Taking Action for Clean Water—Bay Area Total Maximum Daily Load Implementation: Lagunitas Creek Sediment Budget

Final Report

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Prepared by
Stillwater Sciences
Berkeley, California

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Stillwater Sciences

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SUMMARY

Concerns for the effects of erosion and sedimentation on aquatic habitat in Lagunitas Creek (Marin County, CA) have prompted the need for an average annual watershed sediment budget to help elucidate sediment production, yield, and routing. The budget will ultimately help in the formulation of a watershed-wide TMDL aimed at addressing sediment-related factors limiting the abundance of coho salmon (*Onchorynchus kisutch*) and steelhead trout (*Onchorynchus mykiss*) within the watershed. The project is concerned with recent watershed conditions (1983–2008) and builds on a recent sediment delivery assessment (Stillwater Sciences 2007) that included this same time period. The 1983 starting date relates to increasing regulation of flow and sediment from the upper watershed caused by raising Peters Dam by nearly 14 m (45 feet), and to the potential geomorphic "re-setting" of the watershed caused by a large flood event on January 4, 1982.

The Lagunitas Creek watershed extends from the northwest slope of Mt. Tamalpais to Tomales Bay. Flow regulation throughout the watershed causes the total watershed area (213 km^2) to be disconnected, with Peters Dam and Seeger Dam having the most significant impact on flow and sediment impoundment. Peters Dam, first constructed in 1954, regulates flow from the upper watershed (58km^2) and Seeger Dam, completed in 1961, regulates flow from the Nicasio Creek sub-watershed (93km^2). The watershed area downstream of these dams to the Olema Creek confluence (64km^2) is predominantly comprised of mélange of the Central terrane, Franciscan complex. Rainfall patterns are typical of a mild Mediterranean climate and total annual precipitation ranges from approximately 1,000 mm to 1,500 mm to at higher elevations. Land cover in the watershed is currently composed of conifer forested hillsides, grasslands that support grazing activity, and residential development, especially in the San Geronimo sub-watershed. Recent watershed history includes a "typical" pattern of Euro-American settlement: crop production, ranching, and logging for paper production dominated the period from 1850–1918. Thereafter there was a switch from row crops to grazing and the beginnings of flow regulation (1919–1945), limited population increases and the beginnings of significant flow regulation (1945–1982: including the initial Peters Dam and Seeger Dam), and the current period since 1983 that is characterized by continued development in the San Geronimo Creek watershed and increased concerns for environmental quality. Rates of hillslope sediment delivery are likely to have increased dramatically during the initial settlement period and then progressively reduced during subsequent periods in response to flow regulation, with sediment production switching to channel sources. The impacts of development are recorded by several studies that document variable rates of sedimentation into Tomales Bay, studies of sediment yields from neighboring areas, and by channel monitoring activities in the watershed since 1979. The channel monitoring studies recognized the mobility of bed sediments in both Lagunitas and San Geronimo Creeks, and the predominance of supply of finer gravels and sand delivered from San Geronimo Creek, with potential impacts on aquatic habitats.

This sediment budget study uses multiple sources and methods to assess the dominant geomorphic processes and estimate rates of sediment production, delivery, and storage within the regulated portion of the Lagunitas Creek watershed (i.e., the watershed area downstream of Peters Dam and Seeger Dam) upstream of Olema Creek. Background and corroborating data were compiled from sediment source inventories within this and nearby watersheds. Discrete sediment production and delivery sources were examined using a time series of aerial photographs in combination with hillslope and in-channel field data collected as part of this study. Results were digitally extrapolated across the study area using geomorphic landscape units (GLUs), a

representative area approach where measured hillslope and channel sediment production rates are distributed to areas with the same combination of geology, land cover, hillslope or channel gradient, and stream order (for channel GLUs). The delivery of sediment from roads and trails was derived using a digital terrain-based empirical model (SEDMODL2) tied to a recent comprehensive survey of road and trail types within the watershed. Non-point source sediment production and diffusion was based on a digital terrain-based process numerical model developed in the local area at the University of California, Berkeley. Corroboration of these estimates was based on analysis of sediment discharge using flow records from three gauging stations within the watershed, and use of limited bathymetric survey of sediment yield into Nicasio Reservoir. Sediment transport modeling using the TUGS numerical model was used to determine the dynamics of mainstem coarse and fine sediment movement into future as a function of various watershed management scenarios.

The results suggest that the primary sediment source within the watershed (42%, 8,500 t a^{-1}) arises from bed and bank erosion of first- to third-order tributary channels; hillslope slides and gullies account for about a quarter (26%, 5,300 t a^{-1}) of all sediment, and mainstem bed and bank erosion represent just under 20% (4,000 t a^{-1}) of sediment delivered. The Lagunitas mainstem reach between Devils Gulch and the Nicasio confluence is subject to in-channel aggradation which removes approximately 1,300 t a^{-1} of sediment from downstream transport. The San Geronimo sub-watershed, at 38% of the study area, accounts for a little under one-half of all sediment delivered annually (9,400 t) of which approximately 17% is derived from roads and trails, the highest percentage delivery from this source of the study area regions defined by the three gauge locations. Annual unit sediment production (i.e., production rate normalized by either contributing watershed area or channel length) from smaller sub-watersheds (excluding road sediment delivery) is generally proportional to area: rates range from 30–400 t km^{-2} a^{-1} with an arithmetic mean around 200 t km^{-2} a^{-1} and a standard deviation of nearly 100 t km^{-2} a^{-1}. These values are comparable to yields previously estimated from headwater area studies in nearby watersheds.

Hillslope and channel sediment production rates, both total and fine sediment, vary considerably as a function of GLU type. Hillslope unit sediment production rates by GLU are primarily in the range are 10–200 t km^{-2} a^{-1}; three units have rates over 250 t km^{-2} a^{-1} with a maximum of 466 t km^{-2} a^{-1}. Rates appear to be maximized on steep slopes (> 30%) and on agricultural rather than forested lands, irrespective of geology. Caution is noted that forested areas are relatively underrepresented in field survey and aerial photograph analysis. Bank erosion is maximized in first order channels with shrub-forest land cover on Franciscan mélange (0.108 t m^{-1} a^{-1}) due in part to their ubiquity, but rates in the San Geronimo Creek sub-watershed are highest in second order urban channels on Franciscan mélange (0.139 t m^{-1} a^{-1}). Other channel GLU unit rates are below 0.060 t m^{-1} a^{-1}. Highest mainstem bank erosion unit rates occur downstream of the Nicasio Creek confluence (0.166 t m^{-1} a^{-1}). Fine sediment (< 2 mm) in field hillslope samples ranged from 14–95%. When extrapolated, fine sediment is approximately 60% of all hillslope sediment produced in the San Geronimo Creek sub-watershed, 50% in Devils Gulch, and 55% elsewhere. Fine sediment production is proportional to sub-watershed area; production rates (10 to 238 t km^{-2} a^{-1}) are general in the range of 100–125 t km^{-2} a^{-1} with all highest production rates coming from the San Geronimo Creek sub-watershed.

Sediment yield for the Lagunitas Creek watershed is predicted by our study and from gauging station records to be in the range 18,000–20,000 t a^{-1}, giving a unit rate in the region of 300 t km^{-2} a^{-1}. Individual rates range from 140 t km^{-2} a^{-1} using data from the Samuel P.Taylor gauging station to over 460 t km^{-2} a^{-1} achieved by bathymetry surveys of the Nicasio/Halleck Creek arm of the Nicasio Reservoir. In general, our sediment yield rates are higher then estimated by sediment discharge from the three gauging stations (166, 282 and 114%, respectively), and somewhat lower than from bathymetric survey (69 and 81%). Each method has associated errors but the general similarity between the sediment yields achieved at the lowest point of the watershed, and from the independent corroboration of GLU-derived rates with bathymetric survey in the Nicasio sub-watershed suggests some confidence can be attached to the extrapolated rates. By virtue of their extrapolation, the large area unit yields derived from the GLUs are somewhat conservative (285–383 t km^{-2} a^{-1}) in comparison to other data sources, but are generally logical in comparison with rates achieved from survey of sedimentation in Tomales Bay and from a sediment budget from neighboring Redwood Creek.

The overall sediment budget for Lagunitas Creek watershed illustrates a watershed characterized by incision, as might be expected from the amount of flow regulation in the watershed. As such, there are fewer sediment stores than depicted in "classic" sediment budget studies, and the proportion of channel-derived sediment is far higher, relative to hillslope sources. Inputs from hillslope slides, gullies, and soil creep are approximately 8,200 t a^{-1} whereas the estimated total watershed yield is just over 20,000 t a^{-1}, indicating one measure of short-term disequilibrium in the watershed. Flow variability at the three gauging stations indicate that, while average sediment discharges in the watershed are approximately 5,300, 4,300, and 17,200 t a^{-1} at the SGC, SPT, and PRS gauges, respectively, wet year flows may discharge more than 35,000, 30,000, and 60,000 tonnes, respectively, providing a measure of inter-annual sediment variability in sediment transport.

To clarify options for sediment management to benefit aquatic habitat, the TUGS (The Unified Gravel Sand model) sediment transport model was applied to the major spawning reach through San Geronimo Creek down to the Lagunitas Creek-Devil's Gulch confluence. The model was run to reach a quasi-equilibrium under current conditions using multiple cycles of the 27 years of hydrologic record, resulting in a surface sand fraction of 6–7% and the subsurface fraction 17–20%. A fine sediment reduction scenario (reduction of sand supply to 70% of current values from contributing watersheds) and three gravel augmentation scenarios (30, 100, 300 t a^{-1} augmentation) were tested. The fine sediment reduction scenario reduced the surface sand fraction by about 15% on current conditions and reductions of 1.4–14% were achieved with gravel augmentation. Subsurface sand fractions could be reduced by only about 3% under both scenarios, consistent with experimental knowledge that the subsurface sand fraction is more dependent on initial subsurface grain size distributions than of the characteristics of sediment supply.

Overall, the sediment budget for Lagunitas Creek watershed consists of nearly 57% sediment production from channel sources (10% intercepted by channel aggradation) and 34% from hillslope slides, gullies, and soil creep of which one-third is estimated to go into colluvial storage. The results appear consistent with the highly regulated flow and sediment regimes, and urban expansion within the San Geronimo watershed. Sub-watershed sediment production is generally proportion to contributing area but is higher in San Geronimo Creek so that this watershed produces 47% of the total sediment from only 38% of the drainage area. Notable sources in the San Geronimo watershed include erosion from a relatively dense network of roads and trails, contributions from agriculture on steep terrain, and tributary bank erosion in headwater channels and second-order channels draining urban areas. Fine sediment production rates are also highest in the San Geronimo watershed.

By comparison to theoretical and cosmogenic studies of long-term rates of sediment production from neighboring watersheds, present-day human activities in the Lagunitas Creek watershed have cumulatively increased sediment yields somewhere from double to an order of magnitude over such background rates. Factors may include road-related erosion, agriculture, tributary erosion and increases in drainage density, erosion of the bed and banks of mainstem channels, and disconnection of floodplain surfaces. Relative rates of fine sediment production are also likely to have increased. Reducing the fine sediment fraction in bed sediments may be achieved either by fine sediment supply reduction, but achieving sufficient best practice measures may be challenging, by gravel augmentation of large volumes of sediment to be entrained during ENSO flow cycles, or measures intended to re-connect the channel to its floodplain.

Overall, the GLU-derived sediment yield estimates are comparable but consistently higher than yields predicted from gauging station records and lower than those from bathymetric survey, but logical in comparison to yields estimated into Tomales Bay and for neighboring Redwood Creek. Sub-watershed yields compare well to other neighboring small-area studies. Likely error sources may include (1) consistent underestimation of gauging station sediment yields when derived from a rating curve as acknowledged in academic literature; (2) over-prediction of sediment production caused by extrapolation or issues in temporally-bounding erosion volumes, especially under canopy or in tributary channels, respectively; (3) overprediction of rates of hillslope sediment delivery; or (4) omission of estimates for long-term channel margin or overbank storage, especially in the reach of Lagunitas Creek from the San Geronimo to Nicasio Creek confluences. As such, additional studies might profitably be focused on further field studies of hillslope sediment source areas, multi-year monitoring of landslide sediment delivery dynamics, field surveys of long-term channel margin and overbank sediment stores, and monitoring of channel erosion especially of headwater channels and mainstem bed elevations.

1 INTRODUCTION AND PURPOSE

Erosion and sedimentation in the Lagunitas Creek watershed (Marin County, CA) since European settlement is suspected to have impaired aquatic habitats. Multiple studies of sediment supply, transport, and yield in the watershed over the last 20 years have suggested that degraded aquatic habitat and declining fish populations are associated with high fine sediment contributions relative to the total sediment yield to the channels, primarily from the San Geronimo Creek watershed. These studies commonly cite historic slope instability, gully formation, streamside bank erosion, agricultural and logging practices, livestock grazing, and road-related surface erosion as natural and anthropogenic causes (Prunuske Chatham Inc. 1987, 1990; Hecht and Woyshner 1988; Neimi and Hall 1996; Rooney and Smith 1999; Hecht and Glasner 2002; Stetson Engineers Inc. 2002) as the causes for increased relative fine sediment contribution. Subsequently, public agencies have rallied to develop various stream restoration and sediment management and monitoring plans.

A useful tool in helping to determine the source and fate of eroded sediment throughout a watershed is the sediment budget. A sediment budget can be defined as "…an accounting of the sources and disposition of sediment as it travels from its point of origin to its eventual exit from the drainage basin" (Reid and Dunne 1996). More specifically, watershed-scale sediment budgets allow for a detailed determination of rates and process of hillslope and channel erosion, hillslope and channel sediment transport, and hillslope, floodplain and in-channel sediment storage that ultimately control the rate and caliber of sediment delivery out of the watershed. Process-based sediment budgets, in particular, enable accurate determination of sediment production and yield as a function of watershed geologic, topographic, and land use characteristics. Understanding the relative distribution of particle size from erosion sites as a function of watershed characteristics can be a vital component in linking land use dynamics with changes in key aquatic biologic processes.

In an effort to elucidate watershed sediment production and yield, Stillwater Sciences was tasked with constructing an average-annual sediment budget for the Lagunitas Creek watershed for the recent past (1983–2008). The sediment budget combines field data, remote sensing data, applicable process rates, and numerical modeling to constrain the historical and contemporary effects of land use and flow regulation on in-channel erosion and deposition dynamics throughout the watershed. This sediment budget will ultimately help in the formulation of a watershed-wide TMDL aimed, in part, at addressing fine sediment-related factors limiting the abundance of coho salmon (*Onchorynchus kisutch*) and steelhead trout (*Onchorynchus mykiss*) within the Lagunitas Creek watershed.

1.1 Objectives

This project develops a comprehensive sediment budget for the regulated portions of the Lagunitas Creek watershed from the headwaters to the confluence with Olema Creek, including the San Geronimo Creek and Devils Gulch Creek sub-watersheds. The sediment budget builds on a recent sediment delivery assessment of the watershed (Stillwater Sciences 2007) that included a quantitative accounting of watershed sediment production from bedrock, colluvial (hillslope), and alluvial (channel and floodplain) sediment sources and sinks through the identification of primary controls on rates and grain size distributions of sediment delivered to the channel network. This current project extends the geographic extent of the previous sediment delivery assessment to include the region of the watershed from the Devils Gulch confluence to the Pt. Reyes gauging station near the confluence with Olema Creek, and will explicitly account for sediment storage and rates of in-channel sediment transport, which allows for the compilation of a sediment budget. Project objectives were to:

1. Expand geographically and supplement existing sediment source and erosion assessments that have focused in the San Geronimo and Devils Gulch sub-watersheds and, most recently, a Middle Lagunitas Creek sediment delivery assessment (Stillwater Sciences);
2. Integrate existing watershed sediment delivery data with new sediment delivery and yield evaluations to produce a watershed-wide sediment budget (partitioned by fine and coarse sediment) for current (1983–2008) conditions that extends from the headwaters of San Geronimo Creek along the regulated Lagunitas Creek downstream to the confluence of with Olema Creek, just upstream of Tomales Bay;
3. Use a one-dimensional sediment transport model (Cui 2007a, b) to examine the potential future impacts of sediment management alternatives on sediment transport, fine sediment accumulation, and channel aggradation/incision dynamics throughout Lagunitas Creek downstream to the confluence with Devils Gulch;
4. Synthesize these data into an understanding of watershed-scale sediment transport dynamics as the basis for prioritizing areas within the watershed potentially in need of sediment management to maintain a balance between coarse and fine sediment in Lagunitas Creek.

The starting year for this sediment budget (1983) is set by two important events that occurred in the watershed the previous year that have had a significant impact on current geomorphic processes: the January 4, 1982 storm event, and the raising of Peters Dam by nearly 14 meters (45 feet). The storm event caused wide-spread erosion and is suspected to have reset channel conditions, thereby beginning a period of channel recovery set within the context of newly created channel and hillslope erosional features. The raising of Peters Dam to its current elevation (completed in 1982) ensured the trapping of all sediment from upstream of the dam (approximately 20% of the total watershed area), and allowed highly regulated flow releases in all but the wettest periods when large, relatively clear-water flows significantly augment discharge in Lagunitas Creek. Combined, these events helped enact the current period of watershed disturbance and reflect some of the major controls on rates and size classes of current sediment delivery in Lagunitas Creek.

2 STUDY AREA

Material in this section is derived largely from an earlier report (Stillwater Sciences 2007), with appropriate edits, updates, and supplements reflecting the larger study area.

2.1 Watershed Overview

Lagunitas Creek originates on the northern slopes of Mt. Tamalpais (peak elevation of 784 m), and flows through a predominantly oak and redwood forest and grassland landscape before draining to sea level through a broad tidal marsh at the head of Tomales Bay, located within the San Andreas Rift Zone (Jennings 1994). Sediment transport in the watershed is disconnected in several locations by large dams that prevent downstream sediment transfer. Seeger Dam disconnects the majority (93.3 km^2) of the Nicasio Creek sub-watershed, and Peters Dam disconnects the upper Lagunitas Creek sub-watershed (55.7 km^2) (Figure 2-1). As such, the effective area of sediment production and delivery in regulated Lagunitas Creek to the Olema Creek confluence is 64.4 km^2 (62.3 km^2 to USGS gauge 11140600 at Pt Reyes Station), which includes the unregulated San Geronimo Creek sub-watershed (24.3 km^2), Devils Gulch sub-watershed (7.0 km^2), regulated Nicasio Creek (2.3 km^2 area) and a number of other tributary sub-watersheds . The study area is predominantly comprised of mélange of the Central terrane, Franciscan complex (Wentworth 1997, Blake et al. 2000). Mélange is a sheared and deformed mixture composed mainly of greywacke, sandstone, shale, chert, greenstone, and metamorphic rocks integrated with lesser amounts of serpentine and silica-carbonate rocks of the Coast Range ophiolite. Hillslopes in a large portion of the study area are mantled with clay-rich soils derived from highly weathered, matrix supported mélange, supporting a wide variety of vegetative cover and land use types.

The watershed receives most of its precipitation as rainfall from November through March and is typified by a mild Mediterranean climate, dominated by dry summers and wet winters that are punctuated by periods of intense rainfall (Fischer et al.1996). Average annual precipitation from 1950 to 1999 was approximately 1,500 mm at Kent Lake (CDWR gauge #E10 4502 00) and approximately 1,100 mm at Woodacre (CDWR gauge #E10 7787 21). Average annual precipitation from 1977 to 1999 was approximately 980 mm near the Tocaloma pump at Soulejoule Dam in the Walker Creek watershed to the northwest (DWR # E10 8943 20). Annual sediment delivery to channels is highly variable in response to storm intensity so that very intense rainfall is responsible for sediment supply and mobilization from hillslopes, while the potential for sediment transport is related primarily to high magnitude flow events. Actual sediment transport is, therefore, variable according to event and likely at a maximum when high magnitude flow events follow high intensity rainfall events.

Mainstem Lagunitas Creek flows adjacent and parallel to the dominant, northwest-trending San Andreas Rift Zone (Figure 2-1). Valley bottom altitudes range from ~60 m above Mean Sea Level (MSL) just downstream Peters Dam to mean sea level at the outlet of Lagunitas Creek into Tomales Bay. To the west, the Bolinas Ridge ranges in altitude from ~ 400 m above MSL in areas adjacent to Kent Lake to ~270 m above MSL along the ridge, opposite of the confluence of Lagunitas Creek and Devils Gulch. Riparian species such as alders, willows, ash, maples, and creek dogwood occupy the margins of Lagunitas Creek whereas, east-facing slopes of Bolinas Ridge support grassland and scrubland communities, primarily second-growth Douglas Fir stands, and some chaparral (NPS 1992). Land use in the upper Lagunitas sub-watershed was dominated by logging operations in the 19th and early part of the 20th century (Niemi and Hall

1996). Currently, slopes in the area primarily accommodate recreational activities with hillslopes commonly traversed by recreation trails maintained by State or National Park Services.

San Geronimo Creek occupies a roughly east-west trending valley that transitions from a broad alluvial valley at the upstream portion to a confined, bedrock-controlled valley towards the confluence with Lagunitas Creek. The headwaters region is characterized by south-facing slopes with low-moderate relief that support shrubs and grassland species, and steep, north-facing slopes that tend to support more dense conifer growth. The San Geronimo Creek watershed is the most developed of any of the Lagunitas Creek sub-watersheds, and therefore has the highest population density. Residential communities include Woodacre, San Geronimo, Forest Knolls, and Lagunitas, and there are also four Marin County Open Space Preserves designated in the watershed. San Geronimo Creek flows for 7.2 km before entering Lagunitas Creek approximately 0.5 km downstream of Peters Dam.

Devils Gulch drains north-facing slopes dominated by forested land, south-facing slopes dominated by grazed grassland, and is confined within a relatively steep valley. Its drainage area is about 25% that of the San Geronimo Creek watershed, and it shares functionally similar vegetation and hillslope characteristics but with greater topographic relief. Devils Gulch sub-watershed is mostly publicly owned, partitioned between Golden Gate National Recreation Area (GGNRA) in the headwater region and the Samuel P. Taylor State Park (SPTSP) at the downstream end. Mainstem Devils Gulch flows for 2.4 km before entering Lagunitas Creek.

Nicasio Creek is a regulated major tributary that flows for 1.9 km downstream of Seeger Dam before it enter Lagunitas Creek approximately 7 km downstream from the Devils Gulch confluence. The construction of Seeger Dam in 1961 resulted in regulation of over 98 % of the Nicasio Creek watershed and a reservoir that has a maximum area of approximately 352 ha (869 acres) and a storage capacity of approximately 1,230 m^3 (22,400 acre-feet: Smith 1986). The Nicasio Creek watershed drains mostly grasslands in the low-topography northern part of the watershed and mixed grassland/shrub/forested lands in the areas with greater topographic relief (and more resistant underlying geology) to the east.

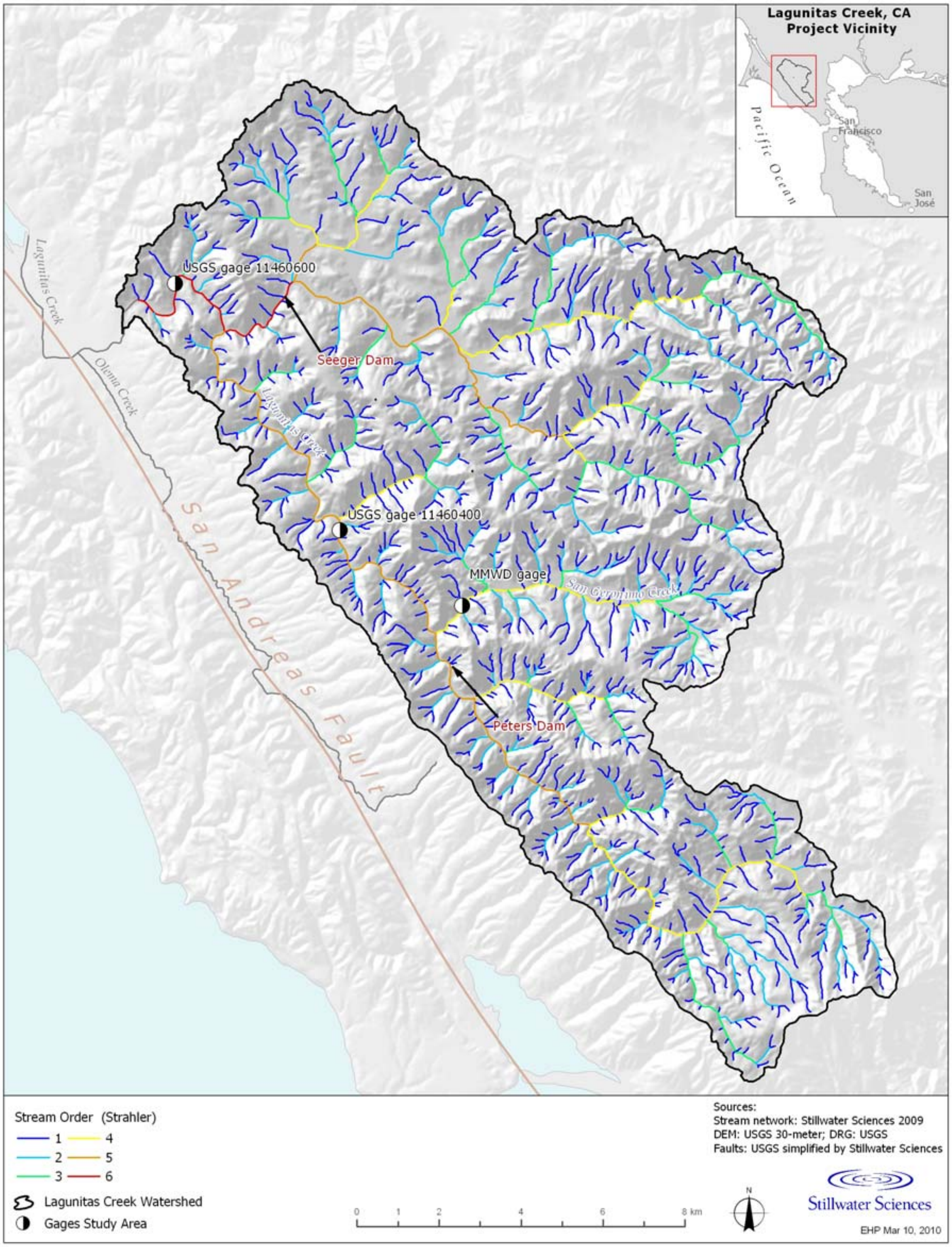

Figure 2-1. Map of the Lagunitas Creek watershed.

2.2 Watershed Disturbance History

Rates of sediment production, delivery and transport in watersheds are profoundly affected by natural climatic events (e.g., high intensity and duration of rainfall, high discharges in stream channels) and by a suite of human activities. The impacts of human activities are generally more noticeable once larger numbers of people inhabit a watershed. As such, the initiation of significant human impacts on watershed sediment processes in the American West is generally associated with the influx of Euro-American settlers in the mid-Nineteenth century, although there were undoubtedly earlier impacts associated with the domestication of woodland and meadow environments by the Coast Miwok who originally settled the Lagunitas Creek watershed. Historical records can be used to determine a chronology of "disturbances" in this regard (Sear et al. 1995), that is, to determine distinct periods where human activities may have resulted in a discrete series of controls on sediment processes. For instance, discrete periods may coincide with early land clearance for agriculture, logging practices, livestock grazing, road and urban construction and development, episodes of channel engineering and, in some areas, such as the nearby Redwood Creek (see Stillwater Sciences 2004), the retirement of agricultural land and its return to "natural" vegetation cover. Historical records obtained from several sources (Niemi and Hall 1996, Marin County Community Development Agency [Marin County CDA] 1997, SFBRWQCB 2002, Tomales Bay Watershed Stewardship Council 2003) allow the post-European watershed history to be divided into discrete time periods that may reflect different controls on rates and size classes of sediment delivery (Table 2-1).

Unlike neighboring watersheds such as Redwood Creek that is 95% parkland and has a very distinct disturbance chronology linked to various preservation and conservation initiatives, the Lagunitas Creek watershed has a far more common progression of increasing development pressure in time, albeit with less urban development than other areas of Marin County. The first period (1850–1918) involved the establishment of European settlements within the San Geronimo Creek and Lagunitas Creek valley and the beginning of crop production, ranching, and logging (in this case directed towards paper production). The remaining three periods fundamentally reflect increasing flow impoundment through the watershed (Table 2-1). The first of these, 1919–1945, is characterized by initial flow impoundments and a switch from row crops to grazing. The second (1945–1982) saw limited population increases in the watershed and involved the greatest extent of additional impoundment with the construction of the original Peters Dam (1954) disconnecting the upper Lagunitas watershed above the current study area, and the completion of Seeger Dam (1961) impounding Nicasio Creek in the north-eastern section of the watershed. The present period (1983–present) is characterized by further increases in flow regulation for Lagunitas Creek but made against a backdrop of legislation that strives to maintain environmental quality in the presence of such disturbances. The period is follows a large flood that occurred on January 4, 1982. Using evidence from available river gauging stations in Marin County supplemented with historical narratives from the Muir Woods National Monument suggested that the 1982 event may have been the largest flow event in the County since an event on February 11, 1925 (Stillwater Sciences 2004, p.50). If these different periods do reflect different controls on rates and size classes of sediment delivery, then the disturbance history provides a context in which to interpret changes observed under the timeframe of the current study (1983–2008), a potentially important factor when considering that landscape changes resulting from geomorphic processes can take many decades if not centuries to complete.

Table 2-1. Chronology of major activity and disturbances in the Lagunitas Creek watershed.

Period	Time period	Watershed activity/disturbance
European arrival and resource development	1850–1918	Establishment of San Geronimo, Lagunitas, Forest Knolls, and Woodacre. Establishment of farms (wheat, oats, barley, and potatoes), ranches (cattle and sheep), and infrastructure (permanent buildings, roads) [1860–1888]. Channelization, construction of levees, extraction of in-channel sediment, and diking of marshes at mouth of Lagunitas Creek for agricultural and development purposes. Establishment of paper mill on Lagunitas Creek initiates intensive logging (1865), North Pacific Railroad track built along Lagunitas (1873–1874), Sir Francis Drake road built (1892). Major fires in watershed (1878 and 1904). First water supply dam constructed (Lagunitas Reservoir 1872: 350AF).
Regulation and grazing	1919–1945	Start of flow impoundment of Lagunitas Creek. Impoundment of Alpine Lake (Alpine Dam 1918: enlarged 1924, 1941: 8,891AF). Change in dominant agriculture practice from crop farming to livestock (1930s). Continued logging in the watershed. Major fire in watershed (1945).
Intensive damming	1946–1982	Increase in population and development directly following World War II (post-1945). Intensive damming of Lagunitas Creek for water supply purposes. Impoundment of Bon Tempe Reservoir (1948: 4,017AF), Kent Lake (Peters Dam 1954, enlarged 1982: 32,895AF) and Nicasio Reservoir (Seeger Dam 1961: 22,430 AF). Continued extraction of natural resources. Mining of mercury ore in open pit mines (1940–1970) and removal of in-channel sand and gravel from stream bed at confluence of Lagunitas and Nicasio Creek (through 1961). End of logging in watershed (1960).
Raising of Peters Dam, planning & mitigation	1983–present	Increasing significance of San Geronimo Community Plan (from 1978). Increased impoundment of water/sediment within the watershed. Peters Dam (Kent Lake) raised 45 ft (completed 1982). Large storm in WY 1982 suspected to have reset channel conditions

Sources: Niemi and Hall 1996, Tomales Bay Watershed Stewardship Council 2003, SFBRWQCB 2002, and MMWD 2007

2.3 Conceptual Understanding

Our conceptual understanding of the geomorphology underpinning sediment production and delivery rates in the Lagunitas Creek watershed is derived from several sources. These include a series of academic investigations of the geomorphology of the Lagunitas and neighboring watersheds (e.g., Lehre 1982, 1987; Haible 1980; Fischer et al. 1996; Niemi and Hall 1996; Smith et al. 1996; Rooney and Smith 1999; Ritchie et al. 2004; Kirby et al. 2007; O'Farrell et al. 2007), understanding gained following a similar investigation in nearby Redwood Creek (Stillwater Sciences 2004), and a series of reports specific to our study area undertaken since 1979 (including Hecht and Enkeboll 1979, 1981; Hecht et al. 1980; Hecht and Woyshner 1983, 1988; Prunuske Chatham and Hecht 1987; Prunuske Chatham 1990, 2003; Hecht 1992; Stetson Engineers 2002; SPAWN 2002; O'Connor and Rosser 2006; Stillwater Sciences 2007).

Context for the project is provided by the history of watershed disturbances derived in Section

2.2. It is clear, for instance, that during the first phase of European settlement in Lagunitas watershed (1850–1918 in Table 2-1), and to some extent during the second phase (1919–1945) rates of sediment delivery were greatly increased by activities associated with livestock raising, the introduction of non-native grasses and intensive logging. Using available map records, Niemi and Hall (1996) documented that Tomales Bay at the mouth of the Lagunitas Creek watershed prograded more than 1 km in the period 1860 to 1918, and an additional 500–800 m along tidal channels in the period 1918–1954. Little further sedimentation occurred in the interval 1954–1982 (roughly contemporaneous with our third period): Niemi and Hall speculate that this relates to reduced rates of sediment delivery in the period, primarily due to sediment interception by Kent Lake (1954) and Nicasio Reservoir (1961). Interpretation of several sediment cores taken in neighboring locations corroborates this interpretation. Rates of sediment accumulation in the period from 1850 to 1900 reach 13–19 mm a^{-1} in Bolinas Lagoon (Bergquist 1977, as cited in Niemi and Hall 1996), before reducing to 3–4 mm a^{-1} in the early Twentieth century, a rate that is argued to be more indicative of long-term rates of Holocene deposition. Similarly, in Redwood Creek, long terms rates of aggradation into Big Lagoon prior to European arrival were inferred to be just over 1 mm a^{-1} (from Meyer 2003, cited in Stillwater Sciences 2004) whereas since European arrival, a rate in excess of 11 mm a^{-1} has been recorded (Wells 1994, cited in Stillwater Sciences 2004). A sediment core taken in Olema Creek also records a greater amount of coarser sediment deposition over the past two centuries. In nearby Stemple Creek, rates of sedimentation on floodplains decreased since the 1950s following a conversion from row crops to pasture in the watershed (Ritchie et al. 2004). In Lagunitas Creek, the change from row crops to pasture occurred in the 1930s so rates of sediment delivery may have reduced earlier than in Stemple Creek.

Overall, the geomorphology of Lagunitas Creek appears to follow a relatively simple path (up to 1982, at least) of greatly increased rates of sediment delivery from Lagunitas Creek to Tomales Bay due primarily to logging and crop agriculture following European arrival, particularly before 1918, and a progressive decrease in sediment delivery thereafter. Chronologically, the decreases appears to relate first, to re-vegetation of some hillslopes in the early Twentieth century, second, to a change from row crops to pasture from the 1930s and, third, to increasing flow and sediment regulation in the watershed from the 1950s. It is also probable that the balance of coarse and fine sediment has altered during this period especially in upstream areas subject to variations in local sediment supply (Hecht and Woyshner 1988). Narrative evidence for increasing fine sediment supply in the San Geronimo valley since approximately 1952 is given in the 1977 San Geronimo Valley Plan where it is suggested that gravel bed siltation (and septic system leachate) have been responsible for reducing salmonid spawning and rearing habitat in the watershed. Recent field-based investigations examining channel geomorphic processes combined with historical information concluded that San Geronimo Creek probably experienced signification channel enlargement during the 19th and first half of the 20th century (i.e., disturbance time periods 1 and 2), but that more recent rates of change have been lower, due in part to bedrock exposure and channel adjustment to watershed conditions (Stillwater Sciences 2009).

Since 1982, this simple trajectory of changing conditions has been subject to a wide variety of competing pressures. The raising of Peters Dam in 1982 further reduced sediment delivery from the upper watershed but this and other factors contributing to channel erosion (particularly incision) may be responsible for increases rates of sediment delivery from alluvial sediment stores in the “middle” watershed reaches, changing the balance of sediment sources from hillslopes towards channels. Factors contributing to channel erosion may have begun with increased rates of rainfall- runoff following deforestation of the watershed; further increases in flood “flashiness” and volume of runoff probably arose as a consequence of an increasing extent of impermeable surface following population increases in the watershed. In addition, the frequency of significant storm events has increased since the 1970s due to a multi-decadal shift in ENSO-influenced climate fluctuation towards a relatively wet climate (Inman and Jenkins 1999). Other potential causes of channel erosion include headwards migrating channel incision triggered by mining of sand and gravel from the confluence of Lagunitas and Nicasio Creeks (see Table 2-1), while damming of Nicasio Creek (Seeger Dam) and Lagunitas Creek (Peters Dam) is likely to have resulted in downstream prograding incision and, potentially, secondary incision in Lagunitas Creek upstream of the confluence with Nicasio Creek. The depth of channel incision in Lagunitas Creek is likely to have been limited by the presence of frequent bedrock outcrops in the mainstem valley, including the Inkwells outcrop which may have prevented upstream incision into San Geronimo Creek. Finally, the progressive increase in the network of unpaved roads in the watershed may be responsible for the existence of new discrete sediment sources, as documented in recent studies (SPAWN 2002, Stetson Engineers 2002).

Additional complexity in the conceptual model of geomorphic functioning of Lagunitas Creek in the recent period is partly matched by additional data available upon which to resolve the model. Since 1979, a series of geomorphology and biology studies have been undertaken designed to produce methods by which to mitigate the possible degradation in Lagunitas Creek caused by the raising of Peters Dam. Monitoring of flow and sediment yields at gauging stations across the Lagunitas watershed, combined with surveys of channel topography, bed configuration, and bed material surveys occurred from WY 1980 to 1982 (Hecht and Enkeboll 1979, Hecht et al. 1980, Hecht and Enkeboll 1981, Hecht and Woyshner 1983) and resulted in a sediment management plan focused primarily on sediment yield reduction from San Geronimo Creek (Hecht 1983). Supplementary sediment transport modeling was performed in 1987 (Hecht and Woyshner 1988) and a collection of cross-sections re-surveyed yearly since 1993 (e.g., Prunuske Chatham 2003). Sediment source analyses have been performed on several occasions as the basis for identifying and later checking on source-reduction prospects (Prunuske Chatham and Hecht 1987, Prunuske Chatham 1990, Stetson Engineers 2002).

In 1992, a summary statement regarding geomorphic conditions in Lagunitas watershed was prepared (Hecht 1992). In brief, the summary recognized that bed sediment in both Lagunitas and San Geronimo Creeks were readily mobilized, with finer gravels and more sand delivered from San Geronimo Creek, which was the primary supplier of sediment to the bed of the upper and middle Lagunitas Creek and capable of filling pools in Lagunitas Creek with sand and fine gravels. The majority of annual sediment transport occurs during a period of 1–3 days of high flows, as might be expected, and the vast majority of sediment transport occurs during wetter years. Sediment sampling indicated that sediment transport rates remain elevated for some weeks after a particularly large magnitude flood, such as that in 1982. Estimates of bedload transport based on simulations of stream flow in the period 1955–1984 suggest that bedload yields from San Geronimo Creek may have been above the level of those estimated in 1982 on three occasions, 1967, 1970, and 1973 (Hecht 1992).

In addition to creek studies of sediment dynamics, measures of watershed sediment yield can provide a means of independently checking that process-based estimates of sediment production, delivery and changes in storage are reasonable in their long-term context. In this regard, several studies of sediment accumulation in the south of Tomales Bay (the mouth of Lagunitas Creek) can provide important context (e.g., Neimi and Hall 1996, Rooney and Smith 1999). Rooney and Smith yielded a modern-day (1957–1994) Tomales Bay sediment accumulation rate of approximately 101 t km^{-2} a^{-1} averaged over the entire 561 km^2 of Tomales Bay contributing watersheds. Assuming a constant yield across all contributing areas, and with 69.8% of the Lagunitas watershed disconnected behind Peters and Seeger dams, a unit rate of 334 t km^{-2} a^{-1} would be required from the current study area to equate to the average value. More specifically, focusing on sedimentation rates in the southern end of Tomales Bay, Rooney and Smith suggest a the combined yield from the Lagunitas and Olema Creek watersheds of 325 t km^{-2} a^{-1} from 1861 to 1931, 290 t km^{-2} a^{-1} from 1931 to 1957, and 190 t km^{-2} a^{-1} from 1957 to 1994 (interpreted from their Figure 3). To the south of Lagunitas Creek, a sediment budget for Redwood Creek (22.7 km^2) estimated a contemporary rate (1981–2002) rate of sediment yield of 198 t km^{-2} a^{-1} from a watershed almost entirely under conservation land uses, reduced from historical high yield rates of 304 t km^{-2} a^{-1} (1841–1920) and 324 t km^{-2} a^{-1} (1921–1980). In neighboring headwaters, Lehre estimated a "long-term" sediment yield of 214 t km^{-2} a^{-1} from Lone Tree Creek (1.74 km^2), rising to 691 t km^{-2} a^{-1} for a three-year period (1971–1974) that encompassed a large storm event. For smaller area still, O'Farrell et al. (2007) computed hillslope erosion rates for the Haypress basin (0.33km^2) in the Tennessee Valley using several methods including pond sediment volume, ^{137}Cs and ^{210}Pb fallout nuclides and cosmogenic analyses and achieved rates equivalent to 224–334 t km^{-2} a^{-1}.

3 METHODS AND RESULTS

3.1 Approach

Sediment budget estimates require multiple approaches and data sources. This Lagunitas Creek watershed sediment budget builds upon the results of earlier sediment studies, named above, and develops, refines, and extends on a recent study of sediment delivery in the middle Lagunitas Creek watershed (Stillwater Sciences 2007). We add accuracy and precision to field estimates of individual geomorphic processes including their age class and textural properties, increase the extent of direct field observation of sediment production processes and rates, extend the spatial coverage of the analysis to include the entire effective area of sediment production and delivery above the Pt. Reyes gauging station slightly upstream of the Olema Creek confluence, and incorporate several numerical models to enhance our understanding of sediment dynamics in the watershed and allow us to extrapolate future sediment conditions under different watershed management scenarios. Example data sources used here include:

- literature reviews of process rate estimates reported for nearby areas with similar lithology and land use (e.g., Lehre 1982, Heimsath 1999, Stetson Engineers 2000, Stillwater Sciences 2004, CRWQCB 2005, PWA 2003, PWA 2007, Kirby et al. 2007, O'Farrell et al. 2007);
- existing quantitative sediment source inventories within the study area (Stetson Engineers 2002, Stillwater Sciences 2007);
- analysis of sequential aerial photographs to determine the occurrence, magnitude, and temporal development of discrete sediment production and delivery sources, where visible;
- hillslope and in-channel field reconnaissance to estimate erosion rates for observed erosion processes;
- digital terrain modeling as the basis for extrapolating field evidence across the study area;
- analysis of gauging records to determine sediment yields at three points within the study area;
- limited bathymetric surveys to determine sediment yields into Nicasio Reservoir;
- application of a road sediment production model (SEDMODL2) to estimate sediment production from roads and trails,
- application of a soil production and diffusion model developed by W.E. Dietrich and colleagues at the University of California, Berkeley, and;
- sediment transport modeling (TUGS) to determine the dynamics of coarse and fine sediment movement.

The specific approach to developing a sediment budget for the regulated portion of the Lagunitas Creek watershed includes:

1. determining patterns and rates of sediment production and delivery for various geomorphic processes and source types by compiling existing and newly-developed erosion data sources listed above (Section 3.2), and;
2. determining mainstem sediment transport and storage using gauge-specific flow and sediment discharge data, bathymetry data collected in Nicasio Reservoir, and reported estimates of sediment deposition rates into Tomales Bay (Section 3.3).

These various estimates are compiled to determine an average annual sediment delivery from the watershed for the 1983–2008 study period, discussed by sub-watershed, by geomorphic landscape unit (GLU, a landscape unit described by a unique combination of geology, land cover, and hillslope or channel gradient), and according to fine sediment source areas (Section 4.1). Comparative values of sediment yield are provided from implied rates of transport through gauging stations and according to values reported in neighboring locations (Section 4.2). An average annual sediment budget is described (Section 4-3) and between-year variability in sediment delivery is examined in relation to the impact of high flow years on sediment yield (Section 4.3). Management implications are discussed in the context of a sediment routing model used to investigate the potential impact of fine sediment reduction and coarse sediment augmentation (Section 5.1) before concluding issues related to the role of human activity (Section 5.2). Insights derived from the sediment budget about the relative contribution of different sediment sources and source areas should ultimately assist in devising appropriate watershed best management practices aimed at achieving a balance of coarse-to-fine sediment loading to biologically important reaches throughout the watershed.

Underpinning the approach, a finite set of relevant probable processes of hillslope and channel sediment production, transfer and storage within the Lagunitas watershed was defined (see Table 3-1). Rate estimates for the identified processes are the basis for the sediment budget that follows.

Table 3-1. Summary of sediment production and storage processes associated with sediment budgets of the California Coast Range.

Category	Sub-category	Geomorphic process	Method of investigation	Sources used in investigation
Sediment Production (*Natural Processes*)	Hillslope mass wasting processes	Creep and biogenic transport	Numerical modeling was used to estimate creep in comparison to field estimates.	Numerical modeling Previous erosion studies (within this and similar watersheds)
		Shallow landsliding	Existing and newly collected data were used to ascertain the location, volume, and timing of shallow landslides, and associated grain size distributions.	Field observations Geologic mapping Landslide inventories Time series of aerial photographs
		Deep-seated landsliding	Existing and newly collected data were used to ascertain the location, volume, and timing of shallow landslides, and associated grain size distributions.	Field observations Geologic mapping Landslide inventories Time series of aerial photographs
	Hillslope overland flow erosion	Sheetwash and rill erosion	Examination of existing and newly collected data to assess relative extent of and causation for sheetwash and rill erosion.	Field observations Appropriate values from literature Previous erosion studies (within this and similar watersheds).
	Channel production processes	Channel head advance and knickpoint migration	Existing and newly collected data were used to determine location of channel heads, rates of channel head advance, and the rates of upstream knickpoint migration.	Field observations Time series of aerial photographs) Previous erosion studies (within this and similar watersheds)
		Gully and channel incision	Spatial comparisons were used to identify stage in gully development. Existing and newly collected data were used to determine erosion and incision rates.	Field measurements of vegetation age and incision Previous erosion studies (within this and similar watersheds)
		Bank erosion	Existing and newly collected data were used to determine the volume of erosion according to channel morphology, vegetation age structure, characterization of grain size distributions, and stratigraphic evidence.	Field measurements Previous erosion studies (within this and similar watersheds)

Category	Sub-category	Geomorphic process	Method of investigation	Sources used in investigation
Sediment Production (*Human Disturbances*[1])	Road-related	Cut and fill failures	Numerical modeling, coupled with field observations in this and similar watersheds, was used to estimate rates and relative timing of sediment input and characterization of grain size distributions.	Numerical modeling (SEDMODL2) Field observations Previous erosion studies (within this and similar watersheds)
		Surface erosion		
		Stream crossing fill failures		
		inboard ditch incision and slope destabilization		
		Gully formation due to runoff associated with inboard ditch relief		
		Accelerated runoff and channel destabilization		
	Agriculture and rangeland	Surface wash rilling and gullying	See methods for rill erosion and gully incision above	Field observations Time series of aerial photographs Previous erosion studies (within this and similar watersheds)
		Accelerated runoff and channel destabilization	See methods for bank erosion and mainstem incision / aggradation above.	
		Shallow landsliding resulting from vegetation removal	See methods for shallow landsliding above.	
		Channel erosion and destabilization from riparian vegetation removal	See methods for bank erosion and mainstem incision / aggradation above.	
	Urban	Fine sediment release following construction	Rates of urban construction were too low to identify discrete fine sediment sources from field survey.	Field measurements Previous erosion studies (within this and similar watersheds)
		Fine sediment flushing resulting from connection of drainage network	Channels were examined above and below storm-water outfalls for erosional changes.	
		Channel erosion resulting from post-construction low sediment and accelerated runoff	See methods for bank erosion and mainstem incision / aggradation above.	
	Channel management	Channel erosion and destabilization through straightening and relocation	Existing and newly collected data were used to determine extent of channelization and effects on destabilization and sediment delivery.	Field observations Previous erosion studies (within this and similar watersheds)
		Channel erosion and destabilization through LWD removal	The history of channel maintenance was examined for evidence of LWD removal.	
		Forced storage resulting from dams and grade control measures	Field surveys were conducted to examine impact of sediment storage reservoirs (e.g., Dickson weir and Roy's Pools).	

Category	Sub-category	Geomorphic process	Method of investigation	Sources used in investigation
Channel sediment routing and storage dynamics		Sediment transport	Existing sediment gauging records were used to determine sediment rating curves. A sediment transport model was used to determine long-term coarse sediment (sand and larger) transport dynamics and estimate inter-annual transport variability. Existing bathymetric data was compared with historic topography to estimate average-annual unit sediment delivery	USGS and MMWD flow and sediment discharge data[2] Channel thalweg data Numerical modeling (TUGS) Bathymetric survey of one or more reservoirs Historic topographic data
		In-channel/overbank sediment storage	Existing and newly collected data were used to determine the volume of erosion according to morphology, vegetation age, near-channel structures, characterization of grain size distributions, and stratigraphic evidence. Spatial comparisons were used to identify stage in erosional development.	Field measurements Time series of cross-sections along mainstem Lagunitas Creek Historic channel thalweg data Previous erosion studies (within this and similar watersheds)

[1] 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.

[2] Includes flow and sediment data for: (1) Lagunitas Creek from USGS gauge at Pt. Reyes Station (11460600) from WY 1975 to present (USGS NWIS); (2) Lagunitas Creek at Samuel P.Taylor State Park (11460400) from WY1980 to present (Curtis 2007); and (3) San Geronimo Creek at Lagunitas Rd bridge (MMWS gauge) from WY 1980 to present (Hecht 1992; Hecht and Glasner 2002; Owens and Hecht 2000a–c, 2001; Owens et al. 2002; Shaw et al.2005; Owens et al.2007). Dataset also includes spill records for Kent Lake and Seeger Dam from WY 1984 to 2008.

3.1.1 Geomorphic landscape units

Because it is not possible to access all areas of the watershed, or to see erosion sources in aerial photographs clearly where canopy tree cover exists, a method is required to extrapolate survey results and analysis and so avoid a systematic underestimation of sub-watershed sediment production. In this regard, a series of geomorphic landscape units (GLUs) were defined in GIS according to landscape characteristics that frequently control processes and rates of erosion. Within each GLU, a suite of similar erosion processes can be expected (from those identified in Table 3-1) resulting in similar rates of sediment production. As such, erosion estimates from the observed portion of each GLU can be extrapolated to the unobserved portion. In common with many other studies (e.g., Reid and Dunne 1996, Montgomery 1999), the GLUs defined here were based on a combination of geology, hillslope or channel gradient, and vegetation cover/land use (Figures 3-1 to 3-4). Descriptions of the component parts of each GLU (listed in Table 3-2) were described in Stillwater Sciences (2007). Sub-watershed statistics for the proportional occurrence of different land cover terrains, geological terrains, and hillslope gradients is given in Tables 3-3, 3-4, and 3-5, respectively (see Figure 3-5 for sub-watershed locations). The extent of common GLUs in the study area as a percentage of various contributing watersheds is given in Table 3-6.

Table 3-2. Numerical Geomorphic Landscape Unit (GLU) code for dominant terrain characteristics in the study area.

Land cover (first digit)	Geologic terrain (second digit)	Hillslope gradient (third digit)
1 = Agricultural/Herbaceous	**1** = Quaternary alluvium	**1** = 0–5%
2 = Mixed Forest >50% canopy	**2** = Nicasio Reservoir	**2** = 5–30%
3 = Mixed Shrub <50% canopy	**3** = San Bruno Mountain	**3** = >30%
4 = Urban/Barren surfaces	**4** = Franciscan mélange	

Example: GLU code 343 represents a geomorphic landscape unit with shrub/forest with less than 50% canopy cover underlain by Franciscan mélange on slopes greater than 30%.

Table 3-3. Vegetation and cover terrains in the study area.

Watershed	Sub-watershed	Total area (km^2)	Percent of sub-watershed area: Ag/Herb	Mixed shrub	Mixed forest	Urban/ Barren
Upper Lagunitas	Upper Lagunitas (u/s of Peters Dam)	55.7	8%	35%	51%	7%
Middle and Lower Lagunitas	Woodacre Creek	3.7	13%	21%	50%	17%
	San Geronimo Creek[a]	20.7	26%	25%	45%	4%
	Devils Gulch	7.0	27%	6%	67%	0%
	Cheda Creek	3.0	51%	5%	44%	0%
	Lagunitas Creek (d/s of Peters Dam)[b]	30.0	37%	6%	57%	0%
Total Middle and Lower Lagunitas		***64.4***	***32%***	***13%***	***53%***	***2%***
Unregulated Nicasio	Unregulated Nicasio Creek (u/s of Seeger Dam)	93.2	56%	9%	32%	4%
TOTAL		**213.2**	**36%**	**17%**	**43%**	**4%**

[a] Excluding Woodacre Creek sub-watershed.
[b] Excluding Devils Gulch and Cheda Creek sub-watersheds.

Table 3-4. Geologic terrains in the study area.

Watershed	Sub-watershed	Total area (km^2)	Quaternary Alluvium	Franciscan Mélange	Nicasio Reservoir	San Bruno Mountain	Open Water[c]
Upper Lagunitas	Upper Lagunitas (u/s of Peters Dam)	55.7	6%	57%	24%	8%	5%
Middle and Lower Lagunitas	Woodacre Creek	3.7	10%	74%	11%	6%	0%
	San Geronimo Creek[a]	20.7	8%	78%	11%	3%	0%
	Devils Gulch	7.0	0%	57%	43%	0%	0%
	Cheda Creek	3.0	0%	61%	39%	0%	0%
	Lagunitas Creek (d/s of Peters Dam)[b]	30.0	2%	38%	29%	31%	0%
Total Middle and Lower Lagunitas		***64.4***	***4%***	***56%***	***24%***	***16%***	***0%***
Unregulated Nicasio	Unregulated Nicasio Creek (u/s of Seeger Dam)	93.2	5%	70%	4%	16%	4%
TOTAL		**213.2**	**5%**	**63%**	**16%**	**14%**	**3%**

[a] Excluding Woodacre Creek sub-watershed.
[b] Excluding Devils Gulch and Cheda Creek sub-watersheds.
[c] Open water areas are in reservoirs.

Table 3-5. Hillslope gradients in the study area.

Watershed	Sub-watershed	Total area (km^2)	Percent of sub-watershed area		
			0–5%	**5–30%**	**>30%**
Upper Lagunitas	Upper Lagunitas (u/s of Peters Dam)	55.7	6%	28%	66%
Middle and Lower Lagunitas	Woodacre Creek	3.7	6%	42%	53%
	San Geronimo Creek [a]	20.7	6%	34%	60%
	Devils Gulch	7.0	1%	27%	72%
	Cheda Creek	3.0	1%	31%	68%
	Lagunitas Creek (d/s of Peters Dam) [b]	30.0	3%	37%	60%
Total Middle and Lower Lagunitas		***64.4***	***4%***	***35%***	***61%***
Unregulated Nicasio	Unregulated Nicasio Creek (u/s of Seeger Dam)	93.2	9%	38%	53%
TOTAL		**213.2**	**7%**	**35%**	**59%**

[a] Excluding Woodacre Creek sub-watershed.
[b] Excluding Devils Gulch and Cheda Creek sub-watersheds.

Table 3-6. Extent of common GLUs in the study area as a percentage of watershed area.

GLU	Upper Lagunitas (u/s of Peters Dam)	Middle and Lower Lagunitas [64.4 km²]						Unregulated Nicasio Creek (u/s of Seeger Dam)	Entire watershed to Olema Creek confluence
		Woodacre Creek	San Geronimo Creek[a]	Devils Gulch	Cheda Creek	Lagunitas (d/s of Peters Dam)[b]	Total		
Area (km^2)	**55.7**	**3.7**	**20.7**	**7.0**	**3.0**	**30.0**	**64.4**	**93.2**	**213.2**
243	18%	27%	24%	28%	19%	12%	19%	18%	18%
142	3%	4%	7%	9%	13%	10%	9%	24%	14%
143	2%	3%	10%	7%	19%	7%	9%	16%	10%
223	14%	4%	6%	25%	14%	13%	11%	1%	8%
343	17%	9%	15%	3%	2%	1%	6%	4%	8%
242	6%	16%	11%	9%	6%	7%	9%	5%	6%
233	6%	1%	1%	0%	0%	14%	7%	5%	6%
342	9%	8%	8%	1%	1%	1%	3%	1%	4%
123	2%	2%	2%	7%	12%	8%	6%	1%	3%
133	0%	2%	0%	0%	0%	2%	1%	5%	2%
323	4%	4%	1%	1%	2%	2%	2%	0%	2%
132	0%	1%	0%	0%	0%	6%	3%	2%	2%
232	1%	1%	1%	0%	0%	6%	3%	1%	2%
222	2%	1%	1%	4%	4%	3%	3%	0%	1%
333	0%	0%	0%	0%	0%	1%	1%	2%	1%
122	0%	1%	1%	4%	6%	2%	2%	1%	1%
111	0%	0%	2%	0%	0%	0%	1%	2%	1%
141	1%	0%	0%	0%	0%	0%	0%	2%	1%
112	0%	0%	2%	0%	0%	1%	1%	2%	1%
312	3%	0%	0%	0%	0%	0%	0%	0%	1%
212	1%	0%	1%	0%	0%	0%	0%	1%	1%
Total representation	**89%**	**82%**	**94%**	**99%**	**99%**	**96%**	**95%**	**94%**	**93%**

[a] Excluding Woodacre Creek sub-watershed.
[b] Excluding Devils Gulch and Cheda Creek sub-watersheds.

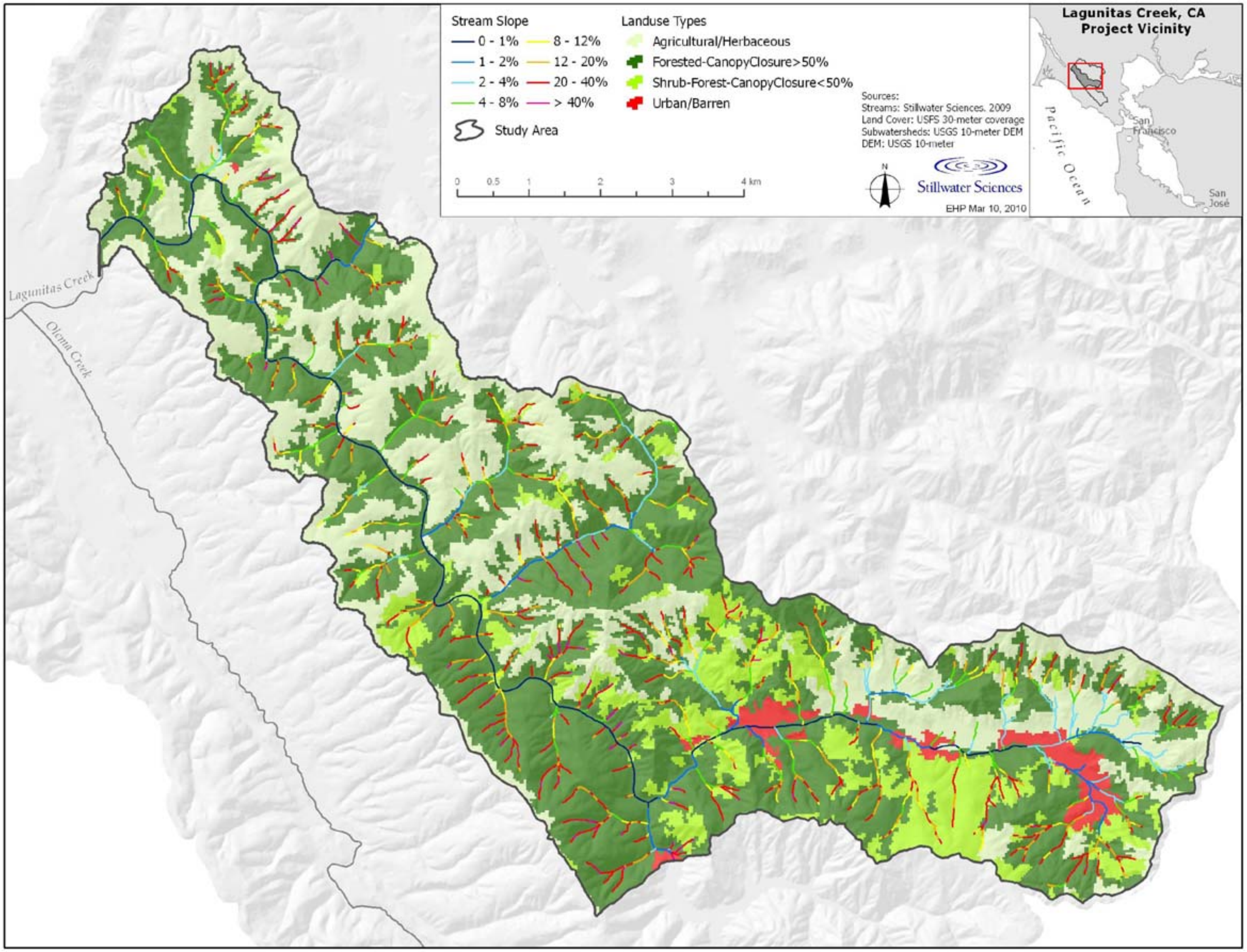

Figure 3-1. Vegetation and land use map of the study area.

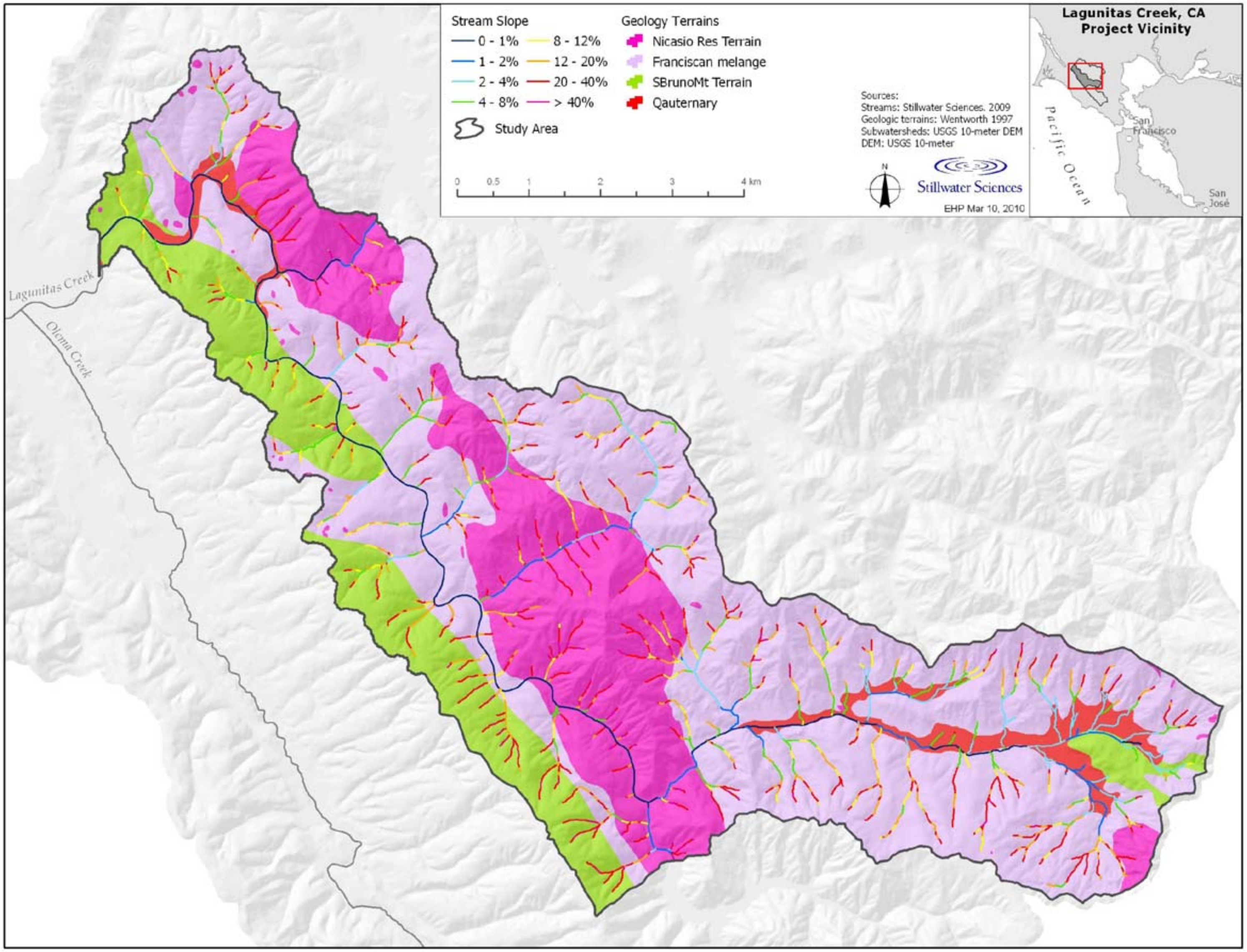

Figure 3-2. Geologic map of the study area.

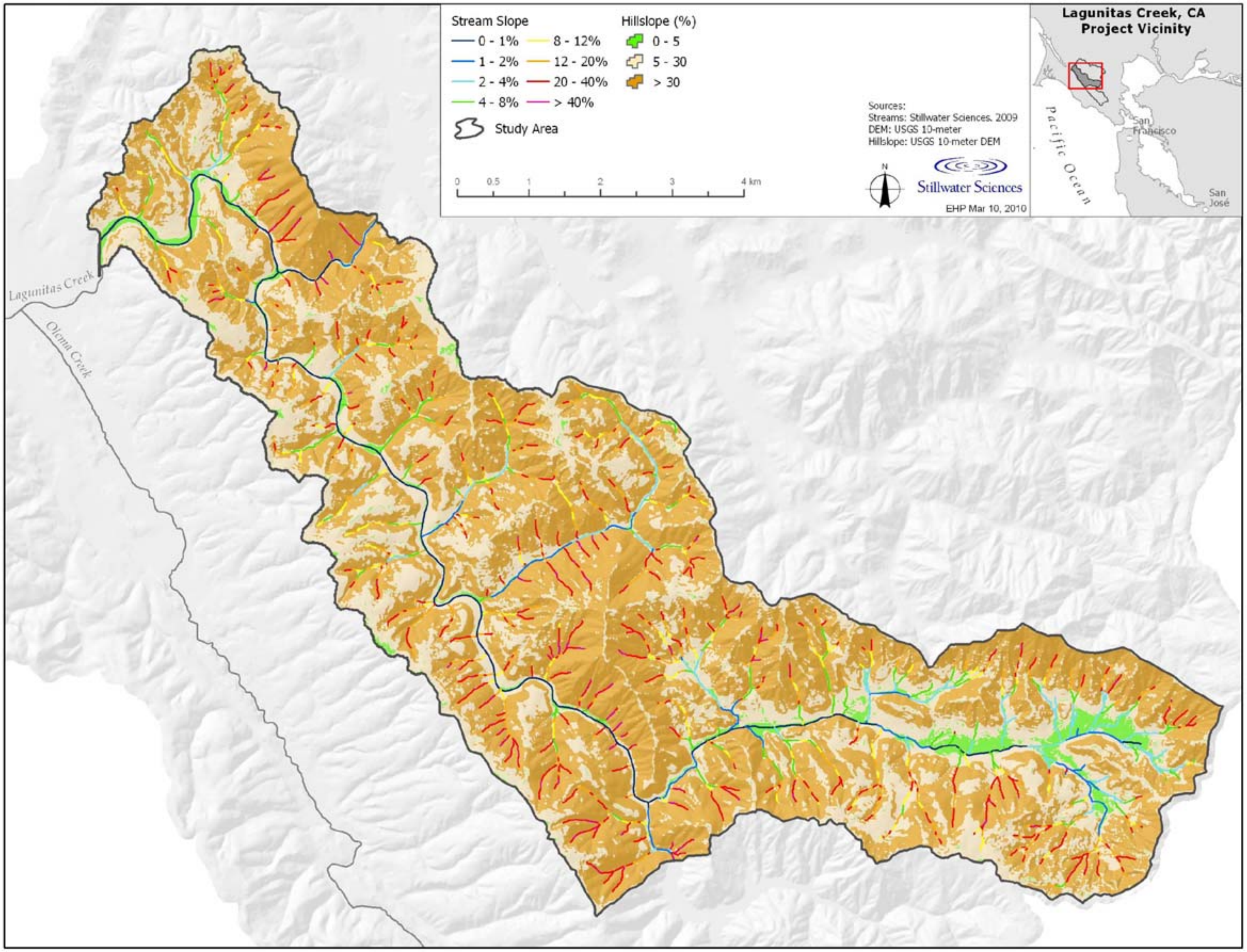

Figure 3-3. Hillslope gradient map of the study area.

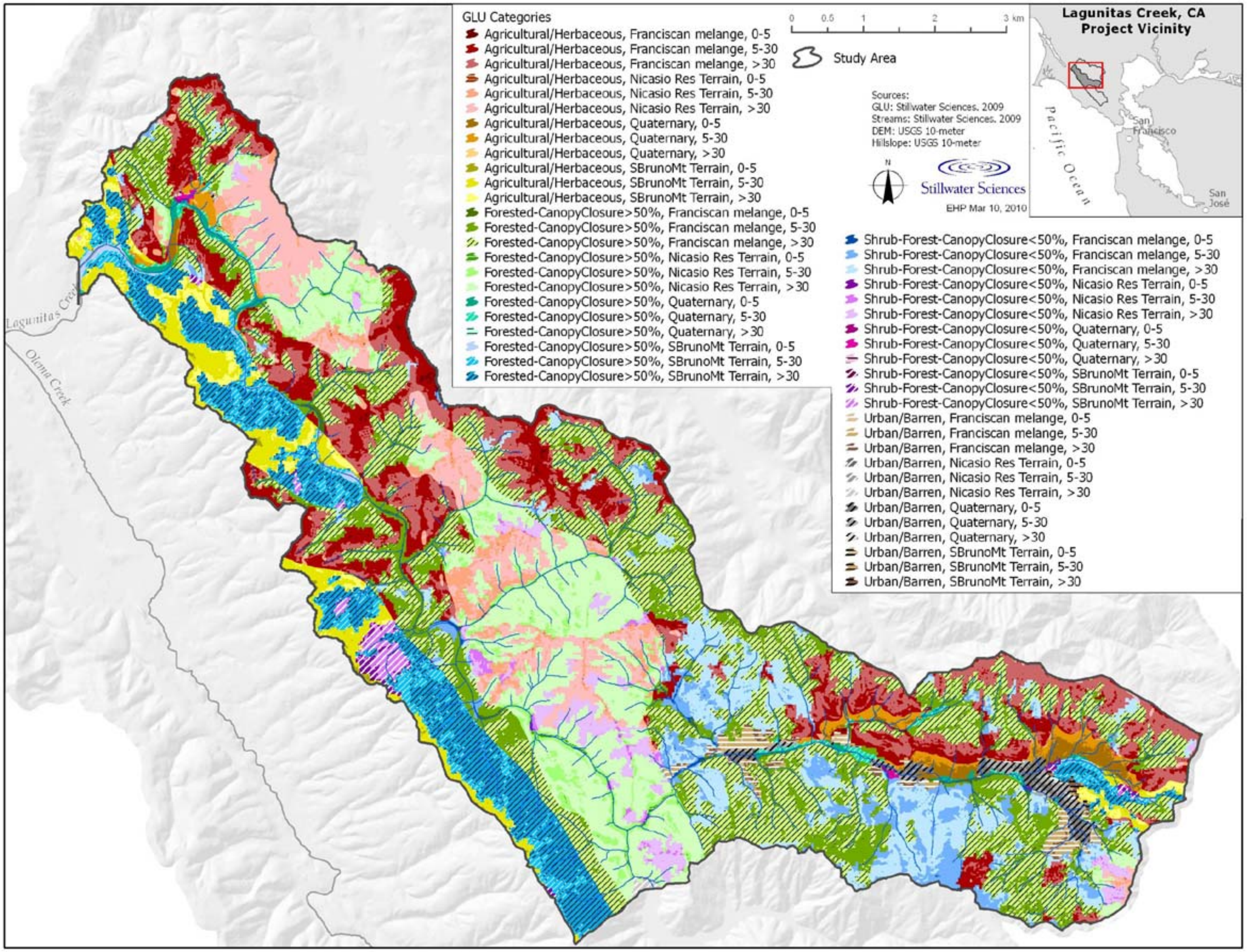

Figure 3-4. Geomorphic landscape unit (GLU) map of the study area.

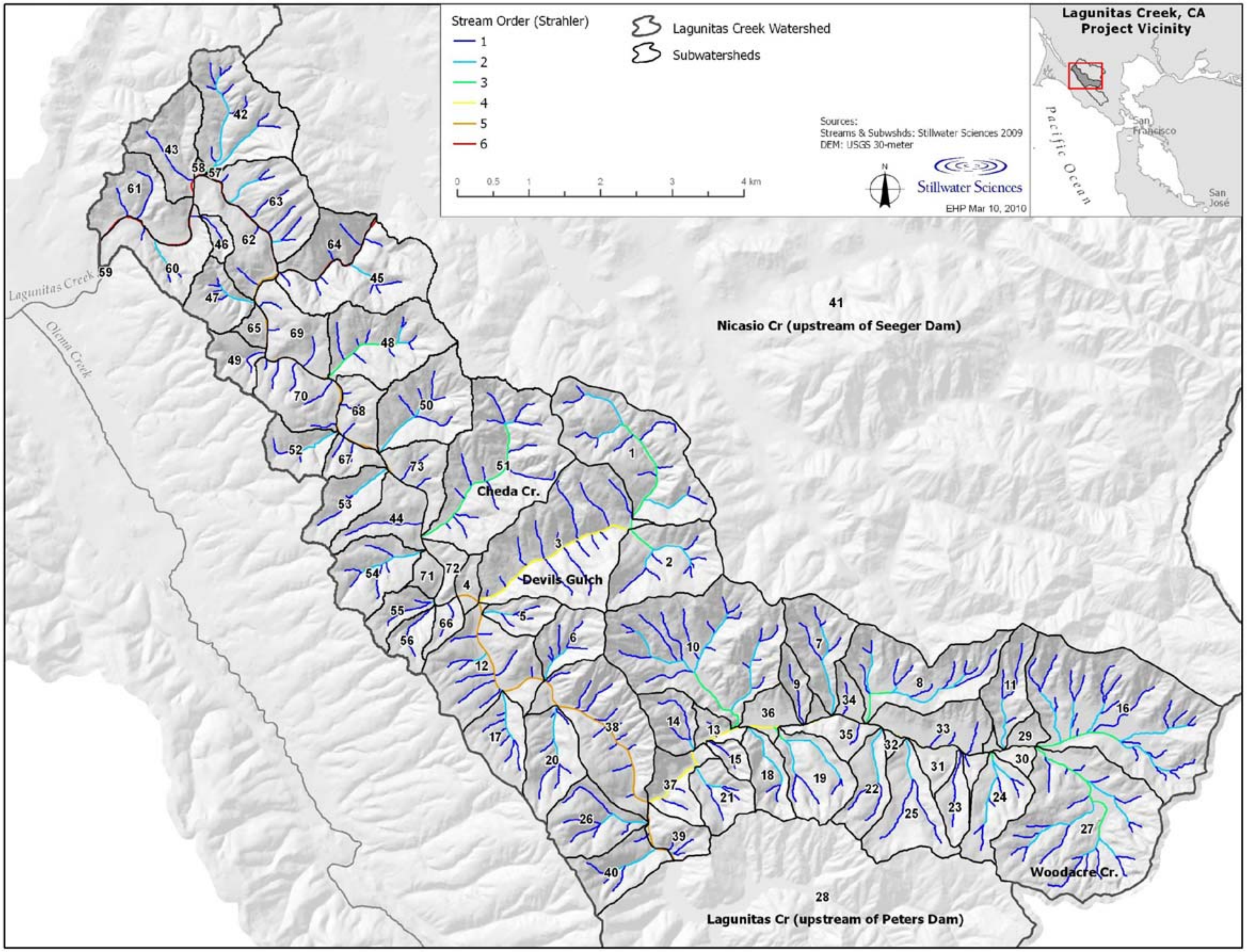

Figure 3-5. Map of sub-watershed ID throughout the study area.

3.2 Sediment Production and Delivery

Rates of sediment production and delivery over the last 26 years (WY1983–2008) were estimated using multiple data sources. For hillslopes and tributaries, sources include aerial photographs, existing data, and field survey. These data were combined to assign a specific sediment production estimate for each GLU, and were then extrapolated throughout the entire study area per GLU in GIS. Sediment delivery from roads and trails was derived separately using a GIS-based numerical model, SEDMODL2 (NCASI 2005) linked to a recently updated database of roads and trails in the Lagunitas watershed (Lnyx Technologies 2007). Non-point sources of sediment were derived using estimates of soil flux obtained from a soil production and diffusion model created by W. E. Dietrich and colleagues at the University of California, Berkeley. Sediment delivery from bank erosion and bed incision into first- to third-order tributaries was estimated from field surveys and aerial photographs. Sediment delivery from bank erosion and bed incision into fourth- to sixth-order mainstem channels was estimated using a combination of field survey and evidence for change from repeat cross-sections.

3.2.1 Discrete hillslope sources

Hillslope sediment production and delivery was estimated using aerial photographs, existing data, and field surveys. The use of aerial photographs provided a limited time series of geomorphic changes during the study period (1982–2008), while the use of existing erosion and sedimentation data, and field survey data collected specifically for this project confirmed air photo-identified feature activity and dimensions. The existing and field survey data also identified new features not visible in the aerial photographs due to photo resolution limitations or vegetation interference.

An aerial photographic time series bracketing geomorphically effective storm and flood events was used to identify and quantify sediment production from hillslope sediment sources including landslides and gulling/rilling (Figure 3-6). To the extent possible, the photographic time series was used to examine channel erosion processes including headward channel extension, channel widening, and other associated bank erosion processes, but canopy cover frequently prevented such analysis. Interpretations from aerial photograph analysis were field verified in sample areas. Erosion processes identified from aerial photographs were extrapolated, by GLU, to areas under canopy and those not field-accessible. A summary of aerial photographs used in this study is presented in Table 3-7.

Existing data sources used in this study included those previously compiled for the Lagunitas Sediment Delivery Assessment (Stillwater Sciences 2007). For the identification of hillslope and tributary erosion features (e.g., landslides and gullies), the sediment source inventory compiled by Stetson Engineers (2002) was again used in this analysis (Figure 3-7).

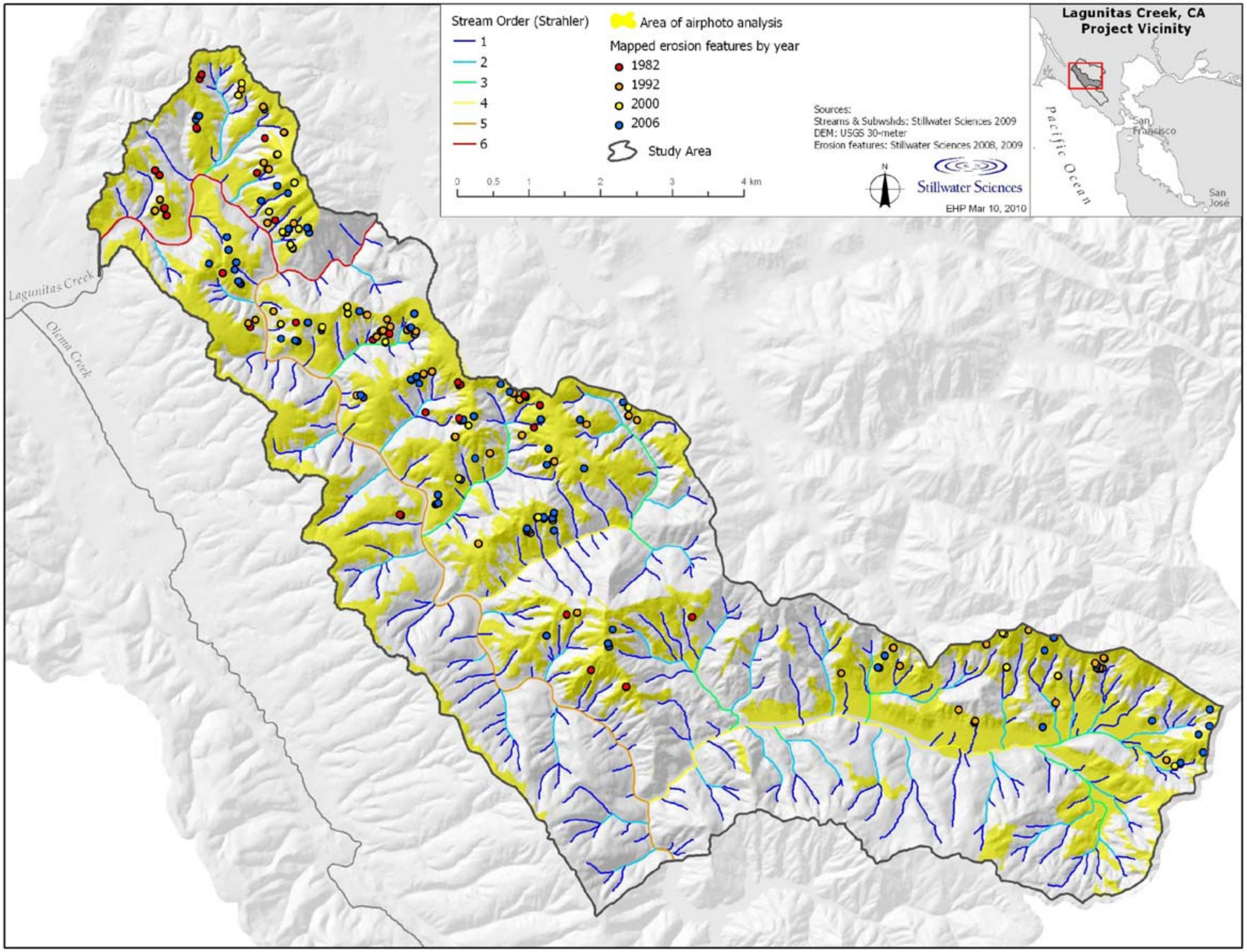

Figure 3-6. Identified erosion sites from aerial photograph analysis.

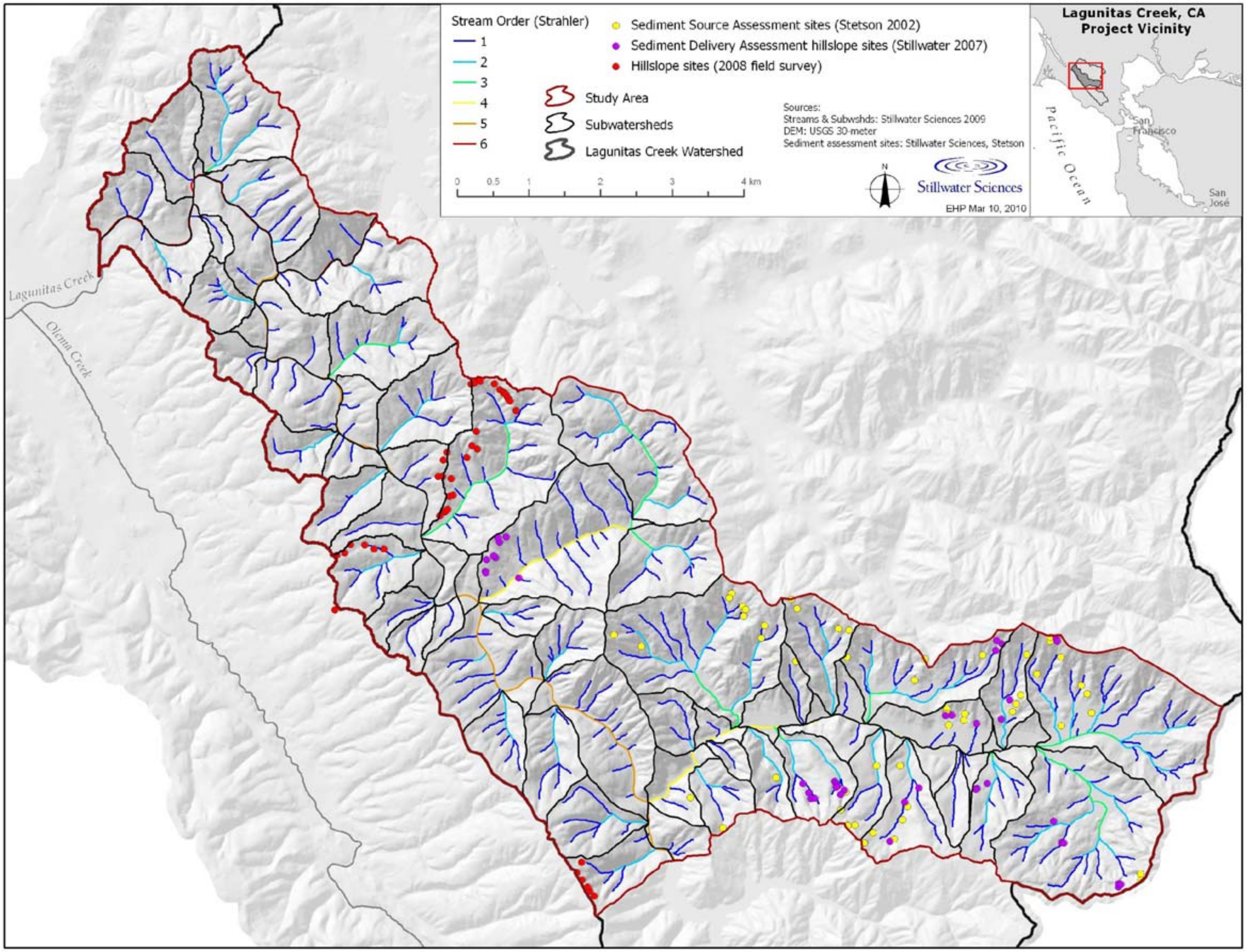

Figure 3-7. Locations of hillslope erosion sites used in determining average annual sediment yield WY 1983–2008.

Table 3-7. Aerial photography sets used in sediment production assessment.

Photography date	Most recent significant storm event	24-hr rainfall total (mm)[a]	Most recent flood event	Estimated peak flow (cfs)[b]	Original scale	Photograph source[c]
Jan 7, 1982	Jan 4, 1982	268	Jan 4, 1982	6,950 (RI ~40 yrs)	1:12,000 (northern portion) 1:20,000 (southern portion)	USGS
Aug 5, 1992	--	--	Feb 18, 1986	3,470 (RI ~ 9 yrs)	1:12,000	PAS
Mar 21, 2000	Nov 5, 1994 Dec 11, 1995	202 196	Feb 3, 1998	5,830 (RI ~10 yrs)	1:20,000	PAS
Mar 2004	--	--	Dec 29, 2003	3,230 (RI ~ 9 yrs)	1:4,800	MCDA

[a] Twenty-four-hour rainfall totals recorded at the Kentfield rain gauge that exceed Wilson and Jayko's (1997) threshold for events capable of triggering debris flows (details in Stillwater Sciences 2007).
[b] Peak flow totals records in Lagunitas Creek at the Samuel P. Taylor stream gauge; recurrence interval (RI) of estimated flow RI also reported.
[c] USGS: U.S. Geological Survey; PAS: Pacific Aerial Surveys; MCDA: County of Marin, Community Development Agency, GIS Division.

Field surveys, conducted in summer 2008, were designed to cover as much of the study area as feasible given constraints of time and accessibility, and to either identify erosion sites or corroborate evidence form previous studies or aerial photograph analysis (Figure 3-7). Sample sites were biased towards locations lacking definitive erosion data from previous studies and locations that constitute a potentially significant contribution to watershed sediment production. The surveys were used to constrain erosion rates (for instance, using the apparent age of crossing structures and vegetation near to eroding surfaces), ground-truth geomorphic landscape unit delineations, estimate sediment transfer and delivery rates, and provide particle size distribution data associated with different landscape units. Typical processes identified during field survey included (1) landsliding (shallow and deep-seated); (2) gully/rill erosion; (3) gully/rill head advance; and (4) soil creep. Sediment sources were marked on field maps (and given GPS coordinates where possible), and estimates made of erosion depth, length, and width using a combination of laser rangefinder/prism and measuring tape. Site characteristics were recorded such as soil depth to bedrock, volumetric estimates of hillslope sediment delivery to the channel network, and visual estimates of the proportion of eroding sediment that is sand or finer in grain size. Several bulk samples were taken at representative hillslope erosion sites and laboratory analyzed to better characterize the grain size of sediment being delivered to the channel network.

Summary results from the field surveys conducted by Stillwater Sciences in 2006 and 2008 are presented in Tables 3-8 and 3-9. Table 3-8 designates sub-watershed sediment production rates and Table 3-9 summarizes hillslope sediment delivery rates by major sub-watershed. Overall, it was found that approximately two-thirds of a given feature's displaced mass, as surveyed in the field, had been delivered to the stream network (Table 3-9).

Table 3-10 is a summary of all hillslope sediment production based on data from all field surveys, including the Stetson Engineers 2002 surveys, and aerial photographic analysis extrapolated by GLU to provide full watershed estimates. Table 3-11 describes the proportion of fine sediment emanating from hillslope erosion sources categorized by GLU, using the grain size distribution from laboratory analysis of field sediment samples. Overall, sediment production in the study area (64.4 km^2) from hillslope erosion sources is estimated to be about 8,000 t a^{-1}, or an unit area rate of 124 t km^{-2} a^{-1}. Fine sediment production from hillslope sources is estimated at about 4,300 t a^{-1}, or 67 t km^{-2} a^{-1}, consequent on determining that approximately half of the sediment produced from hillslope erosion sources is less than 2 mm in diameter. The GLU-specific data are also extrapolated to provide hillslope sediment production rates by enumerated sub-watersheds within the study area for both fine and total sediment load, shown in Table 3-12.

Table 3-8. Summary of hillslope sediment production rates in the Middle Lagunitas Creek study area based on Stillwater Sciences' field surveys conducted in 2006 [n=56] and 2008 [n=59].

Sub-watershed	Drainage area (km^2)	Sediment production[a, b] (t a^{-1})			
		Gully/Rill erosion (n=59; 51%)	Shallow landslides (n=47; 41%)	Deep-seated landslides (n=9; 8%)	Surveyed Total (n=115)
San Geronimo Creek	20.7	202	118	246	566
Woodacre Creek	3.7	7	0	64	71
Devils Gulch	7.0	4	10	0	14
Cheda Creek	3.0	65	173	25	262
Lagunitas Creek [c]	30.0	31	37	0	69
Total watershed	64.4	308	338	335	982
Percent of surveyed sediment production		**31%**	**34%**	**34%**	**100%**

[a] Sediment production rates assume bulk density based on classification of eroded material at each sediment source site, debris = 1.6 t m^{-3}; earth = 1.4 t m^{-3}; Sample inventory includes erosion from primary and secondary geomorphic processes; percentage of total inventory is denoted in parenthesis.
[b] Hillslope erosion estimates based on field surveys of eroded area and assumed slope distance of observed feature.
[c] Lagunitas sub-watershed as presented here includes remainder of the Middle Lagunitas watershed area surveyed, not including San Geronimo, Woodacre, Devils Gulch, and Cheda creeks.
[d] Total sediment production estimates based on field inventory of measured erosion by geomorphic process and representative time period between 1982 to 2008.

Table 3-9. Summary of hillslope sediment delivery rates in the Lagunitas Creek study area: 1982–2008 (Stillwater Sciences field surveys from 2006 [n=56] and 2008 [n=59] only).

Sub-watershed	Drainage area (km^2)	Sediment production (t a^{-1})	Sediment delivery (t a^{-1})[a]	Delivery ratio (%)
San Geronimo Creek	20.7	566	457	81%
Woodacre Creek	3.7	71	24	34%
Devils Gulch	7.0	14	7	50%
Cheda Creek	3.0	262	104	40%
Lagunitas Creek	30.0	69	68	99%
Total watershed	**64.4**	**982**	**659**	**67%**

[a] Delivered volumes estimated in the field by subtracting the volume of material remaining (i.e., stored volume) from the volume of material eroded.

Table 3-10. Summary of hillslope sediment production for the Lagunitas study area and the entire Lagunitas watershed as extrapolated from sampled GLUs using field survey (Stetson Engineers 2002, Stillwater Sciences 2007, Stillwater Sciences 2008) and aerial photographic analysis erosion features.

GLUs with measured sites	Survey [a]	Sample terrain area [b] (km^2)	Sum of terrain mass [c] (t)	Terrain sediment production rate [d] ($t\ km^{-2}$)	Extrapolated to Lagunitas study area [64.4 km^2]			Extrapolated to entire Lagunitas watershed [213.3 km^2] [f]		
					Total terrain area (km^2)	Extrapolated terrain mass (t)	Extrapolated terrain sediment production rate [e] ($t\ a^{-1}$)	Total terrain area (km^2)	Extrapolated terrain mass (t)	Extrapolated terrain sediment production rate [e] ($t\ a^{-1}$)
111	1, 3	0.5	1,609	2,999	0.6	1,688	65	2.5	7,506	289
112	1, 3	0.6	355	579	0.7	396	15	2.4	1,411	54
122	2, 3, 4	1.2	3,004	2,561	1.3	3,420	132	2.6	6,569	253
123	2, 3, 4	2.8	19,549	7,052	3.6	25,230	970	5.5	38,707	1,489
132	3, 4	1.8	837	475	2.0	947	36	3.7	1,769	68
133	3	0.7	2,522	3,605	0.8	2,909	112	5.3	18,970	730
142	1, 2, 3, 4	5.0	22,377	4,499	5.5	24,818	955	29.8	134,192	5,161
143	1, 2, 3, 4	4.9	50,361	10,341	5.5	56,716	2,181	21.3	220,487	8,480
222	1, 3	0.3	120	414	1.6	667	26	3.0	1,262	49
223	1, 2, 3	2.7	2,462	928	7.4	6,855	264	16.7	15,455	594
232	3, 4	0.3	326	1,202	2.0	2,429	93	3.3	4,019	155
233	3, 4	0.3	1,700	4,922	4.3	21,065	810	12.8	63,143	2,429
242	1, 2, 3, 4	2.2	1,714	772	5.6	4,299	165	13.7	10,562	406
243	1, 2, 3	5.3	11,605	2,185	12.2	26,615	1,024	38.5	84,188	3,238
323	1, 3	0.6	6,740	12,126	1.2	14,939	575	3.9	46,894	1,804
342	2, 3	0.9	2,610	2,896	2.1	6,184	238	8.2	23,759	914

GLUs with measured sites	Survey [a]	Sample terrain area [b] (km^2)	Sum of terrain mass [c] (t)	Terrain sediment production rate [d] (t km^{-2})	Extrapolated to Lagunitas study area [64.4 km^2]			Extrapolated to entire Lagunitas watershed [213.3 km^2] [f]		
					Total terrain area (km^2)	Extrapolated terrain mass (t)	Extrapolated terrain sediment production rate [e] (t a^{-1})	Total terrain area (km^2)	Extrapolated terrain mass (t)	Extrapolated terrain sediment production rate [e] (t a^{-1})
343	1, 2, 3	2.1	4,205	1,976	3.8	7,552	290	16.4	32,495	1,250
411	1	0.3	2	9	0.4	3	0	0.4	4	0
Total		**32.3**	132,096	4,085	**60.6**	206,736	7,951	**190.2**	711,390	27,361
Avg annual sediment production rate [e] (t km^{-2} a^{-1}) =					**124**			**128**		

[a] Surveys: (1) Stetson 02 = Stetson Engineers 2002 field surveys, (2) SWS 06 = Stillwater Sciences 2006 field surveys, (3) SWS AP 08 = Stillwater Sciences 2008 air photo analysis, (4) SWS 08 = Stillwater Sciences 2008 field surveys.

[b] Sum of terrain area per GLU with sampled sediment source sites surveyed during one or more of the four survey efforts.

[c] Overlapping sediment source sites from the four surveys were reconciled to avoid double-counting sites. SWS AP 08 sites not used in favor of using field surveyed sites from Stetson 02, SWS 06, or SWS 08. Overlap determined using a 15 m buffer around the digital data points (field survey sites), lines (air photo mapped gully sites), and areas (air photo mapped landslide sites) in GIS. The sum of terrain mass is derived by addition of non-overlapping hillslope sediment source sites from Stetson 02 (n = 54), SWS 06 (n = 56), SWS AP 08 (n = 380), and SWS 08 (n = 46); mass yield assume bulk density values ranging from 1.4 to 1.6 t m^{-3}.

[d] Terrain sediment production rates are used to extrapolate sediment production to similar GLUs across the Middle Lagunitas and the entire Lagunitas study areas.

[e] Estimated terrain sediment production rates assume a representative time period of 26 years (1982–2008).

[f] Entire Lagunitas study area includes watershed upstream of stream gauge; Middle Lagunitas, Upper Lagunitas, and Unregulated Nicasio sub-watersheds.

Table 3-11. Hillslope fine sediment production estimate for sampled GLUs.

GLU	Percent fine sediment (<2 mm) [a]	Terrain sediment production extrapolated to Lagunitas study area [64.4 km^2] ($t\ a^{-1}$)	Extrapolated to entire Lagunitas watershed [213.3 km^2] ($t\ a^{-1}$)
111	83	54	240
112	**83**	13	45
122	**63**	83	159
123	**63**	611	938
132	**43**	16	29
133	43	48	314
142	**50**	477	2,581
143	**50**	1,091	4,240
222	**26**	7	13
223	**26**	69	155
232	56	52	87
233	**56**	454	1,360
242	**53**	88	215
243	**53**	543	1,716
323	**63**	362	1,136
342	**68**	162	621
343	**68**	198	850
411	75	0.1	0.1
Total sediment production ($t\ a^{-1}$)		**4,325**	**14,698**
Total sediment production per unit area ($t\ km^{-2}\ a^{-1}$)		**67**	**69**

[a] Bold percent fine sediment values from sieve lab analysis of field samples, non-bold value is derived from extrapolation of sieve analysis of field samples and field estimates of percent fine sediment.

Table 3-12. Fine and total sediment production for hillslope erosion within sub-watersheds.

Unit	Sub-watershed ID	Sub-watershed Area	Hillslope sediment production (t a^{-1})	Hillslope fine sediment production (t a^{-1})
San Geronimo Creek	16 San Geronimo Creek headwaters	3.8	644	342
	27 Woodacre Creek	3.66	326	184
	29	0.23	24	13
	30	0.15	8	5
	11	0.73	109	56
	24 Willis Evans Creek	0.87	82	50
	33	0.85	135	72
	23 Deer Camp Creek	0.38	32	22
	31	0.39	26	18
	25 Creamery Creek	1.14	86	55
	32	0.07	2	1
	22 Sylvestris Creek	0.66	41	24
	35	0.39	29	17
	8 Larsen Creek	1.81	302	155
	34	0.3	41	21
	7 Clear Creek	0.98	123	66
	9	0.29	23	13
	36	0.39	8	5
	19 Montezuma Creek	0.98	69	38
	18	0.57	38	21
	10 Arroyo Creek	3.49	376	221
	13	0.24	18	12
	15	0.21	16	11
	14	0.54	78	46
	37	0.63	66	36
	21	0.62	37	19
	Total	**24.4**	**2,739**	**1,522**
Lagunitas Creek (San Geronimo Creek to Devils Gulch)	39	0.43	79	47
	40	0.8	85	46
	26	0.94	103	56
	38	2.12	269	152
	20	0.96	103	55
	6 Barnabe Creek	0.69	89	51
	17 Irving Creek	0.74	93	52
	12	1.71	185	105
	5 Deadman's Creek	0.41	45	25
	Total	**8.8**	**1,051**	**590**
Devils Gulch	1	2.5	351	181
	2	1.46	111	57
	3 Devils Gulch mainstem	3.02	320	172
	Total	**7.0**	**782**	**410**

Unit	Sub-watershed ID	Sub-watershed Area	Hillslope sediment production (t a^{-1})	Hillslope fine sediment production (t a^{-1})
Lagunitas Creek (Devils Gulch to Nicasio Creek)	4	0.21	32	18
	66	0.23	20	11
	56	0.36	12	6
	55	0.39	15	8
	72	0.27	36	19
	71	0.21	13	7
	54	0.97	102	54
	51 Cheda Creek	2.98	516	275
	44	0.73	99	50
	73	0.61	150	75
	53	0.68	97	50
	50 McIssac's Creek	1.34	219	115
	67	0.32	41	23
	68	0.52	98	48
	52	0.58	71	37
	48	1.52	243	128
	70	0.91	89	48
	69	0.84	161	81
	49	0.44	44	23
	65	0.18	16	8
	47	0.61	68	36
	Total	**14.9**	**2,139**	**1,119**
Regulated Nicasio Creek	45 Nicasio Creek	1.58	163	81
	64 Nicasio Creek	0.69	104	62
	Total	**2.3**	**267**	**143**
Lagunitas Cr (Nicasio Cr to Pt. Reyes Station)	62	0.84	88	45
	63	1.26	222	138
	42	1.75	307	162
	57	0	0	0
	58	0.03	3	2
	43	1	112	58
	46	0.17	29	15
	Total	**5.1**	**760**	**420**

3.2.2 Non-point source hillslope sources

Non-point source sediment production can be an important component of a watershed sediment budget, but is hard to segregate and quantify due to the inherent difficulty in identifying production locations and transport pathways. For this sediment budget, we estimated soil flux using a soil production and diffusion model developed by William E. Dietrich and researchers from the Geomorphology Group at the Department of Earth and Planetary Science at University of California at Berkeley.

The model is initiated by developing a spatially distributed soil depth grid to represent initial conditions required as the basis for estimating soil flux. An equivalent period of 5,000 years of soil production was used, representative of the late Holocene period and adequate to generate enough soil depth difference in the landscape. Soil depth is created using a soil production function determined to be an inverse exponential function of soil depth, with a maximum inferred production rate of 268 m Ma^{-1} occurring under zero soil depth, using evidence from cosmogenic nuclide decay in nearby Tennessee Valley, Northern California (Heimsath et al. 1999).

The model uses a linear or a non-linear soil diffusion function to generate soil depth and, for the Lagunitas Creek watershed, the difference between these methods was minimal. The linear function accumulated a slightly greater amount of soil in the swales and valleys, based on diffusivity values of 45cm^2/yr from Dietrich et al. (1995, following Reneau 1988). After the initial run, the model was run for 25 years, to simulate the cumulative soil flux occurring after 1983 as well as the average yearly flux. Summary results are presented in Table 3-13.

Table 3-13. Modeling results for annual soil production and diffusion.

Soil production and diffusion by sub-watershed	Area (km^2)	Annual yield ($t\ a^{-1}$)	Annual production and diffusion rate ($t\ km^{-2}\ a^{-1}$)
San Geronimo Creek	24.3	82.6	3.4
Lagunitas Creek (upstream of Devils Gulch confluence)	11.4	57.3	5.0
Devils Gulch	7.5	29.9	4.0
Cheda Creek	3.2	16.0	5.0
McIssacs Creek	1.4	6.9	4.9
Lagunitas Creek (Devils Gulch confluence to Pt. Reyes Station gauge)	18.0	71.8	4.0
Nicasio Creek (upstream of Seeger Dam)	59.1	341.5	5.8
Lagunitas Creek (below Pt. Reyes Station gauge)	3.4	11.1	3.3

In comparison, the work by Lehre (1982 and 1987) in the nearby Lone Tree Creek watershed suggests that soil creep processes yield on the order of 2 to 7 t $km^2\ a^{-1}$ in a watershed with an underlying geology primarily composed of Franciscan mélange and land cover composed of grasslands and forest (similar to the study area within the Lagunitas Creek watershed). The similar results provide some confidence in the model results.

3.2.3 Roads and trails

Sediment delivery from unpaved roads throughout the Lagunitas Creek watershed was assessed using a GIS-based road erosion and delivery model ("SEDMODL2"), designed to identify road segments with high potential for sediment delivery to stream networks. The model is not process-based, but used a factor-based approach, similar to the Universal Soil Loss Equation (USLE).

The model used the following data as input:

- 10-m USGS DEM;
- Geology map for Marin County (Blake et al. 2000);
- High resolution (1"= 200' or 1" = 400') roads and trails (Lynx Technologies 2007);
- PRISM Average Annual Precipitation 1971-2000;
- Channel network extended from 1:24,000 USGS topographic maps to a channel initiation threshold of 4 ha (10 acres);
- 1:24,000 Soil Survey Geographic database SSURGO for Marin County; and
- Vegetation data from CDF-FRAP

SEDMODL2 required data-fields were created and estimates generated for specific factors such as precipitation and geologic erosion rate. Road attributes such as surface type, road type and road use were matched to the categories required by the model. Road widths when not provided by the roads dataset, were averaged from roads with similar attributes. A road age factor of 1 was used, implying roads of greater than 2 years of age, since road ages were not specified in the original dataset. The model was run to obtain an annual road-related sediment yield (t a^{-1}) by sub-watershed (Figure 3-8). Summary results are summarized in Table 3-14.

Table 3-14. Modeling results for annual road-related sediment yield.

SEDMODL sub-watershed	Area (km^2)	Annual road-related sediment yield (t a^{-1})	Annual road sediment rate (t km^{-2} a^{-1})
San Geronimo Creek	24.3	1,569	64.6
Lagunitas Creek (upstream of Devils Gulch confluence)	11.4	228	20.0
Devils Gulch	7.5	64	8.5
Cheda Creek	3.2	6	1.9
McIssacs Creek	1.4	4	2.9
Lagunitas Creek (Devils Gulch confluence to Pt. Reyes Station gauge)	18.0	164	9.1
Nicasio Creek (upstream of Halleck Cr confluence)	59.1	2,443	41.3
Nicasio Creek (between Halleck Cr confluence and Seeger Dam)	41.2	532	12.9
Lagunitas Creek (below Pt. Reyes Station gauge)	3.4	15	4.4

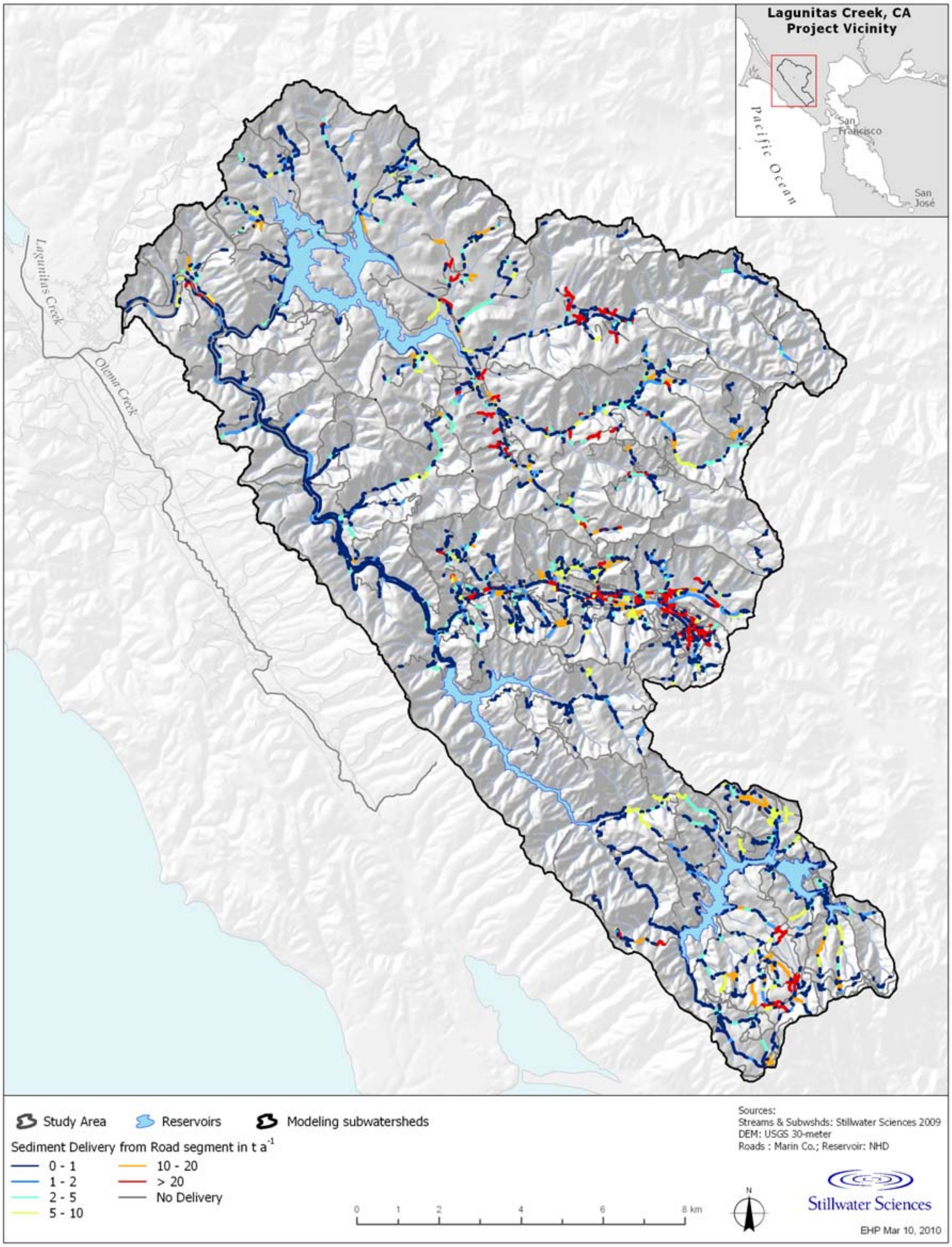

Figure 3-8. Results of road-related sediment modeling using SEDMODL2.

3.2.4 Channels

Channel erosion rates were developed from a combination of newly-collected and pre-existing data pertaining to long-term rates of bank and bed erosion during the study period. A field survey, conducted in Spring 2008 and similar in approach to the 2006 survey (see Stillwater Sciences 2007), documented in-channel erosion for (1) the extent of mainstem Lagunitas Creek not surveyed in the sediment delivery analysis (i.e., from the Devils Gulch confluence to the USGS gauge at Pt. Reyes Station), and (2) other representative tributaries channels downstream of the Devils Gulch confluence not previously surveyed. Low-order tributaries were stratified by stream order, adjacent/contributing landscape units, channel slope, in-channel hydraulic/grade controls, and site access, and several tributaries were chosen for investigation in order to provide a representative sample. These data were combined with channel erosion data collected between 1983 and 2008 to develop unit erosion rates (i.e., production/channel length/time) for all channels throughout the study area.

Bank erosion features examined during the 2008 field survey included both chronic lateral bank retreat and localized mass failures (Figure 3-9). In lower order tributaries, bank erosion features included failure of adjacent hillslope material directly into the channel while, in higher order channels, erosion was predominantly of alluvial floodplain sediments. In-channel erosion sites were noted on a field map (and given GPS coordinates where possible) and pertinent features recorded. At bank retreat sites this included the length, height, and depth of eroded bank material, in order to provide a volumetric erosion estimate. Only "significant" bank retreat sites (i.e., those visually estimated to involve more than 3.0 m^3 [100 ft^3] of eroded material), were recorded in order to expedite the survey. At mass failures, length, height, and depth of bank slumping feature, and the percent of the slump block remaining for subsequent erosion were recorded. At all of the bank erosion sites, natural and anthropogenic features (e.g., stratigraphic evidence, vegetation, exposed tree roots, grade control structures, bridges, etc.) and assumptions about the age of stable banks were used to indicate relative age and timing of sediment inputs and/or to determine the extent of erosion. Site eroded volumes were then converted to sediment production rate by using an appropriate bulk density and erosion time period. These erosion site production rates were converted to unit production rates (i.e., rate/length of channel) by combining the site production rate with the length of the adjacent channel contained within a discrete "channel GLU" (combination of geology and land use only). This procedure was repeated for the erosion site production rates reported by Stetson Engineers (2002) and Stillwater Sciences (2007) (Figure 3-9). All unit production rates were stratified by channel order and adjacent channel GLU and combined to arrive at average unit bank erosion sediment production rates (weighted by observed channel length). These average rates were extrapolated across the study area to determine bank erosion sediment production for the entire length of 1st through 3rd order channels (Table 3-15) and 4th through 6th order channels (Table 3-16)

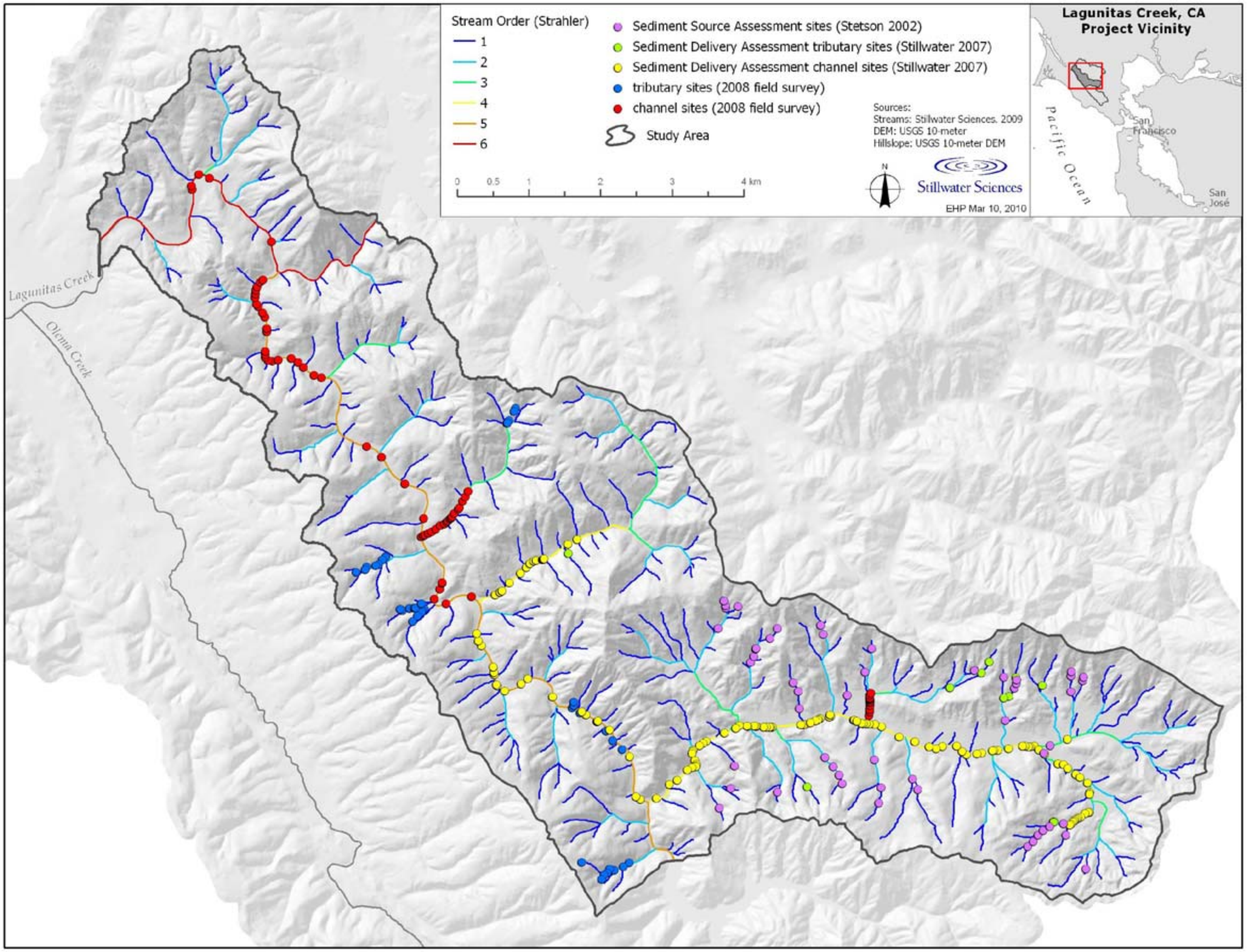

Figure 3-9. Locations of bank erosion sites used in determining average annual sediment yield WY 1983–2008.

Table 3-15. Unit bank erosion sediment production for first- to third-order channels.

Stream order	**Channel GLU**	**Average bank erosion unit sediment production $(t\ m^{-1}\ a^{-1})$[a]**	**% of total channel length (by order)**	**% of channel length observed (by order)**	**% fine sediment (<2 mm)[b]**
1	Agricultural/Herbaceous, Quaternary	**0.003**	4	2	**83**
	Agricultural/Herbaceous, Nicasio Res Terrain	0.017	3	0	**63**
	Agricultural/Herbaceous, SBrunoMt Terrain	**<0.001**	1	9	**43**
	Agricultural/Herbaceous, Franciscan mélange	**0.027**	7	9	**50**
	Forested-CanopyClosure>50%, Quaternary	0.005	1	0	69
	Forested-CanopyClosure>50%, Nicasio Res Terrain	**0.009**	20	2	**2**
	Forested-CanopyClosure>50%, SBrunoMt Terrain	**0.021**	15	12	**56**
	Forested-CanopyClosure>50%, Franciscan mélange	**0.045**	37	5	**53**
	Shrub-Forest-CanopyClosure<50%, Nicasio Res Terrain	**0.020**	2	3	**63**
	Shrub-Forest-CanopyClosure<50%, SBrunoMt Terrain	**0.014**	1	22	60
	Shrub-Forest-CanopyClosure<50%, Franciscan melange	**0.108**	10	6	**68**
2	Agricultural/Herbaceous, Quaternary	0.004	9	0	**83**
	Agricultural/Herbaceous, Franciscan mélange	**0.010**	4	9	**50**
	Forested-CanopyClosure>50%, Quaternary	**0.005**	4	7	69
	Forested-CanopyClosure>50%, Nicasio Res Terrain	0.014	12	0	**26**
	Forested-CanopyClosure>50%, SBrunoMt Terrain	**0.013**	9	23	**56**
	Forested-CanopyClosure>50%, Franciscan mélange	**0.036**	43	6	**53**
	Shrub-Forest-CanopyClosure<50%, SBrunoMt Terrain	**<0.001**	1	7	60
	Shrub-Forest-CanopyClosure<50%, Franciscan mélange	**0.035**	12	4	**68**
	Urban/Barren, Quaternary	**<0.001**	4	0	75
	Urban/Barren, Franciscan mélange	**0.139**	3	28	**28**
3	Agricultural/Herbaceous, Quaternary	0.015	1	0	**83**
	Agricultural/Herbaceous, Franciscan mélange	**0.058**	1	51	**50**
	Forested-CanopyClosure>50%, Quaternary	**0.017**	6	77	69
	Forested-CanopyClosure>50%, Nicasio Res Terrain	0.015	8	0	**26**
	Forested-CanopyClosure>50%, SBrunoMt Terrain	0.050	5	0	**56**
	Forested-CanopyClosure>50%, Franciscan mélange	**0.049**	49	21	**53**
	Shrub-Forest-CanopyClosure<50%, Quaternary	**0.023**	3	0	69
	Shrub-Forest-CanopyClosure<50%, SBrunoMt Terrain	0.015	1	0	60
	Shrub-Forest-CanopyClosure<50%, Franciscan mélange	0.050	6	0	**68**
	Urban/Barren, Quaternary	**0.010**	14	80	75
	Urban/Barren, Franciscan mélange	**0.042**	5	51	**28**

[a] Bold values were obtained directly from field results; non-bold values were derived from field results for similar conditions
[b] Bold values were obtained directly from laboratory analysis of field samples; non-bold values were derived from field observations and laboratory results for similar conditions

Table 3-16. Unit bank erosion sediment production for fourth- to sixth-order channels.

Stream order	Channel GLU	Average bank erosion unit sediment production ($t\ m^{-1}\ a^{-1}$)[a]	% of total channel length (by order)	% of channel length observed (by order)	% fine sediment (<2 mm)[b]
4	Agricultural/Herbaceous, Nicasio Res Terrain	**0.001**	2	62	**63**
	Agricultural/Herbaceous, Quaternary	**0.011**	3	100	**83**
	Forested-CanopyClosure>50%, Franciscan mélange	**0.032**	17	99	**53**
	Forested-CanopyClosure>50%, Nicasio Res Terrain	**0.027**	35	96	**26**
	Forested-CanopyClosure>50%, Quaternary	**0.058**	21	100	69
	Shrub-Forest-CanopyClosure<50%, Franciscan melange	**0.007**	6	100	**68**
	Shrub-Forest-CanopyClosure<50%, Nicasio Res Terrain	**0.007**	2	100	**63**
	Shrub-Forest-CanopyClosure<50%, Quaternary	**<0.001**	0	100	69
	Urban/Barren, Quaternary	**0.023**	14	100	75
5	Agricultural/Herbaceous, Franciscan mélange	**<0.001**	0	100	**50**
	Agricultural/Herbaceous, Quaternary	**<0.001**	0	100	**83**
	Agricultural/Herbaceous, SBrunoMt Terrain	**<0.001**	1	100	**43**
	Forested-CanopyClosure>50%, Franciscan mélange	**0.016**	37	100	**53**
	Forested-CanopyClosure>50%, Nicasio Res Terrain	**0.005**	26	99	**26**
	Forested-CanopyClosure>50%, Quaternary	**0.022**	4	97	69
	Forested-CanopyClosure>50%, SBrunoMt Terrain	**0.017**	22	100	**56**
	Shrub-Forest-CanopyClosure<50%, Franciscan melange	**0.021**	6	100	**68**
	Shrub-Forest-CanopyClosure<50%, Nicasio Res Terrain	**0.007**	2	100	**63**
	Urban/Barren, Nicasio Res Terrain	0.017	3	0	76
6	Agricultural/Herbaceous, Nicasio Res Terrain	0.001	1	0	**63**
	Agricultural/Herbaceous, Quaternary	**<0.001**	8	11	**83**
	Agricultural/Herbaceous, SBrunoMt Terrain	<.001	1	0	**43**
	Forested-CanopyClosure>50%, Franciscan mélange	**<0.001**	1	100	**53**
	Forested-CanopyClosure>50%, Nicasio Res Terrain	**<0.001**	26	0	**26**
	Forested-CanopyClosure>50%, Quaternary	**0.011**	43	56	69
	Forested-CanopyClosure>50%, SBrunoMt Terrain	0.017	19	0	**56**
	Shrub-Forest-CanopyClosure<50%, Quaternary	**0.166**	1	100	69

[a] Bold values were obtained directly from field results; non-bold values were derived from field results for similar conditions
[b] Bold values were obtained directly from laboratory analysis of field samples; non-bold values were derived from field observations and laboratory results for similar conditions

At all bank erosion sites visited during the 2008 field survey, the proportion of the eroding material that was sand or finer was estimated visually, and bulk sediment samples were collected at several representative bank and in-channel locations for laboratory analysis of particle size distribution. These samples were used in conjunction with hillslope bulk samples to ascertain the distribution of sediment sizes being delivered to the tributaries and mainstem channels as a function of geology and land use (Table 3-12 and Table 3-15).

Similar to bank erosion, channel incision rates were also derived through a combination of data collected during the 2008 field survey and pre-existing data. Rates of channel incision were determined by comparing current bed elevations to adjacent age markers (e.g., in-channel structures, vegetation) whose age could be constrained either by direct evidence (e.g., known data of structure placement) or qualitative assessment (e.g., assumed tree age as a function of height and diameter at breast height [DBH]). These data were combined with surveyed incision estimates from channel data collected from gauging stations (USGS gauges 11460400 [1983–2006] and 11460600 [1983–2008]; and the San Geronimo gauge [1997–2007 Owens and Hecht 2008]), and from previous field surveys in 2006 (Stillwater Sciences 2007) and 2008 (Stillwater Sciences 2009) (Figure 3-10). For first- though third-order channels, values were stratified by channel GLU and combined to develop average incision rate categories, yielding six categories ranging from 0 m a^{-1} to 0.035 m a^{-1}. These incision rates, combined with estimates of average channel width by stream order (i.e., 1st order = 0.6 m, 2nd order = 1.2 m, 3rd order = 2.7 m) and an estimate of bulk density (2,000 kg m^{-3}), resulted in average channel incision sediment production estimates that were then applied to low-order channel lengths throughout the study area (Table 3-17). For fourth- to sixth-order channels, reaches were defined based on major confluences and stream gauging locations and incision rates within each defined reach combined to develop an average reach incision rate. Reach average channel width were derived from field measurements and aerial photographs (2.7–15 m) and combined with bulk density to produce average incision sediment production estimates for each reach (Table 3-18).

Table 3-17. Unit channel incision rate for first- to-third-order channels.

Stream order	Channel GLU	Average incision rate (m a^{-1})[a]	% of total channel length (by order)
1	Agricultural/Herbaceous, Quaternary	**0.006**	4.1
	Agricultural/Herbaceous, Nicasio Res Terrain	0.012	2.5
	Agricultural/Herbaceous, Franciscan mélange	**0.012**	6.5
	Forested-CanopyClosure>50%, Nicasio Res Terrain	0.018	19.6
	Forested-CanopyClosure>50%, SBrunoMt Terrain	0.006	15.0
	Forested-CanopyClosure>50%, Franciscan melange	**0.018**	36.4
	Shrub-Forest-CanopyClosure<50%, SBrunoMt Terrain	0.035	1.0
	Shrub-Forest-CanopyClosure<50%, Franciscan mélange	0.012	9.9
2	Agricultural/Herbaceous, Quaternary	0.006	8.3
	Agricultural/Herbaceous, Franciscan mélange	**0.023**	3.4
	Forested-CanopyClosure>50%, Quaternary	0.012	3.5
	Forested-CanopyClosure>50%, Nicasio Res Terrain	0.018	11.8
	Forested-CanopyClosure>50%, SBrunoMt Terrain	0.006	8.8
	Forested-CanopyClosure>50%, Franciscan mélange	**0.006**	42.2
	Shrub-Forest-CanopyClosure<50%, Franciscan mélange	**0.012**	11.4
	Urban/Barren, Quaternary	0.006	3.9
3	Agricultural/Herbaceous, Quaternary	**0.012**	1.3
	Forested-CanopyClosure>50%, Quaternary	**0.012**	6.0
	Forested-CanopyClosure>50%, Nicasio Res Terrain	0.018	8.2
	Forested-CanopyClosure>50%, SBrunoMt Terrain	**0.018**	5.0
	Forested-CanopyClosure>50%, Franciscan mélange	**0.012**	49.0
	Shrub-Forest-CanopyClosure<50%, Quaternary	0.006	3.2
	Shrub-Forest-CanopyClosure<50%, SBrunoMt Terrain	**0.012**	1.0
	Shrub-Forest-CanopyClosure<50%, Franciscan mélange	**0.006**	6.0
	Urban/Barren, Quaternary	**0.006**	13.9
	Urban/Barren, Franciscan mélange	**0.012**	4.9

[a] Bold values were obtained directly from field results; non-bold values were derived from field results for similar conditions

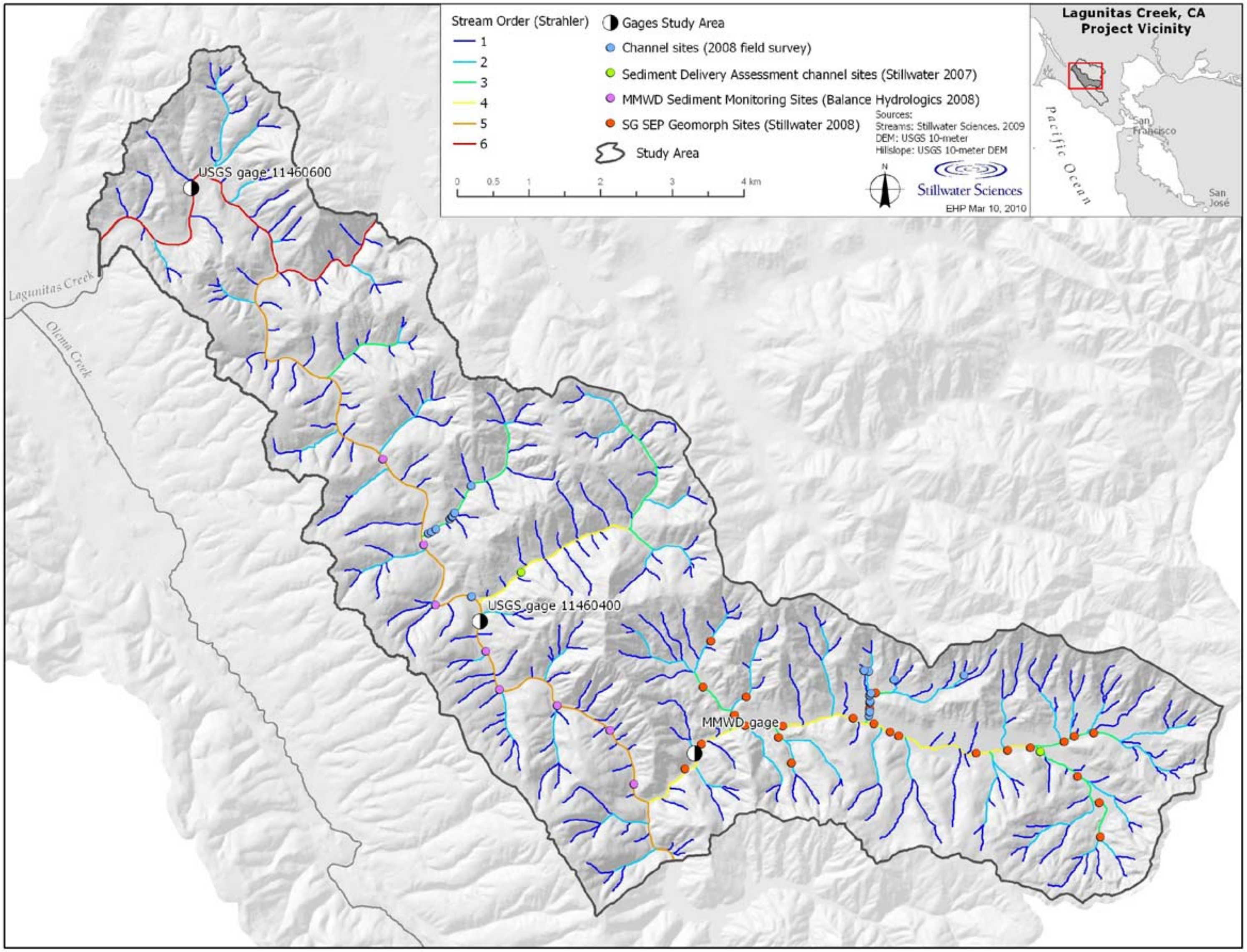

Figure 3-10. Locations of channel incision sites used in determining average annual sediment yield WY 1983–2008.

Table 3-18. Incision rates for fourth- to sixth-order channels

Stream order	Reach	Average incision rate ($m\ a^{-1}$)
4	**SG-1** (Woodacre Creek confluence to MMWD San Geronimo Creek gauge)	0.012
	SG-2 (MMWD San Geronimo Creek gauge to Lagunitas Creek confluence)	0.012
	DG-1 (Mainstem Devils Gulch to Lagunitas Creek confluence)	0.018
5	**L-1** (Peters Dam to San Geronimo Creek confluence)	0.012
	L-2 (San Geronimo Cr confluence to USGS gauge at SPT State Park)	0.008
	L-3 (USGS gauge at SPT State Park to Nicasio Creek confluence)	-0.006[a]
6	**L-4** (Nicasio Creek confluence to USGS gauge at Pt. Reyes Station)	0.015
	N-1 (Seeger Dam to Lagunitas Creek confluence)	0.015[b]

[a] Negative value denotes reach-average aggradation.
[b] Incision rate is estimated based on observations in Reach L-4.

3.3 Sediment Transport, Yields, and Storage

3.3.1 Sediment transport estimated from stream gauging

Flow records were obtained for gauges on San Geronimo Creek at Lagunitas Rd (SGC—unregulated contributing drainage area 23.1 km^2), Lagunitas Creek at Samuel P.Taylor State Park (SPT—unregulated drainage area 32.7 km^2, total drainage area 88.8 km^2), and Lagunitas Creek at Pt. Reyes Station (PRS – unregulated drainage area 62.4 km^2, total drainage area 211.6 km^2). The SGC dataset extends from WY 1980 to 2008 and was collected by MMWD; the SPT dataset extends from WY 1990 to 2008 and was collected by both MMWD (WY 1980–1982) and the USGS (WY 1983–2008 at gauge 11460400); the PRS dataset extends from WY 1975 to 2008 and was collected by the USGS (gauge 11460600).

For each station, a flood frequency curve was determined using standard methods (Bulletin 17B, USGS 1982). The flood frequency curves were then used assess the range in magnitude of annual maximum flows during the study period (WY 1983–2008) and the time between very large flood events (i.e., floods with a recurrence interval > 5 years) (Figures 3-11 to 3-13). For the unregulated San Geronimo Creek, significant flow events (i.e., peak discharge of $Q_{5\text{-yr}}$ or greater) during the period of record occurred in WY 1980, 1982, 1983, 1986, and 2006. Fewer high flow events have occurred at SPT just downstream on the mainstem of Lagunitas Creek (events in WY 1982, 1998, 2006) because of the regulating capacity of the Kent Lake reservoir. High flow events at the PRS gauge, regulated both by Kent Lake and Nicasio Reservoir, occurred in WY 1982, 1986, 1995, 1998, and 2006.

Annual sediment loads during the study period were calculated by combining daily estimates of suspended sediment discharge and bedload discharge at each gauging station. Daily suspended sediment discharge values were calculated from gauge-specific suspended sediment rating curves for daily mean flows (Figures 3-14 to 3-16). For all three gauges, suspended sediment rating curves were developed using a localized weighted scattered smoothing (LOWESS) function (Cleveland 1979) which generates a locally weighted best-fit curve through data points based on the number of local data points, resulting in a curve that is less affected by "outlier" data points than other curve fitting functions (see Warrick 2002 for a detailed discussion of LOWESS functions). Each rating curve is based on different data durations and measurement. The SGC rating curve was generated using instantaneous flow and sediment discharge measurements collected between WY 2005 and 2008 by MMWD (see Owens et al.2007, Owens et al.2008, and Owens and Hecht 2009). The SPT rating curve was generated from instantaneous data collected by calibrated OBS sensor between WY 2004 and 2006 converted to daily mean sediment discharge values by the USGS (see USGS Annual Water Year Reports for gauge 11460400). The PRS rating curve was generated using instantaneous flow and suspended sediment samples collected between WY 1990 and 2005 (see USGS Annual Water Year Reports for gauge 11460600) (Figures 3-17 to 3-19). Conversion of samples based on instantaneous flow measurements to daily mean flow at SGC included an empirical multiplier reported in the gauge annual WY report tables and intended to partially offset the sediment load underestimation inherent in flashy discharge in small contributing drainage areas (Figure 3-20). Adjustment was not necessary at SPT where the USGS have previously developed a rating curve adjusted for daily mean flows. No conversion factor was applied at the PRS gauge due to its larger contributing area and the likelihood of reasonably steady high flows during reservoir releases. In all cases, statistical bias involved in the derivation of a sediment rating curve is likely to result in an underestimate of the actual load transported (Ferguson 1986, 1987) unless transport is strongly affected by sediment supply limitations at higher flows. Therefore, the suspended sediment loads reported in Table 3-18 probably represent minimum sediment load estimates through each gauging station.

Daily bedload discharge values at the stream gauging station locations were estimated by one of two methods, based on the availability of field data. Daily bedload discharge at the San Geronimo Creek gauge was calculated using a bedload sediment rating curve developed using a LOWESS fitting function and field data collected between WY 1982 and 2008 (Figure 3-21) and daily mean flow from WY 1983 to 2008. To account for using daily mean flow with a rating curve derived from instantaneous values, daily bedload discharge values were increased by a factor that ensured that the "corrected" bedload to "corrected" suspended sediment discharge ratio was the same as the ratio for uncorrected values. These data suggest that bedload is 31% of total load which is an extremely high estimate of load for a creek with this drainage area. For Lagunitas Creek, available bedload data stems mostly from measurements made from WY 1979 to 1982 (see Hecht 1983) which are not applicable to current conditions because they were taken prior to the doubling of the capacity of Kent Lake. One bedload sample taken at the PRS gauge in WY 1999 suggested a bedload proportion of 19% of total sediment load but this is also high relative to expectations for a watershed of this size. If indeed the bedload proportion in Lagunitas Creek is very high, it is possible that this occurs because of a high component of very fine bedload material (i.e., material perhaps in the 1–4-mm range, which is potentially of little benefit to native aquatic habitats. Values of 20–31% as bedload is an expectation generally reserved for rivers from more flashy, sand-bedded environments such as to the south of California (e.g., Inman and Jenkins 1999, Willis and Griggs 2003) or to the very high sediment producing coastal watersheds to the north (e.g., Janda et al. 1975, Sommerfield and Nittrouer 1999). Conversely, more generally accepted values of bedload, in the range 5–10% (see Reid and Dunne 1996), appear low in relation to the available data, especially from San Geronimo Creek. As a compromise, we use a bedload proportion of 15% in the on Lagunitas Creek in estimates of average annual load below in Table 3-19. We continue to utilize the measured 31% bedload for

San Geronimo Creek although found it necessary to adjust this value to 20% (and 10% above the Woodacre Creek confluence) for later sediment transport modeling (see Section 5; Appendix A).

Table 3-19. Average annual unit sediment load for WY 1983–2008 estimated from three gauging stations in the Lagunitas watershed.

Gauge Location	Average annual bedload ($t\ a^{-1}$)	Average annual suspended sediment load ($t\ a^{-1}$)	Average annual total sediment load ($t\ a^{-1}$)	Average annual unit total sediment load ($t\ km^{-2}\ a^{-1}$)
San Geronimo Creek at Lagunitas Rd. bridge (MMWD gauge)	1,670	3,668	5,337	231
Lagunitas Creek at Samuel P. Taylor State Park (USGS gauge 11460400)	641	3,631	4,272	131
Lagunitas Creek at Pt. Reyes Station (USGS gauge 11460600)	2,584	14,640	17,224	276

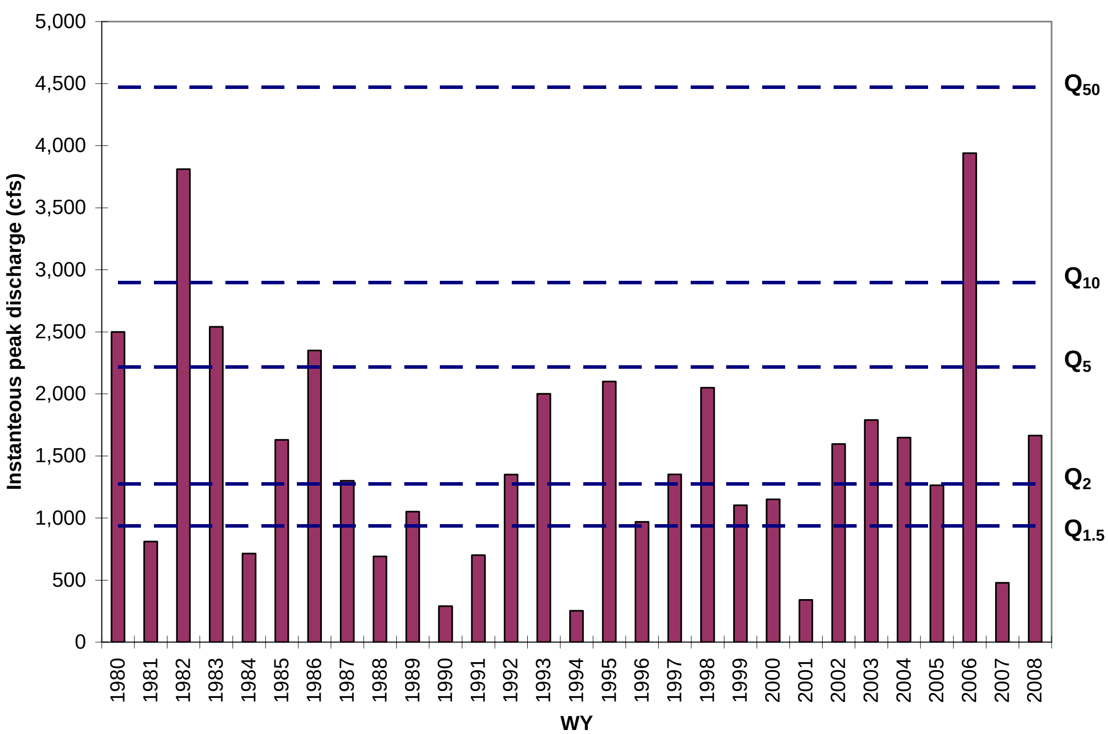

Figure 3-11. Annual maximum discharge for San Geronimo Creek at Lagunitas Rd bridge (MMWD gauge).

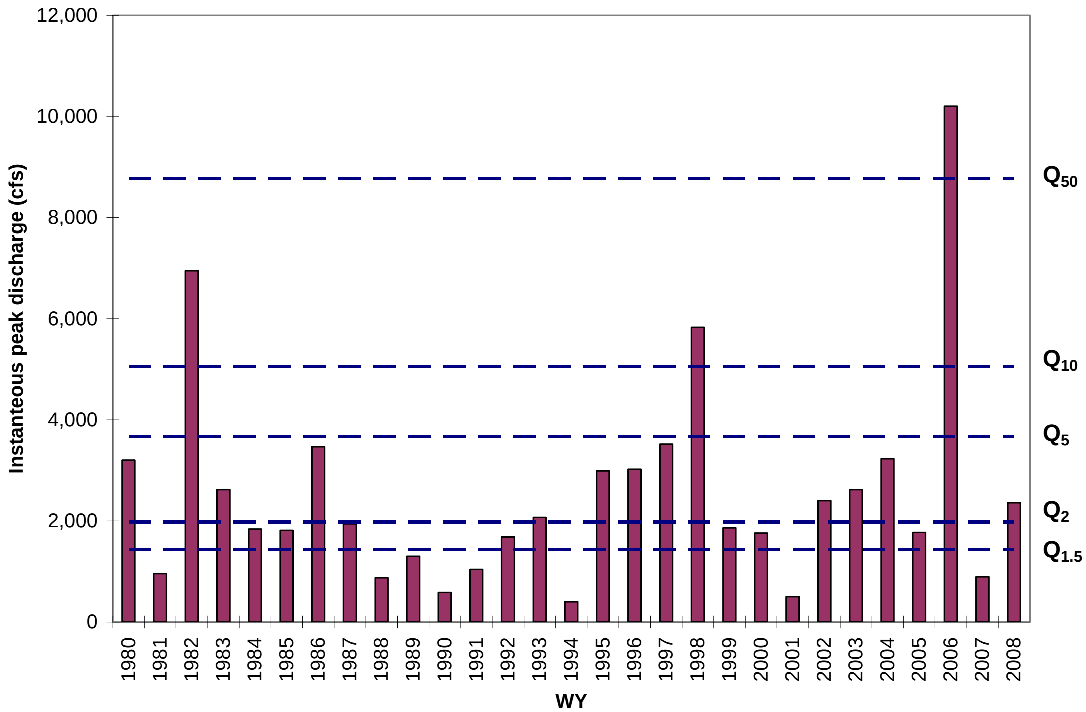

Figure 3-12. Annual maximum discharge for Lagunitas Creek at Samuel P. Taylor State Park (MMWD gauge [1980–1982], USGS gauge 11460400 [1983–2008]).

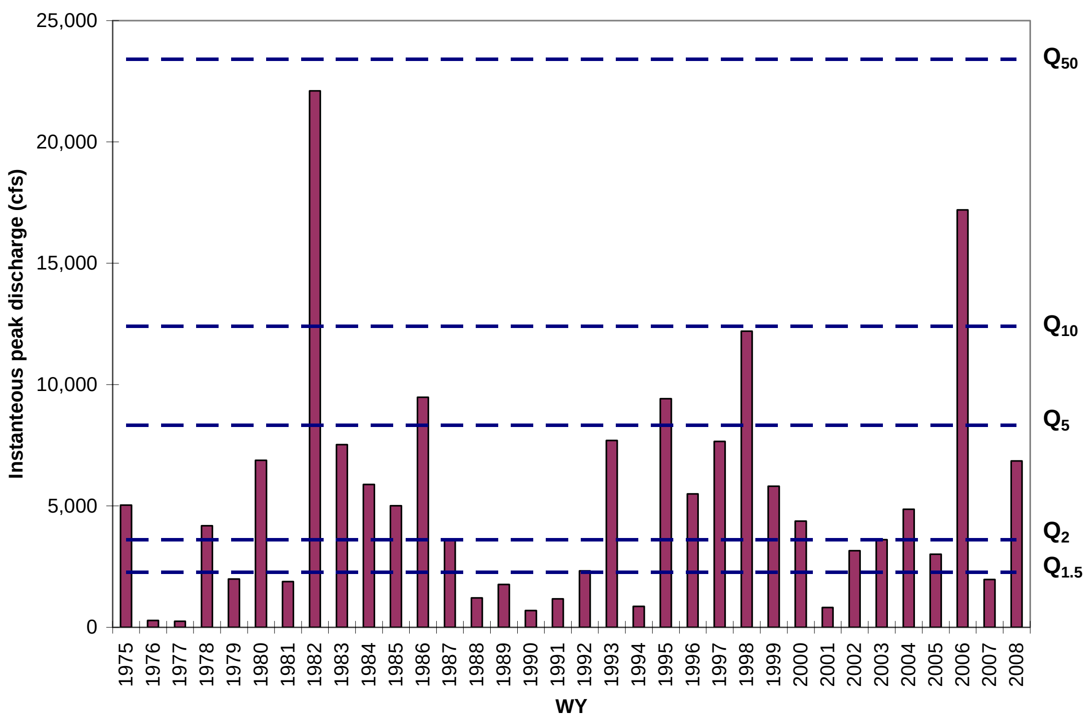

Figure 3-13. Annual maximum discharge at Lagunitas Creek at Pt. Reyes Station (USGS gauge 11460600).

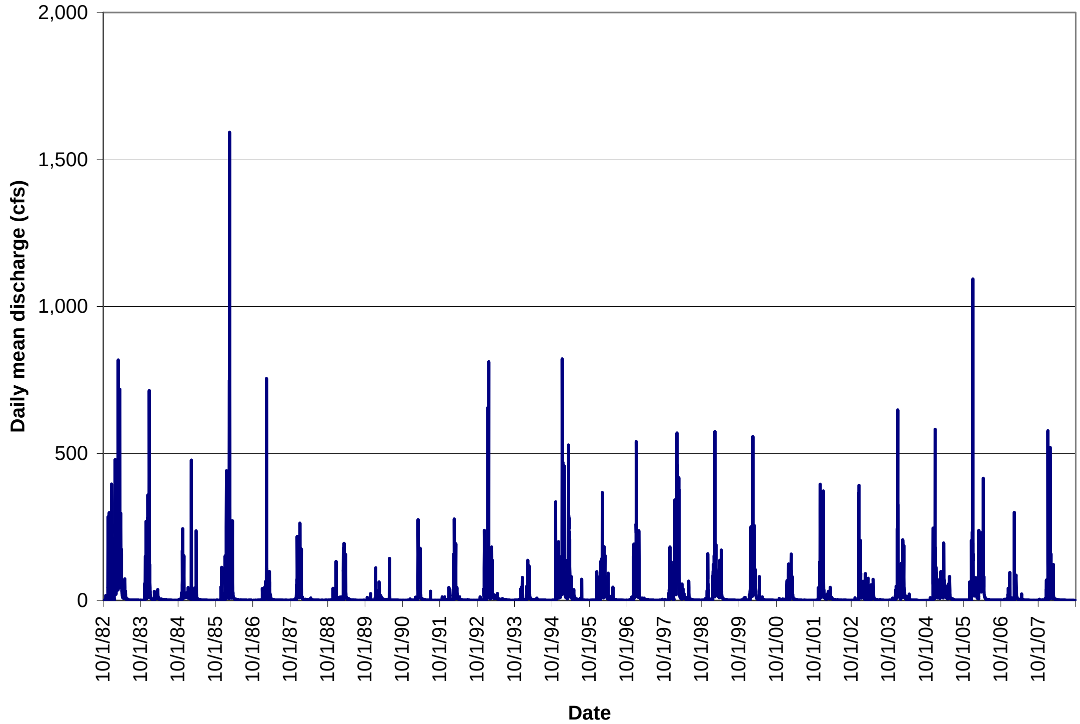

Figure 3-14. Daily mean discharge for San Geronimo Creek at Lagunitas Rd bridge (MMWD gauge).

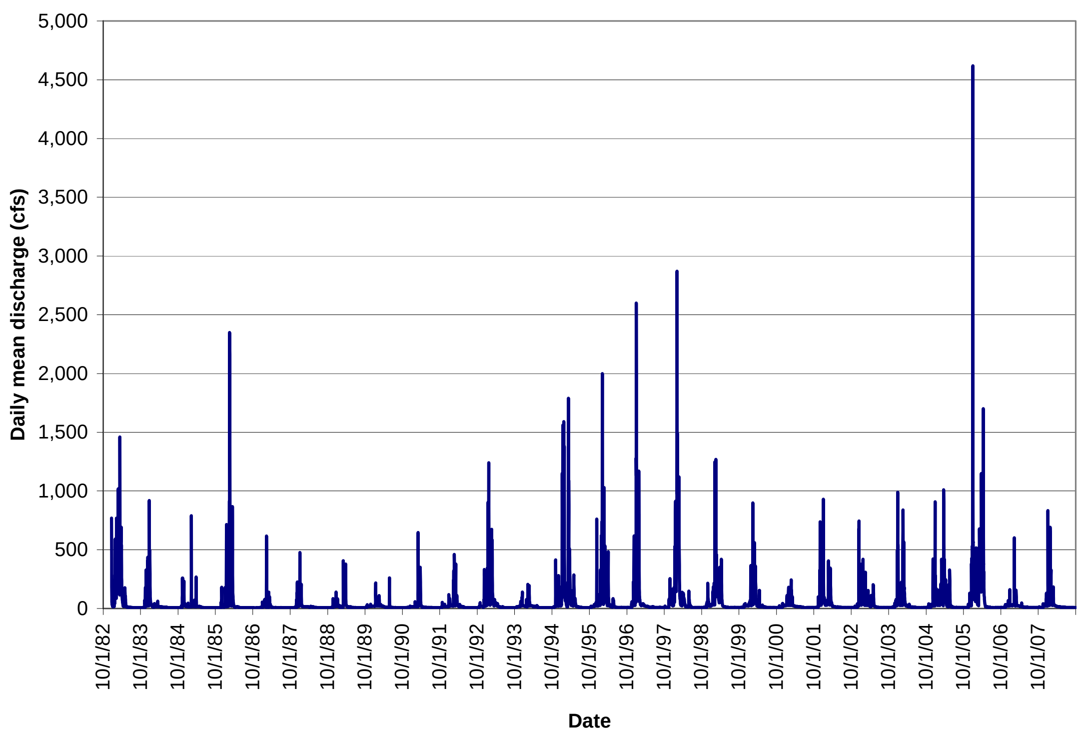

Figure 3-15. Daily mean discharge for Lagunitas Creek at Samuel P.Taylor State Park (USGS gauge 11460400).

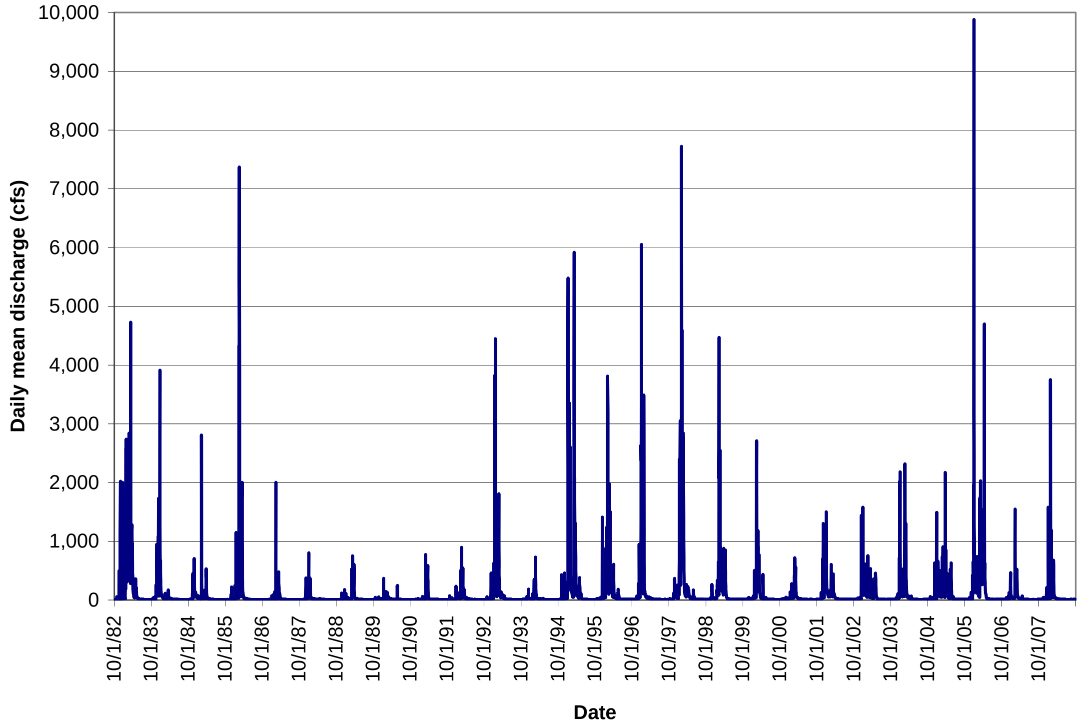

Figure 3-16. Daily mean discharge for Lagunitas Creek at Pt. Reyes Station (USGS gauge 11460600).

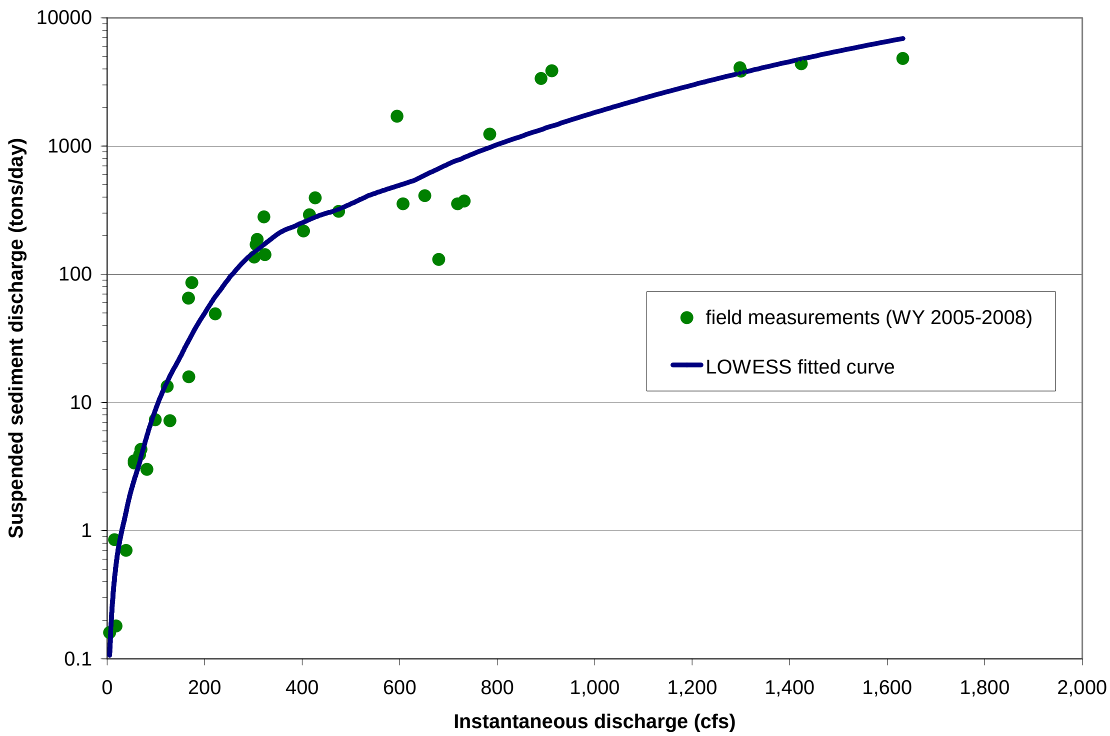

Figure 3-17. Suspended sediment data and LOWESS-derived fitted curve for San Geronimo Creek at Lagunitas Rd bridge (MMWD gauge).

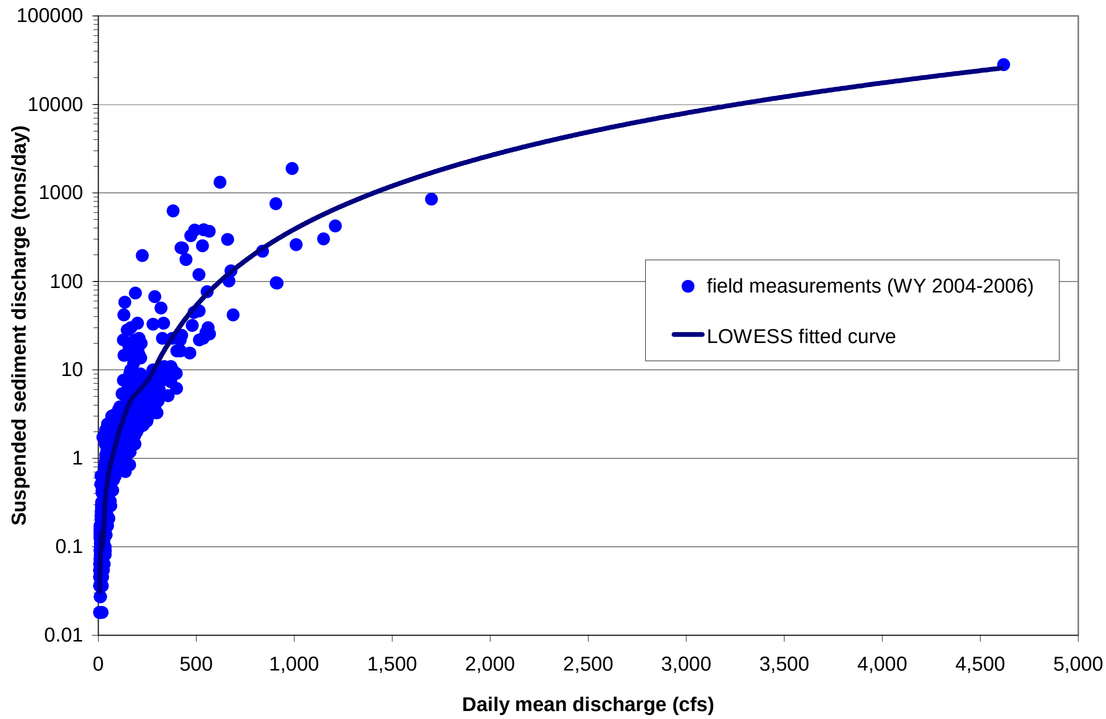

Figure 3-18. Suspended sediment data and LOWESS-derived fitted curve for Lagunitas Creek at Samuel P. Taylor State Park (USGS gauge 11460400).

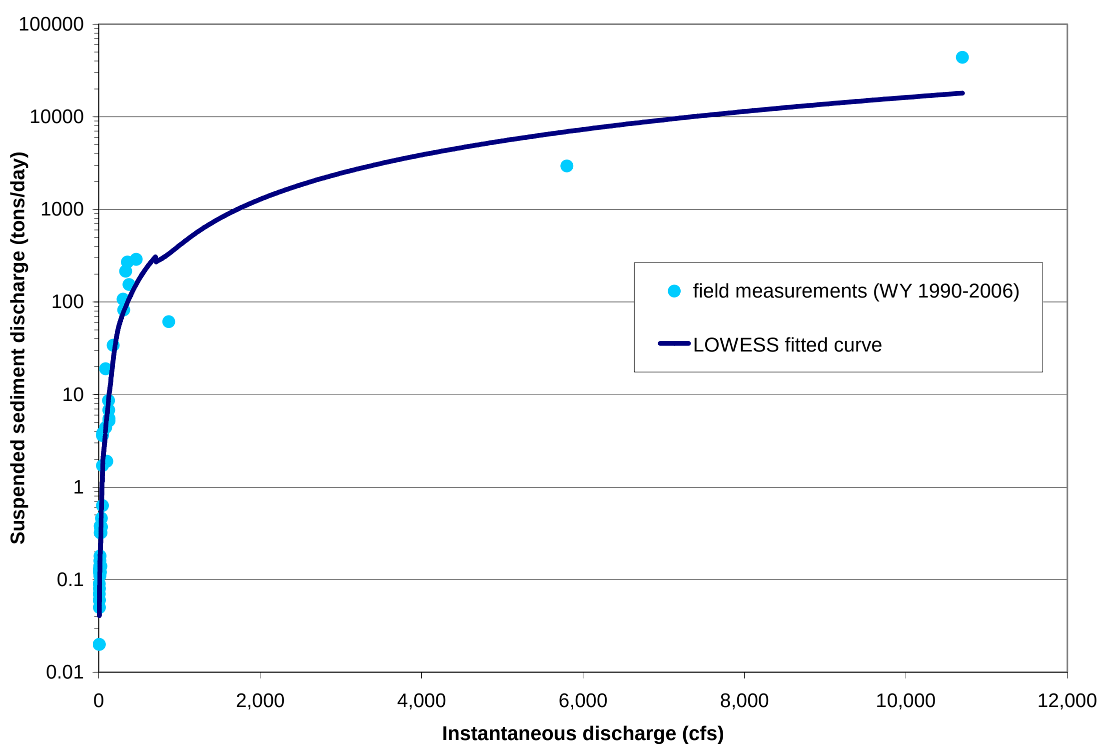

Figure 3-19. Suspended sediment data and LOWESS-derived fitted curve for Lagunitas Creek at Pt. Reyes Station (USGS gauge 11460600).

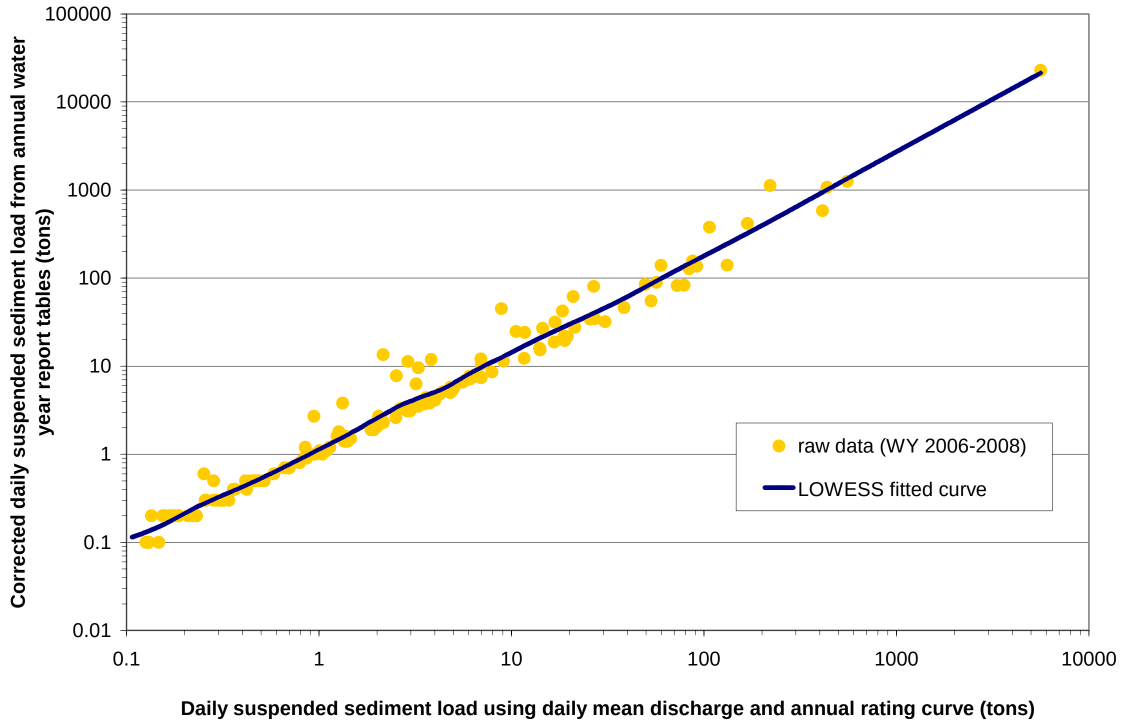

Figure 3-20. Relationship between reported and rating curve-derived daily suspended sediment load from the San Geronimo Creek gauge annual reports (source: Owens et al. 2007, Owens et al. 2008, and Owens and Hecht 2009).

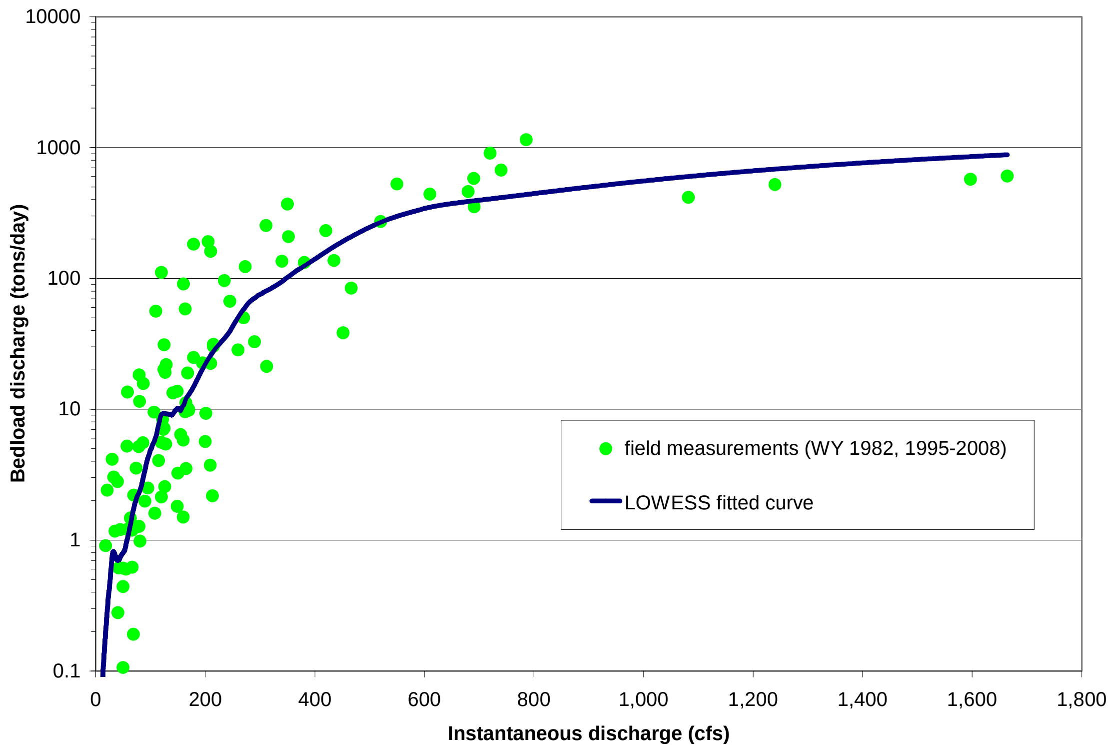

Figure 3-21. Bedload data and LOWESS-derived fitted curve for San Geronimo Creek at Lagunitas Rd bridge (MMWD gauge).

3.3.2 Sediment yields into Nicasio Reservoir

To corroborate sediment delivery rates determined from previous studies and historical aerial photography analysis, and as a check on the likely accuracy of the sediment yield estimates, a bathymetric survey was conducted in the Nicasio/Halleck Creek and Dolcini Creek arms of the Nicasio Reservoir during May 2008 (Figure 3-22). The survey re-occupied a network of cross-sections established by MMWD in 1976 as part of their Nicasio Lake Silt Monitoring Program, and expanded in 1996. The baseline elevation data was derived from a historic, pre-dam closure topographic map and representing 1961 conditions for this analysis. The pre-reservoir data had a 10-ft contour interval spacing whereas the later surveys conducted by MMWD (e.g., 1976, 1987, 1990) have a resolution of 1 ft.

Bathymetric data were collected using an Acoustic Doppler Current Profiler (ADCP) sampling at 0.01-ft resolution measurements of water depth. Measured water depths were subtracted from the uniform (i.e., flat) reservoir water surface elevation, and surveys were undertaken with the reservoir at 100% capacity which allowed for near-complete survey across each measured cross-section. Survey data were tied to differential GPS measurements of geographical location and elevation of the ADCP unit and the data compiled in a GIS. The locations of the surveyed cross-sections are shown in Figure 3-22 and example cross-sections are shown in Figure 3-23 and Figure 3-24.

The present-day bathymetric data at the surveyed cross-sections were compared to historical pre-reservoir topographic data (i.e., 1961) and post-reservoir bathymetric data collected by MMWD from 1976 to 1990 to determine sediment accumulation over the period of record (1961–2008). The change in areas at the surveyed cross-sections is presented in Table 3-20. Sediment accumulation resulting in an increase in reservoir bed elevation occurred at each cross-section, indicating that the water storage capacity in Nicasio Reservoir is decreasing over time. To calculate the volume of accumulated sediment, the areal difference between paired cross-sections was multiplied by the intervening distance to the next cross-section pair as an approximate pyramid, and this process repeated for each cross-section pair up to an origin point in the contributing stream channel. The resultant estimate of total volumetric change in Nicasio/Halleck Creek and Dolcini Creek arms of Nicasio Reservoir was converted to a yield using an assumed bulk density of 1.6 tonnes m^{-3}: results are presented in Table 3-20. The reservoir sedimentation estimates were then compared to GLU-derived estimates of sediment yields from the upstream contributing watershed areas (see Figure 3-25), and to previous sedimentation rate estimates from MMWD for the periods 1961–1970 and 1961–1976. Table 3-21 shows that the different methods provide highly comparable results, recognizing that the different methods estimate yields over different time periods with different storminess. The test, applied to an area of the watershed not subject to field survey, provides some confidence in the utility of GLU estimates for estimating sediment yields.

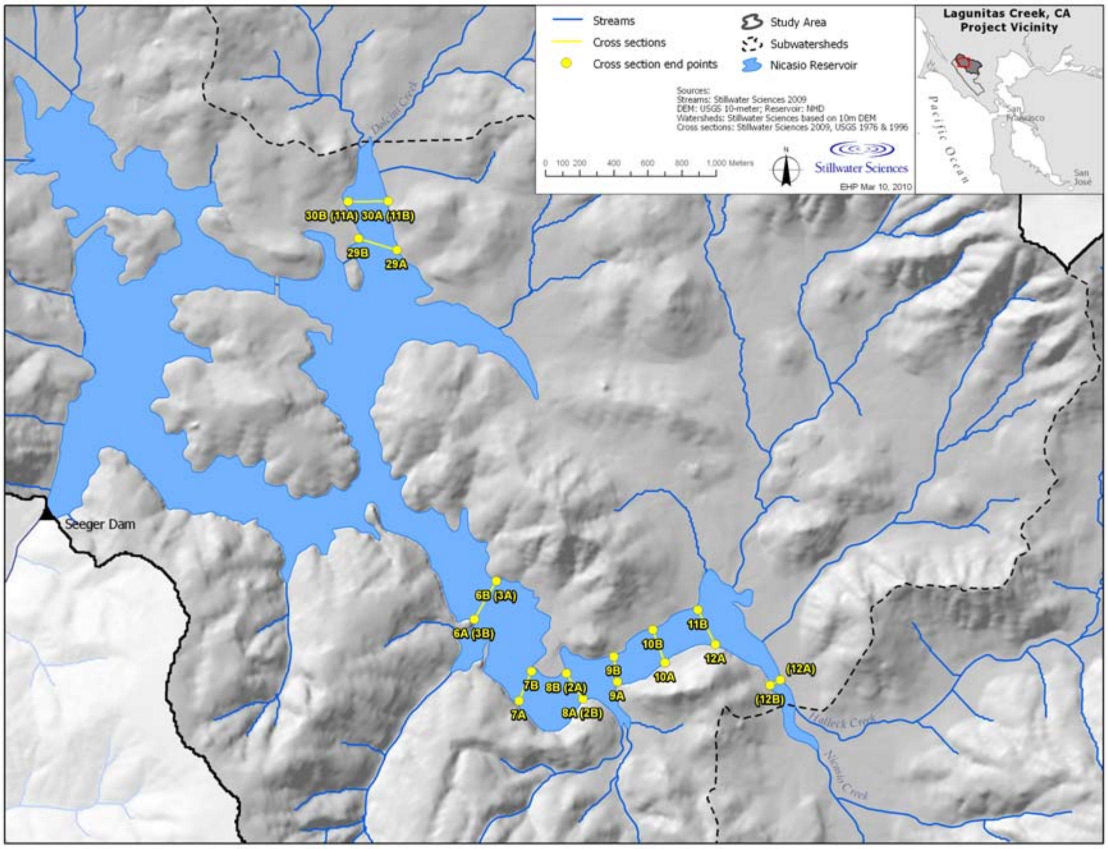

Figure 3-22. Bedload data and LOWESS-derived fitted curve for San Geronimo Creek at Lagunitas Rd bridge (MMWD gauge).

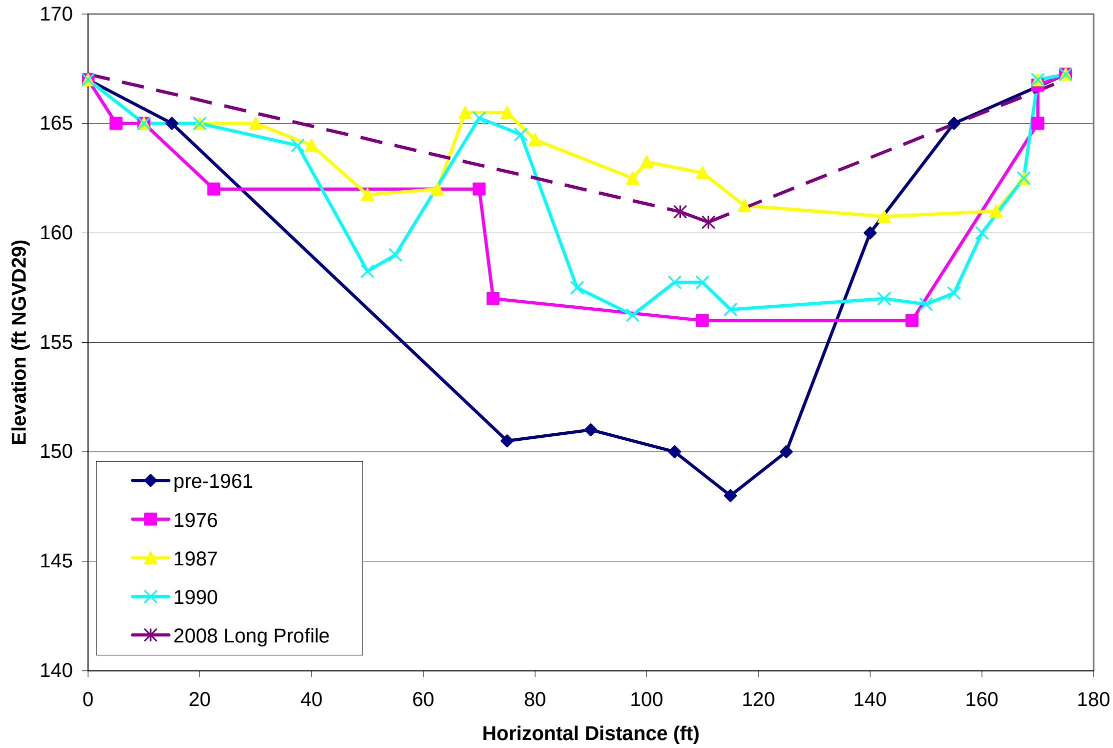

Figure 3-23. Time series of cross-section surveys within Nicasio Reservoir, MMWD Section (12B–12A). The dashed lines represent the interpolated bed surface between measured elevations.

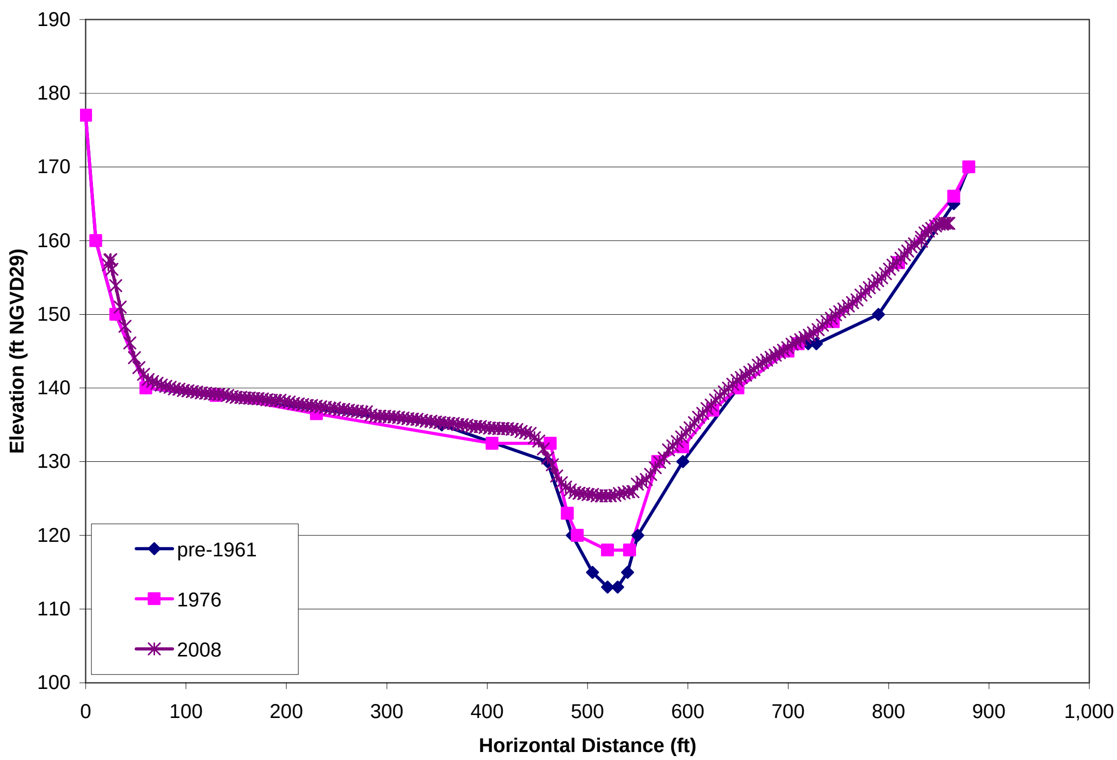

Figure 3-24. Time series of cross-section surveys within Nicasio Reservoir, MMWD Section 6A–6B (3B–3A)

Table 3-20. Sediment accumulation in Nicasio Reservoir 1961–2008.

Reservoir Arm	Cross-section[a]	Total area change rate (m^2 a^{-1})[b]	Total volume change rate (m^3 a^{-1})[c, d]		Total sediment mass change, or sediment yield into reservoir arms (t a^{-1})[e]	Compare sediment yield into reservoir arms estimated by MMWD (1961–1970) (t a^{-1})[f]	Compare sediment yield estimated with GLU analysis (t a^{-1})[g, h]
			Bounding cross-sections [d]	Volume change rate (m^3 a^{-1})			
Nicasio/Halleck Creek (54.9 km^2)	6A–6B (3B–3A)	3.6	6A–6B (3B–3A) to 7A–7B	2,741	25,479	15,100	17,533
	7A–7B	6.2	7A–7B to 8A–8B (2B–2A)	2,663			
	8A–8B (2B–2A)	9.4	8A–8B (2B–2A) to 9A–9B	2,366			
	9A–9B	9.0	9A–9B to 10A–10B (1B–1A)	2,975			
	10A–10B (1B–1A)	11.1	10A–10B (1B–1A) to (12B–12A)	5,085			
	(12B–12A)	2.0	(12B–12A) to arm origin point	94			
Dolcini Creek (7.6 km^2)	29A–29B	1.6	29A–29B to 30A–30B (11B–11A)	526	1,279	N/A	2.439
	30A–30B (11B–11A)	3.1	30A–30B (11B–11A) to origin point	254			

[a] Cross-section locations and name designations established by MMWD. Original cross-section designations shown in parenthesis.
[b] Change in cross-section area over time period calculated by measuring area difference between successive cross-sections; positive values (i.e., cross-section contraction) indicate sediment accumulation; negative values (i.e., cross-section area enlargement) indicate sediment evacuation.
[c] Time period between 1961 and 2008 is 47 years; Seeger Dam closure on the Nicasio Creek occurred in 1961.
[d] Volume between adjacent cross-sections calculated as a pyramid, bounded by both cross-sections spanning distance along the thalweg, as determined using a 10m DEM in GIS. Volumes calculated upstream of the upstream-most cross-sections projected to origin of reservoir arm: upstream extent of Nicasio/Halleck Creek arm is the confluence of Nicasio and Halleck creeks; upstream extent of Dolcini Creek arm is the confluence of an unnamed stream near the crossing of Pt. Reyes-Petaluma Road.
[e] Sediment mass estimate assumes bulk density value equivalent to 1.6 t m^{-3}.
[f] Source: MMWD memorandum from J. D. Stroeh to J. T. Farnkopf; File 217.8, 28 September 1970.
[g] Contributing drainage area includes those areas upstream of the origin of reservoir arm, as determined in GIS; portion of contributing area to the Nicasio/Halleck Creek arm excluded due to stream disconnectivity caused by crossing of Nicasio Valley Road.
[h] GLU-derived average annual sediment production factored over a 26-year time period (1982-2008), and includes contributions from hillslope erosion features, soil creep, tributaries, channel bank erosion, channel incision, and roads.

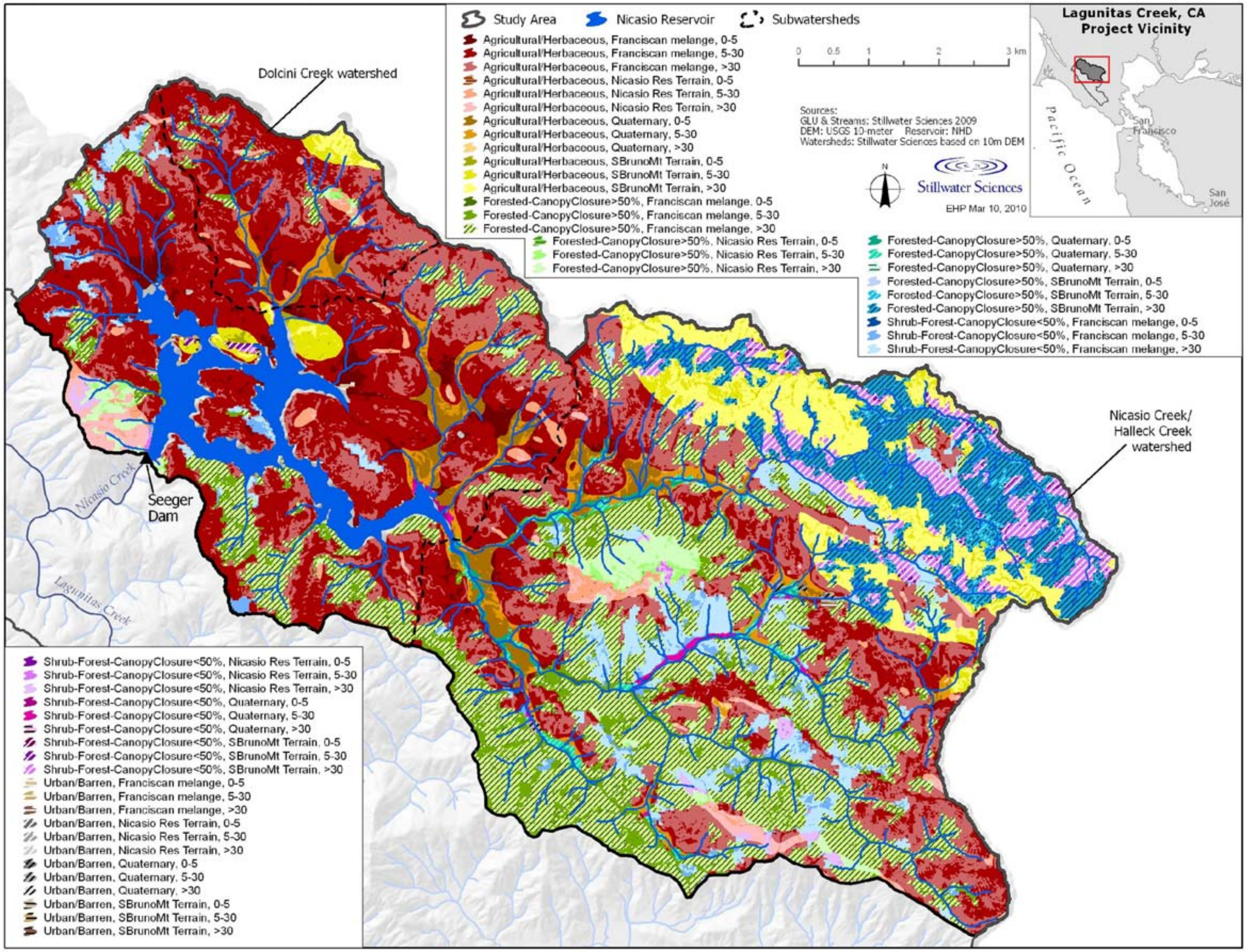

Figure 3-25. Geomorphic landscape unit (GLU) distribution within the Nicasio Creek sub-watershed (upstream of Seeger Dam).

Table 3-21. Comparison of sediment yields into Nicasio Reservoir estimated by MMWD and Stillwater Sciences.

Study area	Contributing drainage area (km^2)	Sediment yield into reservoir study area ($t\ a^{-1}$)			
		MMWD estimate for the period of 1961-1970 [a]	Stillwater Sciences bathymetry survey estimate for the period of 1961-2008	Stillwater Sciences GLU estimate for the period of 1982-2008 [b]	MMWD estimate for the period of 1961-1976 [c]
Nicasio/Halleck Creek arm	54.9	15,100	25,479	17,533	N/A
Entire Nicasio Reservoir (u/s of Seeger Dam)	93.2	N/A	N/A	26,595	32,640

[a] Source: MMWD memorandum from J. D. Stroeh to J. T. Farnkopf; File 217.8, 28 September 1970.
[b] Includes contributions from hillslope erosion features, soil creep, tributaries, channel bank erosion, channel incision, and roads.
[c] Source: MMWD memorandum from B. Heare to Stan Soldavini; File 217.8, 28 February 1977.

3.3.3 Sediment yields from the Upper Lagunitas watershed

For use in later comparisons, an approximate estimate was made of sediment yield from the Upper Lagunitas watershed, above Peters Dam. Note that this estimate is derived purely from extrapolated rates of hillslope and channel erosion derived from our field investigations elsewhere in the Lagunitas watershed, and computer models for road-related sediment and soil production and diffusion. It also takes no account of the interception of sediment by Bon Tempe Reservoir and Alpine Lake, and includes some fourth order channel segments under the area usually inundated by reservoir water. It is therefore more accurately an estimate of potential yield from the Upper Lagunitas watershed under the condition of no reservoirs than a sediment yield into Kent Lake.

The total production was estimated at approximately 17,400 $t\ a^{-1}$, derived from a combination of soil production and diffusion (283 $t\ a^{-1}$), road-related sediment (726 $t\ a^{-1}$), hillslope sediment (5,236 $t\ a^{-1}$) and first to fourth-order channel sediment (11,171 $t\ a^{-1}$). With a drainage area of 55.7 km2, the average annual sediment production rate is approximately 313 $t\ km^2\ a^{-1}$.

4 SEDIMENT BUDGET

4.1 Average Annual Sediment Delivery

4.1.1 By sub-watershed

Rates of sub-watershed sediment delivery encompassing slides, gullies, and creep/sheetwash from hillsides, erosion from roads and trails, and bank and bed erosion from channels, are shown in summary in Table 4-1, and by enumerated sub-watershed in Table 4-2. Sediment contributions from mainstem channels (4th order and above) are accounted separately. Results are shown graphically in Figure 4-1. The results suggest that the greatest source of sediment delivery is from tributary bed and bank erosion (i.e., 1st to 3rd order channels), accounting for nearly 42% (8,542 t a^{-1}) of total sediment delivery, with the majority (63%, 5349 t a^{-1}) coming from tributary bank erosion. The second largest sediment delivery mechanism is hillslope slides and gullies which account for over a quarter of all sediment (26%, 5,327 t a^{-1}). Mainstem bank and bed erosion accounts for a little under 20% (3,956 t a^{-1}) of sediment delivered including nearly 74% (849 t a^{-1}) of the sediment delivered from the remaining extent of Nicasio Creek downstream of Seeger Dam, almost all by incision. Conversely, mainstem Lagunitas Creek between the Devils Gulch and Nicasio Creek confluence is aggrading with net mainstem storage of 1,218 t a^{-1}. Sediment delivery from roads and trails accounts for seven percent or less of sediment delivery from all areas except San Geronimo Creek where it represents a little under 17% of all sediment delivered (1,569 t a^{-1}). This sediment is elemental in causing the San Geronimo watershed to account for nearly one-half (46%, 9,356 t a^{-1}) of the study area sediment delivery. The San Geronimo watershed, at 38% of the study area, also has the second highest unit yield of sediment (385 t km^{-2} a^{-1}) to the small incising section of Nicasio Creek downstream of Seeger Dam (503 t km^{-2} a^{-1}). The lowest unit rate of sediment delivery occurs in the area from Devils Gulch to Nicasio Creek confluences where mainstem storage reduces the effective unit yield from 214 t km^{-2} a^{-1} to 133 t km^{-2} a^{-1} despite the fact that this area has the highest rate of hillslope sediment delivery (96 t km^{-2} a^{-1}), accounting for 73% of all sediment delivered (45% disregarding the mainstem aggradation).

Total sediment delivery by individual sub-watershed (Table 4-2; ranging from 0.03 – 3.8 km^2), excluding sediment delivered from roads and trails which was estimated on a larger unit basis, range from almost zero in sub-watershed 32 in the San Geronimo watershed to a little over 1,000 t a^{-1} in the headwaters of San Geronimo Creek (sub-watershed 16: 1,006 t a^{-1}). In large part, the total sediment yields simply reflects sub-watershed size: the five highest yielding sub-watersheds (all in excess of 700 t a^{-1}) are in the top six largest sub-watersheds, and the tenth highest yielding sub-watershed (over 300 t a^{-1}) has the fourteenth largest area. In contrast, excluding the smallest sub-watershed, the range of sub-watershed sediment delivery rates range from 30 – 400 t km^{-2} a^{-1} (excluding the contribution of roads and trails) and, as might be expected, encompass a range of sub-watershed areas. The top ten sediment-delivering sub-watersheds, by rate (287- 405 t km^{-2} a^{-1}), range in size from 0.21 to 3.49 km^2. Across 67 sub-watersheds, the arithmetic mean is 203 t km^{-2} a^{-1} and the standard deviation 96 t km^{-2} a^{-1}, indicating a wide spread of values around a central tendency. For comparison, in neighboring watersheds, Lehre's (1982) long-term rate of sediment yield for the 1.74 km^2 Long Tree Creek was 214 t km^{-2} a^{-1}, reaching a maximum of 691 t km^{-2} a^{-1} for a three year period (1971–1974) that encompassed a large storm event. In smaller headwaters, O'Farrell et al. (2007) computed hillslope erosion rates for the Haypress basin (0.33km^2) in the Tennessee Valley was in the order 224–334 t km^{-2} a^{-1}. The relative similarity in these values provides some confidence in the sub-watershed yields estimated in this study and, by implication, in the GLU unit rates of sediment delivery.

Table 4-1. Annual rates of sediment delivery from major sub-divisions of the Lagunitas Creek study area.

Unit	Drainage area (km^2)	Sediment delivery ($t\ a^{-1}$)							Sediment yield ($t\ a^{-1}$)	
		Hillslope slides and gullies	Soil creep	Roads and trails	Tributary bank erosion	Tributary bed incision	Mainstem bank erosion	Mainstem bed incision	Unit not including mainstem	Unit including mainstem
San Geronimo Creek	24.33	1,835	90	1569	2794	1400	211	1,457	7,688	9,356
Lagunitas Creek (San Geronimo Creek to Devils Gulch)	8.80	704	50	228	456	373	53	1,196	1,811	3,060
Devils Gulch	6.99	524	30	64	535	433	59	236	1,586	1,881
Lagunitas Creek (Devils Gulch to Nicasio Creek)	14.90	1,433	64	10	992	694	111	-1,329	3,193	1,975
Regulated Nicasio Creek	2.27	179	10	0	36	68	2	847	293	1,142
Lagunitas Creek (Nicasio Creek to Pt. Reyes Station)	7.08	651	32	164	536	225	41	1,072	1,608	2,721
Total study area	**64.37**	**5,327**	**276**	**2,035**	**5,349**	**3,193**	**477**	**3,479**	**16,179**	**20,135**

Table 4-2. Annual rates of sediment delivery (t a^{-1}) from enumerated sub-watersheds of the Lagunitas Creek study area.

Unit	Sub-watershed ID	Sub-watershed Area	Hillslope slides and gullies	Soil creep	Roads and trails	Tributary bank erosion	Tributary bed incision
San Geronimo Creek	16 San Geronimo Creek headwaters	3.8	431	11.5		313	251
	27 Woodacre Creek	3.66	218	15.1		483	226
	29	0.23	16	0.2		1	3
	30	0.15	5	0.2		0	1
	11	0.73	73	2.4		72	56
	24 Willis Evans Creek	0.87	55	3.9		195	58
	33	0.85	91	0.8		8	7
	23 Deer Camp Creek	0.38	22	1.5		110	14
	31	0.39	17	0.6		15	4
	25 Creamery Creek	1.14	58	3.5		195	44
	32	0.07	2	0.1		0	0
	22 Sylvestris Creek	0.66	28	3.0		86	41
	35	0.39	19	1.0		24	7
	8 Larsen Creek	1.81	202	5.7		150	159
	34	0.3	28	0.9		6	5
	7 Clear Creek	0.98	82	4.3		103	61
	9	0.29	16	1.4		61	12
	36	0.39	6	0.4		2	4
	19 Montezuma Creek	0.98	46	5.1		150	58
	18	0.57	26	2.7		76	30
	10 Arroyo Creek	3.49	252	16.5		466	267
	13	0.24	12	0.5		40	8
	15	0.21	11	1.1		64	9
	14	0.54	52	2.1		96	20
	37	0.63	44	2.3		6	15
	21	0.62	25	3.3		73	39
	Total			2.6	**1,569**		

Unit	Sub-watershed ID	Sub-watershed Area	Hillslope slides and gullies	Soil creep	Roads and trails	Tributary bank erosion	Tributary bed incision
Lagunitas Creek (San Geronimo Creek to Devils Gulch)	39	0.43	53	4.7		7	11
	40	0.8	57	8.3		41	30
	26	0.94	69	10.0		86	58
	38	2.12	180	5.2		37	62
	20	0.96	69	4.8		73	44
	6 Barnabe Creek	0.69	60	4.2		22	58
	17 Irving Creek	0.74	62	6.6		51	23
	12	1.71	124	3.2		123	49
	5 Deadman's Creek	0.41	30	10.7		16	37
	Total			5.0	**228**		
Devils Gulch	1	2.5	235	14.2		293	196
	2	1.46	74	0.5		108	90
	3 Devils Gulch mainstem	3.02	214	1.0		134	147
	Total			1.8	64		
Lagunitas Creek (Devils Gulch to Nicasio Creek)	4	0.21	21	1.7		0	0
	66	0.23	13	0.5		23	10
	56	0.36	8	0.3		15	27
	55	0.39	10	5.2		31	25
	72	0.27	24	16.0		0	0
	71	0.21	9	2.2		0	0
	54	0.97	68	1.8		63	35
	51 Cheda Creek	2.98	346	1.9	6.4	295	262
	44	0.73	66	6.9		48	23
	73	0.61	100	1.3		32	16
	53	0.68	65	1.3		52	28
	50 McIssac's Creek	1.34	147	2.3	3.6	105	56
	67	0.32	27	6.2		14	5
	68	0.52	66	3.4		16	8
	52	0.58	48	2.3		32	18
	48	1.52	163	3.0		146	125
	70	0.91	59	0.3		48	17
	69	0.84	108	4.0		39	20
	49	0.44	29	6.9		9	3
	65	0.18	11	3.3		0	0
	47	0.61	45	2.0		24	13

Unit	Sub-watershed ID	Sub-watershed Area	Hillslope slides and gullies	Soil creep	Roads and trails	Tributary bank erosion	Tributary bed incision
Regulated Nicasio Creek	45 Nicasio Creek	1.58	109	7.9		30	55
	64 Nicasio Creek	0.69	70	10.7		6	13
Lagunitas Creek (Nicasio Creek to Pt. Reyes Station)	62	0.84	59	0.0		18	7
	63	1.26	149	0.0		35	69
	42	1.75	206	4.5		152	87
	57	0	0	1.0		0	0
	58	0.03	2	11.5		1	3
	43	1	75	15.1		40	22
	46	0.17	19	0.2		27	10
	Total				**164[a]**		

[a] Value includes all sub-watersheds in downstream of the Devils Gulch confluence except 51 (Cheda Creek) and 50 (McIssac's Creek).

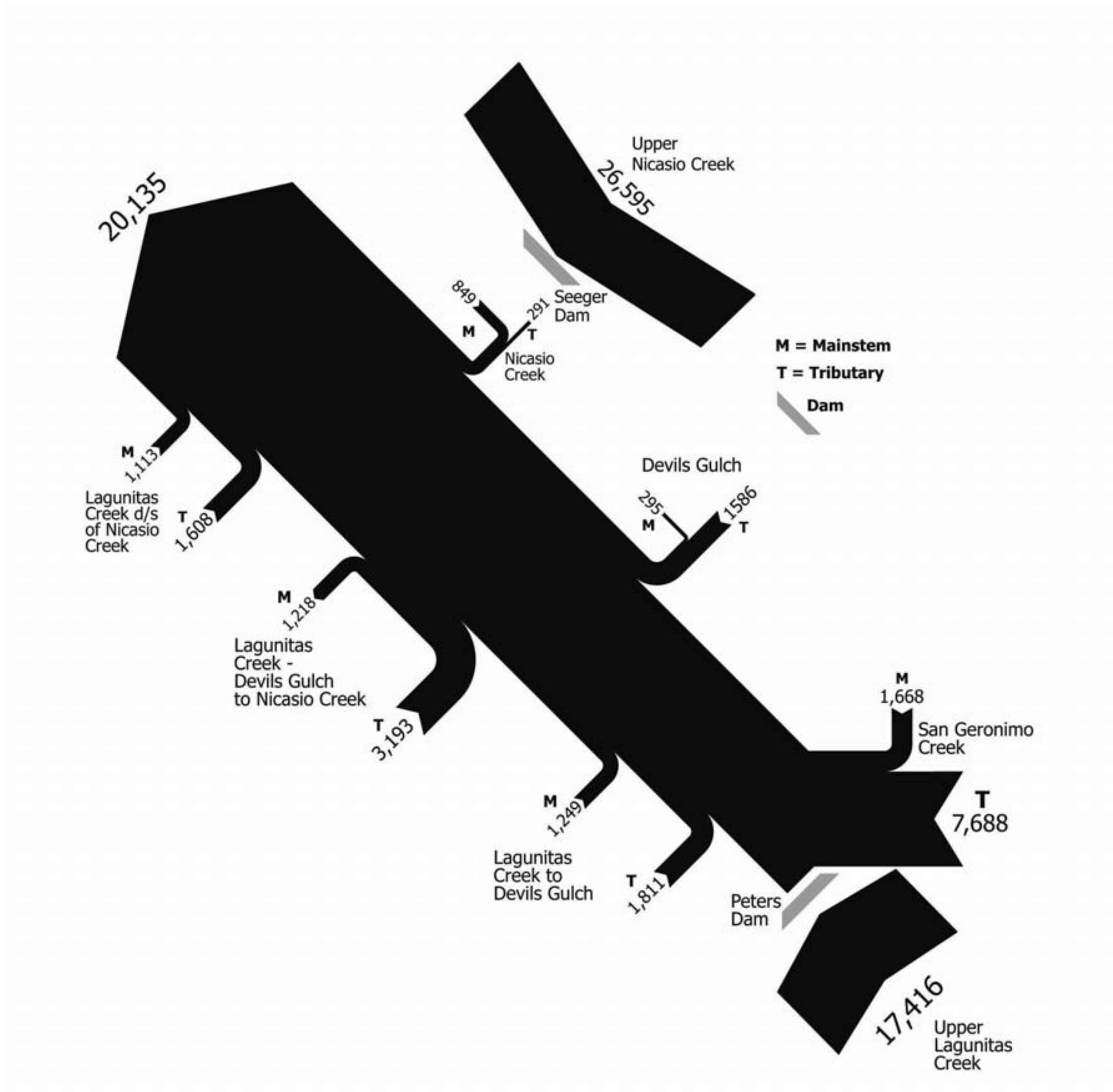

Figure 4-1. Schematic description of sediment yield throughout the Lagunitas Creek watershed study area (t a^{-1}).

4.1.2 By GLU

The highest yielding GLU by unit hillslope sediment *production* (i.e., discrete sources as extrapolated from three field surveys and aerial photographic analysis) in the six primary divisions of the study area is consistently domain 323, mixed shrub land cover on Nicasio Reservoir terrane and with slopes in excess of 30% (Table 4-3). However, the highest total hillslope sediment production is associated with three steep hillslope GLUs: two are associated with agricultural land cover (one with mixed forest) but all non-alluvial geological types are represented (i.e., Nicasio Reservoir [2], San Bruno [3], and Franciscan mélange [4]). The GLUs are in the eight most commonly occurring GLUs in the Lagunitas study area (143 is 9% of the study area, joint 3rd occurrence; 233 = 7% = 6th; 123 = 6% = joint 7th), but neither of the most two commonly occurring GLUs are represented: these share common trait of mixed forest on steep hillslopes (GLU 243 is on Franciscan mélange and covers 19% of the study area; 223 is on Nicasio Reservoir terrain = 11% of the study area). Unless a function of systematic underrepresentation in field survey, there the suggestion that hillslope sediment yields are relatively lower under steep forest lands than steep agricultural lands, irrespective of geological type in each case.

The overall range of units values contained within the hillslope GLUs ranges from 0 to a maximum of 466 t km^{-2} a^{-1} (highlighted in Table 4-3). The majority of the rates are in the range 10–200 t km^{-2} a^{-1}, with the three highest rates over 250 t km^{-2} a^{-1} (i.e., GLU 323 – 466; GLU143 – 398; GLU123 – 271 t km^{-2} a^{-1}, respectively).

Table 4-3. GLUs with the highest hillslope sediment production.

Unit	Maximum unit hillslope sediment production by GLU		Maximum total hillslope sediment production by GLU	
	GLU	Unit sediment production (t km^{-2} a^{-1})	GLU	Total sediment production (t a^{-1})
San Geronimo Creek	323	466	143	905
Lagunitas Creek (San Geronimo Cr to Devils Gulch)	323	466	233	382
Devils Gulch	323	466	143	201
Lagunitas Creek (Devils Gulch to Nicasio Creek)	323	466	143	825
Regulated Nicasio Creek	323	466	123	123
Lagunitas Creek (Nicasio Cr to Pt. Reyes Station)	323	466	123	248

Regarding channel bank erosion, a different pattern emerges. In the tributaries (1st to 3rd order channels), unit length erosion is commonly at maximum in headwater channels with shrub-forest land cover on Franciscan mélange (Table 4-4). One exception occurs in the lower watershed areas where forested (>50% canopy) land covers are highlighted, presumably in part because of its common occurrence: forested Franciscan first-order channels account for over 36% of all first-order channels (Table 3-15). The other exception occurs in the San Geronimo watershed where unit rates are highest in 2nd order urban channels on Franciscan mélange, an infrequently occurring channel GLU. In mainstem (4th to 6th order) channels, highest erosion rates occur generally under forest land cover and Quaternary alluvium except in the steeper valleys of Lagunitas Creek above Devils Gulch and Devils Gulch itself where mainstem channel border Franciscan mélange.

In the tributaries, channel GLU delivery rates range from 0 to 0.139 t m^{-1} a^{-1}, with all but two in the range 0.003 – 0.060 t m^{-1} a^{-1}. The two highest values, both on Franciscan mélange, involve 1st order channels with shrub land cover (0.108 t m^{-1} a^{-1}), and 2nd order channels with urban land cover (0.139 t m^{-1} a^{-1}): see Table 4-4. Mainstem delivery rates range from 0 to 0.166 t m^{-1} a^{-1}, with all but three in the range 0.001–0.030 t m^{-1} a^{-1}. The highest rates occurs along mainstem Lagunitas downstream of Nicasio Creek, the second highest (0.058 t m^{-1} a^{-1}) along mainstem San Geronimo Creek, and the third along mainstem Devils Gulch (0.032 t m^{-1} a^{-1}).

Table 4-4. GLUs with the highest bank erosion sediment production.

Unit	Maximum unit tributary sediment production by channel GLU		Maximum unit mainstem sediment production by channel GLU	
	Channel GLU	**Weighted production rate (t m^{-1} a^{-1})**	**Channel GLU**	**Weighted production rate (t m^{-1} a^{-1})**
San Geronimo Cr	Urban, Franciscan, 2nd order	0.139	Forest, Quaternary, 4th order	0.058
Lagunitas Cr (San Geronimo Cr to Devils Gulch)	Shrub, Franciscan 1st order	0.108	Forest, Franciscan, 5th order	0.016
Devils Gulch	Shrub, Franciscan, 1st order	0.108	Forest, Franciscan, 4th order	0.032
Lagunitas Cr (Devils Gulch to Nicasio Cr)	Shrub, Franciscan, 1st order	0.108	Forest, Quaternary, 5th order	0.022
Regulated Nicasio Cr	Forest, Franciscan, 1st order	0.045	Forest, Quaternary, 6th order	0.011
Lagunitas Cr (Nicasio Cr to Pt. Reyes Station)	Forest, Franciscan, 1st order	0.108	Shrub, Quaternary 6th order	0.166

4.1.3 Fine sediment source areas and dynamics

Fine sediment (<2 mm) within the Lagunitas Creek watershed has been identified as a factor affecting important biological processes. Fine sediment production within the study area sub-watersheds was assessed by assigning a percent fines value for each GLU and compiling these values for each sub-watershed to determine an average percent fines produced (and subsequently delivered to the mainstem channel) from hillslope and bank erosion only (Table 4-5). The percent fines values assigned to the GLUs were derived from laboratory analysis of field samples from individual GLUs and, where field samples were not taken, from field estimates of percent fines within observed eroding areas. The percent fines values from field samples range from 14% to 95%. Overall, sediment production from hillslope and tributary bank erosion is approximately 60% fine sediment in the San Geronimo Creek watershed, approximately 55% fine sediment in the Lagunitas Creek watershed from Peters Dam to Devils Gulch, approximately 50% fine sediment in the Devils Gulch sub-watershed, approximately 55% fine sediment in the Lagunitas Creek watershed from Devils Gulch to Nicasio Creek, and approximately 55% fine sediment in the Lagunitas Creek sub-watershed from Nicasio Creek to Pt. Reyes Station. These results fit the overall conceptual understanding of the watershed in that, on average, the San Geronimo sub-watersheds produce the finer sediment fraction that is delivered to mainstem Lagunitas and that Lagunitas/Devils Gulch sub-watersheds produce the coarser sediment fraction that is delivered to mainstem Lagunitas.

Compiled by sub-watershed, the highest yielding sub-watersheds are also the largest. Total fine sediment yields from hillslope and tributary bank erosion are over 250 t a^{-1} in five sub-watersheds, with a maximum of over 430 t a^{-1} in Arroyo Creek (sub-watershed #10; 3rd largest by area), followed by San Geronimo Creek headwaters (#16; largest area), Woodacre Creek (#27; 2nd largest), Cheda Creek (#51; 5th largest) and the Devils Gulch headwaters (#1; 6th largest).

By rate, fine sediment production rates range from 10 to 238 t km^{-2} a^{-1} (sub-watersheds 36 and 15, respectively). Two sub-watersheds have rates over 200 t km^{-2} a^{-1} (#15 and #23 Deer Camp Creek) and three others over 150 t km^{-2} a^{-1} (#24 Willis Evans Creek, #9 and #14): all occur in the San Geronimo watershed. Of note, the ten largest sub-watersheds for total fine sediment are also in the top twenty for unit rates: the majority produce between 100 and 125 t km^{-2} a^{-1}, with sub-watershed #25, Creamery Creek in the San Geronimo watershed, producing over 140 t km^{-2} a^{-1}.

Table 4-5. Categorization of fine sediment production by sub-watershed.

Unit	Sub-watershed ID	Hillslope sediment yield (t a^{-1})	Percent fine sediment	Hillslope fine sediment yield (t a^{-1})	Tributary bank sediment yield (t a^{-1})	Percent fine sediment	Tributary bank fine sediment yield (t a^{-1})
San Geronimo Creek	16 San Geronimo Creek headwaters	431	53	229	313	56	176
	27 Woodacre Creek	218	57	123	483	52	252
	29	16	53	9	1	65	1
	30	5	55	3	0	61	0
	11	73	52	37	72	53	38
	24 Willis Evans Creek	55	61	33	195	64	124
	33	91	53	48	8	58	5
	23 Deer Camp Creek	22	68	15	110	68	75
	31	17	69	12	15	63	9
	25 Creamery Creek	58	64	37	195	65	126
	32	2	54	1	0	69	0
	22 Sylvestris Creek	28	58	16	86	54	46
	35	19	61	12	24	62	15
	8 Larsen Creek	202	51	104	150	54	80
	34	28	52	14	6	57	4
	7 Clear Creek	82	53	44	103	56	58
	9	16	57	9	61	65	39
	36	6	58	3	2	56	1
	19 Montezuma Creek	46	56	26	150	52	78
	18	26	55	14	76	47	36
	10 Arroyo Creek	252	59	148	466	61	285
	13	12	65	8	40	67	27
	15	11	67	7	64	68	43
	14	52	59	31	96	59	56
	37	44	55	24	6	27	2
	21	25	51	13	73	57	42
Lagunitas Creek (San Geronimo Creek to Devils Gulch)	39	53	59	31	7	39	3
	40	57	54	31	41	51	21
	26	69	54	37	86	51	44
	38	180	57	102	37	37	14
	20	69	54	37	73	51	37
	6 Barnabe Creek	60	58	34	22	27	6
	17 Irving Creek	62	56	35	51	56	28
	12	124	57	71	123	57	70
	5 Deadman's Creek	30	57	17	16	32	5
Devils Gulch	1	235	51	121	293	53	157
	2	74	52	38	108	50	54
	3 Devils Gulch mainstem	214	54	115	134	47	64

Unit	Sub-watershed ID	Hillslope sediment yield (t a^{-1})	Percent fine sediment	Hillslope fine sediment yield (t a^{-1})	Tributary bank sediment yield (t a^{-1})	Percent fine sediment	Tributary bank fine sediment yield (t a^{-1})
Lagunitas Creek (Devils Gulch to Nicasio Creek)	4	21	56	12	0	N/A	0
	66	13	56	7	23	53	12
	56	8	56	4	15	58	9
	55	10	52	5	31	55	17
	72	24	52	13	0	N/A	0
	71	9	54	5	0	N/A	0
	54	68	53	36	63	55	35
	51 Cheda Creek	346	53	184	295	54	160
	44	66	50	33	48	52	25
	73	100	50	50	32	52	17
	53	65	51	33	52	54	29
	50 McIssac's Creek	147	53	77	105	52	55
	67	27	56	15	14	56	8
	68	66	49	32	16	52	8
	52	48	52	25	32	53	17
	48	163	53	85	146	52	76
	70	59	54	32	48	56	27
	69	108	51	55	39	52	20
	49	29	52	15	9	56	5
	65	11	51	5	0	56	0
	47	45	53	24	24	56	13
Regulated Nicasio Creek	45 Nicasio Creek	109	50	54	30	36	11
	64 Nicasio Creek	70	59	41	6	32	2
Lagunitas Creek (Nicasio Creek to Pt. Reyes Station)	62	59	51	30	18	54	10
	63	149	62	93	35	43	15
	42	206	53	108	152	53	81
	57	0	83	0	0	N/A	0
	58	2	51	1	1	69	1
	43	75	52	39	40	52	21
	46	19	51	10	27	57	15

4.2 Comparative Average Annual Sediment Yields

The study area encompasses three gauging station locations from which average annual sediment transport rates have been estimated, and which can be compared against rates obtained from field survey and extrapolated using by GLU. The gauging station estimates are an independent check on the adequacy of the sediment delivery estimate determined from field survey and extrapolated via GLUs (acknowledging that the gauge estimates themselves are likely to underestimate total sediment yield, see section 3.3.1). A further independent check is provided by comparing the extrapolated field survey data to rates of reservoir sedimentation into Nicasio Reservoir estimated using bathymetric survey (section 3.3.2). Comparisons are provided in Table 4-6.

In general the data indicate a reasonably good match between sediment yield data estimated from flow gauges and bathymetry surveys and the sediment delivery estimated from extrapolated field evidence and models (but see below). Extrapolated field data is 166%, 282% and 114% of the SGC, SPT and PRS gauging station data, respectively, and 69% and 81% of the bathymetric survey data. Note that because each estimation method may have significant error associated with it, differences between paired values may simply reflect intrinsic errors associated with the mechanics of estimation in each case. Likewise, the general agreement between paired values may simply reflect spurious correlations, but the general agreement for the methods, especially for the larger contributing areas, would suggest otherwise. In particular, the GLU estimates for the Nicasio watershed are fully extrapolated from data collected elsewhere in the Lagunitas watershed, so providing some confidence in the robustness of the GLUs, in addition to the favorable sub-watershed yield comparisons highlighted in Section 4.1.1. Other accuracy considerations are discussed later but it should be noted that techniques reported here are refinements from those reported in Stillwater Sciences (2007) in which several limitations of the initial data set have been addressed.

As unit rates, the results illustrate a three-fold difference between the lowest estimate rate, just over 130 t km^{-2} a^{-1} using SPT gauge data to over 460 t km^{-2} a^{-1} achieved by bathymetry surveys of the Nicasio/Halleck Creek arm of the Nicasio Reservoir. This spread is halved using the next lowest and highest estimate: namely 231 t km^{-2} a^{-1} at the SGC gauge to 383 t km^{-2} a^{-1} using the GLU extrapolation for the SGC gauging area. Differences in estimates represent some combination of real geographic differences in sediment yields and technique-based errors associated with each of the estimation techniques.

The five GLU-based rates of sediment yield range from 285 – 383 t km^{-2} a^{-1} and obviously represent a somewhat conservative range when a variety of individual GLU-based rates are agglomerated over significant spatial extents. For context (and see section 4.1.2), the range of units values contained within the hillslope GLUs ranges from 0 to a maximum of 466 t km^{-2} a^{-1} (highlighted in Table 4-3) for discrete hillslope production sources only (delivery averages 67%), with most hillslope GLU rates in the range 10-200 t km^{-2} a^{-1} and three over 250 t km^{-2} a^{-1}. Soil creep on average adds 4 t km^{-2} a^{-1} and roads and trails add on average 32 t km^{-2} a^{-1} but up to 64 t km^{-2} a^{-1} in the San Geronimo Creek watershed which has a greater density of roads. Tributary bank and bed erosion adds an average equivalent of 133 t km^{-2} a^{-1} ranging from 46 t km^{-2} a^{-1} in regulated Nicasio Creek to 172 t km^{-2} a^{-1} in San Geronimo Creek, and mainstem bed and bank erosion adds on average 61 t km^{-2} a^{-1} with a maximum of 374 t km^{-2} a^{-1} in regulated Nicasio Creek to a minimum of 82 t km^{-2} a^{-1} of channel *aggradation* (i.e., -82 t km^{-2} a^{-1}) in the reach of Lagunitas Creek between Devils Gulch and Nicasio Creek. (Values are derived from Table 4-1).

As a watershed-scale comparison, rates can be compared with estimates of sedimentation into Tomales Bay (e.g., Neimi and Hall 1996, Rooney and Smith 1999). Rooney and Smith (1999, interpreted from their Figure 3) estimate contemporary (1957–1994) rates of sedimentation into the southernmost part of Tomales Bay (i.e., that part near the mouth of Lagunitas Creek) of approximately 190 t km^{-2} a^{-1}, reduced progressively from a historical maximum of 325 t km^{-2} a^{-1} achieved in the period 1861-1931 and 290 t km^{-2} a^{-1} from 1931 to 1957. Rooney and Smith's 1957–1994 rate encompasses the progressive damming of Lagunitas Creek but it also encompasses the relatively "dry" period until to the 1970s (Inman and Jenkins 1999) and misses a number of large storm events since the mid-1990s. As such, it seems reasonable to assume that the 190 t km^{-2} a^{-1} rate underestimates the contemporary rate of sediment delivery. Also, as the Tomales Bay shoreline prograded primarily in the period 1862–1918 (Niemi and Hall 1996), it seems reasonable to assume that the current sedimentation rates in the southern end of Tomales

Bay are far less than 100% efficient at trapping incoming sediment, further indicating that the 190 t km^{-2} a^{-1} rate is a minimum. A third factor is that this sedimentation rate encompasses sediment both from Lagunitas and Olema Creek and the balance of sediment from these two sources in unclear: Olema Creek was subject to significant incision following channelization of the lower creek (Niemi and Hall 1996), and so the relative effect on the 190 t km^{-2} a^{-1} rate is unknown. Another comparison can be obtained with Redwood Creek (22.7 km^2) to the south of Lagunitas Creek, where an estimated contemporary (1981–2002) sediment yield of 198 t km^{-2} a^{-1} was reduced from historical high yield rates of 304 t km^{-2} a^{-1} (1841–1920) and 324 t km^{-2} a^{-1} (1921–1980) (Stillwater Sciences 2004). Redwood Creek is also highly incised, like Lagunitas Creek (so also minimizing the opportunity for overbank sediment storage), but the watershed is almost entirely under conservation land uses and so, in relation to Lagunitas Creek, sediment yield expectations for Lagunitas Creek are perhaps more aligned with Redwood Creek's historical values in excess of 300 t km^{-2} a^{-1} than with the contemporary rate of just under 200 t km^{-2} a^{-1}.

Table 4-6. Comparison of sediment delivery and sediment yield information.

Watershed	Contributing drainage area	Sediment yield derived from sediment rating data	Unit rate	Bathymetry survey estimate	Unit rate	Sediment delivery estimated from extrapolated field survey	Unit rate
	km^2	WY 1983–2008 $t\ a^{-1}$	$t\ km^{-2}\ a^{-1}$	WY 1961–2008[a] WY 1961–1976[b]	$t\ km^{-2}\ a^{-1}$	WY 1983–2008 $t\ a^{-1}$	$t\ km^{-2}\ a^{-1}$
San Geronimo Creek at Lagunitas Road bridge	23.1	5,337	231	n/a		8,851	383
Lagunitas Creek at Samuel P. Taylor State Park	32.7	4,272	131	n/a		12,331	377
Lagunitas Creek at Pt. Reyes Station	62.4	17,224	276	n/a		19,699	316
Nicasio/Halleck Creek arm	54.9	n/a		25,500 [a]	464	17,553	320
Entire Nicasio Reservoir (u/s of Seeger Dam)	93.2	n/a		32,640 [b]	350	26,595	285

4.3 Average Annual Sediment Budget 1983-2008

Figures 4-1 and 4-2 depict the contemporary sediment budget for Lagunitas Creek watershed in terms of geographical yield (from Table 4-7, below) and process rates (Table 4-1), respectively. For illustration, the uncorroborated sediment yield estimate for Upper Lagunitas Creek (Section 3.3.3 – 313 t km^{-2} a^{-1}) is included in Figure 4-1. The schematic figures suggest a watershed characterized largely by sediment sources (entry arrows) rather than sediment storage (exit arrows), relative to some previously published sediment budgets. This situation arises primarily from field and survey evidence for mainstem and tributary incision and bank erosion in the Lagunitas watershed over the period of record. While bed incision and bank erosion cannot continue indefinitely and is difficult to bound temporally, and so could be overestimated in the sediment budget, the result suggests a reasonable response of the watershed to a condition of significant flow regulation and increasing urban area. The difference between the yield from hillslope slides, gullies, and soil creep (production and diffusion) at approximately 8,200 t a^{-1}, and the apparent watershed yield total of just over 20,000 t a^{-1} is one indication of the short-term sediment disequilibrium in the watershed. Over geologic time, rates of soil production in natural systems without rapidly changing base level control are usually inferred to be in approximate equilibrium with sediment yield, that is, sediment input equals sediment output without net change in storage. Therefore, the inference from our sediment budget (Figure 4-2) (and assuming hillslope processes to be operating at near-natural rates) is that the annual loss of approximately 12,000 tonnes of rock, colluvium and alluvium occurs in the watershed represents one measure of contemporary human impacts on geomorphic processes. In the absence of the dams, that is, with the delivery of the sediments produced upstream of Seegar and Peters dams (see Figure 4-1), there would far larger volumes of sediment passing through the watershed that would presumably result in continued rapid sedimentation into Tomales Bay, similar perhaps to the early phases of Euro-American settlement of the watershed (Niemi and Hall 1996, Rooney and Smith 1999). This would be consistent with notions of accelerated sediment production due to land cover changes and surface disturbances brought about by human activity. However, it would probably also prevent observed channel incision and result in additional sediment going into overbank storage in the lower watershed (such as in nearby Stemple Creek, Ritchie et al. 2004) unless channels were straightened and embanked.

Table 4-7. Summary of sediment production and delivery.

Unit	Mainstem channel (m)	Watershed area (km^2)	Hillslope and tributary sediment yield		Mainstem sediment yield		Total Yield
			t a^{-1}	t km^{-2} a^{-1}	t a^{-1}	t km^{-2} a^{-1}	t km^{-2} a^{-1}
San Geronimo Creek (SGC)	6,227	24.3	7,688	316	1,668	69	385
Lagunitas Creek: SGC to Devils Gulch	4,930	8.8	1,811	206	1,249	142	348
Devils Gulch (DG)	2,448	7.0	1,586	227	295	42	269
Lagunitas Creek: DG to Nicasio Creek	7,640	14.9	3,193	214	-1,218[a]	-82[a]	133
Regulated Nicasio Creek (NC)	1,921	2.3	293	129	849	374	503
Lagunitas Creek (NC to Pt. Reyes Station)	2,430	7.1	1,608	227	1,113	157	384

[a] Negative values indicate net sediment accumulation/deposition.

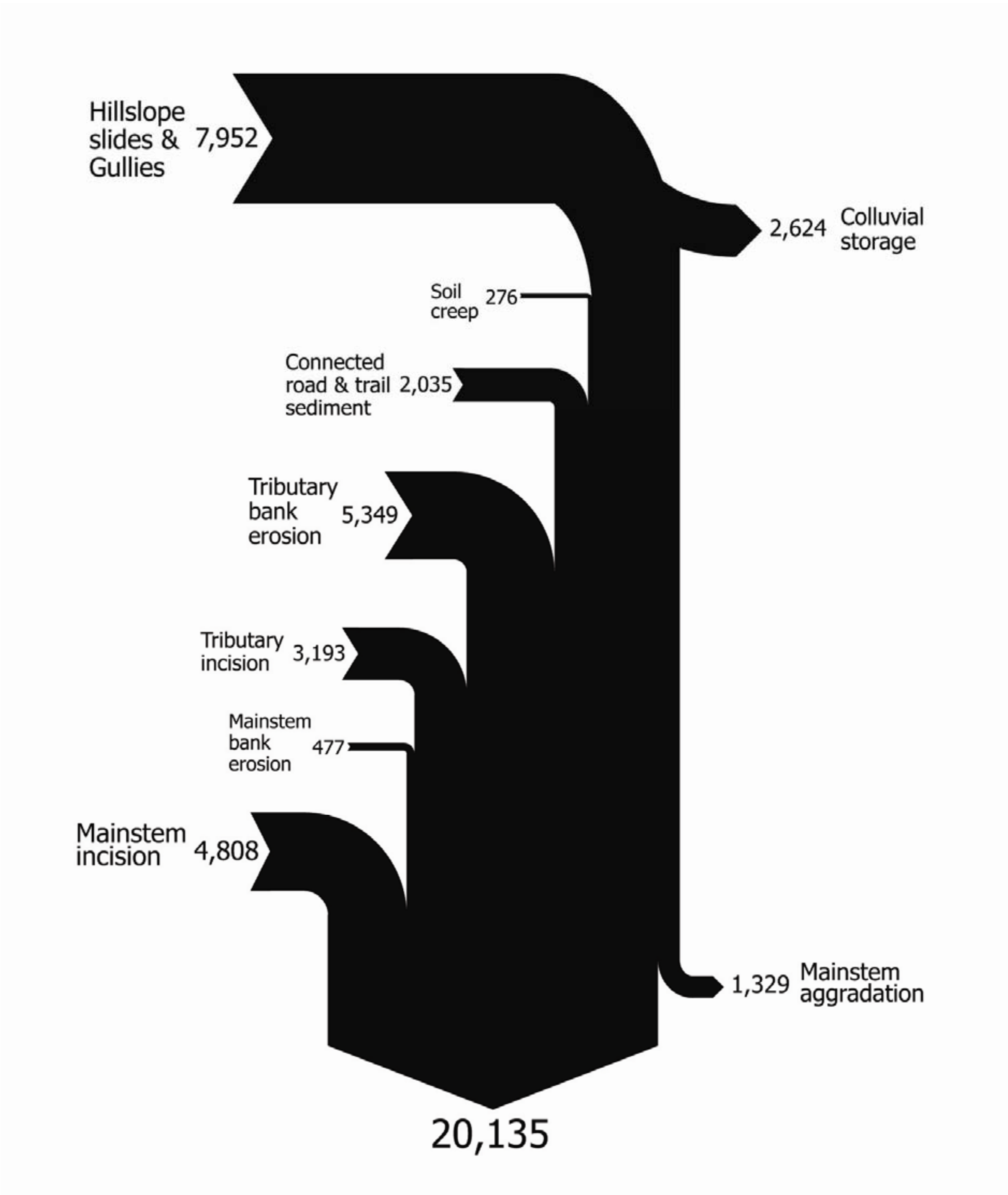

Figure 4-2. Schematic description of sediment source mechanisms in the Lagunitas Creek watershed study area (t a^{-1}).

4.4 Inter-annual Variability in Sediment Transport

High inter-annual variability in sediment delivery is expected because sediment delivery and transport processes are highly non-linear in response to varying year-on-year discharges and, for bed load sediment transport, also require a threshold discharge to entrain bed sediments. Because inter-annual variability in rates of sediment production and delivery from hillslope and discrete erosion sources require very intensive monitoring (with the exception perhaps of landslides which can be related to threshold rainfall amounts and durations), using gauge records is the most feasible means of evaluating variability. Also, in highly regulated watersheds such as Lagunitas, a further threshold situation occurs whereby only in very wet years are flows incoming to reservoirs sufficient to require an “involuntary” downstream flow release and so inter-annual variability in sediment transport is even more pronounced. Annual sediment load statistics from the three gauging stations are provided in Figures 4-3 to 4-5.

In summary, sediment loads in SGC (average 5,337 t a^{-1}) have varied over the period of record from almost zero in very low flow years to >35,000 tonnes during the wet water year of 1986. Sediment loads through SPT (average 4,272 t a^{-1}) vary from almost zero to over 30,000 tonnes during WY2006 when large flow releases were necessary from Kent Lake. In both cases, the highest annual sediment load is approximately double the second highest load, emphasizing the importance of sediment sampling during high flow events to ensure accuracy in sediment transport records. Annual loads through PRS are less variable by year and, from an average of 17,224 t a^{-1}, have exceeded 50,000 tonnes on three occasions (WY 1995, 1998, 2006), achieving over 60,000 tonnes in 1998. Considering that many of these flows presumably emanate as clear-water releases from Nicasio Reservoir, this both emphasizes the ability of the lower Lagunitas Creek to transport sediment more regularly, and may explain the accentuated channel erosion tendency seen in the regulated section of Nicasio Creek and downstream.

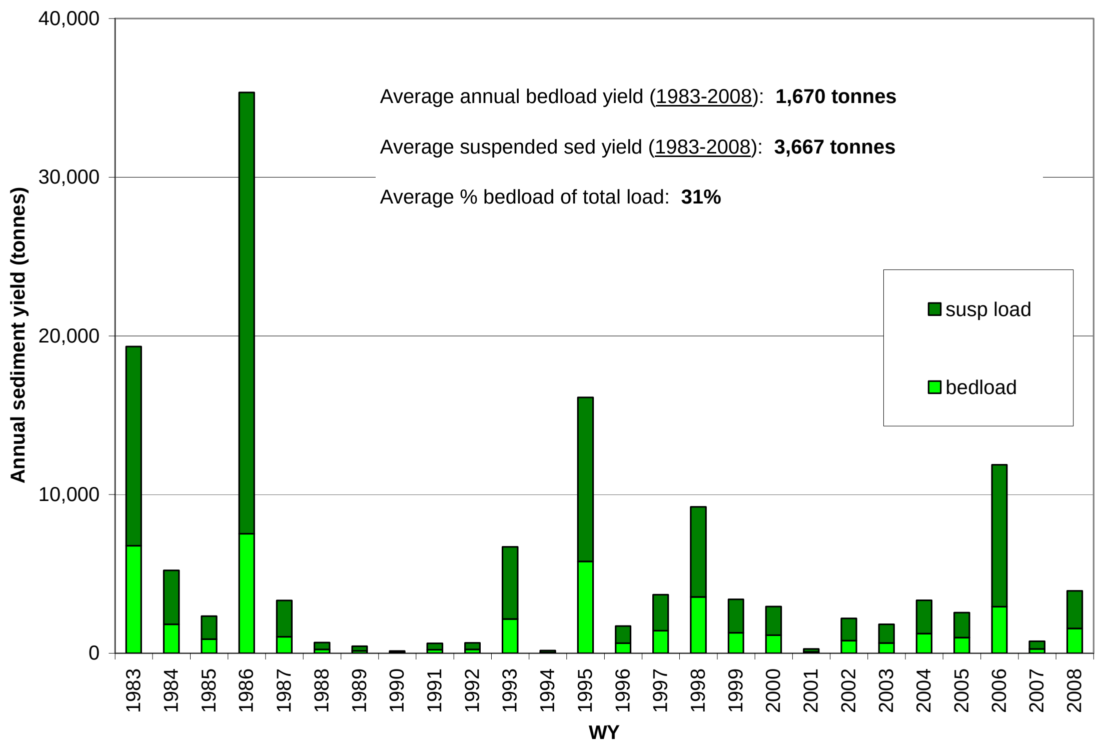

Figure 4-3. Annual total sediment yield for San Geronimo Creek at Lagunitas Rd bridge (MMWD gauge).

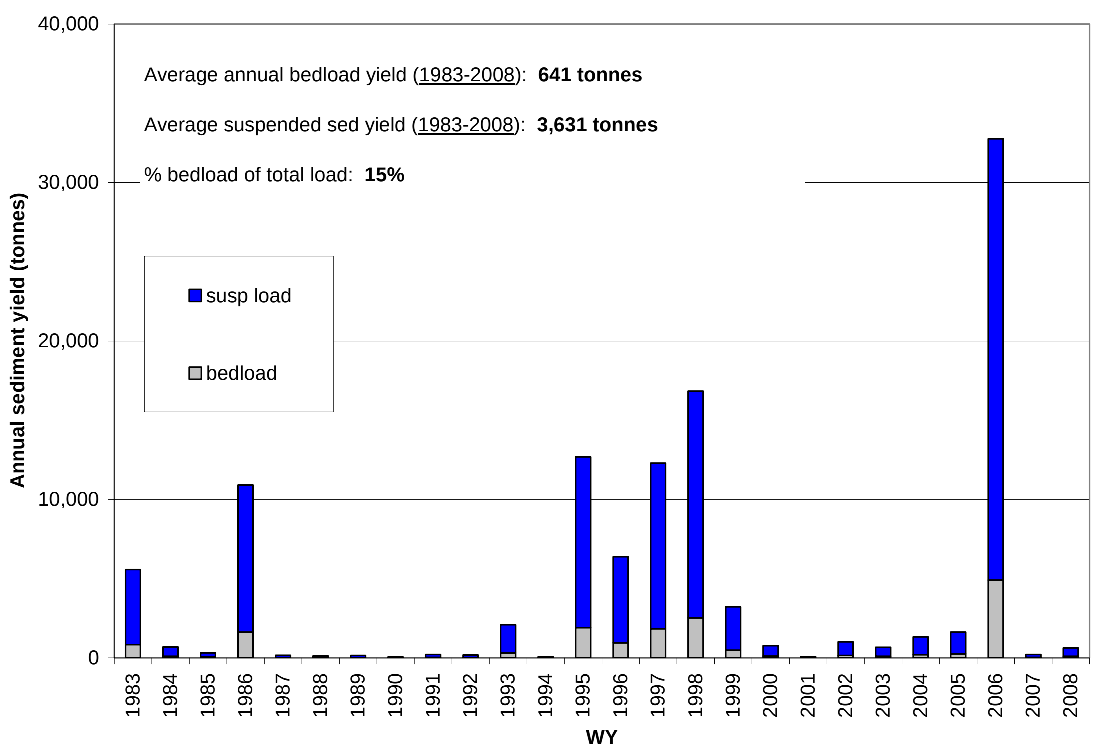

Figure 4-4. Annual total sediment yield for Lagunitas Creek at Samuel P. Taylor State Park (USGS gauge 11460400).

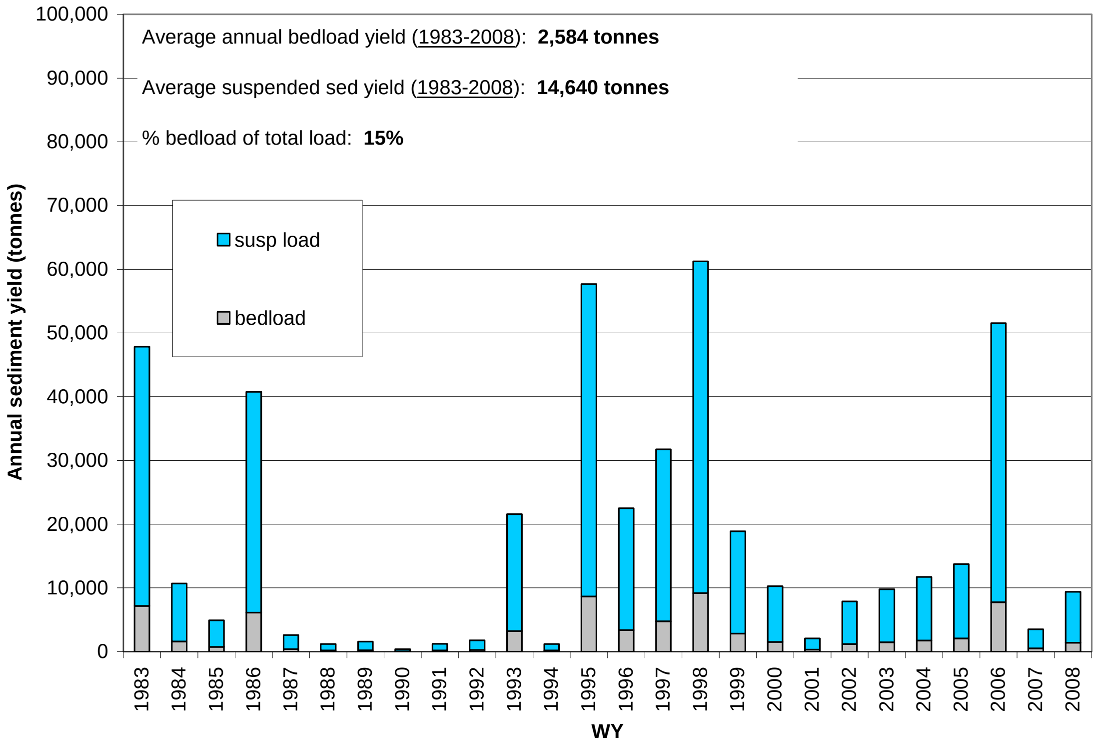

Figure 4-5. Annual total sediment yield for Lagunitas Creek at Pt. Reyes Station (USGS gauge 11460600).

5 MANAGEMENT IMPLICATIONS

5.1 Future Condition Scenarios

To increase the resolution of understanding of sediment flux dynamics in the mainstem Lagunitas Creek and San Geronimo Creek, and as an aid to predicting future conditions, a recently-developed numerical sediment transport model called TUGS (The Unified Gravel Sand model) was used to simulate gravel and sand transport and bed load flux, change in average bed elevation over time, and the fraction of fine sediment in resulting bed deposits (see Appendix A). TUGS model simulates sediment transport within a three-layered domain where a bedload layer is above a sediment deposit that is classified into a coarser surface layer above a subsurface layer (Cui 2007a, 2007b). The model has been rigorously tested against field and laboratory data (see Cui 2007a 2007b; Gomez et al. 2009), and is well suited for use in this channel environment. In summary, the model incorporates:

1. a surface-based bedload equation developed by Wilcock and Crowe (2003) that links local sediment transport capacity to local shear stress and local bed surface grain size distribution;
2. a "gravel transfer function" derived by Hoey and Ferguson (1994) and Toro-Escobar et al. (1996) that links the gravel grain size distribution in the subsurface and surface deposits with bedload;
3. a "sand transfer function" developed by Cui (2007a) that links the sand fraction in the subsurface to sand fraction on the surface;
4. the grain-sized-based Exner equations of sediment continuity, including the abrasion of gravel during transport as proposed by Parker (1991a, 1991b) and used in many subsequent numerical models of sediment transport in gravel-bedded rivers; and
5. equations for open channel flow that provide local shear stress for sediment transport capacity calculations.

The model was used to predict reach-averaged sediment transport dynamics, bed sediment size distribution, and channel aggradation/incision over the recent past from the San Geronimo Creek – Woodacre Creek Confluence downstream to the confluence of Lagunitas Creek with Devil's Gulch, thus encompassing the extent of primary spawning habitat for native salmonids. Model input data includes a time series of daily mean flow, sediment supply data, bed particle size distribution data, and channel elevation data for the individual reaches, details are presented in Appendix A. The model was run for four cycles of the 27-year hydrologic record, repeatedly altering the bed material grain size distribution of the sediment supply (which is largely unknown) until a quasi-equilibrium was achieved in terms of surface and subsurface grain size distributions and the channel long profile. A further two cycles of the hydrologic record was used to simulate current conditions, with the average of the final cycle taken as the current condition status. This final cycle ("Run 1") produced a channel long profile and surface grain size characteristics which compared favorably with the surveyed long profile and available grain size distribution data (see Appendix A). While the channel itself has changed over the last 27 years, achieving a quasi-equilibrium status in the model provides a stable relative basis under which to examine potential channel responses to different sediment management proposals. On average, the study reach surface sand fraction is 6–7% and the subsurface fraction 17–20%.

Four further runs of the model were used to examine two hypothetical sediment management proposals. Run 2 simulated fine sediment reduction by reducing the sand supply from each contributing sub-watershed in the study reach to 70% of its current value, while keeping the gravel supply the same. Runs 3 to 5 simulated gravel augmentation downstream of Peters Dam, where 30, 100, and 300 tonnes per annum are added, respectively, using the same grain size distribution as under current model conditions. Under the fine sediment reduction scenario in Run 2, time- and space-averaged surface sand fractions were reduced by approximately 15%, and subsurface sand fractions by about 3%. Unsurprisingly, the sand fraction reductions under gravel augmentation scenarios are relative to the volume of augmentation. The time- and space-averaged surface sand reduction varies from approximately 1.5 to 14% in Runs 3–5, and the subsurface sand fraction from 0.3–2.7%. Run 5 (300 t a^{-1} gravel augmentation) is markedly more effective than Runs 3 or 4 which augment less material.

Overall, it is apparent that the measures may be effective at significantly changing the surface sand fraction which may have important spawning habitat implications. However, they are far less effective in changing the subsurface sand fraction: this result compares well with experimental studies that have indicated that, because fine sediment does not infiltrate far into the channel bed, the subsurface fine sediment fraction (in this case, sand) is more dependent on initial subsurface grain size distributions than of the characteristics of sediment supply (Wooster et al. 2008). Finally, note that the scenario for fine sediment reduction is achieved without regard for its implementation feasibility. In practice, fine sediment reduction will also cause reductions in coarse sediment supply, and the reductions cannot be achieved evenly between the contributing sub-watersheds. Reduction measures would need to be targeted at those sediment supply sources which preferentially supply fine sediment (e.g., road-related erosion) in areas in which those sources are concentrated (e.g., where road densities are greatest).

5.2 Synthesis: sediment budget and anthropogenic influence in Lagunitas Creek

The sediment budget for Lagunitas Creek illustrates a watershed characterized by largely by sediment sources (contributing over 24,000 t a^{-1}), with far fewer sediment stores (volumetrically 4,000 t a^{-1}) than depicted in many reported sediment budgets. Also, the proportion of channel-derived sediments (nearly 57%) is high relative to hillslope slides, gullies, and soil creep (34%), and higher still when colluvial storage (intercepting one-third of hillslope sediment supply) and channel aggradation (estimated at 10% of channel sediment supply) are considered (Figure 4-2). However, the results appear consistent with the highly regulated flow regime (71% regulated at the downstream Pt. Reyes Station gauge) and urban expansion in San Geronimo Creek both of which should act to promote channel erosion. Further, by our estimates, an additional 44,000 tonnes of sediment produced annually in the upper Lagunitas watershed and in the Nicasio watershed (Figure 4-1) is prevented from entering the middle and lower portion of Lagunitas Creek and undoubtedly changes the dynamics of sediment transfer in these reaches.

Of the contributing source areas, annual sediment production by sub-watershed is generally proportional to contributing area (averaging 100-300 t km^{-2} a^{-1}) and is highest for the sub-watersheds of San Geronimo Creek which, in total, deliver approximately 9,400 t a^{-1} representing 47% of the total sediment yield from 38% of the watershed area. In part, this arises because the density of roads and trails is highest in this sub-watershed and accounts for 17% of the delivered sediment. In general, the contribution from land-based sources is maximized on steep slopes (> 30%) and on agricultural rather than forested lands, irrespective of geology, although forested areas are relatively underrepresented in field survey and aerial photograph analysis. Bank erosion is maximized in first order channels with shrub-forest land cover on Franciscan mélange (0.108 t m^{-1} a^{-1}) due in part to their ubiquity, but rates in the San Geronimo Creek sub-watershed are highest in second order urban channels on Franciscan mélange (0.139 t m^{-1} a^{-1}). Other channel

GLU unit rates are below 0.060 t m^{-1} a^{-1}. Highest mainstem bank erosion unit rates occur downstream of the Nicasio Creek confluence (0.166 t m^{-1} a^{-1}).

Fine sediment (< 2 mm) in field hillslope samples ranged from 14–95%. When extrapolated, fine sediment is approximately 60% of all hillslope sediment produced in the San Geronimo Creek sub-watershed, 50% in Devils Gulch, and 55% elsewhere. Fine sediment production is proportional to sub-watershed area; production rates (10 to 238 t km^{-2} a^{-1}) are generally in the range of 100–125 t km^{-2} a^{-1} with all highest production rates coming from the San Geronimo Creek sub-watershed.

The anthropogenic influence on sediment yields is difficult to quantify but likely pervades all aspects of the sediment budget. With a few exceptions, human activities do not simply add sources or stores of sediment, but act to alter the rates of production, delivery, transport, and deposition from the finite number of geomorphic processes that apply for a particular combination of environment and climate (see Table 3-1). As such, the "background" rate of sediment supply is not obvious. As a surrogate, in nearby Tennessee Valley, the rate of long-term soil production was estimated to be 77–81 m Ma^{-1} or 0.077–0.081 mm a^{-1} based on a combination of theoretical studies and cosmogenic dating (Heimsath et al. 1997, Heimsath 1999). This rate encompasses all hillslope sediment processes and, assuming a weathered bedrock density of 2.2 t m^{-3}, would imply a rate of sediment production of approximately 170 t km^{-2} a^{-1}. This long-term rate encompasses highly infrequent large sediment production episodes, such the excavation of colluvial material from topographic hollows and, further, some of smaller tributaries entering alluvial floodplains may not have delivered sediment directly to San Geronimo or Lagunitas Creek prior to human modification. Consequently, the average annual short-term rate of sediment yield from Lagunitas Creek in the absence of human influence is likely to have been far less than 170 t km^{-2} a^{-1}. In nearby Redwood Creek, the annual sediment yield to Big Lagoon in pre-European times was estimated at the equivalent of approximately 34 t km^{-2} a^{-1}, which compared reasonably well with long-term rates of base-level control provided by sea-level rise (Stillwater Sciences 2004). In comparison we estimate sediment yields to range from approximately 300 t km^{-2} a^{-1} from the regulated Lagunitas watershed to in excess of 400 t km^{-2} a^{-1} in some of the smaller sub-watersheds.

Overall, therefore, the cumulative impact of human activities in the Lagunitas study area is to have increased sediment yields somewhere between double to an order of magnitude over background rates (and see Section 4.3). This cumulative impact arises from a combination of factors including:

- simple discrete increases in supply caused by road-related erosion (approximately 2,000 t a^{-1});
- increases in supply from hillslopes, apparently maximized in areas of agriculture on steeply sloping ground;
- increases caused by extensive erosion of tributary channels, often related to knickpoint-driven headwards extension, and probably involving hydrological feedback processes related to land cover change;
- increases in the sediment delivery ratio from hillslopes to channels caused by increases in drainage density related to tributary erosion and urban drainage networks;
- increases in erosion of mainstem channels related to flow and sediment regime changes caused by flow regulation and urban expansion; and
- increases in the sediment delivery ratio through the mainstem channel network due to disconnection of floodplain access caused by flow regulation and as a consequence of channel incision.

An additional consequence of human activity in increasing sediment yield is generally to alter the grain size distribution of the supplied sediments towards finer sediment. In Lagunitas Creek, this effect is probably the combination of two factors. One is the disconnection of coarse sediment delivery from the steepland areas upstream of Peters Dam. Second is the impact of land cover changes and land use activities that cause increased erosion of land surfaces, especially in San Geronimo Creek where hillslope sediment sample were, on average, finer than in the middle Lagunitas Creek area. Field evidence and numerical modeling suggest that fine sediments derived from road-related erosion, agriculture on steep slopes, and tributary erosion in first-order channels and through second-order urban channels may be the primary areas of concern.

Overall, this sediment budget serves to confirm concerns for the potential degradation of aquatic habitats resulting from high fine sediment contributions from San Geronimo Creek, especially relative to the reduction in coarse sediment delivery from upper Lagunitas Creek caused by disconnecting the sediment supply behind Peters Dam. Notable also is the incision of lower Lagunitas Creek presumed to result from flow and sediment regime changes caused by Nicasio Reservoir: perhaps because of its assumed limited impact on fisheries habitat, this impact has received less attention. Numerical modeling of sediment transport in the mainstem San Geronimo Creek and Lagunitas Creek down to the Devil's Gulch confluence indicates that both reducing fine sediment supply from sub-watersheds or augmenting gravel at the confluence of San Geronimo and Lagunitas creeks may have a significant impact in reducing the fine sediment fraction of the channel bed surface. Neither approach is likely to alter the subsurface sand fraction significantly.

The challenge of fine sediment reduction is to identify a sufficient number of best management practices that can be applied to high fine sediment yielding areas without disrupting coarse sediment supply. Our modeling simulation was based on reducing fine sediment supply to 70% of its current value without regard for the feasibility of this action. Conversely, gravel augmentation is relatively straightforward and its impact is proportional to the volumetric supply rate: from our simulation, a value equivalent to 300 t a^{-1} or more may be required. The influence of 3- to 8-year ENSO cycles in transporting the majority of sediment through Lagunitas Creek means that greater volumes of material could be augmented less frequently for convenience. The other alternative or complementary management approach is to consider measures designed to reduce the degree of incision of Lagunitas Creek and reconnect its floodplain. This would have the potential dual benefit of providing areas for the overbank deposition of fine sediments while reducing the mobility of coarse bed materials by reducing shear stress during high flows.

5.3 Comparison, Accuracy, and Study Limitations

Sediment yield for the Lagunitas Creek watershed is predicted by our study and from gauging station records to be in the range 18,000–20,000 t a^{-1}, giving a unit rate of approximately 300 t km^{-2} a^{-1}. Individually, the GLU-based yields of sediment delivery from Lagunitas Creek are predicted to be in the range of 285–385 t km^{-2} a^{-1}, which is similar although somewhat lower than the corroborating evidence from the limited bathymetric surveys 350–460 t km^{-2} a^{-1}, and slightly higher than the estimate from the downstream gauging station (276 t km^{-2} a^{-1}). The two gauged values from the middle watershed suggest significantly lower unit yields (approximately 130–230 t km^{-2} a^{-1}). Each method has associated errors but the general similarity between the sediment yields achieved at the lowest point of the watershed, and from the independent corroboration of GLU-derived rates with bathymetric survey in the Nicasio sub-watershed suggests some confidence can be attached to the extrapolated rates. By virtue of their extrapolation, the large area unit yields derived from the GLUs are somewhat conservative (285–383 t km^{-2} a^{-1}) in comparison to other data sources, but are generally logical in comparison with rates achieved from surveys of sedimentation in Tomales Bay (Niemi and Hall 1996; Rooney and Smith 1999) and in the context of land use history with yields from neighboring Redwood Creek (Stillwater Sciences 2004). Our GLU-derived estimate decrease downstream as might be expected. Our sub-watershed yields are comparable with small area yields derived from neighboring studies (e.g., Lehre 1982; O'Farrell et al. 2007).

While comparable, the systematic differences between our sediment yield rates relative to the sediment discharge from the three gauging stations (166, 271, and 108%, respectively), and the bathymetric survey (69 and 81%) suggest accuracy issues that do not relate simply to measurement or observation error. In summary, the most likely implications are that:

(1) the gauging station data when converted to a rating curve underestimates sediment yield. The rates are tied to sample measurements but may inherently underestimate rates of sediment transport as a function of their derivation from a rating curve, as long acknowledged in the academic literature (see Section 3.3.1);
(2) our methods systematically over-predict sediment production rates, likely by issues related to extrapolating hillslope erosion source rates into area under canopy, or problems in temporally bounding rates of mainstem or tributary erosion;
(3) our assumed rate of sediment delivery is too high indicating the more material than predicted returns to colluvial storage following production, or;
(4) there are additional stores of in-channel or overbank storage that are not accounted for in the current approach.

The extent to which these matters might be related to sediment dynamics in different parts of the watershed is explored below.

Sediment yields predicted from the tributaries of San Geronimo Creek are approximately 170% of the predicted transport sediment through the San Geronimo Creek gauge. Here, as in almost all areas of Lagunitas Creek except between Devils Gulch and Nicasio Creek, the incising channel morphology argues against significant and increasing overbank sediment stores: there was some indication of vegetated in-channel bars from sediment deposition but available evidence for morphological change did not indicate significant in-channel aggradation. As such, the difference in values is likely to lie in some combination of gauge-based underestimation, and/or an overestimate of sediment production or delivery. Canopy cover in San Geronimo Creek is relatively high, limiting the accuracy of erosion source estimates in these areas, and rates of tributary incision in particular are based on evidence from vegetation and limited structures rather than survey information which may limit their accuracy.

The situation above is more pronounced at the Samuel P. Taylor (SPT) gauge on Lagunitas Creek where the GLU-predicted sediment yield (377 t km^{-2} a^{-1}) is 282% of the gauge value. Here, the prospect of stores of in-channel sediment is given some credibility by the existence of Peters Dam that likely causes Lagunitas Creek below the dam (63% regulated at the gauge) to be "oversized" in relation to its prevailing flow regime. Typically in such cases, while the relatively low sediment concentrations in high discharges promote channel incision, the channel also narrows through lateral bar accretion and sediment stores downstream of unregulated tributary confluences. Limited sediment fingerprinting in the 1980s (Hecht and Enkerboll 1979) concluded that much of the deposited fine sediment in this reach had its origins in the San Geronimo Creek watershed, which would be consistent with this explanation and suggest that the approach herein has underestimated in-channel sediment stores. Downstream of the SPT gauge repeat morphological surveys have documented significant in-channel aggradation (Figures 4-1 and 4-2) as further evidence of the channel's inability to convey an increasing load of sediment from its unregulated tributaries.

At the Pt. Reyes Station (PRS) gauge, the estimates of sediment from gauging and the extrapolated field surveys are within 30 t km^{-2} a^{-1} (Table 4-6). This is all the more remarkable given the very different mainstem dynamics between the SPT gauge to the Nicasio Creek confluence, and downstream of this confluence to the PRS gauge. As noted above, downstream of the SPT gauge the channel has been demonstrated to experience significant in-channel aggradation, which is accommodated in the sediment budget (i.e., results in a far lower sediment yield [133 t km^{-2} a^{-1}] than in other sub-sections of the study area: Table 4-7). But there is also, locally, significant overbank sediment storage but this is not explicitly accounted for in the sediment budget. Below the Nicasio Creek confluence it appears that frequent flow releases from the Nicasio Reservoir are sufficient to provide flows of such magnitude and/or duration to permit both the transport of all upstream sediment and the observed significant incision of the channels of both Nicasio and Lagunitas creeks, despite the extent of regulated watershed at the PRS gauge (71%) being higher than at the SPT gauge. Reference to the annual maximum discharges data in Figure 3-11 through 3-13 indicate that the explanation may lie in the increase in flows between SPT and PRS being +250% for large flood events (i.e., Q_{10}, Q_{50}) driven mainly by the very large discharge through the PRS gauge in the 1982 event. Presumably most of the recent incision in lower Lagunitas Creek can be attributed to this event.

This Lagunitas sediment budget developed from a sediment delivery study of the middle Lagunitas Creek (Stillwater Sciences 2007), and involved an expanded number of data sources and analytical techniques (see Section 3.1) and further field investigation to partially offset limitations inherent to studies based on extrapolation. The resulting sediment yields are comparable to other studies and corroborations herein, and the sediment budget is logical in the context of human activities in the watershed. Both factors provide confidence in the general accuracy of the approach. Based on the discussion above, accuracy might be further improved by:

- additional field study of hillslope sediment sources, focused especially under canopy cover, to further reduce the reliance on data extrapolation;
- examination of hillslope sediment delivery characteristics for a period of years following rainfall of sufficient intensity and duration to cause landslides, to better constrain sediment delivery ratios;
- dedicated field studies to survey long-term channel margin and overbank sediment stores not explicitly enumerated here; and
- long-term studies of channel erosion, focused on monitoring bed and bank erosion in first order channels and bed level changes in mainstem channels (the largest volumetric suppliers to the sediment budget), to better constrain channel supply estimates.

Irrespective of the ability to undertake these studies, this sediment budget has confirmed concerns for the potential degradation of aquatic habitats in the middle Lagunitas Creek and San Geronimo Creek due to human activities in the watershed. Strategic approaches to improving habitat could be based on fine sediment reduction, coarse sediment augmentation, or channel-floodplain reconnection, according to their feasibility and potential impact on factors currently limiting coho salmon and steelhead (Stillwater Sciences 2008). Exploratory sediment transport modeling has indicated that both fine sediment reduction and coarse sediment augmentation may produce significant reductions in the sand fraction of channel bed surface sediments.

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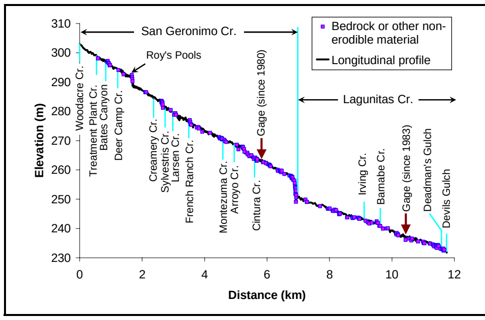
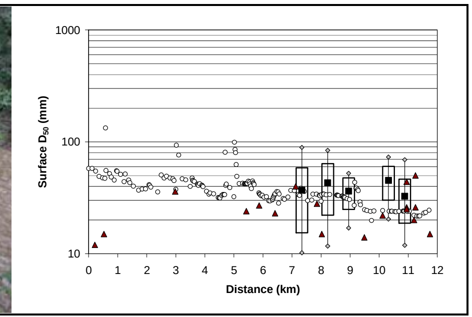
Appendices

Appendix A

Examinations of Potential Channel Responses to Possible Habitat Enhancement Strategies in the Middle Lagunitas Creek Watershed with TUGS Model





Examination of Potential Channel Response to Possible Habitat Enhancement Strategies in the Lagunitas Creek Watershed with TUGS Model

Technical Memorandum

Prepared for
Department of Public Works
Marin County, California

Prepared by
Stillwater Sciences
2855 Telegraph Ave. Suite 400
Berkeley, California

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Stillwater Sciences

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1 INTRODUCTION

It is suggested that the degraded aquatic habitat and declining fish populations in the Lagunitas Creek watershed are associated with "excess" fine sediment contributions primarily from the San Geronimo Creek watershed, particularly when viewed in relation to reductions in the volume of incoming coarse maternal from Lagunitas Creek caused by the existence and subsequent raising of Kent Lake behind Peters Dam in 1982. In this technical memorandum we examine potential channel responses to possible habitat enhancement strategies with a one-dimensional sediment transport model, TUGS. The study reach includes the San Geronimo Creek downstream of Woodacre Creek Confluence and Lagunitas Creek between its confluences with San Geronimo Creek and with Devil's Gulch (Figure 1). Lagunitas Creek upstream of its confluence with San Geronimo Creek is not directly simulated. Instead, flow release from Peters Dam is treated as a point source to the study reach. The model did not extend to downstream of its confluence with Devil's Gulch because (a) relevant information such as channel profile is not available, and (b) the primary spawning habitat is located upstream of the Devil's Gulch confluence. The habitat enhancement strategies examined include: (a) reduction of sediment supply from high fine sediment yield sub-watersheds, and (b) gravel augmentation in the Lagunitas Creek just upstream of its confluence with San Geronimo Creek.

2 OVERVIEW OF TUGS MODEL

TUGS model (short for ***T**he **U**nified **G**ravel-**S**and model*) was developed based on the surface-based bedload equation of Wilcock and Crowe (2003), which calculates the transport of both sand-sized and coarser particles based on the local surface grain size distribution and local shear stress. The Wilcock and Crowe (2003) equation is recognized as the current state-of-the-science sediment transport equation as it calculates sediment transport rate for different grain size groups while considering the interaction of sand and coarser particles. Other than Wilcock and Crowe's (2003) bedload equation, TUGS model also implements the gravel transfer function of Hoey and Ferguson (1994) and Toro-Escobar et al. (1996) developed from flume experimental data, and a sand transfer function developed by Cui (2007a) based on field and experimental data. The gravel and sand transfer functions link the grain size distributions in bedload, surface layer and in subsurface deposits. TUGS model has been examined with flume experimental and field data with satisfactory results, including: the successful reproduction of the observed bed aggradation and downstream fining of three runs of large-scale flume experiments (Cui 2007a); the successful reproduction of the longitudinal profile and general spatial variation of surface and subsurface grain sizes in the Sandy River downstream of former Marmot Dam on the Sandy River, Oregon (Cui 2007b); the successful reproduction of stratified sediment deposit upstream of Marmot Dam (Cui 2007b); and the successful reproduction of bed material grain size distribution and prediction of the general channel aggradation and degradation between 1947 and 2002 in the Waipaoa River, New Zealand (Gomez et al. 2009). Details of the model development and model examinations are not presented here, and interested readers are referred to the original publications (i.e., Cui 2007a,b; Gomez et al. 2009).

Input data for TUGS model include: (a) channel longitudinal profile; (b) bankfull channel width; (c) bed material and surface grain size distributions; (d) water discharge; and (e) sediment supply rate and associated grain size distribution. TUGS model simulates the dynamic response of the channel bed, including bed aggradation and degradation, and evolving grain size distributions of the bed surface and bed material. Here, the surface and bed material grain size distributions include both sand sized and coarser particles which are important parameters for fish habitat evaluation.

3 DATA COMPILATION IN THE STUDY REACH

Stillwater Sciences (2010) provide a comprehensive description of the natural conditions and human disturbance history of the Lagunitas Creek watershed. Below we provide information relevant to the sediment transport modeling work.

3.1 Longitudinal Profile and Channel Dimension of the Study Reach

Longitudinal profile and bankfull channel width of the study reach were surveyed during the summer of 2008. Bed elevation was measured with an autolevel and stadia rod with distance between bed elevations determined with a laser range finder. Bedrock and other non-erodible bed material such as concrete pavement and weirs were identified and documented during the survey. The longitudinal profile of the study reach, along with the identified bedrock exposures, is presented in Figure 2. The frequent bedrock outcropping in the longitudinal profile indicates that the primary control in the present-day study reach is bedrock exposure rather than fluvial transport. The measured bankfull channel widths in the study reach are presented in Figure 3.

3.2 Surface characteristics

Pebble count data from multiple facies were collected in the study reach at five locations in the summer of 2008 (Figure 4). Grain size distributions shown in Figure 4 indicate that there is a relatively large scatter in grain size distributions at the different locations. The large variance of surface grain size is consistent with surface grain size data collected by Balance Hydrologics, Inc. in the study reach over the period of 1979 – 2007 (Owens et al. 2008), as summarized in Figures 5 a through e, and is a normal phenomenon in gravel bedded rivers (e.g., Parker 2008).

3.3 Discharge Records in the Study Reach

Two gauging stations are available in the study reach (Figure 2): the MMWD station in San Geronimo Creek with daily discharge record since 1 October 1979, and USGS station (#11460400) in Lagunitas Creek with daily discharge record since 21 December 1982. Before USGS data collection, Balance Hydrologics, Inc. collected discharge data in Lagunitas Creek starting 1 October 1981. Daily average discharge records for the period of 1 October 1981 and 30 September 2008 at the two stations are presented in Figure 6, and flow duration curve for the two stations for the same time period are presented in Figure 7. Discharge records in Figure 6 indicate that the high flow in Lagunitas and San Geronimo creeks are generally synchronous with one another, and baseflow discharge in Lagunitas Creek is significantly higher than that in San Geronimo Creek. For example, flow in Lagunitas Creek is greater than 1 m^3s^{-1} for almost 20% time but for only 5% of the time in San Geronimo Creek. The discharge records presented in Figure 6 are used as input for TUGS modeling presented later in this memorandum.

3.4 Sediment Delivery to the Study Reach

Annual sediment production in the sub-watersheds that feed into the study reach is summarized in Table 1, using data from the Lagunitas Creek sediment budget (Stillwater Sciences 2010). For modeling purposes, it was assumed that 20% of the sediment production from the San Geronimo Creek sub-watersheds is bedload (sand and gravel) with the exception of the area upstream of Woodacre Creek confluence (discussed below), and 15% of the sediment production from the Lagunitas Creek sub-watersheds is bedload. It was further assumed that there is 70% gravel and 30% sand in the bedload with the grain size distributions provided in Figure 8 based on trial-and-errors to produce reasonable surface grain size distributions compared to observed values. For the area upstream of Woodacre Creek-San Geronimo Creek confluence, using 20% bedload in modeling simulations produced persistent channel aggradation in San Geronimo Creek just downstream of its confluence with Woodacre Creek, and adjusting the fraction of bedload fraction from Woodacre Creek and its north neighbor sub-watershed (ID = 16 in Figure 1) to 10% produced more reasonable results (discussed below). As a result, bedload fraction from these two sub-watersheds was adjusted to 10% for modeling purposes.

Table 1. Sediment production in the study reach.

Sub-watershed Creek	Sub-watershed ID	Sub-watershed Area (km^2)	Sediment Production ($t\ a^{-1}$)
Woodacre Creek	27	3.66	761
Spirit/Flanders/Horse Creek/SG headwaters	16	3.80	692
	29	0.23	34
	30	0.15	14
Treatment Plant Creek	11	0.73	189
Bates Canyon Creek	24	0.87	284
Deer Camp Creek	23	0.38	117
	31	0.39	53
	33	0.85	153
Creamery Creek	25	1.14	280
	32	0.07	5
Sylvestris Creek	22	0.66	167
Larsen Creek	8	1.81	520
	35	0.39	59
	34	0.30	59
Clear Creek	7	0.98	224
	9	0.29	77
	36	0.39	44
Montezuma Creek	19	0.98	273
	18	0.57	139
Arroyo Creek	10	3.49	899
	13	0.24	67
	15	0.21	75
Cintura Creek	14	0.54	157
Unnamed Creek	21	0.62	138
	37	0.63	69
	39	0.43	51
Unnamed Creek	40	0.80	92
Unnamed Creek	26	0.94	125
	38	2.12	247

Sub-watershed Creek	Sub-watershed ID	Sub-watershed Area (km^2)	Sediment Production ($t\ a^{-1}$)
Irving Creek	20	0.96	129
Barnabe Creek	6	0.69	97
	12	1.71	235
Unnamed Creek	17	0.74	98
Dead Man's Gulch	5	0.41	82
Devils Gulch	1	2.50	907
Devils Gulch	2	1.46	323
Devils Gulch	3	3.02	618

4 TUGS SIMULATION: CURRENT CONDITION

TUGS model was set up with the following input data to simulate the current condition: (a) a longitudinal profile within the study reach presented in Figure 2; (b) water discharge series in the study reach, manipulated based on the discharge records presented in Figure 6; (c) gravel and sand supply and their assumed grain size distributions as detailed in Table 1 and Figure 8, respectively; and (d) estimated surface and subsurface grain size distributions within the study reach. Because the study reach is relatively short, abrasion of gravel is not important and we assumed an abrasion coefficient of 0.01 km^{-1} (i.e., 1% of the gravel volume will be lost to abrasion for every 1 km downstream transport). More details of the input data are discussed below.

4.1 Longitudinal Profile

As a requirement for TUGS modeling, bed elevation is broken into two components: a base elevation that marks the non-erodible material (such as bedrock, concrete pavement, or simply a bed elevation deeper than the potential depth of erosion) and a thickness of sediment deposit on top of the base elevation. Base elevations at locations marked as bedrock controls in Figure 2 are set to be identical to current bed elevations, while the initial thicknesses of sediment deposit at these locations are set to zero. At other locations, the thicknesses of sediment deposits are set to a few decimeters to a couple of meters on top of base elevations so that the combination of the thickness of sediment depositions and base elevations are identical to the current bed elevations. The exact settings of base elevations and thicknesses of sediment deposition in places not marked as bedrock control is not important because short-term channel erosion in the study reach is limited due to the frequent bedrock controls.

4.2 Water Discharge

Water discharge at any location within the study reach is manipulated with the discharge data presented in Figure 6 with the assumption that the discharge contribution per unit drainage area is constant throughout the contributing sub-watersheds. More specifically, discharge at any location upstream of the San Geronimo Creek-Lagunitas Creek confluence is calculated with

$$Q_w = \frac{A}{A_{ug}} Q_{wug} \tag{1a}$$

and discharge at any location downstream of the San Geronimo Creek – Lagunitas Creek confluence is calculated with

$$Q_w = \frac{A - A_{dg}}{A_{ug}} Q_{wug} + Q_{udg} \tag{1b}$$

in which Q_w denotes water discharge at any location in the channel within the study reach; A denotes the cumulative drainage area at that location, excluding contribution from the upper Lagunitas Creek (i.e., drainage to Kent Lake); Q_{wug} denotes water discharge at the upstream gauging station (i.e., gauging station located at San Geronimo Creek shown in Figure 2); A_{ug} denotes cumulative drainage area at the upstream gauging station; Q_{wdg} denotes water discharge at the downstream gauging station (i.e., gauging station located at Lagunitas Creek shown in Figure 2); and A_{dg} denotes cumulative drainage area at the downstream gauging station again excluding contributions from the upper Lagunitas Creek.

4.3 Sediment Supply and Associated Grain Size Distribution

As noted previously, average annual sediment supply for TUGS modeling under the current condition is set to be identical to that presented in Table 1. To redistribute the average annual sediment supply to a daily series, it is assumed that sediment supply from any sub-watersheds at any particular day is proportional to daily average discharge at the sub-watersheds to the 2.5 power, so that the sediment supply averaged over the 27-year record period is identical to that provided in Table 1.

Because there is no representative bed material grain size distribution data for sediment supply from the contributing sub-watersheds, we assumed grain size distributions for sand and the coarser sediment. The assumed sand grain size distribution is rather arbitrary. The assumed coarser sediment grain size distribution, however, was adjusted repeatedly until the modeling produced satisfactory results so that the simulated surface characteristics grain sizes (i.e., D_{16}, D_{50}, D_{84}), surface sand fractions and longitudinal profile are in general agreement with field observations (discussed below in Section 4.5).

4.4 Initial Surface and Subsurface Grain Size Distributions

Initial surface and subsurface grain size distributions in the study reach were set somewhat arbitrarily within the observed range shown in Figure 4. TUGS model simulation will adjust the surface and subsurface grain size distributions so that they become consistent with the water discharge series and the rate and grain size distributions of the sediment supply. Because of this adjustment, the exact initial surface and subsurface grain size distributions will only affect how fast the simulation will converge to the final results, which are dependent only on the hydrologic and sediment supply conditions. As a result, the initial surface and subsurface grain size distributions are not presented in this memorandum.

4.5 Simulation Process and Results of Current Conditions

Using the input data discussed above, the model was run repeatedly for 108 years (4 cycles of the 27-year hydrological data series) for the model to adjust the surface and subsurface grain size distributions and the longitudinal profile to achieve a quasi-equilibrium state. Under this quasi-equilibrium state, bed elevation and surface and subsurface grain size distributions may change from year to year in response to the hydrologic and sediment supply conditions, but on a long-term averaged basis, the changes are minimal. Although the study reach may not be in a quasi-equilibrium state due to the large human disturbances (such as the construction of Peters Dam not so long ago), a quasi-equilibrium assumption for modeling allows us to examine the potential relative channel responses if certain restoration measures are implemented.

Upon finishing the 108-year simulation to achieve quasi-equilibrium, the model was run for an additional 54 years (2 cycles of the 27-year hydrologic data) as Run 1, and the averages of the second 27-year simulation results were taken as the final results of the current condition.

Simulated surface characteristic grain sizes D_{16}, D_{50} and D_{84} and surface sand fraction for Run 1 (current condition) are presented in Figures 9a-d, respectively, in comparison with the field data collected by Balance Hydrologics, Inc. (2008), Stillwater Sciences (2005, 2008), and O'Connor (2006). Results in Figure 9 shows that simulated surface characteristic grain sizes and sand fraction generally fall within the observed range except for surface D_{16}, which is slightly under-predicted. The simulated longitudinal profile is provided in Figure 10a in comparison with field survey data, and indicates an almost a perfect match. The simulated subsurface sand fraction is presented in Figure 10b, and the simulated subsurface characteristic grain sizes D_{16}, D_{50} and D_{84} are presented in Figure 10c. No subsurface grain size data are available to compare with the simulation.

5 EXAMINATION OF POTENTIAL HABITAT ENHANCEMENT MEASURES

Following current condition simulation, four runs (Runs 2 through 5) were conducted, examining two hypothetical habitat enhancement measures with the objective of reducing the subsurface fine sediment fraction. The two measures involved (a) a reduction in sand supply (Run 2); and, (b) gravel augmentation (Runs 3 through 5). No feasibility analyses were conducted for the examined measures and the examinations are solely for exploratory purposes to provide interested parties with a basis for further discussions. Specifications of Runs 2 through 5 are provided in Table 2.

Table 2. List of runs examining potential habitat enhancement measures.

Runs	Specifications
Run 2	Sand supply reduced to 70% of its current value from each contributing sub-watershed[a]
Run 3	Gravel augmentation downstream of Peters Dam at 30 metric tons per year[b]
Run 4	Gravel augmentation downstream of Peters Dam at 100 metric tons per year[b]
Run 5	Gravel augmentation downstream of Peters Dam at 300 metric tons per year[b]

[a] Gravel supply at each sub-watershed is assumed to be unchanged;
[b] Assuming augmented gravel has identical grain size distribution to that shown in Figure 7.

The impact on surface and subsurface sand fractions for each of the runs is illustrated in Figures 11 and 12, respectively. Results are shown at six stations downstream of the San Geronimo Creek-Woodacre Creek confluence.

Comparing results for Runs 1 and 2 in Figures 11 and 12 indicates that reducing sand supply by 70% (Run 2) while keeping gravel supply unchanged at each sub-watershed will result in reduction of surface and subsurface sand fraction in the entire modeled reach relative to current conditions. Reducing sand supply while keeping the gravel supply unchanged, however, may be difficult to achieve as most of the sediment reduction measures reduces both gravel and sand supply indiscriminately. Comparing results for Runs 1, 3, 4, and 5 in Figures 11 and 12 indicates that gravel augmentation will result in reduced surface and subsurface sand fractions downstream of the augmentation point, and the benefit in sand fraction reduction increases with the increase of the amount of gravel augmented.

Comparisons are also provided in terms of time-averaged values at the entire modeled reach (Figure 13); averaged in time and space over the entire modeled reach (Figure 14), and averaged in time and over the modeled reach downstream of the gravel augmentation point (Figure 15). Results in Figure 14a indicate that the time- and space-averaged surface sand fraction decreases to 0.056 from 0.066, or approximately 15% of reduction, if sand supply from each sub-watershed is reduced to 70% of its current value. Results in Figure 14b indicate that the time- and space-averaged subsurface sand fraction decreases to 0.153 from 0.158, or approximately 3% of reduction, if sand supply from each sub-watershed is reduced to 70% of its current value. Results in Figure 15a indicates that the time and space-averaged surface sand fraction downstream of the gravel augmentation point is reduced to between 0.059 and 0.068 from the current value of 0.069, or approximately 1.5 to 14% reduction, if different amount of gravel is augmented. Results in Figure 15b indicates that the time and space-averaged subsurface sand fraction downstream of the gravel augmentation point is reduced to between 0.182 and 0.1865 from the current value of 0.187, or approximately 0.3 to 2.7% reduction, if different amount of gravel is augmented. In both potential measures, sand fraction reduction is more significant in surface layer than in the subsurface.

6 DISCUSSION

TUGS model was used to simulate sediment transport dynamics in San Geronimo Creek and the middle Lagunitas Creek using 27 years of hydrologic record and coarse and fine sediment supply rates from the contributing sub-watersheds estimated from sediment budget analyses. With assumed grain size distributions for fine and coarse sediment in sediment supply, the model satisfactorily reproduced the observed longitudinal profile of the entire study reach and the surface characteristic grain sizes D_{16}, D_{50}, D_{84} and surface sand fraction in approximately a 4-km reach near the downstream end of the study reach for which comparison data are available. The good agreement between the simulation and observation suggests that both the sediment budget estimates and the modeling resulting are likely to be reasonable.

As the basis for management discussions, two possible habitat enhancement measures with objectives to reduce fine sediment fractions in bed material are examined with the model without consideration for their implementation feasibility. The first enhancement measure assumes that erosion control measures can reduce sand supply to 70% of its current value from each sub-watershed. Results of this examination indicate that such measures would result in reduced surface and subsurface fine sediment fractions. The second enhancement measure assumes that gravel with the same grain size distribution as the existing sediment supply will be augmented in

Lagunitas Creek just upstream of its confluence with San Geronimo Creek at annual rates of 30, 100, and 300 tonnes. TUGS simulation indicates that this gravel augmentation measure will result in decreased surface and subsurface sand fractions downstream of the augmentation point, and the sand fraction reduction increases with the increase in the amount of gravel augmented.

Because TUGS model is a one-dimensional sediment transport model, it only simulates the reach-averaged sediment transport characteristics (Cui et al. 2008). In the field, however, there is considerable spatial local variance in sediment transport characteristics, including the grain size distributions and fine sediment fractions as evidenced in the field data shown in Figure 5. For surface and subsurface fine sediment fractions, there is relatively less fine sediment in riffles while portions of some of the pools may be completely covered with fine sediment. TUGS cannot simulate which bedforms will have preferentially reduced sand fractions (i.e., whether it is across the board, more at riffles, or more in pools) but it is reasonable to expect that spawning habitat will experience at least some of the benefits.

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Figures

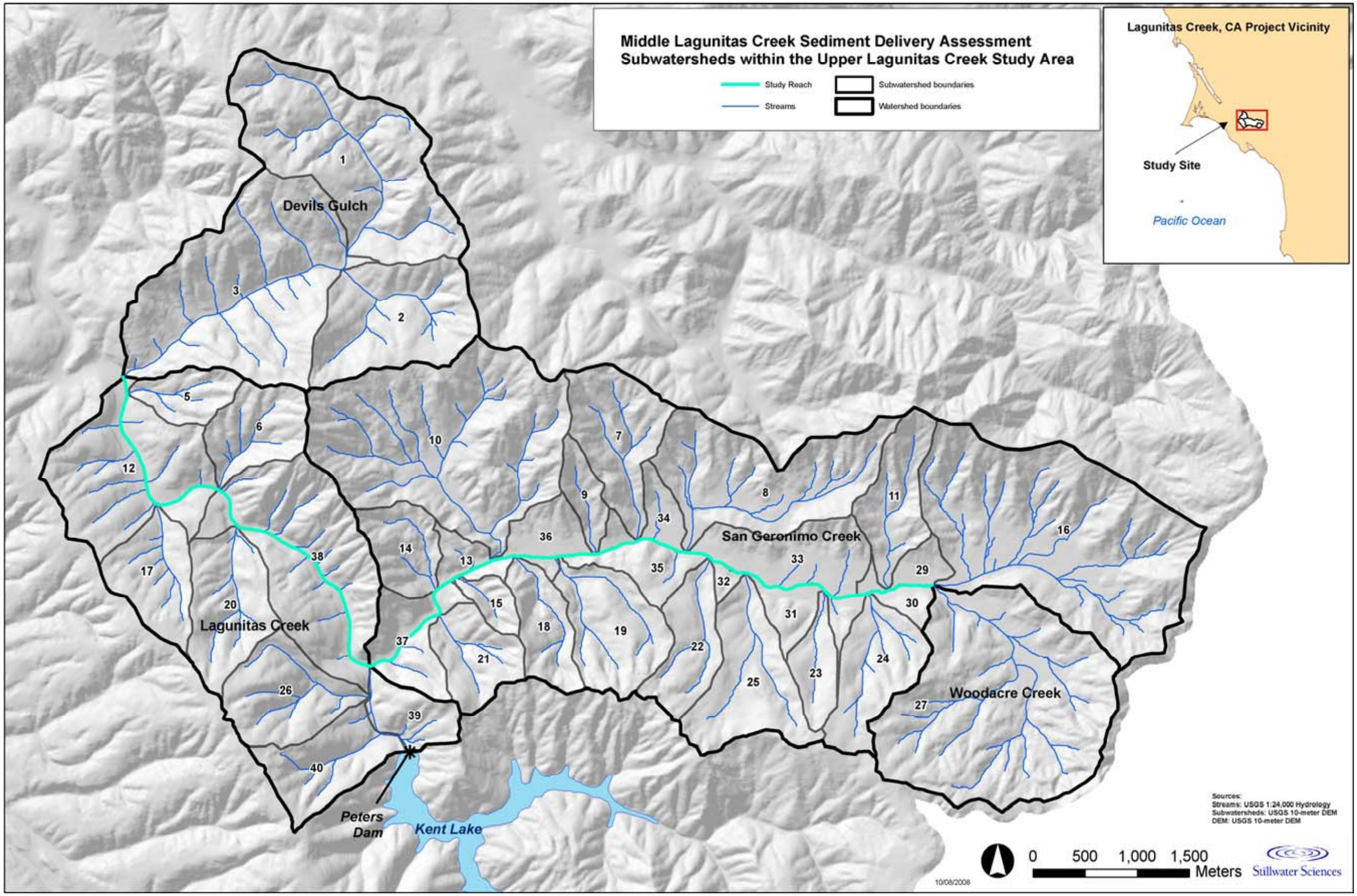

Figure 1. The Middle Lagunitas Creek watershed, showing the study reach for TUGS simulation, showing the study reach and the contributing sub-watersheds. Some of the major sub-watersheds corresponding to the ID number provided in this map are given in Table 1.

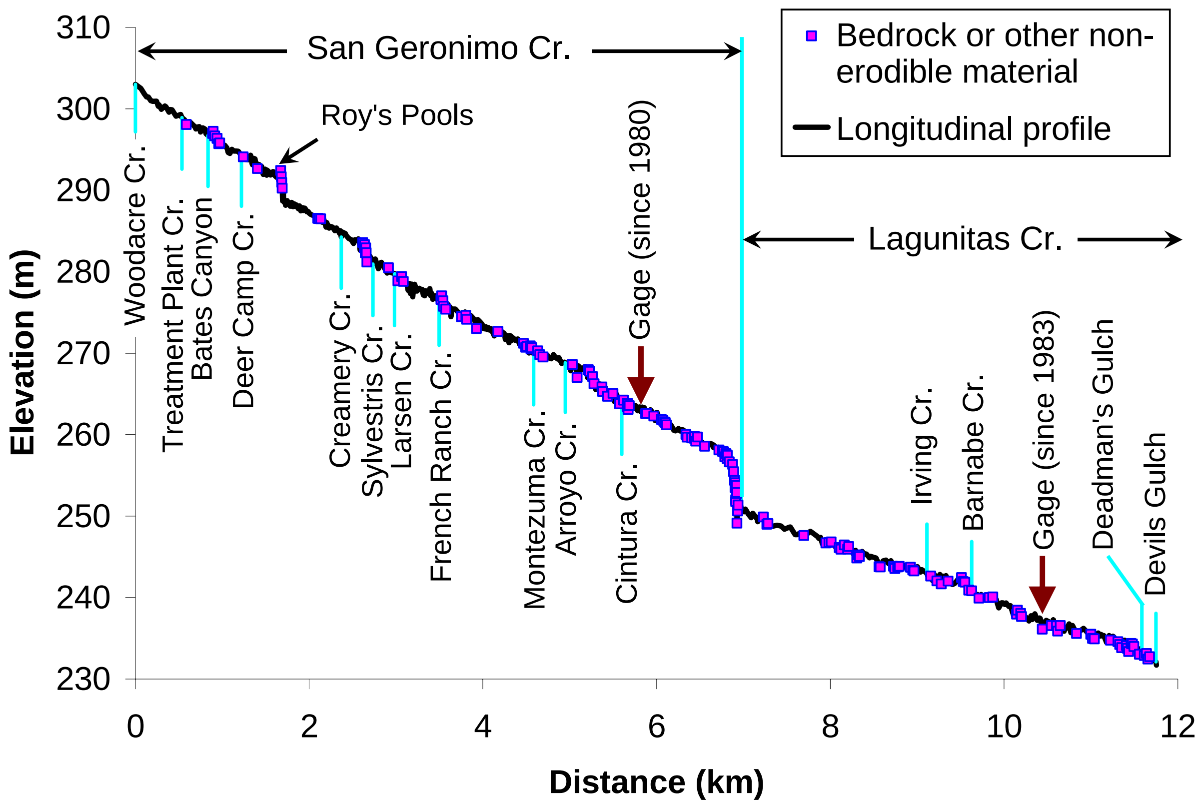

Figure 2. Longitudinal profile of the study reach, showing the major contributing tributaries, gauging locations, and locations of bedrock controls or channel bed with other non-erodible material.

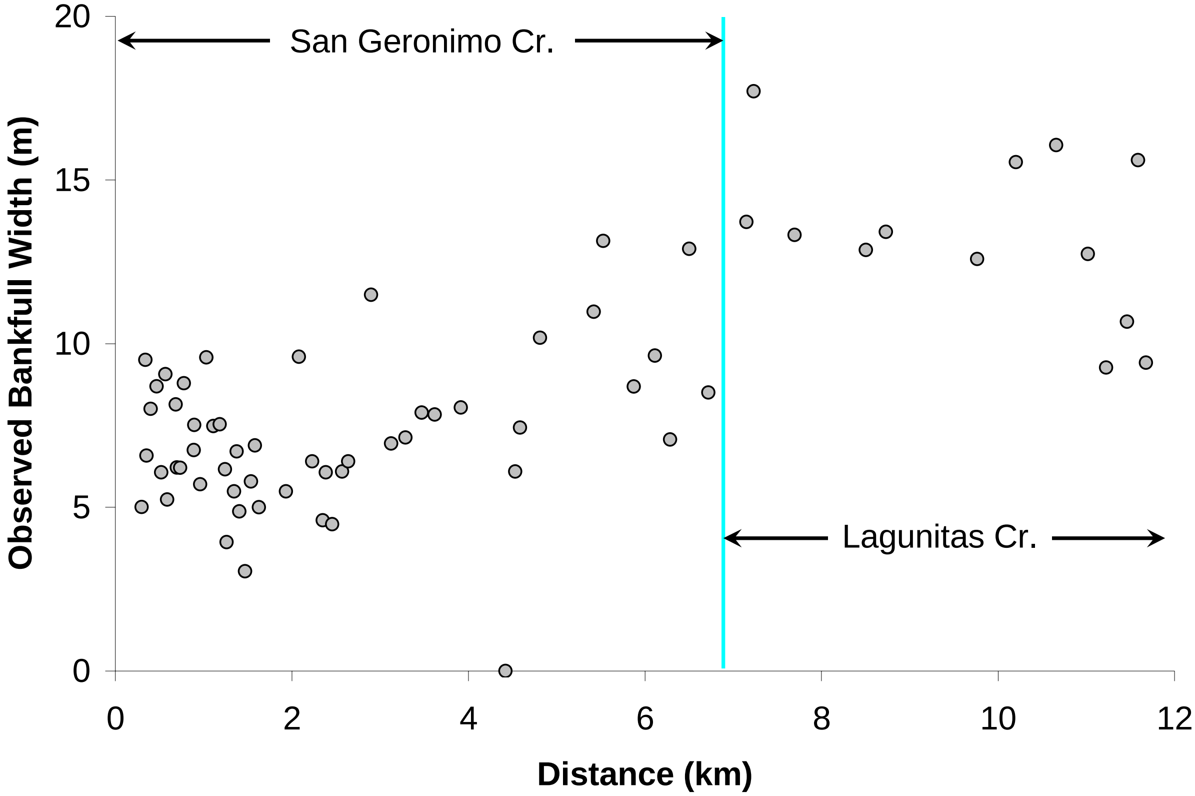

Figure 3. Observed bankfull width in the study reach.

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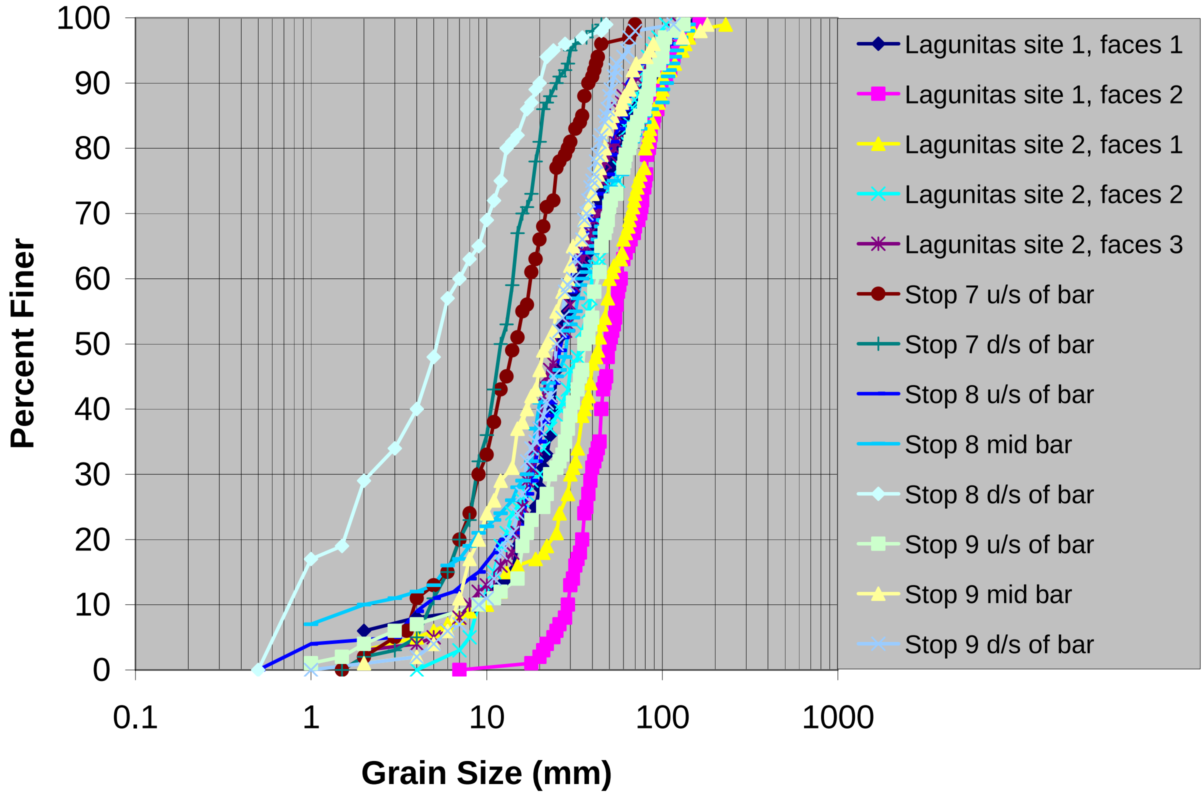

Figure 4. Surface grain size distributions in the study reach based on pebble count conducted in the summer of 2008. Approximate location of the pebble counts sites relative to the distance shown in Figure 2: Lagunitas site 1 = 11.25 km; Lagunitas site 2 = 10.95 km; Stop 7 = 11.75 km; Stop 8 = 5.87 km; Stop 9 = 2.98 km. The primary purpose of this diagram is to show the general range of surface grain size distributions rather than grain size distributions at individual locations.

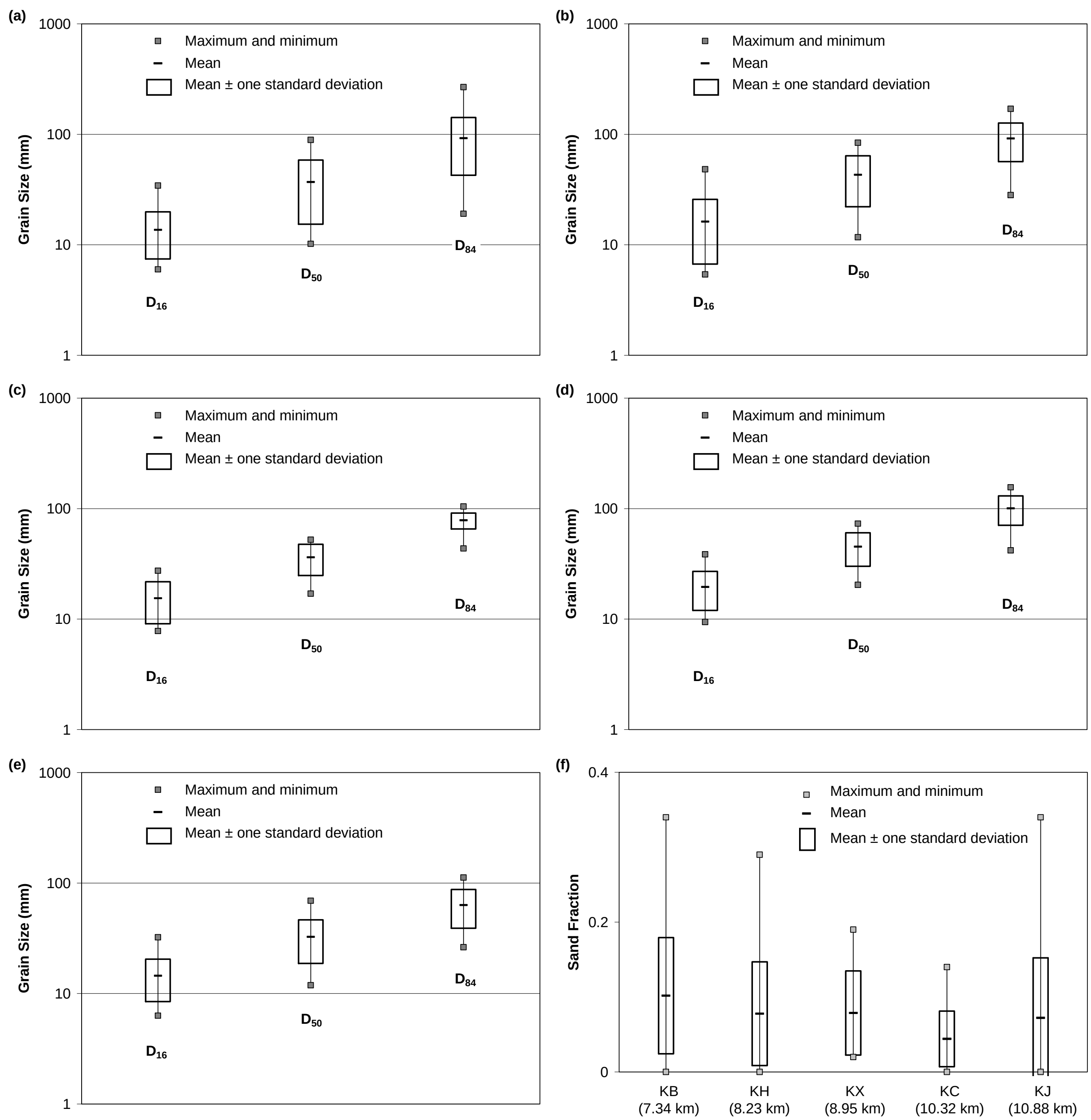

Figure 5. Observed surface characteristics at five locations, based on data collected by Owens et al. (2008) over the period of 1979 to 2007, including: characteristic surface grain size at Balance Hydrologics, Inc. monitoring sites (a) KB (located ~ 7.34 km in Figure 2), (b) KH (~ 8.23 km), (c) KX (~ 8.95 km), (d) KC (~ 10.32 km), and (e) KJ (~ 10.88 km); and (f) sand fraction in the above five monitoring sites. Sand is excluded from the calculation of the characteristic grain sizes.

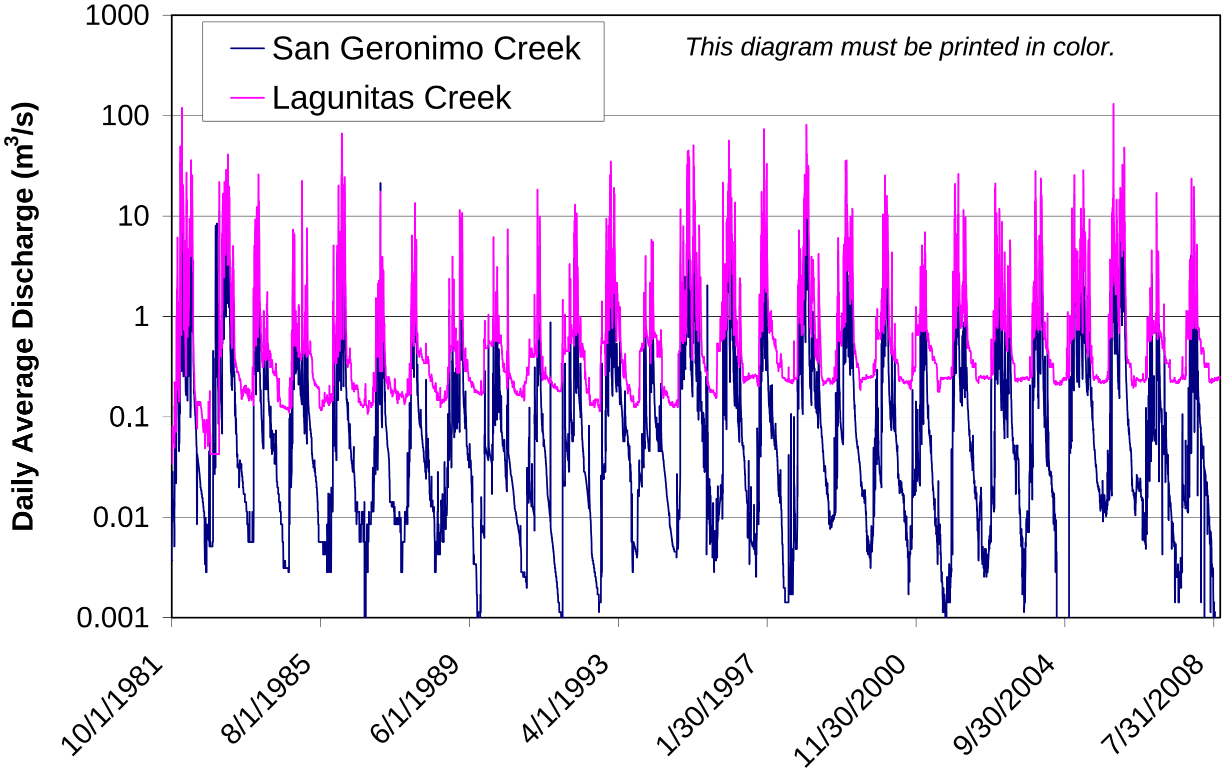

Figure 6. Daily discharge record for the period of 1 October 1981 and 30 September 2008 in San Geronimo and Lagunitas creeks, based on daily average water discharge records at the two gauging stations shown in Figure 2.

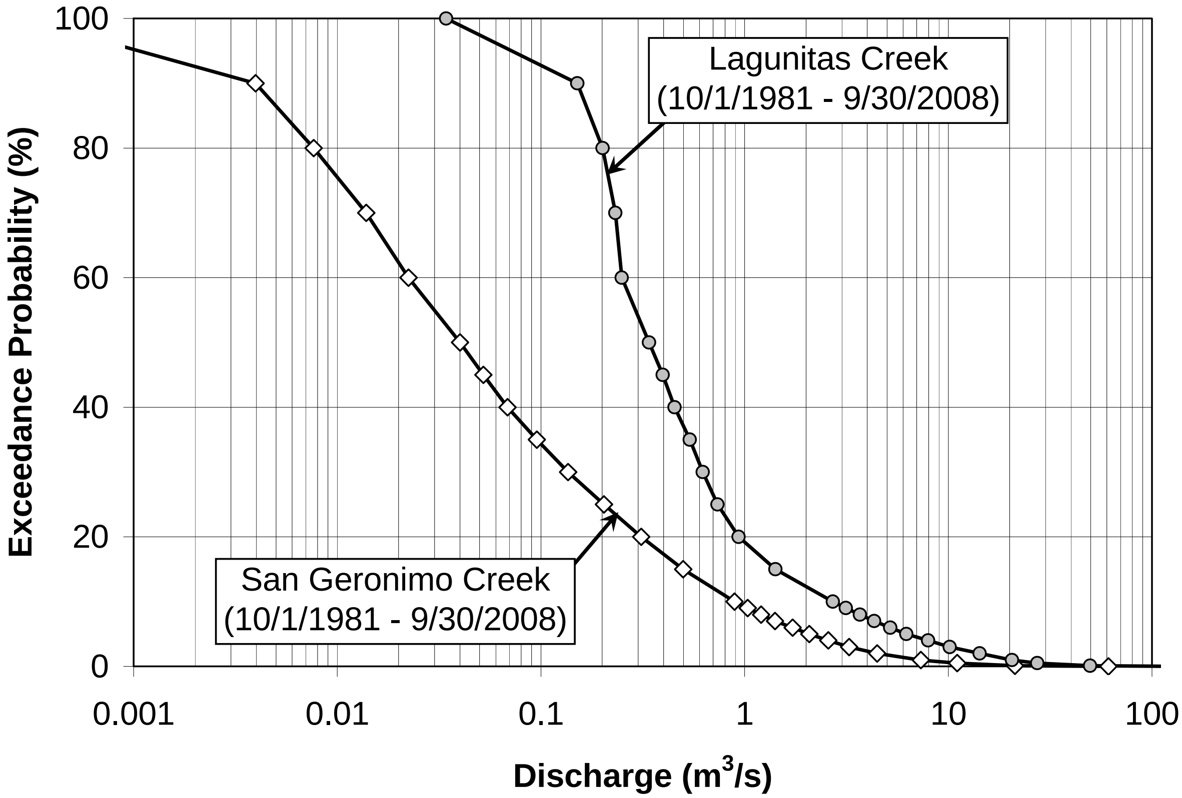

Figure 7. Flow duration curves in San Geronimo and Lagunitas creeks, based on daily average water discharge records at the two gauging stations shown in Figure 2.

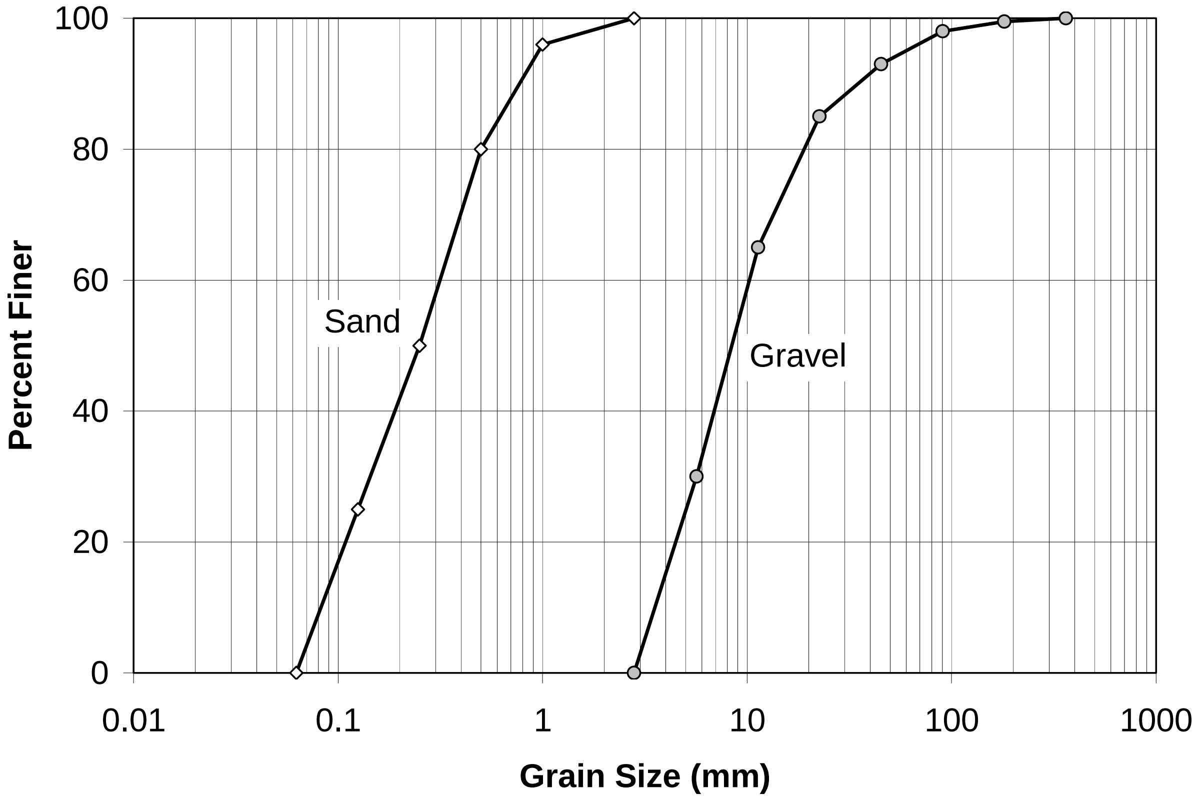

Figure 8. Assumed sand and coarser sediment grain size distributions in sediment supply. Grain size distribution for sand is rather arbitrary, and grain size for gravel was examined through a trial-and-error process so that the simulated characteristic surface grain sizes are in agreement with observations.

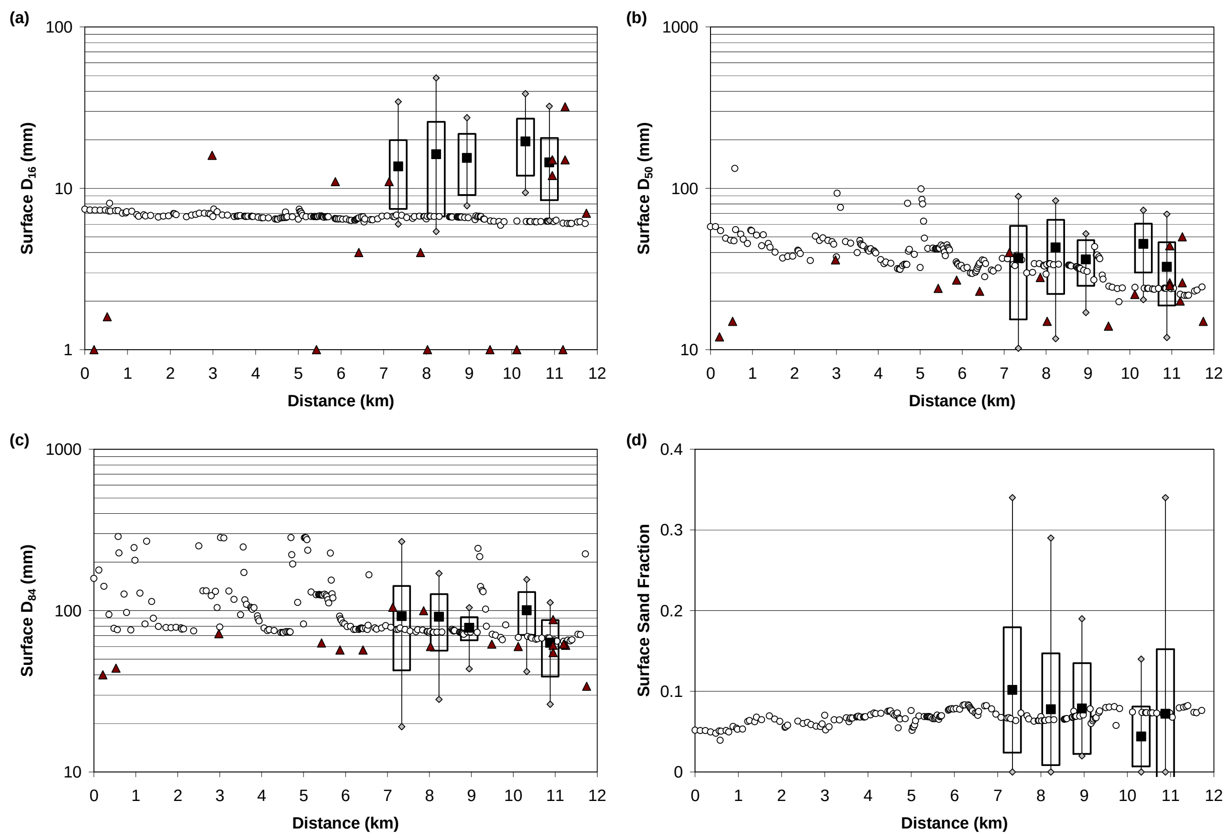

Figure 9. Simulated surface characteristic grain size and surface sand fraction, in comparison with field observations of Owens et al. (2008): (a) surface D_{16}; (b) surface D_{50}; (c) surface D_{84}; and (d) surface sand fraction. Simulated results are in open circles. The solid squares are observed mean values, the diamonds are the observed maximum and minimum values, and the large open rectangles represent mean ± one standard deviation. Solid triangles are pebble counts results by Stillwater Sciences (2005, 2008) and O'Connor and Rosser (2006). Figure 5 provides a more detailed description of the field data.

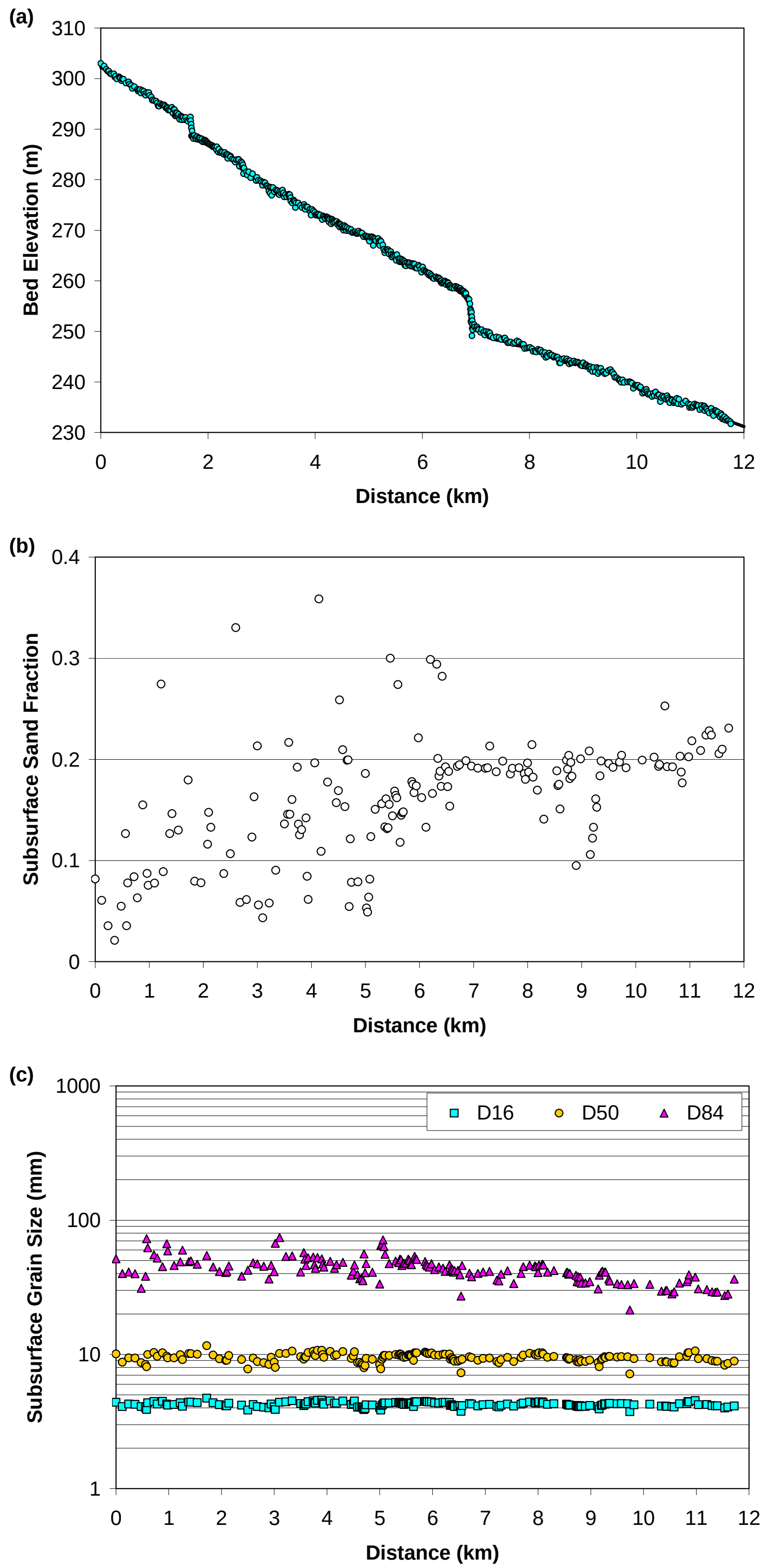

Figure 10. (a). Simulated longitudinal profile of the study reach (solid line, almost completely covered by the circles), in comparison with the surveyed bed profile (circles). (b). Simulated subsurface sand fractions. (c). Simulated characteristic subsurface grain sizes.

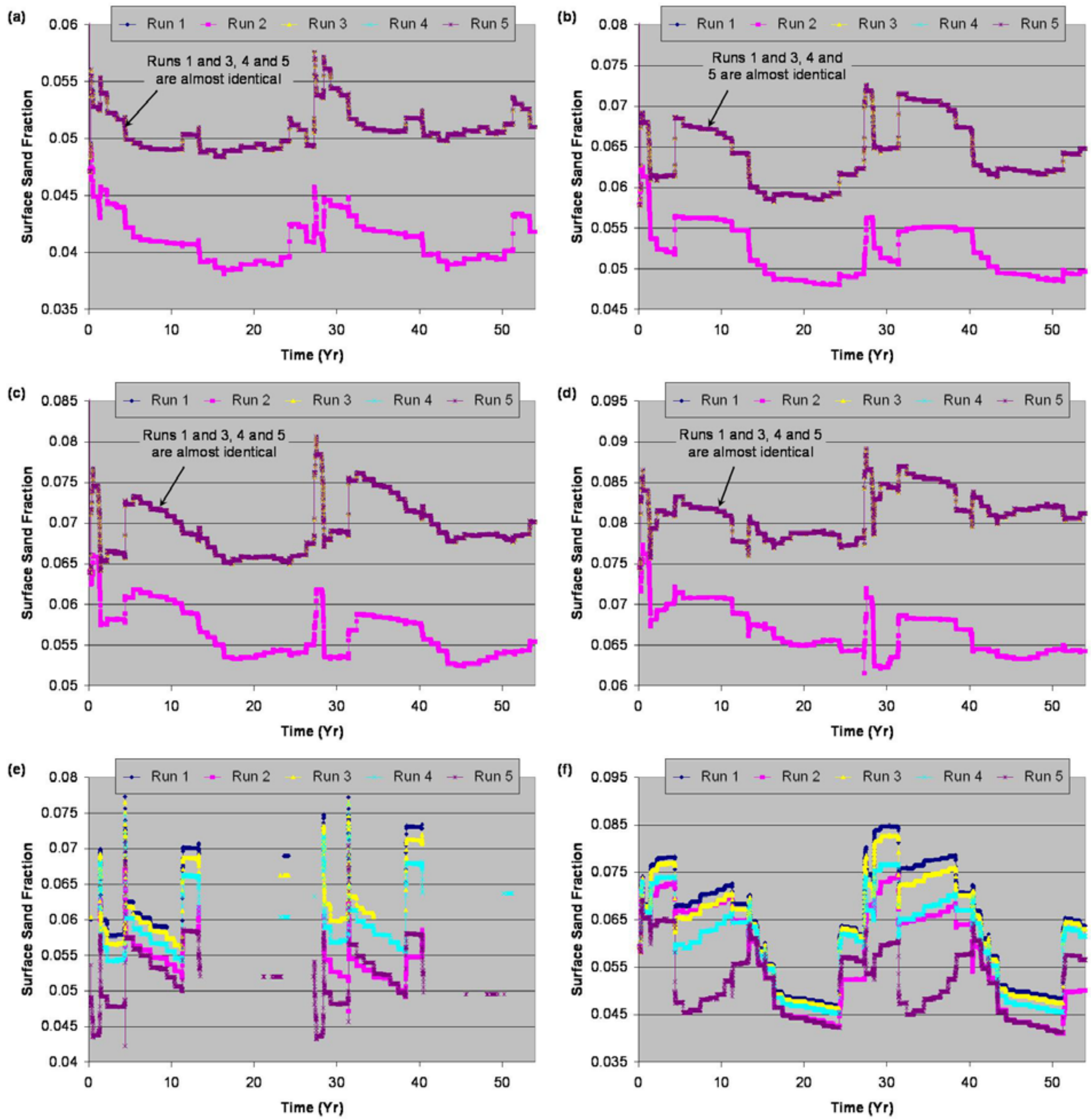

Figure 11. Simulated daily-averaged surface sand fraction at six stations: (a) 0.72 km; (b) 1.84 km; (c) 4.06 km; (d) 6.32 km; (e) 7.54 km; and (f) 8.06 km. Distances are measured from San Geronimo Creek-Woodacre Creek confluence in the downstream direction as shown in Figure 2. (a) through (d) are located upstream of gravel augmentation point while (e) and (f) are located downstream of gravel augmentation point. Missing data indicate bedrock exposure and thus, no surface and subsurface sand fraction data available.

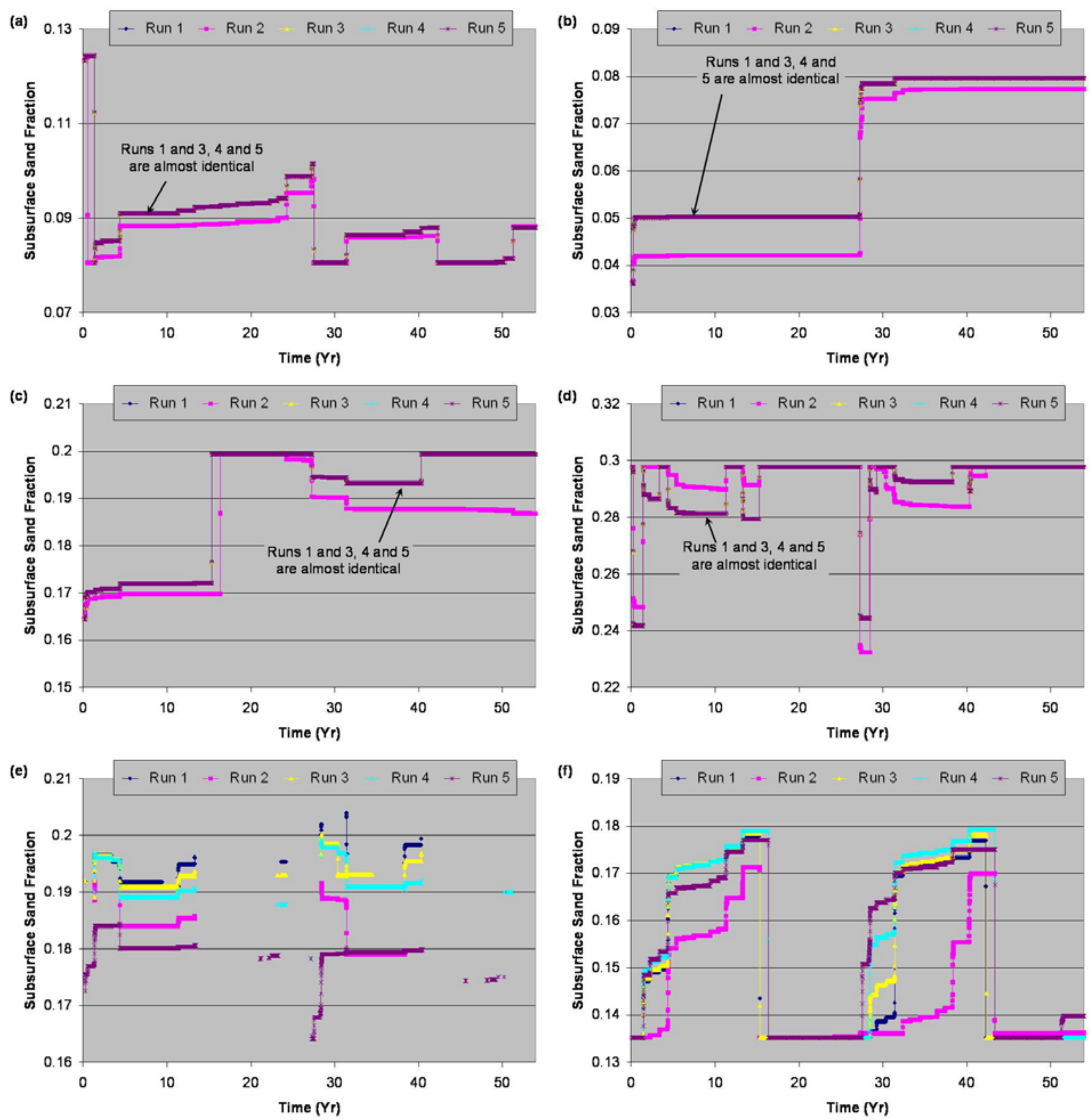

Figure 12. Simulated daily-averaged subsurface sand fraction at six stations: (a) 0.72 km; (b) 1.84 km; (c) 4.06 km; (d) 6.32 km; (e) 7.54 km; and (f) 8.06 km. Distances are measured from San Geronimo Creek-Woodacre Creek confluence in the downstream direction as shown in Figure 2. (a) through (d) are located upstream of gravel augmentation point while (e) and (f) are located downstream of gravel augmentation point. Missing data indicate bedrock exposure and thus, no surface and subsurface sand fraction data available.

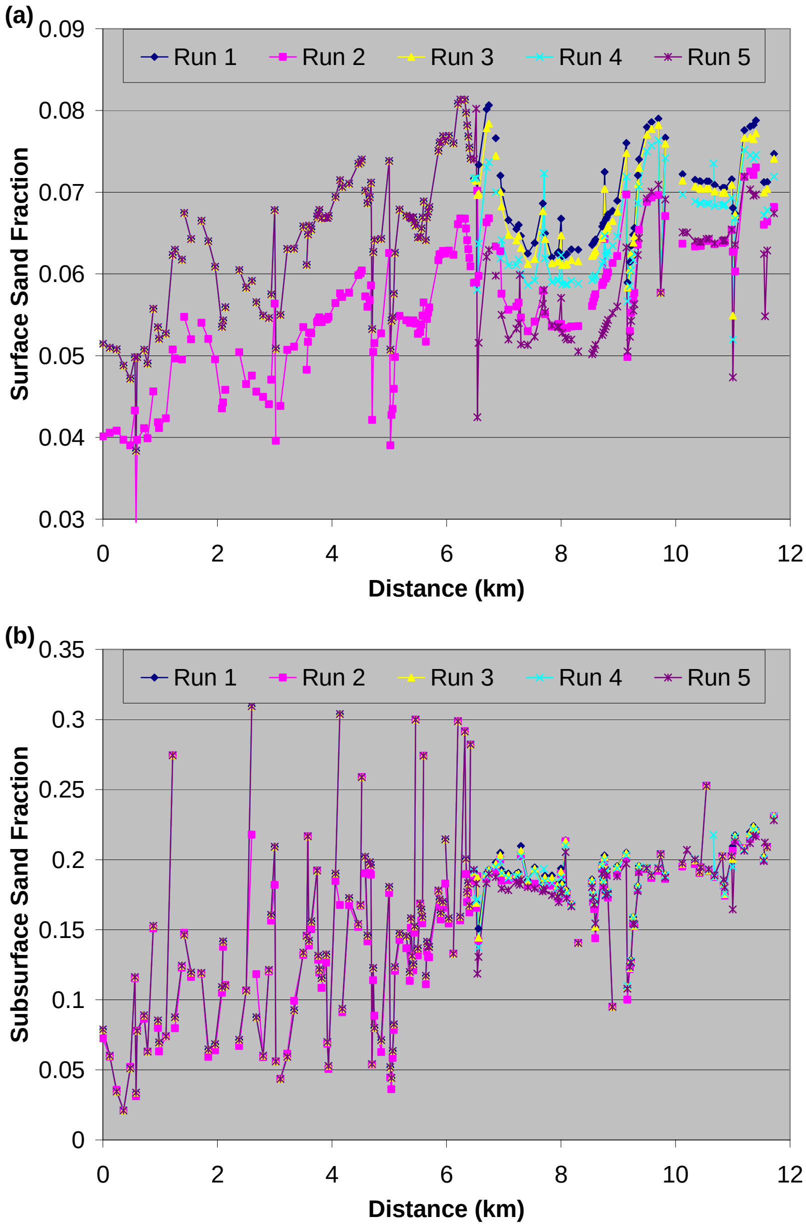

Figure 13. Simulated average surface (a) and subsurface (b) sand fractions in the modeled reach. Results are averaged over the entire 54-year simulation.

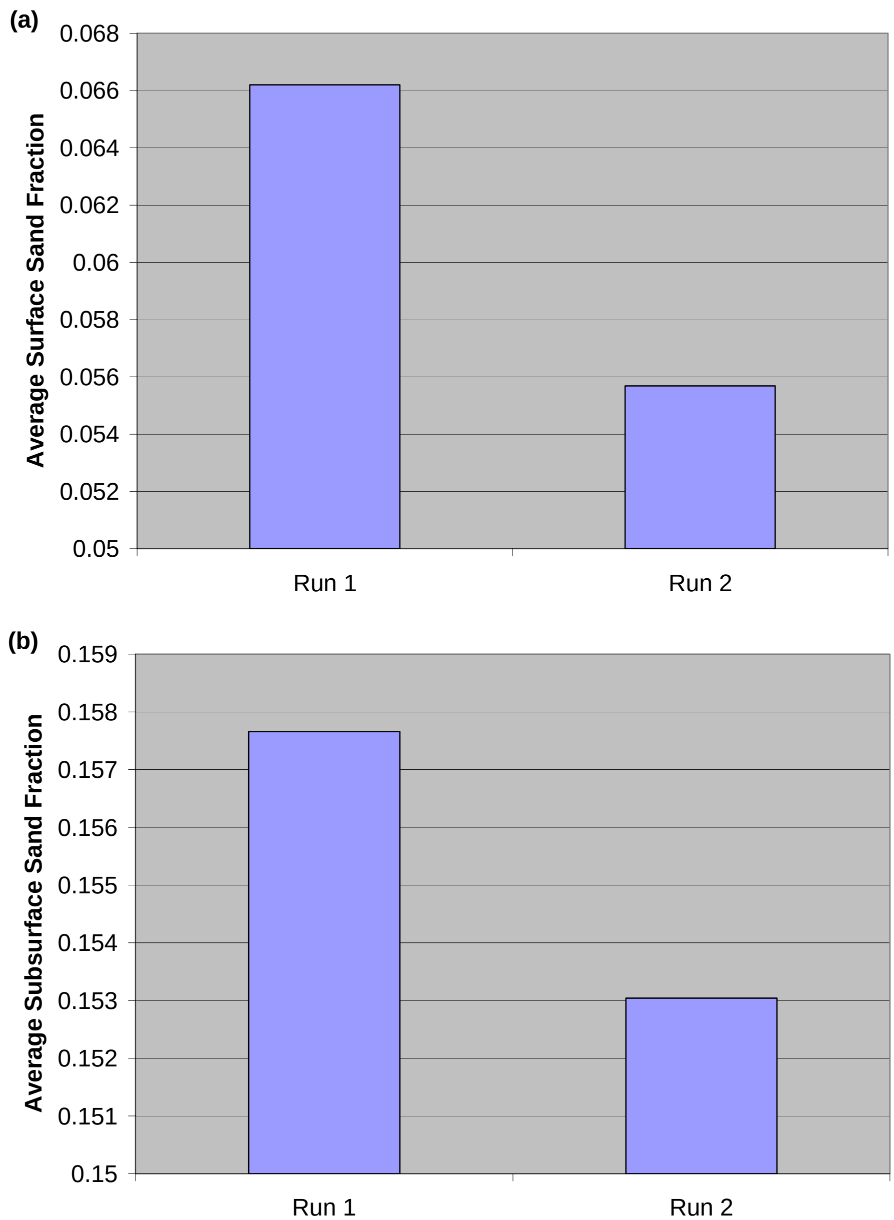

Figure 14. Simulated average surface (a) and subsurface (b) sand fractions for Runs 1 and 2. Results are averaged over the entire 54-year simulation and over the entire 12-km modeled reach.

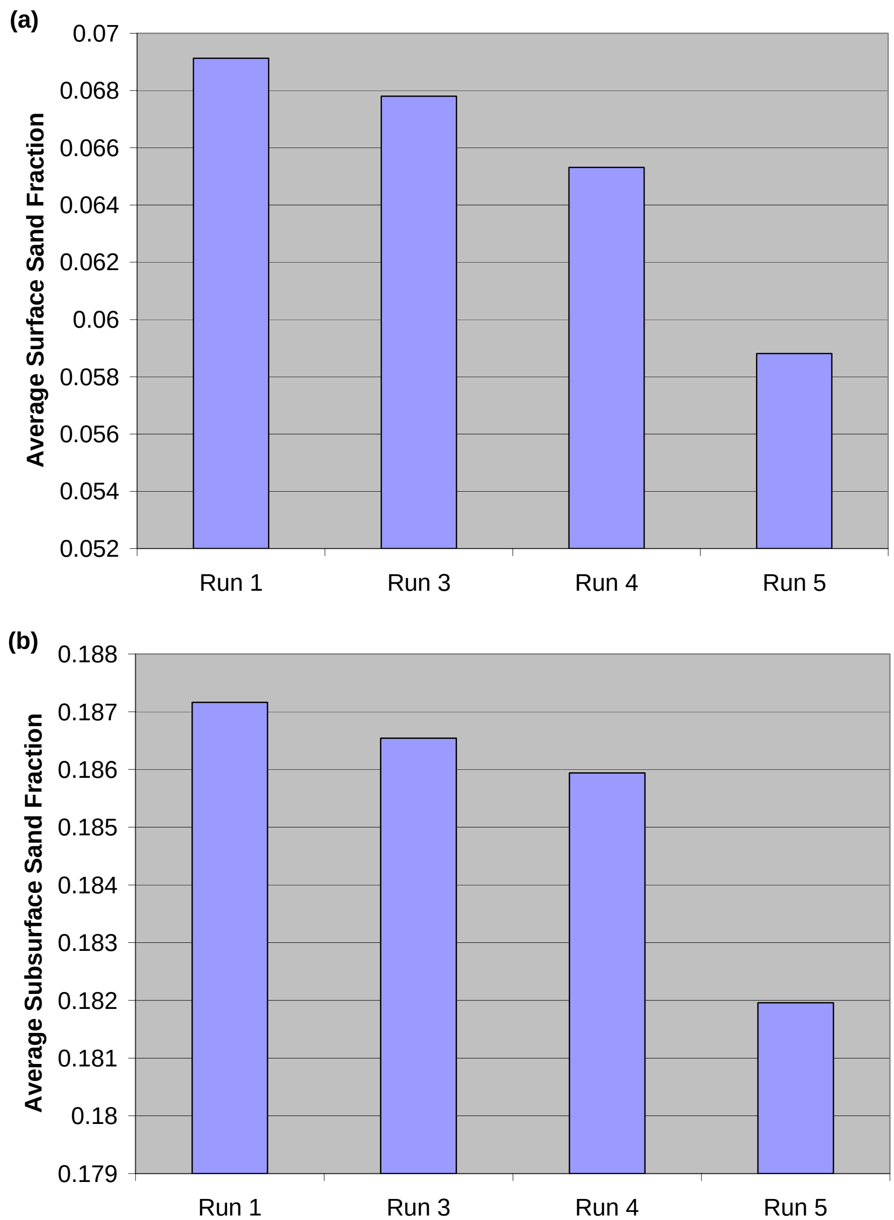

Figure 15. Simulated average surface (a) and subsurface (b) sand fractions for Runs 1, 3, 4, and 5. Results are averaged over the entire 54-year simulation and over the reach downstream of the gravel augmentation point.