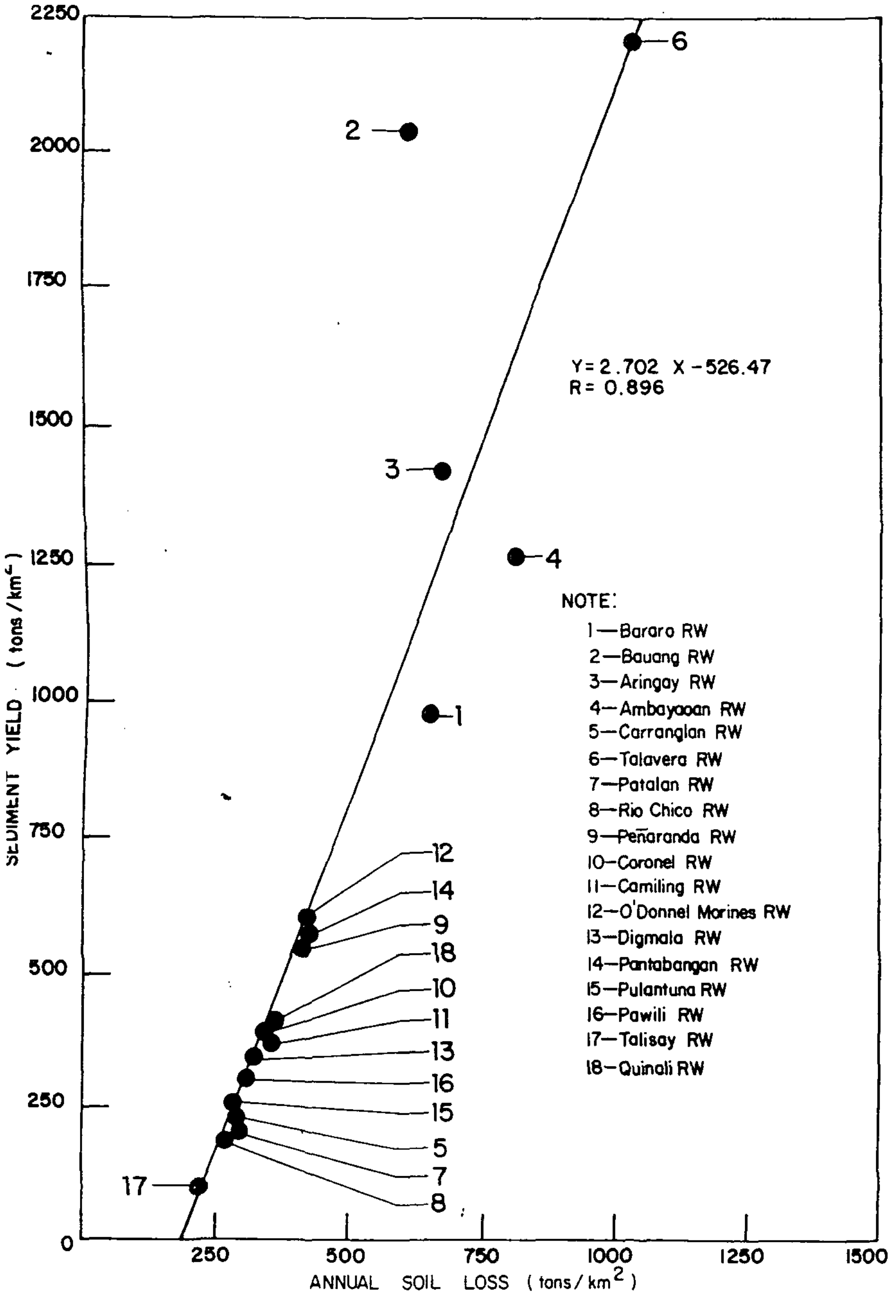

FIGURE 2. Relationship between soil loss and sediment yield.

Nolan, 1981

Erosion and Sediment Transport in Pacific Rim Steeplands. I.A.H.S. Publ. No. 132 (Christchurch, 1981)

Use of short-term water and suspended-sediment discharge observations to assess impacts of logging on stream-sediment discharge in the Redwood Creek basin, northwestern California, U.S.A.

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Abstract. Sediment-transport data resulting from periodic and synoptic sampling of water and suspended-sediment discharge have been used to estimate the degree to which extensive, tractor-yarded, clear-cut timber harvesting has accelerated naturally high erosion in the Redwood Creek basin, northwestern California. Suspended-sediment transport curves (SSTCs) of eight streams draining basins of diverse geology and landuse were compared using analysis of covariance. Adjusted mean values of suspended-sediment discharge per unit area (SSD/A) for streams draining recently harvested terrane were at least twice as great as adjusted means for streams draining physically comparable, nearly uncut basins. Relationships between SSTCs of higher-order streams and those of lower-order tributary streams draining areas with contrasting amounts of timber harvest further indicated that timber harvest caused tributary streams to become major sediment sources at times of high water discharge. Synoptic sampling conducted during nine storms indicated that water discharge per unit area (WD/A) from streams draining harvested terrane was roughly twice that from unharvested terrane under similar hydrologic conditions. Synoptically measured values of suspended-sediment discharge were roughly 10 times greater from harvested terrane than from unharvested terrane.

L'utilisation des observations de peu de duree de l'écoulement de l'eau et du sédiment en suspension pour évaluer l'influence de l'exploitation forestiére sur l'écoulement des cours d'eau du bassin de Redwood Creek du nord-ouest de la californie, états-unis

Résumé. Nous avons utilisé les données des transports de sédiments provenant de l'échantillonnage périodique et synoptique de l'eau et de l'écoulement du sédiment en suspension pour calculer à quel point les coupes à blanc considérables avec débardage à bulldozer ont accéleré l'érosion normalement élevée du bassin de Redwood Creek dans le nord-ouest de la Californie. Nous avons comparé les courbes de transport du sédiment en suspension de huit bassins versants de geologie et d'utilisation des terres variées en nous servant d'une analyse à covariant. Les valeurs moyennes ajustées par unité de surface de l'écoulement du sédiment en suspension des cours d'eau qui drainent des terrains récemment coupés étaient au moins deux fois plus grandes que les moyennes ajustées des cours d'eau qui drainent des bassins physiquement semblables mais presqu'intacts. De plus, les rapports entre les courbes de transport du sédiment d'ũn cours d'eau d'un numéro d'ordre supérieur et celles des affluents d'un numéro d'ordre inférieur qui drainent des terrains trés peu ou beaucoup coupés indiquent que l'exploitation forestière a comme résultat que les affluents deviennent des sources importantes de sédiments pendant un débit de crues. L'échantillonnage [illegible] effectué pendant neuf tempêtes indique que l'écoulement d'eau par unité de surface des cours d'eau qui drainent un terrain coupé était deux fois plus grand que celui d'un terrain intact dans des conditions hydrologiquement semblables. Les valeurs symoptiquement mesurées de l'écoulement du sédiment en suspension d'un terrain coupé étaient à peu près dix fois plus grandes que celles d'un terrain intact.

INTRODUCTION

Records of suspended-sediment discharge collected over the last 20 years suggest that the Coast Ranges and Klamath Mountain provinces of northern California and southern Oregon comprise some of the most actively eroding terrane in North America (Judson and Ritter, 1964; Holeman, 1968; Janda and Nolan, 1979). The impacts of these high sediment discharges on productive wildland soils, anadromous fish habitat, and streamside parklands are of considerable concern to environmentally-concerned groups. Although high erosion rates occur naturally in these areas as a result of their geologic setting and climate, recent changes in land-use patterns have accelerated naturally high rates in many areas (Anderson, 1979). The degree to which land-use practices have accelerated erosion rates has been the focus of considerable public discussion and controversy (U.S. House of Representatives, Committee on Government Operations, 1976, 1977).

Recent controversy has focused on the 730-km^2 drainage basin of Redwood Creek, which contains in its downstream end a major portion of Redwood National Park. Water-and suspended- [illegible] studies conducted in cooperation with the National Park Service to assess man's impact on erosional and depositional processes operating within that basin. Basic data resulting from these studies, as well as complete descriptions of all study basins, are contained in Iwatsubo *et al.* (1975, 1976).

STUDY AREA

Water-and suspended-sediment discharge data from eight subbasins in the northern (downstream) third of the Redwood Creek basin (Fig. 1, Table 1) are included in this report. North coastal California is characterised by a Mediterranean climate with high, moderately intense, wintertime precipitation. Average annual rainfall is approximately 1800 mm in the eight study subbasins.

These basins are underlain by sandstone and quartz-mica schist of the Mesozoic Franciscan assemblage of Bailey and others (1964) (Table 1). Pervasive tectonic shearing has greatly increased the susceptibility of some sandstone units to deepseated slump-earthflow movement. These units are described in Table 1 as non-coherent. Average hillslope gradients range from 15.9 to 20.8 degrees.

The study basins are vegetated predominantly by redwood (*Sequoia sempervirens*) forest but prairie grass, brush, and grass-oak woodland comprise up to 10 percent of their area. Up to 87 percent of some basis is cutover timberland resulting from highly disruptive, large-scale tractor-yarded clear-cutting which began in the early 1960s (Table 1). The percentage of each basin which displayed a high amount of ground disruption at the time of study was measured from color infrared aerial photographs (Table 1).

High sediment yields from the study basins apparently result from a combination of complex mass-movement processes and fluvial erosion (Janda *et al.*, 1975) which occur in response to the interaction of climate, geology, and landuse.

The most visually apparent erosional landforms are active earthflows, streamside rock and debris slides, and gullies associated with road-concentrated drainage (Nolan *et al.*, 1976). Long-term annual suspended-sediment discharge for Redwood Creek at Orick (Fig. 1) has been estimated at 2100 t/km^2 per year by J.M. Knott (U.S. Geological Survey, written comm., 1975), using extrapolation of sediment-transport relations observed in Redwood Creek, and at 2540 t/km^2 per year by H.W. Anderson (1979) using a multiple-regression equation based on regional observations.

STUDY METHODS

Data gathered during periodic and synoptic sampling of water and suspended-sediment discharge during five successive water years have been used to estimate the degree to which man's activities have affected erosion rates within the Redwood Creek basin. Legislative requirements for rapid estimates of probable causes of resource degradation and lack of appropriate unharvested drainage basins precluded use of before-and-after paired-basin studies such as those listed by Fredriksen and Harr (1979).

Periodic measurements of water-and suspended-sediment discharge were taken at eight sites on seven different streams between October 1973 and September 1977, using standard U.S. Geological Survey techniques. Synoptic sampling was used to measure water and suspended-sediment discharge simultaneously in six of these streams during nine separate storms. Basins chosen for synoptic sampling were as similar as possible in geology, physiography, and natural vegetation but were in various stages of the cutover-regeneration cycle.

Sediment-transport characteristics of the study basins were compared using suspended-sediment transport curves (SSTCs) and values of total water and suspended-sediment discharge per unit area [WD/A in $(m^3/s)/km^2$ and SSD/A in $(tons/day)/km^2$] measured during synoptic sampling. Total WD/A and SSD/A for two storm seasons were also synthesised using mean daily values measured during synoptic events and mean daily values measured at Little Lost Man Creek, site of a continuous water-stage recorder.

Measurements of bedload transport using the Helley-Smith sampler were made at all study sites but have not been used in this report because the infrequency and variability of movement resulted in a small, hard-to-interpret data set. In cases where closely spaced measurements of both suspended-sediment and bedload discharge of acceptable accuracy were made, bedload discharge comprised between 20 and 60 percent of total sediment discharge (Janda, 1977).

Suspended-Sediment Transport Curves

SSTCs, as used here, are graphs of logarithmically transformed instantaneous values of WD/A and SSD/A. SSTCs for each of the eight tributary sites listed in Table 1 were described by linear relations determined by regression analysis. WD/A generally ranged through three log cycles and SSD/A through five cycles. SSD/A was used in these comparisons rather than suspended-sediment concentration because our

interest was in the role of suspended-sediment discharge, as an increment of total sediment discharge, in accounting for changing channel morphology and riparian habitat. This form of data presentation is also comparable to that developed by other authors in nearby terrane (Knott, 1971; Brown, 1973). Because of the interdependency caused by the presence of water discharge in both variables correlation tests of individual relations have no physical significance. Values of the coefficient of determination (R^2) and standard error of estimate provide only a general indication of the goodness of fit.

A pronounced increase in the slopes of the SSTCs commonly occurred between 0.11 and 0.17 $(m^3/s)/km^2$. Three changes in channel conditions appear to occur at about this discharge - (1) initiation of bedload transport results in removal of bed armoring, (2) flow reaches bank-to-bank stage and initiates widespread bank erosion, and (3) sediment stored behind small, unstable debris barriers is released to transport. Two separate regression equations were drawn to represent the data when such change in slope occurred. The lowest value of WD/A through which the upper relationship could be extended for all sites was 0.13 $(m^3/s)/km^2$. Comparison of SSTCs for different streams is based solely upon linear regressions developed for observations of WD/A equal to or greater than 0.13 $(m^3/s)/km^2$. Most sediment transport and all channel-sculpting flows occur above this discharge value.

SSD/A and WD/A associated with flows greater than 0.13 $(m^3/s)/km^2$ were fitted to the power function $y=Ax^B$ (Table 2). Many of these generalised relationships consist of internal relationships representing individual storms or even different hydrographic limbs of the same storm. SSTCs therefore describe generalised conditions and may not accurately characterise individual storms.

Comparison of SSTCs by analysis of covariance (Dixon and Massey, 1969) permitted testing the statistical significance of differences in SSD/A predicted for different sites at the same WD/A. This analysis tests for differences between regressions that describe SSTCs within groups by comparing slopes of individual regressions and mean SSD/A (dependent variable) after adjusting for differences in sampled ranges of water discharge. Adjustment of means is performed using a regression line common to all data. The significance of differences in slopes and adjusted mean SSD/A was tested against the F distribution. Regressions within a group were considered different if either the slopes or intercepts tested were found to be significantly different at the 95-percent confidence level.

Comparison of SSTCs

SSTCs of the studied streams were placed in four groups (Table 2). Groups I-III were defined by similarities in basin geology, size, and location and by contrasts in timber-harvest history (Table 2). Group IV is characterised by similarities in timber-harvest history and contrasts in

geology. Each group was analysed to estimate whether the primary within-group contrast (timber-harvest history for groups I-III and geology for group IV) was responsible for statistically different slopes of SSTCs and/or adjusted mean SSD/As. Results of the analysis of covariance for all groups are contained in Table 2.

Data in Table 2 indicate significant differences between adjusted mean values of SSD/A in all groups, but general similarity in slopes. The impact of recent timber harvest on adjusted mean SSD/A is shown by Groups I and III. Adjusted mean values for streams draining recently harvested terrane (Harry Wier, Miller, and Tom McDonald Creeks) were at least twice as high as those for the stream within the same group draining uncut or nearly uncut terrane (High Slope Schist and Hayes Creeks). The persistence of timber-harvest impact on adjusted mean SSD/A values is indicated by Group II. The adjusted mean SSD/A for the recovering basin of Lost Man Creek (logged more than 10 years prior to study) is 1.6 times greater than that from the nearly uncut basin of Little Lost Man Creek.

Group IV has been included to indicate the effect of geology on adjusted mean SSD/A by including streams in uncut or nearly uncut basins draining geologically different terrane. The adjusted mean SSD/A of Hayes Creek, 58 percent of which is underlain by noncoherent sandstone, is 28 times greater than the adjusted mean SSD/A value for High Slope Schist Creek, which is entirely underlain by schist. Geology therefore must be held as a constant factor when choosing stream groups for sediment-discharge comparison in this terrane. Twelve physiographic parameters listed by Iwatsubo *et al.* (1975, Tables 1 and 3) were analysed using multiple regression analysis to determine possible impacts on the variability of SSD/A. None of these twelve parameters was found to explain a significant amount of the variability in SSD/A, and they were not considered when forming stream groups for analysis of covariance.

Comparison of SSTCs for 20 streams in northwestern California by Janda and Nolan (1979), suggests that elevated levels of SSTCs (as inferred from higher adjusted SSD/A at low water discharges) for streams draining cutover areas reflect increased availability of readily transportable material. The similarity of slopes of SSTCs appears to suggest similar sediment-delivery mechanisms and therefore a lack of significant change in those mechanisms as a result of logging activities. This hypothesis is substantiated by field observations and photo-interpretive mapping (Nolan *et al.*, 1976) which show that although timber harvest greatly accelerated erosion, the erosional processes delivering sediment to major stream channels after timber harvest were the same basic mechanisms that had operated prior to timber harvest. Moreover, hydrologic and geologic parameters also influence slopes and levels of SSTCs elsewhere (Bauer and Tille, 1967).

Comparison of SSTCs of higher-order streams and those of lower-order tributaries with contrasting amounts of

harvesting in their basins indicates that timber harvest caused tributaries to become major sediment sources during periods of high water discharge. SSTCs of higher-order streams have, in general, higher levels at low WD/A values but lesser slopes than do SSTCs of their tributaries. Therefore, at high water discharges the SSTCs cross and their relative levels are reversed. For recently harvested tributary basins this reversal occurs at water discharges which can reasonably be expected to occur several times in a decade. SSTCs of unharvested tributary basins, however, have such low levels throughout the full range of reasonably expected water discharges that such reversal would not be expected to occur under present basin hydrologic conditions (Fig. 2).

Repetitive surveys of stream-channel cross-sections and other field evidence (Janda, 1978; Nolan, 1979) tend to substantiate the relationship displayed in Figure 2. This information indicates that during periods of low to moderate discharge much of the suspended sediment transported by the main channel of Redwood Creek is derived from channel scour and bank erosion along the main channel. However, during periods of high water discharge, main-channel aggradation occurs at tributary mouths because an excess of material is supplied by bank erosion, streamside landsliding, and scour in tributary channels draining recently harvested basins.

Synoptic Studies

Synoptic sampling was conducted at six sites during nine storms between 1974 and 1976. Hydrographs of these storms indicate that the percentage of precipitation appearing as storm runoff from basins harvested within five years prior to study was 1.3 to 12 times greater than that from the comparable nearly uncut basin of Hayes Creek (Table 3). Relative runoff differences were generally greatest during storms of low to moderate magnitude. The similarity in runoff during high magnitude storms is most likely due to the prevalence of saturated ground conditions throughout all basins, and thus to an equalisation of partial areas contributing to runoff. Similar conditions have been found by other authors (Fredriksen and Harr, 1979) working in similar terrane.

Runoff percentages from the partially revegetated basin of Lost Man Creek were generally higher than those from the nearly uncut, geologically comparable basin of Little Lost Man Creek except for Synoptic I, when unexplainable high runoff was measured from Little Lost Man Creek.

Field observations during synoptically sampled events indicate that large increases in surface compaction along roads and skid trails and in the number of seeps and springs along banks of road cuts were responsible for some of the increased runoff. Up to 46 percent of the ground surface of some study basins was highly disrupted by timber harvest and related road activity. These observations are supported by Bradford and Iwatsubo (1978), who in a study of water chemistry, found evidence for significantly greater overland flow in recently harvested basins during symoptic studies. Similarly, Lee *et al*. (1975), studying rainfall-runoff relations in the Redwood Creek basin, suggest that ground disruption due to timber harvest caused a 20-percent increase in annual runoff and even greater increased runoff for individual storms associated with moderate antecedent soil moisture conditions.

Values of SSD/A measured during synoptically sampled storms were consistently higher from recently harvested basins than from unharvested basins. During individual storms values of total SSD/A from Miller Creek were 3.8 to 70 times greater than SSD/A from Hayes Creek (Table 3). SSD/A values from Lost Man Creek were 1.8 to 5.1 times greater than values from Little Lost Man Creek.

Flow-duration curves were synthesised for each periodic-record station included in the synoptic sampling program by correlating mean daily water discharges measured during synoptic sampling with simultaneous mean daily water discharge determined at Little Lost Man Creek, which is equipped with a continuous stage recorder. The synthesised curves, plus the one calculated for Little Lost Man Creek, were then combined with mean daily SSTCs to compute total water and sediment discharge for the 1975 and 1976 storm seasons. These computations suggest that total runoff from recently harvested basins for the 1975 and 1976 storm seasons was roughly twice that from the unharvested basin of Hayes Creek (Table 3). This large difference in runoff reflects, in part, generally greater precipitation in the higher, more inland, recently harvested basins. During individual synoptically sampled storms average basin rainfall in Harry Wier Creek ranged from 0.75 to 1.6 times that in Hayes Creek. SSD/A values synthesised for the same period were between 8.4 and 17.5 times greater from recently harvested basins than from Hayes Creek. The synthesised SSD/A value for Lost Man Creek was twice that from Little Lost Man Creek.

CONCLUSIONS

Comparison of adjusted mean values of instantaneous SSD/A determined by analysis of covariance on relationships describing SSTCs suggest that the large-scale, highly disruptive timber harvest conducted in these inherently unstable basins probably increased values of SSD/A associated with values of WD/A above 0.13 $(m^3/s)/km^2$. The magnitude of this increase appears in many cases to have been at least twofold and to have persisted to some degree for at least a decade.

Comparison of the levels and slopes of SSTCs of studied streams, along with earlier reported field observations and studies of sequential aerial photographs, indicates that timber harvest has increased the amount of sediment readily available for transport by tributary streams without introducing new sediment delivery mechanisms, and that harvested tributary basins have become major sources of sediment during periods of high water discharge.

Comparison of total water and suspended-sediment discharge measured during synoptic sampling indicates nearly twofold increases in WD/A and tenfold increases in SSD/A following timber harvest. These effects appear to persist to some

degree for at least a decade. Post-logging increases in SSD/A estimated by the synoptic studies are greater than those estimated by comparison of adjusted mean values of SSD/A. This contrast exists because total values of SSD/A measured during synoptic sampling are the product of both increased water runoff and elevated levels of SSTCs. Runoff differences were removed by the analysis of covariance when comparing adjusted mean SSD/A values.

If erosion rates implied by observed differences in WD/A and SSD/A had persisted for long periods the present physiographic similarities between synoptic basins would not exist. By increasing runoff and making more sediment available to naturally existing delivery systems, recent timber harvesting probably accounts for a substantial part of the observed differences in WD/A and SSD/A.

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TABLE 1. Descriptive data for studied subbasins. Percentage of major rock types measured on maps by Harden et al (D. R. Harden, U.S. Geological Survey, written communication, 1979. Percentage harvested from Iwatsubo et al, 1975. Percentage highly disturbed are areas displaying bare mineral soil measured from color infrared aerial photographs. Station numbers are U.S. Geological Survey station identification numbers.

Station Name and Number	Drainage Area [km²]	Percent of major rock types in basin			Percent Harvested before 1968	Percent Harvested after 1968	Percent Highly Disturbe in 1976
		Coherent Sandstone	Non-coherent Sandstone	Schist			
High Slope Schist 11482140	1.37	--	--	100	0	0	0
Harry Wier Creek 11482225	7.67	40	40	20	0	44	35
Tom McDonald Creek 11482230	17.8	--	--	100	80	6	27
Miller Creek 11482250	1.74	44	56	0	0	87	39
Miller Creek at mouth 11482260	3.52	19	56	22	0	77	46
Hayes Creek 11482330	1.58	36	58	1	4	0	1
Lost Man Creek 11482450	10.3	100	--	--	87	0	15
Little Lost Man Creek 11482468 and 11482470	8.96 1/	100	--	--	6	0	2

1/ Station 11482470 was moved approximately 0.4 km upstream at the end of the 1974 water year.

TABLE 2. Descriptive statistics for relationships describing individual SSTCs and analysis of covariance results.

Stream Name	N	Range in Sampled WD/A [(m^3/s)/km^2]	A	B	r^2	Standard Error of Estimate	Adjusted mean SSD/A [(t/day)/km^2]	95% Confidence limits about Adjusted mean (Upper)	95% Confidence limits about Adjusted mean (Lower)	F Similarity of means	F Common Slope
	Individual relationships $y=Ax^B$						Analysis of covariance results				
Group I - Stream draining non coherent sandstone terrane											
Harry Wier Creek	68	0.001→1.03	206	3.03	0.84	0.292	2.21	2.65	1.84	21.39	0.00
Miller Creek at mouth	53	0.006→0.76	405	3.07	0.68	0.336	3.84	4.83	3.05		
Hayes Creek	21	0.010→0.55	73.8	2.78	0.60	0.467	1.11	1.53	0.80		
Group II - Stream draining coherent sandstone terrane											
Little Lost Man Creek	60	0.002→2.1	51.3	2.95	0.89	0.357	0.77	0.88	0.67	19.52	0.00
Lost Man Creek	51	0.001→2.8	75.5	2.89	0.91	0.195	1.24	1.43	1.08		
Group III - Stream draining schist terrane											
High Slope Schist Creek	5	0.025→0.62	1.80	2.50	0.99	0.096	0.07	0.27	0.02	57.68	0.00
Tom McDonald Creek	10	0.004→0.88	155	2.52	0.54	0.551	5.81	12.05	2.80		
Group IV - Streams draining unharvested or nearly unharvested terrane											
High Slope Schist Creek	5	0.025→0.62	1.80	2.50	0.99	0.096	0.05	0.12	0.02	40.8	0.31
Hayes Creek	21	0.010→0.55	73.8	2.78	0.60	0.467	1.39	1.95	0.99		
Little Lost Man Creek	60	0.002→2.1	51.3	2.95	0.89	0.357	0.75	0.90	0.62		

TABLE 3. Water and suspended-sediment yield for synoptically studied basins during synoptic and synthesized flow periods.

STATION NAME AND NUMBER	SYNOPTIC (TONS PER SQUARE KILOMETER / RUNOFF(mm) (PERCENT RUNOFF))									SYNTHESIZED
	I	II	III	IV	V	VI	VII	VIII	IX	
Harry Wier Creek 11482225	45.5 28 (42)	2.0 8 (13)	0.84 3 (12)	2.5 24 (68?)	0.04 1 (2)	0.1 2 (5)	0.67 3 (10)	7.7 8 (18)	0.74 1 (6)	305 2210
Miller Creek 11482250	30.1 30 (51)	1.6 8 (13)	1.0 1 (1)	1.4 7 (20)	0.05 1 (4)	0.7 3 (7)	0.91 2 (9)	4.9 10 (23)	0.92 1 (6)	235 2515
Miller Creek at mouth 11482260	59.5 23 (42)	1.3 5 (13)	1.6 5 (17)	3.1 8 (22)	0.05 1 (5)	0.7 3 (7)	2.03 2 (7)	24.5 9 (21)	0.53 1 (6)	490 2311
Hayes Creek 11482330	-- 13 (33)	0.07 1 (2)	0.21 1 (1)	0.46 1 (3)	0.00 1 (1)	0.00 1 (2)	0.04 1 (3)	0.35 4 (10)	0.14 1 (4)	28 1270
Lost Man Creek 11482450	11.6 28 (48)	-- -- --	0.42 13 (53)	1.37 3 (9)	0.00 1 (2)	0.07 3 (7)	0.32 4 (17)	2.28 9 (31)	0.71 3 (11)	108 2337
Little Lost Man Creek 11482468 & 11482470	6.6 46 (100?)	-- -- --	0.21 1 (1)	0.42 4 (9)	0.00 1 (1)	0.04 1 (3)	0.11 2 (7)	0.88 6 (15)	0.14 2 (6)	52 2108

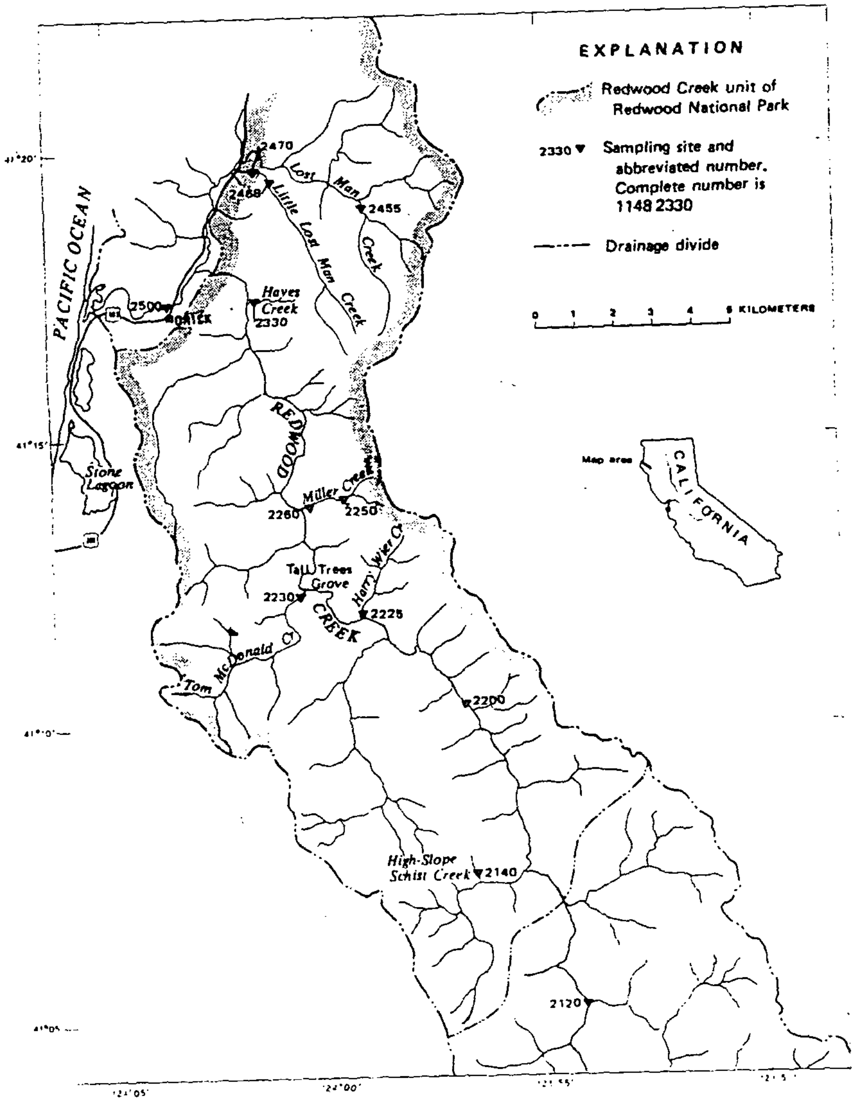

FIGURE 1. Location of sampling sites in the Redwood creek basin.

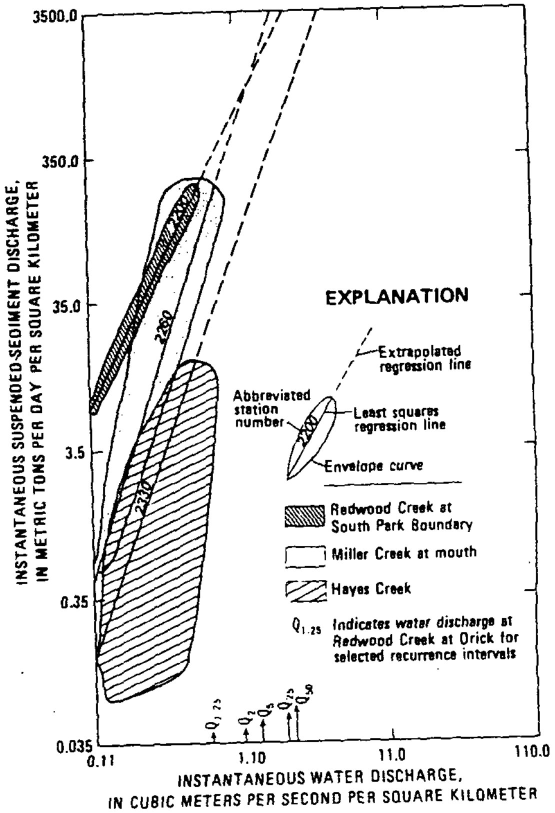

FIGURE 2. Sediment-transport relationships for the main channel of Redwood Creek at South Park Boundary and for tributary streams (Miller Creek at mouth and Hayes Creek) showing envelope curves around actual data points and extrapolation of developed relations. Extrapolation of SSTCs beyond actual observations appears reasonable up to at least Q_{25}. No change in slope was found, up to Q_{25}, in the upper ends of the SSTCs for main channel or tributary sites for which data exist (Janda, 1978, p.53).