

Understanding the Hydrologic Consequences of Timber-harvest and Roding: Four Decades of Streamflow and Sediment Results from the Caspar Creek Experimental Watersheds

Elizabeth Keppeler

*USDA Forest Service, Pacific Southwest Research Station
Fort Bragg, California*

Jack Lewis

*USDA Forest Service, Pacific Southwest Research Station
Arcata, California*

The Caspar Creek Experimental Watersheds were established in 1962 to study the effects of forest management on streamflow, sedimentation, and erosion in the rainfall-dominated, forested watersheds of north coastal California. Currently, 21 stream sites are gaged in the North Fork (473 ha) and South Fork (424 ha) of Caspar Creek. From 1971 to 1973, 65% of the timber volume in the South Fork was selectively cut and tractor yarded, and from 1985 to 1991, 50% of the North Fork basin was harvested, mostly as cable-yarded clearcut. The South Fork logging resulted in annual suspended sediment load increases exceeding 300%. Mass-wasting has been predominantly associated with roads, landings, and tractor skid trails in the South Fork. Accelerated mass-wasting and renewed sediment mobilization in the South Fork have occurred since 1998. Peak flow increases detected following North Fork logging are attributable to reduced canopy interception and transpiration. These recovered to pretreatment levels about 10 years after logging, followed by renewed increases from pre-commercial thinning. Annual sediment loads increased 89% in the partially clearcut North Fork and 123% to 238% in 4 of 5 clearcut sub-basins. Twelve years after logging, elevated storm-event sediment yields persist in some clearcut tributaries.

Keywords: experimental watershed studies, road effects, sediment yield, peak flows, erosion, timber harvesting

INTRODUCTION

For more than four decades, researchers have investigated the effects of forest management on streamflow, sedimentation, and erosion in the Caspar Creek Experimental Watersheds. The California Department of Forestry and Fire Protection and the USDA Forest Service, Pacific Southwest Research Station, began a simple paired watershed study in 1962 with the construction of weirs on the two major Caspar Creek tributaries, the North Fork (NFC) and the South Fork (SFC). Today, researchers operate 21 gaging stations within the experimental watersheds and use data loggers programmed with sophisticated sampling algorithms, instream turbidimeters, and automated pumping samplers to measure water and sediment discharge. Although much of this research is

devoted to quantifying the impacts of modern forest management, it also provides valuable data on hydrologic recovery and the lingering effects of more than a century of timber harvest and roding in the Caspar Creek basin.

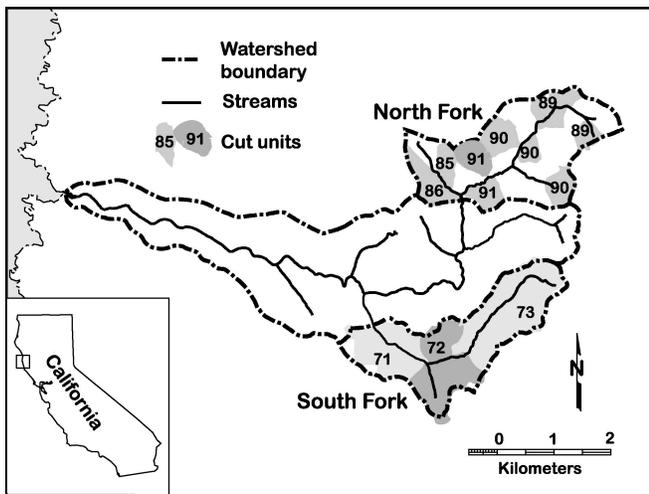
METHODS

Site

The Caspar Creek Experimental Watersheds are located about 7 km from the Pacific Ocean and about 10 km south of Fort Bragg in northwestern California at lat 39°21'N, long 123°44'W (Figure 1). Uplifted marine terraces incised by antecedent drainages define the youthful and highly erodible topography with elevations ranging from 37 to 320 m. Hillslopes are steepest near the stream channel and become gentler near the broad, rounded ridgetops. About 35% of the basins' slopes are less than 17 degrees, and 7% are steeper than 35 degrees. Soils are well-drained clay-loams, 1 to 2 meters in depth, derived from Cretaceous Franciscan Formation greywacke sandstone and weathered, coarse-grained shale.

M Furniss, C Clifton, and K Ronnenberg, eds., 2007. *Advancing the Fundamental Sciences: Proceedings of the Forest Service National Earth Sciences Conference, San Diego, CA, 18-22 October 2004*, PNW-GTR-689, Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Figure 1. Caspar Creek Experimental Watersheds.



The climate is typical of low-elevation coastal watersheds of the Pacific Northwest. Winters are mild and wet, characterized by periods of low-intensity rainfall delivered by the westerly flow of the Pacific jet stream. Snow is rare. Average annual precipitation is 1,170 mm. Typically, 95% of precipitation falls during the months of October through April. Summers are moderately warm and dry with maximum temperatures moderated by frequent coastal fog. Mean annual runoff is 650 mm.

Like most of California's north coast, the watersheds were clearcut and broadcast burned largely prior to 1900. By 1960, the watersheds supported an 80-year-old second-growth forest composed of coast redwood (*Sequoia sempervirens*), Douglas-fir (*Pseudotsuga menziesii*), western hemlock (*Tsuga heterophylla*), and grand fir (*Abies grandis*). Forest basal area was about 700 m³/ha.

Measurements

The 473-ha North Fork of Caspar Creek and the 424-ha South Fork of Caspar Creek have been gaged continuously since 1962 using 120° v-notch weirs widening to concrete rectangular sections for high discharges. During the early 1980s, three rated sections were constructed upstream of the North Fork weir and 10 Parshall flumes were installed on North Fork subwatersheds with drainage areas of 10 to 77 ha.

Stream discharge was initially recorded using mechanical chart recorders. These were replaced in the 1980s with electronic data loggers equipped with pressure transducers. Early suspended sediment estimates were derived from sediment rating curves, manual depth-integrated sampling, and fixed stage samplers (Rice et al. 1979). Statistically based sampling algorithms that trigger automated samplers

were used beginning in the 1980s (Lewis et al. 2001). In addition, the sediment accumulation in the settling basin upstream of each weir has been surveyed annually.

Periodic field surveys have documented the location, size, and disposition of landslides and fluvial erosion. Erosion features greater than 7.6 m³ (10 yd³) have been inventoried annually since 1986 in the North Fork, and since 1994 in the South Fork.

Treatments

After establishing a calibration relationship between the North Fork and the South Fork (1963 to 1967), a main-haul logging road and main spurs were built in the South Fork. The road right-of-way occupied 19 ha, from which 993 m³/ha of timber was harvested. The entire South Fork watershed was logged and tractor yarded between 1971 and 1973 using single-tree and small group selection to harvest 65% of the stand volume. Roads, landings, and skid trails covered approximately 15% of the South Fork watershed area (Ziemer 1981). Almost 5 km of the main-haul and spur roads (out of approximately 10 total km) were decommissioned in 1998.

A study of cumulative effects began in 1985 in the North Fork watershed. Three gaged tributary watersheds within the North Fork were designated as controls while seven were designated for harvest in compliance with the California Forest Practice Rules in effect in the late 1980s. Two units (13% of the North Fork watershed) were clearcut in 1985-86. After calibration, clearcut logging began elsewhere in the North Fork in May 1989 and was completed in January 1992. Clearcuts occupied 30-99% of treated watersheds and totaled 162 ha. Between 1985 and 1992, 46% of the North Fork watershed was clearcut, 1.5% was thinned, and 2% was cleared for road right-of-way (Henry 1998).

In contrast to the harvest treatment of the South Fork in the 1970s, state rules mandated equipment exclusion and 50% canopy retention within 15 to 46 m of watercourses providing aquatic habitat or having fish present. Most of the yarding (81% of the clearcut area) was accomplished using skyline-cable systems. Yarders were situated on upslope landings constructed well away from the stream network. New road construction and tractor skidding was restricted to ridgetop locations with slopes generally less than 20% and affected only 3% of the watershed area. Four harvest blocks, 92 ha total, were broadcast burned and later treated with herbicide to control competition (Lewis et al. 2001). Pre-commercial thinning in 1995, 1998 and 2001 reduced basal area in treated units by about 75%.

RESULTS

Streamflow

Previous publications detail the magnitude and duration of streamflow enhancements following timber harvest in the Caspar Creek basins (Ziemer 1981, 1998; Lewis et al. 2001; Keppeler and Lewis, in press). In the North Fork, the average storm peak flow with a two-year return period increased 27% in the clearcut watersheds (Ziemer 1998) and 15% in the partially clearcut watersheds. Ongoing measurements show a return to pre-treatment flow conditions on NFC approximately 10 to 11 years post-harvest except for a renewed response to the pre-commercial thinning. Of particular interest is that even under the wettest antecedent moisture conditions of the NFC study, increases averaged 23% in clearcut watersheds and 3% in partially clearcut watersheds. These results are explained by wetter soils in logged units resulting from reduced transpiration and increases in net precipitation due to reduced canopy interception after clearcutting (Reid and Lewis, in press).

Sediment Loads

Sediment load estimates for the North Fork and South Fork are the sum of the sediment deposited in the weir pond and the suspended load measured at the weir. Comparison of sediment loads produced following the 1971-73 harvest of South Fork and the 1989-92 harvest of North Fork must be made cautiously. Improved and more intensive sampling methods greatly enhance the accuracy of load estimates for the latter study. Large landslides in the North Fork in 1974 and 1995, and the 1985 harvest in the North Fork complicate the analysis.

South Fork suspended sediment loads increased 335% ($1,475 \text{ kg ha}^{-1} \text{ yr}^{-1}$) after road building and averaged

331% ($2,877 \text{ kg ha}^{-1} \text{ yr}^{-1}$) greater during the 6-year period after tractor logging. Annual sediment load (including suspended and pond accumulations) increased 184% for the 6-year post-harvest period 1972-1978 returning to pretreatment levels in 1979 (Lewis 1998).

North Fork annual sediment loads increased 89% ($188 \text{ kg ha}^{-1} \text{ yr}^{-1}$) in the partially clearcut watershed and between 123% and 238% (57 to $500 \text{ kg ha}^{-1} \text{ yr}^{-1}$) in 4 of 5 clearcut basins during the 1990-96 post-harvest period (Lewis 1998). The load decreased by 40% ($551 \text{ kg ha}^{-1} \text{ yr}^{-1}$) in one clearcut basin. Sediment loads in some North Fork tributaries remained elevated through hydrologic year 2003, twelve years after harvest (Keppeler and Lewis, in press).

Although Thomas (1990) reported that SFC sediment concentrations appeared to be returning to pre-treatment levels in the early 1980s, analysis of more recent data suggests renewed sediment mobilization. The 1998 and 1999 pond depositions were the largest on record at SFC, but not exceptional at NFC. A double mass plot of pond accumulations indicates an increase in deposited sediments at SFC relative to NFC starting in 1998. The same is true to a lesser extent in suspended sediments (Figure 2). Regression analysis of SFC versus NFC pond accumulations indicates a significantly higher slope for the period 1998-2004 compared to 1974-1997.

Since the suspended sediment data have better temporal and spatial resolution, Lewis' 1998 analysis of NFC was extended using storm load data from control tributary gages H and I to investigate whether the relative change in suspended sediment was due to changes in the North Fork, changes in the South Fork, or both. A plot of the percentage departures from the prelogging (1986-1989) regression of NFC versus HI, shows elevated sediment levels for 1993-1998 only (Figure 3). An analogous plot for SFC versus HI shows elevated sediment levels for some small events in 1993-1997, but most consistently for all

Figure 2. Double mass curve of South Fork pond accumulations and suspended sediment relative to North Fork 1986 through 2004.

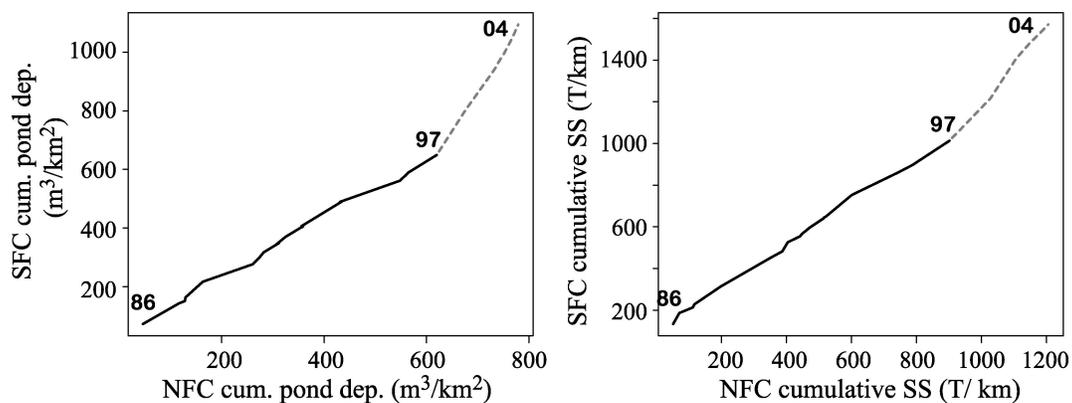
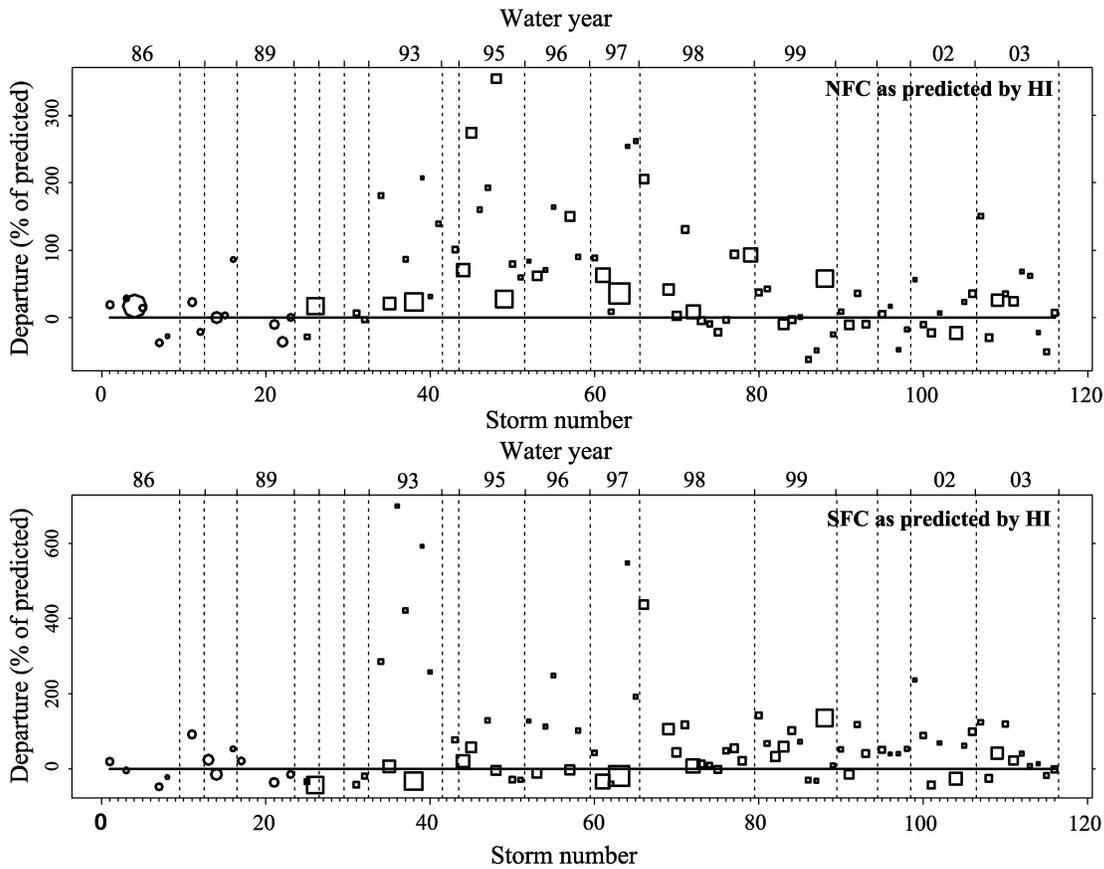


Figure 3. Suspended sediment percentage departures from the 1986-1989 regressions of NFC and SFC versus two untreated North Fork Controls (HI). Marker size is relative to HI storm load.



size events in 1998-2003. Thus the change in relation between NFC and SFC starting in 1998 appears to be a combination of declining loads at NFC and increasing loads at SFC.

To be more rigorous and quantitative about the suspended sediment changes, the gaging records were broken into three periods: NFC prelogging (1986-1989), NFC postlogging (1990-1997), SFC “episode” (1998-2003). These periods included 23, 41, and 52 storm events, respectively. Log-log regression models were fit relating NFC and SFC to HI for the three periods and tested to determine if a unique slope or intercept was appropriate for each period (Figure 4). For the NFC model, a parallel regression model with three intercepts and one slope was adequate. For the SFC model three intercepts and three slopes needed to be retained. Nine post-hoc comparisons of intercept and slope for each period were made. The NFC parallel regression for the 1990-1997 period was significantly different (higher) than either of the other periods, and the SFC 1990-1997 regression had significantly different (lower) slope than the 1998-2003 period. The SFC 1986-1989 slope was

similar to the SFC 1998-2003 slope, but did not differ significantly from the 1990-1997 period, possibly due to the smaller number of storms in 1986-1989 compared to 1998-2003 (Table 1).

Table 1. Comparison of regression and intercepts (NFC and SFC) and slopes (SFC only) for three different time periods. Bonferonni’s procedure was used to limit the experimentwise error rate to 0.05 which requires setting the pairwise comparison error rates to $0.05/9 = 0.0056$. By this criterion, the only significant differences were (1), (3), and (9).

Comparison	Significance (p)
1 NFC 90-97 intercept to NFC 86-89 intercept	0.000014
2 NFC 98-03 intercept to NFC 86-89 intercept	0.50
3 NFC 98-03 intercept to NFC 90-97 intercept	0.00000032
4 SFC 90-97 intercept to SFC 86-89 intercept	0.039
5 SFC 98-03 intercept to SFC 86-89 intercept	0.096
6 SFC 98-03 intercept to SFC 90-97 intercept	0.40
7 SFC 90-97 slope to SFC 86-89 slope	0.096
8 SFC 98-03 slope to SFC 86-89 slope	0.983
9 SFC 98-03 slope to SFC 90-97 slope	0.00037

Table 2. Summary of post-disturbance Erosion Features greater than 7.6m³.

	South Fork Caspar				North Fork Caspar			
	#	Volume (m ³)	m ³ /ha	Delivery	#	Volume (m ³)	m ³ /ha	Delivery
Post-disturbance ¹	130	65312	154	na	116	6496	14	40%
road-related	115	41706	98	68%	7	424	1	8%
wind-related	5	13985	33	na	74	1466	3	29%
> 1000 m ³	18	52120	123	na	1	3605	8	46%
100-1000 m ³	38	10507	25	na	5	944	2	26%
HY1990-2004	38	5804	14	61%	147	9121	19	45%
road-related	34	5557	13	63%	10	2495	5	52%
wind-related	4	264	1	21%	86	1732	4	27%
> 1000 m ³	0	0	0	na	2	5618	12	52%
100-1000 m ³	12	4961	12	62%	5	944	2	26%

¹ Includes hydrologic years 1968-1976 on South Fork, 1990-1998 on North Fork.

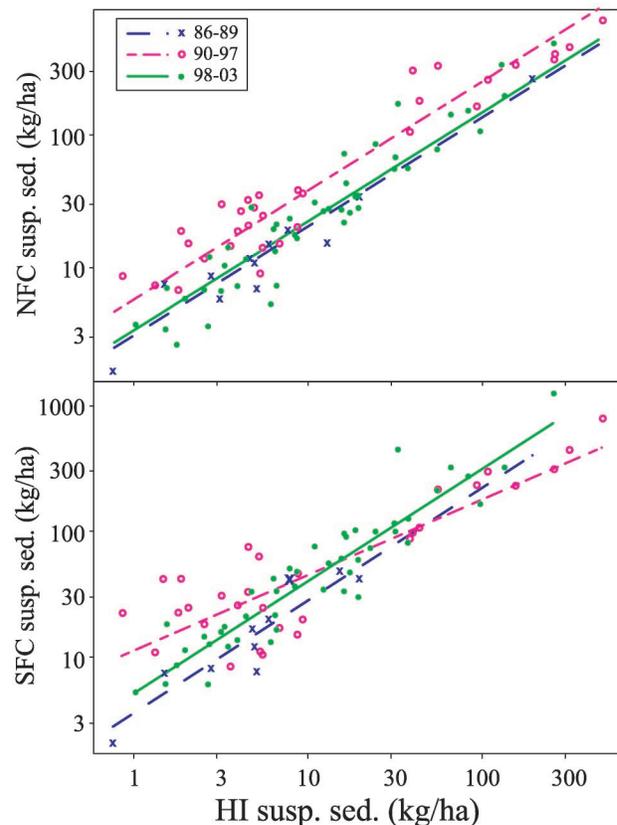
Based on the 1986-1989 relations, the observed sediment from NFC exceeded the predicted sediment by 49% in 1990-1997 and by 12% in 1998-2003. The corresponding numbers for SFC were -20% and +45%, but the only significant difference for SFC was the slope between the last two periods. Based on the 1990-1997 period, the observed sediment from SFC 1998-2003 exceeded the predicted sediment by 36%. If the 1986-1989 and 1990-1997 periods are combined to predict suspended sediment for 1998-2003, the observed sediment from SFC exceeded the predicted sediment by 47% (185 kg ha⁻¹ yr⁻¹). (Compared to the 1986-1989 regression, the combined regression predicts lower loads in large storms above ~50 kg/ha at HI.) Thus, it is only during relatively large storm events (> 20 kg/ha at HI) that SFC suspended sediment systematically exceeds the pre-1998 relationship (Figure 4).

Erosion

Erosion inventory data helps to explain sediment load changes. As with sediment loads, improved protocols provide more detailed information on mass-wasting processes than is available for the earlier SFC inventories. Inventories have been more frequent and more intensive on the North Fork since 1986 and the South Fork since 1994. Nonetheless, the contrasts are quite apparent. During the 1970s, the South Fork landscape experienced mass-wasting an order of magnitude greater than that which followed NFC harvesting of the 1990s. SFC erosion has been predominantly related to the roads, landings, and skid trails. In contrast, most North Fork erosion features have been associated with windthrow disturbances and typically displaced and delivered smaller volumes of material. Two large landslides, one related to a preexisting mid-slope road, account for more than half of NFC mass-wasting (Table 2).

Another episode of road-related landsliding commenced in the South Fork in the mid 1990s. Of the 31 SFC landslides documented between 1995 and 2004, 94% are road, landing, or skid trail related. These more recent landslides displaced 4,123 m³ and had an average delivery ratio of 85%. A deteriorating network of logging roads and skid trails continues to deliver sediment to the stream channel and explains much of the recently enhanced SFC sediment production previously discussed. This

Figure 4. Suspended sediment regression results by period for North Fork (NFC) and South Fork (SFC) versus control (HI).



renewed sedimentation may also be a manifestation of the extreme stormflows of 1998 and 1999 and the erosional costs of recent road decommissioning. The 1998 road decommissioning effort removed almost 18,000 m³ of fill from aging stream crossings, but treatment-related erosion contributed 750 m³ of sediment.

CONCLUSIONS

Timber harvest and road building affect runoff processes, sediment yields, and erosion, but the response is highly variable. Caspar Creek studies document increases in peak flows, suspended sediment loads, and erosion after two very different harvest treatments. California's modern forest practices rules appear to mitigate, but do not eliminate, these impacts.

Erosion and sedimentation from ground extensively disturbed by road building and tractor yarding remain elevated decades after harvest. The present condition of the South Fork watershed is typical of many of the tractor-yarded lands in the redwood region that are entering yet another harvest cycle. Greater understanding of the interactions between proposed activities and prior disturbances is crucial for improved forest management. Thus, a third phase of research is underway to examine the effects of re-entry on the previously tractor-logged South Fork watershed. Much remains to be learned regarding restoring forest ecosystems and mitigating harvest impacts. The Caspar Creek Experimental Watersheds will continue to serve as a resource for furthering this research endeavor.

REFERENCES

- Henry, ND. 1998. Overview of the Caspar Creek Watershed study. In RR Ziemer, tech. coord., Proceedings of the conference on coastal watersheds: the Caspar Creek story, Ukiah, California, 6 May 1998. Gen. Tech. Rep. PSW GTR-168. Albany, CA: USDA Forest Service, Pacific Southwest Forest and Range Experiment Station: 1-9.
- Lewis, J. 1998. Evaluating the impacts of logging activities on erosion and sediment transport in the Caspar Creek watersheds. In RR Ziemer, tech. coord., Proceedings of the conference on coastal watersheds: the Caspar Creek story, Ukiah, California, 6 May 1998. Gen. Tech. Rep. PSW GTR-168. Albany, CA: USDA Forest Service, Pacific Southwest Forest and Range Experiment Station: 55-69.
- Lewis, J, SR Mori, ET Keppeler, and RR Ziemer. 2001. Impacts of logging on storm peak flows, flow volumes and suspended sediment loads in Caspar Creek, California. In MS Wigmosta and SJ Burges, eds., Land use and watersheds: Human influence on hydrology and geomorphology in urban and forest areas. Water Science and Application Volume 2. Washington DC: American Geophysical Union: 85-125.
- Keppeler, ET, and J Lewis. [In press]. Trends in streamflow and suspended sediment after logging, North Fork Caspar Creek. In: Proceedings, Redwood Region Forest Science Symposium March 2004. Santa Rosa, CA. 14 p.
- Reid, LR, and J Lewis. [In press]. Rates and implications of rainfall interception in a coastal redwood forest. In: Proceedings, Redwood Region Forest Science Symposium March 2004. Santa Rosa, CA. 15 p.
- Rice, RM, FB Tilley, and PA Datzman. 1979. A watershed's response to logging and roads: South Fork of Caspar Creek, California, 1967-1976. Res. Pap. PSW-146. Berkeley, CA: USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, 12 p.
- Thomas, RB. 1990. Problems in determining the return of a watershed to pretreatment conditions: techniques applied to a study at Caspar Creek, California. *Water Resources Research* 26(9): 2079-2087.
- Ziemer, RR. 1981. Stormflow response to roadbuilding and partial cutting in small streams of northern California. *Water Resources Research* 17(4): 907-917.
- Ziemer, RR. 1998. Flooding and stormflows. In: RR Ziemer, tech. coord., Proceedings of the conference on coastal watersheds: the Caspar Creek story, Ukiah, California, 6 May 1998. Gen. Tech. Rep. PSW GTR-168. Albany, CA: USDA Forest Service, Pacific Southwest Forest and Range Experiment Station: 15-24.