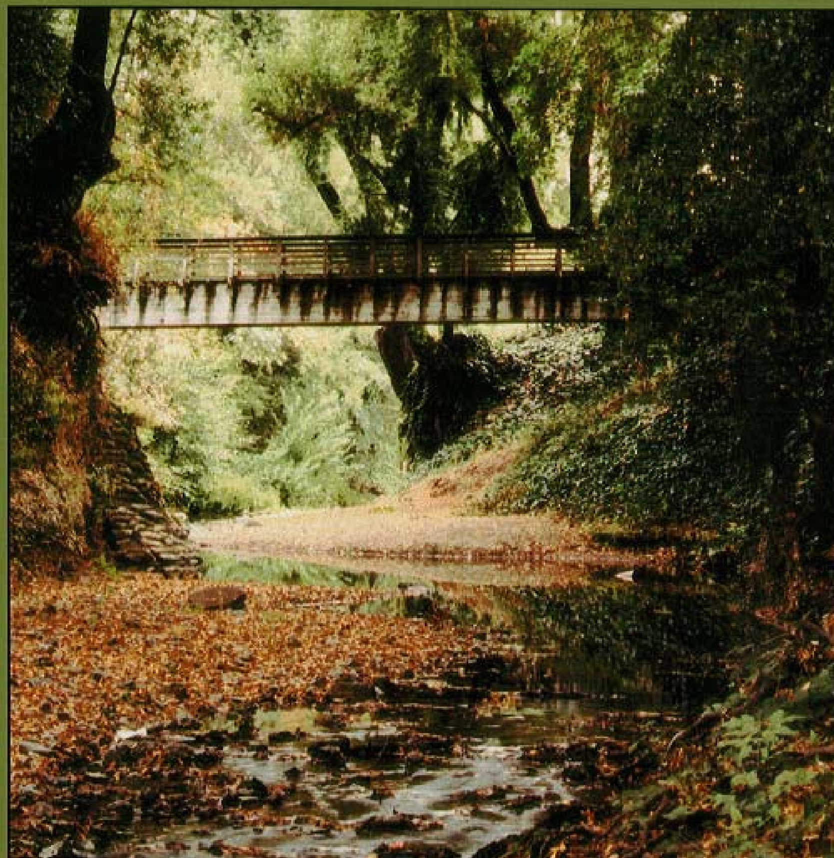
Geomorphic Assessment of the Corte Madera Creek Watershed

FINAL REPORT



PREPARED FOR:
Friends of Corte Madera Creek Watershed
and
Marin County Department of Public Works

December 31, 2000

Stetson Engineers Inc.
in association with
David Dawdy, Consulting Hydrologist

San Rafael and West Covina, California • Mesa, Arizona

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MARIN COUNTY, CALIFORNIA

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TABLE OF CONTENTS

List of Tables

**Tables 4-12 are appended to the end of the document.*

List of Figures

** All figures are appended to the end of the document.*

LIST OF FIGURES (CONT.)

List of Appendices

(The appendices are included in a separate electronic document. The names of the appendices are provided here for reference.)

TECHNICAL INFORMATION

This report is intended to provide interested citizens as well as environmental scientists and engineers with accessible information on historical and present watershed processes. Every attempt has been made to avoid excessive use of technical jargon, without also sacrificing precise technical meaning and concise presentation. Useful definitions and technical information were reserved for this section of the report.

The study distinguishes the upland channel network from the alluvial channel network (Figure 6) for the sediment budgeting purposes. The upland channel network is defined as zero-, first-, second-, and third-order channels rising in steep upland areas where the mainstem channels are cut in colluvium (primarily landslide and earthflow deposits from upslope) in steep v-shaped canyons. By this definition, upland channels do not have floodplains. The alluvial channel network includes mainstem channels and downstream portions of tributary channels cut in the valley fill alluvium deposited during the Holocene by debris flows and overbank flooding on the valley flat. Alluvial channels occupy u-shaped valleys with active floodplains (i.e., flooded at least once every several years) or abandoned floodplains (terraces). Upland-alluvial channel transitions occur at the first point moving downstream where alluvium is present in the channel banks, where mainstem channels leave the confinement of v-shaped valleys, to lower-gradient u-shaped valleys flanked with active or abandoned floodplains (Figure 6).

The study refers to channel entrenchment that occurred throughout the alluvial channel network in response to land use changes associated with European settlement of the region. Entrenchment, or incision, is the lowering, or degradation, of the bed elevation of a stream by channel bed erosion. Channel aggradation refers to increasing channel bed elevation by net deposition of sediment on the bed over time.

The study focusses its analysis and discussion of sediment transport on the portion of the sediment load carried by streams that travels along the channel bed in intermittent contact with the bed, such as by rolling, and skipping along the bed. This portion of the sediment load is referred to as bedload, as distinguished the finer sediment material that is carried within the water column, or suspended load. Bedload is an important management issue, as it is the material that is deposited in the flood control channel at Ross.

This report uses the English units system to maintain consistency with historical data sources, including various COE analyses. Some useful metric conversions are as follows:

1 square mile (sq. mi.)	=	2.56 square kilometers (km^2)
1 cubic yard (yard)	=	0.917 cubic meters (m^2)
1 cubic yard (yard)	=	1.35 english tons (tons)
1 english ton (ton)	=	0.91 metric tonnes (t)
1 english ton per square mile (tons/sq.mi.)	=	0.355 metric tonnes/square kilometer (t/km^2)
1 cubic foot per second (cfs)	=	0.028 cubic meters per second (cms)

EXECUTIVE SUMMARY

Sand and gravel deposition in the flood control channel downstream from Ross creates a common perception that the Corte Madera Creek watershed produces an unnaturally high sediment yield. Channel widening and local bank failures throughout the watershed's alluvial channel network also create a common perception that channel bank erosion produces a significant portion of the sediment yield. Sand and gravel comprise the coarse portion of sediment inflow at Ross, or the 'bedload'. Sand and gravel bedload deposition in the flood control channel significantly reduces its flood control performance. For this reason, estimating the amount and sources of bedload sediment inflow at Ross is of particular concern to this study.

This study presents a preliminary estimated bedload sediment budget for Corte Madera Creek at Ross and evaluates whether or not the sediment load at Ross is unnaturally high. To focus possible future remedial efforts, this study also evaluates whether or not channel erosion contributes a significant portion of the sediment yield. The budget accounts for sediment generated by net channel bed and bank erosion along the alluvial channel network, and sediment generated by fluvial transport from unregulated upland areas above Ross (about two square miles of the Ross Creek subwatershed is regulated by Phoenix Reservoir). The budget provides a preliminary, uncalibrated estimate of total sediment yield at Ross that can be compared to published COE sediment yield estimates at Ross and sediment yields measured or estimated for other comparable watersheds in the region.

This study also presents an independent bedload sediment inflow estimate at Ross obtained from a Parker-Klingeman sediment transport model calibrated with available existing USGS bedload transport data. This yield value can be compared to this study's sediment budget estimates, COE bedload inflow estimates, and other regional data.

Sediment Budget Methods

To quantify the upland sediment budget components, the Parker-Klingeman bedload transport model was used to estimate bedload sediment yield from ten major Corte Madera Creek subwatersheds. Seven of the major subwatersheds contribute sediment from 72 percent of the unregulated drainage area above Ross. The study also substituted Parker-Klingeman shear values with USFS shear values to provide a range of estimated values. The sediment budget allows comparison of sediment contribution per unit drainage area for various upland source areas in the watershed. This study also produced qualitative sediment yield classification maps based on existing USGS landslide habitat and slope stability data to provide independent predictions of relative subwatershed sediment yields.

To quantify sediment contribution from the alluvial zone, this study resurveyed 44 historical channel cross-sections and historical channel bed elevations compiled from 1976 FEMA and HUD Flood Insurance Study records. These comparative data combined with extensive field observations provided average values of net channel bed lowering and channel

bank retreat from which sediment yield by both channel bed and channel bank erosion in the entire alluvial channel network could be estimated for 1976-1999. Thus, the budget also allows sediment yield by channel bed and bank erosion to be compared to sediment yield by fluvial transport from aggregate hillslope sediment sources in the surrounding upland areas.

Sediment Budget Results

This study's uncalibrated sediment budget estimates that the Corte Madera Creek Watershed supplies about 7,250 tons of bedload each year to the reach above Ross. The calibrated Parker-Klingeman sediment transport model estimated average bedload sediment inflow at Ross is about 6,750 tons/year. Using an average of the two results, the study estimates that about 7,000 tons/year of bedload are delivered to Ross, or about 450 tons/sq.mi./year.

This range of estimated values is about 45 percent greater than Lehre's (1982) detailed estimate for the Lone Tree Creek basin (240 tons/sq.mi./year), a comparable basin in southwestern Marin County with fewer upland roads and less precipitation. Due to persistent upland land use impacts, namely increased drainage density caused by 19th century logging and grazing, the Corte Madera Creek watershed's bedload sediment yield can be considered to be unnaturally high. If the natural background rate were estimated conservatively to be 350 tons/sq. mi./year, than the human-induced increase in bedload inflow at Ross would be about 1,600 tons/year.

This study's estimates of bedload inflow at Ross are about 40 percent less than the 11,070 tons/year value the COE's 1989 sediment transport model predicted for average bedload sediment inflow at Ross. It should be noted that this study's bedload sediment yield estimates are expected to be about 10 percent less than the COE's model prediction, because this study's estimate did not include 'very fine' and 'fine' sand size fractions that were included in COE's bedload inflow prediction. Thus, this study's prediction is about 20-30 percent less than COE's estimate.

This study's bedload yield estimates are also about 40 percent less than values estimated in the Eel River watershed, which can be considered upper limit values due to a greater degree of melange deformation and tectonic uplift, and continuing upland land use impacts. Yields from the Eel River basin are among the highest in western North America. The COE's yield estimate is closer to upper limit values measured in the Eel River basin than this study's estimate, or results from other studies in the region.

Sediment Sources in the Watershed

This study's sediment budget estimated that channel bed and bank erosion in the watershed's alluvial channel network generated about 9 percent of the total bedload sediment load at Ross, for 1976-1999. Observed average channel bed incision and bank retreat rate estimates were comparable to average values reported in the existing studies of comparable watersheds (i.e. Novato Creek and Walker Creek). Fluvial transport from upland channel networks generated about 91 percent of the total sediment yield at Ross. This 91:9 ratio of upland/channel bank sediment sources is comparable to results of detailed sediment budgets compiled for other Marin County watersheds and Eel River tributaries.

Total elimination of bank erosion and systemic channel widening throughout the alluvial channel network would probably reduce bedload sediment delivery to Ross by as much as about 430 tons/yr, only 6 percent of the total bedload delivered to Ross. Total elimination of the additional sediment supply by restoration of problem sediment sources and improved hillslope management practices would probably reduce bedload sediment delivered to Ross by as much as about 1,600 tons/yr, or about 20% of the annual bedload inflow.

This study indicates that the San Anselmo Creek and Sleepy Hollow Creek subwatersheds contribute about 29 percent and 26 percent, respectively, of the total bedload sediment inflow at Ross. Detailed sediment budget studies of northern California Coast Range watersheds indicate that the sediment source mechanisms dominating long-term average sediment yield are landsliding and earthflows. Thus, the frequency of mass wasting can probably be considered a suitable surrogate for long-term average bedload sediment yield in the Corte Madera Creek watershed. Available interpretive USGS maps of potential hillslope instability and landslide frequency show that greatest potential hillslope instability and landslide frequency occurs in the San Anselmo Creek and Sleepy Hollow Creek subwatersheds. Field reconnaissance also provided evidence that these subwatersheds produce relatively large sediment yields.

Other studies have shown that underlying geologic type is one of the strongest influences on hillslope and total sediment yield. Kelsey (1980) showed that rolling-to-hummocky grassland and grass-oak woodland-covered Franciscan melange slopes can produce about 30 times more sediment per square mile than steep, forested sandstone and shale slopes. The San Anselmo Creek and Sleepy Hollow Creek subwatersheds have a greater percentage of grassland, grass-oak woodland, and chaparral-covered melange slopes than other Corte Madera Creek subwatersheds. Forested sandstone slopes occur primarily in the Larkspur Creek, Tamalpais Creek, and Ross Creek subwatersheds above Phoenix Lake, and substantial portions of the Fairfax Creek subwatershed.

Present Trajectory of Channel Change

This study also evaluated the present state and trajectory of the channel's natural geomorphic recovery from recent channel entrenchment. Corte Madera Creek's alluvial channel network became moderately to deeply entrenched in the Holocene valley fill in about 1850-1910, abandoning its pre-entrenchment floodplain. Rapid channel entrenchment was evidently in partial response to logging and increasing livestock grazing intensity from the middle to late 1800s, coinciding with a period of somewhat greater than normal precipitation. After about 1910, numerous natural bedrock and human infrastructural grade controls outcropped in the channel bed, slowed the channel incision rate, and accelerated channel widening. Natural geomorphic recovery processes that recover aquatic and riparian habitat lost during channel entrenchment are operating in the Corte Madera Creek watershed, including: progressive upstream channel aggradation in the lower portion of the mainstem Corte Madera Creek, and channel bed level stabilization, channel widening, inset floodplain formation, and pool-riffle development in the middle and upper portions of the alluvial channel network.

Progressive upstream channel aggradation evidently ceased in about 1964. Ongoing channel widening, and inset floodplain formation in the middle and upper portion of the alluvial channel network indicate that natural geomorphic recovery processes are ongoing but incomplete in the Corte Madera Creek watershed. However, constraints imposed by urbanization of the pre-entrenchment floodplain limit the rate of natural habitat improvement both by preventing channel widening with bank protection and flood control structures, and routing storm water directly into the channel network from impermeable surfaces. As a priority, projects intended to improve flood control and/or aquatic and riparian habitat and habitat-supporting processes and flood control should seek opportunities, where possible, to increase active channel width rather than strictly prevent bed incision or bank retreat. This study presents a conceptual demonstration floodplain restoration/construction project design for a hypothetical site in the watershed with sufficient undeveloped land adjacent to the channel. This study also presents a conceptual design for streambank stabilization for a hypothetical site where residential and commercial development prevent extensive floodplain restoration/construction.

This study also presents a methodology and preliminary suitability mapping to implement site stormwater retention/drainage best management practices that would increase alluvial groundwater storage and summer low flow discharges in the watershed. Discontinuous surface flow during the summer low-flow season is an important limiting factor for salmonid habitat.

Estimated Annual Average Bedload Yield from Major Sub-Watersheds

Sub-Watershed		Estimated Total Bedload Sediment Load (tons/year)			Bedload Yield (tons/sq. mi.)	Percent of Bedload Inflow at Ross (%)
Sampled Drainage Area	Sq. Mi.	Using Parker-Klingeman Shear Values	Using USFS Shear Values	Average		
Ross Creek below Phoenix Dam	0.6	550	120	335	560	4.6
Sorich Creek (model invalidated)	0.2	—	—	—	—	—
Sleepy Hollow Creek	2.8	1,050	2,650	1,850	660	25.0
Fairfax Creek	3.6	700	40	370	100	5.1
Deer Park Creek	0.5	70	10	40	80	0.6
Wood Lane Creek	0.4	110	0	55	140	0.7
San Anselmo Creek	3.6	4,100	100	2,100	580	29.0
Upper San Anselmo Creek*	0.8	3,000	70	1,535	1,900	21.0
Total Sampled Area above Ross	11.5	6,600	2,900	4,750	410	65.0

**Upper San Anselmo Creek values are included in San Anselmo Creek values, not reflected in totals*

Comparison of This Study's Bedload Sediment Budget and Yield Estimates with Other Studies

	Bedload Sediment Load (tons/year)	Bedload Yield (tons/sq. mi.)	Percent of Bed Load Inflow at Ross (%)
Estimated Bedload Sediment Budget at Ross (this study)			
Total Sampled Area above Ross (11.5 sq. mi.)	4,750	410	65
Total Unsampled Area above Ross (4.5)	1,850	410	26
Annual Bedload Yield by Bed and Bank Erosion	650	—	9
Total Bedload Sediment Budget at Ross	7,250	450	100
Estimated Bedload Sediment Yield at Ross			
This Study (16.0)	6,750	420	100
Army Corps of Engineers (1989:34) (16.0)	11,070	690	100

1. INTRODUCTION

Stetson Engineers, in association with David Dawdy, consulting hydrologist, prepared a geomorphic assessment of the Corte Madera Creek watershed for the Friends of Corte Madera Creek and the Marin County Flood Control District. The assessment was intended to document historical and ongoing channel changes, infer historical resulting changes in aquatic and riparian habitat, and evaluate the average annual bedload sediment yield from various major subwatersheds. Understanding the distribution of major sediment source areas in the watershed, and the trajectory of ongoing channel changes, are important for outlining and prioritizing demonstration projects intended to reduce excess watershed sediment yield, improve aquatic and riparian habitat, and improve flood management. An Executive Summary is provided at the beginning of this report.

Section 2 summarizes historical changes in channel form (particularly channel entrenchment), and associated changes in habitat-creating geomorphic processes, and resulting aquatic and riparian habitat. Channel entrenchment is attributed to specific historical human-induced and natural changes in peak runoff. Evidence of ongoing natural post-entrenchment geomorphic recovery processes is summarized, and the trajectory of future channel change is discussed. Section 3 summarizes the results of existing data collection, identifying data gaps, as well as data that were useful to the present study. Sections 2 and 3 together provide an historical and technical background for justifying the scope of the study's applied field surveys, sediment yield modeling, and sediment budget estimates. These sections also provide background for properly interpreting the study's results.

Section 4 summarizes field survey and modeling methods used in this study. Additional technical notes are contained in the report's appendices. Section 5 contains results of sediment budget estimates and independent sediment yield estimates for Corte Madera Creek at Ross. These results provide bedload inflow estimates and average watershed and subwatershed sediment yield values that can be compared to results of other studies. Comparisons are drawn in Section 5 and Section 6. Section 6 also discusses implications and reliability of study results, and identifies "problem subwatersheds". Implications for the study results for flood management and habitat restoration goals are emphasized. Study conclusions are contained in the Executive Summary.

Appendix J presents a methodology and preliminary suitability mapping to implement site stormwater retention/drainage best management practices that would increase alluvial groundwater storage and summer low flow discharges in the watershed. Appendix K presents a conceptual design for streambank stabilization for a hypothetical site where residential and commercial development prevent extensive floodplain restoration/construction. Appendix L presents a conceptual demonstration floodplain restoration/construction project design is presented for a hypothetical site in the watershed with sufficient undeveloped land adjacent to the channel.

2. TECHNICAL BACKGROUND AND HISTORICAL ANALYSIS

2.1. DESCRIPTION OF THE CORTE MADERA CREEK WATERSHED AND ITS HOLOCENE CHANNEL EVOLUTION.

Marin County occupies a portion of the northern California Coast Range surrounded by the Pacific Ocean on the west and the San Francisco Bay on the southeast (Figure 1). The landscape is typified by small watersheds draining steep, thinly mantled, forested and grassland slopes. Steep upland channels collect and flow through relatively steep, narrow, clayey and gravelly valley flats resting in deep folds in the terrain, and finally into broad salt marsh estuaries. The landscape is underlain by a highly deformed accumulation of pre-Cretaceous continental margin deposits (primarily marine sedimentary sandstones and shales) of the Franciscan Formation (Figure 17). Watersheds in this geologic province typically produce sediment yields among the highest in North America (Judson and Ritter 1964, Brown and Ritter 1971, Knott 1971, Janda 1975, Brown 1975).

Corte Madera Creek drains a 28-sq. mi. area of eastern Marin County (Figure 1). Its western boundary is formed by a steep, forested ridge running northwest from the East Peak of Mt. Tamalpais (elevation 2,671 ft) to Pine Mountain and then north-northeast to Loma Alta (elevation 1,592 ft). San Anselmo, Fairfax, and Sleepy Hollow Creeks rise along these ridges and drain steep upland areas onto relatively steep and laterally confined alluvial valley flats; these creeks combine as San Anselmo Creek in Ross Valley at San Anselmo (Figure 2). San Anselmo Creek then flows southeast through Ross Valley along the Cretaceous sandstone ridge running southeast along the eastern edge of the basin. Several minor intermittent tributaries rise on the grassland and grass-oak woodland-covered hills along the northern and eastern edges of the basin. Ross Creek is a major tributary to San Anselmo Creek at Ross. The channel is called Corte Madera Creek from the Ross Creek confluence to San Francisco Bay Estuary. It drains into a tidal salt marsh at Kentfield, and then into San Francisco Bay near Corte Madera. Larkspur Creek and Tamalpais Creek are the only major tributaries to Corte Madera Creek that enter downstream from the tidal influenced zone's upstream limit at Kentfield and the USGS Gage at Ross.

Corte Madera Creek watershed's steep relief, high sediment yield, continuing tectonic uplift and faulting, variable and fire-prone vegetative cover, active hillslope processes, and its semi-arid Mediterranean climate punctuated by occasionally severe cyclonic rainstorms, all contribute to its dynamic and spectacular natural environment. About 83 percent of total annual precipitation in the basin occurs as rain in the five months between November 1 and April 1 (COE 1961). Average annual rainfall varies from about 48 inches along its southwestern edge to about 34 inches along its northeastern edge (Figure 4). Distribution of total rainfall across the watershed area during individual large storms varies between storms. Total rainfall is greater in the southwestern portion of the basin than the northeastern portion, as Loma Alta and the Pilot Knob/Ross Hill/Bald Hill areas (Figure 2) typically receive the greatest total precipitation during large storms (COE 1961). The Pilot Knob area near Ross and Kentfield often reports the highest precipitation of any station in the San Francisco Bay Area.

The only USGS stream flow gage in the basin is above the tidal influenced zone at Ross (Figure 2). The Ross Gage captures an 18.3-sq. mi. portion of the 28-sq. mi. basin (COE 1961). The USGS measured mean daily flow at the Ross Gage from 1951 until it was discontinued in 1993. The Marin County Flood Control District maintained the gage after 1993. The largest discharge of record at Ross (about 6,000 cfs) occurred in January 1982. Only about 6 percent of total annual precipitation occurs in the five months between May 1 and October 1 (COE 1961). Summer base flow is low and discontinuous throughout the channel network during normal and dry years (Figure 5). For example, the Friends of Corte Madera Creek (1997) reported there were at least 25 no-flow days per year at Ross, averaging 69 no-flow days per year in 1988-1993. Year-round shallow ground-water discharge maintains discontinuous surface flow at isolated locations throughout the watershed. Rich (2000) details recent field investigations of discontinuous surface flow.

During the rainy season, intermittent stream channels and gullies rise in upland zero-order subbasins with drainage areas greater than about 0.01 square miles (about 5 acres; Figure 6). Upland mainstem stream channels are typically narrow, shallow, straight, steep, boulder cascade and step-pool channels cut in bedrock, colluvium, and landslide and debris flow deposits, sometimes along active faults. Overland and channelized fluvial sediment transport, downslope soil creep, landslides, earthflows, and debris flows transport sediment from hillslopes to mainstem upland channels. Underlying bedrock resistance and longitudinal and lateral (cross-valley) faulting control the long-term downcutting rate in upland stream channels; but episodes of local channel aggradation by landslide and debris flow deposition controls short-term changes in local stream slope, in-channel sediment storage, and shallow ground-water discharge. Between episodes of channel aggradation, headward knick point channel bed and bank erosion is gradual. Debris flows are the principal agent of channel bed and bank erosion in the upland channel network.

Following the Pleistocene-Holocene transition (about 10,000 - 12,000 years BP), increasing sediment yield, rising sea level, and continuing tectonic uplift caused lower portions of eroding v-shaped upland valleys in Marin County watersheds to fill with sediment (Montgomery 1999), creating u-shaped valleys. The present depth to bedrock in Corte Madera Creek alluvial channel network varies from zero ft (by definition) at upland-alluvial transitions to about 40 ft near the upstream limit of the tidal influenced zone at Kentfield (COE 1961; Figure 9). Within the tidal zone, depth of bay mud and alluvium above bedrock increases from about 40 ft at Kentfield to about 147 ft at Highway 101 near the basin outlet (COE 1961). Sea level elevation rose about 16 ft since 5,000 BP (Haible 1980), and about 300 ft from the onset of the Holocene to the present (Rice et al. 1976). Holocene sea level rise probably influenced valley filling and valley flat slope in the alluvial channel network approximately below the City of San Anselmo. The present alluvial channel network is comprised of relatively steep, straight, pool-riffle, step-pool, and plane-bed channel segments laterally confined in a straight and locally meandering channel network moderately to deeply entrenched in the Holocene valley fill. Causes and effects of recent channel entrenchment are discussed below.

2.2. CHANGES IN AQUATIC AND RIPARIAN HABITAT CREATING PROCESSES AND CONDITIONS CAUSED BY RECENT CHANNEL ENTRENCHMENT

Corte Madera Creek watershed's entrenched alluvial channel network sustains less aquatic and riparian habitat than the pre-entrenchment channel network. By inference, the pre-entrenchment channel was a straight and locally meandering, relatively shallow, sand-and-gravel, pool-riffle and plane-bed channel with sand-and-gravel point bars. Lateral channel migration associated with active channel meandering eroded loose alluvial channel banks and deposited gravel transported from upland areas on accreting inside point bars. Lateral channel migration eroded woody debris into the channel, and point bar accretion provided new locations for pioneer riparian plants to establish and survive. Overbank flooding deposited fine sediment over a wide zone on the valley flat during floods. This way, channel meandering and floodplain deposition maintained aquatic habitat complexity and a wide and diverse riparian corridor. The shallow ground-water table recharged by subsurface inflow from beneath the mountain fronts and tributary channels flowing over the clay-rich alluvium supported seasonal floodplain wetlands on the valley flat (Figure 3, Figure 16).

The pre-entrenchment channel network was probably also braided locally and shifted between main channels by channel avulsion during high flows. Such channel forms and processes are typical for streams draining Coast Range Franciscan sandstone and melange watersheds in the semi-arid Mediterranean climate zone (Hecht 1994, Kondolf et al. in press).

Lateral migration, floodplain deposition, channel avulsion, and woody debris recruitment were arrested when the channel cut deeply into the valley fill. The present channel is similar in plan form as the pre-entrenchment channel, but active channel width and riparian corridor width were reduced throughout the alluvial channel network (Figure 3). Entrenchment increased the flood capacity of the channel; much of the alluvial channel network contains the '50-year flood' (HUD 1976). Thus, the channel abandoned the pre-entrenchment floodplain on the valley flat. Entrenchment also drew down the shallow alluvial ground-water table, further reducing riparian, seasonal floodplain wetland and vernal pool habitat on the valley flat (Figure 3).

Entrenchment also increased flow velocity and channel bed and bank shear stress by confining flood flows. Increased velocities and shear stresses during high discharges prevents reestablishment of gravel bars and pool-riffle bed morphology similar to the pre-entrenchment conditions. Narrow, fixed gravel bars dominate the channel bed. Unnaturally high, coarse grained gravel bars throughout the alluvial portion of Fairfax Creek and San Anselmo Creek appear to have been deposited during deep, confined flood flows. These elevated, coarse, well-drained gravel deposits enabled riparian trees to establish and mature within the channel. Reinforcement by mature tree root systems prevented significant erosion during recent, larger floods; the reinforced 'flood bars' act as resistant inset channel banks, further reducing active channel width and further preventing inset floodplain and pool-riffle development as well as increasing flooding potential.

The majority of deep substrate pools are lateral scour pools where high flows impinge obliquely on (and create helical flow patterns along) resistant channel banks, tree roots, floodwalls, and rip-rap. The density and connectivity of these substrate pools is probably much less than for pre-entrenchment substrate pools, assuming the pre-entrenchment channel form supported pool density associated with theoretically normal pool-riffle spacing of about 4-7 channel widths.

2.3. EVIDENCE OF HOLOCENE VALLEY ALLUVIATION AND RECENT CHANNEL ENTRENCHMENT IN MARIN COUNTY WATERSHEDS

Valley filling in northern coastal California began near the Pleistocene-Holocene transition, consistent with the post-glacial valley filling and entrenchment sequence in other parts of California and North America (Montgomery 1999, Harvey et al. 1999a). Radiocarbon (^{14}C) dates of basal gravel contacts in the San Francisco Bay Region showed that regional valley filling began with the late Pleistocene-Holocene transition, about 10,000-12,000 years BP (Montgomery 1999).[1]

Haible (1980) used radiocarbon dating and detailed surveys of exposed channel bank sediment stratigraphy in the Walker Creek basin in northwestern Marin County to show that Holocene valley filling evidently occurred in a single episode (Figure 1).[2] Haible speculated that Holocene alluviation was followed by two recent but distinct channel entrenchment periods. The first phase of channel entrenchment in the high terrace forming the valley flat may have begun in about AD 1720. The second phase of entrenchment indicated by remnants of an inner terrace may have begun in about 1915. Grazing in the Walker Creek basin began in about 1820 and grazing and landscape denudation became most intense in about 1900.

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[1] *Haible (1980) dated one sample of wood from a clayey lens "estimated to be in lower half of basal gravel member", the lower member of valley fill in the Walker Creek basin, northwestern Marin County. Although the single sample was not extracted from near bedrock-basal gravel contacts, Haible (1980) assigned the 5,000 years BP date to the onset of alluviation in Walker Creek. It is likely, however, that valley alluviation in the Walker Creek basin began 10,000-12,000 years BP, consistent with regional observations. Radiocarbon dates of more numerous samples taken from near the bedrock-basal gravel contact would probably verify this.*

[2] *Haible (1980) identified two prominent Holocene alluvial units in the Walker Creek valley fill. The lower member was a cross-bedded gravel deposit about 5 ft thick overlying bedrock, and the upper member was a massive brown sand deposit about 6 to 20 ft thick. A similar Holocene valley fill stratigraphic sequence is exposed in the channel banks in Ross Valley.*

Collins (1998) also concluded that two recent but distinct channel entrenchment periods occurred in the lower Novato Creek watershed in northeastern Marin County (Figure 1). The first phase evidently began in about 1835 associated with the onset of livestock grazing in the 1820s, and the second phase began in the 1950s following construction of Stafford Dam. Collins inferred individual periods of channel entrenchment from the rooting elevation of tree-ring dated riparian trees. A number of even-aged trees rooted on an abandoned inset terrace just below the valley flat elevation were estimated to have been established in about 1835, and a number of even-aged trees rooted on a lower inset terrace were estimated to have begun growth in the 1950s.

Riparian trees in the Corte Madera Creek watershed exhibit similar rooting elevation-age structure as Collins (1998) observed in the Novato Creek basin. Riparian trees greater than 100 years in age are invariably rooted on the valley flat or high on the channel banks just below the valley flat. Riparian trees approximately 50 years in age, primarily Alder (*Alnus*), are rooted on surfaces of high, coarse-grained gravel bars evidently formed during the 1955 flood, or consistent elevations on channel banks. Assuming that the 50-year old trees were in fact established on surfaces of bars deposited in the 1955 flood,[3] rather than on an abandoned floodplain elevation as Collins concluded was the case for lower Novato Creek, the rooting elevation-age structure in the Corte Madera Creek watershed suggests that a single period of channel entrenchment began more than 100 years BP and continued to the present.

Montgomery (1999) used radiocarbon dates of progressively shallower valley fill in Tennessee Valley in southwestern Marin County (Figure 1), to show that valley filling began at the beginning of the Holocene, and that episodic valley aggradation continued from the early Holocene to the present. Montgomery presented geomorphic evidence showing that a single episode of rapid channel entrenchment occurred in Tennessee Valley between 1855 and 1907, followed by minor valley aggradation and relative channel stability since 1907. Tennessee valley was intensively grazed in 1855-1892, but less intensively in 1892-1972.

In summary, the available regional sedimentological data indicate that valley filling began about 10,000-12,000 years BP and continued to the present. Many researchers attribute recent regional channel entrenchment to increased livestock grazing intensity during the latter half of the 1800s, coinciding with a number of wetter than average water years (Montgomery 1999, Collins 1998, Haible 1980, Wahrhaftig and Wagner 1972, Zumwalt 1972). Montgomery (1999) hypothesized that channel response to intense grazing at the turn-of-the-century would continue for hundreds of years. In the Corte Madera Creek watershed, these ongoing responses appear to include: (1) incremental channel head advance in the highest reaches of the drainage network; (2) decreasingly rapid channel bed incision and bank erosion in the upper alluvial channel network; and (3) decreasingly rapid channel bed aggradation in lower reaches of the watershed.

[3] *Long-term creek neighbors on Fairfax Creek recall that the channel bed was devoid of riparian trees in the mid-1950s and remember that the alders in the channel established at about that time (Louis Vaccaro, pers. comm., 1999).*

2.4. DISTINGUISHING BETWEEN PROBABLE CAUSES OF RECENT CHANNEL ENTRENCHMENT IN THE CORTE MADERA CREEK WATERSHED

The available geomorphic evidence indicates that the timing and causes of channel entrenchment in the Corte Madera Creek watershed valley bottoms are consistent with the period of concurrent channel entrenchment in Marin County watersheds. Rapid channel entrenchment in the Corte Madera Creek alluvial channel network between about 1850 and 1910 was probably initiated by altered water and sediment runoff mechanisms due to vegetation removal by logging and grazing, coinciding with a period of frequent and relatively large, but not uncommon storms. To support this assertion, the four possible causal modes of channel entrenchment (Montgomery 1999) and the evidence supporting or refuting each of the four modes are summarized below. This summary also provides additional discussion of historical watershed changes.

TABLE 1
POSSIBLE CAUSAL MODES OF CHANNEL ENTRENCHMENT

MODE	DESCRIPTION
Short-term Climate Variation	A period of extreme rainfall initiates downcutting through a series of unusually high peak discharges;
Declining Sea Level	A falling base level (sea level elevation) at the watershed outlet accelerates erosion upslope in the watershed;
Naturally Unstable Sediment Transport Regime	Sediment transport through fluvial systems is inherently unstable, which results in cyclic aggradation and entrenchment; and
Land Use Modification	Land use modification causes channel entrenchment by changing either the erodibility of valley bottoms or runoff generation mechanisms.

Source: Montgomery (1999)

2.4.1. SHORT-TERM CLIMATE VARIATION

Channel entrenchment in the Corte Madera Creek watershed cannot be attributed to short term climate variation, in and of itself. Regional climatic data shows that the period just prior to and during the period of rapid channel entrenchment is not an anomalous climatic period. A number of wetter than average years occurred during this period, but according to long-term regional dendrochronological data, periods with similar positive departures from long-term mean precipitation rate occurred at least 24 times in the last 1,200 years (Montgomery 1999, Graumilch 1993). High peak flows associated with these wet years were probably a contributing cause, but not the principal cause, of channel entrenchment.

2.4.2. SEA LEVEL DECLINE

Channel entrenchment in the Corte Madera Creek watershed cannot be attributed to declining sea level. Sea level elevation rose about 16 ft since 5,000 BP (Haible 1980), and about 300 ft since about 12,000 BP (Rice et al. 1996:41).

2.4.3. NATURALLY UNSTABLE SEDIMENT TRANSPORT REGIME

Channel entrenchment in the Corte Madera Creek watershed cannot be attributed to its naturally unstable sediment transport regime, in and of itself. Extensive field reconnaissance during this study did not reveal evidence of cyclic entrenchment and aggradation in the Corte Madera Creek watershed. Regional sedimentological evidence indicates that cyclic entrenchment and aggradation did not occur in Marin County watersheds. The Holocene was typified by continuous valley aggradation from the Pleistocene-Holocene transition to the present period of rapid channel entrenchment. Rapid channel entrenchment was caused by increased peak runoff and sediment yield not associated with natural cyclic variation in sediment yield and transport. Land use modifications, such as the introduction of intense livestock grazing, generally increase peak runoff and sediment yields significantly more than natural climatic and sediment transport variation. For example, Prosser and Dietrich (1995) simulated the effect of grazing by clipping vegetation within experimental test sites on grassland hillslopes in Tennessee Valley, western Marin County (Figure 1). They found that critical, or minimum necessary, shear stress for eroding soil particles by overland flow entrainment decreased 3 to 9 times following clipping, a level of change they concluded was greater than climate influences alone generally affects. This experiment demonstrated that the short-term effects of human actions generally dominate the influence of long-term natural processes on runoff and sediment regimes. Other experiments have demonstrated this for impacts on water and sediment runoff mechanisms related to agriculture, construction, logging, and wildfire suppression.

2.4.4. MODIFIED LAND USE

The available evidence supports only the hypothesis that rapid channel entrenchment in the Corte Madera Creek watershed was caused by land use changes, especially logging and increasingly intense livestock grazing in the late 1800s (Figure 11). These rapid land use changes coincided with a number of wetter than average but not uncommon water years (Figure 15).[4] Logging and intense grazing alter vegetation cover, soil permeability, soil moisture capacity, and drainage density so as to increase instantaneous peak flow and sediment discharge, which increases channel depth and channel slope by progressive upstream downcutting and headcut advance extending throughout the affected drainage basin.

Overview of Land Use Modifications

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[4] *Flooding occurred in Marin County in 1861, 1862, 1879, 1881, 1890, and 1895 (Montgomery 1999).*

Corte Madera is Spanish for “cut wood”; virtually all of the trees in the watershed were harvested in the middle 1800s, either for timber or firewood (D. Odion, MMWD, pers. comm., 10/12/99). Spanish Land Grant Ranchos subdivided Marin County. Redwood and fir areas were entirely logged for timber. Oak woodland and chaparral areas were harvested for firewood, and intervening prairies were grazed by sheep or dairy cattle. Marin County Ranchos provided firewood to heat homes in San Francisco. The Spanish Land Grant Rancho located at the present town of Mill Valley and the surrounding watershed was named “Corte Madera del Presidio” -- essentially, in this case, “fire wood for the Presidio”.

A considerable amount of timber was also cut from the hillslopes surrounding Mill Valley. Firewood from the Corte Madera Creek watershed was exported via Kentfield Landing. Baltimore Canyon (the Larkspur Creek subwatershed) was named for the timber sawmill transported to Larkspur from Baltimore, Maryland, by sailboat around Cape Horn in 1849; sawyers harvested old-growth redwood forests from the lower slopes of Mt. Tamalpais in Larkspur Creek, Tamalpais Creek, and Ross Creek basins in short order. A contemporary document concluded that “the principal forest tracts now uncut [in Marin County] are in the Lagunitas Canyon and at Pt. Reyes. The whole slope of Tamalpais in early days was more or less wooded, but by far the greater portion has been denuded. There are about 15,000 acres [23 sq. mi.] of available timber remaining, nearly all of which is in the above localities” (Alley, Bowen & Co. 1880:90).

The distribution of pre-European forested areas and vegetation types in the Corte Madera Creek watershed is approximated by the present distribution of vegetation types in the basin, both being controlled by microclimate and soil type. Thus, the historical distribution of logging and firewood harvesting activities can be estimated by the present distribution of suitable vegetation types. Similarly, the historical distribution of livestock grazing during the 1800s and early 1900s can be estimated by the present distribution of grass-oak woodland and grassland vegetation types (Figure 12). The most extensive oak savanna and grassland areas in the Rancho Canada de Herrera were in the Sleepy Hollow Creek and Sorich Creek basins; dairy ranches persisted in these basins into the middle 1900s. Ranches in the Greenbrae and Laurel Canyon areas along the eastern edge of the basin were urbanized earlier (Figure 13). Virtually all of the valley flats and immediately adjacent hillslopes were certainly grazed, including valley flats in the San Anselmo, Carey Camp, Wood Lane, Deer Park, Fairfax, Bothin, Iron Spring, Tamalpais, and Larkspur Creek basins. Upland areas in Fairfax, San Anselmo, Wood Lane, Deer Park and Ross Creek basins were also certainly grazed, including areas surrounding Loma Alta, White Hill, Happersberger Point, Sky Ranch, Bald Hill, and Ross Hill. The Porteous Ranch occupied the Phoenix Lake basin. A portion of the Lewiz Ranch on the eastern slope of Loma Alta is the only area in the basin that is still grazed (Location 19 in Figure 23).

Forest harvesting and intense grazing modifies or temporarily removes vegetative cover that would reduce and delay fluvial transport of rainfall and sediment to major river channels during rainstorms. An intensely logged or grazed landscape thus transports more water and more sediment to the channel network more quickly. The effect is increased instantaneous peak runoff for a given storm. Concentrated runoff initiates channel head advance, gullying, and drainage network expansion, all of which reinforce increased runoff peaks and fluvial transport of sediment from hillsides to the alluvial channel network.

A contemporary civil engineer reported that livestock grazing "has been so close and continuous, that the forage plants and grasses have nearly disappeared" (Manson 1899:300, as cited in Montgomery 1999). Manson (1899) attributed rapid channel erosion in northern California Coast Range valleys to grazing practices intensifying near the end of the 1800s. Manson wrote:

> When man, actuated by greed or ignorance, or a combination of the two, destroys the protection which nature spreads over rolling and mountain areas, he turns loose agencies which soon pass beyond his control. The protecting agent is vegetation, and whether in the form of forests, brush, or forage plants and grasses, the balance between it and denuding forces is easily tipped, when the inexorable law of gravity unchecked by myriad blades of grass, by leaves, roots, and vegetable mold, gullies the hillside, strips the mountain slope, converts rivulet into the torrent, and causes the steady flow of the river to become alternately a devastating flood or a parched sand-bed. When once this balance has been destroyed, man cannot turn back the torrent and bid it flow once more a living and life-giving stream.

Natural runoff processes probably reestablished in part by the early to middle 1900s as portions of the basin reforested. Natural runoff mechanisms also were partially restored in grassland areas of the basin as grazing intensity gradually reduced in the early to middle 1900s, but many of the grazed areas were rapidly urbanized. Natural runoff mechanisms in steep and/or protected grassland, chaparral, and oak savanna areas, not urbanized in the middle to late 1900s, have more completely restored, but drainage network expansion and gullying have not completely reversed, and shallow-rooted annual European grasses have replaced deep-rooted native perennial bunch grasses. Thus, it is reasonable to presume that the present watershed sediment yield by hillslope processes is greater than for the pre-European watershed condition.

Although natural runoff mechanisms partially recovered in forested areas, and to a lesser extent in grazing areas protected from urbanization, any reduction in instantaneous peak runoff was offset by the reinforcing effect of urbanization (Figure 14). Urbanization further increases drainage density by replacing natural runoff routes with impermeable surfaces, streets and stormwater drains. Urbanization also reinforces increased rainfall runoff by suppressing the natural wildfire regime. When fires do occur, they are hotter and thus remove more vegetative cover and cause greater increases in soil impermeability, particularly in chaparral areas.[5] Urbanization can also induce catastrophic local sediment inputs by causing local landslides,

[5] *Urbanization suppresses the frequency and extent of wildfires, which increases the density of so-called ladder fuel materials above the groundcover and below the canopy (routine wildfires suppress ladder fuel density and are a fundamental ecological process supporting some plant communities, such as chapparal). The result is fewer and less extensive but more intense wildfires, which can produce rapid sediment delivery to the channel network (De Bano 1969).*

gullying, or debris flows by concentrating overland flow and road-cutting on hillslopes. Landsliding into upland channels is the principal sediment source mechanism in northern California Coast Range watersheds. Human actions that increase landslide frequency or magnitude therefore can substantially increase watershed sediment yield compared to natural, pre-disturbance yields.

Corte Madera Creek rainfall runoff peaks can probably be reduced if measures are taken to increase on-site stormwater retention in urbanized areas (Figure 15). However, a high proportion of clay-rich alluvium and local saturation of the alluvial fill during the rainy season limits the potential feasibility and effectiveness of stormwater retention at many sites in the watershed. A methodology for identifying and evaluating suitability of candidate demonstration project sites is outlined in Appendix J.

2.5. NATURAL GEOMORPHIC RECOVERY OF THE CORTE MADERA CREEK WATERSHED'S ENTRENCHED ALLUVIAL CHANNEL NETWORK

Entrenchment is a common geomorphic response to increased peak runoff and sediment yields initiated by intense landscape disturbance; entrenchment enables the channel to transport increased sediment load by increasing flow velocities and channel gradient. Natural geomorphic recovery of entrenched channels occurs primarily by these geomorphic processes: As sediment load decreases following the period of intense disturbance, channel gradient generally decreases by progressive upstream channel aggradation in the lower portion of the watershed, progressive headward channel incision in the upland reaches, and relative channel bed stabilization, channel widening and increased channel meandering in the middle reaches.

Following entrenchment, larger and larger floods were entirely contained in the deepened channel, and more and more excess hydraulic energy eroded the channel bed and banks. This positive feedback mechanism prevents recovery of the pre-entrenchment channel form. Entrenched channels rarely re-occupy their pre-entrenchment floodplain. Rather, entrenched channels typically remain entrenched, but reach a more stable bed elevation (channel depth) and channel slope, and then widen (Schumm 1999, Figure 16).

Widening further increases flood capacity, but also reduces maximum flow velocity and bed and bank shear stress by reducing average flow depth and velocity during floods. Widening also allows some channel meandering to occur, which further reduces channel gradient. Increased width, increased meandering, and decreased gradient allow inset floodplain formation and pool-riffle development within the entrenched channel; active floodplain formation and pool-riffle development also indicate that the natural geomorphic recovery processes are underway.

The process of systematic channel widening can be expected to continue at or near its present rate for at least several more decades or hundreds of years, until the active channel width approaches its pre-entrenchment value (Figure 3). Then, the plan form boundaries of the active channel will become more stable, and habitat-creating processes will occur within entrenched channel that can sustain riparian and aquatic habitat values that are comparable to those formerly sustained by the pre-entrenchment channel (Figure 16).

2.6. SEDIMENT YIELDS AND A PRELIMINARY SEDIMENT BUDGET FOR THE CORTE MADERA CREEK WATERSHED

Sediment load is the measured or estimated amount of sediment flowing past a designated location in the channel network from its contributing watershed drainage area. Sediment load is comprised of bedload, suspended sediment load, and washload (dissolved sediment). *Sediment yield* is the rate of sediment passing from the outlet of a designated drainage basin per unit drainage area, e.g. reported in units such as tons/sq.mi./year. The USGS commonly measures sediment yield at flow gaging stations by periodically sampling bedload and suspended sediment load passing the gage for a range of discharges. Average yield is calculated by integrating over a frequency distribution of discharge from the long-term record. Sediment yield can also be accurately measured for areas draining into reservoirs that trap 100 percent or some known percentage of the total incoming sediment load; yield is calculated by measuring the reduction in reservoir storage capacity caused by sediment deposition in the reservoir over a known time period. Published estimates of sediment yield are available for many drainage basins above USGS stream gaging stations and dams throughout the U.S. These data show that the basin's underlying geologic type strongly influences average annual sediment yield for a given drainage basin area.

USGS or reservoir sediment yield data are often not available at the outlet of the drainage area of interest. In the absence of data, as is the case with the USGS gage at Ross, sediment yield can be reasonably estimated by empirical relations between sediment size distribution present on and beneath the channel bed and sediment transport (e.g., Parker and Klingeman 1982), integrated over a probability function of discharge at the site.[6] Estimates of sediment yield for a given drainage basin should be compared to measured sediment yields for basins with the similar underlying geology, or basins in the same geologic province.

A *sediment budget* is an accounting procedure that adds and subtracts sediment source rates and sediment sink rates identified in the drainage area to account for the measured or estimated total sediment yield at its outlet. For example, Kelsey (1980) constructed a detailed 1941-1975 sediment budget for the Van Duzen River in Humboldt County that distinguishes sediment sources and sinks accounting for measured sediment yield at the basin outlet at Bridgeville (Table 2).

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[6] *Using measurements of the size distribution of sediment present on and below the channel bed, the rate of bedload sediment transport is calculated for each of a range of modeled discharges. Bedload sediment transport rates are multiplied by the probability that those discharges occur at the site (often extrapolated from a nearby flow gage record and corrected for drainage area and orographic effects). Integrating over the data and adding estimated suspended sediment component generates an estimate of the average annual sediment yield at the site.*

Kelsey (1980) showed that fluvial transport from upland hillslope sediment sources produced 95 percent of the sediment delivered to the alluvial channel network in 1941-1975, while channel bed and bank erosion produced only 5 percent. Kelsey also showed that sediment yields per unit drainage area were greater for unforested subwatersheds underlain by less competent Franciscan rocks. For example, rolling and humocky grassland-covered subwatersheds underlain by less competent Franciscan melange rocks comprised only 38 percent of the total drainage area, but yielded 91-99 percent of the total hillslope sediment yield. Steep, forested subwatersheds underlain by more competent Franciscan sandstones and metasandstones comprised 55 percent of total drainage area but produced only 1-8 percent of hillslope sediment yield. Thus, Franciscan melange subwatersheds produced about 30 times more sediment yield per square mile than competent Franciscan sandstone subwatersheds. Kelsey also showed that sediment yield by bedload sediment transport was typically 9-15 percent of the yield by suspended sediment transport in the Van Duzen River watershed.

This study used measurements of changes in historical channel geometry from 1976-1999 and model estimates of average annual bedload sediment yield from major upland subwatersheds to construct a preliminary sediment budget accounting for total sediment yield at Ross (Table 3, Figure 18).

TABLE 2
ESTIMATED SEDIMENT BUDGET FOR
THE VAN DUZEN RIVER WATERSHED AT BRIDGEVILLE
(in tons/sq.mi./year, and percentage of total sediment delivered to the channel)

Total sediment yield measured at Bridgeville (7700, 83%)

= Sediment yield from uplands by fluvial transport from **hillslopes** (6800, **73%**)

\+ Sediment yield from uplands by **landslide** sediment inputs (2000, **22%**)

\+ Sediment yield by **channel bed and bank erosion** along the alluvial channel network (500, **5%**)

– **Channel bed aggradation** in the alluvial channel network (1600, **17%**)

Source: Kelsey (1980)

TABLE 3
PRELIMINARY CONCEPTUAL SEDIMENT BUDGET FOR
CORTE MADERA CREEK WATERSHED AT ROSS

	(1) Total sediment yield estimated at Ross (tons/sq.mi./yr)
=	**(2)** Sediment yield from **upland channel**s/subwatersheds (tons/sq.mi./yr)
+	**(3)** Sediment yield by **channel bed and bank erosion** along the alluvial channel network (tons/sq.mi./yr)
–	**(4) Channel bed aggradation** in the alluvial channel network (tons/sq.mi./yr)

This preliminary sediment budget accounts for sediment generated by hillslope processes in upland subwatersheds and sediment generated by channel bed and bank erosion and channel aggradation in the alluvial channel network. This budget does not distinguish between various sediment source mechanisms (e.g., landslides, debris flows, downslope soil creep, gully transport and gully headcut advance, overland sheetwash, etc.). Rather, it estimates sediment load from upland channel networks by estimating the capacity of the channel outlet to pass sediment, given its hydrology, slope, form, and channel bed sediment size distribution (following Parker and Klingeman 1982). Assuming there is no long-term net channel bed erosion/aggradation in the upland channel network, the estimated load passing the outlet should approximate the load delivered to the channel network by hillslope processes.

The available historical channel geometry, sediment yield, and sediment transport data influenced the time period for which the budget could be estimated, and the methods and assumptions used to quantify estimates for budget components. Existing data and study approach are reviewed below in Section 3, and methods and assumptions are documented in Section 4.

3. THE INFLUENCE OF HISTORICAL DATA SOURCES AND DATA GAPS ON STUDY APPROACH

Section 3.1 reviews hydrology, sediment transport, and sediment yield data useful for estimating sediment yield by various generating mechanisms in the watershed. Section 3.1.6 reviews existing regional data useful for comparing to this study's results, such as sediment transport and sediment yield data from comparable watersheds are summarized in tables appended to the end of this report. Section 3.2 reviews historical channel geometry data, photos, and other accounts useful for quantifying sediment yield by channel bed and bank erosion in the alluvial channel network.

3.1. HYDROLOGY, SEDIMENT TRANSPORT, AND SEDIMENT YIELD DATA

3.1.1. HYDROLOGY DATA

In January 1951, the USGS began mean daily flow measurements about 300 ft upstream of the Lagunitas Road Bridge in Ross (Figure 2). The USGS published mean daily flows and monthly and annual summary data for this gage, Corte Madera Creek at Ross, no. 11460000, until it was discontinued in September 1993. (MCFCD maintained the gage after 1993). The USGS reported that the records were "poor" for some water years. Inaccurate flow records were probably caused by progressive channel bed aggradation at the gage since it was constructed (Figure 10). Although the bed level elevation has recently stabilized, historical fluctuations probably continually caused the stage-discharge relation from which the USGS calculated mean daily flow to change. The gage also does not record a portion of extremely high flows that overflow onto streets parallel to Corte Madera Creek. We used mean daily discharges for the entire period of USGS records (1951-1993) to prepare a flow frequency distribution used in our model estimates of sediment yield by sediment transport past the Ross Gage. We apportioned the flow frequency distribution by subwatershed drainage area to produce distributions used in subwatershed sediment yield estimates.

3.1.2. SEDIMENT TRANSPORT DATA AND SEDIMENT YIELD ESTIMATES

Sediment transport measurements can be used to calibrate analytical sediment transport models for estimating sediment yields and constructing sediment budgets. The USGS published daily suspended sediment concentration data at the Ross Gage for 1978, 1979, and 1980, and several bedload transport measurements in 1978. The EPA (1985) published suspended and bedload sediment size distribution and estimated yield data at the Ross Gage for 1978-1980 (COE 1987). These are the only published historical sediment transport measurements for the watershed. We calculated total suspended and bedload sediment yields for these water years directly from these USGS published data and included these results in our summary comparisons of regional sediment yield data and results of this study (Table 10). We also used these data to calibrate the Parker-Klingeman bedload transport model which we used to estimate annual average bedload transport at the Ross Gage.

Referring to the USGS sediment transport data for 1978-1980, COE (1989:19) noted that "Measured sediment inflow data for Corte Madera Creek are inadequate to determine a reliable sediment inflow rating curve for the entire range of discharges considered in this study." However, based partly on these data and EPA (1985) sediment size distribution data, a 1989 COE sediment transport model estimated the average annual bedload sediment yield at the Ross Gage was about 8,200 cubic yards or 11,070 tons (COE 1989:34). The COE includes very fine sand and fine sand size fractions (0.062-0.250 mm) estimated to pass the gage in the bedload sediment yield (COE 1989:31). This study's sediment transport model assumed sediment less than 0.250 mm would be transported past the gage as suspended load rather than bedload. The COE model should therefore estimate total sediment yield at Ross to be about 10 percent greater than our model results. Noting this difference, we included the COE bedload yield estimate in our comparisons of bedload and total sediment yield estimates at Ross Gage.

3.1.3. Channel Sediment Dredging Records

Repeated channel sediment dredging records can provide estimates of sediment inflow. The Town of Ross extracted sediment in the vicinity of Lagunitas Road Bridge each year since 1987, except 1990 and 1992 (Charlie Goodman, Town of Ross, pers. comm., 2000). These data do not provide a direct measurement or reliable independent estimate of total bedload sediment yield at Ross because only a portion of the bedload transport past Ross is deposited in the extraction reach below the bridge. We obtained these data to provide a lower limit estimate of bedload sediment inflow at the Ross Gage, about 300 feet upstream from the extraction site. These data do not include sediment size distribution for the extracted materials. According to interviews conducted during the course of this study, there was not channel dredging before the Town of Ross started in 1987.

We also obtained data for sediment extracted by the COE and MCFCD from the flood control channel in the vicinity of College of Marin Bridge in 1972, 1986, and 1998 (Jason Nutt, MCFCD, pers. comm., 2000). These data indicate that a small portion of the annual sediment transport was extracted by these dredging activities. The data did not include an estimate of sediment volume extracted by COE in 1972. If these data exist, they might provide an annual deposition value, as the flood control channel was completed in 1971.

Various investigators have collected bed sediment samples from the flood control channel and analyzed sediment size distribution (e.g., Shepherd 1987). However, most of these data have not been published. The COE probably also holds related data not obtained during this study. The complete set of sediment extraction and size distribution data was not compiled in this study. Regardless, these data describe the portion of inflowing material deposited at Ross, and not the entire load, and therefore would only provide an extreme lower limit for sediment yield estimates at Ross.

MMWD dredges approximately 100 yards of bed material along Wood Lane Creek at the subwatershed outlet site (at Marin Stables) in order to prevent sediment deposition from blocking culverts immediately below the site. The volume of sediment potentially trapped in the excavation is in the approximate range of estimated annual bedload sediment yield at the site. It may be possible to roughly calibrate Wood Lane Creek subwatershed sediment yield estimates developed as part of this study with annual extraction and refilling data. We surveyed the post-excavation bathymetry of the trap in order to estimate refilling by repeated surveys, and re-surveyed the bathymetry twice during the 1999-2000 winter rainy season.

Marin County Open Space District (MCOSD) annually excavates sediment plugging more than about 60 culverts along the Southern Marin Line fire road below Corte Madera Ridge (Brian Sanford, MCOSD, pers. comm., 1999). If data were kept to estimate the total excavation volume, they could provide a lower limit estimate of sediment yield from Corte Madera Ridge above the Southern Marin Line fire road (Site no. 2 in Figure 23). Such an estimate would probably reasonably represent the lower limit of sediment yield for those sediment sizes above the dominant size class represented in the excavated material, but would not accurately account for the yield of finer sediment not efficiently trapped by the Southern Marin Line road-cut. Ambrosia beetle infestation is likely to cause substantial die-off of tan oak on Corte Madera Ridge (D. Odion, MMWD, pers. comm., 1999). Monitoring sediment yield above the road-cut might allow an estimate of any increased sediment yield caused by the beetle infestation over time.

3.1.4. RESERVOIR SEDIMENTATION DATA AND DREDGING RECORDS

Reservoir sedimentation rates can provide an accurate estimate of long-term average sediment inflow from the drainage area contributing to the reservoir. Calculated sediment yield can be compared to estimated sediment yields in other comparable portions of the basin. Phoenix Dam was built ca. 1913 to impound runoff from 2.3 square miles of the upper Ross Creek subwatershed for water supply (Figure 2). However, long-term sedimentation rates cannot be calculated for the upper Ross Creek subwatershed because MMWD does not hold as-built or contemporary bathymetric maps of the reservoir (Dana Roxon, MMWD, pers. comm., 1999). The volume of Phoenix Lake, and changes in its volume, cannot be accurately calculated without repeat bathymetric surveys. These surveys are not anticipated, because sedimentation is not considered a problem for Phoenix Lake; MMWD is updating its reservoir capacity database and monitoring program in Lake Nicasio and other watersheds (Dana Roxon, pers. comm., 1999), evidently where sediment yield is greater, and/or demand for reservoir capacity is greater.

MMWD reportedly dredged an unknown volume of Phoenix Creek delta deposits from the reservoir. The volume extracted would not provide an accurate measurement of long-term average sediment yield from the Phoenix Creek subwatershed, because original bathymetric data is not available.

There are several smaller reservoirs and check dams in the watershed that have already completely filled with sediment, preventing calculation of short-term sediment yields. For example, a dam on Bill Williams Creek just upstream from Phoenix Lake is completely filled with sediment. MCOSD installed a series of boulder check dams to slow downcutting near the outlet of Carey Camp Creek in the San Anselmo Creek subwatershed that filled in with sediment in approximately two winters (Brian Sanford, MCOSD, pers. comm., 1999). Westbrae Dam on Fairfax Creek is completely filled with sediment. Lower limits for bedload sediment yield from Bill Williams, Carey Camp, and upper Fairfax Creek could potentially be estimated if data were obtained for these filled reservoirs describing sediment volume, dam construction date, and the date reservoir filled.

3.1.5. Hillslope Process Rate Data

Detailed sediment budget studies generally indicate that sediment transported to the channel network by landsliding and earthflows dominate total sediment yield in northern California Coast Range watersheds underlain by Franciscan melange. Thus, quantifying annual sediment yield from the various discrete hillslope sediment production mechanisms is often important not only for understanding where the sediment is coming from, but also where and how best to improve upland management practices in order to reduce sediment yield.

Hillslopes transport sediment to upland channels by landsliding, earthflows, fluvial transport in gullies, gully headcut advance, downslope soil creep, and overland sheetwash. Detailed sequential aerial photographic interpretation combined with rather extensive ground-truthing can be sufficient to roughly quantify annual yields from some of these discrete source mechanisms. More accurately quantifying annual yields additionally requires longer-term field monitoring using a variety of office and field methods, such as those described by Reid and Dunne (1996). Inevitably however, accurate estimates are naturally confounded by the episodic nature of hillslope sediment contributions in Coast Range watersheds. For example, Kelsey (1980) attributed 21 percent of the total sediment yield for 1941-1975 to landsliding that occurred in 1964. Therefore, aerial photo interpretation and field monitoring must capture a representative portion of the long-term record in order to produce accurate average yield estimates. These methods are also confounded because the view of the ground surface is partially obstructed in forested watersheds.

Quantitative hillslope process rate data were not available for any portion of the Corte Madera Creek watershed. This study did not attempt to quantify sediment yields by discrete hillslope sediment source mechanisms. Rather, this study estimated sediment yield from upland channel networks by sediment transport modeling. The amount of sediment passing upland subwatershed outlet sites is approximately the same as the amount of sediment delivered to upland channels from hillslopes, because upland channels are cut entirely in colluvial materials derived from upslope or bedrock; there is virtually no long-term sediment storage in the channel or floodplain. Partially owing to channel entrenchment, there is little if any alluvial deposition on the channel bed, floodplains, or terraces within the modeled subwatershed areas. Furthermore, the channel dimensions and slope at the subwatershed outlet sites reflect dimensional adjustment to the prevailing sediment load. It follows that the channel dimensions can reflect adjustment to recent episodes of catastrophic sediment inputs, such as may have been contributed by 1981-1982 (Figure 20), and so produce model results that overestimate the long-term average sediment yield.

Although quantitative hillslope sediment yield data were not available, the USGS and other resource agencies have published several detailed geologic maps showing the distribution of landslides, gullies, earthflows, and soil creep zones interpreted from aerial photographs for all or part of the watershed. We compiled many of these data and produced maps covering the watershed area. USGS and other agencies also published qualitative maps showing relative hillslope stability for all or part of the watershed according to aerial photo interpretation of approximate landsliding and earthflow frequency, slope, and detailed field assessment of underlying geology. However, none of these analyses included quantitative estimates of landslide and earthflow frequency, or downslope creep rate, from which hillslope sediment yield could be roughly estimated. Field reconnaissance also revealed general limitations of the existing maps for this purpose. For example, reconnaissance invariably revealed that published gully maps underestimated the gully distribution and density.

Because landslide and earthflow contributions probably dominate the long term average sediment yield of the watershed, a watershed map was produced showing the distribution of USGS hillslope stability and landslide frequency estimates in the watershed (Figure 24). This map shows the relative distribution of hillslope sediment yield approximated by USGS data to provide an independent qualitative estimate of relative sediment yield from the major Corte Madera Creek subwatersheds.

3.1.6. Regional Sediment Transport, Yield, and Budget Estimates from Other Studies

Sediment transport and yield data from comparable watersheds in the region can be used to provide upper and lower limits to constrain preliminary uncalibrated sediment transport and yield estimates. We compiled available transport and yield data for watersheds underlain by highly deformed Franciscan melange rock types, such as the Van Duzen River and the greater Eel River watershed to provide an upper limit for estimates made in this study. Owing to extremely high tectonic uplift rates, intense shearing and melange deformation, exacerbated by periods of intense landscape disturbance by logging, long-term average sediment yields in the Eel River are among the highest in the western United States (Judson and Ritter 1964). Marin County watersheds undergo a lesser but still significant uplift rate, and are lower on the continuum of melange deformation. We also compiled available data for less urbanized Marin County watersheds to provide a lower limit for estimates made in this study, such as Lehre's (1982) 1971-1974 sediment budget for Lone Tree Creek in southwestern Marin County (Figure 1). We also compared this study's budget results to those of Lehre (1982), Collins (1998), and Haible (1980) regarding the relative percentage of total sediment yield generated by channel bed and bank erosion in Marin County watersheds. Comparisons to regional studies are made in summary data tables presented in the study results.

3.2. Historical Channel Planform and Cross-Section Geometry Data

3.2.1. Historical Aerial Photography

Sequential aerial photography can often be used to assess and sometimes accurately measure channel plan form and riparian vegetation changes, depending on scale and view obstruction by vegetation cover. Air photos can also be used to characterize and map hillslope stability, landslide activity, logging and upland road building activities, gully formation and gully headcut advance as discussed briefly in Section 3.1.5. We reviewed 1946, 1960, and 1996 stereo aerial photography of the Corte Madera watershed held in the UC Berkeley Earth Sciences

Library. Scale and other attributes of these and other available aerial photographs covering the watershed are tabulated in Appendix A.

Small air photo scale, dense riparian forest canopy cover, and dense urbanization prevented making reliable measurements or qualitative observations of historical changes in channel plan form, channel bed form, and aquatic and riparian habitat. Regardless, geomorphic reasoning would suggest that there have been no measurable changes in channel plan form after the period of rapid channel entrenchment began in about 1850. The earliest aerial photos, from 1946, were made after the valley flat was nearly entirely urbanized. This prevents accurate assessment of pre-disturbance riparian conditions, or meaningful measurements of riparian zone width changes. An exception is the Sleepy Hollow Creek subwatershed. The 1946 air photos pre-date urbanization of the Canada de Herrera ranch lands along the north and south forks of Sleepy Hollow Creek. The photos indicate heavy grazing impacts on the hillslopes and valley flats. Very little riparian vegetation was established along upper Sleepy Hollow Creek in 1946.

3.2.2. HISTORICAL BED ELEVATION AND CROSS-SECTION DATA

Historical cross-section survey data can be compared to current survey data to accurately measure changes in channel bed elevation and channel width caused by net channel bed incision (aggradation minus degradation) and channel widening. The rate of change in bed elevation and width can be calculated by dividing these measured changes by the period of years between measurements. Sediment yield generated by net channel bed and bank erosion can then be estimated by multiplying the average cross-sectional area change for all resurveyed sites in the watershed by the length of the affected channels. We searched for historical cross-sectional data for these purposes, including as-built bridge documents and bridge foundation inspection and repair records, and historical topographic and cross-sectional survey data for drainage and flooding studies.

We requested bridge records from municipal and county officials, but obtained no information regarding potential sources of these data. We searched mixed historical records held by the City of San Anselmo Public Works Department. This search only revealed various flooding management studies for Sleepy Hollow Creek and San Anselmo Creek showing schematic cross-sections not suitable for resurveying. We also obtained general anecdotal information that most other bridge foundations were culverted or 'box' bridge foundations and so did not experience undercutting (George Davidson, City of San Anselmo, Public Works Department, pers. comm., 1999). An exception was a historic bridge in downtown San Anselmo. We viewed ca. 1913 as-built cross-section data for the bridge at the San Anselmo DPW. The cross-section data was not suitable for dimensional comparison with repeat survey data, but field reconnaissance showed that there had been no significant channel bed elevation change at the bridge since 1913. The contact between channel bed and bridge foundation was similar to that shown in the as-built cross-section.

MCFCD provided a detailed photogrametric topographic map (2 ft contour interval) of Ross Creek and Corte Madera Creek performed by Clair A. Hill and Associates in 1966. The map included tens of cross-sectional surveys demonstrating relatively good resolution. However, obtaining lateral control for resurveying the unmonumented cross-sectional surveys would have been cost prohibitive. We made spot checks of channel width at various locations that revealed no significant channel widening, and reoccupied the longitudinal profile in a reach of Ross Creek from its mouth to Shady Lane Bridge, about 300 ft upstream that showed minor net channel aggradation. Based on these observations, we did not pursue extensive and costly reoccupations of these historical cross-sections.

At the onset of the study, we assumed the most extensive and consistent historical cross-section data set would be contained in 1971-1976 HUD and FEMA Flood Insurance Study (FIS) records. These studies employed hydraulic model input data from the incorporated portion of the alluvial channel network. We obtained all of the available FIS records from Baker Services in Alexandria, Virginia, and exhaustively searched them for original cross-section field survey notes and/or HEC-2 input data used in (FIS) hydraulic modeling. Many of the records were poorly preserved as third- and fourth-generation 1970s xerox copies, or microfiche copies of those. The records were determined to be incomplete. HEC-2 input data were redundant and incomplete for individual FIS studies. Much of the backup data is presumed to have become misplaced while it was held by the USGS in Menlo Park (David Dawdy, consulting hydrologist, pers. comm., 1999).

We were able to identify potentially reliable cross-section survey data for several cross-sections on Deer Park Creek, Larkspur Creek, Sorich Creek, and Fairfax Creek from 1971-1976. We conducted field reconnaissance of these sites to identify addresses of creek neighbors for obtaining advance permission to resurvey the cross-sections, but, in so doing, invariably found problems preventing accurate or fruitful comparisons. All of the Sorich Creek cross-sections were surveyed across reinforced sections of the creek and would not be expected to show channel incision. All of the Deer Park Creek cross-sections were surveyed prior to dense urbanization of the portion of Deer Park Creek below Meerna Ave. In many cases historical cross-section sites were covered with homes, with the creek confined in an underground culvert. The Fairfax Creek and Larkspur Creek cross-sections traversed sections of the creek with one or both creek banks reinforced by rip-rap and flood walls of various generations and ages, and absence of lateral control often prevented useful resurveying. Lateral control was also absent from the cross-sectional profiles we were able to obtain from HEC-2 input data. Based on our data search results and field reconnaissance of the sites, we determined that systematic measurement of channel widening rates could not be accomplished by repeat cross-section surveys. We compiled observations of tree-root scour along channel banks during reconnaissance of survey sites to provide an estimate of channel widening rate absent survey data.

We also obtained historical cross-section surveys of the Ross Gage from 1951, and data summarizing bed elevation changes at the gage over time. We resurveyed the Ross Gage cross-section in January 2000, and compared this to historical cross-sectional geometry. We also superimposed an idealized 'equilibrium' channel cross-section for the Ross Gage based on Luna Leopold's channel dimensions contained in an unpublished data manuscript in the Water Resources Center Archives at UC Berkeley (Figure 10). This demonstrated the difference between the existing entrenched channel condition and 'equilibrium' channel conditions based on Leopold's regression relations for SF Bay Area channels with the same drainage area (Dunne and Leopold 1978).

3.2.3. HISTORICAL LONGITUDINAL PROFILE DATA

Although the available FIS study backup data did not provide necessary and sufficient data for measuring changes in cross-sectional area, the FIS studies contained relatively detailed longitudinal profile data with an approximate vertical accuracy of 0.1 ft. We resurveyed 44 spot channel bed elevations distributed throughout the incorporated alluvial channel network to measure changes in bed elevation from 1976 to 1999. No long profile data were available for Larkspur Creek, Tamalpais Creek, Ross Creek, Deer Park Creek, and Wood Lane Creek. However, as described above, we also resurveyed a portion of the long profile of Ross Creek interpreted from 1966 topographic maps. We did not resurvey spot elevations along Sorich Creek because the channel was heavily reinforced at the time of the historical survey.

3.2.4. HISTORICAL GROUND PHOTOGRAPHY

Historical ground photos can often be used to characterize historical habitat attributes and measure changes in channel depth and width by direct comparison with photos and field surveys (Smeltzer and Kondolf in preparation). However, our literature review at University of California, Berkeley libraries did not reveal historical ground photographs of the watershed. Area historical libraries probably hold historical photograph collections containing at least several useful historical photos of Corte Madera Creek and its tributaries that were not reviewed in this study. It would be useful for FCMCW volunteers to review public historical photo collections for individual photos that show channel depth relative to fixed elevations, riparian tree rooting elevations, or channel bed and bank conditions. Also, the FCMCW should consider making a public request for area families to review their private collections for photos showing these attributes. Some of the citations contained in Appendix I may contain ground photos of the channel network.

We encountered low-quality photographs made of various bridges from the bed of San Anselmo Creek, Sleepy Hollow Creek, and Corte Madera Creek contained in various flood management reports (e.g., Hoffman and Albritton 1970). These photographs were intended to show bridge openings and were not useful for measuring changes in channel width and depth. In general, these and other 1970s photographs reviewed during this study did not show any measurable undercutting of bridge foundations, consistent with present field observations of the same locations.

A circa 1927 ground photograph showing the channel bed near the Lagunitas Road bridge in Ross indicates that the channel bed elevation was several feet lower than it is today (Scott Nicholson, COE, pers. comm., 2000). We did not obtain or review this photograph during this study. This information is consistent with the hypothesis that the majority of channel downcutting was complete by about 1910, and that the lower portion of the channel network has experienced channel aggradation since that time. Figure 10 shows that channel aggradation measured at the USGS gage (about 300 ft upstream from the Lagunitas Road bridge) evidently ceased after about 1964.

3.2.5. HISTORICAL MAPS

Historical maps are often useful for characterizing general historical riparian conditions and channel migration, and sometimes measuring changes in channel plan form. We reviewed several historical maps of Marin County dating back to ca. 1840 held in the Bancroft Library at the University of California at Berkeley. Most of the earliest maps were intended to show the boundaries of Spanish Land Grant Ranchos, such as Canada de Herrera in the northern portion of the Corte Madera Creek watershed. The earliest maps were very schematic and did not accurately characterize the channel network. Unfortunately, the detailed US Coast and Geodetic Survey (USC&GS) maps made during the 1850s of southeastern and western Marin County coastal areas evidently do not cover any portion of the Corte Madera Creek watershed. These maps generally included somewhat accurate representations of channel plan form and width, including the extent of near-channel riparian trees.

We also reviewed privately published maps of Marin County from 1860, 1898, 1910, 1914, 1925. These maps generally showed the progression of railroad and roadway construction in the watershed, but did not include useful data on channel changes or grazing area distribution. We used the extent of urbanization indicated in the 1910 map in conjunction with the later accurate series of USGS 7.5' topographic quadrangles to show the progression of urbanization in Figure 13. We reviewed USGS quads from 1954, 1980, and 1993. USGS quads did not show channel plan form changes or historical riparian forest cover. We used USGS quads to map forested and open vegetation cover types in preparation of Figure 12, Figure 13, and Figure 25.

3.2.6. HISTORICAL ACCOUNTS

Historical accounts, memoirs, and regional historical summaries sometimes provide useful data concerning the early channel plan form and dimensions, although these scant gems are usually buried amidst hundreds of pages of unrelated information, or must be inferred from indirect evidence.

William Brewer traversed eastern Marin County in about 1861, but his published accounts were limited to his experiences at the Spanish Mission at San Rafael and observations of Mt. Tamalpais. Alley, Bowen & Co. published an early history of Marin County in 1880 that failed to include any information regarding Corte Madera Creek or its tributaries. Other historical accounts not reviewed in this study may provide data on the pre-entrenchment channel and floodplain conditions. A number of promising historical accounts are listed in Appendix I. FCMCW should consider identifying volunteers to search remaining sources for references to creek conditions.

Creek neighbors encountered during field surveys and reconnaissance provided us with descriptive accounts of historical channel changes in the creek adjacent their homes. Many of these data were used in the preparation of this report. FCMCW should consider distributing a voluntary survey to creek neighbors soliciting this information for the entire urbanized channel network. A fluvial geomorphologist could review responses to identify interesting accounts worthy of follow up site visits. This process could potentially uncover useful historical channel change data this study did not obtain.

4. SEDIMENT BUDGET METHODS

4.1. MEASURING HISTORICAL CHANGES IN CHANNEL GEOMETRY

Limitations of existing historical channel plan form and channel geometry data were summarized in Section 3.2. Channel bed elevation changes were estimated by surveying 44 spot elevations along San Anselmo Creek, Sleepy Hollow Creek, and Fairfax Creek to replicate longitudinal profile data contained in 1976 FIS studies. Spot elevations coinciding with the 1966 topographic survey of Ross Creek were surveyed, and channel bed width and estimated terrace height were recorded at each of the 44 survey sites.

We conducted a field reconnaissance of these potential survey sites and listed creek neighbor addresses for obtaining necessary permission from creek neighbors. With volunteer assistance, the channel elevations were surveyed with an auto-level referenced to known elevations where available, and otherwise referenced to arbitrary elevations on bridge foundations or bridge decks, manhole covers, or fire hydrants. We provided a list describing arbitrary benchmarks we established at 19 locations in the watershed to MCFCD. MCFCD determined elevations of these benchmarks to within +/- 0.1 ft above mean sea level (NGVD29) (Don Hobbs, MCFCD, pers. comm., 2000). These benchmark descriptions and elevations are tabulated in Appendix D. Benchmark elevations determined by MCFCD were used to calculate present channel bed elevations. The 1999 spot elevations were plotted on a longitudinal profile map adapted from complete 1976 FIS records to show the longitudinal distribution of elevation samples and channel incision. We tabulated average values of channel bed incision for individual tributaries and aggregate values for the alluvial channel network.

4.2. ESTIMATING SEDIMENT YIELD BY NET CHANNEL BED AND BANK EROSION

Measured channel elevation change was multiplied by the measured channel bed width to estimate cross-sectional area change by net channel bed erosion from 1976-1999 at each of the 44 historical data sampling sites. Sediment yield by net channel bed erosion in the alluvial channel network for 1976-1999 was estimated by multiplying the average change in cross-sectional area for each major tributary by its total alluvial length.

To provide an upper limit estimate of sediment yield by bank erosion for the same time period in the absence of systematic channel cross-section data comparison, we estimated that one of the two channel banks retreated a total of 2 feet from 1976-1999. This constitutes a conservative, upper limit value of bank retreat because the maximum lateral root scour measurement of all point measurements in the watershed was about 2 ft. Average cross-sectional area change by bank erosion was calculated at each of the 44 sites by multiplying 2 ft of bank retreat by the measured terrace height. We then estimated sediment yield by bank erosion in the alluvial channel network for approximately 1976-1999 by multiplying the resulting average change in cross-sectional area for each major tributary by its total alluvial length.

4.3. ESTIMATING SUBWATERSHED BEDLOAD SEDIMENT LOADS AND YIELDS

Characteristic reaches were selected along each of ten major Corte Madera Creek tributaries to serve as subwatershed outlet sites for modeling bedload sediment transport and estimating average annual bedload sediment yields. Three types of data necessary for model development were collected with volunteer assistance. First, bed surface sediment size distribution data were collected by the 'pebble count' method (Wolman 1954). This entailed measuring the length of the median axis of about 300 clasts randomly selected from the bed surface and calculating the sediment size distribution at each site. The bed sediment size distribution determines how rough the bed is, and thus, the resistance to stream flow passing over the bed. Bed roughness is thus a necessary input variable for hydraulic model estimates of water depth and energy slope for a given discharge.

Topographic data were collected for three to seven cross-sections along each selected reach as further input data for the hydraulic model. We surveyed the cross-sections about two channel widths apart with an auto-level referenced to arbitrary benchmarks on nearby bridge decks. Subwatershed outlet channel survey data are contained in Appendix E. The cross-section and roughness data were used with a Corps of Engineers hydraulic model (HEC-2) to develop a stage-discharge relation for one of the cross-sections in each reach and to estimate the energy slope of the stream at a chosen cross-section. Appendix H presehnts resutling uncalibrated stage-discharge relations. The energy slope and flow depth determine the given discharge's capacity to transport sediment along the bed at the site.

The stage-discharge relation and the cross-section data were used with a third type of data collected, subsurface or sub-pavement sediment size distribution, to estimate the sediment discharge passing each subwatershed outlet for a given discharge. We used the Parker-Klingeman (P-K) sediment transport model (Parker and Klingeman 1982) to calculate sediment discharge over the range of modeled flows. We also substituted P-K shear values (determined for a large data set collected on Oak Creek, Oregon) with alternate shear values developed by the USFS in recent studies in the North Umpqua basin (Paul Bakke, USFS, Klamath Falls, pers. comm., 1999) to provide comparative results. Summary values were obtained by averaging P-K and USFS results. Average values are for general overview purposes only, and should be distinguished from individual model results.

Total average annual bedload sediment yield was calculated by integrating results over a flow frequency distribution estimated for each subwatershed. The flow frequency distribution was estimated by directly apportioning the mean daily flow frequency distribution calculated for the flow of record at Ross by subwatershed drainage area. A detailed description of sediment transport modeling methods is contained in Appendix C, and sediment size distribution data analyses are contained in Appendix F and Appendix G.

It is important to note that these sediment transport model results are estimates of the channel's capacity to transport sediment. The Parker-Klingeman model assumes that the channel has adjusted so that the input of sediment is carried through the reach. The armor layer of pavement forms on the surface so that the input is equal to the output of bedload. The subsurface size distribution more closely approximates the distribution of the bedload, whereas the surface material is considerably coarser.

4.4. Estimating Total Bedload Sediment Budget at Ross

Estimated bedload loads were summarized for the seven subwatershed areas above Ross (11.5 sq.mi.) to compile a preliminary estimated total sediment budget at Ross (Table 3, Figure 18). Using a ratio calculated from 1978-1980 USGS sediment transport measurements at Ross and other regional values (Table 10), we assumed that bedload comprised 10 percent of total (bedload and suspended load) sediment yield. We then estimated bedload and suspended sediment yield for the unsampled drainage area above Ross (4.5 sq. mi.), assuming that the average yield rate from subwatershed estimates applied uniformly to the unsampled area. To this subtotal, we added estimated yield by net channel bed and bank erosion in the alluvial channel network above Ross (Table 4). The results of preliminary sediment budget compilation are summarized in Table 5 and Table 8, and in the Executive Summary.

To provide an independent estimate of the total sediment budget at Ross, bedload sediment inflow was estimated at the Ross Gage with the Parker-Klingeman model, with methods similar to subwatershed bedload sediment transport modeling methods described in section 4.3. We used available USGS sediment transport measurements for 1978-1980 to produce a calibrated bedload sediment discharge rating curve. We estimated average annual bedload sediment discharge by integrating over the flow frequency distribution calculated over the entire period of record.

Results of the calibrated yield model at Ross were compared to results of the sediment budget estimate at Ross, and to USGS sediment transport measurements, COE estimates, documented gravel extraction rates at Ross, and available regional sediment yield and budget data for comparable watersheds.

5. RESULTS

5.1. ESTIMATED SEDIMENT YIELD BY NET BED AND BANK EROSION

Repeat channel bed elevation measurements show that the average channel bed lowering rate in the alluvial channel network was 0.04 ft/yr for 1976-1999 (Table 4). Figure 26 shows the distribution and elevation of samples, and Figure 9 shows the distribution of sample sites within the entire mainstem of Corte Madera Creek - San Anselmo Creek longitudinal profile. This study estimated average bank retreat was 2 lateral feet per longitudinal foot in the alluvial channel network for the same period. These estimated channel bed incision and bank retreat rates compare well with estimates obtained in other Marin County watershed assessments (Table 11).

Based on historical channel geometry changes measured in this study, the estimated bedload sediment yield by total net channel bed and bank erosion in the alluvial channel network is about 670 tons per year for 1976-1999 (Table 4). Bank erosion generated about 430 tons/year of bedload, and bed incision generated about 240 tons/year.

5.2. ESTIMATED SUBWATERSHED BEDLOAD SEDIMENT YIELDS

This study's uncalibrated sediment transport modeling, using USFS and P-K shear values, respectively, indicates that sampled upland areas contribute between about 2,900 and 6,600 tons of bedload to the channel network above Ross per year (Table 5). Averaging P-K and USFS transport estimates indicates that sampled areas produce about 4,750 tons/year, or 410 tons/sq.mi./yr (Executive Summary Table). This range of bedload yield values is greater than estimates for other, less urbanized Marin County watersheds. Lehre (1982), e.g., estimated that Lone Tree Creek basin in southwestern Marin County (Figure 1) produces about 240 tons/sq.mi./year. The Lone Tree Creek basin receives less precipitation than Corte Madera Creek watershed (Figure 4), has fewer upland roads, and is not urbanized.

This study's uncalibrated subwatershed bedload sediment transport model results[7] indicate that the San Anselmo Creek and Sleepy Hollow Creek subwatersheds produce about 25% and 29%, respectively, of the total bedload sediment inflow at Ross (Table 5, Executive Summary Table). Independent qualitative relative sediment yield classification methods based on existing USGS landslide habitat and slope stability mapping also suggest that San Anselmo Creek and Sleepy Hollow Creek produce greater sediment yields by hillslope processes per square mile than other Corte Madera Creek subwatersheds (Figure 24). Detailed sediment budget studies in Marin County and Eel River tributaries have shown that sediment yield by landslides, earthflows, and downslope soil creep dominate long-term total sediment yields

[7] *The estimated average annual bedload sediment yields are semi-quantitative only, because they are the results from an uncalibrated model. That is, there were no bedload measurements made in the field to verify the model results.*

(Lehre 1982, Kelsey 1980). These studies have also shown that underlying geologic type is one of the strongest influences on hillslope and total sediment yield. Kelsey (1980) showed that rolling-to-hummocky grassland and grass-oak woodland covered Franciscan melange slopes produce about 30 times more sediment per square mile than steep, forested sandstone and shale slopes. The San Anselmo Creek and Sleepy Hollow Creek subwatersheds have a greater percentage of grassland, grass-oak woodland, and chaparral-covered melange slopes than other Corte Madera Creek subwatersheds (Figure 25).[8] Forested sandstone slopes occur primarily in the Larkspur Creek, Tamalpais Creek, and Ross Creek subwatersheds above Phoenix Lake, and substantial areas in the Fairfax Creek subwatershed.

Maximum estimated yield was for the upper portion of the San Anselmo Creek subwatershed (up to 3,000 tons/sq.mi./yr). However, this value is still much less than maximum values Kelsey (1980) measured in comparable small Van Duzen River subbasins (Table 12).

5.3. ESTIMATED SEDIMENT BUDGET AND CALIBRATED YIELD ESTIMATE AT ROSS

This study's uncalibrated sediment budget suggests that between about 4,700 and 9,800 tons/yr of bedload are transported to the channel network above Ross each year (Table 8). The averaged sediment budget estimate is about 7,250 tons/yr, or about 450 tons/sq.mi./yr (Executive Summary Table). The averaged sediment budget estimates that bed and bank erosion generate about 9 percent of the total sediment yield at Ross, and fluvial transport from the upland channel network generates about 91 percent of the total. This 91:9 ratio is comparable to other detailed sediment budget studies reviewed in this report (Table 9). Lehre (1982) estimated the ratio was about 94:6 in the Lone Tree Creek basin, and Kelsey (1980) estimated the ratio was about 95:5 in the Van Duzen River basin. The budget roughly estimates that about 6 percent of the total sediment yield at Ross is generated by channel bank erosion (Table 8). This values is comparable to Lehre's (1982) results for Lone Tree Creek basin (2 percent) and Kelsey's (1980) results for the Van Duzen River basin (5 percent) (Table 9).

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[8] *Figure 25 is partly based on the generalized geology of Blake et al 1974. Subsequent to the preparation of the generalized watershed geology map after Blake et al. (1974) (Figure 17), and Figure 25, discrepancies were revealed between Blake et al. (1974) and Smith et al. (1976). Smith et al. (1976) is the more accurate geology map, but it does not include MMWD lands comprising the larger portion of the Ross Creek, Deer Park Creek, Wood Lane Creek, and San Anselmo Creek subwatersheds. The primary overall difference not reflected in Figure 17, thus also not in Figure 25, is the dominance of upper Cretaceous sandstone and shale in the Larkspur, Tamalpais, and Ross Creek subwatersheds, where Blake et al. (1974) showed these areas were underlain by Franciscan melange.*

The estimated budget also demonstrates that annual average gravel extraction rates near Lagunitas Road Bridge (665 tons/yr) and College of Marin Bridge (about 1000 tons/yr) provide extreme lower limit estimates of the bedload sediment inflow rate at Ross (Table 6, Table 7).

Application of the Parker-Klingeman sediment transport model at Ross, and calibration with USGS sediment transport data, provided an independent total annual bedload sediment inflow estimate of about 6,750 tons/yr (Executive Summary Table).

5.4. HISTORICAL CHANNEL BED INCISION AND AGGRADATION RATES

Historical analysis suggested that channel network entrenchment uncovered numerous resistant bedrock and stiff clay outcrops causing the bed incision rate to decrease beginning in about 1910. Assuming entrenchment began in about 1850, the average annual channel bed incision rate was about 0.20 ft/year for 1850-1910. This study showed that average channel bed lowering rate in the alluvial channel network was 0.04 ft/yr for 1976-1999 (Table 4). Table 4 and Figure 26 show that recent bed incision was greater on Fairfax Creek (0.06 ft/yr) and San Anselmo Creek (0.05 ft/yr) than Sleepy Hollow Creek (0.02 ft/yr). Survey data showed that the lower portion of Ross Creek has aggraded about 0.02 ft/yr during the same period.

This study measured aggradation of about 0.08 ft/yr in the lower portion of the watershed (at the Ross Gage) from 1951-1999. Gage records show that bed aggradation rate evidently slowed after about 1964; the bed aggraded about 0.27 ft/yr from 1951-1964 (Figure 10). A circa 1927 ground photograph showing the channel bed near the Lagunitas Road bridge in Ross indicates that the channel bed elevation was several feet lower than it is today (Scott Nicholson, COE, pers. comm., 2000). This information is consistent with the hypothesis that the majority of channel downcutting was complete by about 1910, and that the lower portion of the channel network has experienced channel aggradation since that time. In an assessment of Novato Creek channel processes, Collins (1998) also observed that channel downcutting rates were higher upstream than downstream. Haible (1980) documented 4 ft of aggradation in the lower portion of Walker Creek basin for 1915-1975 (0.07 ft/yr).

This study also observed systemic channel widening and local bank erosion throughout the alluvial channel network. This study estimated a conservative upper limit value for average annual channel widening of about 0.1 ft/year for approximately 1976-1999.

6. DISCUSSION

6.1. ESTIMATED BEDLOAD SEDIMENT BUDGET AND YIELD AT ROSS

Using an average between calibrated yield results (6,750 ton/year) and the average of the range of uncalibrated budget results (7,250 tons/year), this study indicates that average annual bedload sediment inflow at Ross is about 7,000 tons/yr. This estimate is about 40 percent less than the Army Corps of Engineers (1989) estimate of 11,070 tons/yr. However, the COE model included transport of 'very fine sand' and 'fine sand' (0.0625 - 0.250 mm) in its bedload estimate, and this study did not. This study's estimates can thus be expected to be about 10-20 percent less than COE estimate. This study's estimate can be considered about 20-30 percent less than COE’s estimate.

This study indicates that Corte Madera Creek's bedload sediment yield is about 45 percent greater than an estimate for Lone Tree Creek, a comparable, but less urbanized western Marin County watershed (Figure 1). Corte Madera Creek watershed's greater yield can probably be primarily attributed to its greater intensity of historical land use impacts, greater density of upland roads, and greater peak and average annual precipitation along its western boundary (Figure 4) (A. Lehre, HSU, pers. comm., 2000).

This study estimates that Corte Madera Creek's bedload sediment yield is about 40 percent less than values estimated in the Van Duzen River basin and other parts of the Eel River basin (Table 9, Table 10). The Van Duzen River and Eel River values can be considered upper limit values due to a greater degree of melange deformation and tectonic uplift, and continuing upland land use impacts. Yields from the Eel River basin are among the highest in western North America (Judson and Ritter 1964). The COE’s estimated yield at Ross is closer to upper limit values measured for the Van Duzen River in the Eel River basin than this study’s estimated yield at Ross.

Due to persistent upland land use impacts, the Corte Madera Creek watershed's bedload sediment yield can be considered to be unnaturally high. This study did not estimate its natural background yield. However, it is probably greater than the estimate for Lone Tree Creek (240 tons/sq. mi./year) and less than this study's estimate (about 450 tons/sq. mi./year). If the natural background rate were estimated to be 350 tons/sq. mi./year, than the human-induced increase in bedload inflow at Ross would be about 1,600 tons/year.

As with any model application, this study’s results must be considered estimates, and should be calibrated with bedload sediment transport measurements over a range of discharges at subwatershed outlet sites. Bedload transport measurements were not included in the scope of this study, but we collected a bedload sample at the Upper San Anselmo Creek subwatershed outlet site, about 106 ft upstream from the Cascade Creek confluence during the receding limb of a rainstorm on January 23, 2000. The mass of this isolated sample was about 50 percent less than the model prediction for bedload transport. However, the channel bed pavement was not fully mobilized during the low measured discharge. As is to be expected from the operation of the model, larger sizes were not moving, or were moving at such small rates that none were sampled. The size distribution of the bedload for each discharge is controlled by the exponent in the Parker-Klingeman model. As the discharge increases, the distribution of the bedload approaches that of the subsurface material. For lower discharges, the distribution of the bedload is much finer than that of the subsurface material. Thus, for calibration of the model a range of discharges must be sampled.

We also resurveyed the bathymetry of a sediment trap excavated at the Wood Lane Creek subwatershed outlet site at Marin Stables on February 2, 2000, and February 21, 2000. By the latter date, approximately 75-100 tons of bedload was trapped in the excavation. Marin Stables personnel estimate that comparable excavations fill completely about every other year. This study estimated that the Wood Lane Creek subwatershed is about 110 tons/yr. These observations suggest that the transport model is relatively accurate for the Wood Lane Creek outlet. More accurate collection of future excavation data at the site could be used to further ultimately calibrate the model. In general, as discussed above, more extensive and intensive sediment sampling will be required to calibrate this study's sediment transport model results.

6.2. PROBLEM SUBWATERSHEDS

This study indicates that the San Anselmo Creek and Sleepy Hollow Creek subwatersheds contribute about 29 percent and 26 percent, respectively, of the total bedload sediment inflow at Ross (Executive Summary Table). San Anselmo Creek and Sleepy Hollow Creek generate about 580 and 660 tons/sq.mi./year, respectively. These yield values are comparable to, but less than, upper limit values estimated in the Van Duzen River basin. The Ross Creek and Fairfax Creek subwatersheds are underlain by a combination of Franciscan melange and more resistant Cretaceous sandstones and shales (Figure 25), and generate only about 10 percent of the total bedload yield.

Detailed sediment budget studies of northern California Coast Range watersheds indicate that the sediment source mechanisms dominating long-term average sediment yield are landsliding and earthflows. Thus, the frequency of mass wasting can probably be considered a suitable surrogate for long-term average bedload sediment yield in the Corte Madera Creek watershed. Available interpretive USGS maps of potential hillslope instability and landslide frequency show that greatest potential hillslope instability and landslide frequency occurs in the San Anselmo Creek and Sleepy Hollow Creek subwatersheds (Figure 24).

Aerial photographs from 1946 show the impact of intense grazing in the Sleepy Hollow Creek subwatershed. Hummocky grassland-covered hillslopes show evidence of deep-seated slumps and downslope soil creep. Minor zero-order tributaries form incised channels just below ridge lines and cut across valley flats to join main channels. Terracettes are evident on the present hillslopes. The primary sediment source mechanisms in the Sleepy Hollow Creek subwatershed are probably active hillslope processes at the upstream limits of the North Fork and the South Fork (Figure 20). The melange rock mass is evidently highly deformed and mechanically weak in the vicinity of Loma Alta. Field reconnaissance in the upper north fork revealed large earthflow deposits covering the channel and locally active erosion of earthflow deposits. Field reconnaissance also revealed minor fire damage and active gullying in the sandstone-underlain chaparral area on the northeastern edge of the subwatershed, and many active earthflows along its eastern edge.

Our field reconnaissance showed that neither fork of upper Sleepy Hollow Creek is deeply entrenched, which may be explained by numerous bedrock and stiff clay outcrops observed in the bed and the high upland sediment supply. The mainstem becomes moderately to deeply entrenched at or just below a constriction in the valley width. A shallow bedrock outcrop associated with this constriction may account for the relatively low entrenchment ratio upstream. Numerous bedrock outcrops also regulate channel downcutting rate in the lower portion of Sleepy Hollow Creek. This study showed that its recent downcutting rate was lower than for San Anselmo Creek and Fairfax Creek.

The San Anselmo Creek is also underlain by very highly deformed Franciscan melange rock mass, as indicated by the dense metamorphic rock outcrops and complex fault patterns (Smith et al. 1976). Using P-K shear values, the estimated bedload yield from the Upper San Anselmo Creek subwatershed was much greater per square mile than San Anselmo Creek as a whole. Indeed, the upper portions of San Anselmo Creek, Cascade Creek, Pine Creek, and Carey Camp Creek are extremely deformed and steep (Figure 22), and evidently receive significant sediment contributions from landsliding and earthflows (Figure 20). Presence of chaparral areas might elevate sediment yield from the San Anselmo Creek subwatershed. Rice (1982) found that chaparral areas produce up to 640 tons/sq.mi./year of sediment by dry ravel processes, in the absence of intense rainfall. Rice (1982) also measured sediment yield rates up to 17,871 tons/sq. mi. in the three months following fire in a chaparral area.

Fire road and pipeline access road construction and maintenance probably also elevate sediment production in the San Anselmo Creek subwatershed. For example, MCOSD and MMWD identified a redundant, high-maintenance fire road network below Blue Ridge (Site no. 29 in Figure 23, Appendix B) and a poorly maintained fire road on the ridge crest separating the Upper San Anselmo Creek and Cascade Creek canyons (Site no. 12 in Figure 23, Appendix B). Sediment contributions by landslides are particularly large and numerous in the San Anselmo Creek subwatershed. As an example, a large but not uncommon landslide deposit can be seen on the right bank about 300 ft downstream from the Canyon Road Bridge.

Listing Sleepy Hollow Creek and San Anselmo Creek as the primary problem subwatersheds is not to say that other areas in the watershed do not contribute significant amounts of sediment. For example, the upper reaches of Fairfax Creek draining the southern hillslopes of Loma Alta probably produce sediment yields comparable per square mile to the eastern slopes of Loma Alta in Sleepy Hollow Creek subwatershed. Modeling of sediment yield from Sorich Creek was prevented by invalid hydraulic model results evidently associated with channel steepness and longitudinal profile irregularities. However, Sorich Creek probably produces as much, if not more than the sediment yield per square mile of Sleepy Hollow Creek.

Portions of the upper Ross Creek subwatershed, although relatively well-forested and underlain by sandstones (not mapped correctly by Blake et al. 1974), are very steep and undoubtedly produce high sediment supplies. The southwestern slopes of Bald Hill are intensely deformed and obviously produce very high local sediment supplies. However, these sediment sources are upstream from Phoenix Reservoir, and thus are inconsequential as they do not contribute to sediment inflow at Ross.

6.3. IMPLICATIONS OF RESULTS FOR FLOOD MANAGEMENT GOALS

Coarse sediment deposition in the flood control channel downstream of Ross reduces its flood control performance by reducing its volumetric capacity and increasing channel bed roughness. The COE recently proposed constructing a sedimentation basin at Lagunitas Road bridge in Ross that is expected to reduce the median sediment size of sediment desposited downstream by preferentially trapping the coarsest fractions of the incoming bedload. This would increase the channel's conveyance capacity by reducing channel bed roughness. The Town of Ross has extracted about 670 tons/yr by gravel bar skimming beneath Lagunitas Road bridge almost every year since 1987. This activity has a similar but less significant effect than the proposed sedimentation basin.

This study indicates that upland areas generate about 7,000 tons/yr of incoming bedload, while net channel bed incision and bank erosion contribute about 240 and 430 tons/yr, respectively. Therefore, total elimination of bank erosion and systemic channel widening throughout the alluvial channel network would probably reduce bedload sediment delivery to Ross by as much as about 430 tons/yr, only 6 percent of the total bedload delivered to Ross.

If Corte Madera Creek's natural background sediment yield rate is conservatively estimated to be 350 tons/sq. mi./yr, than the bedload inflow at Ross attributable to persistant land use impacts would be about 1,600 tons/yr. Almost all of this additional sediment is generated in upland areas, with a majority evidently coming from uplands in the San Anselmo and Sleepy Hollow Creek subwatersheds. Total elimination of the additional sediment supply by restoration of problem sediment sources and improved hillslope management practices would probably, over time, reduce bedload sediment delivered to Ross by as much as about 1,600 tons/yr, or about 20% of the annual bedload inflow.

Watershed sediment management actions in the adjacent San Geronimo Creek basin have evidently reduced bedload supply measured at the Town of Lagunitas since 1990 (J. Owens, Balance Hydrologics, pers. comm., 2000). These efforts have also evidently reduced the percentage of fine sediment in the channel bed. This may be a benefit to aquatic habitat (e.g., by increasing salmonid spawning success), but has also led to channel bed coarsening. Any proposed efforts to reduce sediment supply from uplands in the Corte Madera Creek watershed should consider the potential for causing local or systemic bed coarsening which may potentially both offset any benefit to salmonid spawning suitability and reduce performance of the flood control channel.

6.4. IMPLICATIONS OF RESULTS FOR WATERSHED AND HABITAT RESTORATION GOALS

Natural geomorphic responses to channel entrenchment operate in the Corte Madera Creek watershed. A period of progressive upstream channel aggradation occurred in the lower portion of the watershed, evidently ending in about 1964. About 4 ft of channel bed aggradation occurred at the Ross Gage from 1951 to 1964. Anecdotal evidence suggests that channel bed aggradation was ongoing from about 1910 to 1964. These observations are consistent with geomorphic responses observed in other entrenched Marin County streams. Collins (1998) observed that channel downcutting rates were less in the lower portion of the watershed. Haible (1980) documented 4 ft of bed aggradation in the lower reaches of Walker Creek for 1915-1975.

Systemic channel widening and local bank erosion are still active in the upper portion of the alluvial channel network. Channel widening is a natural geomorphic response to channel entrenchment that accelerates following bed elevation stabilization (Schumm 1999). Channel widening is a natural recovery process that recovers aquatic and riparian habitat lost during channel entrenchment by allowing active inset floodplain sedimentation, increased channel meandering, woody debris recruitment, and pool-riffle channel bed morphology development. Geomorphic reasoning would suggest that the process of local and systemic channel widening can be expected to continue at or near its present rate for at least several more decades or hundreds of years, until the entrenched channel's active channel width approaches its pre-entrenchment active channel width. Then, the plan form of active channel boundaries will become more stable, and more natural geomorphic and floodplain processes will occur within the widened, entrenched channel that can sustain riparian and aquatic habitat values that are comparable to those supported by the pre-entrenchment channel (Figure 16).

There are active inset floodplains at a number of locations in the watershed where the entrenched channel was wide enough or became wide enough following entrenchment to allow deposition and storage of relatively fine gravels, particularly at inside bends of widened entrenched meanders. Some pool-riffle development has also occurred, but narrow channel confinement limits its extent. Notably, systemic watershed-wide channel entrenchment did not confine the channel and reduce active channel width at some isolated locations in the watershed, such as an approximately 400-ft reach of Fairfax Creek within Andi Peri Park. Channel meanders, floodplain processes, and gravel bar and pool-riffle development are largely intact at these sites.

However, nearly the entire alluvial channel network is unnaturally narrow and closely urbanized. Urbanization reinforces the channel entrenchment process by routing storm water from hillsides and the valley flat directly into stream channels. Urbanization of the abandoned floodplain also prevents recovery by the associated construction of bank protection and flood control structures to prevent channel widening and progressive upstream aggradation and floodplain recovery. About 50 percent of the basin's channel banks are artificially reinforced to prevent channel widening by bank erosion (Friends of Corte Madera Creek Watershed 1997). In addition, residential and commercial landowners filled the channel margins to increase property acreage. In general, these structures impede natural geomorphic recovery of the channel.

Observed bed level stabilization, channel widening, and inset floodplain formation indicate that natural geomorphic recovery processes are ongoing but incomplete and impeded by artificial bank stabilization in the Corte Madera Creek watershed. As a priority, projects intended to improve flood control and/or aquatic and riparian habitat and habitat-supporting processes and flood control should seek opportunities, where possible, to increase active channel width. Conceptual demonstration project designs for floodplain restoration (for a hypothetical site where widening is possible) and streambank stabilization (for a hypothetical site where widening is not possible) are outlined in Appendix L and Appendix K, respectively.

As noted above regarding flood management implications, any proposed efforts to reduce sediment supply from uplands in the Corte Madera Creek watershed should consider the potential for causing local or systemic channel bed coarsening. Numerous grade controls throughout the alluvial channel network would probably prevent systemic channel incision from proceeding at more than the average rate measured in this study (0.04 ft/yr). Any local channel bed incision would probably only marginally reduce habitat values already significantly reduced by 1850-1910 channel entrenchment. Reduced gravel supply could, for example, further reduce bedform development and aquatic habitat complexity, and decrease substrate pool density. Reduced watershed sediment supply may also reduce the percentage of fine sediment in the channel bed, as has been observed on San Geronimo Creek. However, the presence of fine sediment in the channel bed is not necessarily a limiting factor for fish populations in the Corte Madera Creek watershed (A. Rich, pers. comm., 1999).

7. REFERENCES CITED

Alley, Bowen & Co. 1880. History of Marin County California, including its geography, geology, topography and climatography, together with a record of the Mexican grants, names of pioneers, and a complete political history. San Francisco, CA: Alley, Bowen & Co., Bancroft Library Collection, University of California, Berkeley.

Brewer, W.H. 1949. Up and down California in 1860-1864. Berkeley CA: University of California Press.

Brown, W.M. 1975. Sediment transport, turbidity, channel configuration and possible effects of impoundment of the Mad River, Humboldt County, California. USGS Water Resources Investigation 26-75, 63 pp.

Brown, W.M. and L.E. Jackson. 1973. Erosional and depositional provinces and sediment transport in the south and central part of the San Francisco Bay region, California. USGS Interpretive Report 3.

_________. 1974. Sediment Source and Deposition Sites and Erosional and Depositional Provinces, Marin and Sonoma Counties, California. USGS Miscellaneous Field Studies Map MF-625.

Brown, W.M. and J.R. Ritter. 1971. Sediment transport and turbidity in the Eel River Basin, California. USGS Water-Supply Paper 1986, 70 pp.

Collins, L. 1998. Sediment sources and fluvial geomorphic processes of Lower Navato Creek Watershed. Report to Marin County Flood Control and Water Conservation District, July 1998.

Clair A. Hill and Associates. 1966. Corte Madera Creek Topographic Maps, Ross to San Anselmo, contour interval 2 ft, scale 1 in. = 40 ft. Prepared for US Army Corps of Engineers.

Daetwyler, C.C. 1950. Marine Geology of Tomales Bay. Report to Scripps Institute of Oceanography and to Pacific Marine Station.

Davenport, C.W. 1984. An analysis of slope failures in eastern Marin County, California, resulting from the January 3rd and 4th, 1982 storm. California Dept. of Conservation, Division of Mines and Geology. DMG open-file report 84-22 SF.

Dawdy, D.R., W.C. Wang, and P. Basdekas. 1999. Calibration of the Parker-Klingemas model with variable shear. *In:* A.W. Jayawardena, J.H.W. Lee, and Z.Y. Wang, eds., *River Sedimentation: Proceedings of the Seventh International Symposium on River*

Sedimentation, Hong Kong, China, December 16-18, 1998, pp. 753-756.
DeBano, L.F. 1969. The relationship between heat treatment and water repellency in soils. *In:* Proceedings of the symposium on water-repellent soils, Riverside, CA, pp. 265-279.

Dunne, T. and L.B. Leopold. 1978. Water in environmental planning. San Francisco, California: W.H. Freeman.

Ellen, S.D., D.M. Peterson, and G.O. Reid. 1982. Map showing areas susceptible to different hazards from shallow landsliding, Marin County and adjacent parts of Sonoma County, California. USGS Miscellaneous Field Studies Map MF-1406.

Ellen, S.D. et al. 1997. Map showing principal debris flow source areas in Marin County, California. USGS Open-File Report 97-745.

Emmett, W.W. and H.R. Seitz. 1974. Suspended and bedload sediment transport in the Snake and Clearwater Rivers in the vicinity of Lewiston, Idaho, July 1973 through July 1974. USGS Basic Data Report, 76 pp.

Federal Emergency Management Agency. 1980. Flood Insurance Study, Town of Ross, California, Marin County, 15 pp.

_________. 1983. Flood Insurance Study, City of Larkspur, California, Marin County. 18 pp.

Friends of Corte Madera Creek Watershed. 1997. Background for Long-Range Planning; Corte Madera Creek Watershed, February 25, 1997 (reprinted November 1998).

Graumilch, L. 1993. A 1000-year record of temperature and precipitation in the Sierra Nevada. *Quaternary Research* 39:249-55.

Haible, W.W. 1980. Holocene profile changes along a California Coastal Stream. *Earth Surface Processes and Landforms* 5:249-264.

Harvey, A.M., P.E. Wigand, and S.G. Wells. 1999a. Response of alluvial fan systems to late Pleistocene to Holocene climatic transition: contrasts between margins of pluvial Lakes Lahontan and Mojave, Nevada and California, USA. *Catena* 36:255-281.

Harvey, A.M., P.G. Silva, A.E. Mather, J.L. Goy, M. Stokes, and C. Zazo. 1999b. The impact of Quaternary sea-level and climatic change on coastal alluvial fans in the Cabo de Gata ranges, southeast Spain. *Geomorphology* 28:1-22.

Hawley, N.L. and B.L. Jones. 1969. Sediment yield of coastal basins in northern California. USGS Water Resources Division Open-File Report, 19 p.

Hecht, B. 1994. South of the spotted owl: restoration strategies for episodic channels and riparian corridors in central California. In: D.M. Kent and J.T. Zenter, eds., *Western Wetlands: Selected Proceedings of the 1993 Conference of the Society of Wetland Scientists,* pps. 104-117.

Herd, D.G. and E.J. Helley. 1977. Faults with quaternary displacement, northwestern San Francisco Bay region. USGS Miscellaneous Field Studies Map MF-818.

Hereford, R. 1983. Entrenchment and widening of the Upper San Pedro River, Arizona. *Geol. Soc. Amer. Special Paper* 282. 46 p.

Hoffman and Albritton. 1970. Minimum drainage study, Sleepy Hollow Creek. Report to the City of San Anselmo.

Janda, R.J. 1966. Pleistocene history and hydrology of the upper San Joaquin River. Ph.D. Dissertation, University of California, Berkeley.

Janda, R.J. et al. 1975. Watershed conditions in the drainage basin of Redwood Creek, Humboldt County, California, as of 1973. USGS Open-File Report 75-568, 267 pp.

Judson, S., and D.F. Ritter. 1964. Rates of regional denudation in the United States. *Journal of Geophysical Research* 69(16):3395-3401.

Kelsey, H.M. 1980. A sediment budget and an analysis of geomorphic process in the Van Duzen River Basin, northern coastal California, 1941-1975. *Geol. Soc. Amer. Bull.* Part 2. Vol. 91. Pp. 1119-1216.

_________. 1982. Hillslope evolution and sediment movement in a forested headwater basin, Van Duzen River, north coastal California. *In:* F.J. Swanson, R.J. Janda, T. Dunne, and D.N. Swanson, eds., *Sediment Budgets and Routing in Forested Drainage Basins*. United States Department of Agriculture, Forest Service General Technical Report, PNW-141, 165 p.

Kondolf, G.M. and W.V.G. Matthews. 1991. Unmeasured residuals in sediment budgets: a cautionary note. *Water Resources Research* 27(9):2483-2486.

Kondolf, G.M. and W.V.G. Matthews. 1993. Management of coarse sediment on regulated rivers. Davis CA: University of California Water Resources Center Report no. 80.

Kondolf, G.M., M.W. Smeltzer, and S.L. Railsback. (in press) Design and performance of a reconstructed channel project in a California gravel-bedded stream. Accepted for publication in *Environmental Management.*

Knott, J.M. 1971. Sedimentation in the Middle Fork Eel River basin, California. USGS Water Resource Division Open-File Report, 60 pp.

Larson, K.R. and R.C. Sidle. 1980. Erosion and Sedimentation Data Catalog of the Pacific Northwest, September 1980.

Lehre, A.K. 1982. Sediment mobilization and production from a small mountain catchment: Lone Tree Creek, Marin County, California. Ph.D. dissertation, University of California, Berkeley.

_________. 1982. Sediment Budget of a small Coast Range drainage basin in North Central California. *In:* F.J. Swanson, R.J. Janda, T. Dunne, and D.N. Swanson, eds., *Sediment Budgets and Routing in Forested Drainage Basins*. USDA, Forest Service General Technical Report PNW-141, pp. 67-77

Leopold, L.B. (undated.) unpublished manuscript containing hydraulic geometry data for gaging stations in San Francisco Bay Area. Available in the Water Resources Center Archives, 412 O'Brien Hall, University of California, Berkeley.

Limerinos, J. T. 1970. Determination of the Manning Coefficient from Measured Bed Roughness in Natural Channels, U. S. Geological Survey Water Supply Paper 1898-B.

Manson, M. 1899. Observations on the denudation of vegetation - A suggested remedy for California. *Sierra Club Bulletin* 2:295-311.

Milhous, R.T. 1973. Sediment transport in a gravel-bottomed stream. Ph.D. dissertation, Oregon State University, Corvallis, Oregon.

Montgomery, D.R. 1999. Erosional processes at an abrupt channel head: implications for channel entrenchment and discontinuous gully formation. In: S.E. Darby and A. Simon, eds., *Incised River Channels: Processes, Forms, Engineering and Management.* Chichester, UK: John Wiley & Sons.

Parker, G. 1990. Surface-based bedload transport relation for gravel rivers. *Journal of Hydraulic Research* 28(4):417-436.

Parker, G. and P.C. Klingeman. 1982. On Why Gravel Bed Streams Are Paved. *Water Resources Research* 18(5):1409-1423.

Parker, G., P.C. Klingeman, and D.G. McLean. 1982. Bedload and size distribution in paved gravel-bed streams. *Journal of the American Society of Civil Engineers* 108 (HY4):544-571.

Prosser, I.P. and W.E. Dietrich. 1995. Field experiments on erosion by overland flow and their implication for a digital terrain model of channel initiation. *Water Resources Research* 31:2867-2876.

Reid, L.M. and T. Dunne. 1996. Rapid evaluation of sediment budgets. Catena Verlag, 164 pp.

Rice, R.M. 1982. Sedimentation in the Chaparral. *In:* F.J. Swanson, R.J. Janda, T. Dunne, and D.N. Swanson, eds., *Sediment Budgets and Routing in Forested Drainage Basins*. USDA, Forest Service General Technical Report PNW-141, pp. 39-49.

Rice, S.J., T.C. Smith, and R.G. Strand. 1976. Geology for planning: central and southeastern Marin County, California. California Division of Mines and Geology Open File Report 76-2.

Rich, A.A. 2000. Fishery Resources Conditions of the Corte Madera Creek Watershed, Marin County, California. Prepared for Friends of Corte Madera Creek Watershed by A.A. Rich and Associates, San Anselmo, California, November 10, 2000.

Riley, A.L. 1998. *Restoring Streams in Cities*. Covelo CA: Island Press.

Royston, Hanamato, Beck and Beck, Inc. 1977. Corte Madera Creek: A Flood Control Study, Marin County, California. Prepared for the Department of the Army, San Francisco District, Corps of Engineers.

Schumm, S.A. 1999. Causes and Controls of Channel Incision. In: S.E. Darby and A. Simon, eds., *Incised River Channels: Processes, Forms, Engineering and Management.* Chichester, UK: John Wiley & Sons.

Schumm, S.A., M.D. Harvey, and C.C. Watson. 1984. *Incised Channels: Morphology, Dynamics and Control.* Littleton CO: Water Resources Publications.

Shepherd, A. 1987. Corte Madera Creek particle size distribution analysis. Unpublished report, including HEC-2 data appendix.

Simon, A. and C.R. Hupp. 1986. Channel evolution in modified Tennessee channels. In: *Proceeding of the Fourth Federal Interagency Sedimentation Conference,* Volume 2. Washington, D.C.: US Government Printing Office, 5-71 to 5-82.

Smeltzer, M.W. and G.M. Kondolf. in preparation. Historical Geomorphic Analysis of the Owens River Gorge. For submission to *Catena.*

United States Army Corps of Engineers (COE). 1961. Survey Report for Flood Control and Allied Purposes, Corte Madera Creek, Marin County, California. Department of the Army, San Francisco District.

_________. 1987. Final Supplemental Environmental Impact Statement, Corte Madera Creek Flood Control Project Unit No. 4, Marin County, California. Department of the Army, Sacramento District.

_________. 1989. Sedimentation Study, Corte Madera Creek Flood Control Project, Marin County, California. Prepared for Sacramento District COE, by R.R. Copeland and W.A. Thomas, COE Hydraulics Laboratory, Vicksburg, Mississippi, January 1989.

_________. 2000. Corte Madera Flood Control Project Alternative Screening Conference Document, Draft 2. Prepared by San Francisco District COE, January 2000.

COE, USEPA, BCDC, SFBRWQCB, SWRCB. 1978. Long-term management strategy for Bay Area Dredged Material. Final Environmental Impact Statement, Environmental Impact Report.

United States Department of Housing and Urban Development. 1977. Flood Insurance Study, City of San Anselmo, California, Marin County. 14 pp.

_________. 1977. Flood Insurance Study, Town of Fairfax, California, Marin County. 13 pp.

Porterfield, G. 1980. Sediment Transport of Streams Tributary to San Francisco, San Pablo, and Suisun Bays, California, 1906-66. US Geologic Survey, Water Resources Investigations 80-64.

United States Geologic Survey. 1978. Surface water supply data, Volume 2.

United States Geologic Survey. 1979. Surface water supply data, Volume 2.

United States Geologic Survey. 1980. Surface water supply data, Volume 2.

Wahrhaftig, C. and J.R. Wagner. 1972. The geologic setting of Tomales Bay. *In:* R. Corwin, ed., *Tomales Bay Environmental Study.* Washington, D.C., the Conservation Foundation.

Westworth, C.M. and V.A. Frizzell. 1975. Reconnaissance landslide map of parts of Marin and Sonoma counties, California. Menlo Park: USGS Open-file report 75-281.

Wiberg, P.L. and J.D. Smith. 1987. Calculations of the Critical Shear Stress for Motion of Uniform and Heterogeneous Sediments. *Water Resources Research* 23(8):1471-1480.1

Wolman, G.M. 1954. A method of sampling coarse river-bed material. *Transactions, American Geophysical Union* 35:951-956.

Zumwalt, C.W. 1972. Consideration of vegetation and soils on the Tomales Bay Watershed. In: R. Corwin, ed., *Tomales Bay Environmental Study.* Washington, D.C., the Conservation Foundation.

8. TABLES

Table 4. Estimated annual average bedload sediment yield by net bed and bank erosion in the alluvial channel network above Ross, 1976-1999.

		SAMPLED REACH LENGTH						TOTAL ALLUVIAL REACH LENGTH [11]		
SUBWATERSHED	TOTAL ALLUVIAL LENGTH ABOVE ROSS GAGE (FT)	SAMPLED REACH LENGTH (FT)	NUMBER OF ELEVATION SAMPLES	ESTIMATED AVERAGE NET BED LOWERING RATE (FT/YEAR)	ESTIMATED SEDIMENT YIELD BY NET BED EROSION [6] (TONS/YEAR)	ESTIMATED SEDIMENT YIELD BY BANK EROSION [7] (TONS/YEAR)	TOTAL ESTIMATED SEDIMENT YIELD BY NET BED AND BANK EROSION (TONS/YEAR)	ESTIMATED SEDIMENT YIELD BY NET BED EROSION (TONS/YEAR)	ESTIMATED SEDIMENT YIELD BY BANK EROSION (TONS/YEAR)	TOTAL ESTIMATED SEDIMENT YIELD BY NET BED AND BANK EROSION (TONS/YEAR)
Ross Ck [1]	5,200	455 [5]	7	-0.017	-5.79	16.6	10.8	-66.2	189	123
Sorich Ck	4,900	-- [10]	--	0	0	0	0	0	0	0
Sleepy Hollow Ck	22,700	8,120 [3]	17	0.015	98.3	415	514	275	1,160	1,435
Fairfax Ck	20,600	4,950 [4]	9	0.059	209	311	520	870	1,290	2,160
Deer Park Ck	3,600 [8]	-- [10]	--	0	0	11.8	11.8	0	11.8	11.8
Wood Lane Ck	2,800 [9]	-- [10]	--	0	0	0	0	0	0	0
San Anselmo/Corte Madera Ck	27,650	22,750 [2]	11	0.047	1,070	1,340	2,410	1,300	1,630	2,930
TOTALS	87,450	36,275	44	0.041	1,372	2,094	3,467	2,380	4,280	6,660
TOTALS (TONS/SQ.MI./YEAR)								149	268	416
as bedload (TONS/YEAR) [12]								238	428	666
as bedload (TONS/SQ.MI./YEAR)								15	27	42

1 Data for 1966-1999 (Source: Clair A. Hill and Assoc. 1966)
2 From Ross Gage to Canyon Rd Bridge
3 From outlet at San Anselmo Ck to Caleta Rd Bridge
4 From culvert at Andi Peri Park to Westbrae Dam
5 From outlet at Corte Madera Ck to Sylvan Lane Bridge
6 Bed erosion (ft^3/ft) in each sampled reach was calculated by average of change in bed elevation (ft) x bed width (ft) for all sample sites in reach
7 Bank erosion (ft^3/ft) in each sampled reach was estimated by average of 1 ft * [left terrace bank height (ft) + right terrace bank height (ft)] for all sampled sites in reach
8 900 ft of the alluvial reach length are subject to bed and bank erosion; subject reach is partially culverted and has partial bank reinforcement
9 500 ft of the alluvial reach length are subject to bed and bank erosion; subject reach is depositional and partially culverted
10 Historical data not available; estimates based on random field observations throughout alluvial reach
11 Average erosion measured in the sampled reach length was distributed uniformly throughout the associated total alluvial reach length to calculate total sediment yield by bed and bank erosion.
12 Assumes that 90% of eroded bed and bank material volume contributes to suspended sediment yield and 10% contributes to bedload sediment yield.

Table 5. Estimated annual average bedload sediment yield from major Corte Madera Creek subwatersheds.

				USING PARKER-KLINGEMAN SHEAR VALUES			USING USFS SHEAR VALUES		
SUBWATERSHED	OUTLET	SAMPLED DRAINAGE AREA (SQ. MI.)	PERCENT OF TOTAL DRAINAGE AREA ABOVE ROSS (%)	ESTIMATED TOTAL BEDLOAD SEDIMENT YIELD [6] (TONS/YEAR)	PERCENT OF ESTIMATED TOTAL BEDLOAD SEDIMENT YIELD AT ROSS (%)	ESTIMATED BEDLOAD SEDIMENT YIELD (TONS/SQ.MI./YEAR)	ESTIMATED TOTAL BEDLOAD SEDIMENT YIELD [7] (TONS/YEAR)	PERCENT OF ESTIMATED TOTAL BEDLOAD SEDIMENT YIELD AT ROSS (%)	ESTIMATED BEDLOAD SEDIMENT YIELD (TONS/SQ.MI./YEAR)
Larkspur Ck [4]	Cane St	1.3	–	–	--	–	--	–	--
Tamalpais Ck	Evergreen Rd	0.8	--	636 [3]	--	795 [3]	–	–	--
Ross Ck below Phoenix Dam	Corte Madera Ck	0.6	3.8	550	6.0	917	124	3.1	207
Sorich Ck [5]	Sacramento Ave	0.2 [8]	–	–	--	–	--	–	--
Sleepy Hollow Ck	Caletta Ave	2.8	18	1,050	11	375	2,645	65	945
Fairfax Ck	Andi Peri Park	3.6	23	701	7.7	195	42	1.0	12
Deer Park Ck	Meerna Ave	0.5	3.1	73	0.8	147	7	0.2	14
Wood Lane Ck	Marin Stables	0.4	2.5	107	1.2	268	0	0.0	0
San Anselmo Ck	Wood Lane Ck confluence	3.6	23	4,088	45	1,136	96	2.4	27
Upper San Anselmo Ck	Cascade Creeek confluence	0.8	5.0	3,039	33	3,798	69	1.7	86
Total sampled drainage area (DA) above Ross [1]		11.5	72	6,570	72	571	2,914	72	253
Total unsampled unregulated upland DA above Ross		4.5	28	2,571	28	571	1,140	28	253
Corte Madera Creek at Ross [9]		16.0	100	9,141	100	571	4,055	100	253

[1] Includes sum of drainage areas and yields from Ross Ck below Phoenix Lake, Sleepy Hollow Ck, Fairfax Ck, Deer Park Ck, Wood Lane Ck, and San Anselmo Ck.
[3] Values reported for energy slope = 0.009; Values for energy slope = 0.0096: 897.3 tons/year, 1122 tons/sq. mi./year
[4] Hydraulic model failed to compute consistent energy slope
[5] Hydraulic model failed to generate subcritical energy slope
[6] Bedload sediment yield estimates using Parker-Klingeman shear values (Parker and Klingeman 1982)
[7] Bedload sediment yield estimates using USDA Forest Service shear values (Paul Bakke, USFS, Klamath Falls, pers. comm., 1999)
[8] Sorich Ck drainage area not included in total sampled drainage area above Ross because hydraulic model results were invalid
[9] Sum of bedload sediment yield estimated for sampled and unsampled areas above Ross.

Table 6. Sediment extracted from Corte Madera Creek in the vicinity of Lagunitas Rd Bridge at Ross, 1987-1999. (Source: Charlie Goodman, pers. comm., January 12, 2000)

YEAR	DATE	AMOUNT REMOVED (CU. YARDS)	AMOUNT REMOVED (TONS) [1]	AMOUNT REMOVED (TONS/SQ.MI.)	TOTAL COST ($)	COMMENTS
1987	23-Oct	648	875	55	$8,719	
1988	29-Oct	200	270	17	$3,000	
1989	7-Nov	200	270	17	$2,780	
1990	--	--	--	--	--	none extracted
1991	2-Oct	400	540	34	$7,500	
1992	--	--	--	--	--	none extracted
1993	28-Sep	870	1,175	73	$12,655	
1994	5-Nov	608	821	51	$6,090	
1995	19-Oct	400	540	34	$4,500	
1996	23-Sep	640	864	54	$6,000	
1997	17-Oct	744	1,004	63	$6,000	
1998	27-Oct	1,200	1,620	101	$6,000	
1999	--	--	--	--	--	data not yet available
TOTAL		5,910	7,979	--	$63,244	
AVERAGE PER EXTRACTION		591	798	50	$6,324	
ANNUAL AVERAGE, 1987-1999		493	665	42	$5,270	

[1] Data provided in cubic yards and converted to tons as follows: 1 yard = 1.35 tons.

Table 7. Sediment extracted from channel bed in the vicinity of College of Marin Bridge at Kentfield, 1972-1998 (Source: Jason Nutt, MCFCD, pers. comm., January 16, 2000)

YEAR	LOCATION	AGENCY	RIVER STATION (FTx100)	AMOUNT REMOVED (CU. YDS)	AMOUNT REMOVED (TONS) [1]	COMMENTS
1972	--	COE	--	--	--	No data Flood control channel completed in 1971
1986	Near College Ave to Ferry Building	COE-MCFCD	--	about 9,000	about 12,000	Comparison of project cross-sections indicates that amount removed was approximately equal to 9,000 yards removed to achieve design depth in 1998.
1998	Near College Ave	MCFCD	345 - 315	22,000	29,700	9,000 yards removed to achieve design depth from STA 345 to STA 318 13,000 additional yards extracted from STA 318 to STA 315 by removal of cofferdam 50-100 ft downstream of box culverts Maximum sediment size was about 20 mm

[1] Data provided in cubic yards and converted to tons as follows: 1 yard = 1.35 tons.

Table 8. Preliminary estimated sediment budget for the Corte Madera Creek Watershed at Ross, 1976-1999.

SEDIMENT BUDGET COMPONENT	USING PARKER-KLINGEMAN SHEAR VALUES[2] ESTIMATED SEDIMENT YIELD (TONS/YEAR)	ESTIMATED SEDIMENT YIELD (TONS/SQ.MI./YR)	PERCENT OF TOTAL SEDIMENT BUDGET (%)	PERCENT OF BEDLOAD SEDIMENT BUDGET (%)	USING USFS SHEAR VALUES[3] ESTIMATED SEDIMENT YIELD (TONS/YEAR)	ESTIMATED SEDIMENT YIELD (TONS/SQ.MI./YR)	PERCENT OF TOTAL SEDIMENT BUDGET (%)	PERCENT OF BEDLOAD SEDIMENT BUDGET (%)
Sediment yield by fluvial transport from hillslopes in sampled upland subwatersheds								
as bedload	6,570	571	6.7	67	2,914	253	6.2	62
as suspended, through-put, and washload [1]	59,130	5,142	60	--	26,230	2,281	56	--
Sediment yield by fluvial transport from unsampled areas [4]								
as bedload	2,570	571	2.6	26	1,140	253	2.4	24
as suspended, through-put, and washload	23,139	5,142	24	--	10,264	2,281	22	--
Sediment yield from net channel bed erosion								
as bedload	428	27	0.4	4	428	27	0.9	9
as suspended, through-put, and washload	3,852	241	3.9	--	3,852	241	8.2	--
Sediment yield from channel bank erosion								
as bedload	238	15	0.2	2	238	15	0.5	5
as suspended, through-put, and washload	2,142	134	2.2	--	2,142	134	4.5	--
TOTAL	98,069	6,129	100	100	47,208	2,951	100	100
as bedload	9,807	571	10	100	4,721	295	10	100

[1] Assumes bedload sediment yield is 10% of total sediment yield.
[2] Bedload sediment yield estimates using Parker-Klingeman shear values (Parker and Klingeman 1982).
[3] Bedload sediment yield estimates using USDA Forest Service shear values (Paul Bakke, USFS, Klamath Falls, pers. comm., 1999).
[4] Assumes sediment yield per unit drainage area in unsampled areas equals that of sampled areas.

Table 9. Comparison of estimated sediment yields and budget to other sediment yield and budget studies in northern California Coast Range watersheds.

	SEDIMENT YIELD BY SEDIMENT BUDGET COMPONENT IN TONS/SQ. MI./YEAR AND % OF TOTAL YIELD			
STUDY	Stetson (2000)[1] P-K shear values	Stetson (2000)[2] USFS shear values	Lehre (1982)	Kelsey (1980)
LOCATION	Corte Madera Creek at Ross	Corte Madera Creek at Ross	Lone Tree Creek at Highway 1	Van Duzen River at Bridgeville Eel River Basin
	E. Marin County	E. Marin County	W. Marin County	Humboldt County
UNDERLYING GEOLOGIC TYPE	Franciscan melange/ sandstone	Franciscan melange/ sandstone	Franciscan melange/ sandstone	Franciscan melange/ sandstone
VEGETATION COVER	wooded/grassland	wooded/grassland	wooded/grassland	wooded/grassland
HISTORICAL AND PRESENT LAND USE	logged/grazed partially urban	logged/grazed partially urban	grazed retired	logged/grazed partially active
DRAINAGE AREA (SQ. MI.)	16.0	16.0	0.68	224.3
PERIOD OF RECORD	1976-1999	1976-1999	1971-1974	1941-1975
NUMBER OF YEARS	23	23	3	34
SEDIMENT BUDGET COMPONENT				
Sediment yield by fluvial transport from hillslopes				
landslides			1,680 (66%)	2,000 (22%)
landslide scar and scarp erosion			228 (8.9)	
gullies and headcut erosion			468 (18%)	
soil creep and earthflow			16.9 (0.7%)	6,800 (73%)
overland fluvial transport (sheetwash)			11.3 (0.4%)	
Transport through channel network				
bedload	571 (9.3%)	253 (8.6%)	240	767
suspended, through-put, and washload	5,142 (83.9%)	2,281 (77.3%)	1,712	6,620
Sediment yield by net bed and bank erosion				
net channel bed erosion (erosion - aggradation)	149 (2.4%)	149 (5.1%)	104 (4.1%)	-1600 (-17%)
channel bank erosion	268 (4.4%)	268 (9.2%)	45 (1.8%)	500 (5%)
Total sediment yield	6,129	2,951	2,553	7,700

[1] Budget compiled with bedload sediment yield estimates using Parker-Klingeman shear values (Parker and Klingeman 1982).
[2] Budget compiled with bedload sediment yield estimates using USDA Forest Service shear values (Paul Bakke, USFS, Klamath Falls, pers. comm., 1999).

Table 10. Summary of existing suspended and bedload sediment yield data for Northern California Coast Range watersheds

RIVER/BASIN	LOCATION	DRAINAGE AREA (SQ. MI.)	PERIOD	TOTAL SEDIMENT YIELD (TONS/ SQ. MI./ YEAR)	SUSPENDED SEDIMENT YIELD (TONS/ SQ. MI./ YEAR)	BEDLOAD SEDIMENT YIELD (TONS/ SQ. MI./ YEAR)	PERCENT AS BEDLOAD (%)	SOURCE
Corte Madera Ck	Ross	16.0	1978	1,456	1,194	261	17.9	USGS (1978)
			1979	369	255	20	5.4	USGS (1979)
			1980	1,975	1,876	103	5.2	USGS (1980)
			1978-80	1,267	1,108	128	9.5	USGS (1978, 1979, 1980)
			1977-80			692		COE (1989:34)
			1976-99	6,129	5,517	613	10.0	Stetson (2000); P-K shear values; uncalibrated sediment budget
				2,951	2,655	295	10.0	Stetson (2000); USDA FS shear values; uncalibrated sediment budget
			1951-93			422		Stetson (2000); calibrated sediment yield estimate
Napa River	St. Helena	81	1958-60		781			Judson and Ritter (1964:3397)
		81.4	1957-59	627	587	40.4	6.4	Porterfield (1980:84)
			1957-66	853	799	53.8	6.3	Porterfield (1980:85)
			1909-59	781	736	44.9	5.7	Porterfield (1980:85)
			1909-66	799	754	44.9	5.6	Porterfield (1980:85)
Sonoma Ck	Boyes Hot Springs	62.2	1957-59	564	499	64.6	11.5	Porterfield (1980:84)
			1957-66	552	487	64.6	11.7	Porterfield (1980:85)
			1909-59	576	511	64.6	11.2	Porterfield (1980:85)
			1909-66	576	505	70.5	12.3	Porterfield (1980:85)
Petaluma Creek		41	1957-59	401	374	26.7	6.7	Porterfield (1980:84)
			1957-66	392	365	26.7	6.8	Porterfield (1980:85)
			1909-59	517	472	44.5	8.6	Porterfield (1980:85)
			1909-66	517	472	44.5	8.6	Porterfield (1980:85)
Russian River	Mendocino Reservoir	272	1952-85	2,000				Kondolf and Matthews (1993:35)
	Guerneville	1,340	1965-1971		2,829			Ritter and Brown (1971:24)
	near Ukiah	99.7	1965-68		2,640			
	Cloverdale	502	1965-68		1,803			Ritter and Brown (1971:24)
Big Sulphur Ck	Cloverdale	82.3	1965-68		4,600			Ritter and Brown (1971:24)
Dry Creek	Geyserville	162	1965-71		5,250			Brown and Jackson (1974:2)
Walker Creek	Tomales	15.7	1971		1,120			Brown and Jackson (1974:2)
	Tomales Bay	69.3	1860-1930	948				Daetwyler (1950) as cited in Haible (1980:252)
Pine Creek	Bolinas	7.8	1968-70		1,760			Brown and Jackson (1974:2)
Lone Tree Creek	Highway 1	0.68	1971-74	1,952	1,712	240	12.3	Lehre (1982)
Colma Ck		12.5	1957-66		6,730			USGS Water Resources Investigations 80-64, p. 87
Eel River	near Hulville	288	1920-59		977			Larson and Sidle (1980)
	Scotia	3,113	1958-60		5,846			Judson and Ritter (1964:3397)
	near Scotia	3,113	1958-68		10,038			Larson and Sidle (1980)
	Scott Reservoir	291	1921-84	1,780				Kondolf and Matthews (1993:35)
	Middle Fork near Dos Rios	753	1958-68		2,660			Larson and Sidle (1980)
Van Duzen River	Bridgeville	224.3	1941-75	7,249	6,620	767	10.6	Kelsey (1980:1133,1145)
			1958-64		6,820			Hawley and Jones (1969)
	near Carlotta	216	1958-67		7,280			Larson and Sidle (1980)
Mad River	Arcata	485	1948-60		3,711			Judson and Ritter (1964:3397)
Alameda Ck	Niles	633	1957-60		349			Judson and Ritter (1964:3397)
			1957-70	302				Brown and Jackson (1973)
Walnut Ck	Contra Costa County	79.2	1957-62		1,070			
Uvas Ck	Uvas Reservoir		1962-70	1,326				Brown and Jackson (1973)

Table 11. Comparison of estimated channel incision and channel bank retreat rates with results of other studies in the region.

STUDY	Stetson (2000)	Collins (1998)	Haible (1980)
LOCATION	Corte Madera Creek above Ross	Lower Navato Creek	Walker Creek at Tomales Bay
	E. Marin County	E. Marin County	W. Marin County
UNDERLYING GEOLOGIC TYPE	Franciscan melange/ sandstone	Franciscan melange/ sandstone	Franciscan melange
VEGETATION COVER	wooded/grassland	wooded/grassland	wooded/grassland
HISTORICAL AND PRESENT LAND USE	logged/grazed partially urban	logged/grazed partially urban	partially grazed
DRAINAGE AREA (SQ. MI.)	16.0	24.5	69
PERIOD OF RECORD	1976-99	--	1915-75
NUMBER OF YEARS	23		60
AVERAGE CHANNEL INCISION RATE (FT/YEAR	0.04 [1]	0.03 - 0.04 [3]	0.08 [5]
AVERAGE COMBINED BANK RETREAT RATE (FT/YEAR	0.09 [2]	0.11 [4]	--

[1] Value estimated by 44 point channel bed elevation measurements replicating 1976 survey data.
[2] Upper conservative value; assumes observed lateral tree root scour occurred since 1976 and uniform distribution of average of measured values (2 ft).
[3] Estimated by relative elevation of tree root-trunk transitions; average value for 31 1987-1997 photograph comparisons was 0.03.
[4] Average combined total bank retreat reported as 3.5 ft as estimated by point lateral tree root scour measurements; upper conservative value; assumes total bank retreat occurred since germination date of youngest trees in sample (Collins 1998:28).
[5] Value estimated by measurement of bed incision below anecdotally dated inset floodplain surface.

Table 12. Comparison of relative total subwatershed sediment yields generated by fluvial transport from hillslopes by underlying geologic type and results of other studies.

Corte Madera Creek Watershed

	SUBWATERSHED	UNDERLYING GEOLOGIC TYPE	VEGETATION COVER/TERRAIN	Kelsey (1980) classification	TOTAL SEDIMENT YIELD BY FLUVIAL TRANSPORT FROM HILLSLOPES (TONS/SQ.MI./YEAR) Using P-K shear values	Using USFS shear values
1	Larkspur Ck	Upper Cretaceous sandstone	Steep, moderate to well-drained conifer-forested sandstone slopes with v-shaped stream canyons and sharp ridge crests and high drainage density; partially roaded;	II	--	--
2	Tamalpais Ck	Sandstone and shale with minor bodies of melange and greenstone	Steep, moderate to well-drained conifer-forested sandstone slopes with v-shaped stream canyons and high drainage density; rolling, hummocky, grassland-covered gullied melange slopes; densely roaded/urbanized uplands;	II, Ib, IIIe	7,950 - 8,970	--
3	Ross Ck above Phoenix Dam	Franciscan melange and sandstone with minor bodies of greenstone	Steep, moderate to well-drained conifer-forested sandstone and melange slopes with v-shaped stream canyons; minor hummocky, gullied grassland-covered melange slopes; partially roaded;	II, Ib, IIIe		
	Ross Ck below Phoenix Dam	Sandstone with minor bodies of melange and greenstone	Steep, conifer and oak woodland covered, urbanized, gullied sandstone slopes with widespread creep and earthflow and landslides to main channels;	II	9,170	2,067
4	Sorich Ck	Franciscan melange	Rolling, smooth-to-hummocky, grassland and grass-oak woodland covered, gullied, moderately to highly deformed melange hillslopes with widespread rapid creep and earthflow directly to main channels; terracettes; rounded melange ridge crests; slightly entrenched main channel variably cut in earth-flow deposits;	Ib, Ic, Id, and Ie	--	--
5	Sleepy Hollow Ck	Franciscan melange with minor bodies of sandstone and greenstone	Same as Sorich Creek, but main channel is moderately to deeply entrenched downstream of constriction in valley flat width;	Ib, Ic, Id, and Ie	3,750	9,447
6	Fairfax Ck	Franciscan melange and sandstone with minor bodies of greenstone, chert, and serpentine	Variable vegetation cover/terrain; Steep, moderate to well-drained conifer-forested and grassland and grass-oak woodland covered sandstone slopes, and steep, poorly to moderately drained, highly gullied, grassland covered moderately to highly deformed melange slopes; landslides not delivered to main channels;	Ib, Ic, Id, Ie, II, IIIe	1,950	116
7	Deer Park Ck	Franciscan melange with minor bodies of sandstone and greenstone	Moderately steep, moderate to well-drained mixed forested, moderately deformed melange slopes; moderately entrenched channel cut in landslide and earthflow deposits; moderate to high downslope creep rate;	Ib, Ic, Id, Ie, IIIe	1,470	141
8	Wood Lane Ck	Franciscan melange with minor bodies of sandstone and chert	Same as Deer Park Ck, but channel is less entrenched and floodplain is active at upland-alluvial transition;	Ib, Ic, Id, Ie, II	2,680	0
9	San Anselmo Ck	Franciscan melange with minor bodies of serpentine, greenstone, chert, and sandstone	Very steep, poorly to moderately drained, gullied, chaparral and mixed forest-covered, highly deformed melange slopes with variably rounded ridge crests, high landslide frequency and road density; steep channel cut in earthflow and landslide deposits; high downslope creep rate;	Ib, Ic, Id, Ie, II, IIIb, IIIc	11,360	268
10	Upper San Anselmo Ck	Franciscan melange and serpentine	Same as San Anselmo Creek	Ib, Ic, Id, Ie, II, IIIb, IIIc	37,980	864

Van Duzen River Watershed, 1941-1975

	DESCRIPTION OF UNDERLYING GEOLOGIC TYPE/VEGETATION COVER/TERRAIN (Kelsey 1980:1147)	TOTAL SEDIMENT YIELD BY FLUVIAL TRANSPORT FROM HILLSLOPES (TONS/SQ.MI./YEAR)
I	**Franciscan melange slopes: grassland and grass-oak woodland and minor coniferous forest**	
Ia	melange: smooth-textured rolling terrain with good drainage	3,949
Ib	melange: rolling, smooth-to-hummocky terrain, moderate to poor drainage, widespread slow mantle creep, localized slumps	13,821
Ic	melange: earthflow landslide areas with hummocky and highly gullied slopes, undrained depressions, extensive ground disruption	39,487
Id	melange: same as Ic except earthflows directly to major river channels, downslope movement is faster, ground disruption and gullying greater	74,179
Ie	melange: flat-topped summits and broadly rounded ridge crests	987
II	**Forested sandstone slopes: steep, well-drained conifer-forested slopes with v-shaped stream canyons and sharp ridge crests**	282
III	**Barren or sparsely vegetated slopes with bedrock at or near surface**	
IIIa	sandstone: barren slopes of high drainage density forming badlands topography	564
IIIb	serpentine	282
IIIc	greenstone: small rocky and jagged outcrops of metavolcanics	0

9. FIGURES

Figure 1 Location of Corte Madera Creek Watershed

FIGURES (CONT.)

Figure 2 Corte Madera Creek Watershed and major subwatersheds

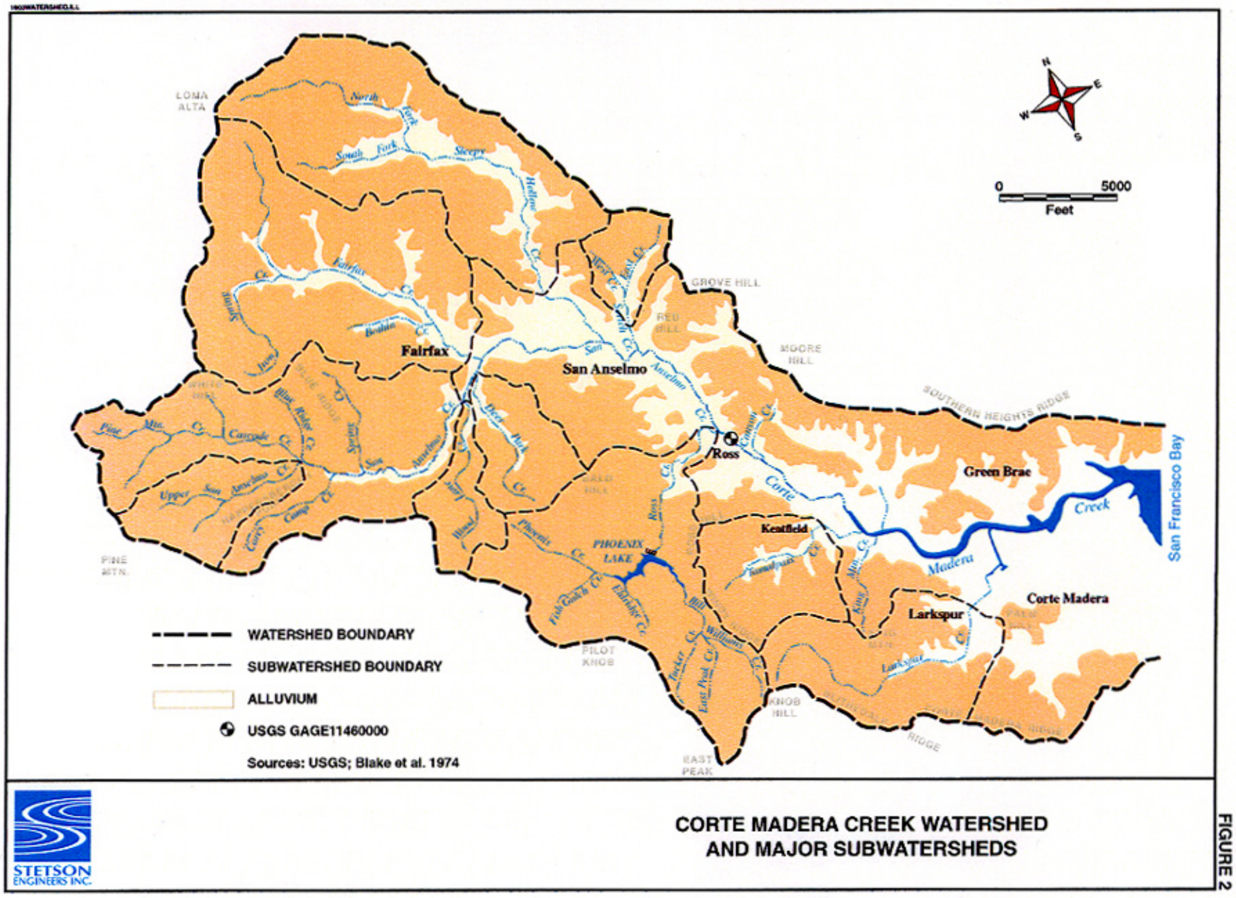


Figure 3 Schematic view of pre-entrenchment and post-entrenchment riparian corridor in lower alluvial channel network

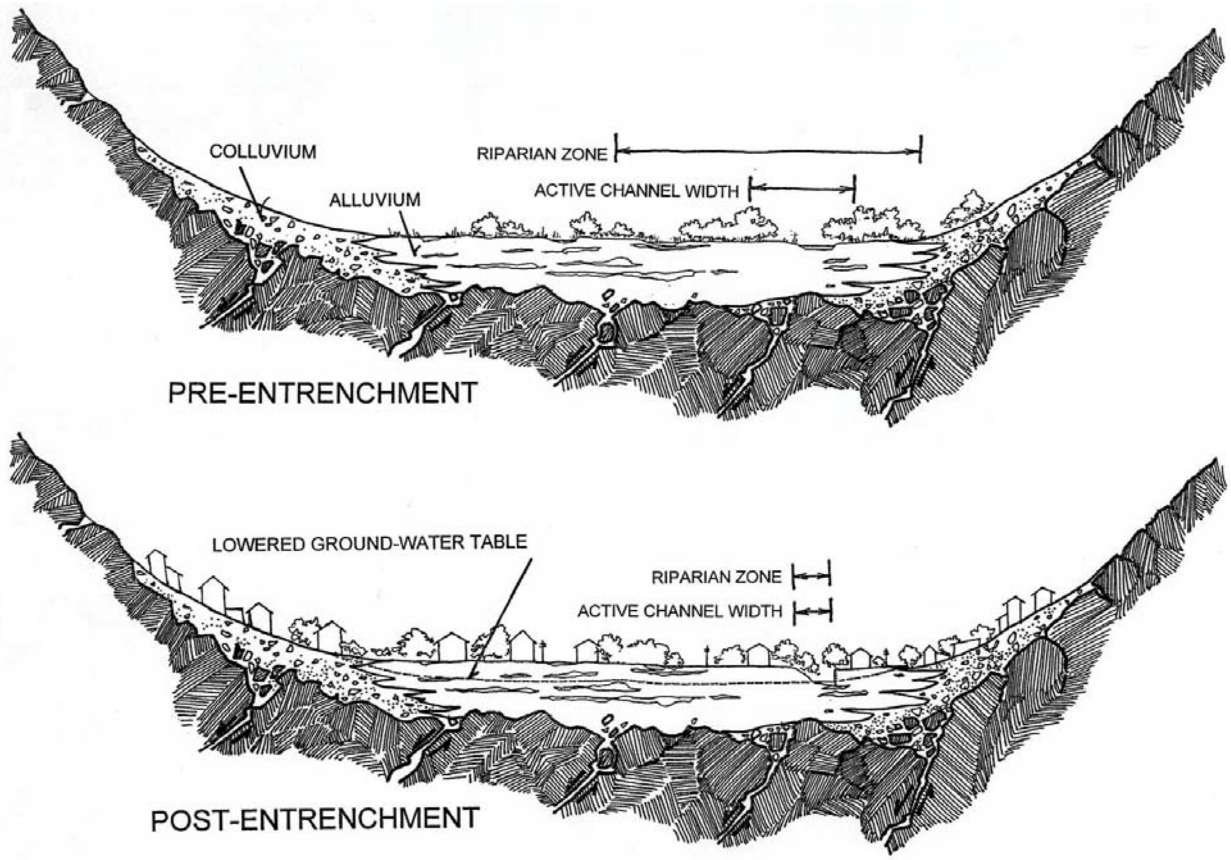
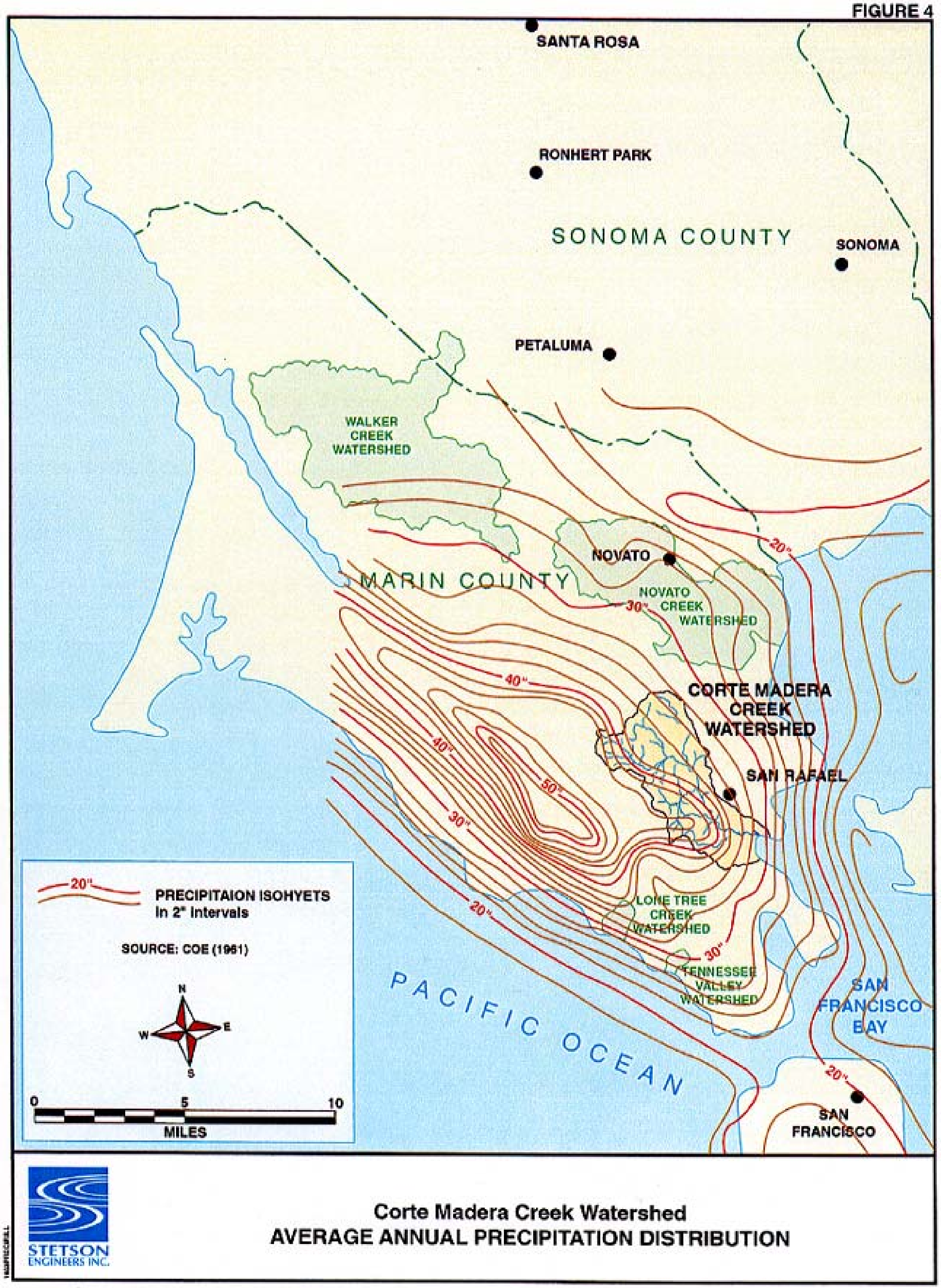


Figure 3. Schematic cross-sectional view of pre-entrenchment and post-entrenchment riparian corridor in a u-shaped valley in the lower alluvial channel network of Corte Madera Creek, showing active channel and riparian corridor width reduction, and lowered allluvial groundwater table, and valley fill interbedded with colluvium and clay lenses.

Figure 4 Average annual precipitation distribution



FIGURES (CONT.)

Figure 5 Average annual hydrograph at Ross Gage, 1951-1993

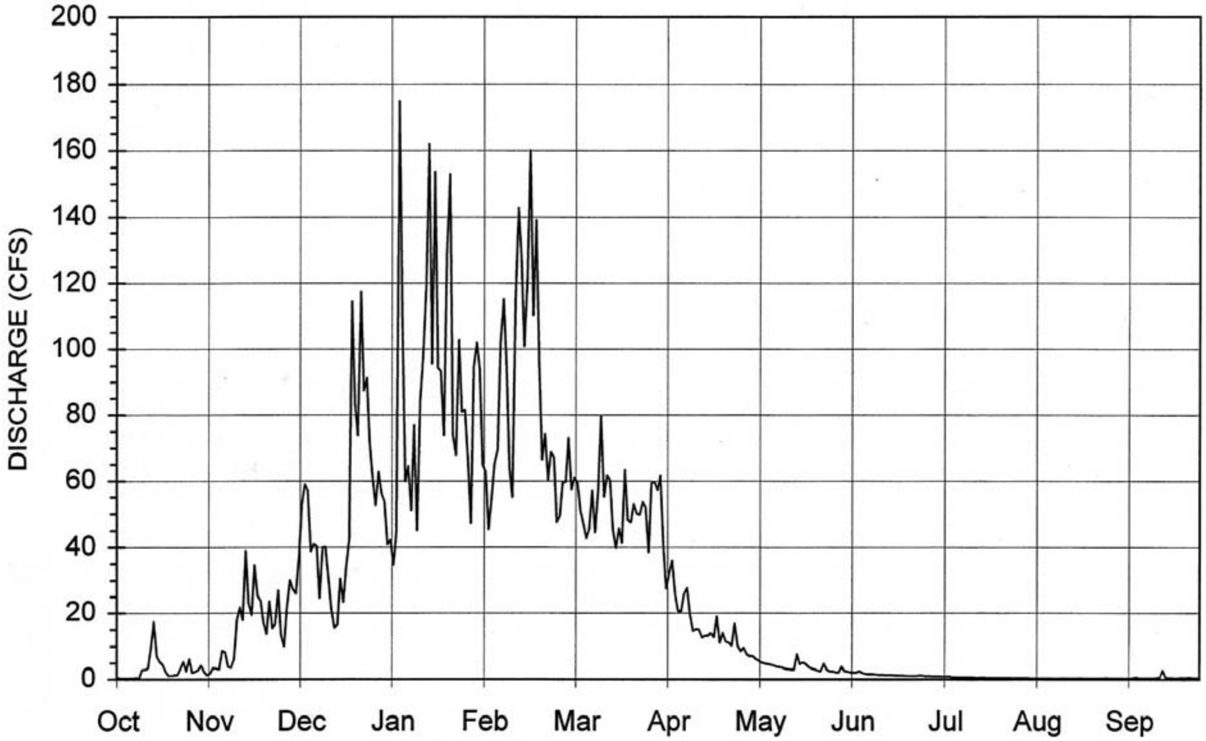
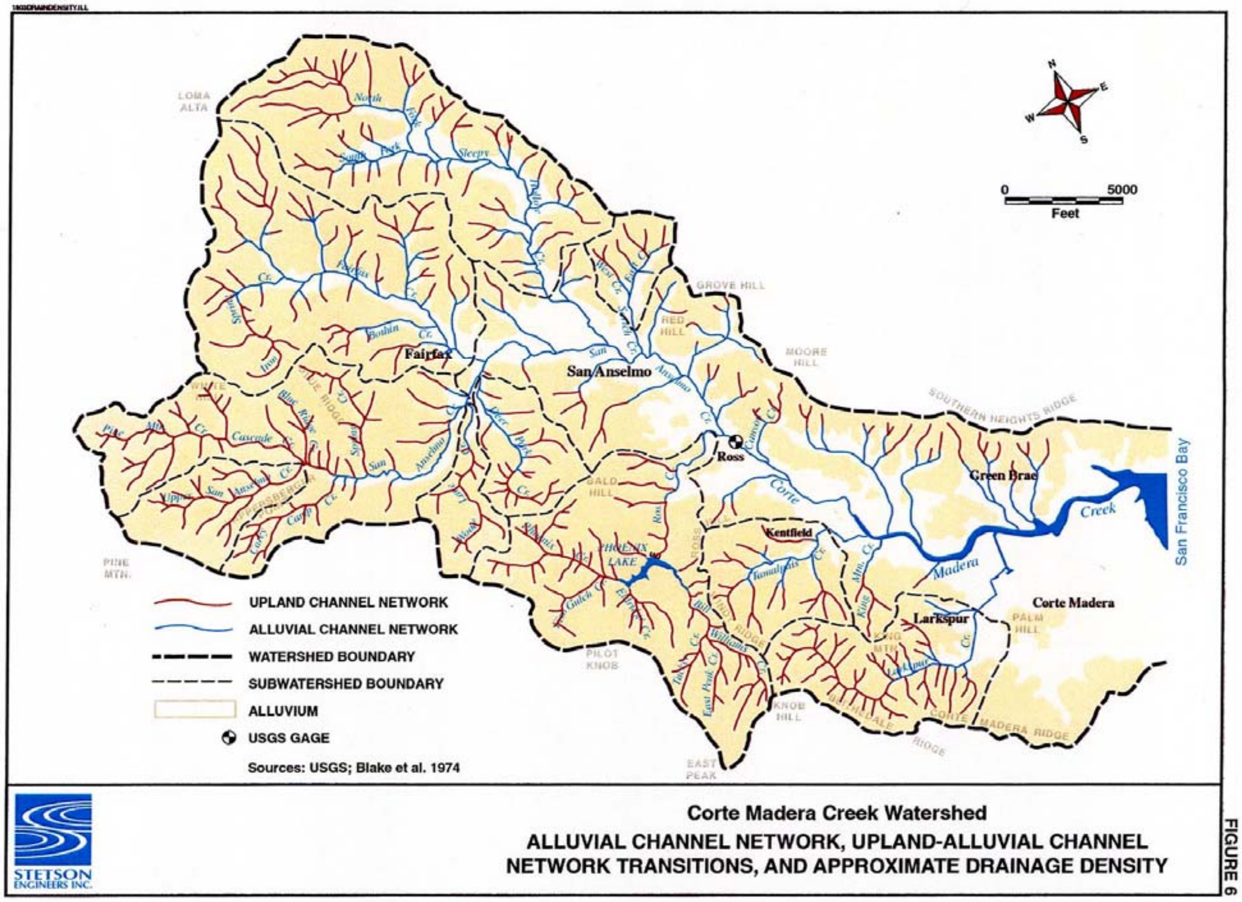


FIGURE 5. AVERAGE OF ALL ANNUAL MEAN DAILY FLOW HYDROGRAPHS AT ROSS GAGE, 1951-1993.

Figure 6 Alluvial channel network, upland-alluvial channel network transitions, and approximate drainage density



(Figures 7 and 8 have been omitted.)

Figure 9 Longitudinal profile of the mainstem Corte Madera - San Anselmo Creek

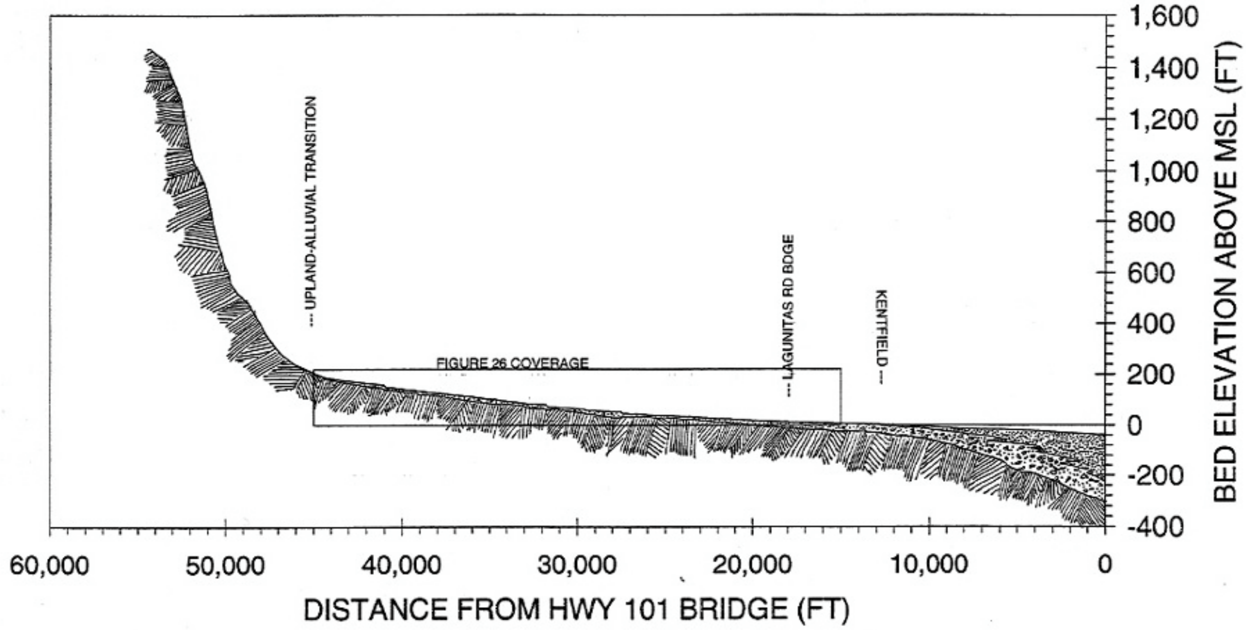


Figure 9. LONGITUDINAL PROFILE OF THE MAINSTEM CORTE MADERA - SAN ANSELMO CK

Figure 10 Historical channel geometry and channel bed elevation fluctuation at Ross Gage

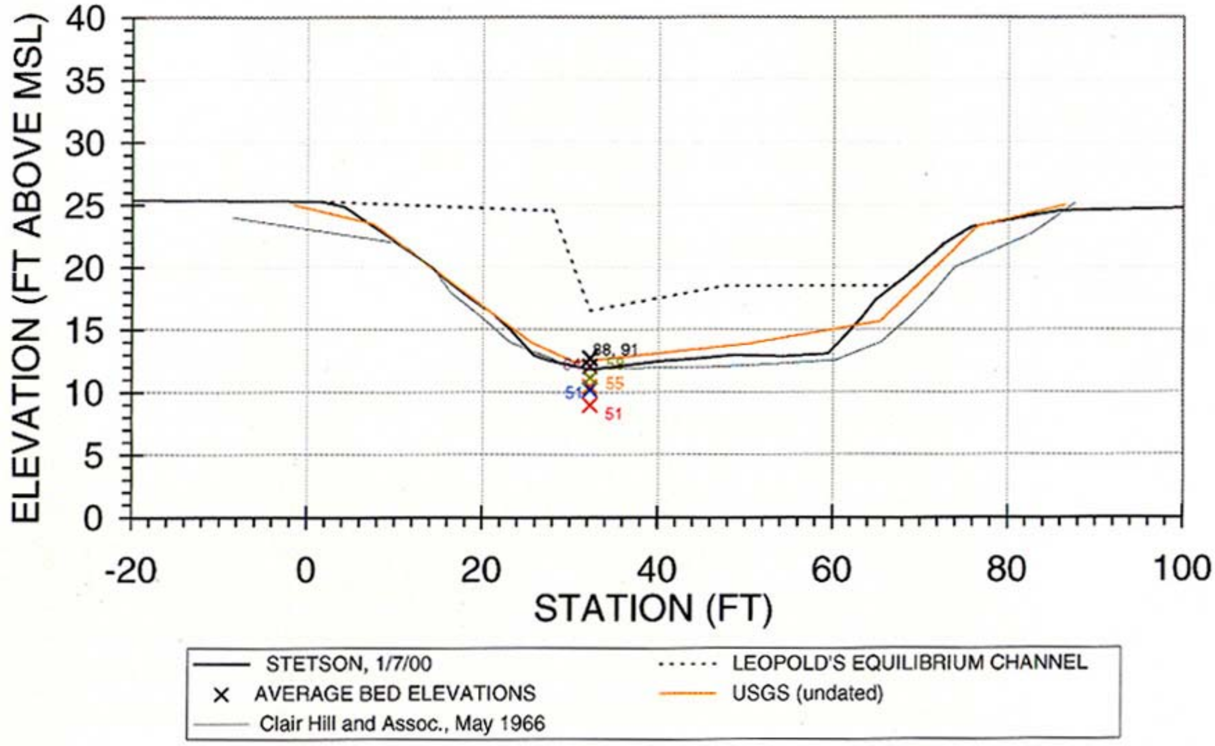


Figure 10. HISTORICAL CHANNEL GEOMETRY AND CHANNEL BED LEVEL FLUCTUATION AT ROSS GAGE, 1951-2000.

Figure 11 Head of cattle in Marin County, 1830 - 1910

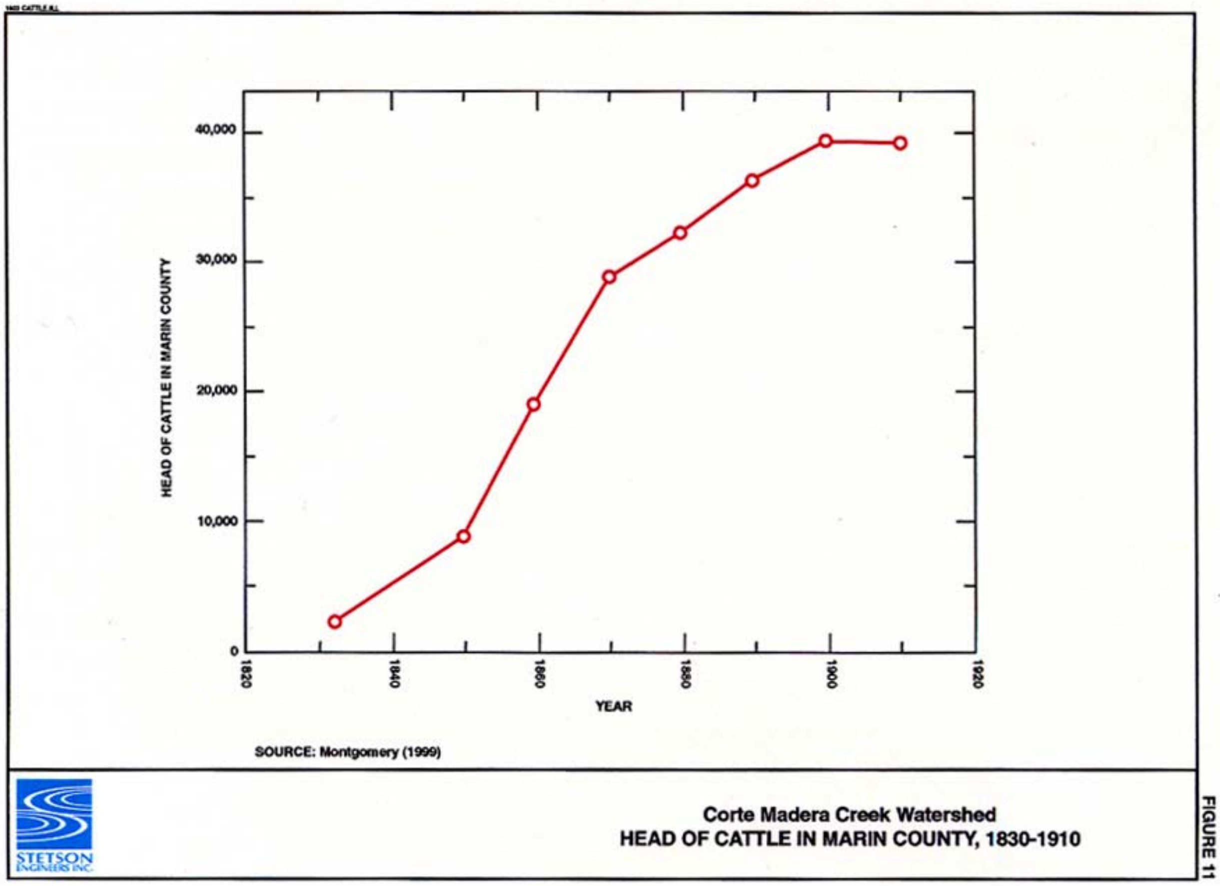


Figure 12 Historical distribution of livestock grazing

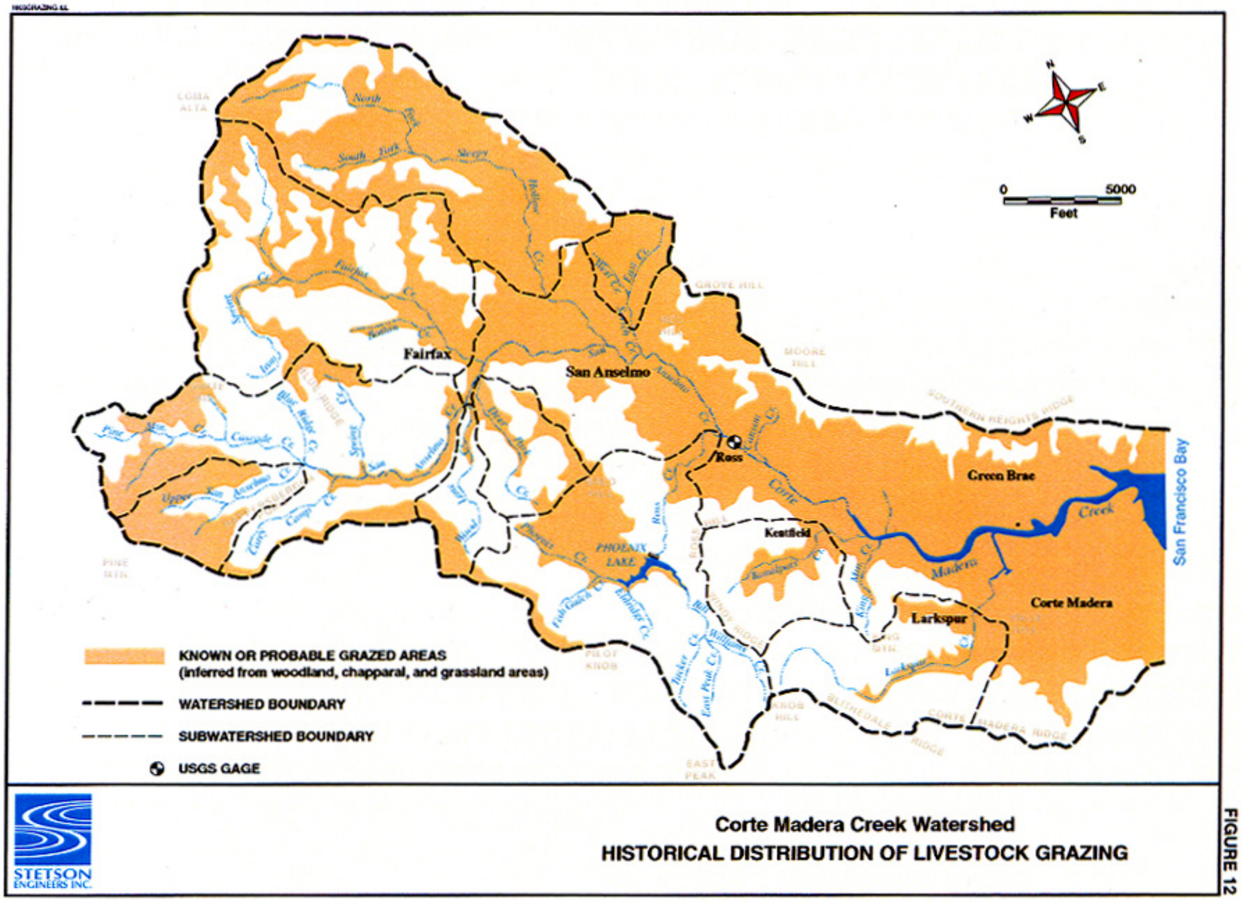


Figure 13 Historical distribution of forested versus grassland, grass-oak woodland, or chaparral vegetation cover and urban land uses

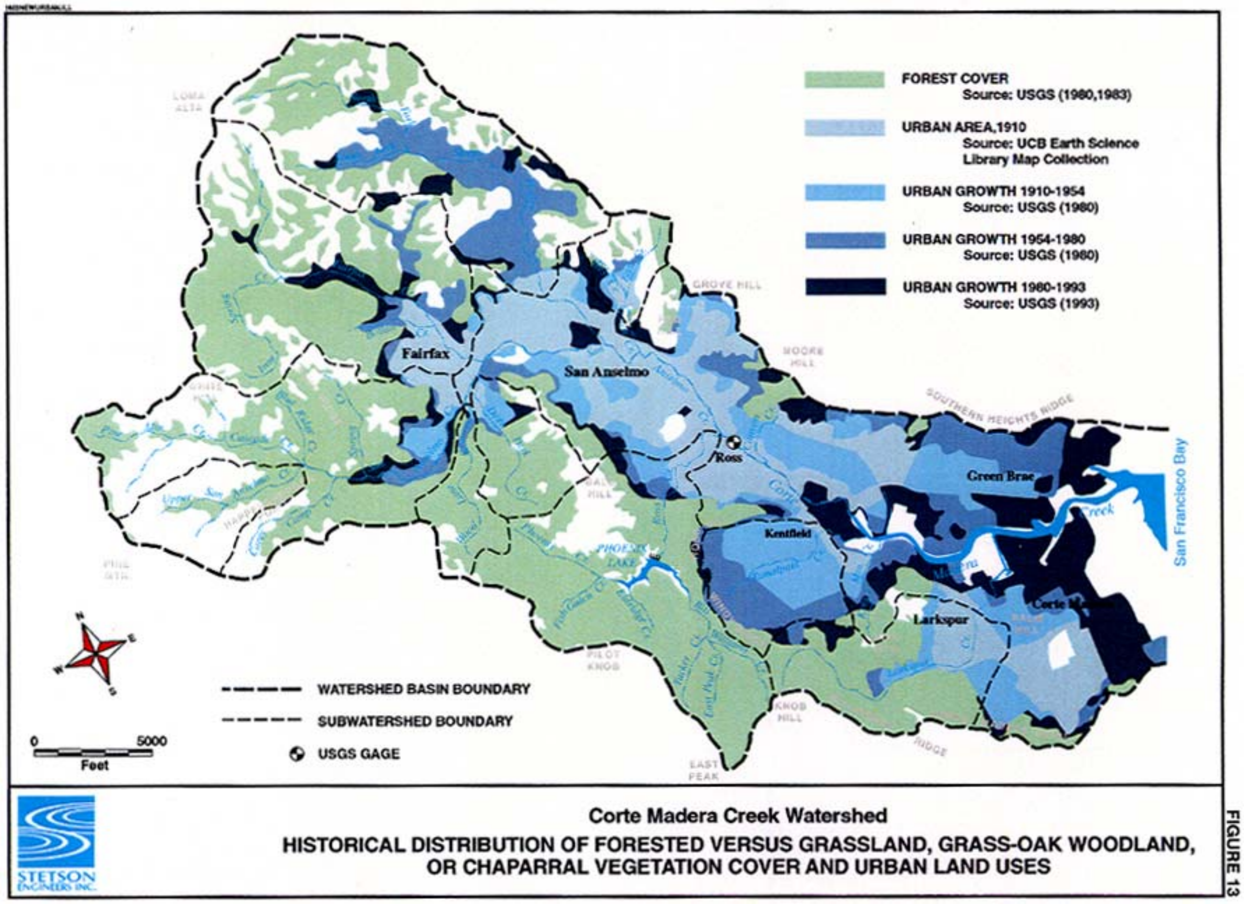


Figure 14 Schematic pre-urbanization and post-urbanization flood hydrographs

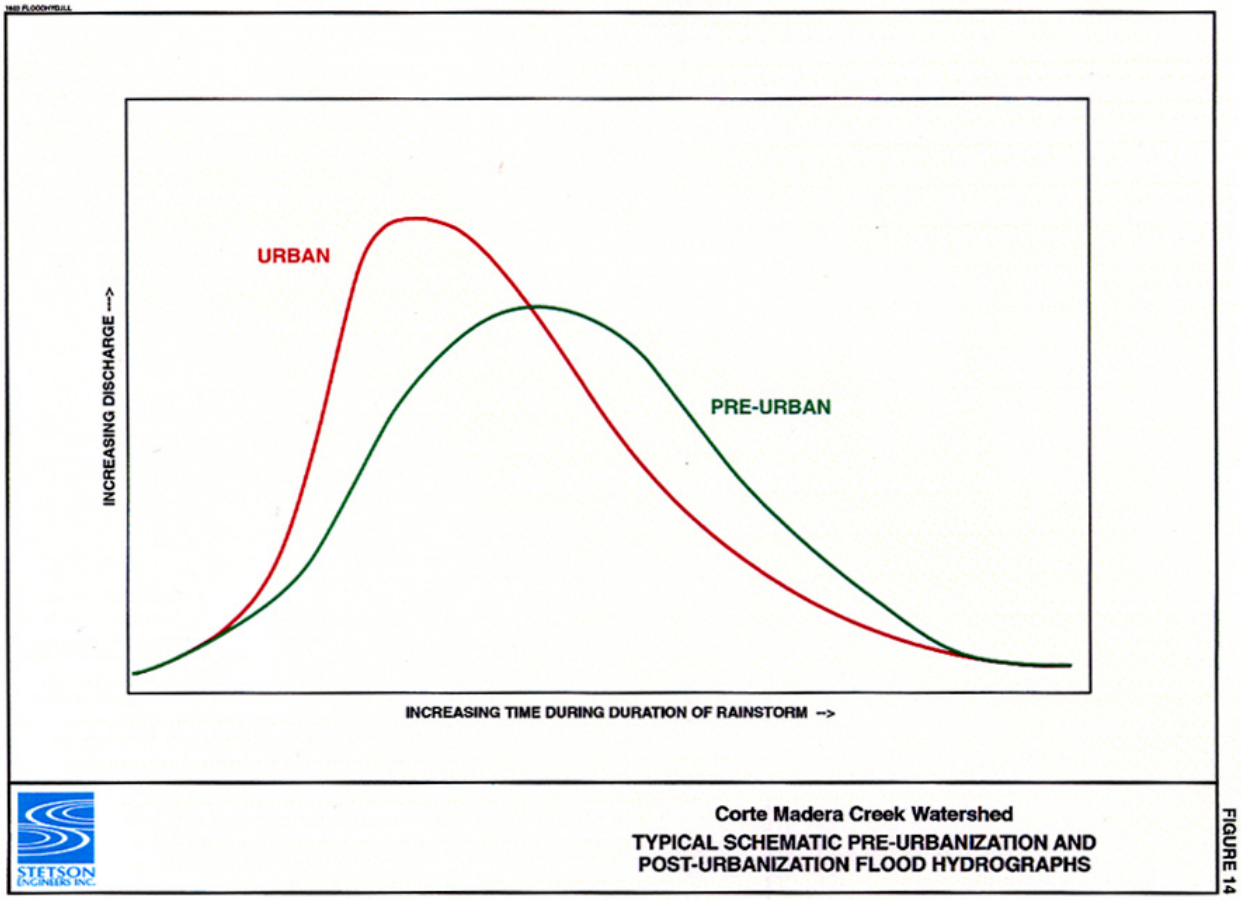


Figure 15 Conceptual timeline of land use, peak runoff, sediment yield, and channel responses in the Corte Madera Creek Watershed, 1800-2100

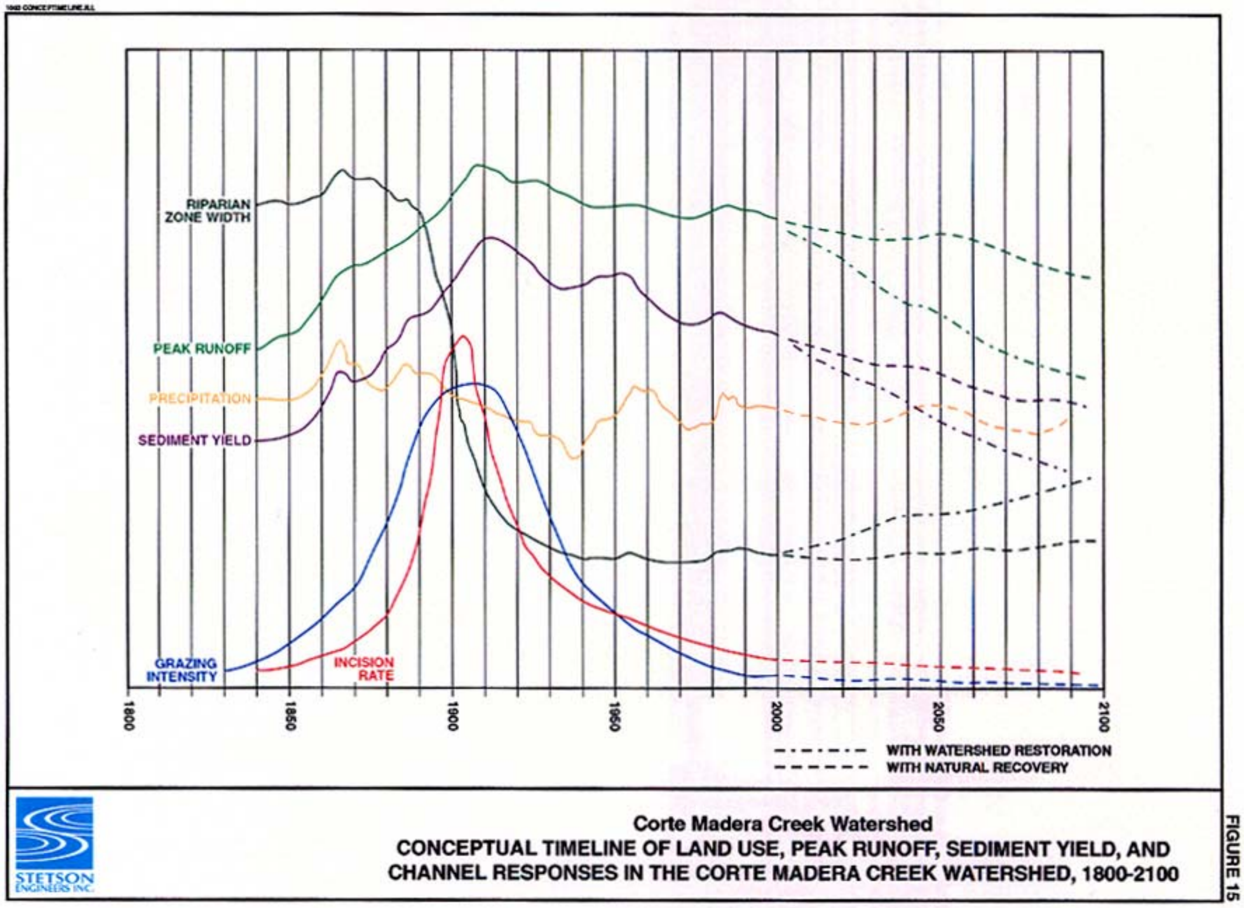


Figure 16 Conceptual representation of natural geomorphic recovery of Corte Madera Creek's entrenched alluvial channel network

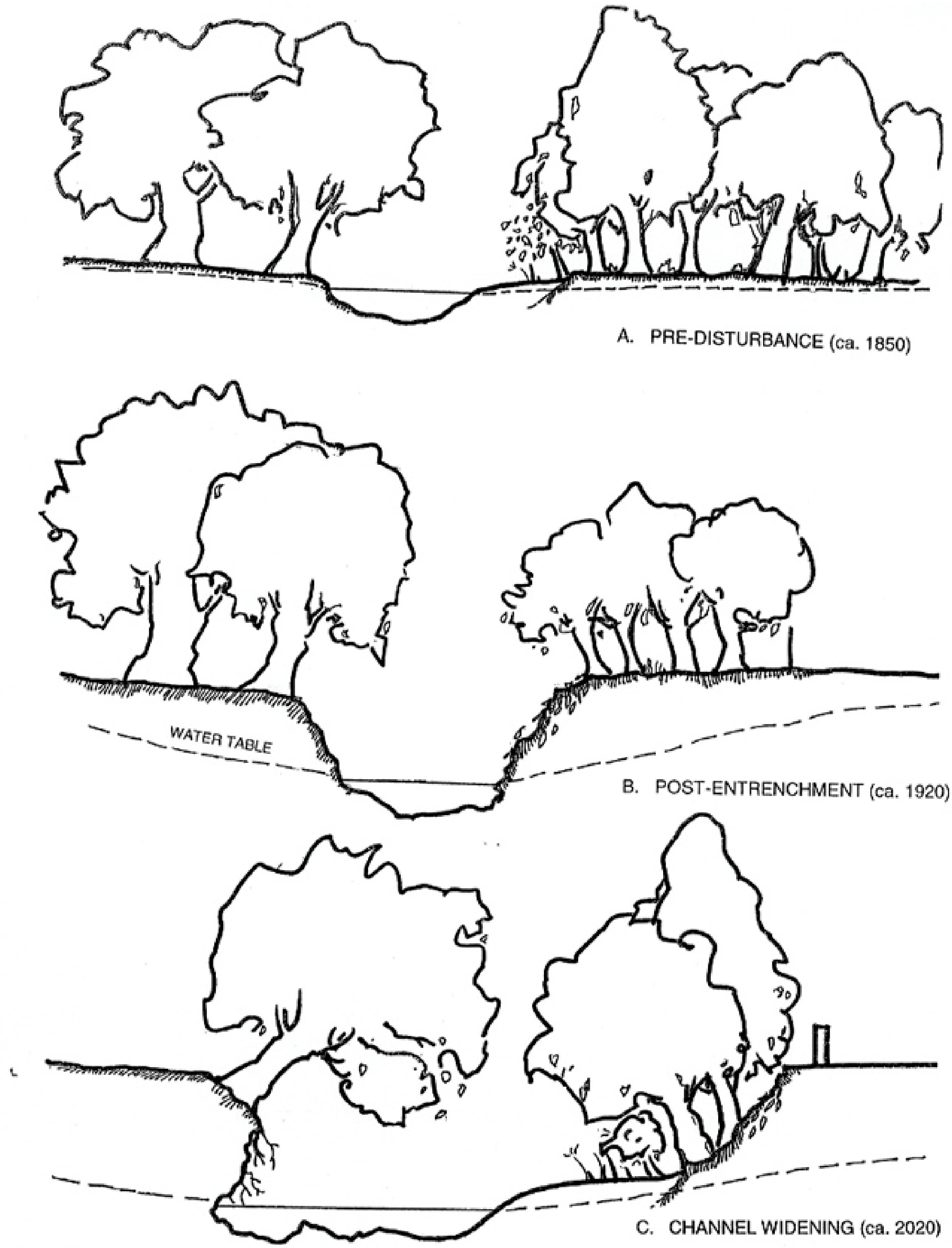


Figure 16. Conceptual representation of natural geomorphic recovery of entrenched stream channels showing pre-entrenchment condition, entrenched condition with confined active channel width and no gravel bar of floodplain formation, and recovered channel with increased active channel with, bar and floodplain formation, and increased near-channel riparian forest.

FIGURES (CONT.)

Figure 17 Generalized geology map

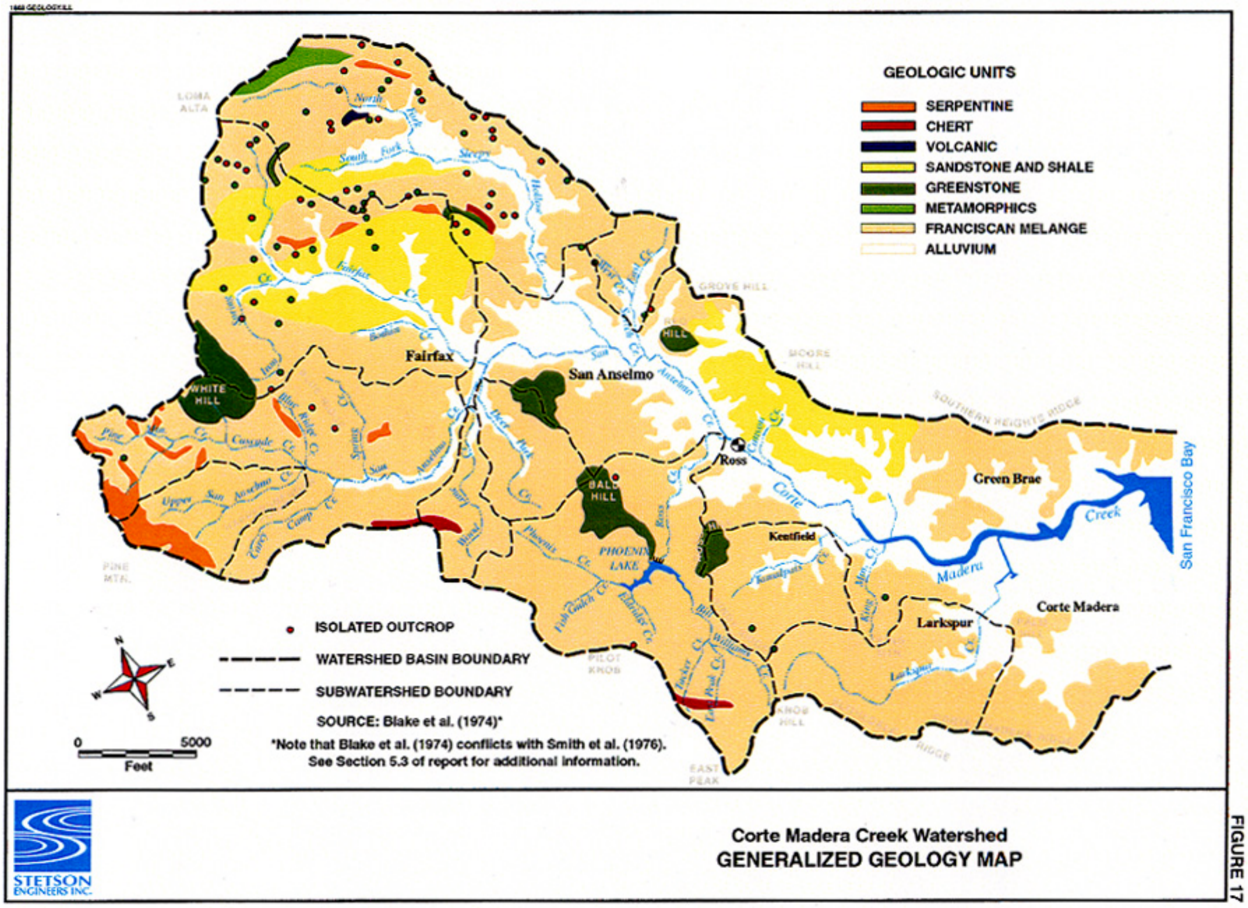


Figure 18 Preliminary sediment budget

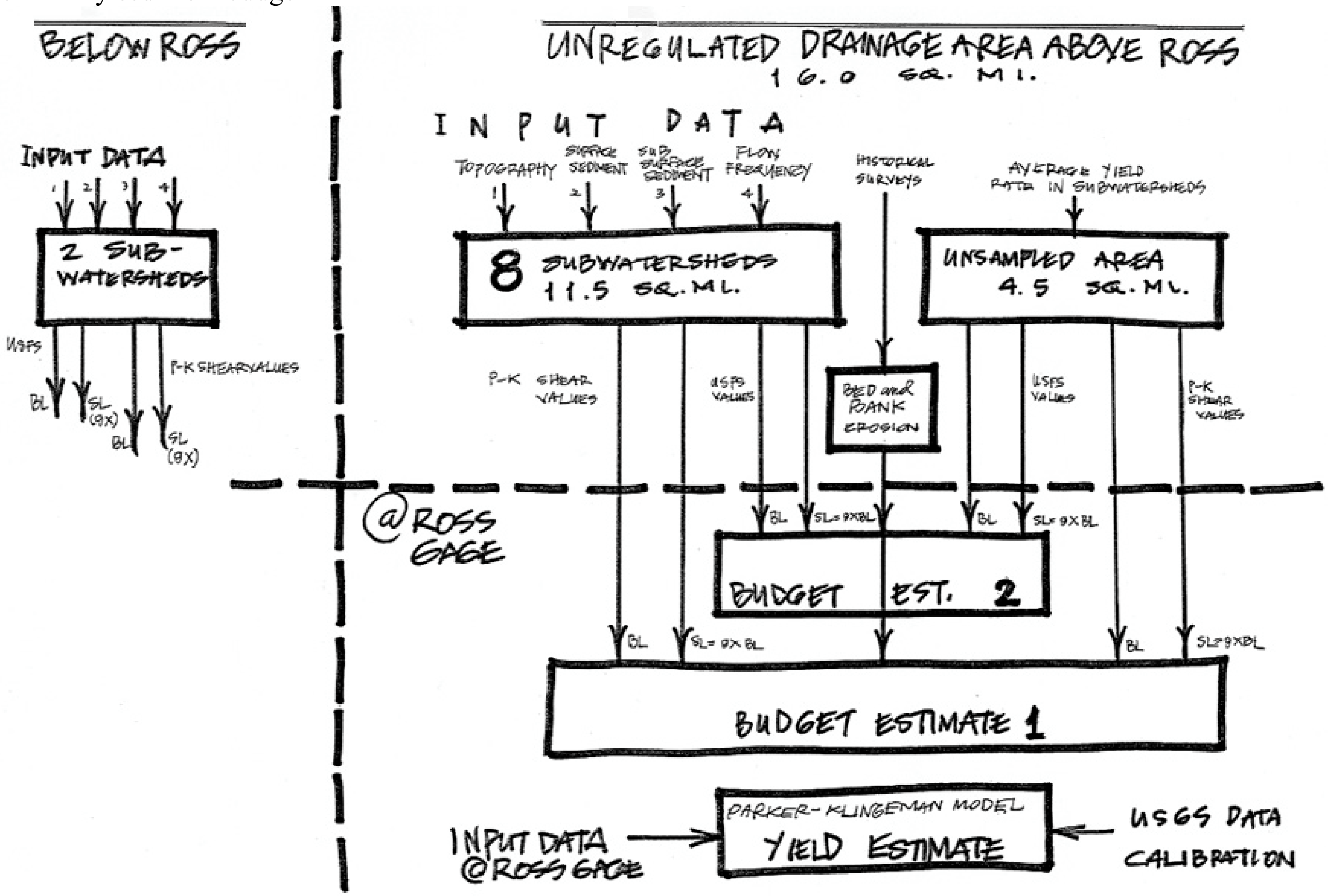


Figure 18. Preliminary sediment budget for the Corte Madera Creek Watershed above Ross showing budget estimate 1 using Parker-Klingeman shear values and budget estimate 2 using USFS shear values. An independent estimate of bedload sediment inflow at Ross is also shown, by a calibrated bedload sediment transport model applied for Ross Gage site parameters.

Figure 19 Locations of modeled subwatershed outlet sites

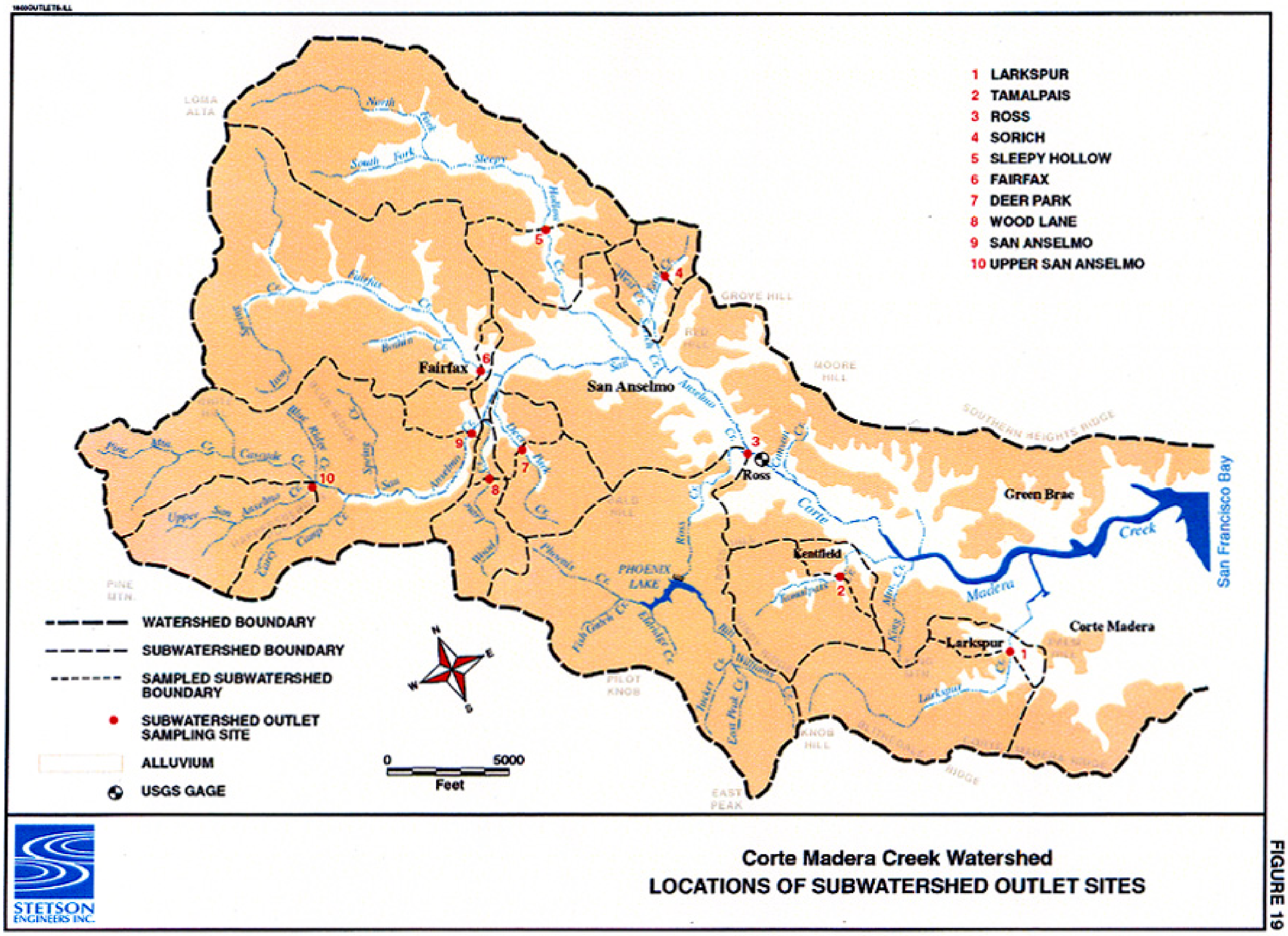


Figure 20 Landslide distribution

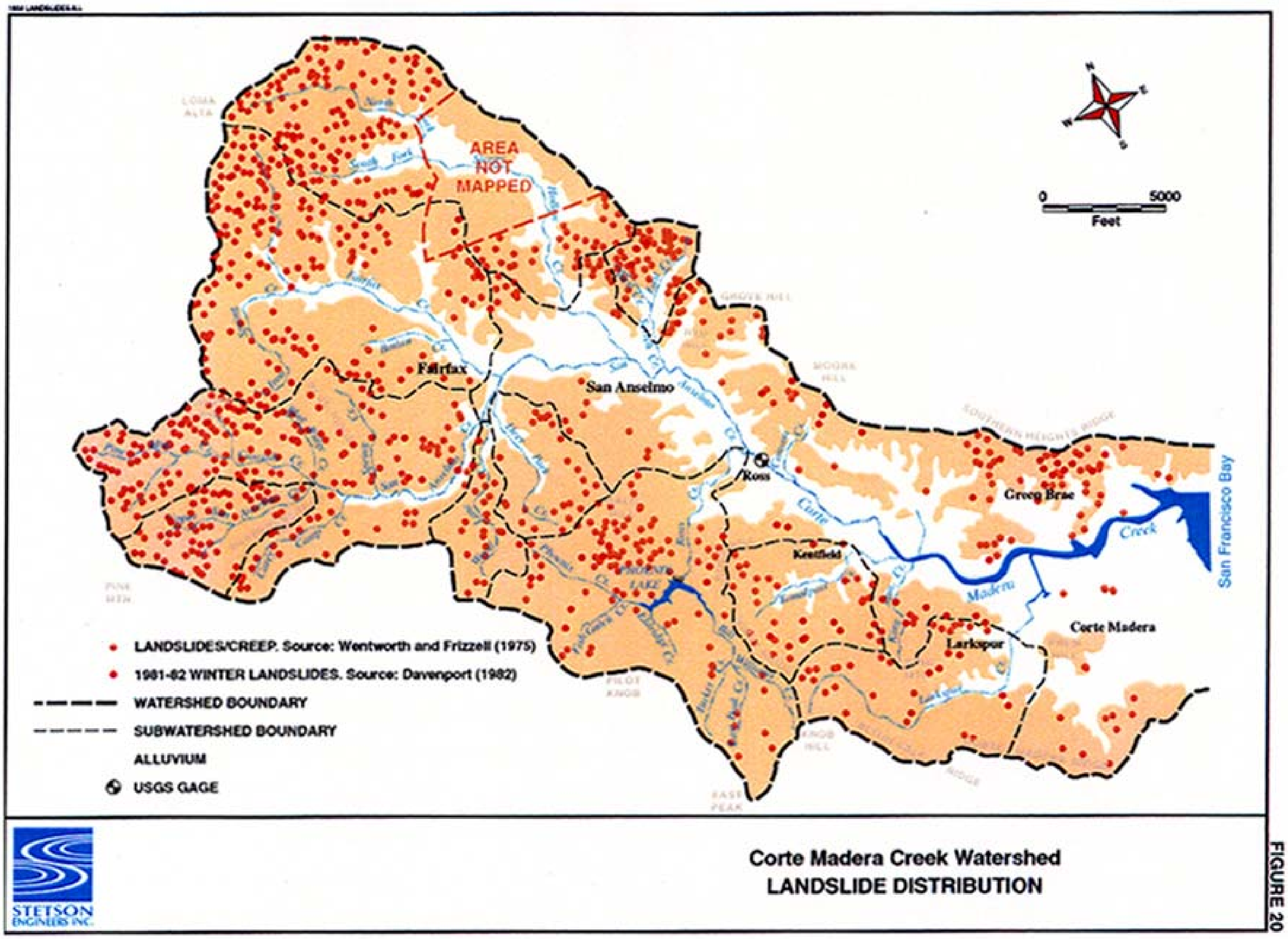


Figure 21 Gully distribution

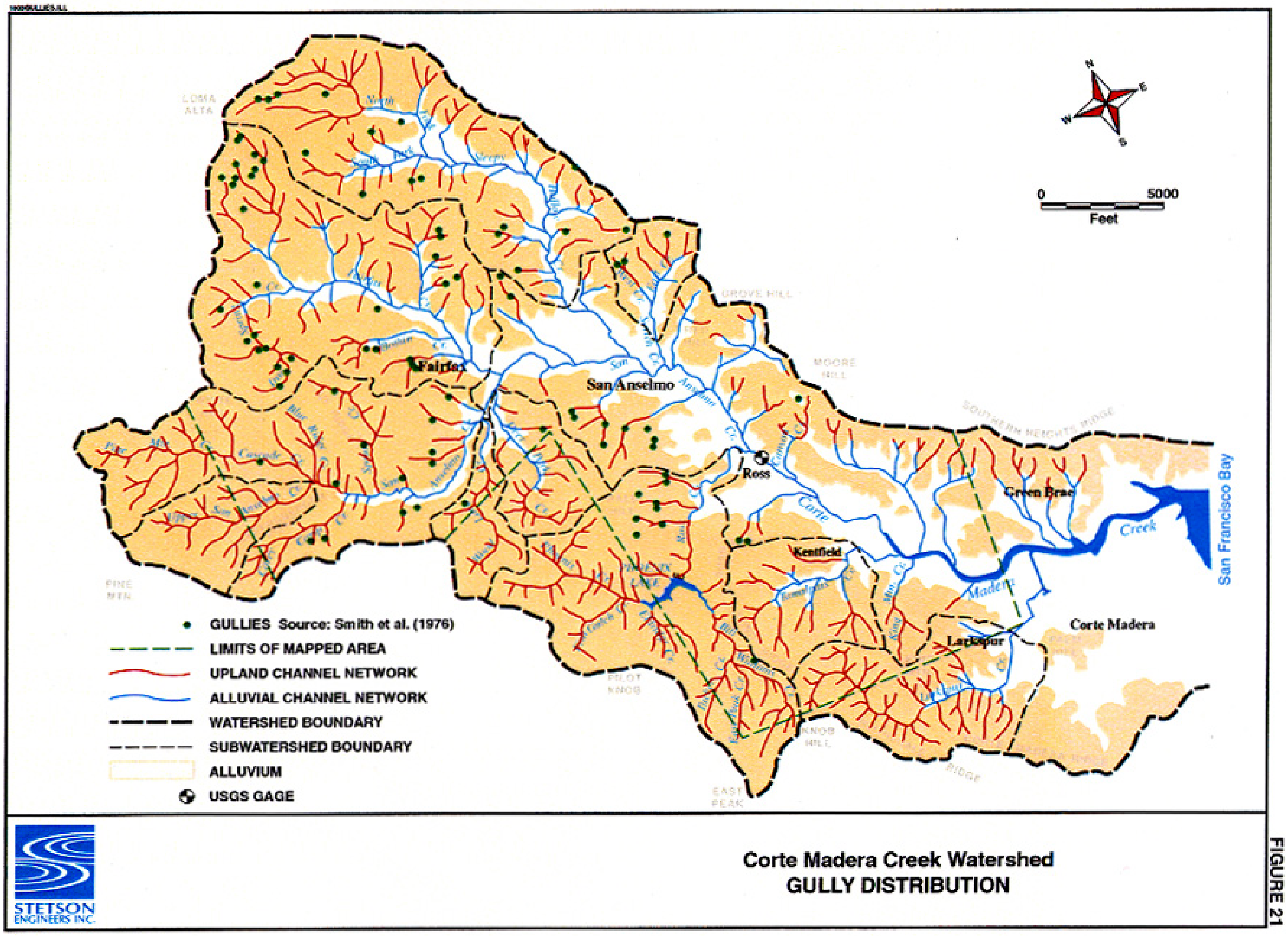


Figure 22 Percent hillslope distribution

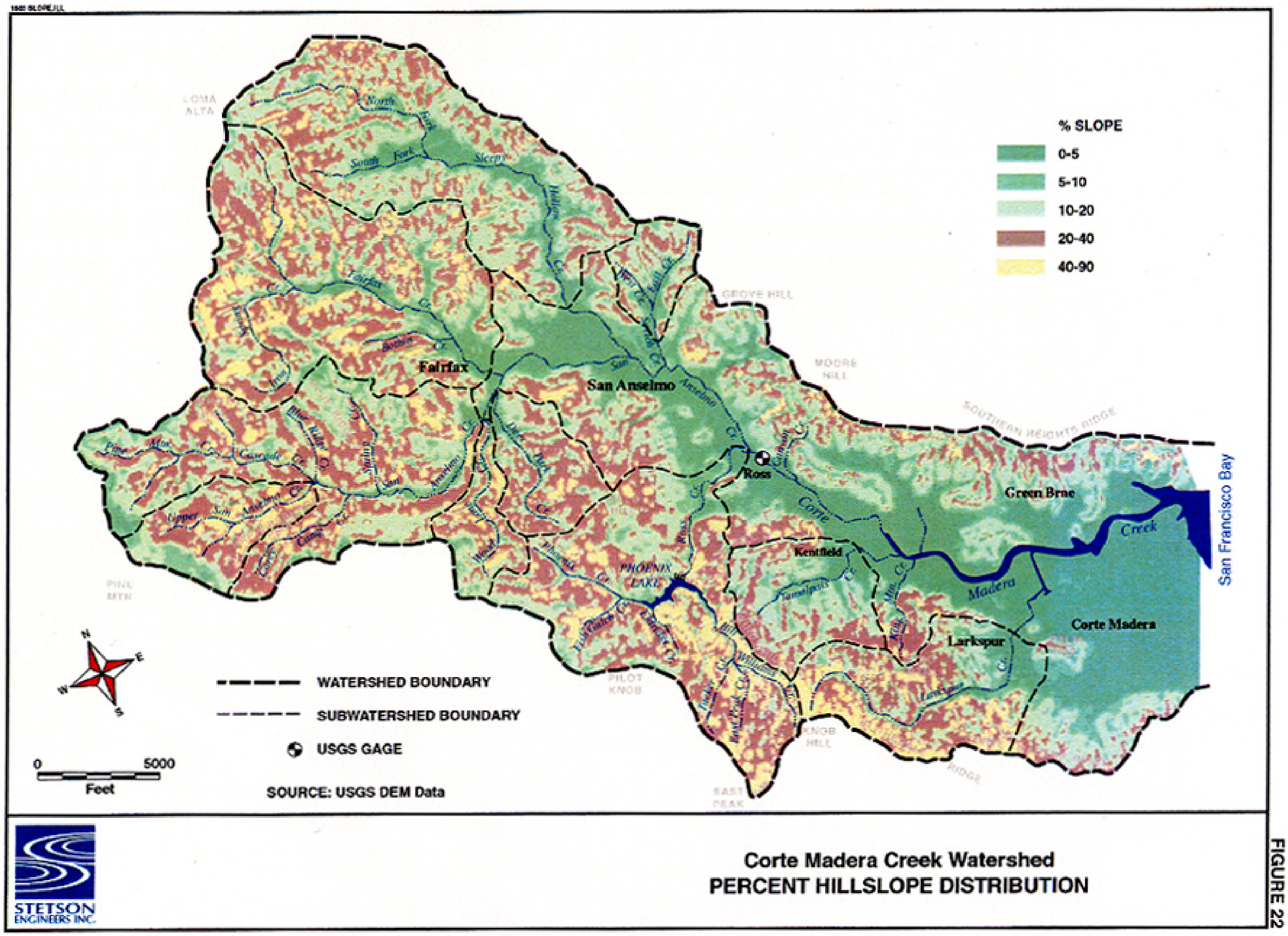


Figure 23 Locations and descriptions of typical active upland sediment sources and erosion management problems

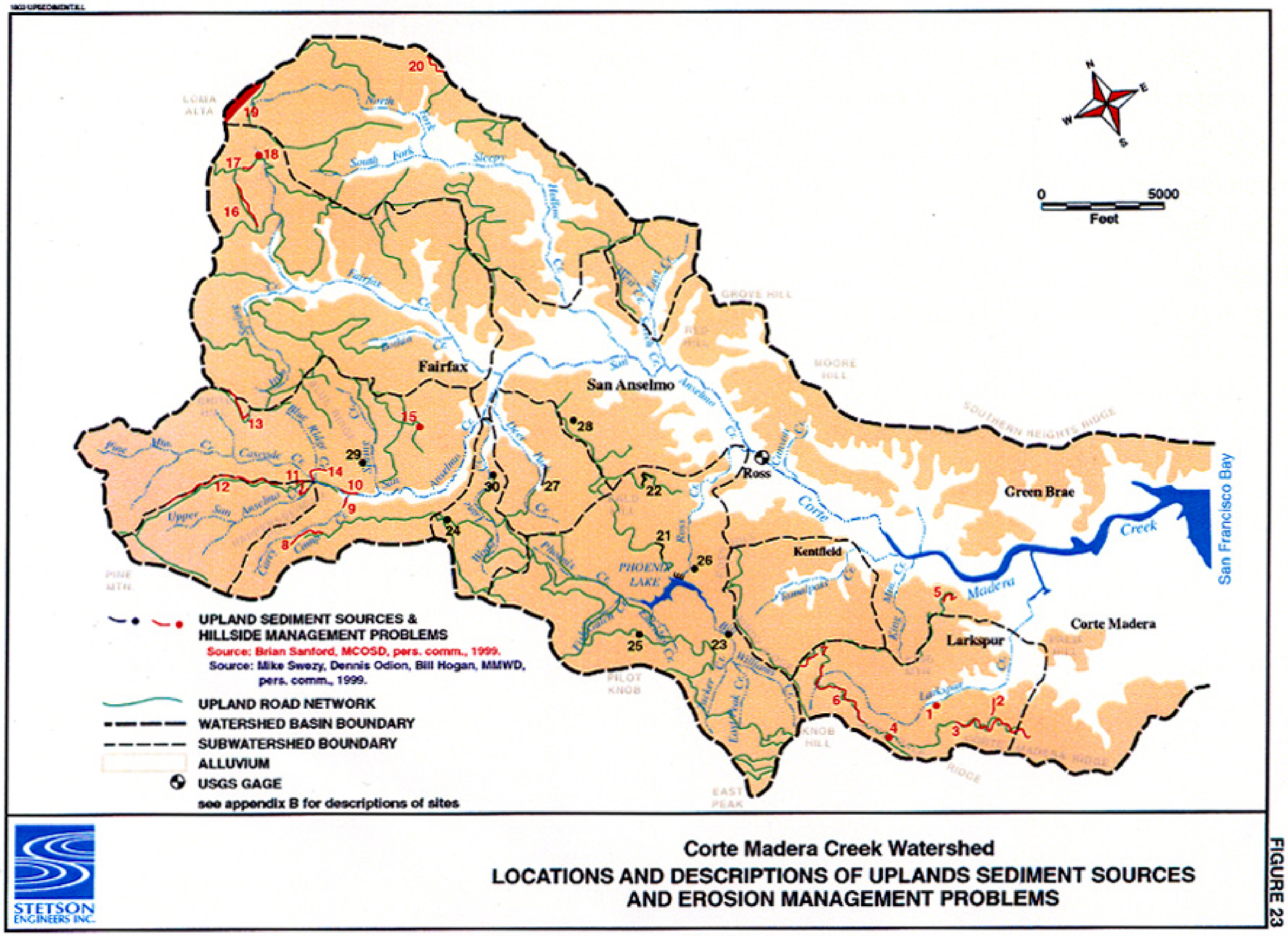


Figure 24 Geologic terrain types ranging from highest to lowest landslide frequency and hillslope instability

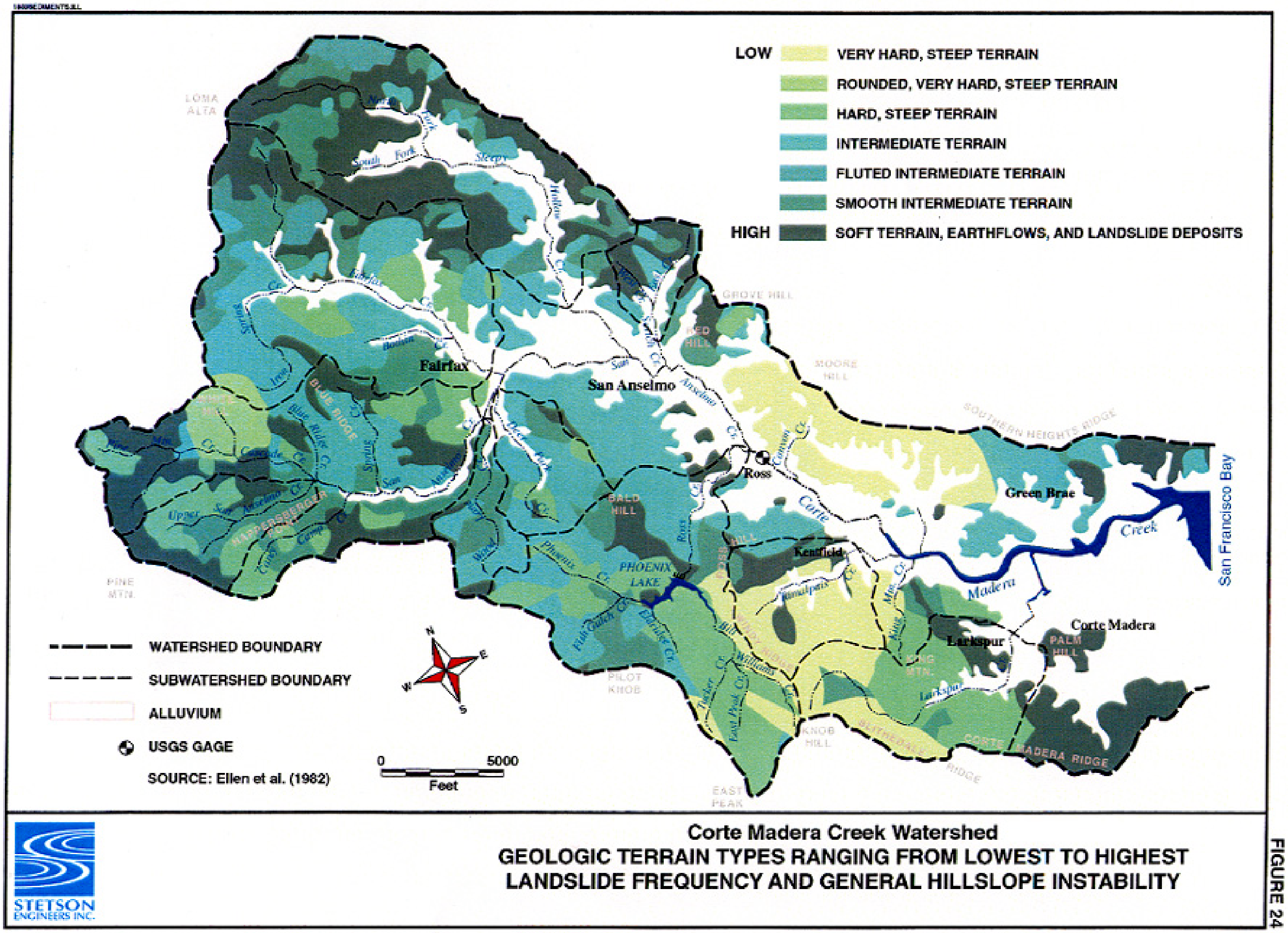


Figure 25 Underlying geologic type and vegetative cover

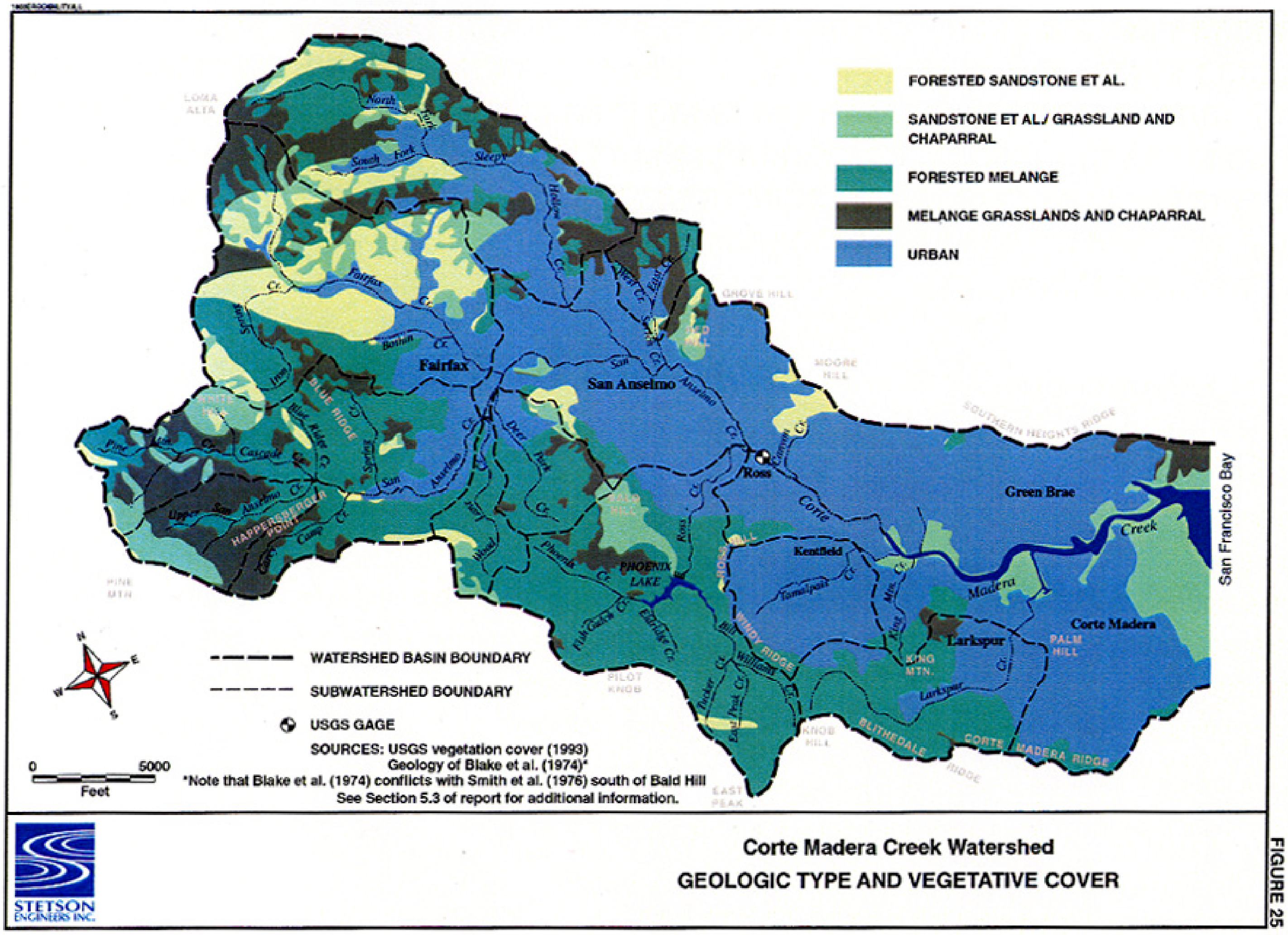


Figure 26 Measured historical channel bed elevation changes in alluvial channel network, 1976-1999

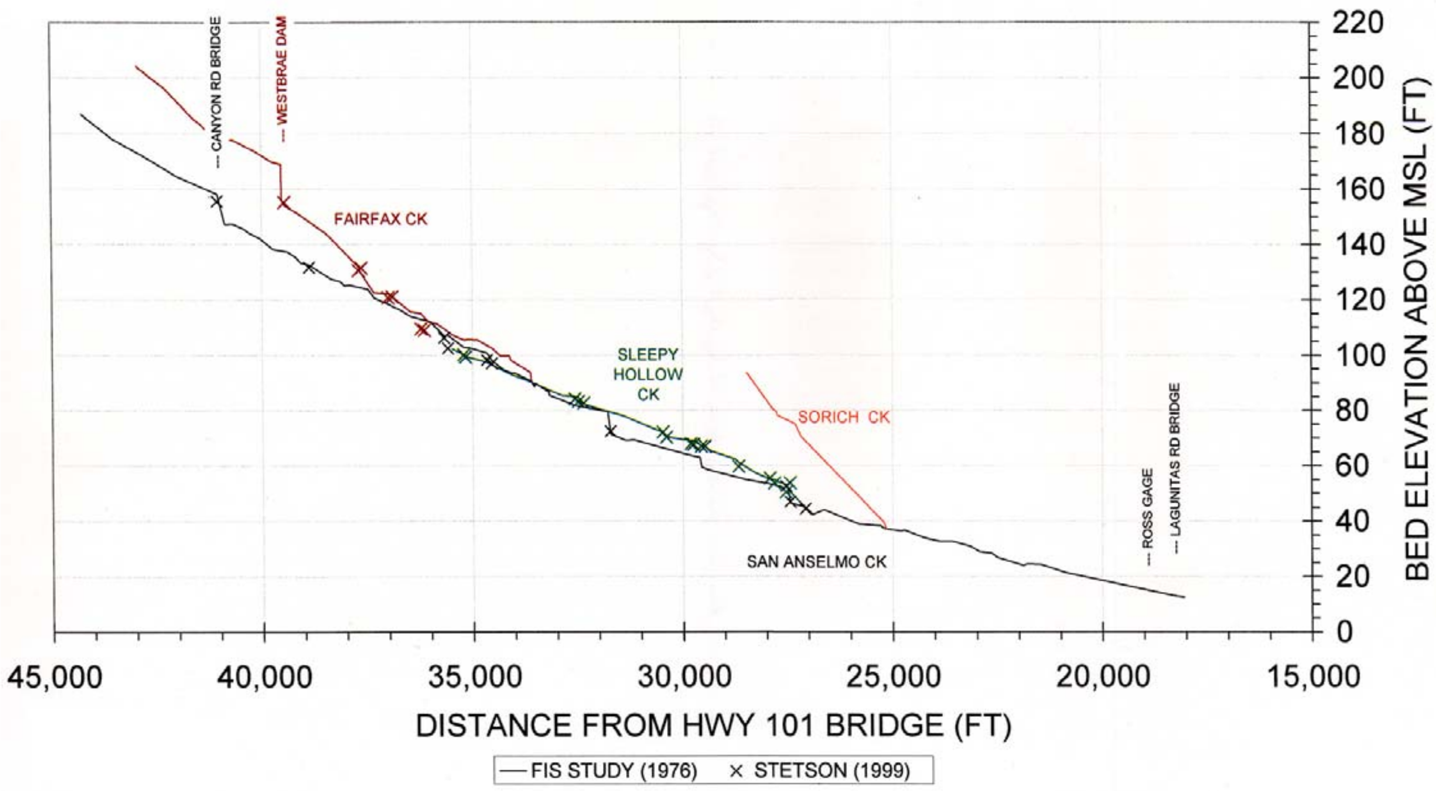


FIGURE 26. MEASURED HISTORICAL CHANNEL BED ELEVATION CHANGES IN THE ALLUVIAL CHANNEL NETWORK, 1976-1999.