

Sediment Production in a Coastal Watershed: Legacy, Land Use, Recovery, and Rehabilitation¹

Elizabeth T. Keppeler²

Abstract

Sediment production has been measured for nearly half a century at the Caspar Creek Experimental Watersheds. Examination of this sediment record provides insights into the relative magnitudes and durations of sediment production from management practices including road construction, selection harvest and tractor skidding, and later road-decommissioning. The 424-ha South Fork was harvested under standards that applied before passage of the 1973 Forest Practice Act. Regression analysis of annual suspended sediment loads on peak flows indicates that sediment production roughly doubled, with a return to pre-treatment levels about 11 years after harvest ended. However, sediment production again increased in the 1990s as road crossings deteriorated in response to large storms. Road crossings decommissioned in 1998 eroded a volume equivalent to more than half of the total yield in 1999 and enlarged another 20 percent over the last decade. Suspended sediment yields since decommissioning were reduced only for small storms. Recent assessment of 1970's era roads and skid trails found 443 remaining stream and swale crossings. Stream crossings have eroded an average volume of 10 m³. Stream diversions are common, and many sites have the potential for future diversion. Diversions along incised roads and skid trails contribute to episodic sediment inputs. Mainstem sediment loads are elevated relative to those at tributary gages located above the decommissioned riparian haul road, indicating that sediment yields at the weir are enhanced along the mainstem itself. Since turbidity monitoring began in 1996, South Fork mainstem turbidities have exceeded ecosystem thresholds of concern a higher percentage of time than those in the North Fork.

Key words: erosion, legacy, logging, sediment, roads, road decommissioning

Introduction and site description

Two centuries of logging in the redwood forests of northern California have transformed the region. Although the redwoods remain the defining natural characteristic of this “other California”, the landscape has been altered in a myriad of ways, some obvious and some subtle. Management activities such as timber harvest, road construction and use, and site preparation have been shown to deliver sediment, nutrients, and other pollutants to streams. Temporal and spatial variability of management impacts continues to be a topic of major concern—one that long-term research is particularly suited to address (Anderson and Lockaby 2011). The Caspar Creek Experimental Watersheds are a source of such data for the region.

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² Hydrologist, U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, 802 N. Main St., Fort Bragg, CA 95521. (ekeppeler@fs.fed.us).

The Caspar Creek research watersheds are within the Jackson Demonstration State Forest, 5 km from the Mendocino coast. Streamflow and sediment data are collected from weirs constructed in 1962 on the 424 ha South Fork and 473 ha North Fork and from tributary gages installed between 1983 and 2001 (*fig. 1*). Over a 20-year period of rapidly evolving management practices, the 100-year-old 2nd-growth redwood and Douglas-fir forest of this coastal basin was selectively tractor-logged (South Fork, 1971 to 1973) and partially cable clear-cut (North Fork, 1985 to 1992). New roads were constructed in both watersheds in conjunction with timber harvest. A 4.7 km mainline riparian road was built in South Fork 4 years prior to harvest and decommissioned in 1998, 25 years post-harvest. These varied treatments influence hydrologic processes, recovery time-frames, and restoration responses.

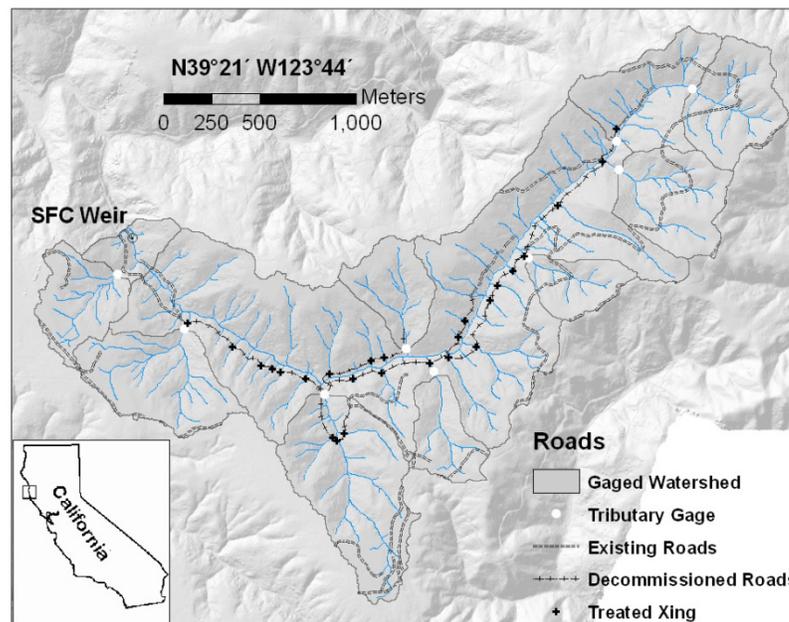


Figure 1—South Fork Caspar Creek watershed.

Several reports document enhanced sediment production in response to South Fork road construction, logging, and tractor-yarding (Lewis 1998, Rice et al. 1979, Tilley and Rice 1977). These prior reports rely on North Fork comparisons for estimates of South Fork sediment increases. Lewis (1998) found suspended sediment in the South Fork increased 335 percent the year after road construction, while yields for the next 3 years did not increase significantly. For the 6 years following logging, suspended sediment yields increased an average of 212 percent over expected values, or 331 percent when North Fork yields were adjusted to remove the effect of a large 1974 North Fork landslide. Suspended sediment yields recovered to background levels by 1979 and remained at background levels until 1985, when logging in the North Fork began. This report re-examines South Fork (SFC) suspended sediment trends through 2010 using analyses independent of North Fork (NFC) data and addresses the analytical problems presented by changing sampling protocols and episodic perturbations resulting from large landslides. Results are reviewed in light of erosion trends documented during 4 decades of field studies.

Methods

Sediment production estimates in the two watersheds are derived from water samples collected at the weirs (suspended loads) and annual bathymetric surveys of weir pond deposition. Pond deposition consists of approximately 40 percent suspended sediments and 60 percent bedload (Lewis 1998). Suspended sediment sampling protocols evolved over time. Initially, rising-limb data from fixed-stage siphon samplers were supplemented with manual DH-48 sampling during receding flows. Pumping samplers have been the primary means of suspended sediment sampling since 1976. Sediment concentrations, derived using standard gravimetric methods, were used to estimate loads using flow-duration sediment rating curves. Instream turbidimeters, deployed in 1996, are currently used in conjunction with pumped and DH-75 water samples to refine load estimates according to Turbidity Threshold Sampling protocols (Lewis and Eads 2009). Storm events are defined as the hydrograph rise to, and the ensuing recession from, a peak discharge exceeding 1.6 L/s per ha (0.17 yr recurrence interval).

Annual loads include an estimate of sediment flux between storm events and have been multiplied by a factor of 0.45 for years 1963 to 1975 to remove bias introduced by fixed-stage samplers. Lewis (1998) demonstrated the bias introduced by disproportionate sampling of rising hydrographs and the strong correlation between annual suspended loads and annual runoff. Using NFC calibration data, Lewis (personal communication, 2007) regressed annual loads on annual peaks and compared deviations to conclude that estimates prior to the 1976 change in sampling protocol are consistently higher than those of the subsequent period by a factor of 2.22 and proposed this same correction for both NFC and SFC annual loads.

To allow SFC sediment loads to be analyzed after 1985, when logging began in the North Fork control watershed, the present study employs a calibration relation between SFC annual suspended sediment loads and SFC annual maximum peakflows, using 1963 to 1967 and 1984 to 1992 data. The calibration relation is used to estimate expected annual loads under pretreatment (and post-recovery) conditions, and observed loads can then be compared with expected loads to calculate deviations associated with road construction, harvest, and later road decommissioning. A similar approach was taken using storm-based loads and peaks for the 1986 to 2009 data set to explore changes associated with road decommissioning.

The potential implications of altered sediment loads are evaluated using the 15 years of 10-min-interval turbidity now available for NFC and SFC. The number of days per year with turbidities exceeding the stream ecosystem stress thresholds proposed for Northern California watersheds (Klein and others 2008) were compared between sites using a paired t-test.

Erosion features larger than 7.6 m³ were mapped in 1994, and subsequently after peak flows exceeding the 4 year return period (1997, 1998, and 1999). Beginning in 2000, this inventory was repeated on an annual basis. Slide dimensions and volumes were recorded.

Between 2004 and 2006, an inventory of legacy sediment sources was performed in the South Fork watershed based on protocols used for the Sinkyone Wilderness State Park Road Rehabilitation Project (Merrill 2003). Untreated roads and skid trails were evaluated in the field, using 2-m LiDAR and 1975 air photo imagery to help

locate the features. Stream and swale crossings, roads, landings, gullies, stream diversions (existing and potential), and landslide locations were mapped. In addition, the field crew attempted to remeasure voids from historic slides. At stream and swale crossings, erosion voids were measured to an accuracy of 20 percent, and erosion potential, the amount expected to erode over the next 3 decades, was estimated based on drainage area, vegetation, and bank condition.

Erosion measurements along the haul road decommissioned in 1998 (Keppeler and others 2007) were repeated in 2011. The field crew evaluated 35 treatment sites for “sediment delivery potential” and gully “activity level” (Merrill 2003). At 10 sites, thalweg profiles and three to five cross-section transects were surveyed using control points established in 1999 to estimate erosion in the intervening period.

Results

Regression results confirmed the strong correlation between annual suspended sediment load and peakflow ($r^2 = 0.90$), allowing prediction of SFC loads independently of NFC measurements. SFC suspended sediment loads averaged 44 t/km² per year during the 1962 to 1967 calibration period while NFC averaged 56 t/km² per year (68 ± 40 (0.95 CI) for 22 pre-treatment years). This revised analysis, correcting for sampler bias, resulted in an estimate of excess suspended sediment produced post-logging of 928 t/km² (116 t/km² per year) through 1979 (*fig. 2*).

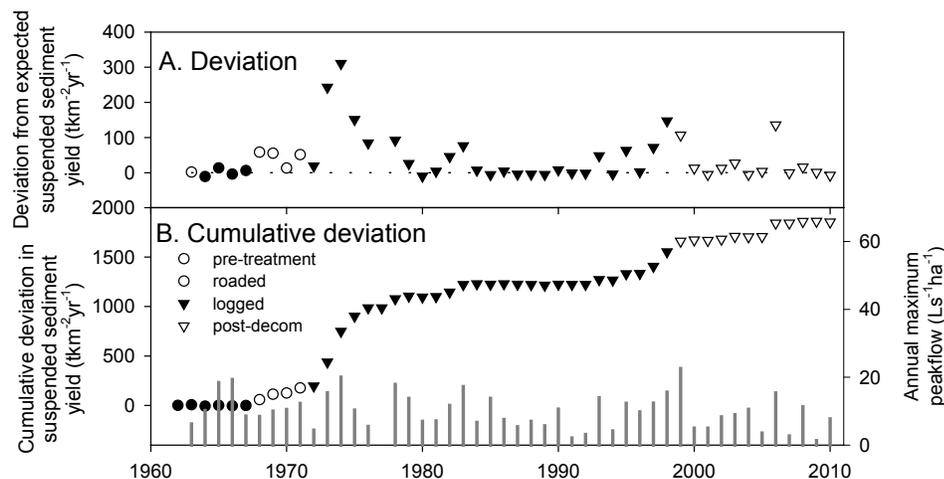


Figure 2—Excess suspended sediment production by year for (A) annual and (B) cumulative deviation from predicted load.

Beginning about 10 years after timber harvest, sediment production returned to pre-harvest levels, and this pattern persisted for another decade. Elevated sediment production was renewed in 1993 and was most evident during years with peak flows larger than the 4 year return interval flow (about 12 L/s per ha). Keppeler and Lewis (2007) detected SFC storm load increases of about 40 percent during 1998 to 2003, suggesting an episode of elevated sedimentation spanning the decommissioning treatment. Regression analyses of SFC storm loads on storm peaks for 1986 to 1998 and 2000 to 2009 show no significant difference ($p < 0.05$) after decommissioning for peaks larger than the 0.4 yr recurrence interval, but for smaller peaks, loads were significantly reduced (*fig. 3*).

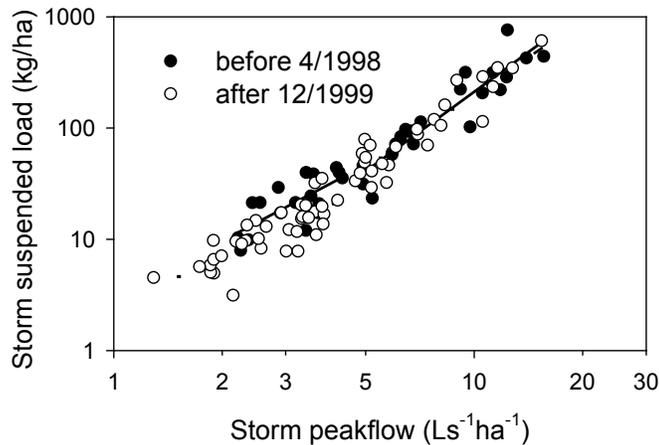


Figure 3—Sediment loads as a function of storm peak before and after decommissioning, divided into two peak discharge classes at the 0.4 yr return period.

Since implementation of continuous turbidity monitoring in 1996, SFC turbidities have exceeded ecosystem thresholds of concern more commonly than NFC turbidities. When turbidity records were tallied by stream ecosystem stress thresholds exceeding 25 (moderate), 50 (severe), 100 ntu (extreme) (Klein and others 2008) for each hydrologic year, SFC averages exceeded NFC's by 50, 60, and 120 percent ($p < 0.014$), respectively—a fairly consistent pattern even during years when NFC logging effects were evident. This result may reflect high inputs of fine sediments from road surfaces and bare ground in the South Fork, or may indicate that the physical properties of the sediment transported through the two weir ponds differ. The difference in ratios of average storm load above and below the two weirs supports the latter hypothesis. The weirs trap an estimated 20 to 30 percent of suspended sediment and virtually all bedload, thus the rationale for siting sampling stations ARF and QUE immediately upstream of the NFC and SFC weir ponds. Based on storm load data from 2001 to 2009, NFC transported just 70 percent of the load entering the pond, while SFC transported 80 percent.

Information from field-based sediment source assessments provides a context for interpreting the patterns of suspended sediment yield (*table 1*). The inventory of the entire South Fork watershed performed between 2004 and 2006 documented 443 remaining stream and swale crossings on untreated roads and skid trails. Of these, 325 had experienced partial failure. Swale crossings numbered 208, including 102 that had remained stable in the 3 decades since construction and only four that had eroded more than 10 m^3 . In contrast, only 16 of 235 stream crossing had experienced no notable erosion. Eroded volume per stream crossing averaged 10 m^3 , but most of this erosion did not appear to be recent. Fill material at risk of further erosion accounted for 16 percent of the estimated initial crossing fill. Stream crossings accounted for 82 percent of the “at risk” projection of erosion potential. Diversions onto roads and skid trails were common. Roughly 10 percent of stream crossings were active diversions while a similar number were “at risk” because a minor blockage could redirect flow onto the road surface. More than 300 m of entrenched diversions and active gullies were noted.

Table 1—Field-based sediment source measurements (in-channel erosion from Reid and others 2010).

Type	Years	m ³	m ³ /yr	Method
<u>Logging period</u>				
landslides (re-assessed)	1971-76	7944	1324	inventory 2004-2006
<u>Recovery period</u>				
untreated crossing erosion	1971-06	2827	79	inventory 2004-2006
gully erosion	1971-06	932	26	inventory 2004-2006
mass-wasting > 7.6 m ³	1977-94	1705	95	inventory 1994
mass-wasting > 7.6 m ³	1977-06	2897	97	inventory 2004-2006
mass-wasting > 7.6 m ³	1995-99	4008	802	inventory, irregular
<u>Post-decommission period</u>				
mass-wasting > 7.6 m ³	2001-10	553	55	annual inventory
treated crossing erosion	1999	651	651	survey, 1999
treated crossing erosion	2000-01	108	54	survey, 2001-2002
treated crossing erosion	2002-11	150	15	survey, 2011
in-channel erosion	2001-08	na	291	survey, irregular

Landslide voids encountered during the recent inventory included 7944 m³ (18.7 m³/ha) from slides listed in the 1976 data set and 2897 m³ (6.8 m³/ha) in more recent features. However, half the slides in the 1976 data set were not relocated.

Soil displacement by mass-wasting for events larger than 7.6 m³ declined since the 1970s and again in the most recent decade relative to the 1990s. Through 1994, the rate was 95 m³/yr; from 1995 to 1999, 802 m³/yr; and since 2000, 55 m³/yr. Seven of 10 slides in the 1994 inventory were along haul roads and landings, but these accounted for less than 20 percent of the total volume. Only two failures along the mainline road were attributed to 1993. Between 1993 and 1999, 17 slides accounting for 70 percent of the mass-wasting volume occurred along the mainline road—15 resulted from culvert or fill failures. In the post-decommissioning data set, the largest feature was a 255 m³ slide that originated along an untreated mid-slope road routing entrenched flow from a stream diversion to the fill slope. The slide traveled down the tributary channel as a debris torrent, depositing debris in the 1998 restored stream crossing void and continuing on to the South Fork mainstem.

Keppeler et al. (2007) report that the 1998 road decommissioning, followed by the largest peakflow of the 49 year SFC record, profoundly impacted sediment production in 1999. Re-evaluation of 35 treated crossings in 2011 indicated that erosion is ongoing at 31. Sediment transport potential was rated “high” or “extreme” at 12 of 37 sites. The predominant “Activity Class” (Merrill 2003) for the gullied crossings was “3” (indicating “good vegetative cover” with less than 50 percent of the incised area subject to erosion and transport). However, five were characterized as “1” (exhibiting “widespread transport and little or no vegetation”) and five were rated as “4” (supporting “good vegetative cover” and having gentle side-slopes).

The 2011 re-survey of channel cross-sections and profiles established at 10 sites in 1999 quantified additional scour and fill since 2001. Incision and widening were evident at 60 and 40 percent, respectively, of 42 cross-section transects, while 30 percent of transects showed neither. Mean profile elevation decreased by 0.09 m.

Headcut retreat was evident along all 10 surveyed profiles. In sum, these 10 sites enlarged by 80 m³, or about 20 percent, since last assessed. Assuming a similar rate of erosion from the 25 sites that were not re-surveyed, total enlargement is estimated to have been about 150 m³ over the last decade. A foot trail along the former road surface receives semi-regular (unsanctioned) bicycle and motorcycle use. The road has not fully revegetated and delivers an unknown amount of sediment to the stream.

Discussion

To relate erosion measurements to recent trends in suspended sediment yields at the weirs, it is helpful to compare unit-area sediment loads measured immediately upstream of the weirs with those measured at upstream tributary gages to identify areas contributing disproportionate amounts of sediment. Since 2000, when nine tributary gages were installed in the South Fork watershed, NFC event-based storm loads averaged 104.3 kg/ha based on contributions from the two gages delivering directly to the weir pond. Upstream gages produced similar loads, averaging 99.3 kg/ha. In contrast, South Fork event-based loads (the sum of mainstem loads measured 50 m upstream of the weir pond and the tributary gage load delivered directly to the weir pond) averaged 75.8 kg/ha. South Fork tributaries draining 52 percent of the watershed area produced 54.1 kg/ha per event, on average. Assuming the few small ungaged tributaries are not generating disproportionately high amounts of sediment, the SFC load is enriched below tributary gages and along the mainstem. Three of the tributary gages are sited within 42 m upstream of stream crossings restored during the 1998 decommissioning of the mainline road, and paired water samples were collected above and below the crossings during water years 2004 and 2006. These samples indicate suspended sediment concentrations were enriched below the decommissioned crossings ($p < 0.012$), reflecting the net contributions of erosion within the restored stream crossings and from the old road surface.

During the last decade, the volume of fine sediments in pools declined along the lower 490 m of mainstem channel above the SFC weir. However, pool depths decreased as well. Mainstem cross-sections, measured biennially since 2000 along 3100 m of channel, scoured 59 m³ from 2000 to 2010³. It is likely that sediment inputs from both recent and historic mass-wasting, including materials eroded from failed and decommissioned crossings, were re-mobilized during high flows and augmented suspended sediment loads generated in upland portions of the South Fork watershed. In-channel erosion processes were also active in South Fork tributaries and account for a substantial portion of the suspended load at SFC (Reid et al. 2010).

Conclusions

Measured rates of suspended sediment yield in the South Fork Caspar Creek watershed were highest during the first decade after selection harvest and tractor-yarding was completed in 1973. A second episode of increased suspended sediment yield, coinciding with a notable increase in road-related mass-wasting, commenced 20 years post-harvest. Since decommissioning of the riparian road in 1998, reduced sediment yields have been detected only for small storms, though the incidence and

³ S. Hilton, Hydrologist, U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, 2011, personal communication.

magnitude of mass-wasting was lower during the last decade than in the 1990s. Mainstem channel measurements and tributary gage data suggest that sediment deposited prior to 2000 was mobilized and transported during the last decade. Erosion in upland areas, including diversion-induced mass-wasting, incision of crossings along untreated roads and skid trails, and in-channel gullying, remains active. Potential interactions with persisting legacy effects should be considered when modern forest management practices are superimposed on landscapes still responding to past disturbances.

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