Attachment 3
San Gregorio Creek Watershed
Rapid Sediment Budget

SAN GREGORIO CREEK RAPID SEDIMENT BUDGET

Prepared for San Francisco Regional Water Quality Control Board

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Final Report

SAN GREGORIO CREEK RAPID SEDIMENT BUDGET

Scope and Objectives

A sediment budget is a useful organizing framework to help understand sediment processes within a fluvial system and to identify gaps in knowledge needed to answer particular questions (Reid and Dunne, 2003). Examination of sediment erosion, transport, or deposition processes focused toward answering specific questions regarding sediment sources, sinks, and yield was termed a “rapid sediment budget” (Reid and Dunne, 1996). Because instrumental records are relatively short compared to the time-span of historical land use changes in the San Gregorio watershed, and quantitative long-term data documenting magnitude, rates, and distribution of geomorphic processes over the period of human changes are not available for the San Gregorio watershed—this study utilizes the rapid sediment budget approach as the context to help understand changes in sediment delivery and storage processes in San Gregorio Creek watershed over the historical period. Development of relevant time periods for a rapid sediment budget is dependent on both the record of land use history and the spatial availability of quantitative data for analysis.

The scope of this study includes review of historical documents to understand the timing and nature of land use changes, review of prior geomorphic mapping that documents hillslope processes such as landslides and debris flows, and review of quantitative data related to sediment collected in the San Gregorio watershed, such as USGS gaging station records and results of other prior data collection efforts. In addition, this study includes results of field data collection at six study sites conducted in Fall of 2014, and analysis of 1941 aerial photographs (the highest resolution earliest photographic record available) and 2007 aerial LiDAR (the most recent high resolution imagery available with temporally correlated 2006 NAIP aerial photography). This work builds on the sediment components of numerous other past management and restoration studies and complements those underway.

The objectives of this study are to synthesize the available data and results of field work conducted during the Fall of 2014 and to the extent possible address the significant active geomorphic processes that deliver sediment to channels, identify physical and climatic attributes of the watershed that influence sediment dynamics, current and/or historical landuse activities that influence sediment delivery rates relative to pre-disturbance natural background rates, changes in channel sediment storage and sediment supply in alluvial channel reaches and the lagoon, and relationships between grain size distributions in channels and bed mobility, pool filling, and sediment supply. Finally, gaps in knowledge identified and future studies warranted to understand geomorphic processes in San Gregorio Creek are discussed.

Physical and Climatic Attributes of the San Gregorio Creek Watershed

San Gregorio Creek drains ~135 km^2 of the Santa Cruz Mountains within the California Coast Ranges. The San Gregorio Creek drainage network includes La Honda and Alpine Creeks that join to form San Gregorio Creek ~11 km upstream of the Pacific Ocean. Tributaries joining San Gregorio Creek from the north include Harrington Creek, Bogess Creek, El Corte de Madera Creek, Clear Creek, Coyote Gulch, an unnamed tributary, and Palmer Gulch. Kingston Creek joins San Gregorio Creek from the south (Figure 1).

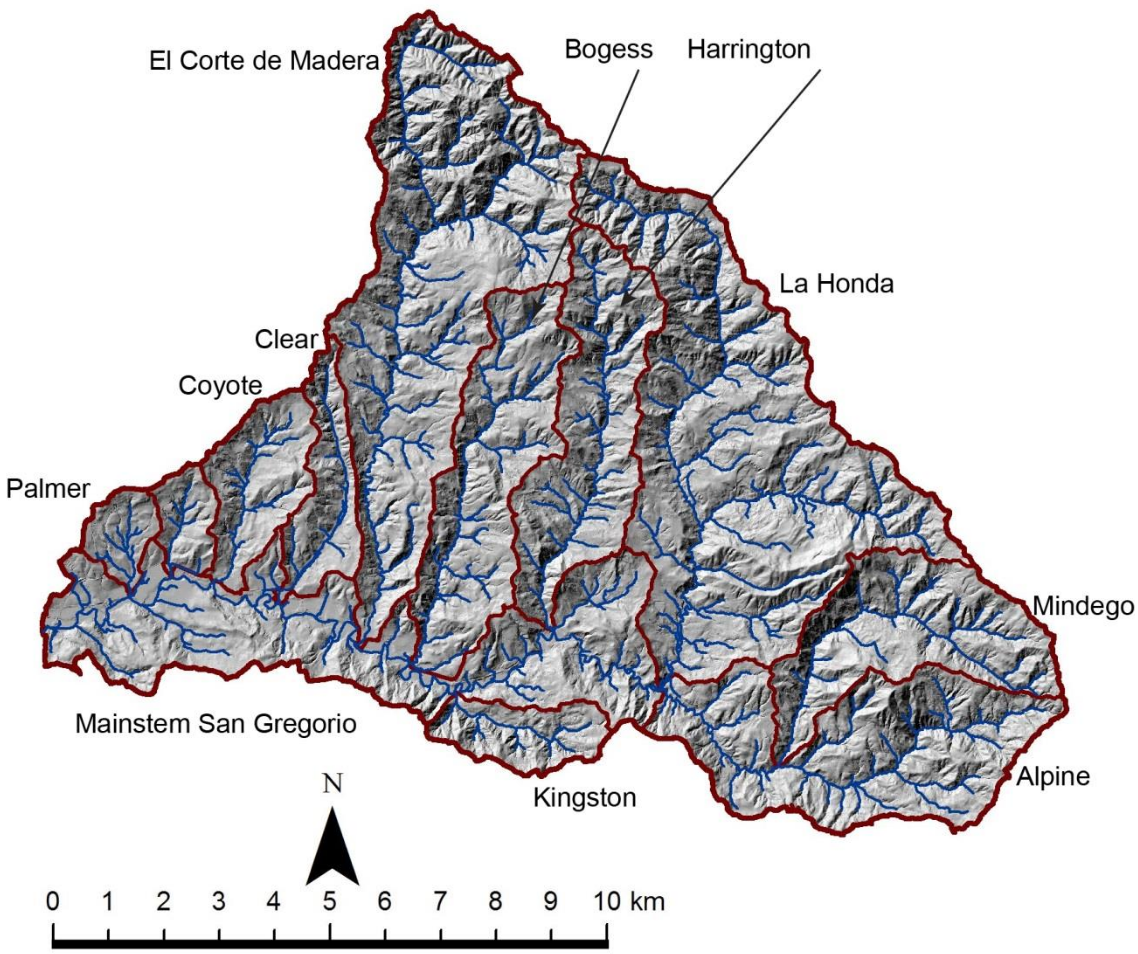


Figure 1. Map showing subbasins in San Gregorio Creek watershed.

The San Francisco Peninsula is underlain by complex geology that is influenced by active lateral movement and uplift, and changes in Pleistocene and Holocene sea level (Sloan, 2006). Lithologic associations in San Mateo County are divided in to assemblages within large blocks bounded by faults where Tertiary strata overlie Mesozoic rock complexes (Brabb et al, 1998;

Graymer et al., 2006). The San Gregorio watershed lies within the La Honda Block—an assemblage of rock sequences bounded by two northwest-southeast trending faults in the San Andreas Fault system: the Pilarcitos Fault to the east and several strands of the San Gregorio Fault that cross San Gregorio Creek near the mouth of the watershed. Recent estimates of slip on the San Andreas Fault are ~15-18 mm/year (d'Alessio et al., 2005). Estimates of vertical uplift rates reflected in six uplifted marine terraces near Pidgeon Point (adjacent to the elevated Santa Cruz Mountains and the Pacific Ocean) range from ~0.3 mm/yr (Figure 1.8 in Weber and Allwardt, 2001; Gudmundsdottir et al., 2013) to as much as 1.2 to 1.4 mm/yr (Perg et al., 2001). Earthquakes may be a significant trigger for landslides in the San Gregorio Creek watershed because of its proximity to faults within the San Andreas system. For example, Wieczorek and Keefer (1984) documented a seismically induced landslide near the town of La Honda during following the 1984 Morgan Hill earthquake.

The La Honda block itself consists of a thick sequence of marine sedimentary and volcanic rocks that are internally faulted, folded, and tilted such that smaller fault-bounded blocks are present within the larger La Honda block. Tertiary lithology within the La Honda block, from older to younger is comprised of the Butano Sandstone (Tb), the San Lorenzo Formation (Tsl), the Vaqueros Sandstone (Tvq), the Mindego Basalt (Tmb), the Lambert shale (Tla), the Lambert shale and San Lorenzo Formation undivided (Tls), and several sandstone and shale members of the Purisima formation (Tp_x). Quaternary lithologies include Pleistocene Marine Terrace (Qmt) and Older Alluvial Fan deposits (Qof). The Pleistocene fans (e.g. Qof) have been uplifted several meters since deposition (Brabb et al., 1998). Holocene lithologies comprise Alluvium, deposited by San Gregorio Creek (Qal), colluvium, the weathered sediment on hillslopes (Qcl), and Younger Alluvial Fan deposits (outer-Qyfo, inner-Qyf).

The northern and eastern portion of the watershed has somewhat higher relief and longer tributary lengths than the southern portion. The influence of tectonics is illustrated in the northwest oriented hillslopes separating the tributaries draining the northern drainage divide that follow the trend of the San Andreas Fault system. The watershed rises from the Pacific Ocean to ~770 m in elevation within ~20 km of the coast resulting in terrain with diversity in climate zones and associated vegetation and in slope that gives rise to variation in channel morphology. Morphology in headwater channels are debris-flow dominated; as slope decreases, morphology transitions to cascades, step-pool and riffle-pool sequences (*sensu* Montgomery and Buffington, 1997).

The valley bottom along the mainstem San Gregorio Creek is relatively narrow with Pleistocene and Holocene side-valley tributary fans present adjacent to the creek. Active floodplain processes are not prominent in the lowland portion of the main channel; instead, the main channel of San Gregorio Creek is incised into sediment mapped as Pleistocene alluvial fan and stream terrace deposits (Qof) and smaller and younger Holocene alluvial fan deposits (Qyf [inner]; Qyfo [outer]; Brabb and Pampayan, 1972). In the narrow tributaries, valley bottom sediment is derived from hillslopes and side valley tributary fans. The creek flows into a small lagoon before joining the Pacific Ocean. A small bar-built seasonal estuary present at the mouth of the watershed is intermittently opened by high flows in San Gregorio Creek.

Climate Variation

The Mediterranean climate of coastal California is characterized by variability on a seasonal basis, as well as variation caused by cyclic and episodic climate phenomena that occur over years, decades, centuries, and millennia. Available precipitation and discharge records illustrate short-term variability. For example, the annual rainfall distribution in San Gregorio Creek is strongly seasonal, with the majority of the rainfall occurring between November and March. During the 24 year period between 1950 and 1977 at La Honda (data from http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?ca4660), annual precipitation ranged from 356 mm to 1,205 mm, with a mean annual rainfall of ~761 mm.

The El Nino Southern Oscillation (ENSO) phenomenon that occurs on an ~3-6 year time scale (Ghil et al., 2002) includes the El Nino phase, with wet winters in southern California and dry winters in the Pacific northwest, and the La Nina phase with the reverse pattern; however, central California is situated such that conditions can be wet or dry during either phase. The Pacific Decadal Oscillation (PDO, Mantua et al, 1997) occurs on a longer time scale of ~20-30 years and has a similar precipitation pattern. Large storms generated by Atmospheric Rivers are thought to have recurrence intervals of ~200 years (Dettinger and Ingram, 2013). Wildfires are a natural consequence of dry conditions during the annual or multi-annual drought conditions.

The timing, frequency, magnitude, intensity, and duration of storms strongly influence fluvial sediment transport and delivery of sediment from hillslope sources to stream channels. Although detailed measurements are not available at the scale of the watershed, Wiezorek (1987) reports detailed data for rainfall before and during 10 storms occurring between 1975 and 1984 near La Honda. His work illustrated the importance of antecedent moisture conditions such that no debris flows were triggered before 28 cm of rainfall had accumulated each season, with the number of flows increasing with duration and intensity above that threshold. The largest of these events occurred in 1982, an El Nino year. As a consequence of the variable climate and rainfall patterns, flow discharge is highly variable (Figure 2).

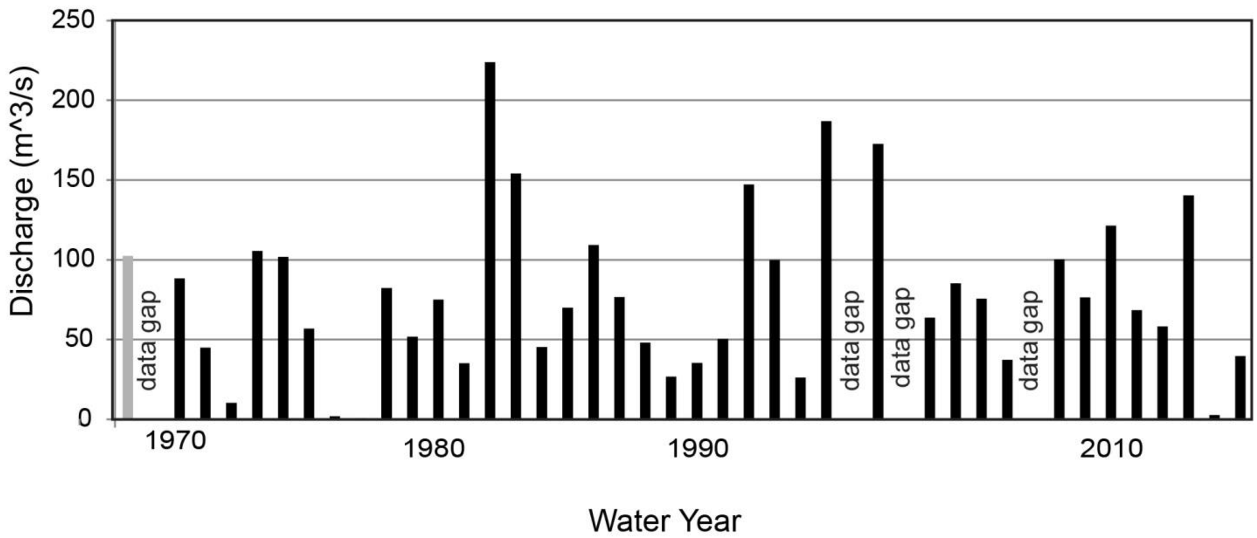


Figure 2. Peak flow measured at USGS gage 11162570: San Gregorio Creek at San Gregorio CA.

In central California, the annual dry season often lasts over half the year, whereas, high magnitude river flows that transport bedload have short duration. During the period of record (~1970 to 2015), gaging data suggests relatively high flows (> 100 m^3/s) occurred during water years 1973, 1974, 1982, 1983, 1986, 1992, 1993, 1995, 1997, 2008, 2010, and 2013. A data gap was present during the relatively high flow generated by the 2006 storm. Drought conditions occurred in 1976-7 and 2014.

Timeline of Landuse Changes

3500 BC - 1769

The coastal Ohlone (also known as Costanoan) native American tribes that occupied San Gregorio watershed harvested seeds, nuts, and edible plant bulbs, and hunted deer, pronghorn, Tule elk, brown and grizzly bears, mountain lion, and other game. They created a managed landscape while burning and pruning plants for thousands of years (Mark Hylkema, Associate State Archaeologist; Interpretive sign at Russian Ridge Open Space Preserve on Alpine Road). At Sand Hill Bluff, ancestral home of the Ohlone north of Santa Cruz, CA., archaeological investigations include radiocarbon dated items indicating that the dune was first occupied ~3,500 B.C., e.g. suggesting that the California Central Coast was inhabited by at least ~5,500 years ago (http://www.parks.ca.gov/?page_id=24203). The first Spanish exploration, The Portolá Expedition, encountered the Olijon tribe in the San Gregorio Watershed during the fall of 1769, as described in historical records provided by Milliken et al. (2009): *"…At San Gregorio*

Creek the Oljons gave a festive welcome to the Spaniards: As soon as we had reached this place ... the whole of the big village here came over... They brought us large shares of big dark-colored tamales they make from their grass-seeds…. The Portola party stayed with the Oljon tribe for two days, over which time they were fed at each meal time."

Although the natural fire return interval of ~135 years would be expected for redwood forest in the Santa Cruz Mountains (Greenlee and Langenheim 1990), recent work conducted in Quiroste Valley (~20 km south of San Gregorio Creek) suggests that by at least 950 years ago, frequent low intensity fires were intentionally ignited every one to five years to maintain grasslands (Lightfoot, K.G., et al., 2013). Despite the anthropogenic increase in fire frequency, sedimentation rates (measured in a pond) remained low, averaging only 0.5 mm per year (Cowart and Byrne, 2013).

1770 - 1822 Spanish Rule, Mission Period in California

By the end of 1793 in the northern and central Peninsula—the coast from the Golden Gate south to San Gregorio Creek—was devoid of tribal villages as Native Americans died or were relocated to the missions (http://www.nps.gov/goga/historyculture/upload/Chapter-4.pdf). The Santa Clara (established in 1770), Dolores (established in 1776), and San Mateo (established in 1793) missions brought agricultural activities and grazing to nearby landscapes that was accompanied by the transformation of native watershed vegetation to European grasses conducive to cattle ranching.

1822 - 1850 Mexican Rule, Establishment of Ranchos and Mexican Land Grants, Agricultural Activities

Rancho San Gregorio, an ~18,000 acre parcel formerly belonging to the missions, was given by Governor Juan Alvarado to Antonio Buelna in 1839. The *Diseño del Rancho San Gregorio in present day San Mateo Co., Calif* map shows the boundaries of the land grant extending north to south from Tunitas to Pomponio Creek and extending west to east from the Pacific coast to the mountains including La Honda (http://content.cdlib.org/ark:/13030/hb396nb0w4/?). The Rancho period brought an intensification of agriculture including cattle and sheep ranching, dairying, and dry farming. Buelna built the first road in the present location of La Honda and Old La Honda Road traversing Sky Line Ridge. Decedents of Buelna began to divide and sell land in the 1850s.

1850 - 1890 California Statehood, post-Gold Rush Population Influx, Rural Development, and Expanded Agriculture

The 1848 discovery of gold in California brought an influx of immigrants and their descendants who obtained and further subdivided land. Foss (1941) describes land use activities that followed the land purchases. Table 1 documents examples of construction of homes, cottages, and farming activities that may have been accompanied by vegetation clearing and soil disturbance. Foss (1941) noted a large forest fire near La Honda in 1887.

Table 1. Farming Activities 1850-1920 (after Foss, 1941); Total area described = 15,383 ac (62.3 km^2)

Date*	Immigrant	Area (acre)	Sub-Watershed	Land Uses
1853	Weeks	2,300	La Honda	Established dairy, supplied butter and cheese to lumber mills on the summit and Deer Gulch region. Subdivided-sold land to Knotts (300 ac), built a home and started a dairy, kept fowl.
1856	John and Dubbs	1,500	Harrington Creek	Constructed dairies, raised livestock, and grew wheat, hay, and grain.
1858	Steinberg	130	La Honda	Started a dairy and raised fruit trees, mostly apple. In 1875 purchased additional 400 ac where he constructed a cabin for summer guests.
1860	Woodhams	1,120	Questa La Honda	Built home, dairy, barns and raised cattle and hogs, grew hay and grain (wheat, oats, barley). 1879 built new home later used as guesthouse.
1861	Sears	373	Harrington or La Honda?)	Built a 2-story home and barn.
1872	Mendico	840	Alpine (Mindego)	Owned and operated a large cattle ranch.
1865-1875	Ridgeway and A.B. Rowley	5,000	Alpine and La Honda	Raised cattle.
1880	Iverson	na	La Honda	Bought steam thresher and threshed grain for local farmers.
1867	Rogers	320	Alpine	Built house.
1875	Blomquist		La Honda	Farmed.
1869	Bartley	na		Worked on Dubbs Ranch.
1872	Langley	2,000	La Honda	Built home.
1870	Edwards	60	Alpine	Built home, grew grain (oats) and hay.
1870	Wilbur	400	La Honda	Raised grain (barley, oats) and hay.
1870	Lowd	"Small strip"	La Honda	Built cabin. In 1880, purchased chicken ranch.
1871	Rich	900	La Honda	Rented land.
1873	Monotti	400	La Honda	Raised beef cattle, had a dairy, and raised hay and grain.
1890	Rapley	40	La Honda	Sons raised cattle and farmed.

*Date of earliest activity

<u>Road construction</u> initiated during the Rancho Period, connected the Rancho San Gregorio to land on the eastern side of Skyline Ridge along San Francisco Bay. Further development was undertaken by an influx of immigrants following California's Gold Rush (Table 2).

Table 2. Road Construction Activities (after Foss, 1941; Wikipedia, 2014)

Date*	Immigrant	Activities
1839	Buelna	Constructed La Honda Road and Old La Honda Road over summit
1872	Weeks	Obtained contract and constructed road from La Honda junction to San Gregorio House.
1873	Rodgers	Road over the Alpine to the top of the ridge
1878	Rowley	Lobbied for and finished road connecting La Honda to Summit Springs Road over the Alpine
1882	Murphy	Rebuilt road across Alpine Creek
1886	Edwards	Worked on crew to gravel part of La Honda Road
1887	Edwards	Worked on crew to gravel road from Weeks ranch home to La Honda Road

*Date of earliest activity

1859-- Logging and Milling Activities

Tree removal for fuel and land clearing for agriculture during Spanish and Rancho Periods expanded as the post-gold rush San Gregorio Creek watershed population increased. The first mills documented by Foss (1941) presumably cut lumber from nearby sources in the San Gregorio Creek Watershed beginning in the late 1850's. Milling and associated logging activities intensified in the next several decades. Logging of second/third growth forests occurred in the next century. Foss (1941) and Stanger (1967) describe concurrent milling activities that followed the land purchases. Table 3 documents at least 25 mills present in the watershed between 1859 and 1890.

Table 3. Milling and Logging Activities 1859-1890 (after Foss, 1941; Stranger, 1967)

Date*	Immigrant	#	Sub-Basin	Activities
1857	Jones & Mills	1	La Honda	In 1856, John Franklin persuaded Jones and Mills to buy Dennis Martin mill and in 1857 they moved it to the Headwaters of La Honda Creek where they cut timber off the western slope for 4 years. In 1860 old type of mill replaced with circular saw.
1859	Gilbert, Gilbert & Irish	1	Harrington	Built shingle mill in headwaters of Harrington Creek using water to propel the mill until Gilbert purchased it in 1865 and replaced it with a circular saw.
1859	Carter & French	2	San Gregorio	Carter opened water propelled mill in 1859 on San Gregorio Creek ~one mile from La Honda Creek, and another mill closer to the junction.
1860	A. Saunders Mill	1	Arroyo El Corte de Madera	http://www.weeklywalker.com/Walks%20by%20county/San%20Mateo/elcorte_thenorthernloop.htm from "Sawmills in the Redwoods" by Frank M. Stanger, published by the San Mateo Historical Association, 1967.
1861	Harrington Mill	1	Harrington	Built mill on western slope of Harrington Cr—but abandoned because transportation was poor.
1861	Morrison	1	Bear Gulch	Morrison built saw mill in Bear Gulch just below the summit in 1861. In 1865 it was purchased by Hanson & Ackerson.
1861	Gilbert & Stambaugh	1	NE corner of Rancho San Gregorio	Saw and Shingle Mill auction http://www.sfgenealogy.com/sanmateo/history/gazette/smnews43.htm.
1862	Judge Templeton Mill	1	San Gregorio	Shown on map in Foss (1941); two miles from San Gregorio 1876 sold to Hanson Ackerson--Ad appeared in paper when mill opened on May 20, 1876—cutting 15-20 thousand feet under supervision of Palmer.
1865	Hanson& Ackerson	1	La Honda	Hanson & Ackerson moved Morrison mill from Bear Gulch to Deer Gulch in La Honda (closed in 1871 because prices fell—but started next year). They also purchased the Judge Tempelton Mill.
1865	Hansen & Ackerson	2	La Honda	Mill in La Honda (headwaters) and another mill upstream of Langley Mill.

1865	Pharis (Shingle Mill)	1	Arroyo El Corte de Madera	http://www.weeklywalker.com/Walks%20by%20county/San%20Mateo/elcorte_thenorthernloop.htm from "Sawmills in the Redwoods" by Frank M. Stanger, published by the San Mateo Historical Association, 1967.
1865	Templeton	1	La Honda	Reported in SFEI, 2004 (from Stranger, 1967).
1867	Peers	1	Alpine	Purchased mill in Pescadero headwaters that gave him access to 1040 acres of redwood and fir in Alpine Creek. Continued mill through 1888.
1876	Hanson & Ackerson	1	San Gregorio	Moved San Gregorio mill near the junction another mile downstream to a new body of timber; started to cut tank bark in addition to timber.
1876	Weeks &Sons	3	La Honda	Weeks started "Centennial" lumber mill. Sons later started another mill below the farm house, and another at confluence of La Honda and Woodruff Creeks. Trees cut in upper Woodruff Cr and hauled to mill at lower end by bullwhackers.
1881 1884 1886	Hansen & Ackerson	3	Alpine	Shown on map in Foss (1941). 1886: San Gregorio junction mill moved upstream into Alpine Cr.
1886	Jones & Franklin Mill	1	La Honda	Mill on tributary to La Honda Creek. (SFEI notes earlier operation 1856-1859, destroyed by fire).
1882	Maddox Mill	1	Alpine	Shown on map in Foss (1941).
1890	Langley Brothers	1	La Honda	Started small mill on tributary to La Honda Creek.
1895	Blomquist	1	Alpine	Shingle mill; ran it until 1903.

Foss (1941) noted high degree of milling activity at various times, for example in 1877: "teamsters hauling lumber 12 hrs/day out of deer gulch mill and San Gregorio mill, just below the junction" and suggested that the high yield Hanson-Ackerson mills peaked 1881-1882.

1920-- Rural Residential Development

Rural residential development initiated during the immigration influx following the gold rush occurred as immigrants built homes and cabins, described above. Further construction and land development took place as property was subdivided. The watershed was promoted as a vacation destination, primarily for fishing, with renewed development occurring in the 1920s. For example, the Cuesta La Honda Guild, incorporated in 1936, included hundreds of homes in the hills near La Honda. Initially built as vacation homes, the area later transitioned to year-round residency. USGS has investigated hillslope instability in this area (e.g. Jayko et al., 1998). Besides rural residential development in La Honda, there is sparse development in the town of San Gregorio, and along San Gregorio and Alpine Creeks.

1920-- Oil and Gas Development

The La Honda Oil Fields consist of a "main" area north of Hwy 84 in the Harrington Creek drainage, and a "southern" area in an unnamed tributary to San Gregorio Creek northeast of Kingston Creek and in the headwaters of Kingston Creek. These areas within Miocene sedimentary rocks were first developed for oil extraction in the 1920's, however the majority of the extraction started in 1956. A 1986 report (Hector, 1986) shows diminishing oil, gas, and water yields and indicates that increased production would be possible in the future.

1960--Large Woody Debris Removal

The headwaters of Alpine and Mindego Creeks, La Honda Creek, Harrington Creek, and El Corte de Madera Creek are all within a zone that once included old growth Redwood and Douglas fir forests. It is likely that large woody debris was supplied to these channels and influenced sediment transport and storage rates as well as pool and bar development in downstream areas. Large woody debris jams were often considered a barrier to fish passage prior to the 1990's; thus, their presence was noted during DFG stream inventories starting in the 1960s (Table 4; San Gregorio Creek Book 1, 2, and 3 and Compendium of Reports compiled by Robert Zatkin). Subsequent removal of debris jams would have released stored sediment. Because of the recent understanding that large woody debris provides significant aquatic habitat complexity, currently, large woody debris is added to stream channels as part of habitat restoration efforts.

Table 4 Examples of Large Woody Debris noted by Department of Fish and Game, DFG (source: Zatkin, San Gregorio Creek I, II, and III and Compendium of Reports).

Location	Feature Documented	Data Source
Alpine	Log and brush jam: ~3.1 miles upstream of confluence with La Honda	DFG, 1963 from Zatkin SG#1
Alpine	Log jam: 12 foot high (New Growth Forestry contracted by DFG to remove jam by winter 1986)	DFG, 1985 from Zatkin SG#1
Alpine	Log jam: ~stream mile 0.5: , 7.5 ft high, 80 ft long, 42 ft wide (upstream channel bed aggraded 7 ft); minor log jams over a 25 ft length	DFG, 1997 from Zatkin SG#1
Mindego	Log jams: numerous	DFG, 1964 from Zatkin SG#2
Mindego	Log jams: numerous 3 to 5 ft jams bet. mile 2.25 and 4.25	DFG, 1973 from Zatkin SG#2
La Honda	Log jams: 20 partial, 3 complete	DFG, 1964 from Zatkin SG#1
La Honda	Log and earth blockages: ~3 caused by logging road construction	DFG, 1973 from Zatkin SG#1
La Honda	Log and debris jams: 26 present	DFG, 1985 from Zatkin SG#1
La Honda	Log jam: upstream of Woodruff Cr; 100 ft x 20 ft x10 ft	DFG, date unknown from Zatkin SG#3
El Corte de Madera	Brush and log jam: mapped in lower creek	DFG, 1964 from Zatkin SG#1
El Corte de Madera	Reach 2-3: Many log jams, some as high as 25 ft on their downstream side caused by poor logging practices; Reach 4: two log jams 30 ft high on downstream side and 10 ft and 7 ft high on upstream side; Reach 5: log jam 10 ft high on downstream side and 3 ft high on upstream side	DFG, 1985 from Zatkin SG#1
Harrington	Log jams: Numerous "Harrington creek underutilized as steelhead spawning habitat…effort should be made to remove log jams."	Seldon, 1972 from Zatkin SG#1
Kingston	Log jams: 6 present	DFG, 1985 from Zatkin SG#3
San Gregorio	No barriers	DFG, 1975 from Zatkin SG#2
San Gregorio	Log jams: sketch map shows 2 present	DFG, 1985 from Zatkin SG#1

Roads: a Legacy of Logging Era and other Watershed Land Uses

One legacy of the prior century's logging and development practices was the construction of networks of unpaved roads. Although logging activities are not current, some roads remain in use for recreation in portions of the watershed that are now part of the watershed's open space. Work to evaluate and minimize road erosion and to prioritize sites for future restoration is on-going through inventories conducted by the open space preserve district (Best, 2002; 2005; 2007; 2012). Table 5 summarizes length and density of roads inventoried in various lithologic units. El Corte de Madera subbasin, with the majority of the forested area and where logging activities were most prevalent in the late 1800s currently has the highest road density.

Table 5. Roads inventoried in the San Gregorio Creek Watershed.

Location	Area (km^2)	Length Roads* (km)	Road Density (km/km^2)	Primary Lithologic Units	Data source**
El Corte de Madera Open Space Preserve	11.3	56.3	5	Butano Sandstone, Lambert Shale and Vaqueros Sandstone	Best, 2002
Russian Ridge, Rappley	8	29.8	3.7	Lambert Shale and San Lorenzo Formation with large deep seated translational landslide/earthflow complexes	Best, 2005
Mindego Ranch	4.2	14.7	3.5	Mindego Basalt	Best, 2012
La Honda Open Space Preserve	8.4	24	2.9	Butano Sandstone, undifferentiated Lambert Shale and San Lorenzo Formation	Best, 2007

*represents the length of roads inventoried

**more detailed information may be found in these sources

Recent land uses

Today a large portion of the San Gregorio watershed that was previously logged or, grazed or farmed is in open space preserves or parkland. Recreational use by motorcycles and logging of second or third growth occurred in the El Corte de Madera basin prior to land acquisition of the land by the open space district. Current land uses in the watershed include recreation and restoration for conservation in open-space and parks, grazing, farming and sparse rural residential development. Over ~60 km^2 are publically owned; additional information related to current land uses is detailed in Stillwater, et al (2010).

Erosion Processes Active in San Gregorio Creek

Channel Incision

Channel incision in tributaries and main channels within a watershed is a potential source of sediment to downstream areas of a fluvial system. Moreover, bank erosion is often associated with incised channels when bank heights exceed thresholds of stability. To assess whether incision occurred in the past and if incision is currently an active geomorphic process in the San Gregorio Creek Watershed that delivers sediment downstream, field data from six study sites, recent LiDAR, historical stream gage data, and historical maps are analyzed. Observations from aerial photographs suggest that the riparian zone along San Gregorio Creek is limited to elevations below both surfaces, which may correspond to proximity to the ground water table. Bare banks are not commonly observed from aerial photographs except for a few locations along the outside of bends—erosion on the outside of bends is an integral component of sediment dynamics in natural rivers.

Field surveys collected in 2014 for this study enabled utilization of a dimensionless metric "relative incision," h_t/d_e, that quantifies the ratio of terrace height (h_t) relative to effective flow depth (d_e), e.g. the flow required to transport sediment to a gravel bar surface (Florsheim et al., 2013). Prior estimates in stable northern California alluvial creeks suggest that bar surface elevation is ~71% of bankfull depth. Using the relative incision ratio, it is possible to objectively determine if a channel is incised. The ratio is predicted to be near a threshold value of 1.0 in stable alluvial channels; in incised alluvial channels the dimensionless ratio is predicted to exceed 1.0. Table 6 reports average terrace heights and bar heights above the channel thalweg, and the ratio h_t/d_e. At the study sites where h_t/d_e is calculated, the ratioranges from 2.0 to 3.8—indicating objectively that the tributaries and main stem of San Gregorio Creek incised at some time in the past. Incision increases the transport capacity as flows become deeper when confined within the channel instead of overflowing onto a wider floodplain.

Table 6. Average terrace heights and bar heights above the channel thalweg and the ratio h_t/d_e.

Field Site	Av Terrace Height (m)	Av Bar Height (m)	h_t/d_e
Alpine Creek @ Sam MacDonald County Park	2.9	0.3	8.2
La Honda Creek @ Open Space Preserve	3.4	0.5	4.8
San Gregorio Creek @ Apple Orchard I	3.7	0.6	4.4
San Gregorio Creek @ Apple Orchard II	4.2	0.3	9.3
Harrington Creek @ Driscoll Ranch	2.6	0.4	4.6
El Corte de Madera Creek @ Open Space Preserve	na	0.5	na

Upstream of the lagoon, the main channel of San Gregorio Creek incised into Pleistocene alluvial fan and stream terrace deposits (Qof) and smaller and lower elevation Holocene younger alluvial fan deposits (Qyf) (Figure 3). Measurement of surface elevations (where there are approximately level areas adjacent to the channel) of the two surfaces relative to the channel bottom was conducted using the 2007 LiDAR. These data indicate that Qof is ~12.1 m above the channel bed, on average, whereas, Qyf is ~3.5 m above the channel bottom, on average. These surfaces were not mapped further inland from the coast—however the elevation measured from the LiDAR images is similar to the elevation measured in the field at study sites further upstream and on tributaries to the San Gregorio mainstem, where bank heights between the channel bed and adjacent terrace average 3.4 m (range from ~2.9 m – 4.2 m). These field data suggests that a similar Holocene surface is present further upstream from the coast in the San Gregorio system. Figure 3 shows elevation contours (contour interval ~1 meter) that illustrate the relative elevation of the older Pleistocene and younger Holocene surfaces in the downstream portion of San Gregorio Creek. The timing of the incision of San Gregorio Creek into these fan deposits is uncertain; however, Cuthrell et al. (2013) suggests that in nearby Quiroste Valley (~20 km south of San Gregorio Creek), Whitehouse Creek was already deeply incised within its alluvial valley by the beginning of Spanish colonization. Age dating of strata within the Holocene terraces Qyf would aid in understanding when these landforms were deposited and incised relative to the timeline of human activities.

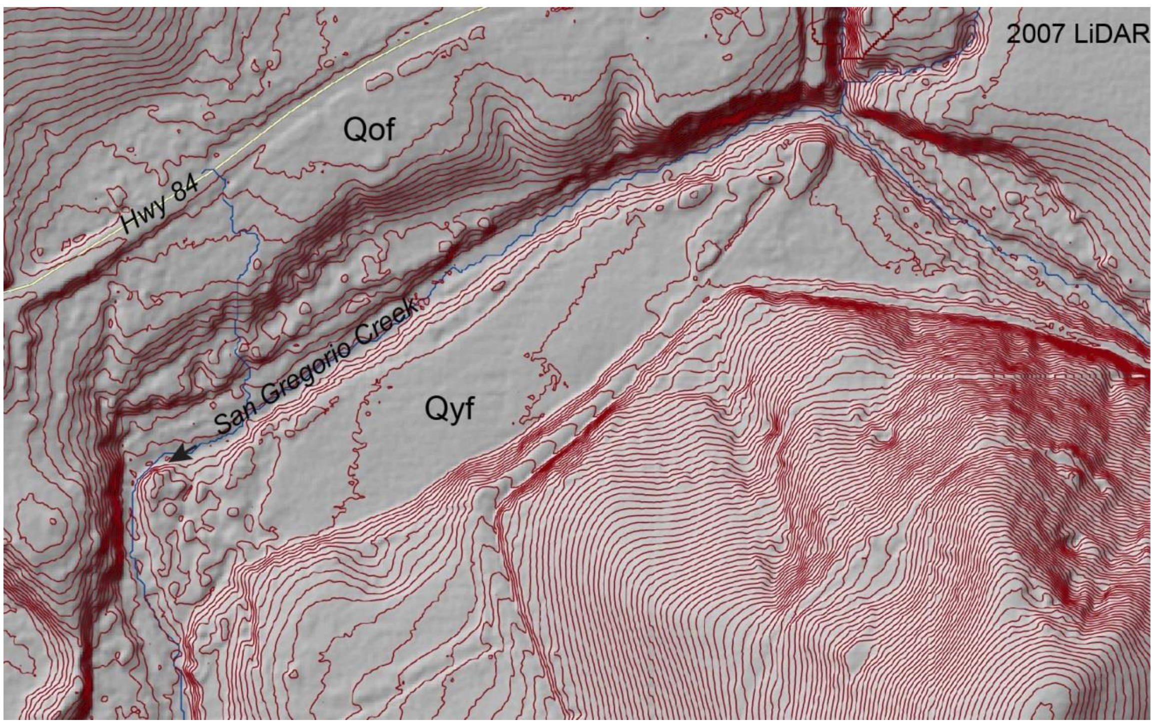


Figure 3. Elevation contours (contour interval 3 ft) that illustrate the relative elevation of the older Pleistocene and younger Holocene surfaces in the downstream portion of San Gregorio Creek.

Analysis of USGS stream gage records offers evidence for variation in bed elevation at the USGS gaging station at the downstream portion of the San Gregorio system during the instrumental period 1969 to the present. From field measurements, average bed elevation can be estimated as the recorded gage height (*GH*) minus the average flow depth (*d*), where flow depth is calculated as the discharge (*Q*) divided by the product of channel width and velocity (*w v*):

$$Bed\ Elevation = GH - (Q/(w\ v))$$

Over the period of record, field data have been collected in various locations and (with various naming conventions) near the gaging station. Figure 4 illustrates variation in approximate stream bed elevation based on field data collected by USGS field scientists over the 45-year period of record. Measurements included in the analysis were al taken from or close to the bridge at Stage Road or adjacent to the gage. Overall, Figure 4 illustrates variation of bed elevation, suggesting that bed elevations respond to variations in discharge and sediment load supplied from the upstream watershed without an apparent long-term trend toward either deposition or incision during the instrumental period.

An assumption in this analysis is that the water surface and bed elevation is similar at the gage and at the bridge at Stage Road immediately upstream of the gage and that averaging hydraulic and physical parameters over the relatively narrow channel width is valid; however, there is uncertainty in this method and in using data recorded at the various locations near the gage to approximate stream bed elevations during the instrumental period.

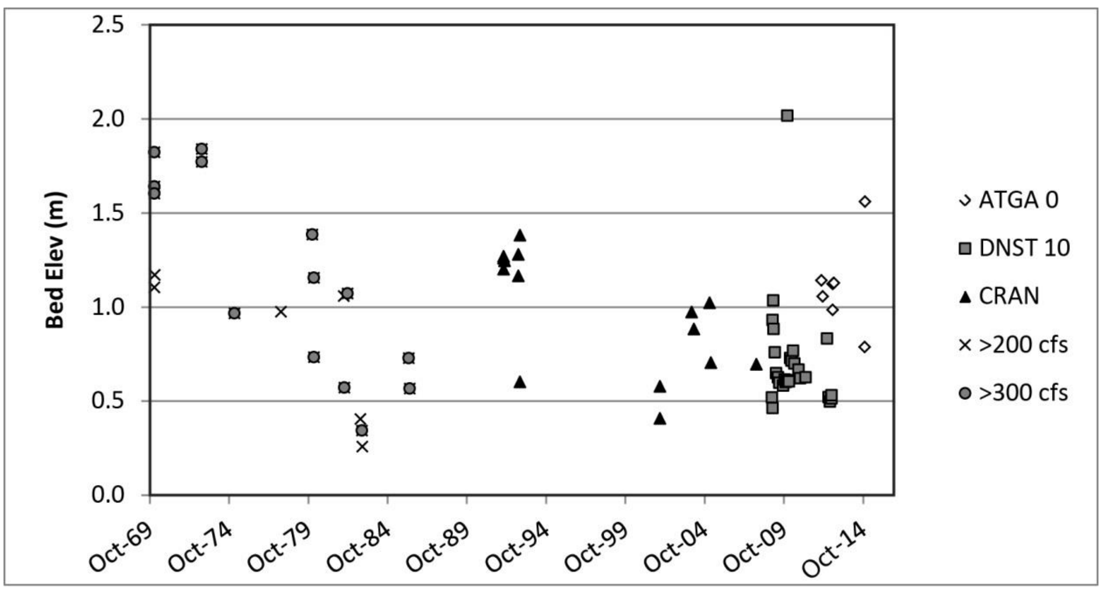


Figure 4. Variation in ~stream bed elevation at USGS gage. ATGA 0 is at the gage; DNST 10 is the downstream side of Stage Road bridge; CRAN indicates data collected from the downstream side of the Stage Road bridge using a crane; >200 cfs and >300 cfs are data where no location was recorded, but assumed to be measured from the Stage Road bridge because wading is not possible at such high magnitude discharges.

Historical maps offer another viewpoint related to the timing of incision in San Gregorio Creek. Figure 5 shows changes in San Gregorio Creek and tidal lagoon at four points in time—1854, as depicted on the T-sheet; 1941, shown on one of the earliest aerial photographic sets; 2007, the time investigated on the LiDAR imagery, and 2015, the most recent imagery both available on Google Earth. The main changes between 1854 and the present were caused by the construction of Highway 1, which isolated a part of the lagoon. The T-sheet shows that farming on the downstream-most floodplain was already underway by 1854.   The riparian zone along the creek had diminished by 1941, but expanded by 2007. The relatively small size of the estuary even before construction of Hwy 1 and the apparent constancy of its planform suggest that river flows that seasonally breach the sand bar are likely capable of transporting river sediment through the tidal system. The symbol for steep banks such as are present along the eroding coastline mapped in the 1854 T-sheet intermittently extends upstream along the San Gregorio Creek channel, suggesting that some incision in the lower reach of San Gregorio Creek had already occurred by 1854; however riparian vegetation mapped upstream of the lagoon suggests proximity to the channel flows or shallow groundwater.

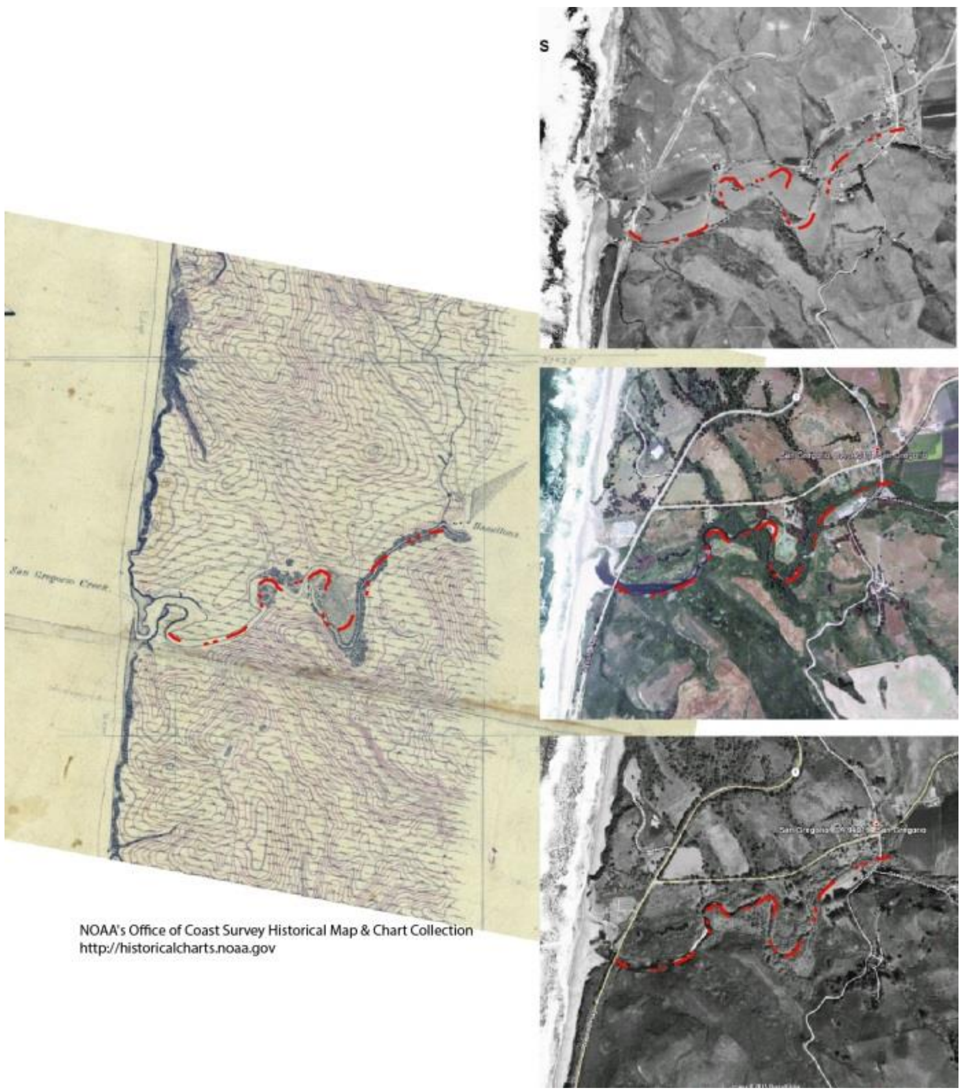


Figure 5. Lagoon and San Gregorio Creek downstream of Stage Road in the 1854 T-sheet, and from top to bottom photographs 1941, 2007, and 2015. For comparison, red dashed line shows the approximate creek flow path upstream of Hwy 1 in 2015 for reference.

Finally, changes in bed elevation further upstream on San Gregorio Creek is investigated by comparing a detailed topographic map constructed in 1911 (Grunsky, 2011; available at Bancroft Library) showing creek bed elevation downstream of the confluence of La Honda and Alpine Creeks relative to elevations extracted from the 2007 LiDAR image (Figure 6).

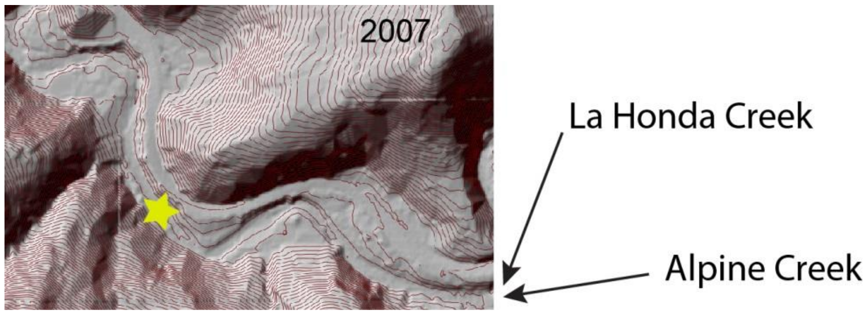


Figure 6. Creek bed elevation downstream of the confluence near the confluence of La Honda and Alpine Creeks (arrows point to confluence; contour interval = 5 ft on the 2007 LiDAR image).

The Grunsky map (Grunsky, 2011) indicates channel bed elevation is 93.57 m (307 ft)—analysis of the 2007 LiDAR image indicates that the channel bed elevation is 93.27 m (306 ft). Because these data represent only one point within the watershed, the following inferences can't be applied at the watershed scale. However, the similarity of elevations in data obtained almost a century apart suggest that at this location, either the bed elevation is stable, or that it changed and recovered during the 96 year period, or that change and recovery occurred prior to 1911.

<u>Mass Wasting</u>

Mass wasting processes including landslides and debris flows are significant erosional process on many hillslopes in the San Gregorio watershed. Indeed, in a summary map prepared by Wentworth et al (1977), the majority (~60%) of hillslopes in the San Gregorio Creek watershed is mapped as vulnerable to slumps, earth flows, and translational slides. Similarly, a 2011 map showing susceptibility to deep-seated landslides in California shows regional likelihood of deep seated landsides for the San Gregorio watershed as comparatively high based on estimates of rock strength and slope steepness where landslide susceptibility increases with slope and in weaker rocks shows areas (Willis et al., 2011). Relatively steep slopes, one factor that contributes to instability, are present locally throughout the San Gregorio watershed (Figure 7)—and in particular in the headwaters of El Corte de Madera, La Honda, Mindego, Alpine, and Kinston Creeks.

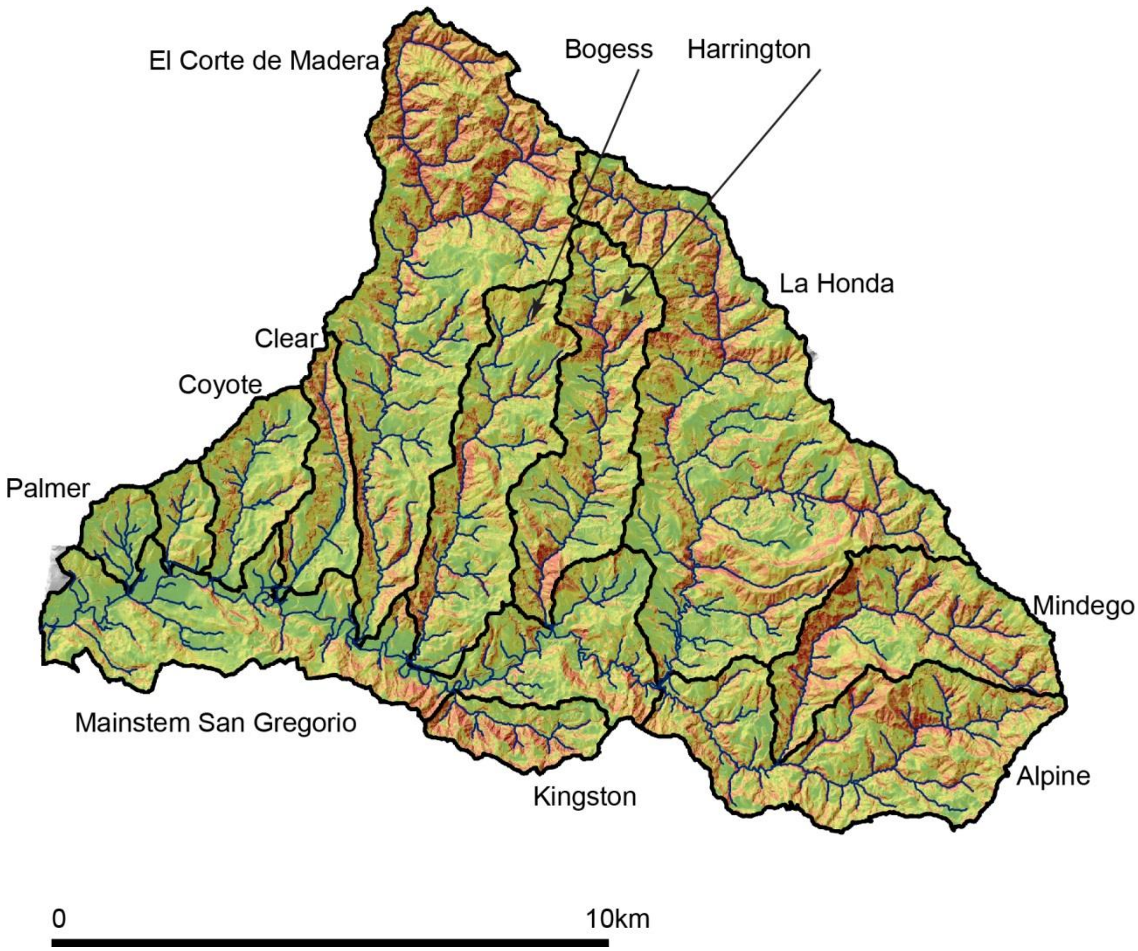


Figure 7. Slope map of San Gregorio watershed generated from 2007 LiDAR illustrating areas with relatively high slope (red and orange colors).

Detailed mapping of pre-historic landslides in the San Gregorio watershed (Brabb and Pampayan, 1972) illustrates the spatial distribution of large complex landslide features visible in aerial photographs taken prior to the 1970s (Figure 8). These landslides are recognized as structures that include small isolated ponds, many natural springs, sudden changes in topography or hummocky topography, changes in slope and drainage patterns, steep curved scarps at the upper edge of the deposit, irregular soil and vegetation patterns, disturbed vegetation, and/or flat areas, and numerous smaller, younger slides that form within older, larger landslide deposits (Nielson et al., 1979). As such, complex landslides are structures with characteristics of more than one type of landslide. This, in combination with forest cover present in portions of the watershed that precludes visibility of the ground surface in some locations, may render classification uncertain. Nonetheless, the detailed map of pre-historic landslides and continued monitoring led to the recognition that future slides are most likely to occur within hillslope areas that have previously failed (Nielson et al., 1979). Thus, the 1972 map provides a watershed-scale context for examining historical and future landslides and other hillslope erosion processes. In particular, various portions of the mapped slides are episodically active and contribute sediment to streams when bank erosion erodes the toe of the slides.

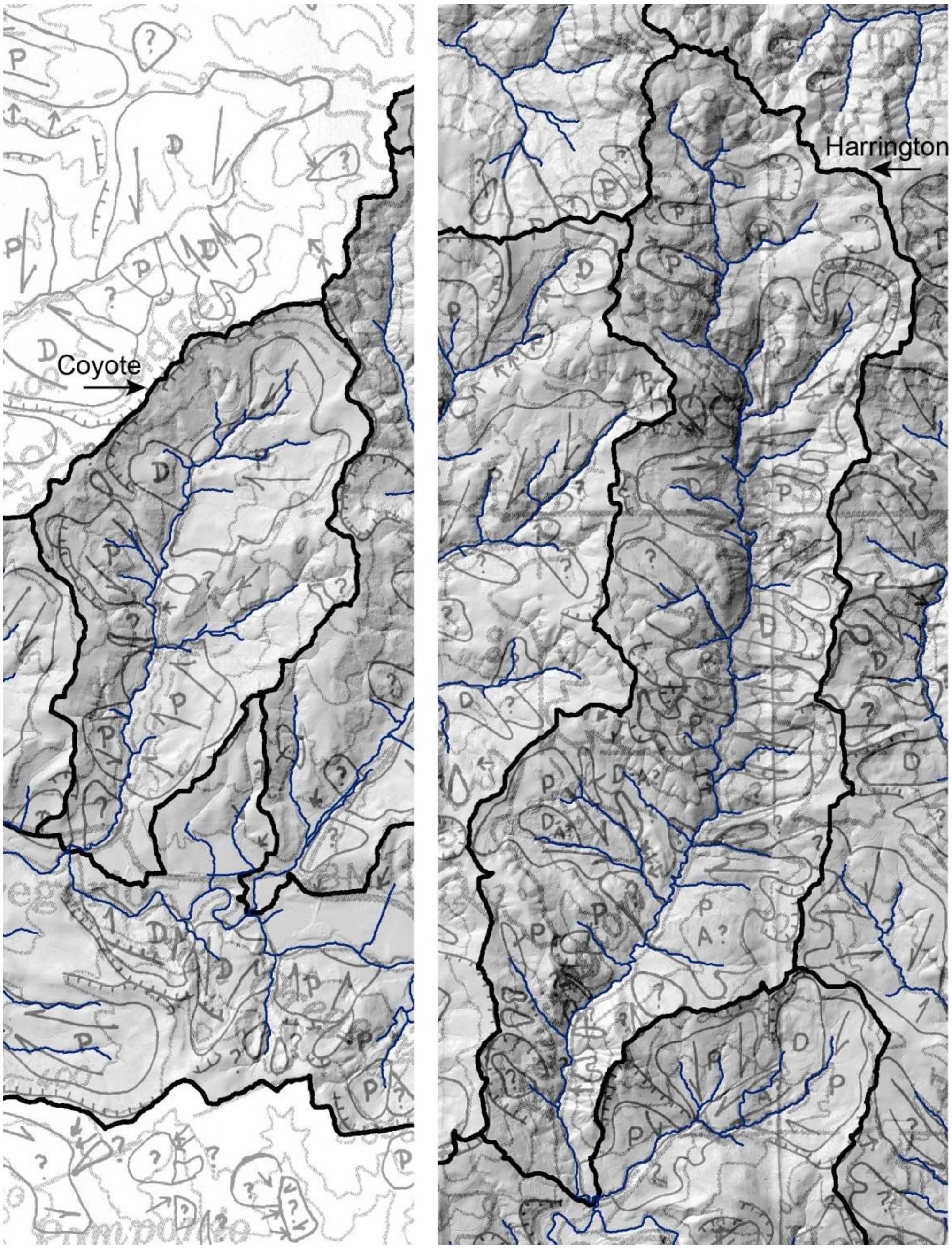


Figure 8. Large prehistoric landslides mapped in San Gregorio watershed (Brabb and Pampayan, 1972): detail shown for Coyote and Harrington subbasins. D = definite, P = probable, A = active, arrows indicate direction of movement.

Deep-seated rotational or translational slumps that involve large intact blocks of material are a common type of failure in the San Gregorio watershed. Detailed field investigations in the La Honda area suggests that damaging slumps that occurred during the 1998 (Jayko et al., 1998; Jayko et al., 1999) and 2006 (Wells, et al., 2006) storms and likely during the 1984 Morgan Hill earthquake (Wieczorek and Keefer, 1984) and that these mass movements occurred within the footprint of the larger pre-historic landslides or in areas already mapped as highly susceptible by Wentworth (1977). Differential rates of movement within a slump in La Honda that was monitored for a period during 1998 varied between few mm/day to about 20 cm/day (Jayko et al., 1998).

Besides deep seated landslides that re-activate portions of the larger pre-historic landslide complexes present in the watershed, shallow debris slides and debris flows are significant hillslope erosion processes. Ellen and others (1988) reported that nearly all of the debris flows in the San Francisco Bay region triggered by the 1982 storm developed during pulses of intense rainfall from one or more small shallow slides in soils termed “soil slips” or debris slides from slopes > 26°. Most of the sides had widths of five to 15 m (but ranged from one to 60 m) and had depths of 0.5 to ~3.0 m. Relatively shallow translational or translational debris slides occurred near La Honda during storms occurring between 1975 and 1983 when antecedent moisture was already high on slopes steeper than 20° to 26°, respectively (Wieczorek and Sarmiento, 1988). Cannon (1988) identified a threshold for rainfall intensity and duration required to trigger debris flows. Highlighting the significance of soil moisture, Wieczorek (1987) utilized measurements piezometric levels in hillside soils near La Honda together with measurements of rainfall between 1975 and 1984 to examine, storm rainfall intensity and duration and the influence of antecedent rainfall on elevating pore pressure. He found that no debris flows were triggered before 28 cm of rain accumulated each season and that the threshold for triggering (at least one debris flow) was:

$$D = 0.90 / (I-0.17)$$

where D = continuous rainfall duration (hours), I = intensity (cm/hour). Moreover, Wieczorek (1987) found that the number of debris flows increased as storm intensity and duration increased above the threshold. Wieczorek et al (1987) suggested that moderate intensity storms of long duration triggered complex slump-debris flows, whereas high intensity, short duration storms caused soil slide-debris flows. Keefer et al. (1987) reported that during the 1986 storm, debris flows and slumps were the predominant landslides west of San Francisco Bay in the Santa Cruz Mountains; however, the number of events during 1986 was fewer than during the larger 1982 storm. In a summary of 31 years of debris flow activity, Wieczorek et al (2007) documented at least 248 debris flows within 10 km^2 northwest of the town of La Honda that occurred during 18 intense storms between 1975 and 2006. Ellen and Wieczorek (1988) reported that the El Nino storm in January 1982 triggered 856 debris flows from small debris slides in the San Gregorio watershed. However, forest cover in the upper portion of Harrington Creek likely precluded identification of small sides and associated debris flows under the forest canopy.

Examination of the 1941 aerial photographs illustrates apparent tracks from debris flows generated during the 1940 storm (Figure 9) suggesting that rainfall characteristics during and antecedent moisture prior to the 1940 exceeded thresholds for initiation of small debris slides and generation of debris flows.

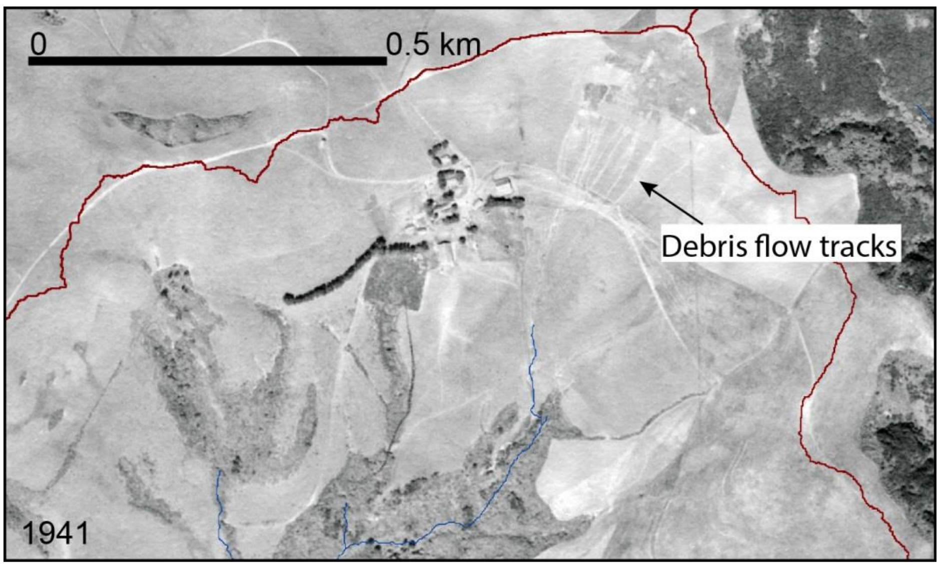


Figure 9. Apparent debris flow tracks on the 1941 photograph within the relatively steep headwater area of Coyote Creek watershed.

To highlight the spatial distribution of debris flow origin, Figure 10 shows features mapped within two subbasins: Coyote Creek and Harrington Creek for the 1940 storm. The debris flows mapped in Coyote Creek overlain on a slope map suggests that the small slides and debris flows are generated on relatively high slopes. Debris flows resulting from the 1940 storm mapped using the 1941 photographs illustrates ~41 debris flows that occurred in Coyote Creek subbasin, and ~43 occurred in Harrington subbasin (Figure 10). However, some features may be obscured beneath the tree canopy in the forested headwaters of Harington Creek. Mapping similar features from the 2006 NAIP imagery following the 2006 storm includes 13 potential shallow debris slides and associated debris flows in Coyote Creek subbasin and 11 in Harrington (the NAIP photographs are utilized in order to determine where bare ground was present; e.g LiDAR imagery illustrates topography).

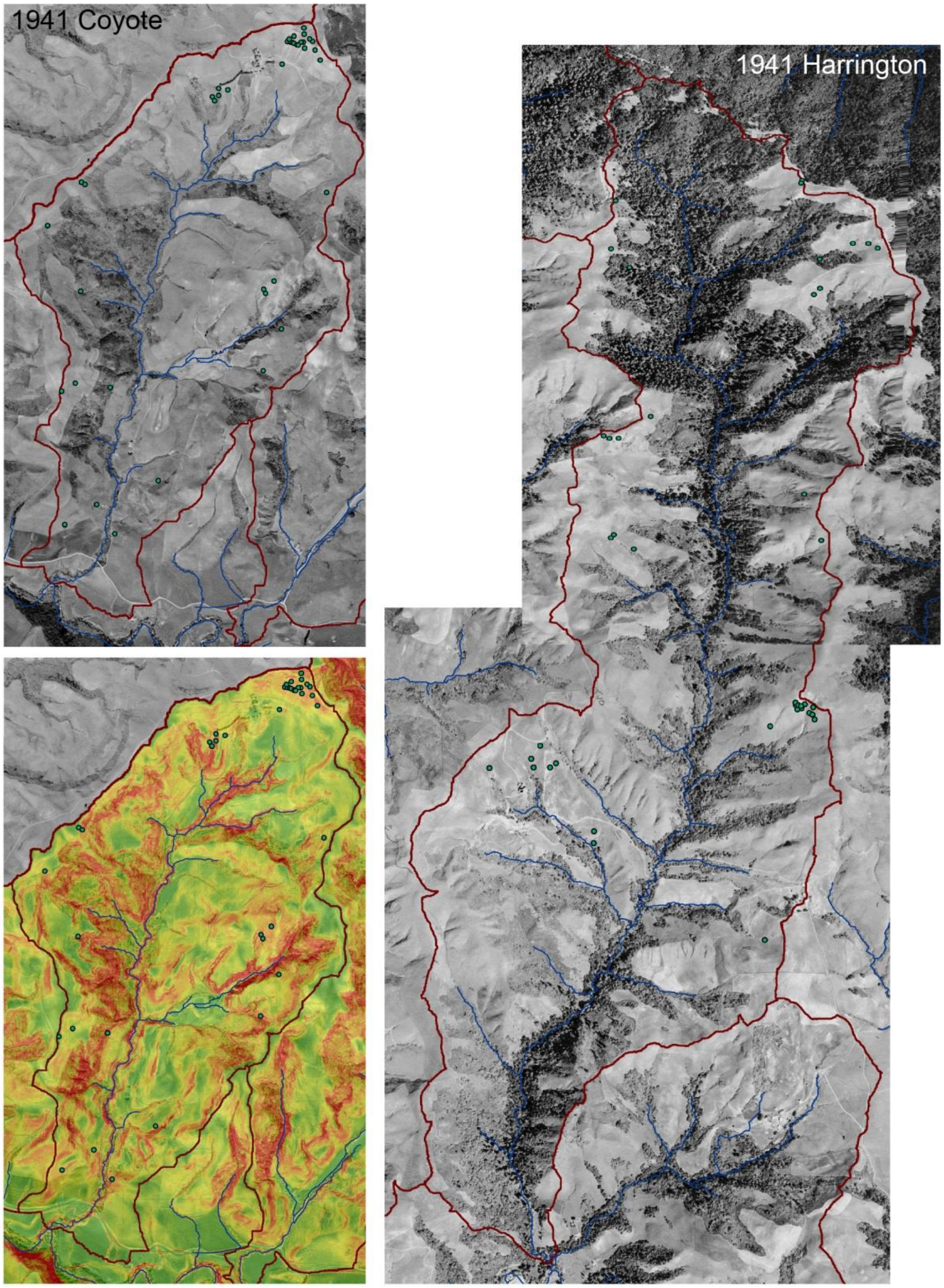


Figure 10. 1941 photos of Coyote and Harrington Creek subbasins showing locations of small shallow landslides initiated during the 1940 storm. The lower map of Coyote subbasin provides an example to highlight the relation between slope and location where debris flows originate.

For comparison, 46 of the debris flows that occurred during the 1982 storm mapped by Ellen and Wieczorek (1988) were in the Coyote Creek subbasin and almost 100 were in the Harrington Creek subbasin. The apparent differences including fewer debris flows in Harrington Creek subbasin in 1940 relative to 1982 could be due to a combination of the lower storm intensity and duration, an artifact of a difference in resolution of photos used to map the two data sets, or other reasons. Nonetheless, together with the identification of debris flows near La Honda between 1975 and 2006 prepared by Wieczorek et al (2007), mapping the debris flows that occurred during the 1940 storm shows that small debris slides and associated debris flows have been important as erosion and transport processes in the watershed since at least 1940 and likely long before that.

Gullies and Eroding Channel Heads

Gullies In the San Gregorio watershed are identified quasi-linear erosional features characterized by steep head scarps and side walls that form in colluvial material on slopes and that are not surficially connected to the drainage network. Thus, for this study, gullies are mapped as isolated features, in order to differentiate these landforms from similarly quasi-linear erosional features that are connected to the drainage network, discussed subsequently. "Eroding channel heads" are mapped to illustrate headward extent of the connected drainage systems at two time periods, 1941 and 2007. At the resolution and ability to georeference the available imagery, uncertainty in mapping these features is high especially in comparing position of features from 1941 aerial photos vs 2007 LiDAR (gullies and channel heads mapped from the LiDAR are more apparent than from the aerial photographs where vegetation may obscure such features). Moreover, some of the linear features identified from the photographs may be linear landslide scars, trails, or agricultural artifacts instead of channels.

Gullies and eroding channel heads often are formed within the hummocky footprint of complex landslides. Heads are often present at the base of apparent smaller slide scars, suggesting that the mechanisms for formation may be associated with debris flow erosion. Thus, one possible explanation for the observation that the features appear to shift slightly either upstream or downstream as channel heads episodically fill or erode may be related to episodic landslide erosion and subsequent transport of landslide debris via debris flows or fluvial flows. The discontinuous nature of gullies and channel heads in the transitional zone where channels begin is typical of geomorphic processes in headwaters of drainage systems (Montgomery and Dietrich, 1994).

Disconnected gullies mapped from 1941 vs 2007 images in the Coyote Creek subbasin shows a similar number of features and relatively small linear extent, suggesting that these features had already formed prior to 1941 and that significant headward erosion did not occur between 1941 and 2007 (Table 7). Because such features are disconnected from the drainage network, they don't contribute significant sediment to the fluvial system.

Table 7. Disconnected Gullies in Coyote Creek subbasin.

Year of image	Number Disconnected Gullies #	Linear Extent m
1941	12	601
2007	14	587

Channel heads mapped from the 1941 and 2007 images in Coyote and Harrington subbasins are illustrated in Figure 11a and 11b. Of the channel head locations visible for both time periods, there is no apparent trend, suggesting that channel head erosion dynamics has not appreciably changed since 1941, similar to observations from the disconnected gullies.

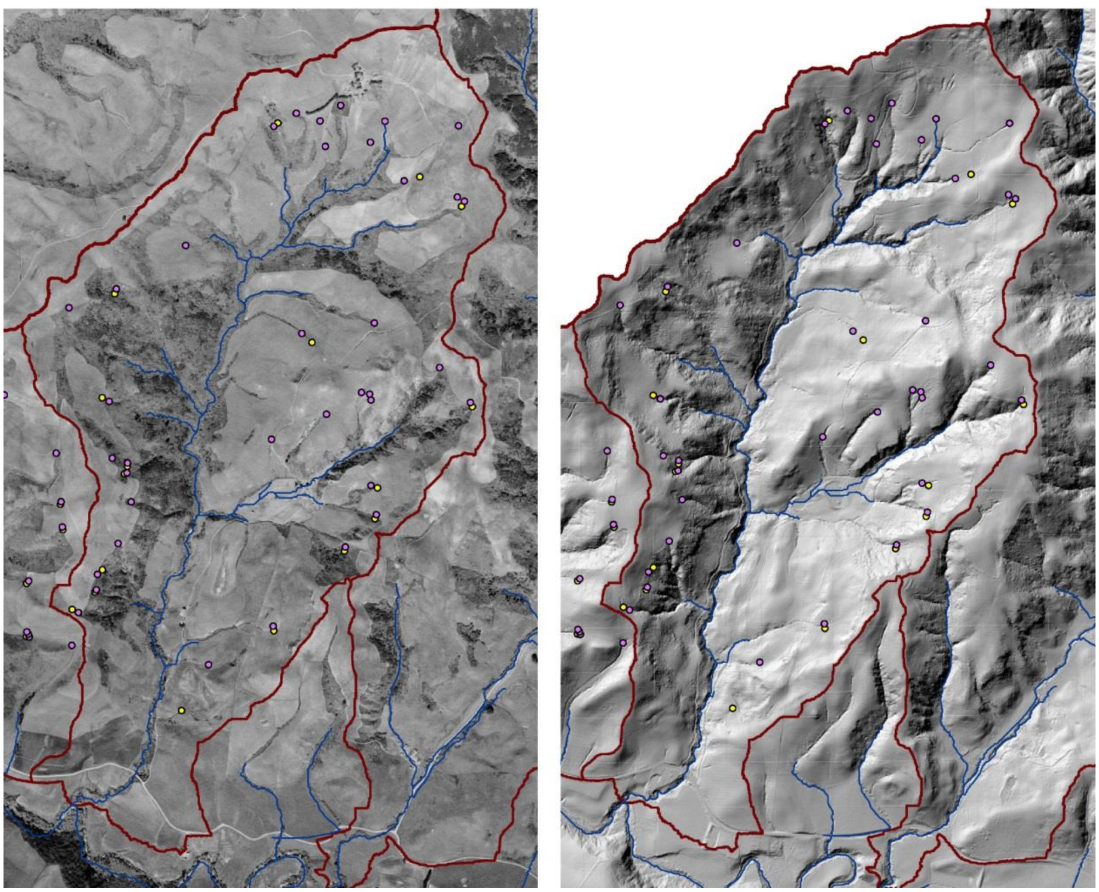


Figure 11a. Channel heads in Coyote Creek subbasin shown on 1941 photograph and 2007 LiDAR image. Yellow dots represent channel head locations in 1941, purple dots represent channel head locations in 2007 (with dots shown on images for both dates).

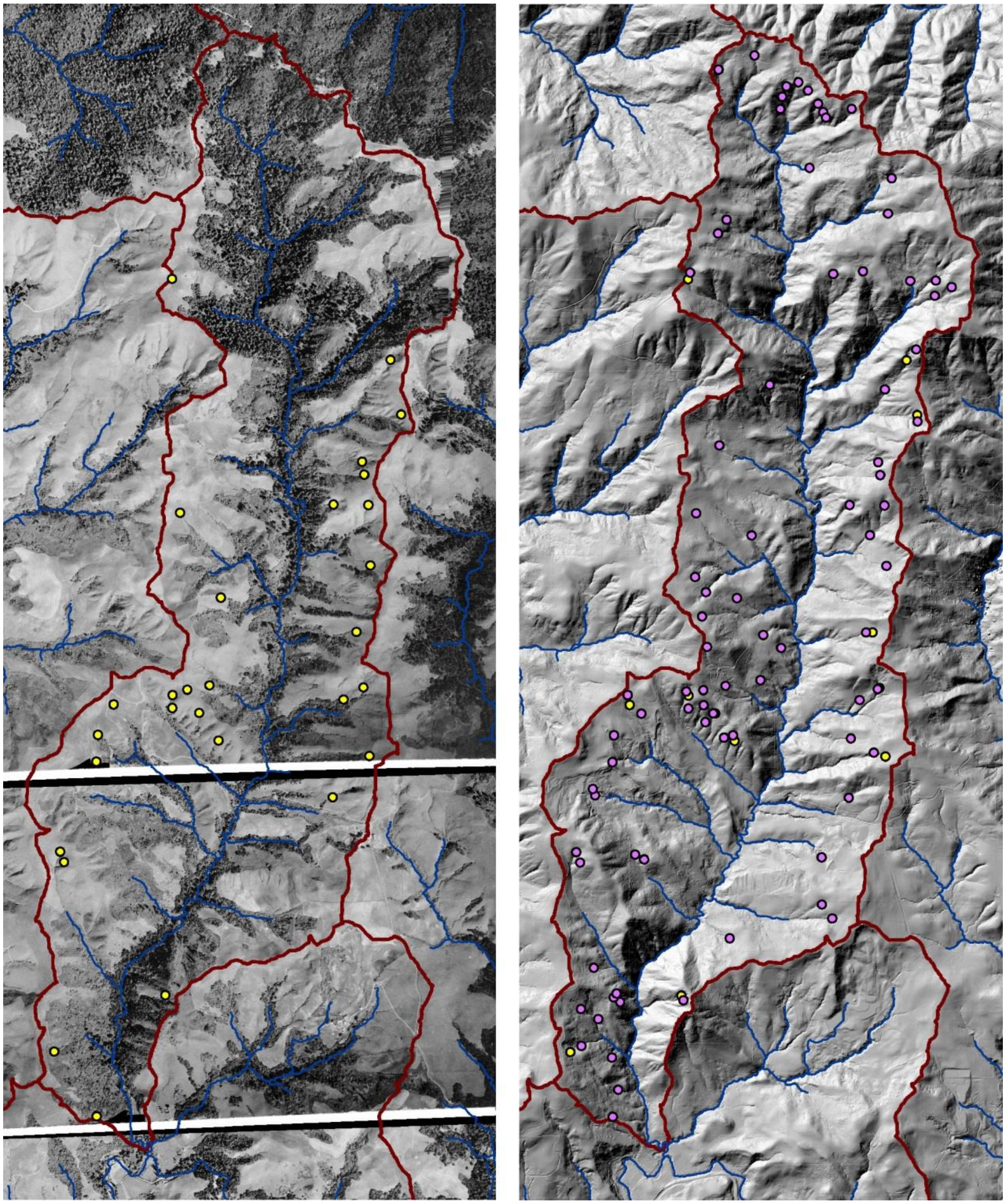


Figure 11b. Channel heads in Harrington Creek subbasin shown on 1941 photographand 2007 LiDAR image. Yellow dots represent channel head locations in 1941, purple dots represent channel head locations in 2007.

Pre-disturbance Erosion Rates Estimated from Cosmogenic Radionuclides

Pre-disturbance landscape lowering, or erosion rate estimates are inferred from measurements of the abundance of the cosmogenic radionuclide ^{10}Be in quartz isolated from river sediment samples collected at three locations in the San Gregorio Creek watershed (Perg et al., 2003; Gudmundsdottir et al., 2013). Long-term basin-averaged denudation rates are available for the tributary El Corte de Madera Creek watershed and at two locations in San Gregorio Creek: 1) near the confluence of La Honda and Alpine Creeks; and 2) near the USGS gaging station near the mouth of San Gregorio Creek (Table 8).

Table 8. Long-term denudation rates.

Sample Location	Basin Area (km^2)	Denudation Rate (mm/yr)	Reference
El Corte de Madera	25.3	0.159	Gudmundsdottir et al., 2013 supplement
San Gregorio nr confluence La Honda and Alpine Creeks	55.6	0.355	Gudmundsdottir et al., 2013 supplement
San Gregorio nr USGS gage	131.2	0.21*	Perg et al., 2003

*Uncertainty provided in estimate from Perg et al. (2003) is ± 0.02

Gudmundsdottir et al. (2013) calculated basin-averaged denudation rates inferred from measurements of the abundance of the cosmogenic radionuclide ^{10}Be in quartz isolated from sand in fluvial sediment sampled upstream of the mouth of the basin. Perg et al (2003) used data from the sample taken on San Gregorio Creek near the USGS gaging station to calculate long-term average annual fluvial sediment discharge of 3.1 ± 0.02 10^3 m^3/yr (Q_{riv} (kg/yr) was obtained using the equation: $Q_{riv} = A_{basin}\ \varepsilon_{basin}\ \rho_{bed}$, where A_{basin} (m^2) is the basin area, ε_{basin} is the basin erosion rate, and ρ_{bed} (kg/m^3) is the rock density). The results based on cosmosgenic data assume a topographic steady-state where denudation is balanced by uplift; as such the denudation rates reflect long-term average rates over a period of 1,500 -1,600 yrs, including the pre-disturbance time period of the sediment budget.

Storage Processes Active in San Gregorio Creek

San Gregorio Creek actively stores sediment on its channel bed. At six field sites investigated for this study, the volume of sediment stored in channel bars above the channel thalweg is estimated as an average volume based on average bar height, bar length, and bar width (Table 9). The estimates are intended as a relative indicator of where sediment is stored within the fluvial system. The median grain size of channel bed sediment on riffles and adjacent bars is shown on Table 9 (data are shown as a range when the reach not relatively homogeneous). Of the six study sites, San Gregorio Creek @ Apple Orchard I stores an order of magnitude more sediment in the channel above the thalweg than the other sites. Within this site, the largest bar is formed directly beneath a slide on the outer creek bank that is ~10 m high. During the Fall of 2014, most of the pools in the study sites contain some fine sediment above coarser substrate. The deepest pool was present at the San Gregorio Creek @ Apple Orchard II site in association with a large root-wad. The majority of pools and some bars present in the study reaches were present in association with large woody debris or bedrock outcrops.

Table 9. Results of field data collected at six study sites.

Field Study Reach	Approximate Sediment Storage in Bars (m^3)	Reach Length (m)	Relative Storage (m^3/m)	Median Grain Size (Riffles+Bars) (mm)	Residual Pool Depth (m)
Alpine Creek @ Sam MacDonald County Park*	33.9	102.6	0.3	30	0.17 to 0.25
La Honda Creek @ Open Space Preserve	66.6	146.5	0.5	20 to 50	0.17 to 0.55
San Gregorio Creek @ Apple Orchard I	395.4	152.0	2.6	17 to 50	0.42 to 0.64
San Gregorio Creek @ Apple Orchard II	40.3	137.4	0.3	50	0.15 to ~0.83
Harrington Creek @ Driscoll Ranch	25.8	115.4	0.2	30	0.20 to 0.55
El Corte de Madera Creek @ Open Space Preserve**	36.9	121.2	0.3	39	0.11 to 0.51

* Low silty floodplain volume of ~ 10. 6 m^3 not included in channel bed storage volume.

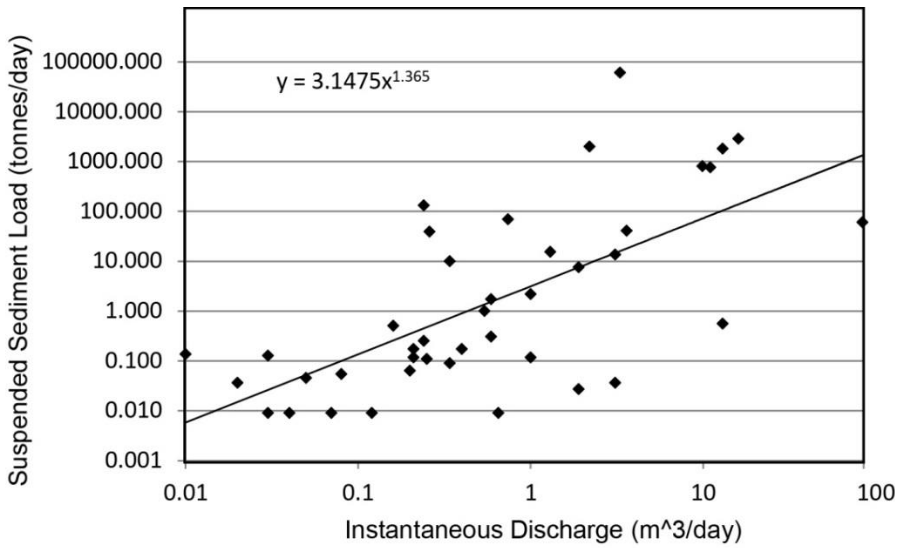
** High narrow sandy terrace volume of ~4.1 m^3 not included in channel bed storage volume.

Stillwater et al., (2010) summarized embeddedness information available for the San Gregorio watershed suggesting that fine sediment deposition has been observed to embed coarser substrate material in numerous creek inventories and that some of the inventories conducted during summer low flow suggested that the fine sediment may wash out during higher winter flows (e.g. see compilation of CDFG reports compiled by Zatkin: San Gregorio 1, 2, and 3; and Pearce et al. (2007)). Stillwater et al. (2010) notes that although coarse sediment was not considered to be a limiting factor for spawning habitat, the magnitude of fine sediment impacts on salmonid populations in the watershed is still not well understood.

Sediment Transport Processes in San Gregorio Creek

Sediment Yield: Water Year 1985-1993

During an eight-year period between 1985 and 1993, USGS collected 44 suspended sediment concentration samples at the gaging station at flow discharges ranging from 0.02 to 84 m^3/s (Figure 12). Fifteen bedload samples were collected during the same period at flows ranging between 1.0 and 15 m^3/s (Figure 12).



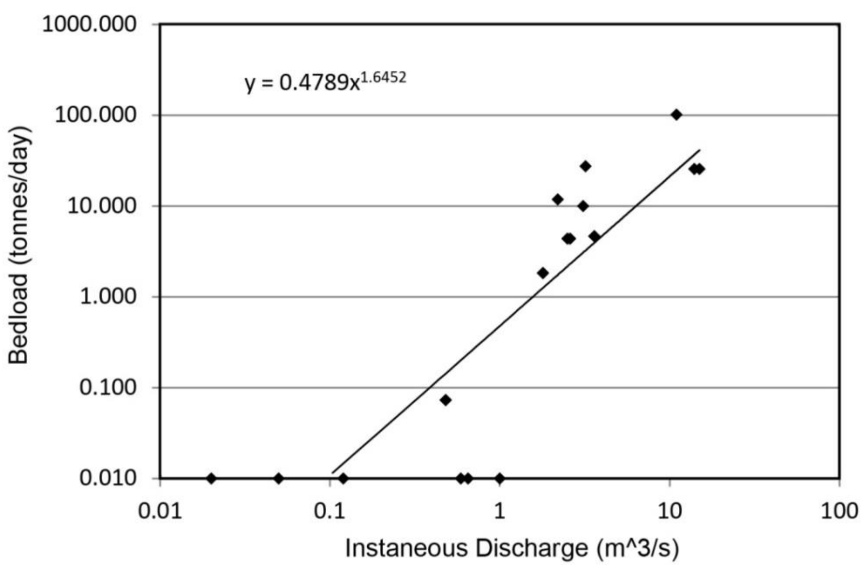


Figure 12. Bedload and suspended sediment rating curves at the USGS gage based on data collected between water year 1995 and 1993.

The rating curves relate suspended sediment load and bedload to the instantaneous discharge when the sample was collected. Power law regression equations shown on Figure 12 for bedload and suspended sediment (Q_x) take the form:

$$Q_x = aQ^b$$

where flow *Q* is discharge and a and b are empirical coefficients. Potential problems with use of the rating curve method to calculate daily suspended sediment load (Q_s, kg/d) are well documented and include presence of hysteresis associated with variable sediment supply seasonally and during rising and falling limbs of the hydrograph (Ferguson, 1986; Asselman, 2000; Horowitz, 2003). Errors in estimates of sediment load using this method may range from 15% (Horowitz, 2003) to 50% (Ferguson, 1986). For example, Figure 12 illustrates almost 6 orders of magnitude of scatter in the suspended sediment data for San Gregorio Creek. Bedload measurements are also subject to uncertainty related to temporal and spatial variability relative to sample time and location.

Using the empirical transport rate curves for the San Gregorio watershed in combination with the flow hydrograph (Figure 13a) and corresponding flow duration curve (Figure 13b) based on USGS gaging station data allows approximation of total sediment yield during the period when measurements were taken.

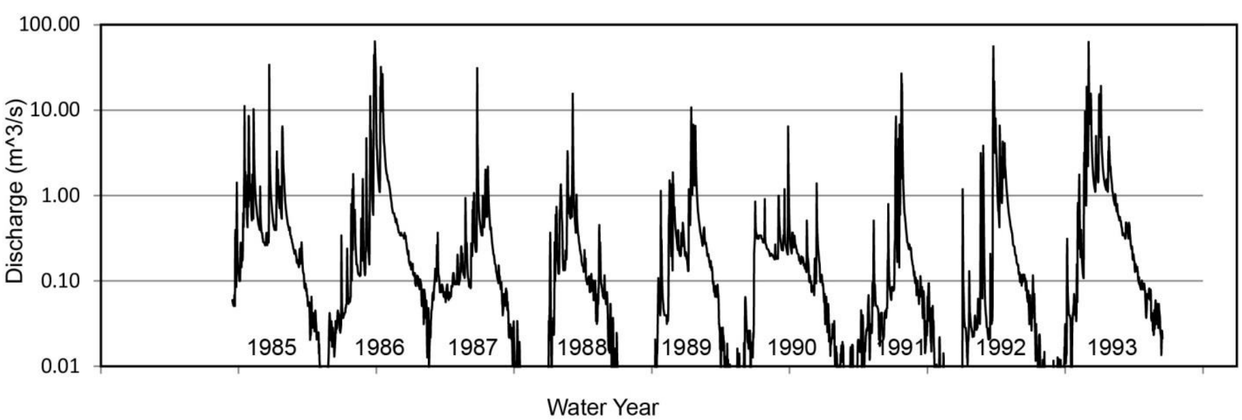


Figure 13a. Discharge hydrograph shown for water years 1985-1993.

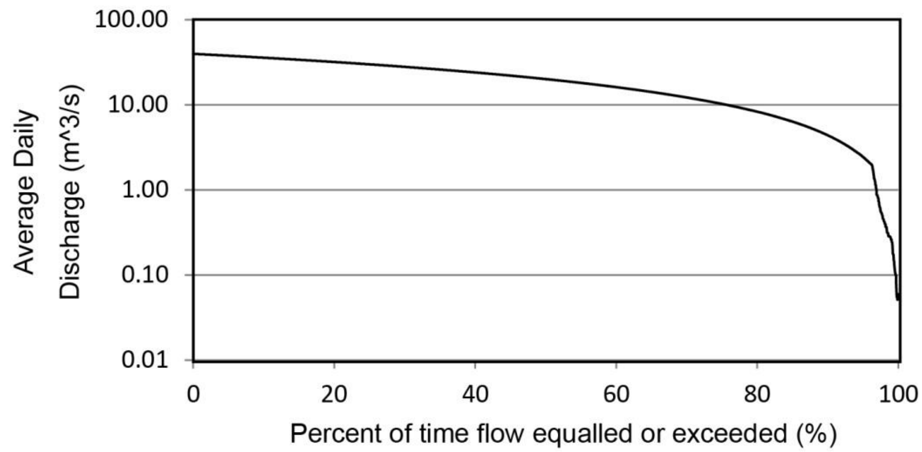


Figure 13b. Flow duration curve for water years 1985-1993.

Over the period between water years 1985 and 1993, the average annual total sediment load measured at the USGS gaging station is approximated as ~63,900 tonnes/year (63,900,000 kg/yr); however, it is important to note that there is a large uncertainty inherent in this estimate. The median (D_{50}) grain size of the bedload transported during this period measured at the USGS gaging station ranged between ~0.3 mm to 2.4 mm and bed material ranged between ~1.0 mm and 17 mm.

The calculated total annual sediment load—or the erosion rate, E (kg/y), normalized by drainage basin area—approximates the rate of removal of a mass of sediment from a unit area within the basin, r (kg/km^2/y):

$$r = E/A$$

where A is basin area (km^2) (*sensu* Florsheim et al., 2011). Using the calculated rate corresponding to the period between water years 1985 and 1993 to approximate a basin scale lowering rate, L (mm/y) may be calculated as the unit erosion rate divided by the density of sediment, ρ_s (g/cm^3):

$$L = r/\rho_s$$

where density of rock is estimated as 2.5 g/cm^3. An integrated watershed scale lowering rate is approximated as 0.20 mm/yr. This short-term-estimate for the period between water years 1985 and 1993 is similar to the long-term basin-scale rate reported by Perg et al., 2003.

Additional quantitative sediment data available from prior work conducted by Balance Hydrologics in the San Gregorio watershed include a recent measurement of sediment yield from a location within the El Corte de Madera tributary (drainage area 12.3 km^2) during water year 2007 of ~52 tonnes/yr; Gartner et al., 2008). Turbidity data collected by SGERC and summarized in Stillwater et al (2010) reported that turbidity in the watershed does not chronically exceed levels that would impact Salmonids. For example, turbidity levels measured at five sites between 2003 and 2008 were highest in winter months during storm flows and lowest in the late spring and fall within ranges that would not be detrimental to aquatic species. Higher values at the downstream ends of both San Gregorio and La Honda creeks for a four-month period during January through April in 2006 is also attributed to storms during that year.

Relevant Time Periods for the Rapid Sediment Budget and Associated Changes in Sediment Supply, Storage, and Yield

Development of relevant time periods for the sediment budget depends on both land use history and the spatial availability of quantitative data for analysis. A time line documenting relevant time periods of erosion and sedimentation processes for the sediment budget was synthesized using a variety of historical resources previously discussed. The following includes elements of a conceptual model thought to be significant with respect to geomorphic processes in relation to the period of human activities: Possible changes to hillslope hydrology and sediment erosion and in to the Creek's ratio of discharge to sediment load (Q/Qs) may have accompanied events after human interactions with the landscape.

Prior to human disturbances, sediment supply, storage, and yield increased and decreased episodically in response to forcing from climate and tectonics. Most subsequent land use changes increased rates of supply, storage, and yield—with the Q/Qs determining landscape change. An exception was the effort that took place between 1960-1990 to remove large woody debris from creeks, which likely reduced sediment storage and morphologic diversity in channels.

Although land use changes in the San Gregorio Creek watershed are well documented, quantification of a rapid sediment budget is limited by the relatively long historical period of land use changes that occurred prior to the relatively short period with available quantitative geomorphic data or imagery from which quantitative data could be generated. Therefore, the following conceptual model shows the direction of change in rates of supply, storage, and yield qualitatively (increase or decrease) for each period.

<u>Pre-human disturbance:</u> Episodic variation of both Q and Qs as a result of storms, earthquakes, mass movements:

- Proximity to active faults, folded, tilted, faulted fault blocks, and weak lithology.
- Climate variation inherent in California's Mediterranean coastal environment with episodic storms and droughts on annual to millennial time scales.

- Spatially frequent pre-historic landslides indicate significant hillslope instability prior to human disturbances.
- Relatively narrow valley bottom throughout most of the watershed and the presence of Pleistocene and Holocene side-valley alluvial fans precluded extensive floodplain formation.

Rate	Increase	Decrease
Sediment Supply:	x	x
Sediment Storage:	x	x
Sediment Yield:	x	x

<u>3500 BC to 1769:</u> Possible increase in both Q and Qs as a result of increased runoff and surficial sediment erosion rates following vegetation denudation.

- Frequent, small fires used to manage vegetation.

Rate	Increase	Decrease
Sediment Supply:	x	
Sediment Storage:	x	
Sediment Yield:	x	

<u>1770 to 1850:</u> Possible increase in both Q and Qs as a result of increased runoff and sediment supply rates following vegetation transformation in grazed areas, and denudation in logged areas; likely increase in Qs likely from increased sediment supply rates from surficial erosion on hillslopes from logging disturbances, road related erosion; likely modification of stream channel morphology and riparian zone function resulting from milling activities and transport of logs.

- Beginning of transformation of native vegetation with grazing that likely began during the Spanish mission period and initiation of farming during the Mexican Rancho period.
- Compaction of soil from grazing.
- Initiation of logging and road construction and associated erosion.

Rate	Increase	Decrease
Sediment Supply:	x	
Sediment Storage:	x	
Sediment Yield:	x	

<u>1850 to 1900:</u> Possible increase in both Q and Qs as a result of increased runoff and sediment supply rates following intensification in farming; likely increase in Qs likely from increased sediment supply rates from surficial erosion on hillslopes from logging disturbances, road related erosion; likely modification of stream channel morphology and riparian zone function resulting from milling activities and transport of logs; likely increase in Qs likely from increased sediment supply resulting from intensified road construction.

- Population increase, intensification of farming and logging (and direct hillslope and channel disturbances from road construction, mills, etc.).
- Intensification of road construction.
- Continued grazing.

Rate	Increase	Decrease
Sediment Supply:	x	
Sediment Storage:	x	
Sediment Yield:	x	

<u>1900 to 1960:</u> Possible increase in both Q and Qs as a result of increased runoff and sediment supply rates following various developments.

- Continued rural residential and vacation destination development.
- Oil and gas development.

Rate	Increase	Decrease
Sediment Supply:	x	
Sediment Storage:	x	
Sediment Yield:	x	

<u>1960-1990</u>: Likely decrease in sediment storage in channels upstream of large woody debris jams and increase in sediment supply rates to downstream areas; loss of complexity.

- Large woody debris jam removal from stream channels

Rate	Increase	Decrease
Sediment Supply:	x	
Sediment Storage:		x
Sediment Yield:	x	

Summary of Current Geomorphic Conditions at Six Study Sites

Current conditions in the watershed was evaluated at six study reaches located within the watersheds open space. The field data collected during Fall 2014 provide a snapshot of geomorphic conditions following a dry year:

- Using terrace elevation as an indicator, the majority of the study sites have incised, with bank heights ranging from ~2.9 to 4.2 m and the relative incision ratio, h_t/d_e at the field study sites ranged from ~2.0 to 3.8 indicating that the tributaries and main stem of San Gregorio Creek incised at some time in the past. Future work to date strata within the Holocene terraces Qyf could help fill gaps in knowledge about when these landforms were deposited and incised relative to the timeline of human activities.
- Incision increased the transport capacity as flows become deeper when confined within the channel.
- Grain size distributions measured in riffles illustrate the presence of gravel sized sediment at all of the study sites; the median grain size in riffles ranged from ~17 to 50 mm.
- The majority of pools present at all of the study sites are forced pools (pools associated with the presence of large woody debris, large boulders, or bedrock protrusions); residual pool depths were low on average and ranged from ~0.11 to 0.83. Pools contained sand or smaller sized sediment.
- Bank erosion was present but not pervasive at the study sites.
- Relative sediment storage at the study sites ranged from ~0.2 to 0.5 m^3. Some bars present are also associated with the presence of large woody debris.

Quantitative Evidence for Changes in Geomorphic Processes over Anthropogenic Period

There are relatively few quantitative sediment transport measurement data collected in the San Gregorio watershed, and those that exist have been taken in different locations, over different time periods. Although uncertainty is high, the available quantitative data that do exist are important as baseline information that could be used in comparison to future quantitative data collection efforts made in the same locations.

- There is evidence that long-term erosion rates based on cosmogenic nuclide investigations are similar to relatively short-term erosion rates based on USGS sediment transport data over the period of measurement from 1985 to 1993.
- There is evidence that hillslope processes are episodic and that hillslope landslides and debris flows occur in response to large storms that exceed thresholds for antecedent moisture, and rainfall intensity and duration—documented following storms in 1940, 1982, 1998, and 2006 among others. One series of measurements of rates of movement within one slump in La Honda during 1998 varied between few mm/day to about 20 cm/day (Jayko et al., 1998). Debris flows transport sediment from hillslopes to channel rapidly, during storm event.

- There is evidence that the channel bed has varied at about the same elevation at least since 1911 in the upstream portion and at least since 1969 in the downstream portion of the mainstem of San Gregorio Creek. Near the confluence of Alpine and La Honda Creeks, the similarity of elevations in data obtained almost a century apart suggest suggests several possibilities: the bed elevation is stable, or that it changed prior to 1911 and has been stable since then, or that it changed and recovered during the 96 year period, or that change and recovery occurred prior to 1911. Downstream bed elevation variation occurs in response to sediment load and discharge supplied by the watershed without a consistent trend.
- There is evidence that the majority of gullies present in the watershed in 2007 were already present in 1941. There is also evidence that channel heads were in approximately in the same location during the two periods.

Conclusions

The San Gregorio watershed is characterized by erosive sedimentary strata prone to land sliding as a result of tectonic activity and large storms. The history of land use activities within the San Gregorio watershed documented in this report suggest that anthropogenic disturbances such as logging, road construction, rural development, and agriculture may have increased sediment supply to the fluvial system and altered the ratio of discharge to sediment load (Q/Qs). However, effects of this historical legacy of landuse activity on the watershed's sediment budget appear to have occurred prior to various data collected in ~1911 to 1941. Utilizing the available quantitative data suggests that long-term erosion rates based on cosmogenic radionuclides are similar to erosion rates based on more recent sediment transport measurements from the period between 1985 -1993. Although uncertainty is high, the available data suggest that at the basin scale, recent rates of erosion are similar to long-term rates integrated at the scale of the watershed.

Wohl et al. (2015) suggest that factors operating at the watershed scale influence sediment regimes; whereas, local factors operating at the reach scale have a greater influence on habitat and river biota. It follows that reach scale morphology and local changes in sediment characteristics are significant with respect to riparian habitat and restoration. For example, local changes in volumes and patterns of sediment in storage, changes in sediment patch distribution, and reduction of habitat complexity in channels may have been caused by historical landuse activities such as logging that reduced the source for large woody debris and more recent activities such as the direct removal of large woody debris channels. Conversely, recent local restoration efforts that add large woody debris to channels or that minimize sediment sources from roads may improve habitat. This is consistent with field data collected at six study reaches in the San Gregorio watershed illustrating that pools present exist mainly in association with large wood or bedrock protrusions that create structure in the channels.

Detailed long-term quantitative data collection efforts locally focused on specific aspects of a watershed's sediment budget (e.g. incision or aggradation rates, erosion and transport rates, and changes in morphology, substrate size or embeddedness etc.) are rare. Nonetheless, quantification of a rapid sediment budget to assess historical changes in geomorphic processes and sediment supply, storage, and yield for the San Gregorio Creek watershed is dependent on the availability of such long-term quantitative data. This report provides a summary of data that are currently available or that could be developed toward this effort; additional data could help quantify the rapid sediment budget if it becomes available. A long-term and spatially distributed and comprehensive data collection effort focused to address specific questions would help quantify future changes in sediment erosion, storage, and yield from tributaries and from the main channel.

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References

Asselman, N.E.M., 2000. Fitting and interpretation of sediment rating curves. Journal of Hydrology 234:228–248.

Cannon, 1988. Regional Rainfall-Threshold Conditions for Abundant Debris-Flow Activity. In: Landslides, Floods, and Marine Effects of the Storm of January 305, 1982, in the San Francisco Bay Region, California. USGS Professional Paper 1434. P. 35-42.

Cloud, R.W., 1928. History of San Gregorio, California. From: The Story of San Mateo County, California. S.J. Clarke Publishing Company. Chicago, Ill. http://history.rays-place.com/ca/sm-sg.htm

Cowart, A., and Byrne, R., 2013. A paleolimnological record of late Holocene vegetation change from the Central California Coast. California Archaeology 5(2):337–352.

Cuthrell, R.Q., Hylkema, M.G., Collins, L., 2013. Natural Resources, Geomorphology, and Archaeology of Site CA-SMA-113 in Quiroste Valley Cultural Preserve, California. California Archaeology, 5(2):247–264.

d'Alessio , M.A., Johnson, L.A., Burgmann, R., Schmidt, D.A., Murray, M.H., 2005. Slicing up the San Francisco Bay Area: block kinematics and fault slip rates from GPS-derived surface velocities: Journal of Geophysical Research, v.110, p. B06403, doi:10.1029/2004JB003496.

Ellen, S.D., 1988. Description and mechanics of Soil Slip/Debris Flows in the Storm. In: Landslides, Floods, and Marine Effects of the Storm of January 305, 1982, in the San Francisco Bay Region, California. USGS Professional Paper 1434. P. 63-112.

Ferguson, R.I., 1986. River loads underestimated by rating curves. Water Resources Research 22:74–76.

Florsheim, J.L., Pellerin B., Oh, N.H., Ohara, N., Bachand, P., Bachand, S., Bergamaschi, B., Hernes, B. Kavvas, M.L., 2011. From deposition to erosion: spatial and temporal variability of sediment sources, storage, and transport in a small agricultural watershed. *Geomorphology* 132(3-4):272-286.

Florsheim, J.L., Chin, A., Gaffney, K., Slota, D., 2013. Thresholds of stability in incised "Anthropocene" landscapes. *Anthropocene* 2:27-41.

Gartner, J., Owens, J., Hecht, B., 2008. Streamflow and Sediment Monitoring, El Corte de Madera Creek, Water year 2007 El Corte de Madera Creek Open Space Preserve, San Mateo County, California. Report prepared for Midpeninsula Regional Open Space District. Balance Hydrologics, Inc., March 2008. 19 p.

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

Greenlee, J. M., and Langenheim, J.H., 2013. 1990 Historic Fire Regimes and Their Relation to Vegetation Patterns in the Monterey Bay Area of California. American Midland Naturalist 124:239–253.

Hector, S.T. 1986. La Honda Oil Field. Division of Oil and Gas, Sacramento, CA. p. 11-21. Map showing fields: ftp://ftp.consrv.ca.gov/pub/oil/maps/dist/w3-10/Mapw3-10.pdf

Horowitz, A.J., 2003. An evaluation of sediment rating curves for estimating suspended sediment concentrations for subsequent flux calculations. Hydrological Processes 17: 3387–3409.

Jayko, A.S., Rymer, M.J., Prentice, C.S., Wilson, R.C., Wells, R.E., 1998. Scenic Drive Landslide of January-March 1998, L Honda San Mateo County, California, U.S. Geological Survey. Open File Report of98-229(poster).

Jayko, A.S., De Mouthe, J., Lajoie, K.R., Ramsey, D.W., Godt, J.W., 1999. Map Showing location of damaging landslides in San Mateo County, California, resulting from 1997-98 El Nino Rainstorms. Miscellaneous Field Studies MF-2325-H.

Keefer, D.K., Wilson, R.C., Mark, R.K., Brab, E.E., Brown, W.M., Ellen, S.D., Harp, E.L., Wieczorek, G.F., Alger, C.S., Zatkin, R.S., 1987. Real-Time Landslide Warning during Heavy Rainfall Science, New Series, 238(4829):921-925.

Lightfoot, K.G., et al., 2013. Anthropogenic Burning on the Central California coast in the late Holocene and Early Historical Times: Findings, Implications, and Future directions. California Archaeology 5(2):371–390.

Lisle, T.E., 1987. Using "residual depths" to monitor pool depths independently of discharge. Res. Note PSW-394. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 4 p.

Milliken, R., Shoup, L.H., Ortiz, B.R., 2009. Ohlone/Costanoan Indians of the San Francisco Peninsula and their Neighbors, Yesterday and Today. Prepared by Archeological and Historical Consultants Oakland, California for the National Park Service, Golden Gate National Recreation Area, San Francisco, California. June 2009. 308p.

Nilsen, T.H., Wright, R.H., Vlasic, T.C., and Spangle, W.E., 1979. Relative slope stability and land use planning in the San Francisco Bay Area. USGS Professional paper 944. 96 p.

Stillwater Sciences, Stockholm Environment Institute, San Gregorio Environmental Resource Center (SGERC), 2010. San Gregorio Creek Watershed Management Plan. Report Prepared for the Natural Heritage Institute, June 2010. 150 p.
Weber, G.E., Allwardt, A.O., 2001. The geology from Santa Cruz to Point Ano Nuevo: The San Gregorio Fault zone and Pleistocene marine terraces: USGS Bulletin, v. 2188, p. 1-32.

Wells, R.E., Rymer, M.J., Prentice, C.S., Wheeler, K.L., 2006. Map showing Features and Displacements of the Scenic Drive Landslide, La Honda, California, During the Period March 31, 2005-November 5, 2006. Open-File Report 2006-1397; Sheet 1 and 2 of 2.

Wieczorek, G.E., 1987. Effect of rainfall intensity and duration on debris flows in central Santa Cruz Mountains, CA. In: Geological Society of America Reviews in Engineering Geology, Volume II. P. 93-104.

Wieczorek, G.F., and Keefer, D.K., 1984. Earthquake-triggered landslide at La Honda, California. In: The Morgan Hill Earthquake of April 24, 1984, Seena N. Hoose (ed.). USGS Bulletin 1639. P. 73-79.

Wieczorek, G.E., and Sarmiento, J., 1988. Rainfall, Piezometric levels, and debris flows near La Honda, California in storms between 1975 and 1983. In: Landslides, Floods, and Marine Effects of the Storm of January 305, 1982, in the San Francisco Bay Region, California. USGS Professional Paper 1434. P. 43-61.

Wieczorek, G.F., Wilson, R.C., Ellen, S.D., Reid, M.E., Jayko, A.S., 2007. Thirty-one years of debris-flow observation and monitoring near La Honda, California, US. Conference Paper: International Conference on Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment, Proceedings. http://pubs.er.usgs.gov/publication/70033603

Willis, C.J., Perez, F.G., and Gutierrez, C.I., 2011. Susceptibility to Deep-Seated Landslides in California, Map Sheet 58.

Wohl, E., Bledsoe, B.P., Jacobson, R.B., Poff, N.L., Rathburn, S.L., Walters, D.M., and Wilcox, A.C., 2015. The Natural Sediment Regime in Rivers: Broadening the Foundation for Ecosystem Management. BioScience 65(4): 258-371.

Wolman, M.G., 1954. A method of sampling coarse river-bed material. Eos Transactions AGU 35:951-956.