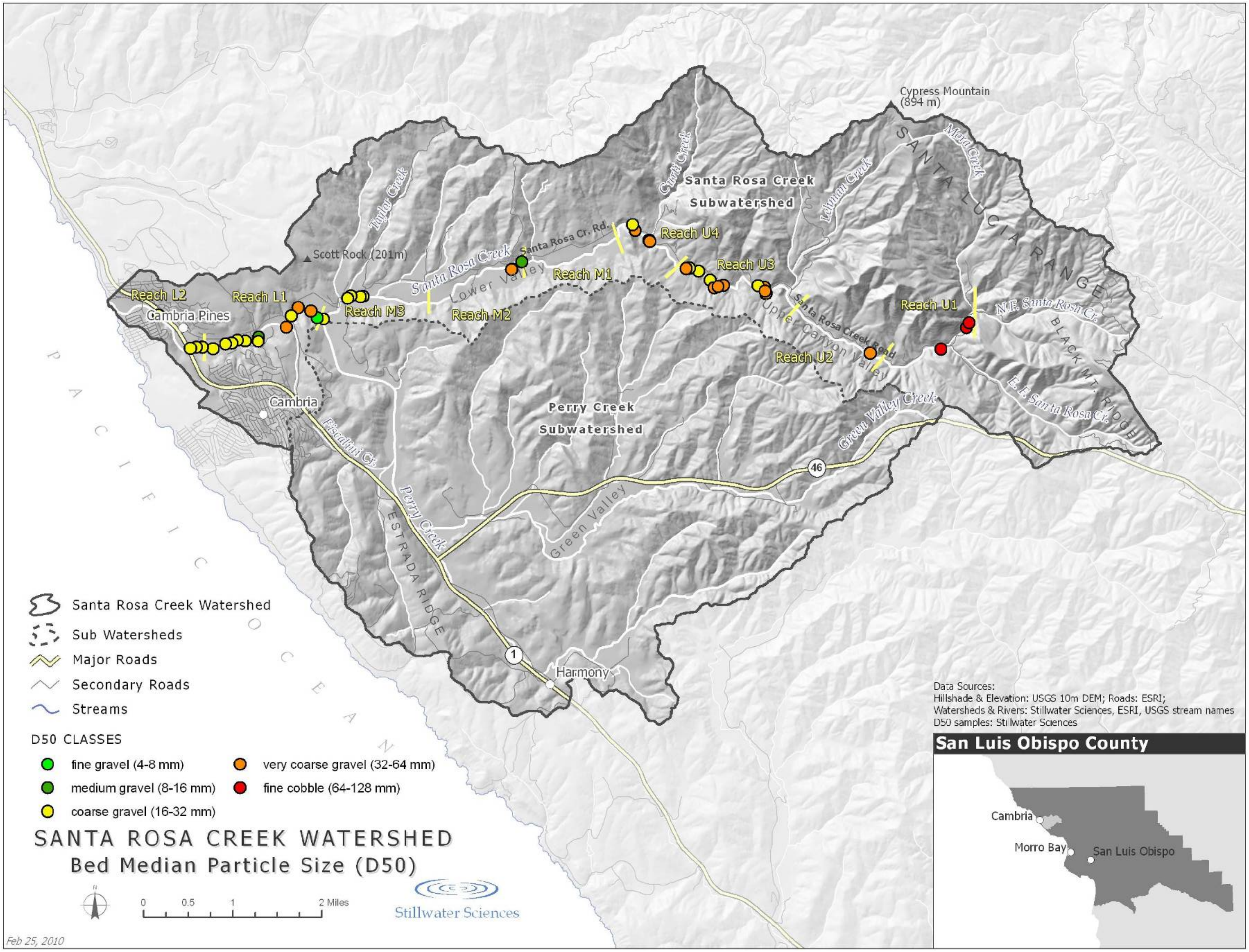


Figure 4-9. Median bed particle size (D_{50}) along the mainstem Santa Rosa Creek.

4.3.2 Perry Creek

Perry Creek enters mainstem Santa Rosa Creek approximately 3 km (1.8 mi) upstream of the Highway 1 bridge and is the largest tributary comprising almost 50% of the overall Santa Rosa Creek watershed (drainage area = 59.3 km^2; 22.9 sq. mi). Perry Creek is characterized by a moderately confined channel with finer bed sediment that flows approximately 16 km (10 mi) from the town of Harmony downstream to the confluence with Santa Rosa Creek. The channel transitions from an actively meandering planform in the upper reaches to a straight-cut planform that extends for the majority of the channel length downstream from Harmony. Channel straightening occurred in two phases, first, related to the draining of Estrada Lagoon in the 1870s to form Lower Perry Creek and then further modifications during the improvements of Highway 1. The degree of channel incision increases downstream, reaching a maximum of approximately 8–10 m (26–33 ft) at the Santa Rosa Creek confluence: incision reduces upstream from the confluence until it reaches an abrupt knickpoint (i.e., distinct break in the channel gradient) approximately 0.6 km (0.4 mi) upstream. Perry Creek has a consistently low gradient along the entire length (average gradient is less than 0.005 [0.5%] (Figure 4-6). The creek transports a mixed sediment load skewed toward finer sediment that includes silt/fine sand to fine cobbles, with the dominant sediment bed particle size ranging from coarse gravel in the upper reaches to fine gravel in the lower reaches.

The major tributary of the Perry Creek subwatershed is Green Valley Creek, which enters Perry Creek approximately 5 km upstream from Santa Rosa Creek confluence. Green Valley Creek originates in the steep, south-facing hillslopes along Highway 46, flows west through a confined alluvial valley, and enters Perry Creek in a broad alluvial zone near to Highway 1. Like the Santa Rosa Creek subwatershed, the Green Valley Creek subwatershed is also highly asymmetrical with long, steep tributaries draining from the northern edge of the watershed south into the west flowing Green Valley Creek. From limited field observation and available data, the upper reaches of mainstem Green Valley Creek appear somewhat similar to the upper reaches of Santa Rosa Creek in terms of valley confinement, but unlike Santa Rosa Creek, Green Valley develops a very wide alluvial valley through its middle and lower reaches. The sediment load includes silt/fine sand to boulders, with the dominant sediment bed particle size ranging from medium gravel in the upper and lower reaches to very coarse gravel in the middle reaches. The middle reaches are highly incised and actively eroding their banks with the amount of incision decreasing as the creek approaches the Perry Creek confluence. The middle and lower reaches are primarily low gradient, with an average channel gradient less than 0.01 [1%] (Figure 4-6).

4.4 Dynamics of Channel Morphology and Sediment Transport

This section extends the section above to describe the morphological dynamics of the creek network using historical data, measures of the potential for sediment transport, and our understanding of the history of direct and indirect human impacts on the creek to determine how and potentially why the creek has changed in the recent past. Understanding historic changes in channel morphology can be important in determining the expected future conditions as the channel morphology evolves. Determining which reaches have been relatively static and which are highly changeable is useful information, especially if the changes can be linked to watershed perturbations such as major storm events, changes in sediment and/or water inputs, or management modifications of the channel. Such information is a critical component in developing a watershed management plan that accounts for both natural geomorphic variability and the short- and long-term impacts of restoration actions.

4.4.1 Recorded changes in channel planform, 1937-2007

Various channel morphologic characteristics, including channel centerline location, channel sinuosity, and channel width were compared over the past 70 years (the limit of available historic sources). Data sources included orthorectified topographic maps from 1937, 1948, and 1959, and aerial photography from 2007. Examination of changes in channel-bed elevation along mainstem Santa Rosa Creek, however, was precluded by lack of available data. The following sections discuss the differences in channel morphology and associated drivers for geomorphic change, or lack of change, over the last several decades.

Comparing the 1937 to 2007 channel centerline reveals a relatively modest degree of channel planform change over the past 70 years within the upper (U1–U4) and lower reaches (L1–L2) of Santa Rosa Creek (Figure 4-10). Conversely, the middle reaches (M1–M3) experienced considerable planform change and channel adjustment, expressed by significant increases in channel sinuosity (Table 4-3). These recorded changes in the middle reaches took place largely during a reasonably static period in land use history (see Section 2), but during a period that encompasses large flood flows resulting from the relatively intense ENSO period since 1969 (see Section 4.1).

Table 4-3. Channel sinuosity change by reach (1937–2007).

Zone	Reach	% change in channel sinuosity (1937–2007)
Upper	U1	+1.2%
	U2	+2.1%
	U3	+2.2%
	U4	+0.5%
Middle	M1	+8.6%
	M2	+17.9%
	M3	+8.3%
Lower	L1	-0.3%
	L2	+4.2%

Within the Upper reaches, the relative lack of change in observed centerline location, sinuosity, and channel width from 1937 to 2007 is likely due to the relatively high degree of channel confinement caused by extensive bedrock controls that limit channel migration (Table 4-3; Figure 4-10a, b). A small amount of sinuosity increase did occur in the mid-upper reaches (U2 and U3) and is interpreted to reflect the somewhat lower degree of channel confinement in these reaches. Reach U4 had the lowest overall amount of change in channel planform, but significant channel change did occur in several locations including downstream near Mammoth Rock where a channel meander migrated downstream over 50 m (165 ft) over the 70 years.

In the middle reaches downstream of Mammoth Rock to the Perry Creek confluence, valley confinement gives way to a broad alluvial valley setting in which the channel has been very active over the past 70-years (Table 4-3; Figure 4-10b, c). The channel centerline position shifted up to 50 m towards the opposite bank in several locations and channel width increased by over 50 m at the meander just downstream of Mammoth Rock. The active meandering has resulted in a considerable increase in channel sinuosity throughout the Middle reaches (Table 4-3) but especially in reach M2 where the sinuosity increased by 18%. Increased sinuosity reflects a lengthening of the channel and a decrease in channel slope suggesting the channel is trying to "recover" from a severe disturbance (e.g., Schumm et al., 1984; Simon 1989; Hupp and Simon 1991). This interpretation is given extra credence because of the incision of the middle reaches from the original floodplain surface, which is now commonly over 6.1 m (20 ft) above the channel bed. The most likely explanation is that increases in flow resulting from land clearance in the Nineteenth century caused the significant incision and the channel is now attempting to gain a new energetic "equilibrium" with its surroundings by developing a new inset floodplain and a more gentle channel gradient. A conceptual model of this channel evolution process, as developed by Hupp and Simon (1991), is shown in Figure 4-11 to help illustrate the likely evolution and trajectory of Santa Rosa Creek.

In the lower reaches downstream of the Perry Creek confluence, the channel is subject to increased confinement again as a combination of valley topography and, more recently, utilization of floodplain for the urban growth of Cambria, enlargement of Highway 1, and related bank protection efforts. Therefore, a narrower meander zone exists with less opportunity for centerline movement than in the middle reaches, but there are local areas of channel widening, centerline migration, and increased sinuosity towards the downstream end (Table 4-3; Figure 4-10c). For instance, within a relatively unconfined area just downstream of the Highway 1 bridge (which was not present in 1937), the channel widened by approximately 20 m and the centerline location shifted approximately 50 m towards the opposite bank. This channel widening may be associated with a depositional zone caused by flow expansion downstream of the bridge during large flood events.

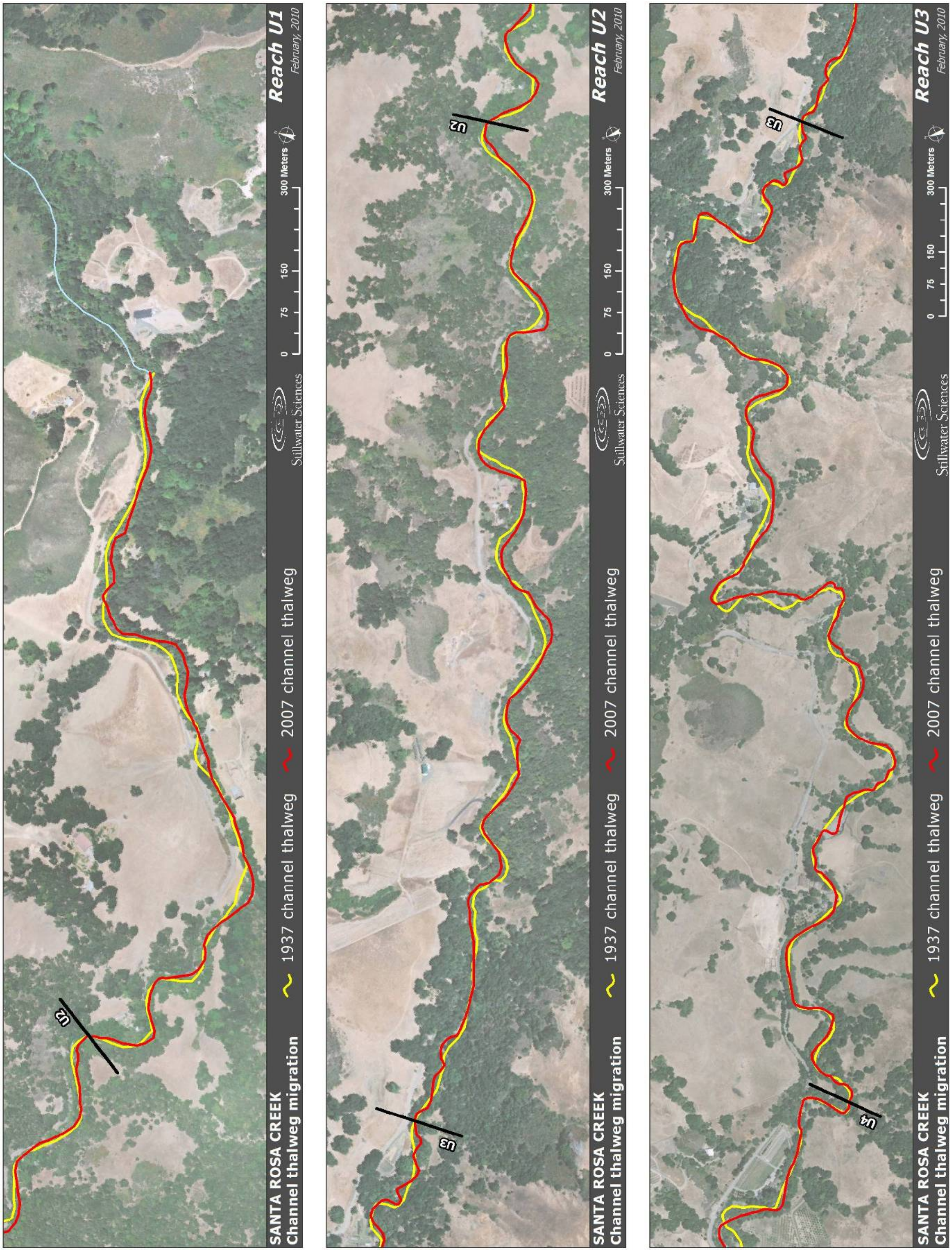


Figure 4-10a. Santa Rosa Creek centerline migration 1937–2007—Reaches U1, U2, and U3.

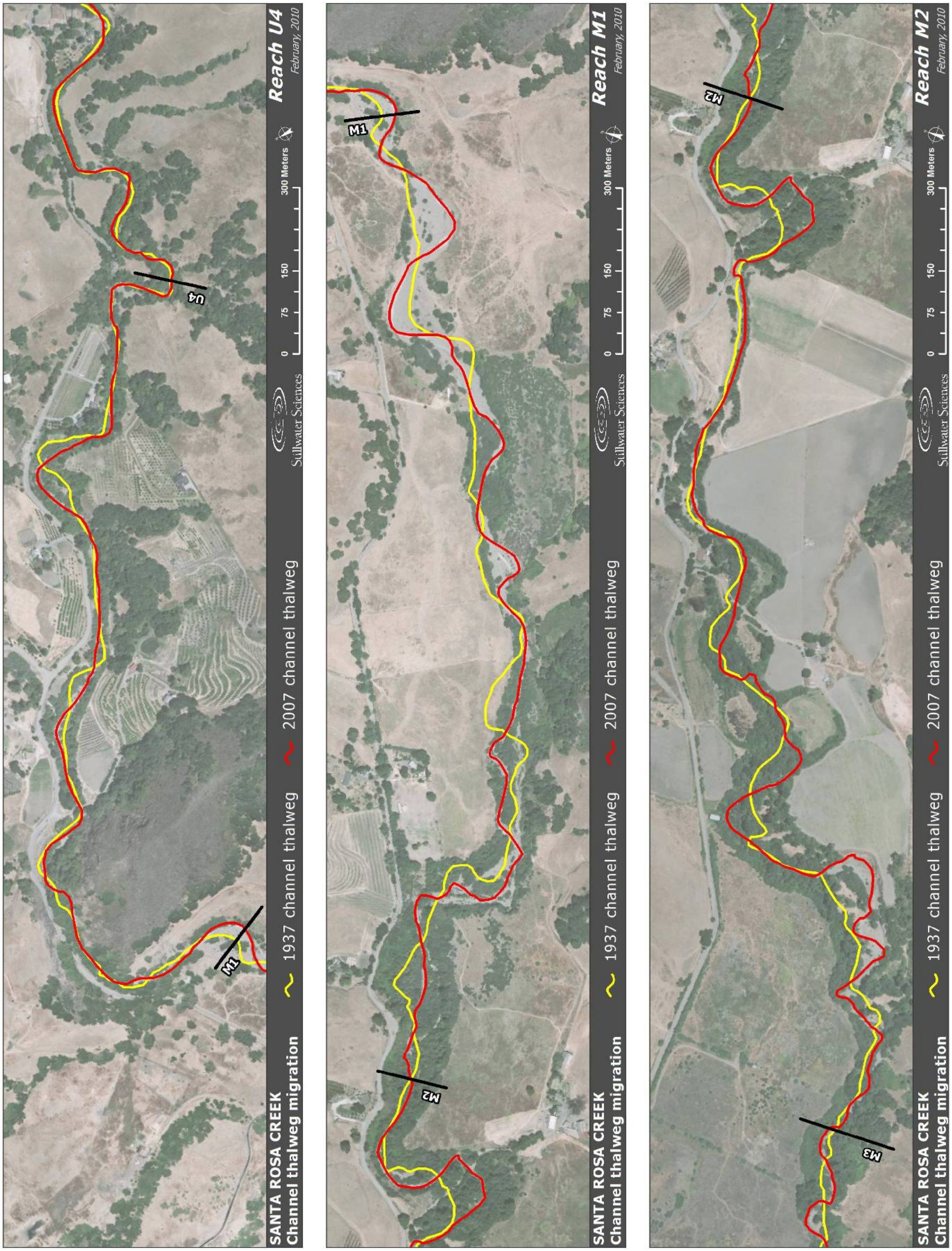


Figure 4-10b. Santa Rosa Creek centerline migration 1937–2007—Reaches U4, M1, and M2.

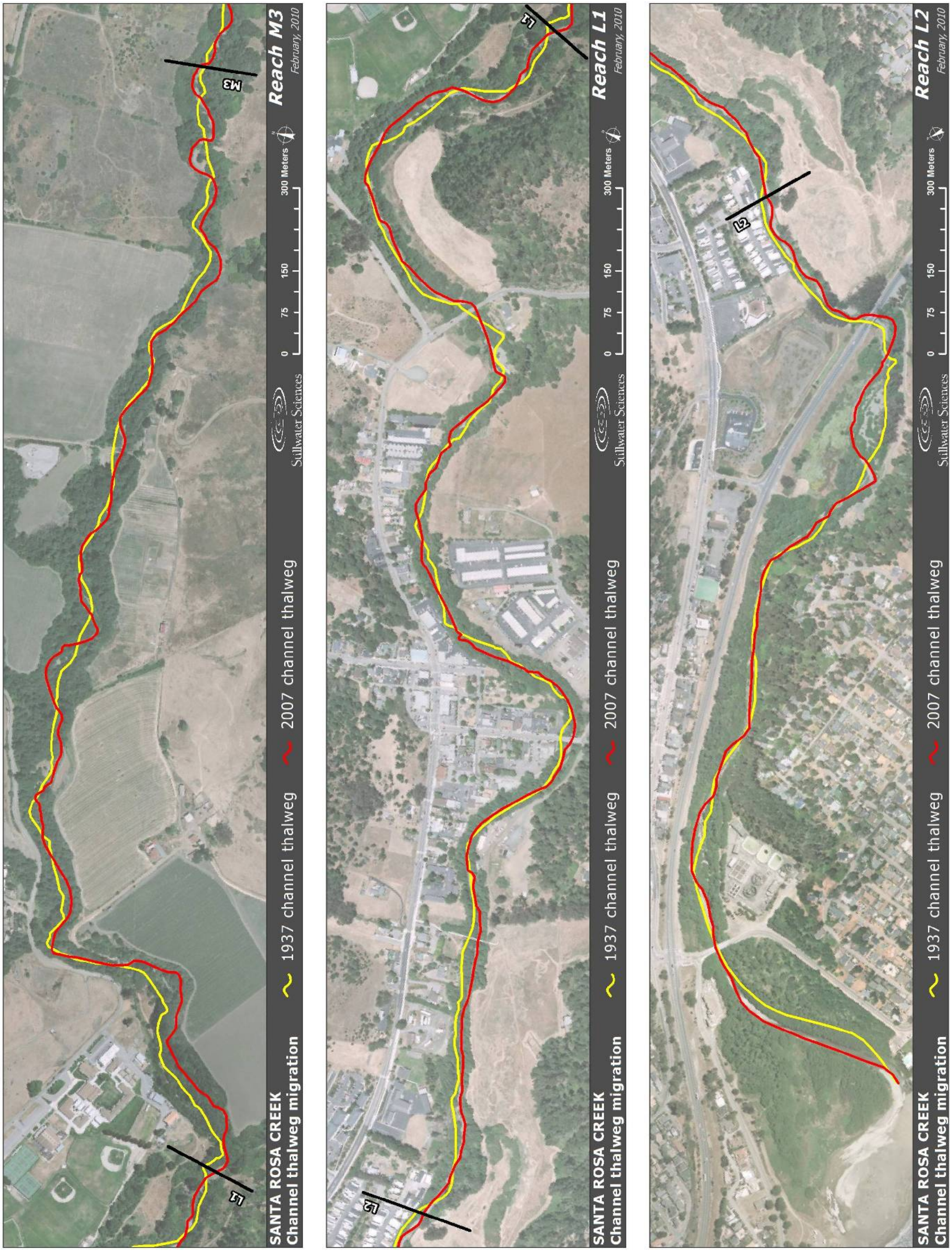


Figure 4-10c. Santa Rosa Creek centerline migration 1937–2007—Reaches M3, L1, and L2.

Stage 1:
Undisturbed

Stage 2:
Channel disturbance
(channelization, riprap, changes to runoff patterns in drainage network)

Stage 3:
Degradation
(channel bed incision)

Stage 4:
Degradation and widening

Stage 5:
Aggradation and widening

Stage 6:
Quasi-equilibrium
(channel re-adjustment)

Stage 7:
Late stage/evolution

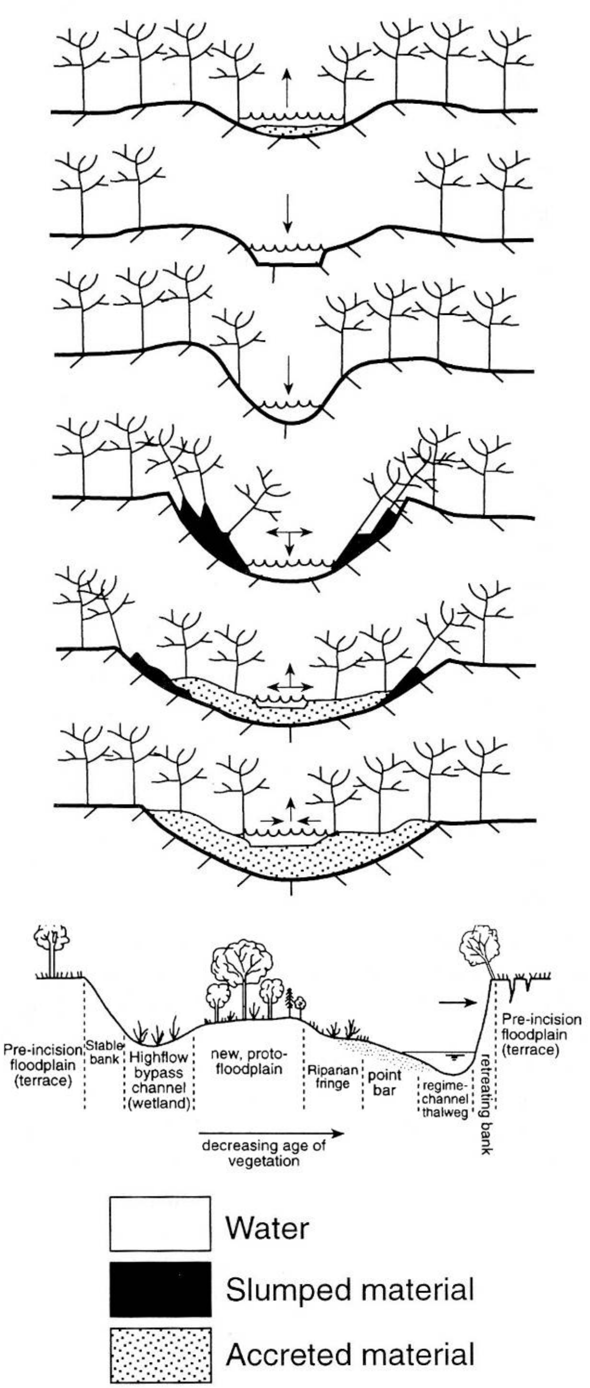


Figure 4-11. Conceptual model of channel evolution following watershed disturbances, such as channelization or incision. Arrows indicate the direction of degradation or aggradation (reprinted from Simon and Hupp [1986] and Hupp and Simon [1991], Copyright ©1991, Elsevier Science).

4.4.2 Potential for future change and sediment transport

Analysis of changes in channel morphology, as permitted by available data, indicated a combination of local changes in individual bends of the river in combination with more extensive alternations in the middle reaches of the river over the past 70 years. However, it is also apparent from reconnaissance surveys that large sections of the creek are significantly incised in character, indicative of a response to a strong perturbation in watershed conditions. Like many other creeks, there is insufficient channel bed survey data available to understand quite how bed elevations have changed over time, preventing a simple extrapolation of how the channel may change in the future. As a surrogate, several indices reflecting the channel's *potential* for change were estimated from collected field data, and compared against expected or threshold values as the basis for inferring the potential for change.

One index for reach-level potential for morphological change is unit stream power. Unit stream power is the energy available per unit area of river bed to overcome friction and transport sediment. It can be used as a surrogate for potential sediment transport (e.g., Bagnold 1966), but is more generally used to indicate the potential energy available to "do work" generally in the channel (Bull 1979), with higher stream power indicative of channels more likely to change their form (Richards 1982, Graf 1983). Stream power is usually reported per unit area of the channel bed ("specific stream power", Wm^{-2}, commonly given the symbol ω) and is proportional to the channel gradient and the discharge per unit of channel width (e.g., cubic meters per second per meter of channel width). Because normalization of discharge by channel width reduces the significance of downstream increases in discharge, the unit stream power in steep watersheds varies largely with channel gradient and this is witnessed in Santa Rosa Creek where our estimated relationship with drainage area (*Ad*) is:

$$\omega = 3128.7\, Ad^{-0.7026} \qquad (r^2 = 0.70)$$

Consequently, results range from approximately 500 Wm^{-2} upstream to 135 Wm^{-2} downstream (Figure 4-12). The highest stream power occurs in the upper reaches (200–500 Wm^{-2}) with similar ranges in the middle and lower reaches (135–300 Wm^{-2}). The results are indicative both of a significant reduction in the downstream ability to do work, which is consistent with the notion of creeks eroding material in their upper reaches and then depositing some of it in their lower reaches, but also of a highly dynamic channel overall. In comparison with a study made for various channel settings in Australia (Nanson and Croke 1992), the results represent a high (>300 Wm^{-2}) or medium-high (50–300 Wm^{-2}) energy floodplain setting. In lowland settings, a value of 35 Wm^{-2} has been used to indicate "active" channel environments (Brookes 1990) whereas low energy channels general subject to deposition are general represented by values of unit stream power below about 10–15 Wm^{-2} (Brookes 1990; Nanson and Croke 1992). Clearly, in comparison, Santa Rosa Creek is a highly dynamic stream channel.

Related more directly to the ability to transport sediment, we also calculated the shear stress of flows at bankfull discharge relative to the shear stress required to move the median-sized bed particles at this flow. By definition, "bankfull discharge" refers to the discharge required to fill a stream channel in equilibrium with the surrounding landscape to the point at which flow starts to overtop the banks; statistically, this flow event has a return period of 1.5-2 years (Williams 1978). In incised channels, such as the lower parts of Santa Rosa Creek, it takes a much larger discharge (i.e., far in excess of 1.5-2 year return period) to overtop the banks but the 1.5-2 year return period discharge is still called the bankfull discharge to allow comparibility between streams. Shear stress (Nm^{-2}) is a measure of the force acting parallel to the bed of the creek; that is, the force generated by moving water that is available to overcome forces of friction and gravity that keep bed material particles in place on the bed of the creek. The critical shear stress is the exact measure of shear stress needed to cause the median particle size to become mobile. If the ratio of shear stress at bankfull flow to critical shear stress exceeds unity, then bed particles are likely to be in transport at bankfull and higher flows.

Based on our available data, the shear stress ratio at nine sites varied between 3 and 16, indicating that the bed of Santa Rosa Creek is highly mobile even in flood events that occur with a recurrence interval of two or less years (Figure 4-12). While the sample set is relatively small, it is notable that the range in shear stress ratios increased downstream (upper reaches: 3.2 – 4.8; middle reaches: 3.5 – 7.5; upper reaches: 3.8 – 16.3) perhaps indicating the progressive input of excess fine sediment into the fluvial system. Certainly the highest ratio (16.3) occurs in finer-grained material just downstream of the Perry Creek confluence which is suspected of supplying high volumes of fine sediment. Overall, we can conclude, therefore, that during large flood events, such as those that frequently occur during ENSO years, Santa Rosa Creek is probably capable of transporting large volumes of sediment along its bed (coarse sands, gravel, and cobbles) and in suspension in the water column (silts, clays, and fine sand). The shear stress values are sufficient also to erode the bed and banks in those reaches of the creek not controlled by bedrock or bank revetments.

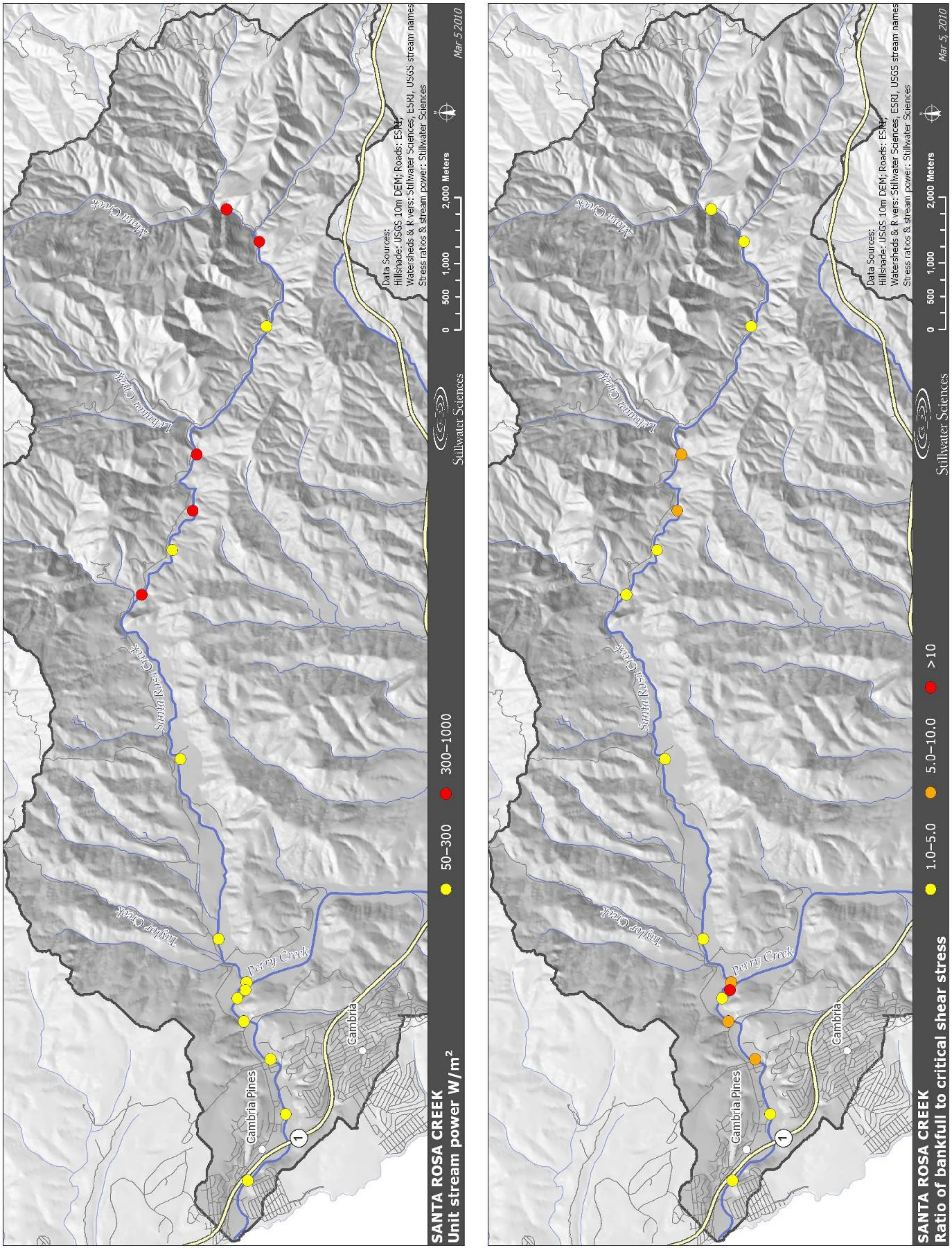


Figure 4-12. Calculated unit stream power and the ratio of bankfull to critical shear stress in Santa Rosa Creek.

4.4.3 Inference of human impacts

Like all watersheds, stream channel morphology and process in Santa Rosa Creek and its tributaries is influenced by a combination of natural and human factors. The human factors, especially land cover changes and near- and in-channel infrastructure, frequently create the challenges facing contemporary river channel management. Further, because geomorphological systems change over multi-decadal timeframes, creek morphology and process can still be influenced by factors that occurred many decades or centuries before, meaning that historical changes in land cover can still present issues for modern-day management.

4.4.3.1 Land cover change

From the chronology of watershed changes described in Section 2.1, and summarized in Figure 2-1, there are two time periods in recent history that likely had the greatest effect on watershed geomorphic processes.

The first was during the Nineteenth century, when Euro-American settlers moved to the watershed and progressively replaced native trees, shrubs, and grasses with non-native species less suited for preventing erosion. This period probably reached its peak during the period 1860 – 1880 as the watershed became more densely settled and developed with more intensive agricultural practices, accelerated logging rates, mercury mining, and associated expansion of road and urban infrastructure. It is apparent from historical sketches that as early as the 1870s the majority of this "first-wave" of land cover changes was complete (Angel 1883; see Figures A-3, A-4, and A-5). The impact of changes in the rainfall-runoff relationships caused by such land cover changes were probably magnified by the large California flood of 1862 (Engstrom 1996) followed by the devastating droughts of 1863 and 1864 and the increased storm activity of the 1880s. The overall result of land cover changes in addition to general soil erosion in the watershed was the development of an extensive series of gullies across the watershed that are still active today (see Figure 3-1).

The relative economic quiescence of the watershed from the 1880s until the 1950s means that land cover changes in this period were generally minimal (see comparative photographs from 1930 and 2009 in Figure A-6) and so influences on geomorphic processes during this period would have been largely restricted to legacy impacts resulting from earlier land cover changes, and changes to the character of farming, both again focused in wetter periods and large storm events (e.g., 1884–94, 1901–17, 1935–45).

Thus, the second period of land cover change that may have impacted Santa Rosa Creek watershed involves population expansion in the watershed from about 1950 into the mid-1990s. This period saw a 278% increase in the urban area of the watershed around Cambria (1959–1996: Table 2-2) which has had impacts on water abstraction rates in the watershed resulting in lower base flows and some subsidence during dry periods. However, because Cambria is near the mouth of the watershed, the geomorphic impacts of changes in runoff caused by urban development will have been focused in those lower reaches of the creek (e.g., reach L1 and especially reach L2) downstream of drainage outfalls. The other major land cover change during this period involved several changes to the road network within the watershed, particularly the improvement of Highway 1 and the construction of Highway 46, completed in 1974. The attendant need for an extensive series of fill embankments and cuttings for Highway 46 greatly increased rates of fine sediment input to Green Valley Creek during and shortly after construction, and has led to on-going problems of embankment and culvert-related erosion since (see Figure 3-1), as well as accelerating runoff into Green Valley Creek.

Overall, the two periods of intensive development will have both led to increased flashiness of flows, more rainfall entering the creek as runoff than from baseflow, and increases to the volume of sediment entering stream channels, especially fine sediment. In comparison, it is likely that land clearance for lumber and agriculture probably created more extensive geomorphic impacts, including the majority of the 1,048 gullies still in evidence across the watershed, whereas the impact of road and urban developments more recently will have preferentially impacted Green Valley Creek and the lower reaches of Perry Creek and Santa Rosa Creek.

4.4.3.2 Water-related infrastructure and anthropogenic channel modifications

While the impact of land cover changes on channel morphology and process is usually indirect, being transmitted through changes in rainfall-runoff relationships and sediment supply and texture, near- or in-channel infrastructure has the potential to directly modify geomorphic processes and channel morphology. Infrastructure involves physical features such as dams, roads, and bridges, and facilities related to water diversion and return. Channel modifications include straightening channels, construction of levees for flood control purposes, and bed and/or bank revetments as protection against bank erosion. Generally, these modifications are related to the development of floodplains including routing of roads near stream channels.

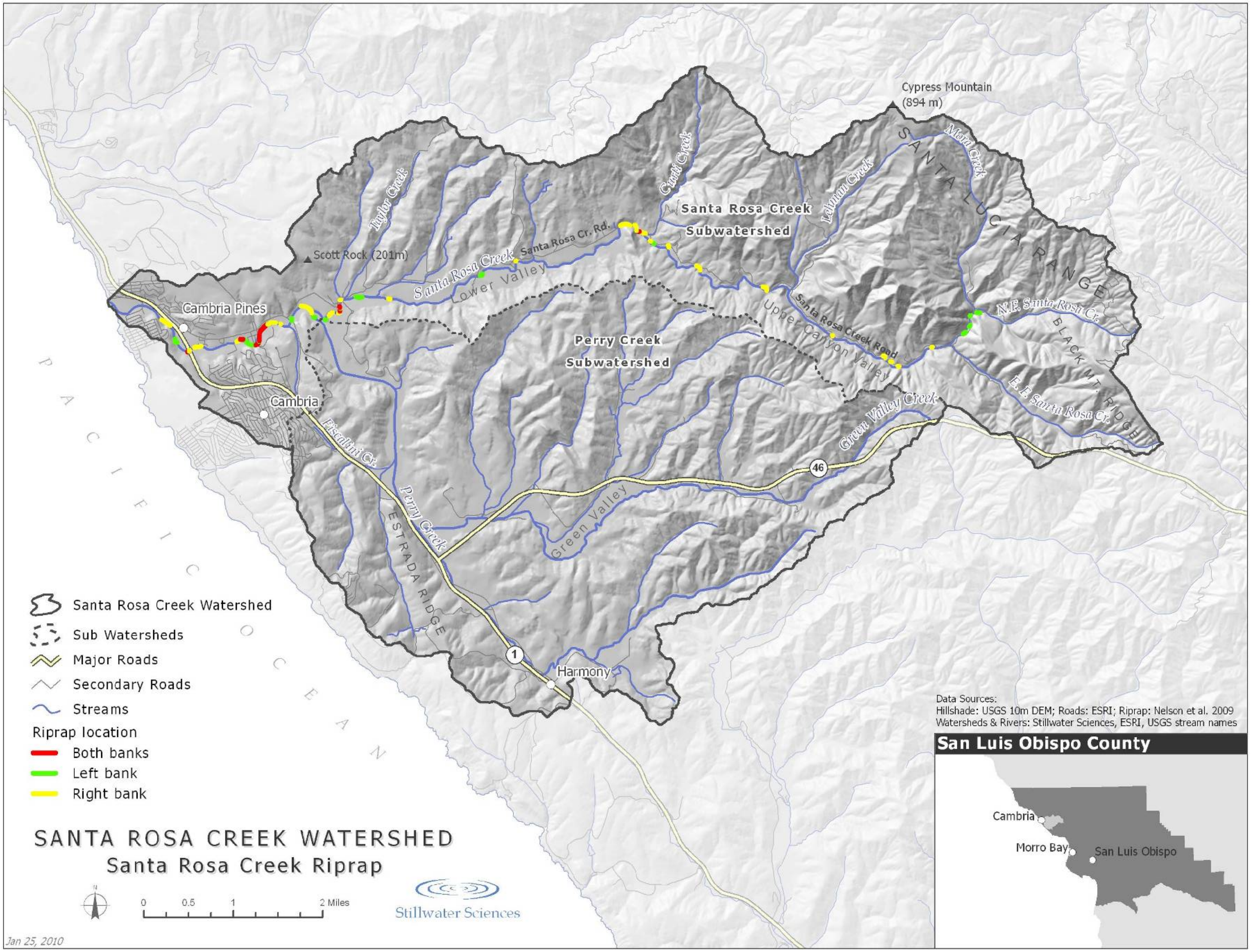
Much infrastructure in the watershed is related to creek crossings, and most of these are highlighted as potential fish passage barriers in Figure 1-5. Bridges and other crossings frequently cause hydraulic constrictions during high flow, which promote local geomorphic changes including sediment deposition upstream of the structure and erosion of the bed and banks of the creek downstream of the structure as flow accelerates. Likewise, when crossing structures are not built to grade seamlessly with the channel bed, similar impacts are likely. Both causes may result in a significant “step” in the channel bed thereby disrupting geomorphic processes locally (and can be an impediment to upstream fish passage). Along Santa Rosa Creek, no significant steps are known to occur; however, constrictions that limit sediment transport occur under most bridge crossings; the only remaining significant channel crossing is the Ferrasci Road bridge and fish ladder, which is currently being planned for removal in the near future.

In Santa Rosa Creek watershed, there is a concentration of road drainage and crossing-related impacts along Green Valley Creek as part of the Highway 46 construction in 1970s. Perhaps the greatest geomorphic impact has come from drainage modification approximately 5 km from the junction of Highways 1 and 46. At this location, road drainage is directed towards Green Valley Creek (outboard side of Highway 46) and towards a south-facing tributary (inboard side of Highway 46) (Figure 4-13). The south-facing tributary flow (including the inboard road drainage) is now diverted through a 7-ft culvert under Highway 46 near the historic tributary confluence (Figure 4-14). The increase in flow to Green Valley Creek at this location appears to have, at least in part, caused substantial downstream channel enlargement (i.e., bed incision and channel widening) in Green Valley Creek and erosion of the tributary channel downstream of the culvert. The impact appears to extend approximately 2 km downstream to where the channel gradient decreases, the channel width increases, and sediment deposition is observed to occur. Upstream of the road drainage and culvert, exposed bedrock and coarse bed material seem to be controlling the channel grade, thereby inhibiting channel enlargement due to the flow increase.

Figure 4-13. Historical (1937) and current (2009) aerial photographs showing the reach of Green Valley Creek with the large culvert drainage adjacent to Highway 46.

Figure 4-14. View looking upstream at a large, 7-ft diameter culvert that passes beneath Highway 46 and drains into Green Valley Creek.

There are also numerous instances of bank revetment in the watershed, lining one or both banks of the creek (Figure 4-15). The majority of riprap, which is composed primarily of boulder-size quarry rock, was reportedly installed immediately following the damaging floods of 1969 to repair banks that had eroded during the floods (D. Dunlap, pers. comm., 2009). In most instances, bank revetment is frequently installed as a piecemeal solution to an on-going bank erosion concern that either threatens infrastructure or results in land loss. Unfortunately, bank revetment is also a symptomatic solution that does not account for the reason that high energy flow exists and is causing erosion. Therefore, bank revetments frequently cause flow to be deflected back across the channel resulting in further erosion downstream (e.g., Brookes 1988). The subsequent threat to downstream land and infrastructure promotes the continuing construction of further revetments and maintenance of existing revetments until such time that the channel is almost entirely revetted. Extensive revetment tends to cause channel incision, more rapid flows, channel bed armoring (i.e., coarse bed surface layer), and reduced topographic complexity of the channel bed resulting in significant reductions in habitat suitability for native aquatic organisms including salmonids.



Data Sources:
Hillshade: USGS 10m DEM; Roads: ESRI; Riprap: Nelson et al. 2009
Watersheds & Rivers: Stillwater Sciences, ESRI, USGS stream names

Figure 4-15. Bank riprap locations along Santa Rosa Creek (after Nelson et al. 2009).

In addition to in-channel structures, development along channel banks and the adjacent floodplain can have a significant impact on channel morphology. There are two primary drivers for channel change caused by floodplain development: (1) increased runoff associated with impervious area that has the potential to cause channel incision and/or widening (see Section 4.4.3.1); and (2) increased channel confinement associated with bank hardening and structures built along channel banks. Increased confinement also has the potential to cause channel incision due to increased flow velocities during high flow events. Since 1937, there has been concentrated development on the north bank (i.e., right bank) floodplain along Santa Rosa Creek in the Lower reaches from Highway 1 downstream (Figure 4-16). The floodplain development includes building of Highway 1, a housing development, and many of the businesses and residences along Main Street. During the improvement of Highway 1 (bypass construction), many of the lower reaches of the channel were modified. In an effort to improve building conditions, an abandoned channel meander approximately 0.5 km downstream of the Highway 1 bridge was filled-in sometime after 1937. These development features have undoubtedly played some role in controlling the current channel geomorphic character.

Figure 4-16. Historical (1937) and current (2009) aerial photographs showing the Lower reach of Santa Rosa Creek near the town of Cambria.

4.5 Lagoon Morphology and Dynamics

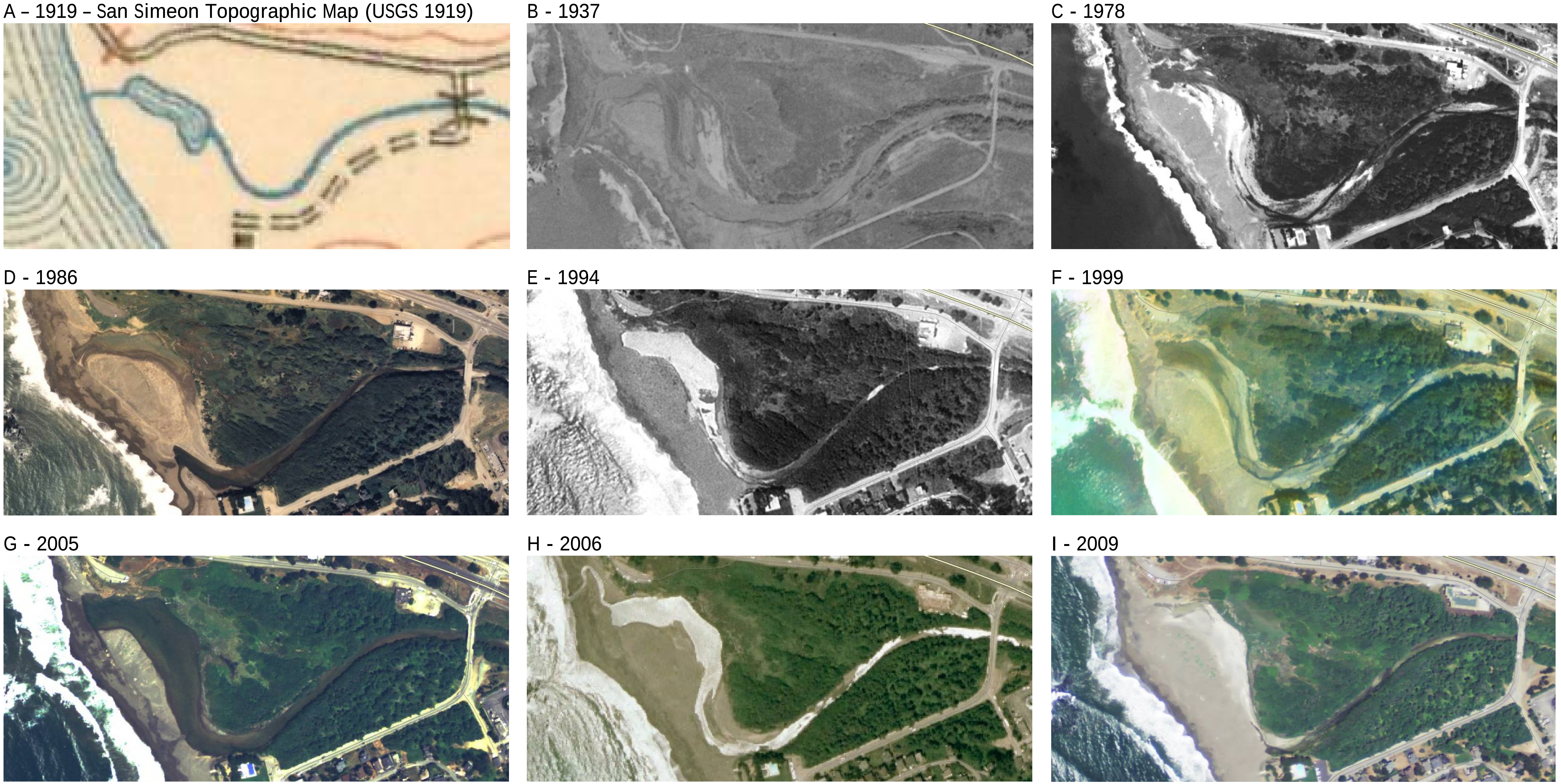
Understanding the sedimentation dynamics in the lower reaches and lagoon of Santa Rosa Creek are vital in understanding the stability of the lagoon and suitability of aquatic habitats (e.g., residing tidewater goby and migrating southern steelhead). Santa Rosa Creek discharges into a seasonal lagoon located behind Moonstone Beach before reaching the Pacific Ocean. By definition, a coastal lagoon is a body of water fed mostly by freshwater streamflow and is generally separated from the sea by a sandbar, except when that sandbar is breached during high-flow events (Carter 1988). The amount of freshwater and sediment throughput past the lagoon to the ocean is variable depending on streamflow and tidal elevation. Lagoon morphological change over short and long time periods can provide an indication of changes to historical land-sea interactions (i.e., sea-level change) and contributing watershed streamflow and sediment delivery dynamics. To date, there have been very few studies conducted to characterize the morphologic evolution or depositional history of the Santa Rosa Creek lagoon. This section, therefore, provides a baseline summary of the lagoon's historical and current morphology based on available information, including fisheries monitoring reports, regional studies, field observations, and historic aerial photographs.

The Santa Rosa Creek lagoon is a barrier lagoon separated from the Pacific Ocean by a sandbar for much of the year (Figure 4-17). Quaternary-age marine terraces (unit Qm in Figure 1-3) effectively constrain the maximum width of lower Santa Rosa Creek valley and also the lagoon. The south bank (or left bank) at the upstream end of the lagoon near Shamel Park is presently protected from wave attack by riprap materials on both the lagoon-side and creek-side banks. The adjacent floodplain to the east of the lagoon is a well vegetated expanse of scrub-shrub that remains dry except during extreme flood events. The small rock island situated approximately 150 m (~500 ft) offshore from Moonstone Beach functions as a natural breakwater that reduces approaching wave energy. The combination of marine terrace confinement and approaching wave direction causes the Santa Rosa Creek lagoon to be situated north (or upcoast) of the mainstem river channel. The upstream end of the lagoon is defined by the upstream extent of tidal influence. Although tidal records are available for use to help calculate this location, identification of the upstream end is not possible due to the lack of high resolution channel elevation data; however, the upstream end of tidal influence is likely well below the Highway 1 bridge crossing based on the fact that a stream gauge once occupied that location.

Similar to other lagoons along the California coast, the Santa Rosa Creek lagoon exhibits a "wet" and "dry" state during any given year, whereby winter and spring flows fill up the lagoon and the lack of flows during late summer and early fall often result in a dry lagoon. During the relatively wet year of 2005, D. W. Alley & Associates (2006) reported that the lagoon remained full throughout the monitoring they conducted during the dry months. They also reported that lagoon water depth was predominantly controlled by streamflow and that tidal overwashes and throughflow (i.e., subsurface flow through the sandbar) had a minimal effect. Sandbar breaching typically occur in the winter when high streamflows rapidly fill the lagoon and cause the natural barrier to fail. Often, high wave energy can also contribute to sandbar breaching. Reformation of the sandbar and closure of the lagoon occurs when lower stream discharges and lower-intensity wave action facilitate onshore sediment transport and deposition at the mouth. Lagoon closure can take weeks to months, depending on the stream discharge and wave conditions.

Figure 4-17. Oblique view of the Santa Rosa Creek lagoon looking east toward Cambria and the watershed with the Santa Lucia Mountain Range in the background (Photo taken October 28, 2005, Copyright © 2002–2009 Kenneth & Gabrielle Adelman, California Coastal Records Project, www.californiacoastline.org).

The general planform of lower Santa Rosa Creek and the lagoon have remained relatively static in recent time, as seen in one historical topographic map from 1919 and a series of eight historical and present-day aerial photographs taken since 1937 (Figure 4-18). Two main features are made apparent when examining these historical views of the lagoon: (1) the mouth is nearly always positioned on the north end of the beach adjacent to the marine terrace, with few exceptions (e.g., 1986), and (2) the amount of vegetation cover adjacent to the lower creek channel and lagoon appear to have increased considerably between 1937 and 1976. The "upcoast" lagoon orientation is common among lagoons of similar size along the central and southern California Coast. Although no known aerial photographs of the lagoon were taken prior to the 1930s, we can infer from Julien Estrada's sketch diagram of his holdings of Rancho Santa Rosa in 1841 that the lagoon may have exhibited a similar planform whereby the creek and lagoon sharply curved from the south to the north just before discharging to the ocean (see Figure A-2 in Appendix A). However, given that this diagram was not drawn to scale and there are insufficient landmarks shown, it is possible that the northerly "swing" of the lower creek may represent the portion of Santa Rosa Creek below present-day Highway 1 rather than the lagoon. The vegetation cover as viewed in the 1937 aerial photograph is limited to the a riparian corridor that lines the lower creek channel as it enters the lagoon, but minimal woody vegetation is present upon the adjacent floodplain areas. By 1976, the floodplain areas supported a denser vegetation cover comprised of woody scrub/shrub, riparian forest, and wetland plants (see Figures 1-6 and 4-16). The reason for this lack of vegetation cover in 1937 is unknown, but may be due to general land clearing that occurred throughout the watershed during the late 1800s and early 1900s. The subsequent re-vegetation of the lagoon area has implications maintaining the lagoon's position (i.e., vegetation providing bank strength) and promoting overbank deposition (i.e., decreased competence due to presence of roughness elements).



A – 1919 – San Simeon Topographic Map (USGS 1919)

B - 1937

C - 1978

D - 1986

E - 1994

F - 1999

G - 2005

H - 2006

I - 2009

Figure 4-18. Historical topographic map and aerial views of the Santa Rosa Creek lagoon. The lagoon has generally maintained a similar planform shape since the early 1900s, with few exceptions (e.g., 1986). Also shown are examples of a breached sandbar during higher stream flow conditions (e.g., 2005) and a closed sandbar during lower flow conditions (e.g., 2009).

In general, sands that make up Moonstone Beach and the majority of California beaches are supplied from a combination of stream discharge and seacliff erosion (Patsch and Griggs 2006). These sands only temporarily reside at any one beach, including Moonstone Beach, as they are transported along the coast by a nearshore, or littoral, current. Along the entire California coast, waves breaking onshore are generated in the winter by extra-tropical storms, mid-latitude low-pressure systems, and cold fronts that originate in the North Pacific (Hapke et al. 2006). During the remainder of the year a weaker, southern swell dominates that is generated by winter storms in the Southern Hemisphere (Hapke et al. 2006). As a result, the predominant direction of littoral sediment transport along the California coast is from north to south; however, local reversals in this general direction can occur seasonally and/or where variations in the coast orientation relative to the approaching currents exist (Patsch and Griggs 2006). Southward transport can also be reduced or reversed during El Niño winters when waves generally approach from the west or southwest (Patsch and Griggs 2006). Santa Rosa Creek likely discharges into a littoral cell with a reverse transport direction based on an airphoto review of the morphology exhibited by its lagoon and by several other lagoons in the region. Littoral cells are discrete coastal regions that can be considered closed systems within which sediment is transported. All of the significant streams in this region between San Simeon Point to the north and Point Buchon to the south of Santa Rosa Creek (e.g., Pico, San Simeon, Villa, and Morro creeks) have lagoons that discharge to the ocean on the north- or northwest-end of their beaches, which is likely driven by wave action that approaches these beaches from the west-southwest direction (Figure 4-18).

As stated above, sedimentation dynamics within the Santa Rosa Creek lagoon are driven by both fluvial and littoral sediment transport processes; however, little is known about whether net sediment aggradation or erosion has been occurring over time. D. W. Alley & Associates (2006) recorded discrete, yet not significant bed elevation changes in the lagoon between Shamel Park and the downstream (northern) end of the lagoon during the years of 2003 through 2005 as part of their fish monitoring study. These observations represent short-term bed elevation changes rather than long-term changes in the lagoon's evolution.

Overall, it can be inferred from the historical aerial photographs shown in Figure 4-18 that neither net aggradation nor erosion has occurred during the past 70-plus years based on the following: (1) the lower stream channel and lagoon have maintained a relatively static position (i.e., no meandering or avulsions); and (2) the lower stream channel exhibits a similar, albeit transitory, bar and pool morphology. This has positive implications for the continued functionality of an ecologically-important lagoon.

5 DISCUSSION

5.1 Summary: Understanding of Watershed Geomorphology

The Santa Rosa Creek watershed drains 123 km^2 (48 mi^2) of the southern Coast Range, rising on the western flanks of the Santa Lucia Mountain Range and emptying into the Pacific Ocean by the town of Cambria. The three main creeks, Santa Rosa, Perry, and Green Valley, and their tributaries are set primarily on Franciscan mélange and other meta-sedimentary rock units. Crustal convergence along the San Andreas Fault Zone has resulted in the occurrence of relatively weak rock units at higher elevations (e.g., Monterey Formation shales) which gives the watershed relatively high natural rates of erosion. Natural erosion is driven by the winter storms typical to a Mediterranean climate and is high flashy, accentuated by the high relief of the watershed—the highest point of the watershed at Cypress Mountain (894 m; 2,922 ft) receives nearly twice the rainfall at the coast (940 mm [37 in] versus 533 mm [21 in]). The highest rainfall events, and thus storm flows typically (but not always) occur during ENSO cycles. Land cover in the watershed is primarily grassland related to cattle grazing and other agriculture practices; the urban footprint is limited to the town of Cambria near the mouth of the creek, and two highways.

Like much of the American West, the greatest single physical change in the watershed occurred with the onset of Euro-American settlement in the mid-1800s: high population growth resulted in land clearance for agriculture and lumber, with native tree, shrub, and grass species replaced by shallow-rooted non-native grasses. These vegetation changes created a more flashy rainfall-runoff regime while at the same time providing less reinforcement of soils against erosion. The large California flood of 1862 followed by the devastating droughts of the 1860s and the increased storminess of the 1880s likely exacerbated the impacts of this land conversion, with significant erosion of both hillslopes and river channels (see below). The most significant channel modification during this period was probably the draining of Estrada lagoon and its replacement by the trapezoidal ditch that now forms the lower part of Perry Creek. However, unlike many other watersheds in California, the relative isolation of Santa Rosa Creek meant that this period of disturbance (focused around 1860–1880) was followed by quiescence until about 1950.

Since 1950 until about 1995, population in Cambria again began to increase partly because of the post World War II increase in population in California generally, but also because improvements to Highway 1 (early 1960s) and the building of Highway 46 along Green Valley (completed 1974) allowed the development of a thriving tourism industry. This period probably represents the second greatest impact on the geomorphology of the watershed, albeit with impacts focused on erosion in Green Valley Creek, and around the town of Cambria. Significantly, limited extent of the aquifer in the lower watershed meant that population growth has slowed since 1995 partly because of limits to water resources, safeguarding the largely rural nature of the watershed.

Hillslope erosion processes are similar to those active elsewhere throughout much of the southern Coast Range region: gullies are the most evident “macro-scale” erosion accounting for 72% of observed features including landslides, road-related erosion, and other macro-scale features. The gullies have evidently been in existence for a long time, being illustrated in sketches of the watershed from the 1880s and evident in aerial photographs from the 1930s. A coarse estimate of gully-based erosion annualized for the 150 years since 1860 would indicate gullies to have contributed 17,000 tonnes of sediment annually, although in reality much of the sediment delivery would have been focused in the early years of gully existence. Other sediment sources in the watershed include "micro-scale" erosion features such as dry ravel, soil creep, and rilling, and erosion of channel bed and banks. By inference with nearby watersheds and regional tectonic uplift rates, the total erosion rate may be around 420 t km^{-2} a^{-1} (52,000 tonnes, annually). This value is somewhat higher than typically estimated in coastal watersheds around the Bay Area of California farther north where rainfall extremes are less pronounced, but less than estimated for watersheds draining the highly erodible Transverse Ranges to the south; thus, in the absence of watershed-specific data, it appears to be credible. By our coarse estimate, macro-scale erosion such as that from gullies may account for approximately one-third or less of this erosion total, suggesting that soil creep, dry ravel, rilling, and channel erosion are also significant sediment sources. A small proportion (<8%) of this eroded sediment may be intercepted by small water-storage basins.

Overall, hillslope erosion is focused particularly in grassland landscapes that are underlain by rock composed of the highly sheared and fractured Franciscan mélange and characterized by moderately steep slopes (10–40%). This combination of geology, land cover, and hillslope gradient is also the most prevalent in the watershed, accounting for approximately one-third of the watershed area. This combination of features was assigned an erodibility rating of "Medium", which applies to 84% of the study area and emphasizes the largely uniform terrain conditions in the watershed. Erosion by unit area, most discretely in the form of gullies, is concentrated in rock units of the fine–weak Monterey Formation and the coarse–weak Franciscan mélange, on grassland/ herbaceous land cover, and moderately steep (10–40%) hillslopes. Landslides were observed to concentrate primarily in mixed forest and scrub/shrub-covered terrains but are somewhat insignificant in terms of total eroded area. By subwatershed, hillslope erosion rates are estimated to be largely related to watershed size. Thus erosion in the Santa Rosa Creek sub-watershed closely matches that from the Perry Creek (erosion ratio = 56:44; area ratio = 52:48). To the extent that our method and available data allows, sediment supply per unit area is highest in the subwatersheds of East Fork Santa Rosa and Curti creeks and two unnamed tributaries draining to Green Valley; and it is lowest from the hillslopes draining directly to the Lower reach of Santa Rosa Creek. Given the relative uniformity of rock type and land use in the watershed, these results are entirely consistent with the fact that the high yielding subwatersheds have the highest relief and the lowest yielding have the lowest relief.

Significant rates of geomorphic process activity in stream channels of the watershed occur in response to rainfall-driven storm events (e.g., during El Nino years of the ENSO cycle). Streamflow gauges have been deployed in the upper watershed (WY 1958–1972) and in two locations of the lower watershed (WY 1976–1992; WY 1989–present). Unfortunately, the rating curve of the current gauge is inadequately calibrated, reducing confidence in flow records since 1994. Following a previous report (Yates and Von Konyenburg 1998), flow records are supplemented with records from Santa Rita Creek (WY 1958–1992). To the extent allowed by available data, bankfull flow in the lower watershed is approximately 50–78 m^3 s^{-1} (1,802–2,744 cfs) while the 10-year recurrence interval event has an approximate magnitude of (~216 m^3s^{-1}; 7,600 cfs). Since 1958, large flood events have occurred in 1967, 1969, 1973, 1978, 1986, 1993, 1995, and 2005, corresponding with the increase in ENSO circulation intensity in the latter year of the Twentieth century (Inman and Jenkins 1999). Of these, the two largest were probably 1969 and 1995.

Channel morphology of Santa Rosa Creek can be usefully subdivided into an upper, middle and lower zone and a total of 9 reaches therein. Channel gradients by reach vary from 0.032 in the creek headwaters to 0.003 near the river mouth, with an average gradient of 0.009 (i.e., 0.9%). The Upper zone is characterized by a steep, boulder-cobble-gravel bedded reach above Mammoth

Rock and the Middle reaches extending down to Perry Creek are incised into alluvium with a sinuous cobble-gravel bed characterized by pool-riffle bedforms. Bedrock control returns at the junction with the Lower reaches which have a sand-gravel bed and are moderately confined by terrain and development and show signs of aggradation before becoming tidally influenced near the river mouth. From deposits at tributary confluences, it appears that Lehman and Curti creeks provide significant coarse sediment delivery to Santa Rosa Creek while Perry Creek delivers abundant fine sediment. The pattern of creek morphology transformations in Green Valley Creek is similar to those of Santa Rosa Creek but occurs over a shorter distance. The upper reaches of Perry Creek are meandering and finer-grained than either of Santa Rosa and Green Valley creeks. Lower Perry Creek was channelized from the former Estrada Lagoon and begins as a trapezoidal cut roughly paralleling Highway 1 while the lowest reach is incised into the organic-rich sediments of the former lagoon.

Human influences on Santa Rosa Creek include the impacts of land cover changes and water-related infrastructure. Regarding land cover change, it appears that in Santa Rosa Creek the biggest single influence was the conversion from native woodland and shrub/scrub to non-native grasslands subsequent to the arrival of Euro-American settlers in the mid-Nineteenth century. This likely resulted in the observed incision of the Middle, and to some extent, Lower reaches which still influences creek dynamics today. In Green Valley Creek, it seems probable that a second major impact relates to the construction of Highway 46 in the early 1970s. Regarding infrastructure, there are numerous creek crossings along Highways 1 and 46 and Santa Rosa Creek Road that may locally influence the dynamics of deposition and erosion, most recently including the series of culverts related to the drainage of Highway 46 in Green Valley Creek. Along Santa Rosa Creek and likely along some sections of Perry and Green Valley creeks, there are also numerous instances of localized bank revetment but no extensive bank protection or levee building.

Evidence for channel dynamics can be derived from aerial photographic overlays and from hydraulic geometry relationships. Comparing photographs from 1937 to 2007, there have been local changes in planform in both the Upper and Lower zones of Santa Rosa Creek, with a significant increase in the sinuosity of the Middle zone, especially reach M2 which has increased in sinuosity by 18%. The increase in sinuosity of this incised reach is taken as indicative of evidence that the channel is still recovering from the impact of land cover change in the mid-Nineteenth century. Evidence for the potential for channel change was determined using field measurements collected as a by-product of the reconnaissance survey. While a dedicated campaign of data collection is ideally required, this available data indicates both a logical relationship between channel width, depth, and drainage area. Derivative measurements indicate that the channel should be highly dynamic in its alluvial reaches according to stream power, while estimates of shear stress on the bed of the channel suggest that the bed sediments are highly mobile even in frequently occurring high flows such as bankfull (recurrence interval of 1.5–2 years).

The morphology of the coastal barrier lagoon at the mouth of Santa Rosa Creek is influenced by prevailing onshore currents and the effects of a rock island close offshore, by flows from Santa Rosa Creek, and by topographic constraints that are both geologic and a function of a landfill and riprap. Overall, the lagoon responds largely to incoming streamflow including its pattern of seasonal breaching which is usually in response to high discharges from Santa Rosa Creek that overwhelm the capacity of the lagoon. The morphology has remained remarkably static since available records began which likely indicates that the morphology of the lagoon, unlike its seasonal breaching, is controlled primarily by the prevailing direction of coastal sediment transport. While the majority of coastal sediment movement in California is from north to south, the lagoon morphology at Santa Rosa Creek and of neighboring creeks suggests a south to north movement, presumably in response to dominant wave action from the west-southwest direction.

5.2 Sediment Production, Transfer, and Storage

As a geomorphic unit, a watershed serves to transport sediment from its place of origin to an eventual place of lasting storage. In so doing, a distinctive relief is developed in the watershed that reflects the balance between long-term processes of tectonic uplift and rates of erosion driven by physical, chemical and biological factors. This balance is generally achieved through the medium of moving water. Sediment sources are those sites predominantly characterized by erosion and often most commonly have steep slopes. Sediment storage, particularly in a small coastal watershed such as Santa Rosa Creek, occurs mostly offshore as sediment-laden water exits the watershed, but it also occurs where sediments are deposited on floodplains (where the material is termed *alluvium*) and at breaks to gentler hillslope gradients (termed *colluvium*). Connecting sediment sources with their sites of long-term storage is a flux of sediment transport through the watershed, typically occurring on a time scale from years to centuries. The flux of sediment is intermittent and driven mostly by large rainfall or streamflow events, and so most such “short-term” sediment transfer occurs along the river channel. The exact locations of the short-term sources and storage sites of sediment, however, are influenced as strongly by human activities as by natural factors. A typical short-term sediment source is the erosion of alluvial river banks, representing the re-mobilization of previously stored sediment; while short-term sediment storage often occurs on the channel bed in the form of a wave of “excess” sediment deposited after a flood event. Therefore, the typical transfer of sediment through a watershed involves a flux in which changes to the creek morphology is an integral part.

As aquatic habitats are intimately linked to creek morphology and process, it follows that habitats also respond to the flux created by sediment sources and storage sites within a watershed. They are particularly affected by changes away from “normal” conditions. For this reason, aquatic habitats are closely linked to geomorphic processes and the influence of human activity. The benefits and hazards of living near to a river are also linked strongly to changing channel morphology and process. Using the same examples as above, significant erosion of channel banks is often perceived as land loss by the owner, while sediment deposition raises channel bed elevations and makes the adjacent floodplain more prone to flooding. As such, understanding of geomorphic processes and their alteration is also central to river and watershed management in general.

As a gauge of relevant activities, we have characterized a series of sediment sources and stores through this report, and estimated the dynamics of sediment transfer. This characterization is summarized in Table 5-1 and the various source locations brought together in Figure 5-1.

Table 5-1. Sediment sources, storage, and transfer dynamics in the Santa Rosa Creek watershed.

Location	Process/Description
Sediment Sources	
Landslides	Only 17 landslides (combination of shallow and deep-seated) are recorded in the areas of watershed without canopy cover, but they are individually high-yielding accounting for approximately 3,500 m^3 of material per slide. Landslides are concentrated in high relief, steep-sided subwatershed areas, primarily in the headwaters of Santa Rosa Creek. Landslides erode previously stored colluvium on hillslope swales and, potentially, weathered bedrock closer to the failure plane. Mixed-load sediments released as part of large deep-seated landslides, as mapped in geologic maps of the watershed, may reside for years to centuries before eventually being completely delivered to the stream network.
Gullies and rills	Gullies (macro-scale features) and rills (micro-scale features) are numerous throughout the watershed. Over 1,000 gullies have been recorded and many have evidently been present since the late Nineteenth century and so may be past their sediment production peak. These features primarily result in the production of fine-grained sediments as they erode soil-mantled, moderately steep hillslopes and, because they are often connected directly to the stream network, a near 100% delivery ratio of sediment can be inferred. The inception of gullying in the watershed is likely to have resulted in far higher volumes of fine sediment delivered to the channel network
High yielding Geomorphic Landscape Units	By our estimates, areas of the watershed with the highest sediment yield potential are primarily situated on steep, grassland and barren hillslopes composed of weak rock. These areas result in the production of both coarse and fine sediments, but fine sediments are probably derived preferentially from the widespread Franciscan mélange terrain. Sediment delivery from these GLUs is likely high given the steep hillslopes and confined and steep channels.
Creek incision	Channel incision in the major streams is assumed to have occurred quickly after initial land clearing activities began in the mid-Nineteenth century. Incision is widespread but focused in the Middle reaches of Santa Rosa Creek and the middle and upper reaches of Perry and Green Valley creeks. Incision initially releases channel bed sediments which may be relatively coarse.
Bank erosion of high bluffs following incision	Over time, channel incision eventually causes the mass instability of channel banks of the former floodplain which then makes them a highly effective source of finer sediment as the channel widens. More recently, meander activity as the incised reaches try to recover their equilibrium has allowed erosion of high alluvial banks of the former floodplain, causing a net sediment supply biased towards fine sediment.
Road-related erosion	Over 250 instances of recorded road-related erosion exist in the watershed. Erosion is focused along cut and fill sections of Highway 46 and Santa Rosa Creek Road (and to a lesser extent Highway 1). Because road drainage frequently serves channel road runoff from the road surface efficiently to the channel network, sediment (particularly fine sediment) is also delivered very effectively to the channel network.
Sediment Storage	
Lower Perry Creek in the vicinity of the former Estrada lagoon	Historically, Estrada Lagoon at the downstream of end Perry Creek probably trapped all coarse and most fine sediments delivered by the contributing streams, meaning that few sediments from the Perry Creek subwatershed ever reached Santa Rosa Creek. Subsequent draining of the lagoon to create a

Location	Process/Description
	trapezoidal channel permitted the transport of sediment, especially fine sediment, from the Perry Creek subwatershed into Santa Rosa Creek. Subsequent incision of the lowest reach of Perry Creek must have resulted in the remobilization of former lagoon sediment (i.e., fine, organic-rich sediment). The broad-bedded, low gradient ditch farther upstream still favors the deposition of coarse sediments before Santa Rosa Creek, and a noticeable fining of bed material occurs on Santa Rosa Creek downstream of the Perry Creek confluence.
Water storage ponds	There are 41 recorded small water storage ponds throughout the watershed, with a greater proportion in the Perry Creek subwatershed. They regulate 8% of the watershed area but are likely to have low sediment-trapping efficiencies, trapping primarily a small amount of coarser-grained sediments.
Channel bed in upper reaches	Field evidence indicates temporary storage of coarse sediments delivered from the steep, high relief tributary subwatersheds (e.g., East Fork Santa Rosa and Curti creeks) into mainstem Santa Rosa Creek. Along the mainstem, there is also field evidence for the temporary storage of coarse material in channel and floodplain locations. Remobilization of the coarse sediment occurs during high flow events with material either wholly entrained or abraded into finer, more easily-transportable particles.
Channel bed in lower reaches	While lower gradient reaches are frequently characterized by finer sediment beds and sediment deposition, field evidence of short-term storage of fine material on the channel bed may reflect high rates of fine sediment supply to the lower reaches, especially from the Perry Creek subwatershed.
Transfer Dynamics	
Upper reaches	The shear stress ratio (3.2–4.8) indicates that the upper reaches are competent to transport the median grain sizes (~50–90 mm) and larger supplied to the reaches during even moderate flood events. Very high stream power (~200–500 Wm^{-2}) also indicates a highly active channel. Fine sediment is presumably transferred quickly from the reaches, whereas field evidence indicates the temporary storage and probable breakdown of very coarse material.
Middle reaches	The shear stress ratio (3.5–7.5) indicates that the middle reaches are competent to transport the median grain sizes (~20–50 mm) and larger supplied to the reaches during even moderate flood events. High stream power (~135–275 Wm^{-2}) also indicates a highly active channel, borne out by increased sinuosity in these reaches since the early Twentieth century in which coarse sediment is deposited in the form of channel bars and larger volumes of fine sediment are derived from the high banks of the former floodplain surface.
Lower reaches	The shear stress ratio (3.8–16.3) indicates that the lower reaches are highly competent to transport the median grain sizes (~5–45 mm) and larger supplied to the reaches during even moderate flood events. Stream power (~150–300 Wm^{-2}) is unusually high for such low gradient reaches and may reflect bank protection which prevents the exchange of sediment from channel banks and prevents channel widening in response to flood events.

In summary, present day Santa Rosa Creek watershed is characterized, as most other watersheds, by a wide variety of sediment sources that potentially affect management decisions. Of particular note is the potential for high sediment yields from the very steep hillslopes in the headwaters of Santa Rosa Creek (and some tributaries in Green Valley Creek), and the extent of highly effective sediment delivery from active gullying, high bluff bank erosion, and road-related erosion in the middle watershed areas. In the lower watershed areas, the primary impacts probably relate to the "reconnection" (in terms of sediment) of Perry Creek to lower Santa Rosa Creek achieved by draining Estrada lagoon. Direct impacts on channel morphology with repercussions for future management decisions include piecemeal bank protection in various locations through the watershed, and the somewhat undetermined effect of extensive bank protection and other channel modifications of lower Santa Rosa Creek. Other than the potential for high sediment yields from steep gradient locations, the other highlighted sources result primarily from previous land and channel management actions. It seems likely that, in geomorphic terms, the historically-noted fish populations in the watershed result in part from the habitats created by the delivery of very coarse sediment from the upper reaches of Santa Rosa Creek. Human actions, in addition to increasing the flashiness of runoff in the watershed, have apparently served primarily to increase the fine sediment component of the river bed which has probably been deleterious to steelhead habitat. Study is required of the cumulative effect of various physical, chemical, and biological factors currently limiting steelhead trout populations to determine whether fine sediment impacts are among the primary causes of fish population decline.

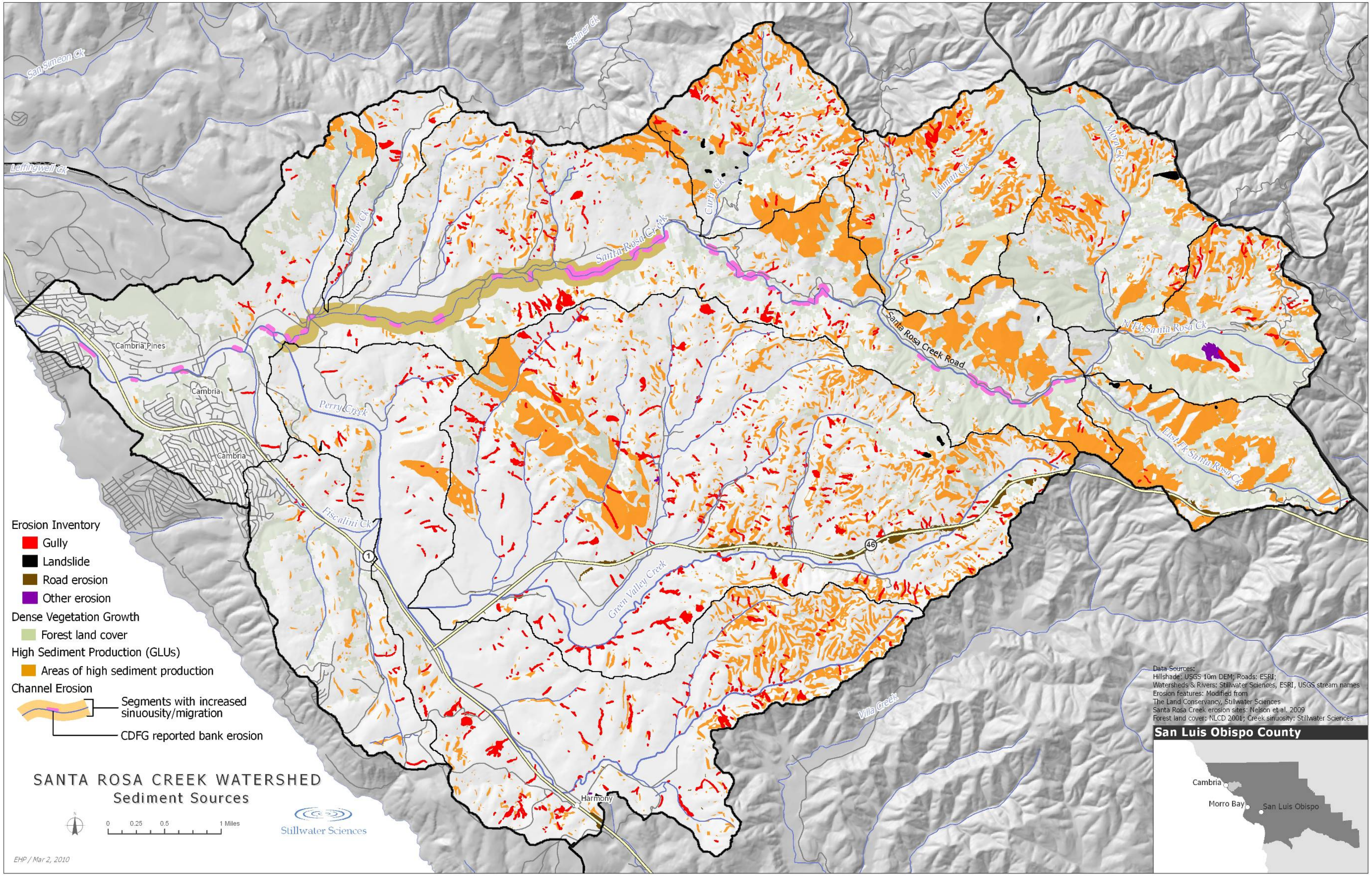


Figure 5-1. Sediment source and transfer areas in the Santa Rosa Creek watershed.

5.3 Data Gaps in the Current Understanding

Through the process of compiling the data to undertake the analysis required for this report, we have become aware of several significant gaps in the availability of data that might be used to better characterize geomorphic processes, and so as to better support watershed management planning. The data gaps are listed below in the hope that resources might eventually be made available to fund their collection.

- ***Reliable calibration of the lower watershed gauging station (SLO #21)***: reliable flow information is central to nearly every facet of watershed management, and is especially critical where water resources are limited. The current gauging station at the Main Street bridge urgently needs real-time flow measurements taken during high discharge events as the basis for constructing a reliable stage-discharge relationship that maximizes the utility of the gauge. Taking high flow measurements is potentially dangerous and must be made by qualified hydrology technicians.
- ***Aerial LiDAR scanning as the basis for more accurate characterization of the watershed topography***: aerial laser swath mapping, commonly known as LiDAR (Light Detecting And Ranging) is revolutionizing watershed characterization, allowing a far greater resolution of the watershed surface than achieved by photogrammetrically derived USGS Digital Elevations Models. The accuracy of LiDAR mapping is frequently to decimeter-scale (inches) in the horizontal and vertical. Other than the inherent advantages of a more accurate base map of the watershed, computer algorithms developed for LiDAR data can be used to create a "bare earth" surface (i.e., an image cleared of surface vegetation and buildings) allowing the identification of erosion sources that cannot otherwise be seen, such as old landslides under canopy cover that might still be providing a significant source of sediment. County-wide programs of LiDAR mapping are rapidly being added to surveys of aerial photography (e.g., Ventura County).
- ***Comprehensive (headwater-to-mouth) survey of stream channel conditions***: the channel surveys in this report represent a strategic sampling of conditions to establish a baseline understanding of general conditions. A more thorough survey would enable better understanding of the extent of incision-related erosion problems in the watershed and the dynamics of habitat conditions. LiDAR data could be used in place of ground surveys to some degree (see above).
- ***Additional research on the extent of direct channel change brought about by channel management activities and the construction of Highway 46***: in many watersheds including Santa Rosa Creek, it is difficult to build an exact picture of the extent to which past management activities have directly impacted river channels. We are aware, from anecdotal evidence that the improvement of Highway 1 involved some creek modifications and that extensive riprap placement in the lower creek followed the flood of 1969, but were not able to discover engineering plans for these activities within the timeframe and resources allocated to this project. Further, we are aware that the construction of Highway 46 involved large volumes of fill material some of which subsequently entered the channel system during the wet winter of 1972/3, but are unaware of any systematic recording of this event. Acquisition of official information in any of these matters would create a better understanding of creek change that might benefit assessment of habitat conditions, particularly in the lower watershed.

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APPENDICES

Appendix A

Historical Watershed Impacts

Table A-1. Chronology of major activities and geomorphic disturbances in the Santa Rosa Creek watershed.

Historical period		Watershed activity/Disturbance
European Arrival: Resource Development (1760s–1859)		• 1769 – Portola Expedition encounters ~300 Native Americans residing in Santa Rosa Creek area. Portola records observations of a “canyon… and arroyo surrounded with hills of pine” in the area now known as Cambria. [1] • Late 1700s – Early coast trail established; followed Perry Creek along eastside of the “Estrada Laguna”, crossed Santa Rosa Creek, and headed west toward coast [1, 2] • 1840 – Establishment of Rancho Santa Rosa; primary land use is ranching of cattle, sheep, and horse [1, 2, 3, 4] • 1850 – Coast wagon road constructed between San Luis Obispo and Santa Rosa Creek following coast trail [3] • 1859 – First Americans settle Santa Rosa Creek and Green Valley lowlands [1, 2] • 1859 – Early Santa Rosa Creek Road/Trail established [1]
Ranching, Logging, and Mining (1860–1949)	Rapid Development Period (1860–1880)	• 1862 – Little Bonanza mercury deposit discovered immediately east of watershed [1, 4, 5] • 1863/64 – Severe drought kills off livestock; shift to crop cultivation and dairy cattle and processing [1, 2, 3, 4] • 1865 – Watershed-wide logging of pines and oaks begins [1, 3] • 1866 – Establishment of Cambria [1, 2, 3, 4]; filling of gullies within town limits [1] • 1868 – “Cienaga Trail” established along Green Valley [1, 6] • 1870s – Walker Ditch constructed to drain “Estrada Laguna” along lower Perry Creek [1, 2] • 1874 – Oceanic Quicksilver Mine begins production in Curti Creek subwatershed; quicksilver mining boom continues elsewhere throughout region [1, 3, 4, 5] • 1875 – Cambria population: ~300 [7]; Cambria and vicinity population: ~1,000-2,000 [1] • 1876 – Coast Road re-routed away from lower Perry Creek to along present day Main Street [1]
	Quiescent Period (1880–1949)	• 1889 – Cambria Fire destroys downtown [1, 4]; largest recorded fire in watershed [8] • 1890 – Cambria population: 700 [7]; Santa Rosa Creek Valley is “quite thickly settled” [3] • 1900 – San Simeon Township (Cambria, San Simeon, and surrounding areas) population: 1,036 [7] • 1914 – January floods occurred during wet water year; Cambria flooded [1] • 1914-1918 – Second peak in production at Oceanic Quicksilver Mine [1, 4, 5] • 1916 – Logging production declines with removal of old growth [1] • 1927 – Cambria Development Company begins housing development of Cambria Pines [1, 4] • 1939 – Highway 1 and Santa Rosa Creek Road improved (oiled) [1]

Historical period		**Watershed activity/Disturbance**
Urbanization (1950–2010)	Population Growth Period (1950–1994)	• 1950 – Cambria population: 788 [7] • 1956 – Second large flood event, again inundated Cambria [1, 2] • 1958 – Tourism industry begins with opening of Hearst Castle [1, 4] • 1960 – Cambria population: 1,260 [7] • 1960s – Third peak in production at Oceanic Quicksilver Mine [1, 4, 5] • 1960s – Unauthorized logging of California bay trees in upper watershed [2] • 1960s – Shift from dairy cattle back to beef cattle [1, 2] • 1964 – Highway 1 bypass constructed around downtown Cambria [1, 4] • 1965 – Cambria population: 2,010 [7] • 1969 – Third large flood event [1, 2]; greatest annual precipitation amount on record, estimated at 12-21 inches over 8 days [9, 10]; widespread bank erosion and bed scouring [2] • 1971 – Closure of last sawmill in watershed (near Scott Rock) [11] • 1974 – Highway 46 constructed through Green Valley [1, 4] • 1976 – Municipal groundwater extraction from the Santa Rosa basin peaks at 520 acre-feet [12, 13] • 1980 – Cambria population: 3,061 [14] • 1980s – Steelhead population decline [15] • 1990 – Cambria population: 5,382 [14]
	Population Growth Slow Down Period (1995–2010)	• 1995 – Fourth large flood event with water depths in Cambria reaching 6 feet [2, 10]; several landslides occurred in upper watershed [2] • 2000 – Cambria population: 6,232 [14] • 2003 – San Simeon magnitude 6.5 earthquake buckles roads throughout County and alters stream flow patterns in adjacent watersheds [16] • 2009 – Cambria population: 6,624 [17]

Sources:

1. Hamilton 1974
2. D. Dunlap, pers. comm., 2009.
3. Angel 1883
4. Baker 2003
5. Cambria Historical Society, pers. comm., 2009.
6. Harris 1874
7. A. Ochs, pers. comm., 2009.
8. CAL FIRE 2009
9. SLO County Water Resources Division of Public Works rain gauges: Cal Poly #1, Cambria #180, Soto Ranch #169
10. SLO County 2005
11. Coffman 1995
12. Yates and Van Konyenburg 1998
13. CCSD 2009
14. US Census Bureau 2003
15. McEwan and Jackson 1996
16. USGS 2004
17. Cambria Chamber of Commerce, pers. comm., 2009.

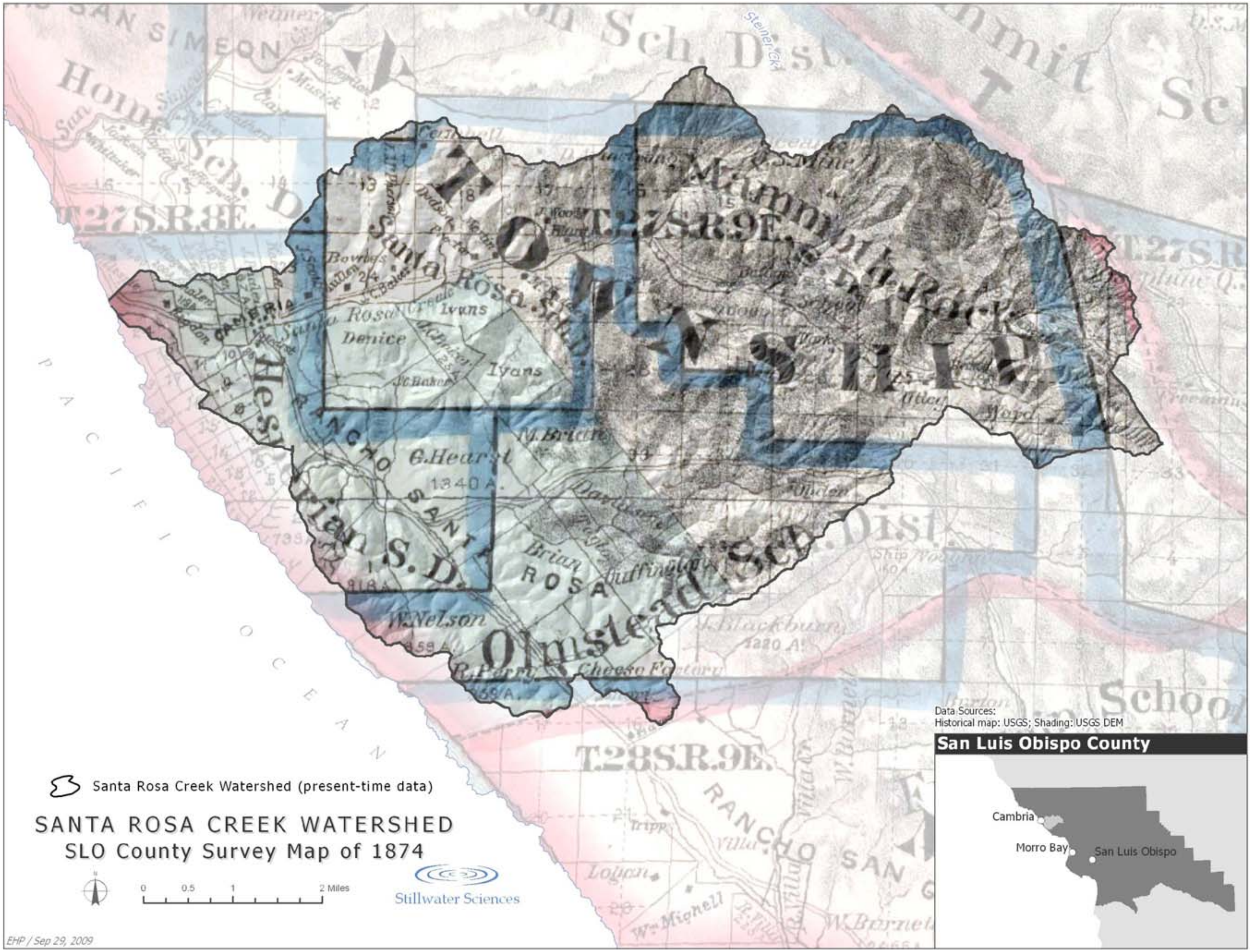

Figure A-1. Santa Rosa Creek watershed and vicinity as depicted in the first survey map of San Luis Obispo County (Harris 1874).

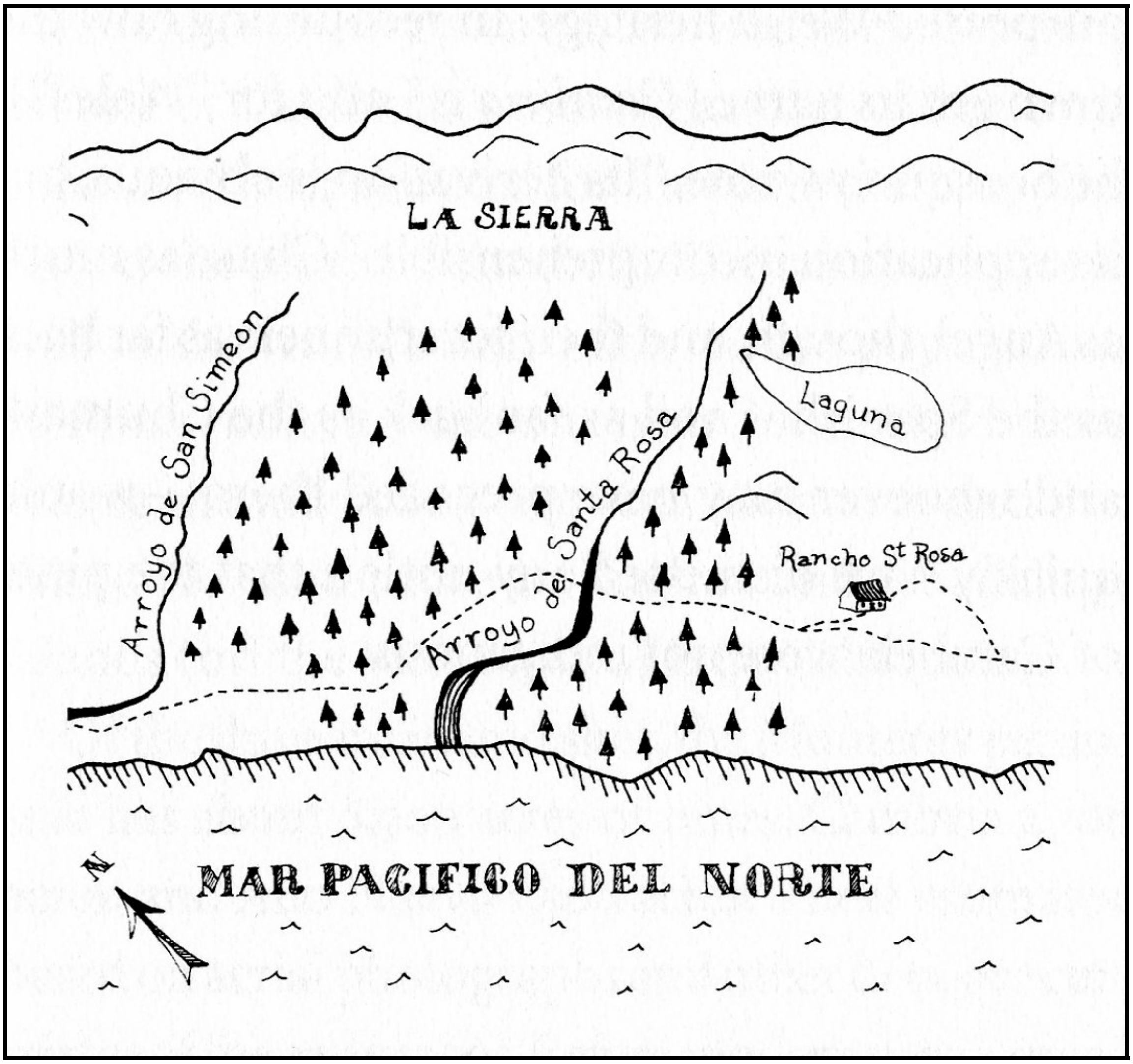

Figure A-2. Illustration of Rancho Santa Rosa drafted by its owner, Don Julian Estrada, as part of his application for the land grant in 1841. Visible in this image are Santa Rosa Creek, the pine tree forest along hillslopes surrounding present-day Cambria, a coastal trail/road running parallel to the coast, and "Estrada Laguna" located along where lower Perry Creek flows into Santa Rosa Creek. Illustration source from Coffman 1995.

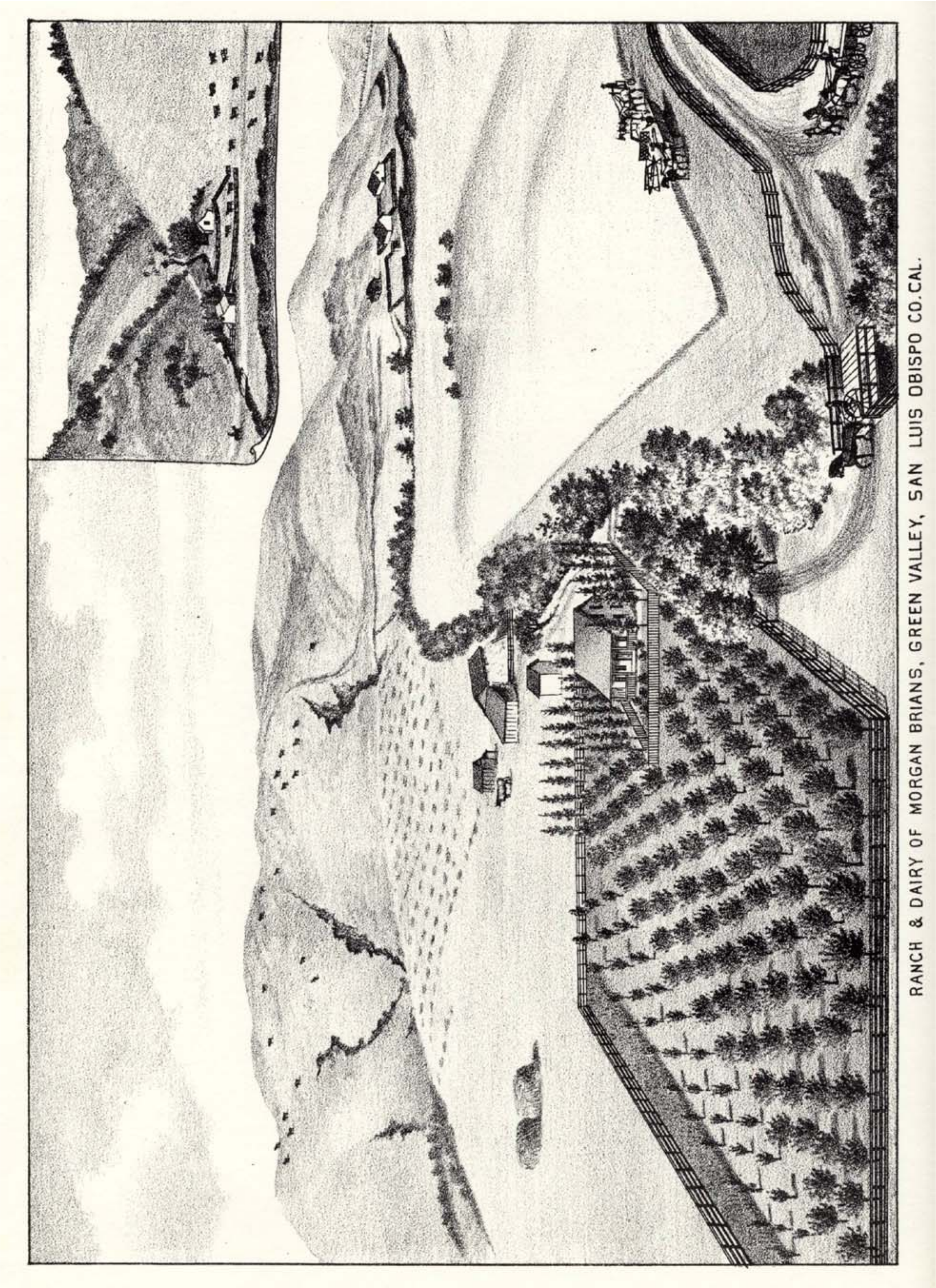

Figure A-3. Historical illustration of the Morgan Brians property in Green Valley (Angel 1883). Illustration depicts hillslopes free of trees or shrubs, with gullies developed in swales.

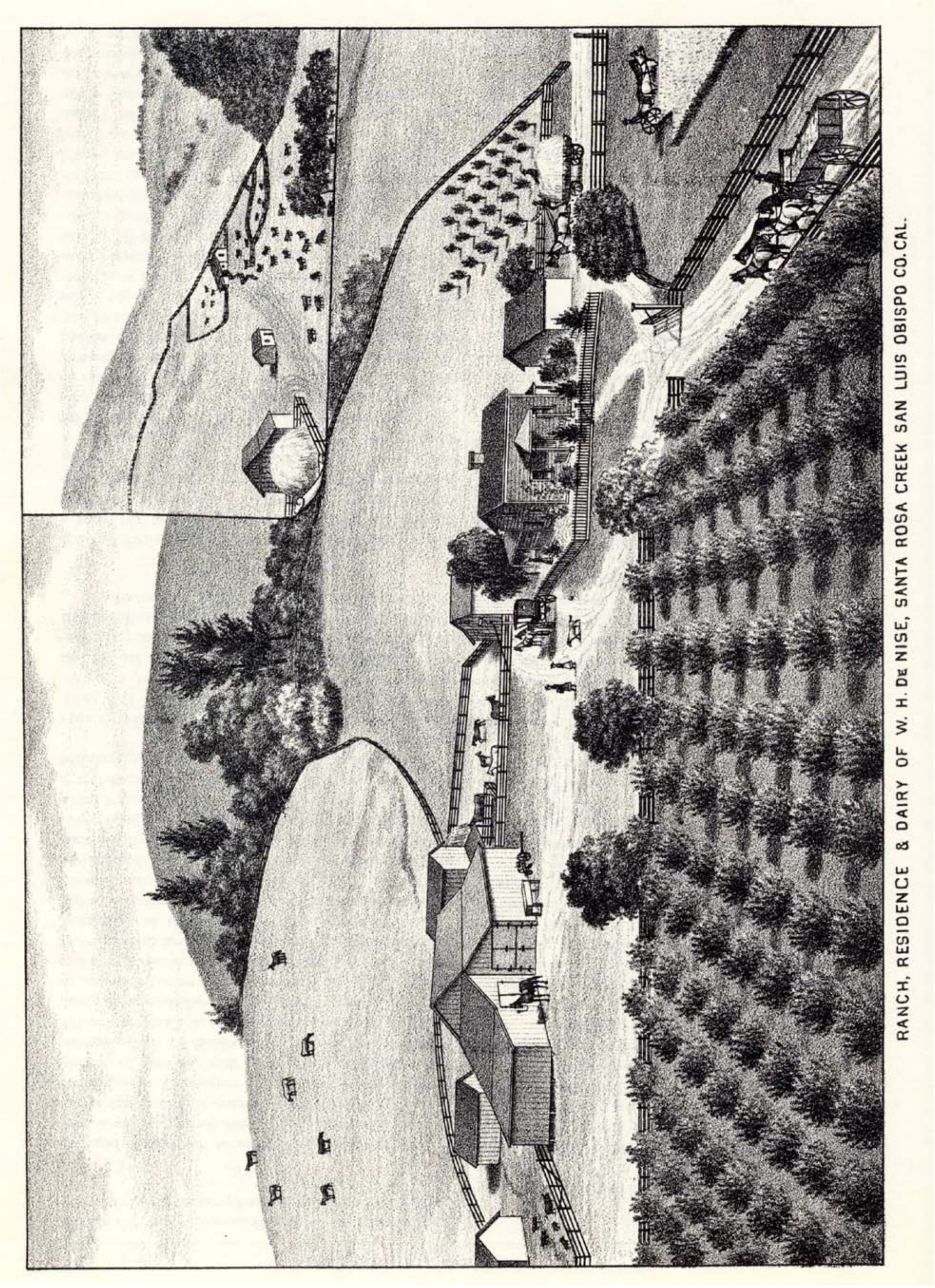

Figure A-4. Historical illustration of the W. H. De Nise property in near in Santa Rosa Creek valley (Angel 1883). Illustration depicts mostly hillslopes free of trees or shrubs, but with patch of forest remaining between ridges.

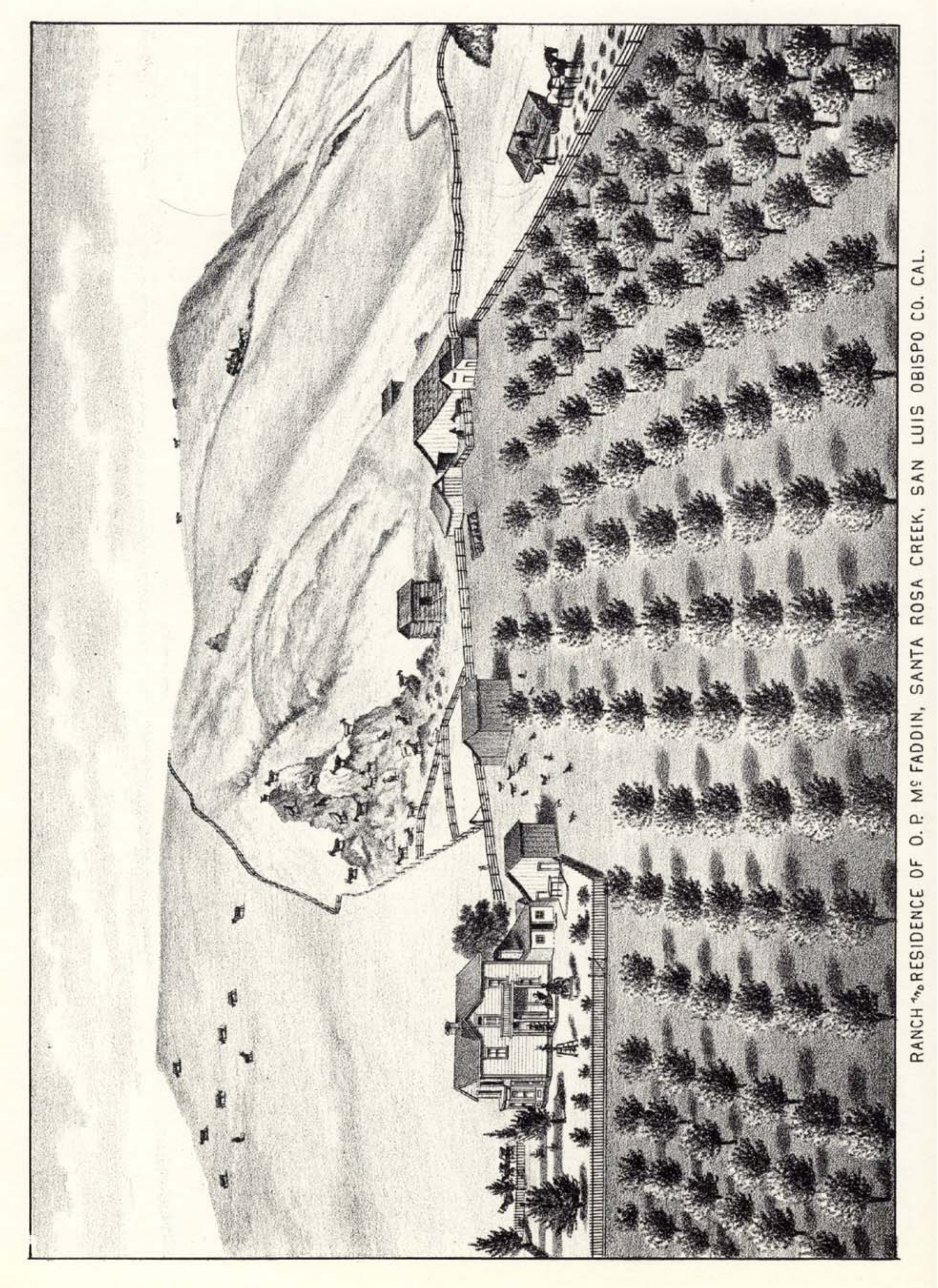

Figure A-5. Historical illustration of the O. P. McFaddin property in the Santa Rosa Creek valley (Angel 1883). Illustration depicts hillslopes free of trees or shrubs, with large bedrock outcrop of Franciscan mélange and gully development in swale behind farm.

Figure A-6. Comparison of similar areas of south-facing, pine tree-covered hillslopes in the Santa Rosa Creek valley near Cambria. Upper photo taken as part of the Wieslander Vegetation Type Mapping project, 11 December 1930. Lower photo taken by G. Leverich, Stillwater Sciences, 27 July 2009.

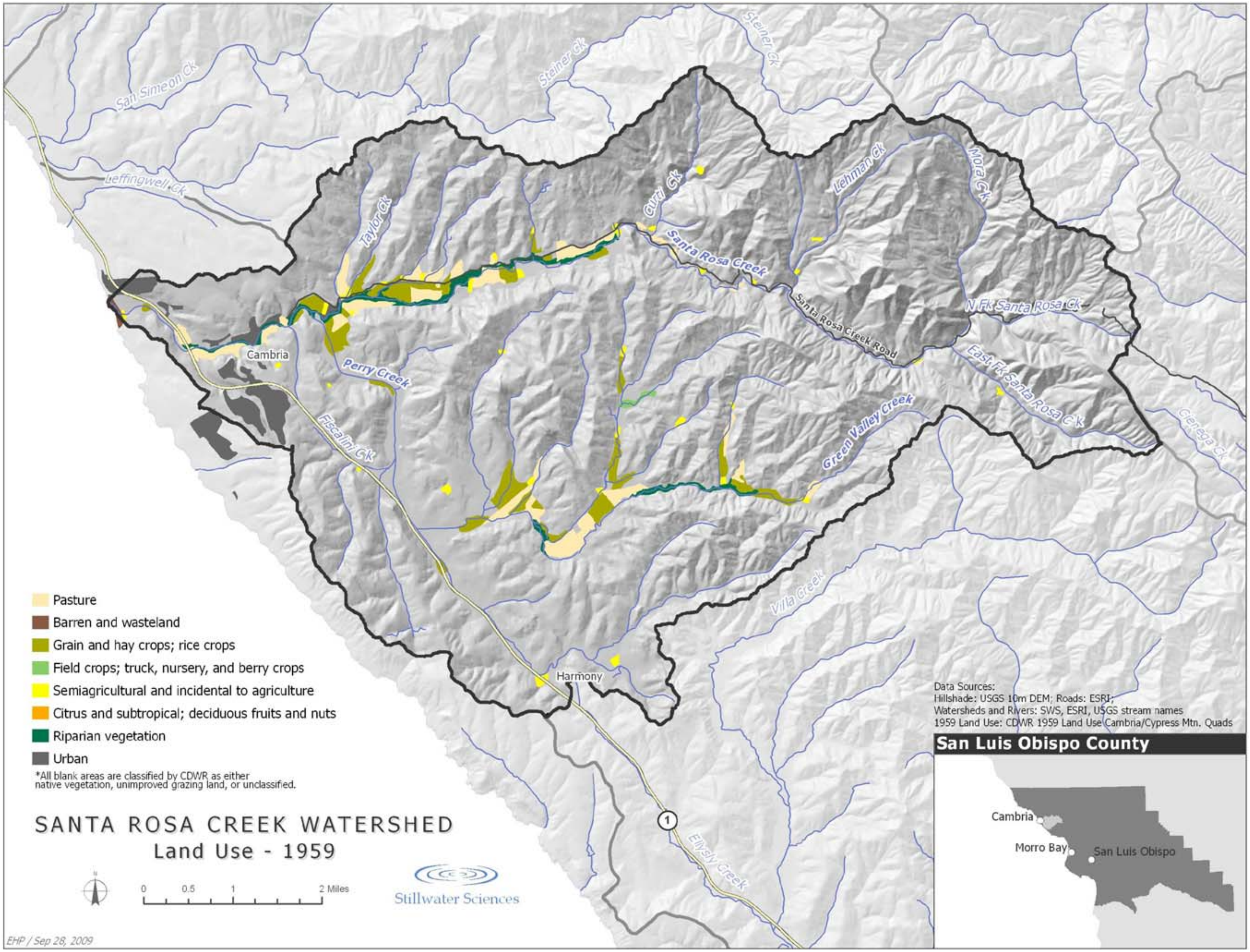

Figure A-7. Land use types present in 1959 within the Santa Rosa Creek watershed (after CDWR 1959).

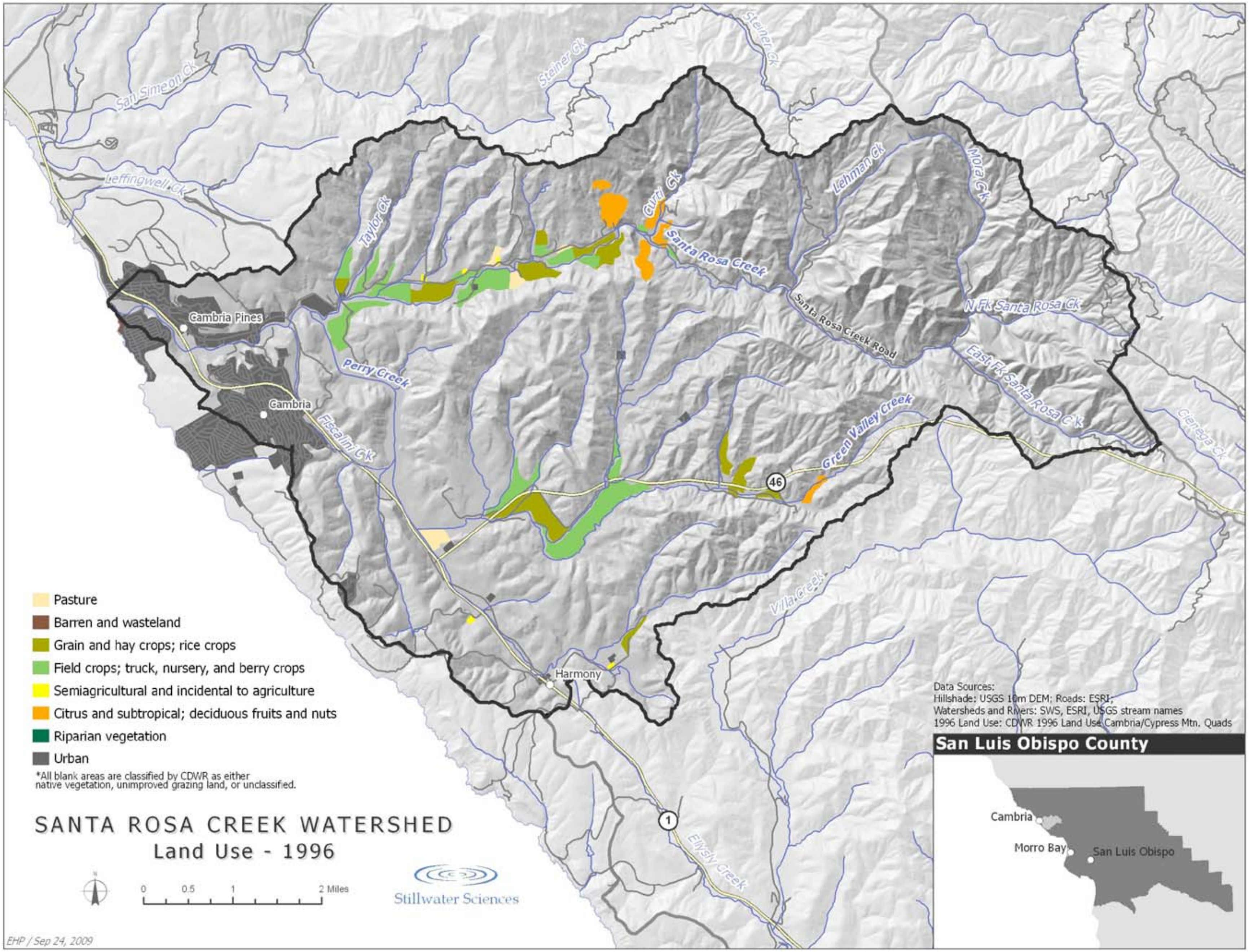

Figure A-8. Land use types present in 1996 within the Santa Rosa Creek watershed (after CDWR 1996).

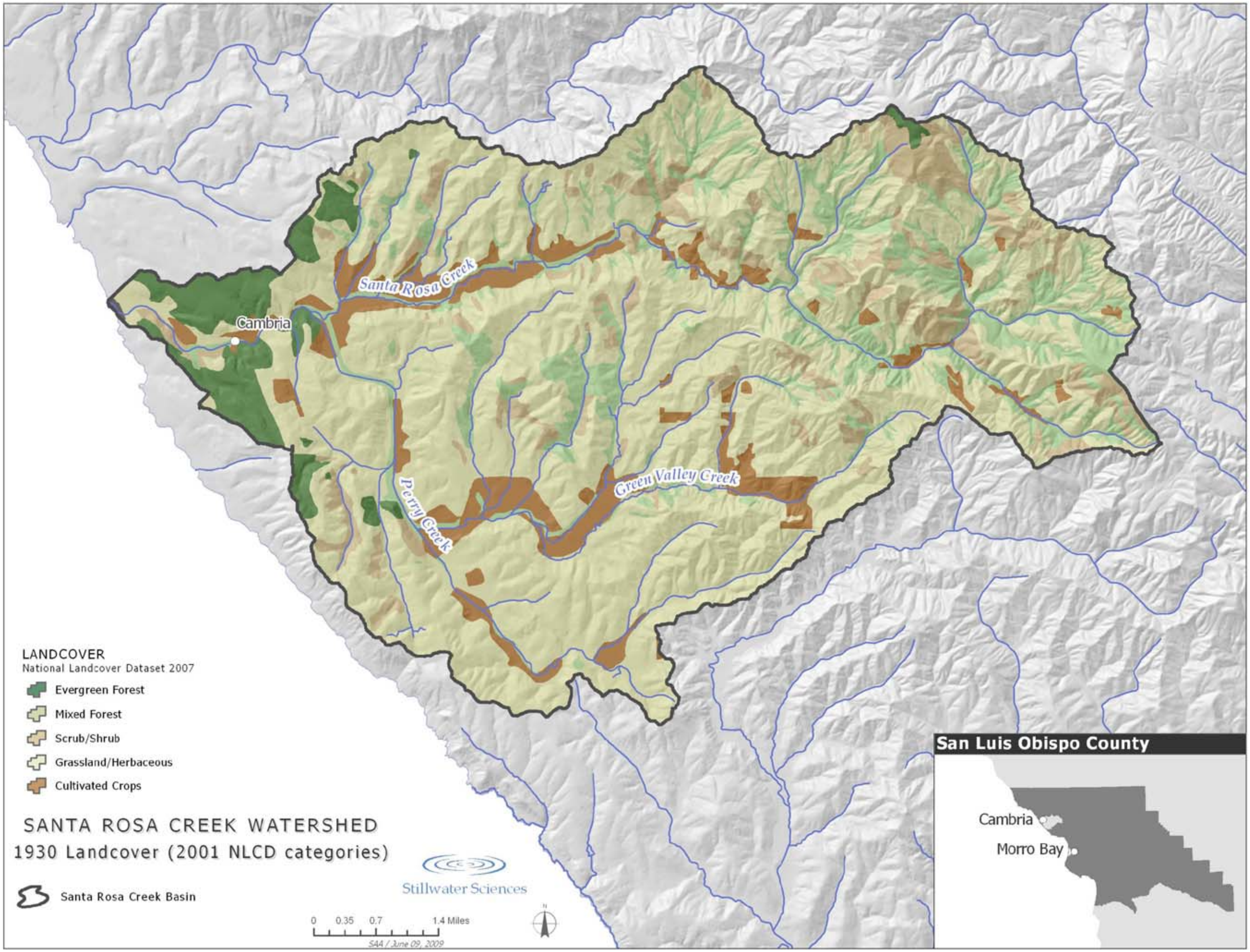

Figure A-9. Land cover present in 1930 within the Santa Rosa Creek watershed (after Weislander 1930).

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Appendix B

Supporting Data for the Geomorphic Landscape Units (GLUs) Analysis

SUPPORTING DATA FOR THE GEOMORPHIC LANDSCAPE UNITS (GLUs) ANALYSIS

This appendix provides supplementary data that were used in the geomorphic landscape unit (GLU) analysis performed for this study to estimate relative sediment production rates across the Santa Rosa Creek watershed. Specifically, data presented here were used in the development of the GLU analysis for this study. The results of the analysis, along with several tables and figures, are presented in the Chapter 3 of the main report. References cited here are listed in the main report.

Geologic Units

Underlying geology information used in the GLU analysis was based on information contained within geology maps published by Dibblee (2007a, 2007b) (see Figure 1-3 in the main report). A list of rock units occurring within the watershed boundaries is presented below in Table B-1, along with rock unit descriptions, relative proportions within the watershed, and the assigned category used in the GLU analysis. Figure 3-3 in the main report shows the generalized geologic categories used in the GLU analysis. These categories represent relative erodibility (i.e., rock strength) of the unit and particle size of the unit's constituent materials (e.g., sand or silt). The relative proportions of the geology GLU categories in the watershed are presented below in Table B-2.

Table B-1. Geologic units within the Santa Rosa Creek watershed.

Geologic unit [1]		Age [1]	Description [1]	% of watershed area [2]	GLU category [3]
Symbol	Explanation				
Qa	Surficial sediments	Holocene	Unconsolidated alluvial gravel, sand, and clay	10.6%	Coarse weak
Qls	Landslide debris	Holocene	Unconsolidated landslide debris	1.9%	Coarse weak
Qm	Marine terrace	Pleistocene	Older marine terraces of unconsolidated cobble-pebble gravel	2.4%	Coarse weak
Tpsl	Pismo Formation	Late Miocene	Marine siltstone or claystone, white, fractured	0.9%	Fine weak
Tps	Pismo Formation	Late Miocene	Marine sandstone, light brown, fine to medium grained, arkosic	0.6%	Coarse competent
Tm	Monterey Formation	Miocene	Marine shale, white weathered, thin-bedded, brittle,	0.03%	Fine weak
Tml	Monterey Formation	Miocene	Marine shale, cream-white to tan, thin-bedded, platy to soft fissile to silty	11.2%	Fine weak
Tt	Monterey Formation	Miocene	Marine tuff, white, very fine-grained	0.1%	Fine weak

Geologic unit [1]			**Age [1]**	**Description [1]**	**% of watershed area [2]**	**GLU category [3]**
Symbol	**Explanation**					
Tb	Obispo Formation		Miocene	Basalt, black weathered dark brown, find-grained, massive, somewhat incoherent, locally pillowed, includes intrusive diabase	2.7%	Coarse weak
Tot	Obispo Formation		Miocene	Volcanic tuff and tuff breccia, white to tan	0.4%	Coarse competent
Tr	Rincon Formation		Early Miocene	Marine claystone and siltstone, gray to light brown, vaguely bedded, crumbly	0.7%	Fine weak
Tvq	Vaqueros Formation		Early Miocene / Late Oligocene	Marine sandstone, light gray to light brown, arkosic	2.7%	Coarse competent
Tlc	Lospe Formation		Oligocene	Non-marine green to red conglomerate, sandstone, and claystone with clasts of volcanic rocks and Franciscan detritus (fs and fg)	2.1%	Coarse competent
Tf	Cambria Felsite		Oligocene	Volcanic: hard rhyolite-dacite gray-white felsite with some soft white tuff, poorly bedded	1.2%	Coarse competent
Kss	Unnamed Sedimentary Rocks		Upper Cretaceous	Marine sandstone, arkosic, with some micaceous shale	8.6%	Coarse weak
Ktsh	Toro Formation		Cretaceous	Marine clay shale, dark gray, micaceous, thin layers of fine-grained sandstone	1.1%	Fine weak
sp	Serpentinite		Jurassic-Cretaceous	Metamorphosed ultramafic igneous rocks, blue-green-gray, fractured with slickensided surfaces	2.2%	Coarse weak
fm	Franciscan Assemblage (marine, sedimentary and volcanic rocks)	Mélange	Jurassic-Cretaceous	Mix of sheared rocks, mostly greywacke and argillite, with fragments of fc, fs, fg	47.8%	Coarse weak
fc		Chert	Jurassic-Cretaceous	Chert, brittle, thin-bedded; contorted	0.3%	Coarse weak
fs		Graywacke	Jurassic-Cretaceous	Graywacke sandstone, hard, massive, shattered	1.3%	Coarse weak

Geologic unit [1]			Age [1]	Description [1]	% of watershed area [2]	GLU category [3]
Symbol	Explanation					
fg		Greenstone	Jurassic-Cretaceous	Greenstone altered from basalt, moderately sheared	1.3%	Coarse competent

[1] After Dibblee 2007a, 2007b.
[2] Proportion of rock unit within the total watershed area determined in GIS.
[3] GLU category based on literature information and field observations.

Table B-2. Geology GLU categories within the Santa Rosa Creek watershed.

GLU xategory [1]	% of watershed area [2]
Coarse competent	8.2%
Coarse weak	77.8%
Fine weak	14.0%

[1] GLU category based on literature information and field observations.
[2] Proportion of geology GLU category within the total watershed area determined in GIS.

Land Cover Units

Land cover was based on a data contained within the National Land Cover Database of 2001 (Homer et al. 2004) at 30-m resolution (see Figure 1-6 in the main report). A list of land cover types occurring within the watershed boundaries is presented below in Table B-3, along with relative proportions within the watershed and the assigned category used in the GLU analysis. Figure 3-7 in the main report shows the generalized land cover categories used in the GLU analysis. These categories represent a simplified division of land cover, or vegetation types as they relate to a relative degree of erosion resistance in different landscape units (e.g., forested hillslopes would be less erodible than those covered only with grasses). The relative proportions of the land cover GLU categories in the watershed are presented below in Table B-4.

Table B-3. Land cover classes within the Santa Rosa Creek watershed.

Land cover classes [1]	% of watershed area [2]	GLU category [3]
Developed, open space	6.4%	Developed
Developed, low intensity	1.3%	Developed
Developed, medium intensity	0.4%	Developed
Developed, high intensity	0.01%	Developed
Evergreen forest	6.4%	Forest
Mixed forest	9.5%	Forest
Scrub/shrub	10.6%	Scrub/shrub
Grassland/herbaceous	63.4%	Ag/grass
Pasture/hay	0.1%	Ag/grass
Cultivated crops	1.2%	Ag/grass
Woody wetlands	0.5%	Scrub/shrub
Emergent herbaceous wetland	0.01%	Ag/grass

[1] Source: National Landcover Dataset of 2001 (Homer et al. 2004).
[2] Proportion of land cover category within the total watershed area determined in GIS.
[3] GLU category based on literature information and field observations.

Table B-4. Land cover GLU categories within the Santa Rosa Creek watershed.

GLU category [1]	% of watershed area [2]
Forest	16.0%
Scrub/shrub	11.1%
Ag/grass	64.7%
Developed	8.2%

[1] GLU category based on literature information and field observations.
[2] Proportion of land cover GLU category within the total watershed area determined in GIS.

Hillslope Gradient Units

Hillslope gradients in the watershed were based on elevation data contained within a 10-m resolution digital elevation model (DEM) dataset provided by the USGS. Using this data in a GIS, a histogram of hillslope gradient values were plotted to visualize the distribution of slopes in the watershed (Figure B-1). For the purposes of the GLU analysis, it is necessary to group the slope values into as few classes as possible provided that each class represents unique ranges of relative erosion and slope instability in the watershed. Based on the distribution of slopes and on field observations, the continuous range of hillslope gradients was categorized into three groups: 0-10%, 10-40%, and steeper than 40% (Table B-5; see Figure 3-8 in the main report).

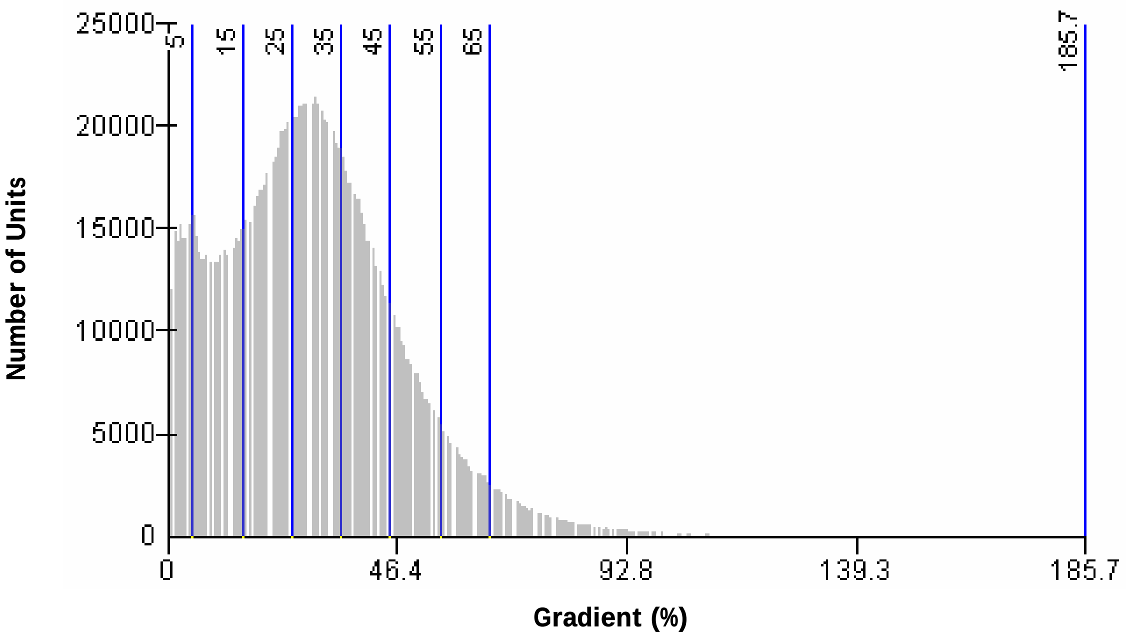

Figure B-1. Histogram of hillslope gradient values in the Santa Rosa Creek watershed.

Table B-5. Hillslope gradient GLU categories within the Santa Rosa Creek watershed.

GLU Category [1]	% of Watershed Area [2]
0-10%	15.3%
10-40%	60.1%
>40%	24.6%

[1] GLU category based on distribution histogram statistics and field observations.
[2] Proportion of hillslope gradient GLU category within the total watershed area determined in GIS.

Appendix C

Channel Reach Descriptions

DESCRIPTIONS OF CHANNEL REACHES

This appendix provides supplementary information on the channel morphology of the stream reaches delineated for the watershed geomorphology assessment. This reach information is based on field assessments made as part of an in-channel geomorphic survey conducted during July 2009. The purpose of the survey was to examine the current conditions in the mainstem Santa Rosa Creek and major tributaries in order to help understand controls on current geomorphic process and help inform the watershed management plan. The geomorphic survey included traversing the mainstem channel and examining geomorphic characteristics and sediment transport dynamics. In addition to general geomorphic information noted during the traverse and estimates of bed particle size, detailed geomorphic data were also collected at 25 locations (15 sites along the mainstem channel at representative locations and 10 sites at major tributaries confluences). The general information and detailed data were compiled with other data sources (e.g., DEM-derived channel network) to develop a comprehensive geomorphic characterization of the channel. The survey locations are shown in Figure C-1 and the geomorphic characterization by channel reach is detailed below. The reaches are shown in Figure 4-6 of the main document.

Upper Zone

The upper-most reach in the Upper Zone (Reach U1) begins at the confluence with Mora Creek and extends 2.4 km downstream to the Unnamed Trib SRC-1 confluence. Throughout the course of this reach, the channel is steep, coarse-bedded, and highly confined by the adjacent valley wall (left bank) and Santa Rosa Creek Rd (right bank). The average reach channel gradient is the steepest of all reaches in the mainstem Santa Rosa Creek subbasin (2.29%), and is strongly influenced by exposed bedrock. Bankfull channel width and depth are relatively low (8–10 m and 0.75–1.0 m, respectively) and the channel bed is moderately entrenched (i.e., several meters below the adjacent, narrow left bank floodplain terrace). The channel transitions from a cascade/plane bed morphology in the steeper upstream end to a pool-riffle morphology at the downstream end where the local channel gradient decreases. The channel bed elevation appears to be relatively stable (as determined from mature vegetation in the active channel) and the bed texture is predominantly poorly-sorted boulder-gravel-cobble (BGC), with a median particle size (D_{50}) between 64 to 128 mm. Channel bars have a similar texture as the bed and are well-vegetated and stable (as determined from mature vegetation on bars), with recent fine sediment deposits on many bars from the last major storm event. Channel banks are composed of bedrock and fine sediment deposits over bedrock, are well-vegetated, and appear to have a low to moderate amount of erosion over the past several decades (based on bank erosion estimates using exposed tree roots at eroding banks and estimated tree age). The reach appears to have some flow throughout the year (summer baseflow at the time of the survey was between 2 to 4 cfs).

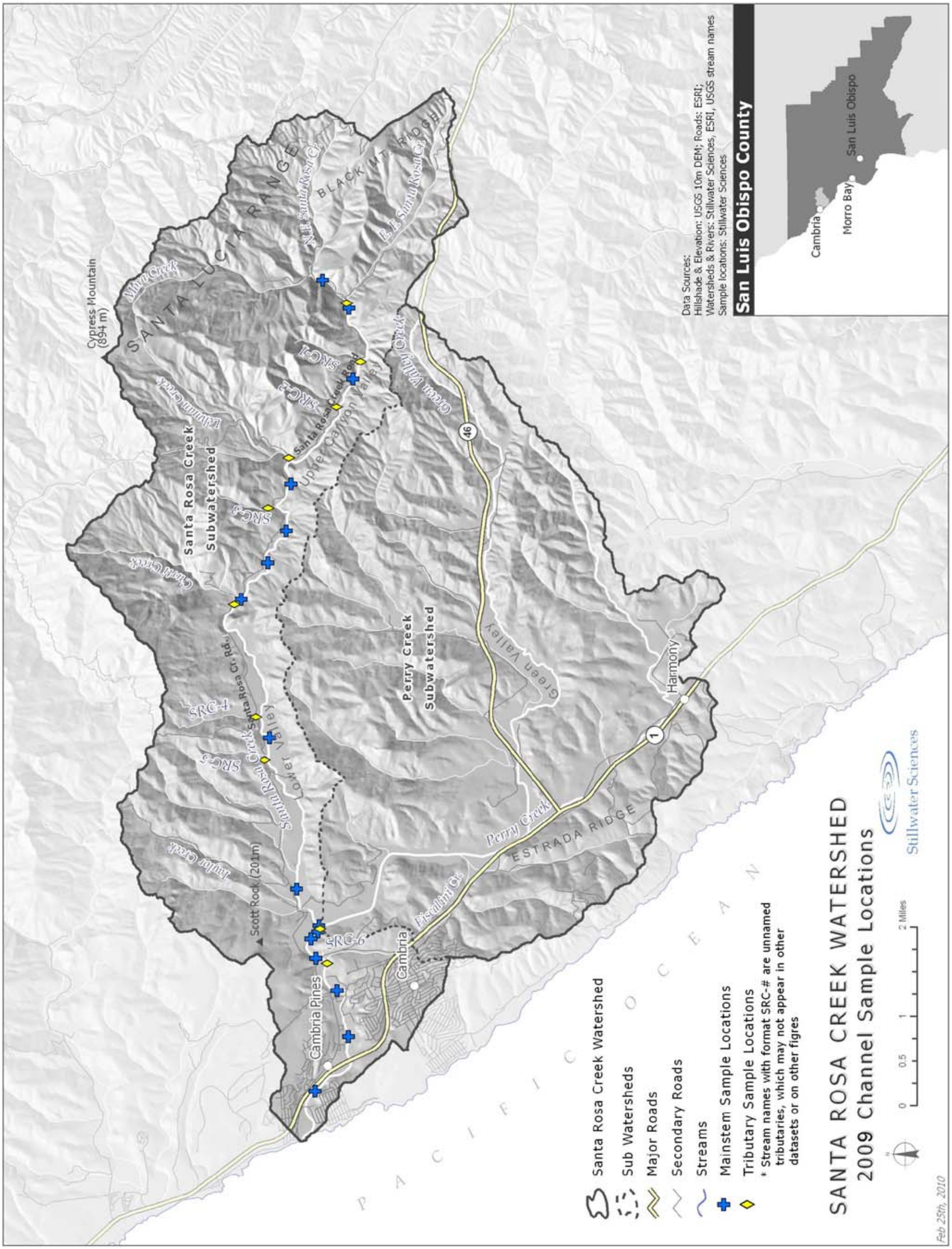

Figure C-1. Stream survey locations along Santa Rosa Creek.

East Fork Santa Rosa Creek enters Reach U1 approximately midway through the reach and is one of the few tributaries in the reach that appears to be a notable source of sediment. At the confluence with Santa Rosa Creek, East Fork Santa Rosa Creek has a relatively moderate channel gradient (1–2%), is moderately entrenched (3–6 m), and appears to have no summer baseflow (as determined from the lack of flow during the summer 2009 field visit). The tributary delivers sediment ranging in size from silt/sand to boulders, but the depositional bar at the mouth suggests the load is predominantly BGC (D_{50} between 64 to 128 mm). The tributary currently appears to be a moderate source of coarse sediment and a low source of fine sediment to the mainstem Santa Rosa Creek, however sediment delivery from the tributary is currently influenced by LWD-induced sediment deposition beginning ~30 m upstream from the confluence. It is not known, the length of time that this hydraulic control has been affecting sediment deposition or how far upstream East Fork Santa Rosa Creek the depositional zone extends.

In spite of it's relatively small drainage area (0.6 km^2), Unnamed Trib SRC-1 appears to be a relatively important source of sediment to mainstem Santa Rosa Creek within Reach U1. Unnamed Trib SRC-1 is a short, steep channel (gradient >5%) on the south-facing hillslopes that appears to have no summer baseflow. Like most Santa Rose Creek tributaries draining south-facing hillslopes, the channel goes through a culvert under Santa Rosa Creek Road before entering mainstem Santa Rosa Creek. Upstream of the culvert, the channel is predominantly depositional but is incised 0.5–1 m. Downstream of the culvert, the channel is unstable and has several headcuts. The tributary delivers sediment ranging in size from silt/sand to boulders, but the sediment load appears to be predominantly CG (D_{50} between 32 to 64 mm). The tributary currently appears to be a moderate source of coarse sediment and a low source of fine sediment.

Downstream of Reach U1, the channel enters a lower gradient, less confined reach that extends downstream for approximately 2.1 km (Reach U2). The average reach channel gradient is relatively steep compared to the other mainstem Santa Rosa Creek reaches (1.17%), although it is approximately one-half the value for Reach U1. Similar to Reach U1, channel gradient throughout the entire reach is strongly influence by exposed bedrock. The decreased channel confinement contributes to a wider bankfull channel than upstream (12–14 m), however bankfull depth is similar to upstream values (0.75–1.0 m). The channel bed is moderately entrenched (but less entrenched than upstream) and has a pool-riffle morphology throughout the reach. The bed elevation appears to be stable and somewhat aggradational (as determined from mature vegetation in the active channel) and the channel bed texture is predominantly cobbley-gravel (CG) and more well-sorted than upstream (D_{50} between 32 to 64 mm). Channel bars have a similar texture as the bed, are well-vegetated and appear stable/aggrdational and more mobile than bars in upstream reach. Channel banks are predominantly composed of bedrock, are well-vegetated, and appear relatively stable but somewhat more erosional than banks upstream. The reach appears to have flow throughout the year and has a summer baseflow discharge similar to Reach U1 (between 2 to 4 cfs).

Unnamed Trib SRC-2 enters the mainstem Santa Rosa Creek in the middle of Reach U2 and appears to be a primary source of sediment to mainstem Santa Rosa Creek within the reach. At the confluence with Santa Rosa Creek, Unnamed Trib SRC-2 has a relatively steep channel (gradient of 2–4%) with no summer baseflow. Similar to the other south-facing valley wall tributaries, the channel goes through a culvert under Santa Rosa Creek Road before entering mainstem Santa Rosa Creek. Upstream of the culvert, the channel has a relatively narrow riparian buffer (low herbaceous vegetation and some mature trees) and appears to be eroding through a recent sediment deposit. Downstream of the culvert, the channel has several headcuts and is incised 2–3 m. The tributary delivers sediment ranging in size from silt/sand to fine gravel, but the sediment load appears to be predominantly fine gravel (Gf) (D_{50} between 2 to 4 mm). The tributary currently appears to be a low source of coarse sediment and a moderate source of fine sediment.

The channel then transitions to a 3.3 km long reach that is characterized by a meandering channel and a more erosional bed (i.e., sediment supply-limited conditions) than upstream reaches (Reach U3). The average reach channel gradient is relatively steep compared to the other mainstem Santa Rosa Creek reaches (1.16%) and is essentially the same as Reach U2. Channel gradient is strongly influenced by both bedrock exposures and bend-induced sediment deposition along the entire reach. Bankfull width throughout this reach is very similar to the bankfull width for Reach U2 (estimates range from 11 to 15 m), however bankfull depth is slightly greater (estimates range from 1.0 to 1.25 m). The channel bed is moderately entrenched (but is more entrenched than Reach U2) and the channel has a pool-riffle morphology in the lower gradient, less confined sections and plane bed morphology in the steeper, more confined sections. Pools within this reach have more fine sediment accumulation than seen upstream and are up to 50 m in length. The channel bed appears to be somewhat incising and channel bed texture is predominantly poorly-sorted CG (D_{50} between 32 to 64 mm). Channel bars have a finer texture than the channel bed (CG with a D_{50} between 16 to 32 mm) and range from well-vegetated and stable to moderately stable and more mobile/depositional. Several vegetated bars at the downstream end of the reach have recent fine sediment deposits. Channel banks are predominantly composed of alluvial deposits (finer and coarse sediment) with bedrock exposures, are well vegetated, and appear moderately stable. Bank erosion estimates range from 0.3 to 0.6 m in the last 30–40 years to 0.6–1.3 m in the past 40–50 years (based on vegetation indicators). The reach appears to have flow throughout the year and has a summer baseflow discharge similar to the upstream reaches (between 2 to 4 cfs).

Lehman Creek is the most upstream major tributary (i.e., large watershed area and high sediment load) draining all of the south-facing hillslopes along mainstem Santa Rosa Creek (downstream of Mora Creek) and enters the mainstem Santa Rosa Creek towards the upstream end of Reach U3. At the confluence with Santa Rosa Creek, Lehman Creek has a relatively steep channel gradient (3–4%), is moderately entrenched, and has a relatively high summer baseflow compared to other tributaries (~5 cfs). The tributary delivers sediment ranging in size from silt/sand to boulders, but the relatively large depositional bar at the mouth suggests that the load is predominantly BCG (D_{50} between 32 to 64 mm). Lehman Creek currently appears to be a high source of coarse sediment and a moderate to low source of fine sediment to the mainstem Santa Rosa Creek.

Unnamed Trib SRC-3 enters the mainstem Santa Rosa Creek in the middle of Reach U3 and appears to be the secondary source of tributary-derived sediment in the reach. Unnamed Trib SRC-3 drains a steep, south-facing catchment and has a relatively moderate channel gradient (2–3%) and high degree of channel entrenchment (~10 m) at the confluence with Santa Rosa Creek. The tributary also has mature riparian vegetation close to the confluence and no summer baseflow. There appears to be historic bank failures adjacent to the road culvert under Santa Rosa Creek Rd associated with the road crossing. The tributary delivers sediment ranging in size from silt/sand to cobbles, but the load appears to be predominantly CG (D_{50} between 16 to 32 mm). Unnamed Trib SRC-3 currently appears to be a low to moderate source of both coarse and fine sediment to mainstem Santa Rosa Creek.

Downstream of Reach U3, the channel then enters a somewhat more confined reach that extends 1.8 km downstream to Mammoth Rock (Reach U4). The average reach channel gradient is relatively steep compared to the other mainstem Santa Rosa Creek reaches (1.20%) but is essentially the same as Reach U3. Channel gradient is strongly influence by the Mammoth Rock bedrock outcrop and associated channel meander at the downstream end of the reach. Bankfull width throughout this reach is very similar to estimates for both Reaches U2 and U3 (estimates range from 11 to 12 m) and bankfull depth is similar to estimates for Reach U3 (estimates range from 1.0 to 1.25 m). The channel bed is moderately entrenched (but less entrenched than Reach U3) and channel morphology can be classified as glide/run, as there is no distinct morphologic structure or depositional bars. The channel bed texture is predominantly well-sorted CG (D_{50} between 32 to 64 mm). The bed sediment is somewhat indurated (i.e., cemented) and downstream hydraulic control induced by Mammoth Rock makes this an aggradational reach. Channel banks are predominantly composed of alluvium deposits (finer and coarse sediment) with bedrock exposures, are well-vegetated, and appear relatively stable. Summer baseflow is infiltrated into the channel bed at the upstream end of the reach and re-emerges at the downstream end of the reach where the channel becomes confined by Mammoth Rock.

Curti Creek is the most downstream major tributary draining the south-facing hillslopes along mainstem Santa Rosa Creek (downstream of Mora Creek) and enters mainstem Santa Rosa Creek in the middle of Reach U4. At the confluence with Santa Rosa Creek, Curti Creek has a relatively steep channel gradient (ranging from 2 to 4% at the mouth to 4 to 8% 50 m upstream), is moderately entrenched (~3 m) with lower inset terraces, and has no summer baseflow. The tributary delivers sediment ranging in size from silt/sand to boulders, but the relatively large depositional bar at the mouth suggest that the load is predominantly CG (D_{50} between 32 to 64 mm). Sediment storage upstream of the Santa Rosa Creek Rd culvert is relatively high. The considerable amount of embeddeness by finer sediment and mature vegetation on the bar surface suggests that the bar is stable/depositional. Curti Creek currently appears to be a high source of coarse and fine sediment to the mainstem Santa Rosa Creek.

Middle Zone

Downstream of Mammoth Rock, the channel confinement decreases and the channel enters the Middle Zone. The upper-most reach in the Middle Zone is within a broad alluvial and is valley that allows active thalweg migration. The average reach channel gradient is moderate compared to the other mainstem Santa Rosa Creek reaches (0.80%) and is strongly influenced by exposed bedrock and channel confinement at the downstream end of the reach. The channel bed is very entrenched (~10 m below adjacent terrace) and is organized into a quasi pool-riffle morphology in short steeper sections, but generally lacks a coherent morphology throughout most of the reach. The channel bed texture is predominantly poorly-sorted GC (D_{50} between 32 to 64 mm). Channel banks are composed of alluvium except along sections at the upstream and downstream ends of the reach where the channel is up against bedrock along the right bank. Where channel banks are composed of alluvium, the banks are actively eroding and are a local supply of fine sediment. Summer baseflow is infiltrated into the channel bed at the upstream end of the reach and re-emerges at the downstream end of the reach where the channel becomes more confined.

Unnamed Trib SRC-4 enters the mainstem Santa Rosa Creek towards the downstream end of Reach M1 and appears to be the primary source of tributary-derived within the reach. At the confluence with Santa Rosa Creek, Unnamed Trib SRC-4 has a relatively steep channel (gradient of 2–4%), is highly incised (~5 m below the adjacent terrace), and has no summer baseflow. Local channel gradient is strongly influenced by the bridge the channel passes through before the confluence with Santa Rosa Creek, and the channel is currently incising through the sediment deposit upstream of the bridge. Observations of the current channel condition and location within the adjacent floodplain suggest that the channel has moved east towards the toe of the adjacent valley wall sometime in the past century. The tributary delivers sediment ranging in size from silt/sand to boulders, but the sediment load appears to be predominantly very coarse gravel (Gvc) (D_{50} between 32 to 64 mm. The tributary currently appears to be a moderate source of coarse sediment and a low source of fine sediment.

At the downstream extent of Reach M1, the channel transitions to a 2.4 km long reach that is characterized by a moderately confined, meandering channel (Reach M2). The average reach channel gradient is somewhat less than Reach M1 but still moderate compared to the other mainstem Santa Rosa Creek reaches (0.62 %) and is strongly influence by exposed bedrock and meander-induced deposition. The channel is very entrenched (~10 m below adjacent terrace) and has a pool-riffle morphology with low terraces that are up to 1 m above the channel bed. Bankfull width estimates along the reach range from 12 to 14 m and bankfull depth estimates range from 0.75 to 1 m. The channel bed elevation appears to be relatively stable/aggradational and the bed texture is predominantly well-sorted GC, with the D_{50} between 32 to 64 mm range. Channel bars are generally somewhat finer than the bed (Gc with a D_{50} between 16 to 32 mm) and vary in degrees of mobility (i.e., bars range from well-vegetated to bare). Several bars with established vegetation have recent fine sediment deposits. Channel banks are composed of bedrock and fine-grained alluvium and are predominantly well-vegetated. Meander bends through this reach have a relatively high bank erosion rate compared to the rest of the reach (estimates from vegetation indicators are as high as 0.75 m in the past 10–20 years) and provide a local supply of fine sediment. Summer baseflow through this reach is somewhat lower than in upstream reaches (summer baseflow at the time or the survey was between 1 to 2 cfs).

Unnamed Trib SRC-5 enters mainstem Santa Rosa Creek in the middle of Reach M2 and appears to be the primary source of tributary-derived sediment within the reach. Unnamed Trib SRC-5 drains a small south-facing catchment and has no summer baseflow. Channel morphology and sediment delivery dynamics are strongly influenced by an old (80–100 years old) road culvert the channel passes through before the confluence with Santa Rosa Creek. Upstream of the culvert, the channel has a relatively moderate gradient (~1 %) and the channel appears stable (as determined from mature riparian vegetation established on the channel bed). Downstream of the culvert, the channel is approximately 8–10 m below the culvert elevation, has a relatively moderate gradient (~1 %), and has banks that are actively eroding. Similar to Unnamed Trib SRC-4, the channel appears to have changed course some time in the past. The tributary delivers sediment ranging in size from silt/sand to coarse cobble, but the sediment load appears to be predominantly medium (D_{50} between 8 to 16 mm). The channel appears to be a moderate supply of both coarse and fine sediment.

The channel then transitions to a moderately confined and entrenched reach that extends 2.4 km to the Perry Creek confluence (Reach M3). The average reach channel gradient through this reach is somewhat steeper than Reach M2, but still moderate compared to the other mainstem Santa Rosa Creek reaches (0.75 %). In-channel bedrock exposure and bend-induced deposition are the primary controls on reach-average channel gradient throughout reach. Local influences on channel gradient and sediment depositional/transport dynamics include the Fistillini Restoration site, a large in-channel LWD structure downstream of the Taylor Creek confluence, and the Fish Ladder. The channel is moderately entrenched for most of the reach (~2–5 m below adjacent terrace) and has a pool-riffle morphology with several long glide/run sections. Bankfull width estimates along the reach range from 9 to 11 m and bankfull depth estimates range from 1 to 1.25 m. The channel bed elevation appears to be relatively stable/aggradational and the bed texture is predominantly well-sorted cobble-gravel (D_{50} between 32 to 64 mm). Channel bars range from coarser-grained stable bars with mature vegetation to finer-grained mobile bars with little to no vegetation cover. Depositional bars can be relatively large compared to upstream reaches, particularly at channel bends. Similar to upstream reaches, bars with established vegetation have recent fine sediment deposits. Channel banks are predominantly composed of fine-grained alluvium, are well-vegetated, and appear relatively stable. Summer baseflow at the time of the survey is estimated to have been between 1 to 2 cfs.

Perry Creek is the largest tributary entering mainstem Santa Rosa Creek and is therefore a primary source of sediment to Reach M3. At the confluence with Santa Rosa Creek, Perry Creek has a relatively low channel gradient (<1%), is very entrenched (8–10 m below the adjacent terrace), and has no summer surface flow yet appears to be discharging subsurface water to mainstem Santa Rosa Creek during the summer (as suggested by the deep pool at the confluence). Approximately 600-m upstream of the confluence is a 2-m high knickpoint that appears to be a result of historic channel re-alignment and re-grading. In general, the tributary has a relatively fine sediment load that includes sediment ranging in size from silt to fine gravel. The very large depositional bar at the mouth suggests that the load is predominantly very fine gravel (Gvf) (D_{50} between 2 to 4 mm). Perry Creek currently appears to be a low source of coarse sediment and a high source of fine sediment to the mainstem Santa Rosa Creek.

Lower Zone

Downstream of the Perry Creek confluence, the gradient decreases and the channel enters the Lower Zone. The upper-most reach (Reach L1) extends 2.9 km downstream from the Highway 1 bridge through Cambria Pines and is characterized by a confined meandering channel. The average reach channel gradient through this reach is relatively low (0.33 %) and less than one-half the gradient of the upstream reach. In-channel bedrock exposure and bend-induced deposition strongly influence reach-average channel gradient throughout reach. The channel is moderately entrenched and has a pool-riffle morphology with several long glide/run sections. Bankfull width estimates along the reach range from 12 to 19 m and bankfull depth estimates range from 1 to 1.25 m. The channel bed elevation appears to be relatively stable for the most part, with localized areas of scour and deposition resulting from localized channel confinement and in-channel bridge infrastructure. The channel bed texture is predominantly poorly-sorted cobble-gravel (D_{50} between 32 to 64 mm), although there are several areas where the bed is composed of poorly-sorted sandy gravel (D_{50} ranging between 4 to 8 mm and 16 to 32 mm). Channel bars have a similar texture as the channel bed and range from relatively mobile bars with little vegetation cover to relatively static bars with mature vegetation established. Vegetated bars at the downstream end of the reach have recent fine sediment deposits. Channel banks are composed of bedrock and fine-grained alluvium, are well-vegetated, and appear moderately stable throughout. Bank erosion estimates range from <0.3 m in the past 20–30 years to >0.6 m in the past 10 years. At the downstream end of the reach, rip rap has been placed at bank toes to help deflect flow in an effort to prevent localized bank erosion. Summer baseflow at the time of the survey is estimated to have been between 1 to 2 cfs at the upstream end of the reach and becoming less downstream as the flow infiltrated into the channel bed.

Unnamed Trib SRC-6 drains a steep, relatively small north-draining catchment (0.8 km^2) that enters mainstem Santa Rosa Creek towards the upstream end of Reach L1 and is the dominant tributary sediment source in the reach. At the confluence with Santa Rosa Creek, Unnamed Trib SRC-6 has a relatively moderate slope that becomes steep at the channel mouth (1–2 %), is moderately entrenched (1–2 m below the adjacent terrace), and has no summer baseflow. Local tributary channel gradient and sediment transport/deposition dynamics are strongly influenced by in-channel LWD approximately 20 m upstream of the confluence. The large bar at the mouth appears to have been deposited in the recent past, causing the tributary channel to change course and the confluence to migrate approximately 10 m downstream. Observations of the channel bed upstream of the confluence and the large bar at the confluence suggest that the tributary has a load ranging from silt/sand to boulders, with a current sediment load that is predominantly very coarse gravel (D_{50} between 32–64 mm). Coarse sediment buried beneath the large depositional bar suggests that the tributary load may have been coarser in the past. Unnamed Trib SRC-6 currently appears to be a high source of both coarse and fine sediment to the mainstem Santa Rosa Creek.

The channel then transitions to a lower gradient depositional reach that flows through Cambria Pines and extends 2.5 km downstream to the channel mouth (Reach L2). The average reach channel gradient through this reach is the lowest in the Santa Rosa Creek subbasin (0.29 %) and is influenced by tidal elevation and at the mouth. The channel is moderately entrenched and becomes less confined downstream of Cambria Pines near the mouth. Bankfull width estimates along the reach range from 20 to 22 m and bankfull depth estimates range from 1.25 to 1.5 m. The channel bed has a pool-riffle morphology and currently appears aggradational, with the channel bed being at a similar elevation as adjacent bars. The channel bed texture is predominantly well-sorted very coarse gravel (D_{50} between 16 to 32 mm), transitioning from coarser sediment upstream to finer sediment downstream. Channel bars have a similar texture to the channel bed and are relatively large compared to upstream reaches, indicating a considerable amount of sediment storage within this reach. Overall, the channel bars appear mobile, but most are covered in young vegetation that has established since the last major storm event. Channel banks are composed of fine-grained alluvium, are well-vegetated, and appear moderately stable throughout (estimates range from 0.3 to 0.6 m in the past 20 years). The reach appears to remain dry during the summer (i.e., there was no baseflow within the reach at the time of the survey in summer 2009).