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A Watershed's Response to Logging and Roads:

South Fork of Caspar Creek, California, 1967-1976

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IN BRIEF...

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A long-term study of the effects of logging and roadbuilding on streamflow and sedimentation is underway at Caspar Creek, near Fort Bragg, California. Two experimental watersheds are being studied: North Fork and South Fork of the Creek. The study is a joint effort by the Pacific Southwest Forest and Range Experiment Station and the California Department of Forestry. Results of the first 14 years of the study are reported here.

The forest in the South Fork, the logged watershed, was about 85 years old in 1962, when the study was begun. It consisted mainly of redwood, Douglas-fir, Grand fir, and hemlock. In summer 1967, 4.2 miles (6.8 km) of logging roads were built. The effects of that activity were measured for 4 years and then, during 1971-73, about 65 percent of the stand volume was removed. On-site erosion, annual suspended sediment loads, and debris basin accumulations were estimated in order to evaluate the effects of road construction and the timber harvest.

Erosion associated with logging was measured on seven plots totaling 94 acres (38 ha). They were distributed throughout the watershed so as to be representative of site variability and the three seasons of cutting. Suspended sediment load was estimated each year by multiplying the volume of flow in each of 19 discharge classes by the mean suspended sediment concentration in each class and summing. Annual debris basin accumulations were estimated by comparing annual surveys of the basins. Two regression equations were computed in order to predict the effects of roadbuilding and logging. They estimated the suspended sediment load or debris basin accumulation in the South Fork based on streamflow and suspended sediment load or debris basin accumulation in the North Fork.

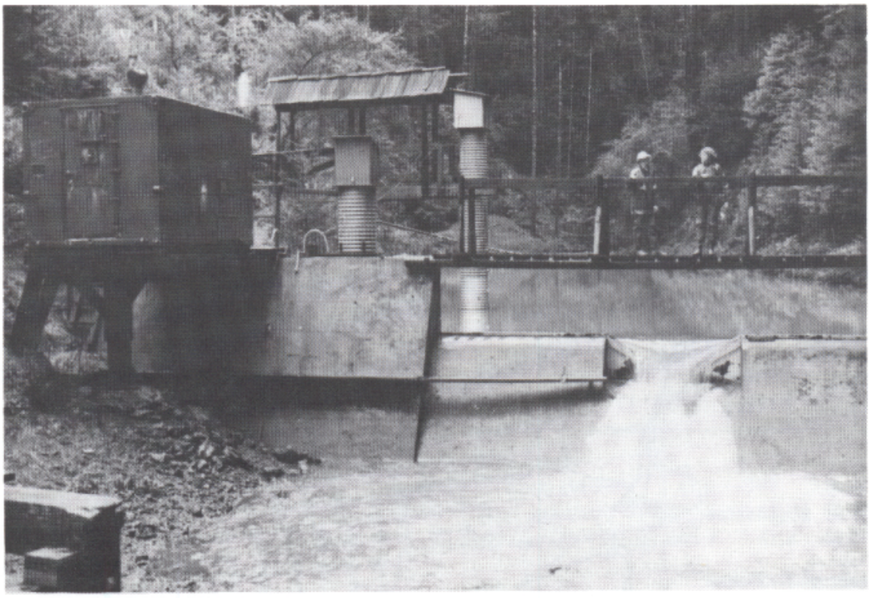
During logging, an additional 0.7 mile (1.1 km) of spur road was constructed. Of the total 4.9 miles (7.9 km) of roads, 2.4 miles (3.9 km) of the main haul road, and 1.3 miles (2.1 km) of spur roads were within 200 feet (61 m) of the stream. During the 4 years of measurement before logging began, we estimated that 1304 cu yd/sq mi (385 m^3/km^2) excess sedimentation occurred, or about 80 percent above the amount that would be predicted for the South Fork in an undisturbed condition.

The South Fork watershed produced a total of 4787 cu yd/sq mi (1413 m^3/km^2) excess sediment during the 5 years after logging was started. This sediment represents nearly a threefold increase over that which would have been expected had the watershed remained undisturbed. Analysis of the sediment/stream power relationship of Caspar Creek strongly suggests that the reason for the increase in sedimentation is that logging and roadbuilding had made additional sediment available for transport. In the undisturbed condition, the

Caspar Creek watersheds showed relatively modest increases in sediment load as stream power increased. After disturbance, the South Fork showed substantial increases in sediment transport as stream power increased. The undisturbed regime was highly dependent on supply; the disturbed regime became more dependent on stream power.

The erosion and sedimentation data collected as part of this study were used to estimate the long-term impacts of repeating such disturbances at 50-year intervals. If the estimated erosion rate reflected losses of soil from the site, the soil would be completely eroded in about 7900 years. If, on the other hand, excess sedimentation rates were a better measure of soil loss, exhaustion would occur in about 34,000 years. Either of these estimates is so far beyond current planning horizons that they have little relevance to current management until they are more accurately estimated.

Activities in the South Fork of Caspar Creek may have resulted in turbidities in excess of those permitted by local water quality regulations. Turbidity was not measured as part of this study but because of the nature of the suspended sediment load of Caspar Creek, turbidity increases would probably parallel closely the observed suspended sediment increases. If that is true, then the average turbidity of the South Fork exceeded background by more than 20 percent (the limit set by regulation) in 8 of the 9 years after road construction was started.



Data recorded at weirs in the Caspar Creek drainage in northern California will show effects of logging and roadbuilding on streamflow and water quality.

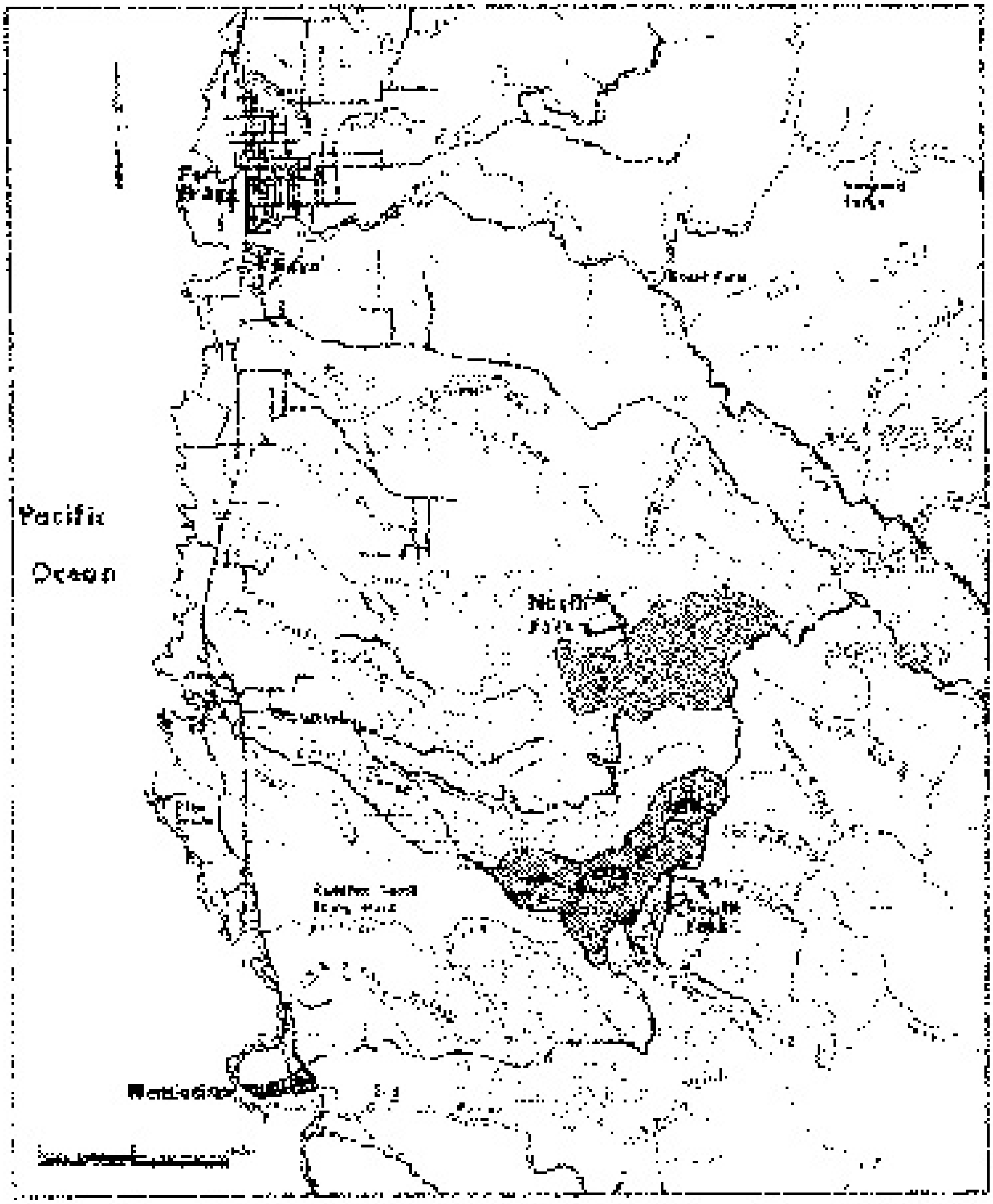


Figure 1—The two experimental watersheds, the North and South Forks of Caspar Creek, are on the Jackson State Forest, in northern California.

This paper offers a simple description of how road building and logging affect sedimentation. Field experiments are, however, rarely simple. Experimental results reflect not only the effects of conditions being tested, but also the vagaries of man and nature. In addition to the perturbations introduced into our data by weather patterns, malfunctioning instruments, and vandalism, our experiment included three other extraneous events of a less conventional nature.

A dam which had been storing sediment for 80 years failed in December 1967, the winter following road construction. During logging, one landing was constructed on an old landslide and subsequently produced exceptionally large amounts of erosion. During the winter after the completion of logging, a large landslide in the unlogged watershed yielded more sediment than measured in any 2 years in the rest of the study. Although these events complicated our analyses, we do not believe that any of them negate the general trends of our findings. As appropriate, in the various sections which follow, we will explain how each complication was dealt with in order to improve our interpretation of the results.

CASPAR CREEK WATERSHED

Jones' Law: *Things are always more complicated than they have any right to be.*

The Caspar Creek Watershed Study is a joint investigation of the California Department of Forestry and the Pacific Southwest Forest and Range Experiment Station. It was planned as a traditional investigation of paired watersheds-one logged, one left alone (fig, 1). After a period of calibration during hydrologic years 1963 through 1967, the main road network was constructed in the South Fork drainage *(table 1)*. During 197l-73, after the effects of road construction had been evaluated (Krammes and Burns 1973), the South Fork was selectively logged and the effects of the harvest monitored until the end of hydrologic year 1976. We are continuing to measure streamflow and sediment production from the two watersheds in anticipation of the next phase of the Caspar Creek Watershed Study, an evaluation of skyline logging which is planned to begin in 1984.

The North and South Forks of Caspar Creek have areas of 1225 acres (508 ha) and 1047 acres (424 ha) respectively; they are located about 7 miles (11 km) southeast of Fort Bragg, California. Soils are mainly Hugo or Mendocino, overlying sedimentary rocks of Cretaceous age. The climate is typical of the northern California coast, having mild summers with fog but little or no precipitation. The watersheds receive about 40 inches (1000 mm) of rainfall each year, concentrated in the months of October through April. Both watersheds were clearcut and burned in the late 1880's.

Table l-*Details of timber harvest in the South Fork of Caspar Creek*

Item	Year logged					
	1967[1]	1971	1972	1973	Average	Total
Area logged (acres) (M bm)	47	249	316	435	—	1047
Total stand/acre	85.1	69.9	62.7	51.3	61.3	
Harvest/acre (M bm)	85.1	41.4	43.0	33.1	39.2	
Road construction (acres)	47	[2]5.0	[2]1.2	[2]1.7	—	54.9
Skid trails (acres)		21.7	27.6	38.0	—	87.3
Landing (acres)		8.7	3.3	9.0		21.0
Percent of logged area sampled in 1976	100	12.1	10.8	7.4	9.4	-

[1] Logging only for right-of-way clearing.

[2] Temporary road not included in road work described by Krammes and Burns (1973).

METHODS

Stephen's Law: *The stature of a science is often measured by the extent to which it utilizes mathematics.*

Streamflow

From the outset, the Caspar Creek investigation was aimed primarily at determining the influence that logging and road building might have on streamflow peaks and sediment loads. It was expected that increases, if any, in total water yield as a result of harvest would be of little importance in northwestern California. With this emphasis on peak flows and sediment, little effort was made to ensure that complete records of summer flows were obtained. The lack of complete summer records had two consequences. First, we were unable to determine if any water yield increases occurred because they are characteristically manifested as increased summer flows (Anderson and others 1976). Second, we had to reconstruct records in order to estimate annual suspended sediment loads. These reconstructions were based, in large measure, upon the performance of the companion watershed. This procedure may have induced a higher degree of correlation between the two catchments than exists in nature. The reconstructed data does not, we feel, seriously affect our analyses. Practically all the reconstructions apply to low flow periods during which a minute fraction of the total sediment load is transported, so the effect on annual loads would be minor.

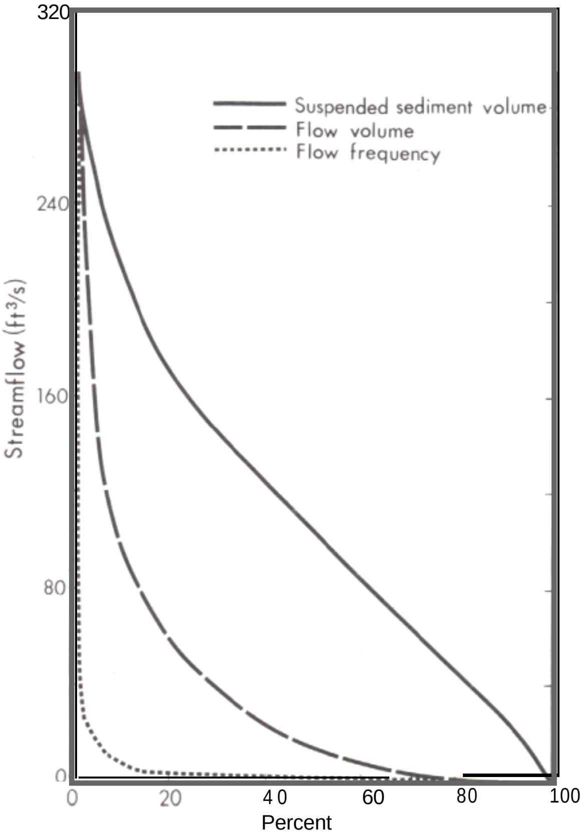


Figure P-Flow and sediment regimes of South Fork Caspar Creek showing the percentage of the flow frequency, flow volume, and sediment volume occurring at higher discharges than the level indicated. For example: about 80 percent of the sediment transport takes place in flows greater than 40 ft^3/s.

The flow regime of the South Fork is typical of many small forested watersheds in that for most of the time, flows are low relative to maximum discharges; most of the flow volume, and especially most of the sediment load, is carried during relatively brief periods of high discharges *(fig. 2)*. For example, discharges greater than 45 cu ft/s (1.27 m^3/s) occur approximately 1 percent of the time, but carry 26 percent of the volume of the water and 81 percent of the suspended sediment that is discharged annually by the stream. Recognition of these relationships led to the creation of a variable, $N\bar{Q}_{25}$ to index the year-to-year variability in sediment transport capability of the North Fork of Caspar Creek. $N\bar{Q}_{25}$ was the mean discharge rate of the flows which yielded the upper 25 percent of the flow volume of the North Fork. Throughout this paper, the term "stream power" will be used as a synonym for either $N\bar{Q}_{25}$ or the similar measurement in the South Fork, $S\bar{Q}_{25}$.

Suspended Sediment

Annual suspended sediment loads were estimated by multiplying the volume of flow in each of 19 discharge classes by the mean suspended sediment concentration in each of those classes and summing. Class boundaries were located so that approximately 5 percent of the annual flow occurred in each class. The weight of sediment thus computed was converted to a volume, assuming a factor of 74 pounds per cubic foot (1185 kg/m^3). As we had few data relating sediment concentration to steady or recession flows, our estimates of suspended sediment load had to be based on rising stage relationships. Because rising flows typically carry more sediment at a given discharge than recession flows, this compromise caused us to somewhat overestimate suspended sediment discharge of both the North Fork and the South Fork. The absolute increases in suspended sediment production as the result of logging or road building are therefore somewhat inflated, although the relative increases are likely to be near their true values. Because streamflow records were incomplete, about 0.02 percent of the streamflow record for discharges greater than 30 cu ft/s (0.85 m^3/s) was reconstructed. We are confident that neither of these compromises needed to estimate annual suspended sediment discharges had an appreciable effect on our results or conclusions.

During the calibration period (1963-67), a single composite sediment-discharge relationship was used to estimate annual suspended sediment loads for the South Fork of Caspar Creek. In subsequent years, while the South Fork was being disturbed by the effects of road building and logging, individual relationships were developing for each year. This procedure was used to guard against the possibility that the sediment-discharge relationship was changing from year to year. A single relationship was used throughout the study to estimate the suspended sediment load of the North Fork. This procedure differs from that of Krammes and Burns (1973), who used normalized suspended sediment discharges, after Anderson (1971). Consequently, our data differ from theirs for hydrologic years 1963-71.

Debris Basin Accumulation

The remainder of the sediment discharge was captured as deposits in the stilling ponds upstream from each of the Caspar Creek weirs. Annual accumulations were estimated by comparing bottom profiles of the sediment at approximately 24 cross sections in each of the reservoirs. When the reservoirs approached approximately one-half capacity, they were excavated during the summer season. On three occasions, this survey and cleanout procedure led to apparently illogical results-negative reservoir deposition during hydrologic years 1972 and 1976 *(table 2).* These negative numbers may be the result of surveying errors: they may represent actual losses over the weir of remobilized bottom sediment; they may represent settling of the deposits or decay of organic material. Because all of the negative “accumulations” occur in dry years, we think the last explanation is the most probable. In either basin, less than 3 inches of settling could account for these differences. Assuming that a certain amount of compaction of sediment takes place in every year, we have chosen to use these negative numbers as our best estimates of the debris basin accumulations.

Calibration Equations

Two regression equations were computed in order to estimate the changes in sediment yield of the South Fork which may have resulted from road construction and logging. Each of the equations was based on two independent variables. The first independent variable was the estimated sediment discharge (either suspended sediment or debris basin accumulations) of the North Fork. The second variable was $N\bar{Q}_{25}$. The regressions were based on the relationships which existed during the calibration period (hydrologic years 1963-67). They were

$$SSF = 17.5 + 1.02\ SNF - 4.65\ N\bar{Q}_{25} \qquad (1)$$

$$DSF = 114 + .38\ DNF - 2.15\ N\bar{Q}_{25} \qquad (2)$$

in which

SSF = the annual suspended sediment discharge of the South Fork of Caspar Creek (yd^3/mi^2)

SNF = the suspended sediment discharge of the North Fork of Caspar Creek (yd^3/mi^2)

$N\bar{Q}_{25}$ = the mean discharge of the upper 25 percent of the flow volume of the North Fork of Caspar Creek (ft^3/s/mi^2)

DSF = the annual debris basin accumulation behind the South Fork weir (yd^3/mi^2)

DNF = the annual debris basin accumulation behind the North Fork weir (yd^3/mi^2)

Both the suspended sediment and the debris basin regression equations gave excellent fits to the data. They had coefficients of determination of 1.00 and 0.93, respectively.

Table 2—*Annual sedimentation and streamflow from the Caspar Creek watersheds*

	NORTH FORK				SOUTH FORK							
						Suspended sediment			Debris basin accumulation			
Hydrologic year	$N\bar{Q}_{25}$	Suspended sediment	Debris basin accumulation	Total sediment	$S\bar{Q}_{25}$	Observed	Predicted	Increase	Observed	Predicted	Increase	Total Increase
	Cu ft/s/sq mi	*Cu yd/sq mi*			*Cu ft/s/sq mi*	*Cu yd/sq mi*						
					Calibration period							
1963	24.50	101.15	56.32	157.45	24.68	160.94	164.30		77.04	82.64		
1964	30.23	54.00	64.00	158.00	33.84	130.28	130.35		44.80	73.24		
1965	68.36	612.54	685.44	1297.98	75.90	481.65	482.43		233.99	229.48		
1966	112.61	744.04	827.49	1571.53	110.84	411.30	410.90		193.27	188.63		
1967	24.30	138.24	60.16	198.40	24.73	206.90	203.09		109.44	84.55		
Total		1689.97	1693.41	3383.38		1391.07			658.54			
Average		337.99	338.68	676.68		278.21			131.71			
					Road construction evaluation							
1968	20.99	67.65	53.76	121.41	28.06	547.03	146.42	400.61	133.77	89.22	44.55	445.16
1969	44.99	389.99	394.23	784.22	44.59	565.97	363.90	202.07	234.23	168.12	66.11	268.18
1970	52.93	387.21	227.19	614.40	50.14	312.15	324.18	−12.03	147.19	86.93	60.26	48.23
1971	67.51	490.09	371.82	861.91	79.83	596.28	361.37	234.91	418.54	111.00	307.54	542.45
Total		1334.94	1047.00	2381.94				825.56			478.46	1304.02
Average		333.74	261.75	595.49				[1]206.39			[1]119.62	[1]326.01
					Logging evaluation							
1972	18.38	51.15	−80.00	−28.85	19.35	199.08	141.71	57.37	−149.75	43.52	−193.28	−135.91
1973	47.40	326.41	179.83	506.24	58.82	1894.91	287.78	1607.13	238.71	80.68	158.03	1765.16
1974	82.11	2707.48	1219.15	3926.63	93.43	2392.49	2554.82	−162.33	347.51	400.74	−53.23	−215.56
Adjusted[3]		601.15	573.51	1174.66			406.97	1985.52		156.99	190.52	2176.04
1975	48.89	393.01	238.07	631.08	41.23	1168.08	348.85	819.23	102.39	99.31	2.58	821.81
1976	22.78	52.81	−35.20	17.61	29.27	286.13	122.94	163.19	48.00	51.24	−3.24	159.95
Total		3530.86	1521.85	5052.71				2484.59			−89.14	2395.45
(Adjusted)[3]		(1424.53)	(876.21)	(2300.74)				(4632.44)			(154.61)	(4787.05)
Average		706.17	304.37	1010.54				[1]496.92			−17.83	[1]479.09
(Adjusted)[3]		(284.91)	(175.24)	(460.15)				[2](926.49)			[1](30.92)	[2](957.41)
					Combined data-road construction and logging							
Total		4865.80	2568.85	7434.65				3310.15			389.32	3699.47
(Adjusted)[3]		(2759.47)	(1923.21)	(4682.68)				(5458.00)			(633.07)	(6091.07)
Average		540.64	285.43	826.07				[1]367.79			[1]43.26	[1]411.05
(Adjusted)[3]		(306.61)	(213.69)	(520.30)				[2](606.45)			[1](70.34)	[2](676.79)

[1] Increase statistically significant $p < 0.05$ level according to Chow's (1960) test.

[2] Increase statistically significant $p < 0.01$ level according to Chow's (1960) test.

[3] Adjusted by using the normal sedimentation of the North Fork for 1974 rather than the observed rate resulting from the landslide.

RESULTS

Gumperson's Law: *The probability of anything happening is in inverse ratio to its desirability.*

Road Construction

The effects of road construction and logging were analyzed separately. Each of these analyses had two parts. Erosion was estimated to quantify the impact of the activity on the watershed and sediment increases were tested statistically to evaluate the response of the watershed to that impact.

Erosion

The main road in the South Fork of Caspar Creek was constructed during the summer of 1967. During the following December, an old splash dam failed in the South Fork drainage, about 300 feet (91 m) downstream from a major stream crossing of the road. The dam had been storing sediment for approximately 80 years since it was last used to flush logs downstream during the original logging of the South Fork. Krammes and Burns (1973) estimated that slightly in excess of 925 cu yd (707 m^3) of the 5600 cu yd (4282 m^3) of stored sediment were released. Although the exact cause of failure is not certain, we believe the road construction, and especially disturbance at the stream crossing, was probably responsible.

In addition to the erosion of splash dam sediment, Krammes and Burns (1973) estimated that about 6.50 cu yd (497 m^3) of erosion occurred on the road in the immediate vicinity of the stream channel. They acknowledged, however, having no estimate of the material eroded during the construction of the stream crossing or the amount that may have spilled into the stream during road maintenance, and make no mention of measurements of surface erosion on the road prism. Consequently, in our appraisal of the impact of road construction, we have chosen to consider that the splash dam failure and its sediment were entirely attributable to road construction. In this way we are compensating, in part, for the underestimation of road prism erosion which apparently occurred.

Sedimentation

Suspended sediment production during the winter following road construction was over 3.7 times that predicted (*fig. 3*). The amount of excess suspended sediment declined in hydrologic year 1969 and the observed sediment load in 1970 was below that predicted. Since about 2.4 miles (3.9 km) of the main road and 1.3 miles (2.1 km) of spur roads in the South Fork were within 200 feet (61 m) of the stream channel, we feel that this rapid decline in suspended sediment was to be expected. It agrees with the findings of Megahan (1974) in his studies of erosion following road construction in Idaho. In 1971, in response to high streamflow, suspended sediment observed in the South Fork rebounded to exceed that predicted by 65 percent.

Debris basin accumulations in the first year following road construction were about 50 percent greater than predicted (fig. 3). This increase persisted through 1969 and 1970. In 1971, the increase was more than four times the predicted value. This large increase is probably the result of two factors. First, flows in the South Fork that winter were high enough to have the ability to entrain incipiently unstable sediment throughout the stream channel. Second, the heavier fractions of splash dam sediment released in 1968, some 10,800 feet (3292 m) upstream from the debris basin, were finally reaching it.

In total, over the 4 years between road construction and the beginning of timber cutting, the South Fork watershed produced about 1304 cu yd/sq mi (385 m^3/km^2) excess sedimentation, which we attribute to the construction of approximately 3.7 miles (6.0 km) of logging roads in the riparian zone of the South Fork of Caspar Creek.

Logging

Erosion

Estimates of erosion were obtained from seven plots in the South Fork of Caspar Creek. Those plots were selected so as to sample the three ages of cutting and to be representative of the condition of the South Fork watershed. Measurement procedures were identical with a more general study of logging-related erosion in northwestern California (Datzman 1978) and very similar to methods used by the California Department of Forestry in a statewide study (Dodge and others 1976). The plots were rectangular, 10 chains (201 m) wide and from 10 to 16 chains (201 to 322 m) long, depending on the distance from which logs were being yarded to the landing. Within the plots, gullies greater

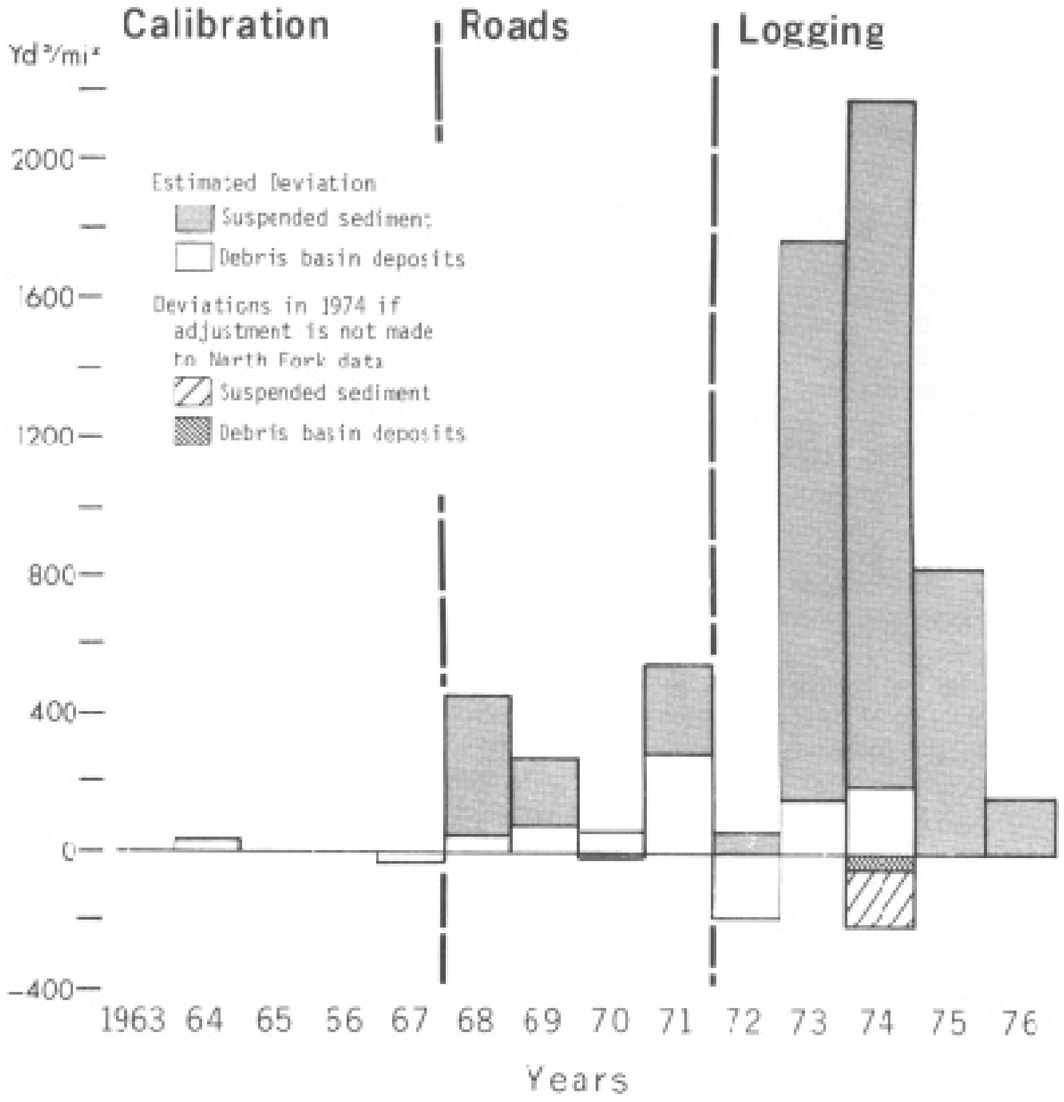


Figure 3—Deviations of sediment yield in the South Fork of Caspar Creek from the amount predicted from observations in the North Fork.

than 1 sq ft (0.09 m²) in a cross section and mass movements displacing more than 1 cu yd (0.76 m³) of soil were completely measured. Ground conditions and minor erosional features were sampled on transects at 2-chain (40-m) intervals along the length of the plots. From these data we estimate that the timber harvest resulted in 42.9 cu yd/acre (81.1 m³/ha) excess erosion.

Sedimentation

The response of the South Fork watershed to the logging disturbance, though quite dramatic, must be considered together with the fact the post-harvest period included years of both very abundant and very deficient rainfall and runoff. Overwhelmingly, logging affected suspended sediment discharges *(fig. 3)* more than debris basin accumulation.

The stream power of both forks of Caspar Creek was lower in hydrologic year 1972 than in any other year in the study. This apparently resulted in a very small suspended sediment increase. The small increase also may be due, in part, to the fact that only 25 percent of the watershed had been logged the previous summer. During the following winter, with over one-half the watershed logged and somewhat above normal rainfall and stream power, suspended sediment loads were 6.6 times greater than predicted (*table 2*).

Events during hydrologic year 1974 greatly complicated our efforts to estimate the effect that timber harvest was having on the suspended sediment discharge of the South Fork watershed. Two large landslides occurred adjacent to stream channels during a March storm. One was in the North Fork; one was in the South Fork. The North Fork slide, 4234 cu yd (3306 m^3), dumped much of its sediment directly into the stream, which transported it to the weir where it was measured. The South Fork slide, 727 cu yd (556 m^3), knocked down riparian trees and built itself a bridge above the stream. As a consequence, only a comparatively small portion of its total sediment had entered the stream by the end of the study. As a result of these two unusual events, a straightforward use of equation 1 leads to an estimated decrease in suspended sediment load in the South Fork for hydrologic year 1974. If the suspended sediment discharge in the North Fork is adjusted to its normal relationship with stream power (*fig. 4a*), equation 1 leads to a more reasonable estimated increase in suspended sediment of almost six times the predicted value.

Suspended sediment increases, both in absolute and relative terms, decreased in hydrologic year 1975 and again in hydrologic year 1976. In total, suspended sediment production for the 5 years following the beginning of logging was 4.5 times greater than the amount predicted by the calibration equation.

Following the 1972 hydrologic year, surveys of the debris basins indicated negative accumulations in both the North Fork and the South Fork. As noted earlier, we elected to use these negative numbers together with equation 2 to estimate the effect of logging. That estimate, however, may be subject to large errors, as it was computed using values which were much beyond the range of the calibration data. In hydrologic year 1973, a modest increase in debris basin accumulation was estimated. In 1974, a similar increase was arrived at using adjustments similar to those used to estimate suspended sediment increases. From these data it appears that the effect of logging on suspended sediment is much greater than its effect on debris basin accumulations. It may be, however, that since the logging disturbances occurred farther from the weir than those associated with road construction, the heavier materials which would be measured as debris basin accumulation have yet to arrive at the weir. At this time there is no clear indication which interpretation is correct.

In summary, the effect of logging on sedimentation in the South Fork was mainly expressed as increases in suspended sediment discharge. Although the record was complicated by the events of 1972 and 1974, we have been able to adjust our estimates to overcome the difficulties presented. Using the adjusted predictions, we estimate a sediment increase of about 4787 cu yd/sq mi (1413 m^3/km^2). We feel that such an adjusted estimate is probably closer to the typical response to logging than one which would have resulted from the rigid use of the predisturbance regression equation with the observed data.

INTERPRETATIONS

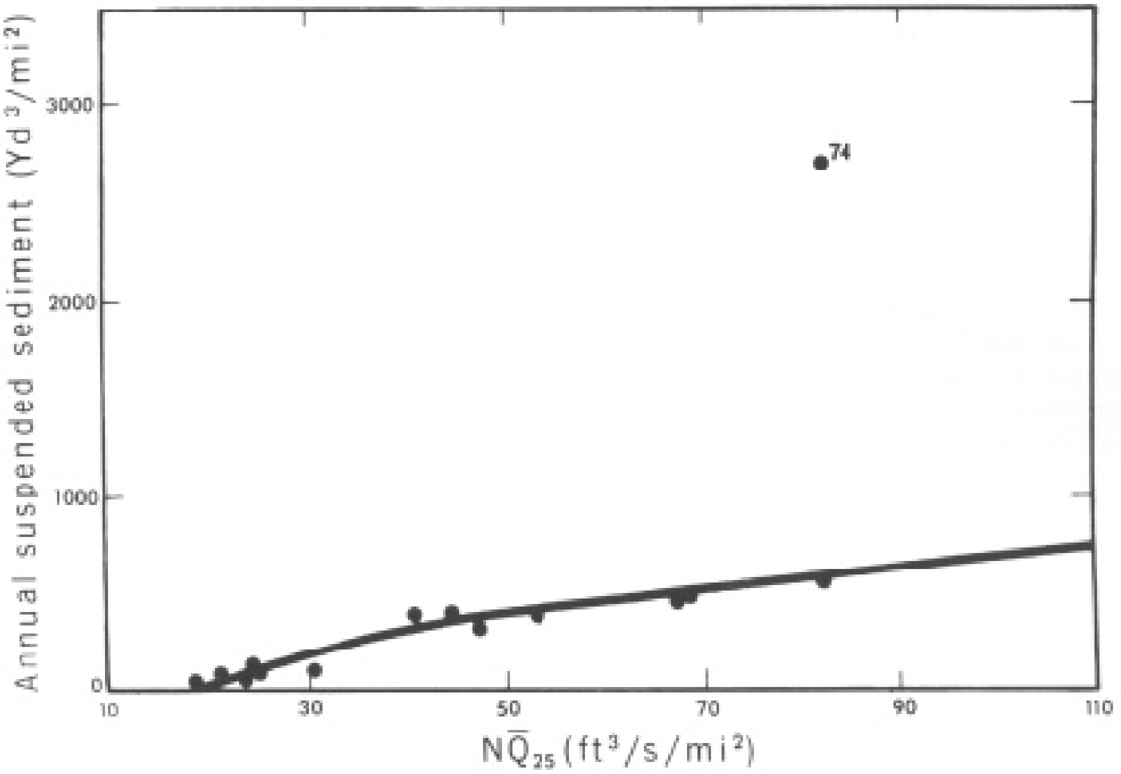
Hoare's Law: *Inside every large problem are small problems struggling to get out.*

It is not enough to know that a particular logging operation had a particular effect on sedimentation. Other questions need to be answered, at least in part. What mechanisms have caused the observed changes in sedimentation? What might be the long-term implications of repeated management impacts such as those described here? How does this logging operation relate to others?

Mechanisms

Inspection of the South Fork's suspended sediment data suggests that the relationship between suspended sediment and stream power changed appreciably during some of the postcalibration years (*fig 4b)*. The most marked differences were seen in the postlogging years of 1973-75, and only hydrologic year 1970 had a suspended sediment discharge lower than predicted by the calibration equation. The years that roadbuilding and logging began (1968 and 1972) also appear to fit the same curve as 1973-75, although the very low year of 1972 could be fitted to either curve. Since some suspended sediment increase in response to logging one quarter of a watershed would be expected, we have chosen to include 1972 with what we shall call the "disturbance" years (hydrologic years 1968, 1972-75). With the exception of the disturbance years, the relationship between suspended sediment and stream power in the South Fork is quite similar to that which exists in the North Fork (*fig. 4*). Both watersheds show only a modest increase in suspended sediment load with increases in stream power. The disturbance years show a much different relationship. Suspended sedi-

a North Fork



b South Fork

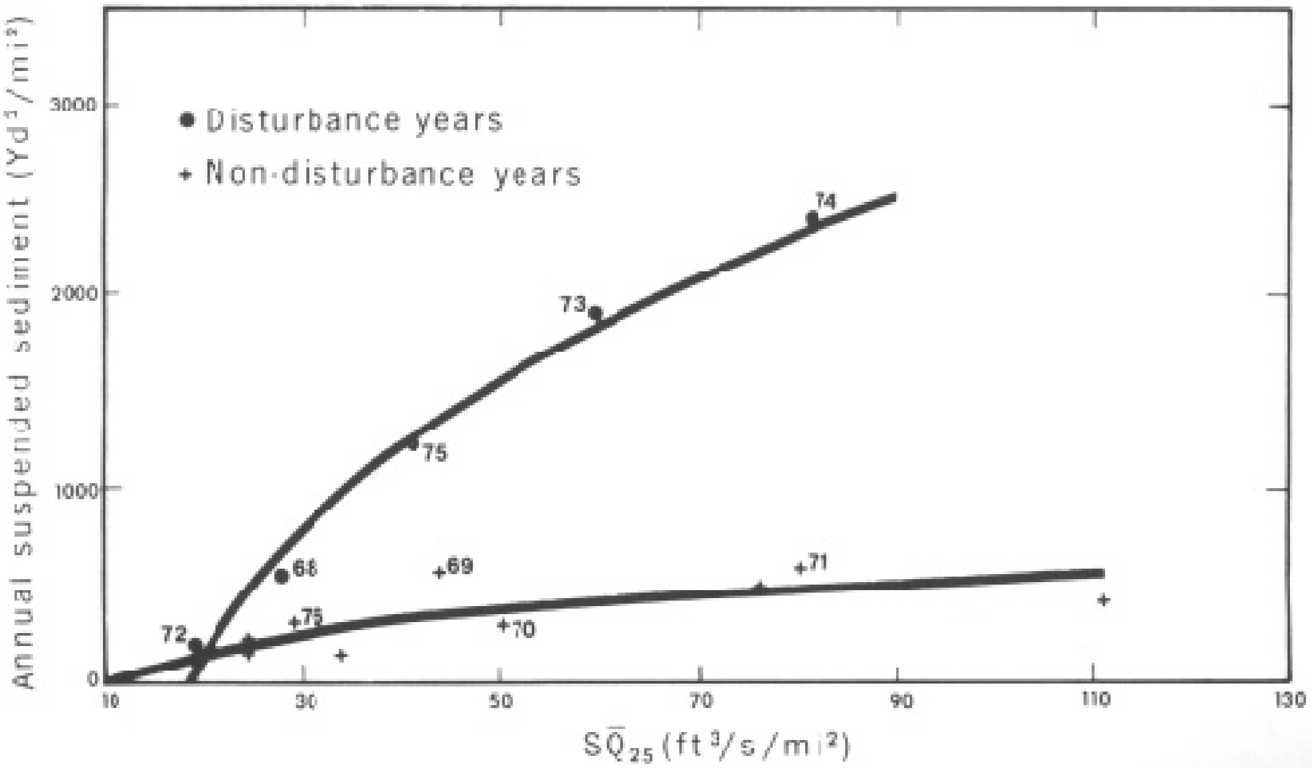


Figure 4—Annual sediment discharge of the forks as related to stream power as indexed by $\bar{Q}_{25}$ (the mean discharge for the top 25 percent of the flow volume)

ment discharge increases markedly with increased stream power. We believe the two curves describe fundamentally different flow regimes. In the "nondisturbance" years, stream channels and the watershed surface are so stable that the stream has transporting power in excess of the available sediment. Consequently, this regime is *supply dependent*. During the disturbance years, on the contrary, a superabundance of transportable material is delivered to the drainage system. Sediment discharge is no longer determined solely by the availability of sediments; rather, it is mainly a function of the transporting ability of the stream. In this circumstance, the regime is *stream power dependent*. Debris basin accumulations also show a similar shift from supply dependence to stream power dependence, although not as dramatic as the shift for suspended sediment. It appears, then, that the principal effect that logging and roadbuilding have had is to deliver sediment to the stream.

Soil Loss

A fundamental question remains: What is the long term impact of roading and logging in the South Fork of Caspar Creek? To answer it, we need to distinguish between the estimated physical consequences of the operation and our professional and esthetic appraisals of it. In keeping with the Forest Practice Rules in existence at the time, relatively little consideration was given to erosion control or the control of water. Water bars were infrequently and inexpertly installed. Ephemeral channels were frequently used as skid trails, and landings were located with little regard to slope hydrology or slope stability. Four years after logging the scars had yet to heal. The measurable physical impacts were much less dramatic. The 10 percent of the watershed which had been severely disturbed by skid trails and landings *(table 1)* presumably may be less productive. Similarly, the 5 percent of the watershed now occupied by road prisms will yield few forest products. The road system, however, represents a necessary permanent investment in the management of the drainage. To the extent that landings and skid trails are reoccupied for later harvests, they too can be considered as necessary deductions from the area available to grow trees. Because the future utilization of the currently installed transportation network is uncertain, it is difficult for us to say how much of the land thus taken out of production was unnecessarily lost. Our best *guess* would be about 3 percent.

The average soil depth in the South Fork of Caspar Creek is about 4 feet (1.2 m). Assuming that the measured "erosion" represents the excess loss of soil from the site for each harvest (that is, natural erosion equalled replenishment from natural soil genesis), and assuming that similar disturbances would occur at approximately 50-year intervals, the soil resource would be totally exhausted in about 7900 years *(table 3)*. Our sedimentation data, however, indicate that only about

Table *3-Short-and long-term impacts of logging and road construction in the South Fork of Caspar Creek*

Disturbance	Delivery ratio	Soil lost due to disturbance: Volume: Erosion	Soil lost due to disturbance: Volume: Sedimentation	Soil lost due to disturbance: Proportion of soil mantle[1]: Erosion	Soil lost due to disturbance: Proportion of soil mantle[1]: Sedimentation	Estimated time for complete removal of soil mantle[2]: Erosion	Estimated time for complete removal of soil mantle[2]: Sedimentation
		Cu yd/sq mi		*Percent*		*Years*	
Road construction	1.35	962.75	1,304.02	0.0233	0.0316	214,497	158,362
Logging, observed	.091	26,221.75	2,395.45	.635	.0580	7,875	86,208
Logging, adjusted[3]	.183	26,221.75	4,787.05	.635	.116	7,875	43,046
Total, observed	.136	27,184.50	3,699.47	.658	.0896	7,596	55,821
Total, adjusted[3]	.224	27,184.50	6,091.07	.658	.148	7,596	33,903

[1] Assumes a soil depth of 4 feet.

[2] Assumes that similar impacts occur at 50-year intervals and that new soil forms during the period at a rate equal to natural erosion

[3] Adjusted by using the normal sedimentation of the North Fork for 1974 rather than the observed rate resulting from the landslide.

22 percent of the eroded material has left the watershed. Using sediment volume with similar assumptions, we estimate the soil would not be exhausted for 33,900 years. Clearly, both of these figures, which include stringent and unfavorable assumptions of repeated *equal* impacts and no increased rate of soil formation, represent planning horizons much beyond what a forest manager must consider. It might be argued that our calculations underestimate site degradation, because erosional processes will remove a disproportionate share of the more fertile surface layers of the soil. Undoubtedly, this is true to some extent; however, our erosion measurements recorded only 3 percent of the total erosion as rill erosion. The remainder occurred as landslides or large gullies which remove mainly the less fertile subsoil. Although we are not advocating unnecessary erosion, these inferences and extrapolations from our data would suggest that timber harvest, such as we measured in the South Fork, would not cause unacceptable site damage.

Water Quality

In any appraisal of forest management impacts, water quality is a major concern. The implications of our estimates are more gloomy here. Although the first and fourth largest South Fork discharges occurred during the 5-year calibration period, suspended sediment loads during 6 of the 9 postcalibration years exceeded any recorded in the South Fork while it was undisturbed. With similar disturbances and 50-year intervals assumed, it is doubtful that the aquatic ecosystem can maintain itself when perhaps 10 percent of the years in each century are above the normal range of variability. In addition to possible ecological impacts, forest managers need to consider the legal restraints on water quality degradation. If turbidity changes have paralleled suspended sediment changes, as we would expect, in 8 of 9 postcalibration years turbidity exceeded the standards of the North Coast Regional Water Quality Control Board (no increases greater than 20 percent above background). We may now ask, which is at fault, the logging and roadbuilding methods or the water quality standards? The new Forest Practice Rules may be expected to reduce considerably the amount of water pollution which may result from timber harvest. It appears unlikely, however, that even operations totally in keeping with the Forest Practice Rules will avoid all turbidities in excess of 20 percent above background. Therefore, it might be more prudent to modify water quality standards so that they specify more attainable goals.

Comparison to Other Logging

Fortunately, information that allows appraisal of the "representativeness" of the Caspar Creek Study is available from an investigation of erosion of logged areas in northwestern California (Datzman 1978). This study included 102 plots stratified so as to sample as many combinations of important site variables as possible. The seven Caspar Creek plots were compared with two groups of plots from Datzman's data. Both groups were composed of plots which had been logged at about the same time as Caspar Creek, and which had supported second-growth timber (''second-growth" includes all plots other than old-growth redwood). One group of plots was composed of partial cuts and the other included plots which had been tractor yarded.

Our comparisons were based on two erosion variables, 14 site variables, and 12 surface condition variables *(table 4*). The Caspar Creek plots were most like the other four partially cut plots, with respect to site and surface condition variables, and none of the differences between the Caspar Creek plots and the 14 tractor-yarded plots appears serious. Comparison of the erosion variables shows obvious important differences. Caspar Creek appears to have experienced significantly more erosion and possibly higher values of the variable Net Soil Loss as well. Seeking an explanation, we found that the landing at one of the Caspar Creek plots had been located on the toe of an incipient unstable rotational failure. When the predictable slump occurred, it yielded almost one-half of the erosion measured in Caspar Creek.

Had ours been the only observation of a data set being dominated by an extreme event, we might have had serious reservations about the "representativeness" of the Caspar Creek experiment. It appears, however, that such domination may be common. Datzman's (1978) data are dominated by five large events and another large data set of road-related erosion is dominated by three. Consequently, although we might prefer the data to be well behaved, it probably represented the sort of random perturbations to be found in most investigations of erosion. Thus, we believe that the *interim* use of Caspar Creek as a prototype for logging impacts in second-growth tractor harvest of timber in northwestern California is warranted. Another reason for this position is that we, like Froelich (1973), believe that the most important determinant of erosion and disturbance is not variation in site conditions, but differences in operator performance-the mistakes that led to erosion in Caspar Creek could be made on future timber harvests.

Table 4-*Characteristics of logged plots in Caspar Creek watershed study and of other second-growth plots (comparable with respect to time elapsed since logging) in northwestern California*

Characteristic	South Fork Caspar Creek	Partially cut plots[1]	Tractor yarded plots[2]
Plots (number)	7	4	14
Area sampled (acres)	94	44	164
Erosion variables (yd^3/acre):			
Erosion[3]	42.9	10.6	8.3
Net soil loss[3]	150.9	90.0	134.1
Site variables:			
Age since logging (yr)	3.86	4.75	4.50
Mean annual precipitation (in)	44.29	61.25	67.50
10 yr maximum 24 hr (in)	4.56	6.42	6.81
2 yr maximum 6 hr (in)	1.80	2.10	2.16
Aspect severity[4]	5.29	4.75	4.50
Slope (pct)	29.7	31.0	38.5
Elevation (ft)	634	1638	1936
Sand in surface soil (pct)	58.6	51.6	50.2
Clay in surface soil (pct)	17.7	19.3	21.7
Sand in subsurface soil (pct)	43.7	55.4	50.7
Clay in subsurface soil (pct)	29.4	19.9	22.7
Field aggregate stability[5]	4.34	5.10	5.43
Lab. aggregate stability surface[6]	31.2	36.8	42.4
Lab. aggregate stability subsurface[6]	45.9	35.0	41.6
Surface condition variables:			
Area in roads (acres)	0.149	0.298	0.249
Area in landings (acres)	.281	.223	.349
Area in skid trails (acres)	1.43	1.12	1.26
Bare ground (pct)	7.9	12.0	21.4
Slash (pct)[7]	20.6	14.8	16.2
Litter (pct)[7]	27.6	22.2	18.3
Wood (pct)[7]	7.1	11.8	10.7
Herbaceous plants (pct)	13.3	13.5	8.4
Shrubs (pct)	2.9	17.8	15.1
Conifers (pct)	16.6	4.8	2.6
Hardwoods (pct)	3.4	3.0	2.4
Rock (pct)	0.9	1.3	5.4

[1] Includes both cable and tractor yarding.

[2] Includes both partial cuts and clearcuts.

[3] Erosion included all mass failures, all gullies with cross-sectional area greater than 1 ft^2, and rills (based on transect sampling) with cross-sections greater than 0.1 ft^2. Erosion + excavation – till = net soil loss.

[4] Rated on a scale from 1 (N) to 8 (S).

[5] Rated on a scale of decreasing stability from 1 to 10 (Calif. Reg., For. Serv. 1968).

[6] Represents the ratio of hydrometer readings after final time period in dispersed and aggregated suspensions.

[7] Slash is organic debris between 0.5 inches and 6 inches in diameter. Litter is smaller material and wood is larger.

CONCLUSIONS

Weinberg's Sixth Law: *If you never say anything wrong, you never say anything.*

In summary, we conclude that the study of roading and selective timber harvest in the watershed of the South Fork of Caspar Creek suggests that

- The watershed appears representative of other harvested areas investigated in northwestern California.
- The information gained in this study applies most directly to tractor-yarded, partially cut second-growth redwood and old-growth timber of other species.
- Disturbances from roadbuilding and logging changed the sediment/discharge relationship of the South Fork from one which was supply dependent to one which was stream power dependent, resulting in substantial increases in suspended sediment discharges.
- Although roadbuilding and logging apparently increased debris basin deposits as well, the nature of the increase is much less clear. Lags in the movement of bed material through the stream system may be the confusing element.
- The overall effect on site quality, as estimated by erosion or sedimentation, does not appear to be a cause for concern.
- Road construction and logging appear to have resulted in increases in average turbidity levels (as inferred from suspended sediment increases) above those permitted by Regional Water Quality Regulations.

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