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Logging Effects on Streamflow: Water Yield and Summer Low Flows at Caspar Creek in Northwestern California

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Streamflow data for a 21-year period were analyzed to determine the effects of selective tractor harvesting of second-growth Douglas fir and redwood forest on the volume, timing, and duration of low flows and annual water yield in northwestern California. The flow response to logging was highly variable. Some of this variability was correlated with antecedent precipitation conditions. Statistically significant increases in streamflow were detected for both the annual period and the low-flow season. Relative increases in water yield were greater for the summer low-flow period than for annual flows, but these summer flow increases generally disappeared within 5 years.

INTRODUCTION

In rain-dominated portions of the Pacific Northwest, annual water yield may be enhanced by the removal of forest vegetation from small upland watersheds. Yet questions and misconceptions linger regarding the effects of logging operations on streamflow under the variety of climatic, physiographic, and vegetative conditions of this region. Timber harvesting impacts have not been fully evaluated for the coastal region of northern California.

Previous studies at the Caspar Creek paired watersheds, near Fort Bragg in northern California, investigated the impacts of selected harvest of a second-growth Douglas fir and redwood forest on peak streamflow [*Ziemer,* 1981; *Wright,* 1985], hydrograph lag time [*Sendek,* 1985], and sediment production [*Rice, et al.,* 1979]. However, the effect of logging and related factors upon summer low-flow quantity and timing at Caspar Creek was not evaluated.

Vegetation affects the proportion of precipitation that is evaporated and transpired and, consequently, the amount available for soil moisture storage, groundwater recharge, and dry weather streamflow. The proportionate contribution of precipitation to streamflow varies by the manner in which interception and evapotranspiration are influenced by vegetation type, development, rooting depth, and health.

Research on upland watersheds indicates that water yield can be augmented by vegetation removal [*Ponce and Meiman,* 1983]. However, responses to treatment are highly variable and depend on the particular watershed system studied [*Hewlett and Hibbert,* 1967].

Logging operations alter the conditions and processes involved in the generation of streamflow. Most notably, evapotranspiration is reduced by the removal of forest vegetation. Also, soil characteristics are inevitably modified by the construction of roads, landings, and skid trails that accompanies timber harvesting, particularly when ground skidding is used [*Stone,* 1977]. Localized soil disturbances associated with this construction include reduced infiltration capacity, increased bulk density, and a conversion of soil macropores to micropores. In addition, soil drainage patterns may be altered. Although the impacts of road construction and tractor logging on soil surfaces have been documented by substantial research, the effects of these activities on the generation of streamflow are not fully understood [*Sendek,* 1985].

In reviewing the results of catchment studies at 11 locations in western Oregon and western Washington, *Harr* [1979] reported annual water yields that increased as much as 62 cm following timber harvest, while summer low flows as much as quadrupled. This difference implies reduced evapotranspiration and greater soil moisture levels on the logged basins. These increased water yields diminished with revegetation, with annual flows returning to pretreatment levels within 4-5 years.

A time duration model predicts streamflow increase for a regrowing eastern forest [*Douglass and Swank,* 1972]:

$$Q_i = a + b\,(\log\ T_i)$$

where Q_i is the increase in flow year i, a is the first-year increase, T_i is the ith year after treatment, and b is a negative coefficient. A similar relationship could hold in other regions. As a gross index of revegetation and renewed interception and evapotranspiration losses, time since logging has been identified as the most important variable in explaining water yield increases in the Pacific Northwest region [*Harr,* 1979].

Harvest Practices

Hibbert [1967] reported increases in streamflow proportional to the amount of cover removed. Partial cutting is less effective than clearcutting at augmenting streamflow [*Rothacher,* 1971]; partial cutting may actually enhance water use by the trees and understory vegetation that remain [*Kittredge,* 1948]. *Greenwood et al.* [1985] concluded that reduced evapotranspiration from overstory vegetation following clearing may be strongly countered by increased evapotranspiration from the understory due to increased availability of energy and soil water.

Site Conditions

Site conditions are an important factor influencing streamflow response to the removal of vegetation. Streamflow increases in watersheds with soil and topographic conditions favorable for tree growth are smaller and diminish faster than those in watersheds with less favorable conditions,

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owing to the prompt recovery of the forest [*Nakano,* 1967]. Water yield increases in the Pacific Northwest are short-lived because of favorable conditions that support rapid regrowth of forest and other vegetation [*Harr,* 1983]. At the H.J. Andrews Experimental Forest east of Eugene, Oregon, annual water yield increases were similar after clearcutting 130 and 450-year-old Douglas fir forests [*Harr et al.,* 1982].

Precipitation

Annual precipitation influences the magnitude of water yield increases that follow timber harvest operations in forested watersheds. Greater increases are found in wetter years [*Harr,* 1979; *Ponce and Meiman,*1983]. *Bosch and Hewlett* [1982] suggest that streamflow response also depends on the mean annual precipitation of the area. Increases are generally greatest in areas of high rainfall, but they are short-lived due to rapid regrowth of vegetation. According to *Bosch and Hewlett* [1982], actual precipitation is influential only in low-rainfall areas, In high-rainfall areas they found water yield changes as a result of treatment were independent of actual precipitation. This view contradicts those of *Harr* [1979] and *Ponce and Meiman* [1983].

Season

As an indicator of potential evapotranspiration, season is an important variable that affects the streamflow response to logging. Seasonal analyses of yield increases on experimental forests in western Oregon by *Rothacher* [1970], *Harr et al.* [1979], and *Ingwersen* [1985] indicate that most of the increases in annual water yield in response to logging occurs in the October-March rainy season. Logging reduces transpiration during the growing season, as well as interception losses. Soil on logged watersheds has a relatively high moisture content at the onset of the rainy season in comparison to uncut watersheds, requiring less rainfall to recharge soil moisture levels, thus allowing more precipitation to become available for streamflow. *Ziemer's* [1981] analysis of peak flows on the Caspar Creek watershed supports this explanation. *Douglass and Swank* [1975] presented the same explanation in their study of eastern forest watershed responses to deforestation, but the timing of yield increases was different. Relative to prelogging summer flow patterns, logging-related streamflow increases in the eastern forests were negligible until June, increased as the growing season advanced, and peaked in September. During the growing season, the East Coast is wetter than the West Coast.

In the Pacific Northwest the greatest relative increases in streamflow have been observed during the summer season, although in absolute terms, larger increases have occurred during the rainy season. These summer increases are short-lived, however, lasting only 2-3 years [*Harr,* 1979]. The number of low-flow days (where streamflow has fallen below some preset threshold value) was used to evaluate flow changes in the Alsea Watershed Study in the Oregon Coast Range; fewer low-flow days were found after logging [*Harr and Krygier,* 1972].

Fog Interception Processes

An important contradiction to the pattern of increased flows after logging was observed in the Fox Creek watershed study within Portland's Bull Run municipal watershed, where a small decrease in annual water yield was noted. After timber harvest, the number of low-flow days increased, suggesting summer flows were actually reduced as a result of logging. *Harr* [1980] hypothesized that this anomaly was the result of reduced fog drip interception after clearing the forest. In a subsequent study, as much as 44% more net precipitation was measured in late spring and summer beneath the forest canopy than in a clearing. During two fall seasons, differences of 18 and 22% were observed [*Harr,* 1982]. Within the forest, fog drip accounted for roughly one third of all precipitation for the May-September period. *Harr* concluded that in addition to offsetting canopy interception and evaporation losses, fog drip at this site may have provided about 50 cm additional water to the forest floor.

Subsequent analysis of recent streamflow data from the Fox Creek experimental watershed indicates that a recovery has occurred from the harvest impacts on summer water yield due to loss of fog drip [*Ingwersen,* 1985]. These results suggest that by the elimination of fog drip through the removal of forest vegetation, anticipated enhancement of summer flows may not be realized in areas where fog occurrence is a frequent source of significant moisture. The occurrence of fog and its role in influencing moisture conditions in coastal California and Oregon has been well documented, lending support to the hypothesis that significant amounts of moisture can be delivered in areas with a high frequency of advected fog [*Byers,* 1953; *Oberlander,* 1956; *Azevedo and Morgan,* 1974; *Goodman,* 1985]. Summer fog is common in the Caspar Creek watersheds.

This paper analyzes streamflow data at Caspar Creek in northwestern California over a 21 -year period to determine the effects of logging and related factors upon low flows and annual water yield.

STUDY AREA AND TREATMENTS

The study watersheds (North and South Forks of Caspar Creek) are located in the Jackson Demonstration State Forest, 11 km southeast of Fort Bragg, California, and about 7 km from the Pacific Ocean (Figure 1). The North and South Forks of Caspar Creek drain watersheds having areas of 483 and 424 ha, respectively. The elevation of the watersheds ranges from 37 to 320 m. Topography of the North and South Fork watersheds runs from broad, rounded ridge tops to steep inner gorges. The median side slope of the watersheds is 20". Watershed soils formed in residuum derived predominantly from sandstone and weathered coarse-grained shale of Cretaceous age. Soils are well drained, having high saturated and unsaturated hydraulic conductivities [*Wosika,* 1981]. The climate is Mediterranean, having dry summers with coastal fog. Summer temperatures are mild, ranging from 10^o to 25^oC. Winters are mild and wet, with temperatures ranging from between 5^o and 14°C and a rainfall average of about 1200 mm per year [*Ziemer,* 1981]. Caspar Creek does not receive any appreciable snowfall.

The North and South Forks of Caspar Creek were originally clearcut logged and burned in the late 1800s, the North Fork about 15 years after the South Fork [*Tilley and Rice,* 1977]. Since then, fairly dense stands of second-growth redwood *(Sequoia sempervirens* (D. Don) Endl.) and Douglas fir *(Pseudotsuga menziesii* (Mirb.) Franco) developed, with some associated western hemlock *(Tsuga heterophylla*

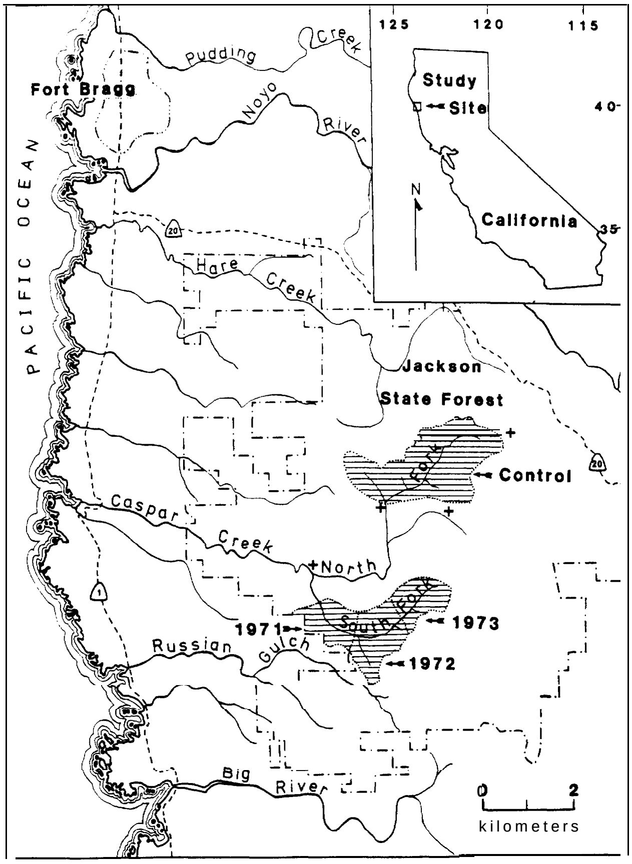

Fig. 1. Caspar Creek experimental watersheds: North Fork (control) and South Fork (areas logged each year are indicated).

(Raf.) Sarg.) and grand fir (*Abies grandis* (Dougl.) Lindl.). At the onset of the study, timber volume of both watersheds was estimated at about 700 m^3 ha^{-1} [*Krammes and Burns,* 1973]. The North Fork was selected as the control watershed because its timber was younger. Road location and construction, and timber harvest practices in the South Fork were designed to meet standards that were considered “state of the art” but also considered commercially acceptable by the local timber contractors.

Construction of stream gauging stations on both forks was completed in the summer of 1962. Flow was measured with compound weirs consisting of a 6.1 m x 0.91 m rectangular sharp-crested weir superimposed upon a 0.61 m 120° v notch weir. Precipitation was estimated from four weighing rain gauges.

Both watersheds were monitored in an undisturbed condition during hydrologic years (October-September) 1963-1967. Road construction in the summer of 1967 was monitored through hydrologic year 1971 when logging began. Logging effects were followed through hydrologic year 1983.

Of the total 6.8 km of road constructed in the South Fork watershed during the summer of 1967, 6 km were within 61 m of the stream. Coarse debris, resulting largely from right-of-way clearing, was removed from the stream and from along the stream banks after road construction [*Krammes and Burns,* 1973]. The roads (including cut and fill slopes) occupied 19 ha (4.5% of the total watershed area) from which 993 m^3 ha^{-1} of timber was removed.

About 110 m of stream bed were disturbed by tractor operation directly in the stream. These areas were primarily around bridge crossings, landings, and in a stretch where the stream was cleared of debris deposited during the road construction. All fill slopes, landings, and major areas of soil exposed by the road building were fertilized and seeded with annual ryegrass in September 1967. The grass was well established before the first rains in November [*Jackman and Stoneman,* 1973].

Logging, which began on the South Fork of Caspar Creek during the summer of 1971, continued over a three-year period. The South Fork watershed was divided into three sale areas. Selective cutting started at the weir and progressed up the watershed on successive years. All logging was done by tractor, but many of the skid trails did not have adequate cross drains installed. By the completion of logging over 15% of the watershed was in roads, landings, and skid trails and considered heavily compacted.

The area of the first sale was 101 ha from which 59% of the stand volume was harvested. The following summer, 69% of the volume was taken from a 128-ha area. During the final summer, 65% of the volume was cut on the remaining 176 ha of the South Fork watershed. In aggregate, road construction and harvesting removed 67% of the timber volume (nearly 200,000 m^3). No cultural measures were taken to foster regeneration. Consequently, most of the regrowth was either true fir seedlings or redwood sprouts. The residual stand did not respond vigorously to the reduced competition resulting from logging.

DATA ANALYSIS

In the present study the low-flow season was defined as the part of each year when the flow response from Caspar Creek was predominated by base flow rather than storm flow or quick flow processes. The great variability in the arrival and cessation of the rainy season each year precludes the use of a constant starting and ending date for the low-flow season throughout the study period. Defining the starting and ending dates of the low-flow season in terms of a moisture index is more meaningful than using arbitrary preset dates.

The source of summer flow was groundwater and soil moisture storage. Lacking actual records of this storage component, an indirect measure of ground and soil water levels was needed.

Soil moisture and runoff levels were indexed by an antecedent precipitation index (API), using precipitation data and the exponential law of decay [*Ziemer,* 1984]. The antecedent precipitation index is defined as

$$\mathrm{API}_i = K * \mathrm{API}_{i-1} + P_i$$

where API_i, is the index value, P_i is the precipitation occurring on the ith day of the calculation, and K is the recession factor ($K \leq 1$). A recession factor of 0.97 was found to satisfactorily predict hydrograph response at Caspar Creek.

The low-flow season began and ended when the daily API fell below and exceeded, respectively, a threshold value of 10 cm. From this definition, each “API year” in the study period began at the end of the preceding low-flow season and continued through the final day of the current low-flow season. The starting dates of the low-flow season were found to correspond with a North Fork flow of approximately 28 L s^{-1}.

TABLE 1. Streamflow Variables (Dependent Variables)

Name	Definition
	Basic Variables
SUMVOL	the total flow volume for the low-flow period, defined in terms of an antecedent precipitation index or roughly corresponding to that period when the North Fork mean daily flow was less than 28 L s^{-1}, 1000 m^3
TOTVOL	the total flow volume for the low-flow season and the preceding rainy season, i.e., the total flow volume for the API year, 1000 m3
PARTVOL	the ratio of total summer flow volume to total API year flow volume, i.e., SUMVOL/TOTVOL
LOFLOZ	the number of days during the low-flow season when the mean daily flow rate is less than 5.66 L s^{-1}, days
START	the mean daily flow rate on the first day of the low-flow season, L s^{-1}
END	the mean daily flow rate on the final day of the low-flow period, L s^{-1}
	Ratio Variables
SUMVOLSN	ratio of difference between seasonal flow volume (SUMVOL) on the South and North Forks ((SF-NF)/NF)
TOTVOLSN	ratio of difference between annual flow volume (TOTVOL) on the South and North Forks ((SF-NF)/NF)
PARTVOLSN	ratio of difference between proportionate seasonal flow volume (PARTVOL) on the South and North Forks ((SF-NF)/NF)
LOFLOZSN	ratio of difference between the number of "low-flow days" for the season (LOFLOZ) on the South and North Forks ((SF-NF)/NF)
STARTSN	ratio of difference between the start-of-season rate of flow (START) on the South and North Forks ((SF-NF)/NF)
ENDSN	ratio of difference between the end-of-season rate of flow (END) on the South and North Forks ((SF-NF)/NF)

Twelve dependent variables were developed to evaluate the streamflow process and changes after logging: six basic variables and six difference ratio variables (Table 1). The data were divided into two classes for analysis: prelogging (1963-1970) and postlogging (1971-1983). The postroad construction years (1967-1970) were included in the prelogging group. Previous Caspar Creek studies found that road construction activities did not alter the hydrologic response of the basin during winter to a statistically detectable extent [Ziemer, 1981; *Sendek,* 1985].

For each of the six basic streamflow variables a simple linear regression model was developed for the prelogging calibration period and the posttreatment period, respectively. Ninety-five percent prediction limits [*Neter et al.,* 1983] were calculated to determine if the postharvest responses were within the range predicted by the calibration relationships. This calculation was done both to test the magnitude of the impacts of the logging operations on streamflow and to determine the duration of statistically significant changes in the summer flow response at Caspar Creek. All statistical tests were performed at the 0.05 significance level.

Multiple regression analysis was used to identify which management and climatic variables might be most influential in affecting the extent and duration of changes in summer flow processes at Caspar Creek. To study the relative change between the two watersheds, a difference ratio was chosen for the dependent variables (Table 1).

A large set of potential independent variables was organized into four categories: logging, precipitation, antecedent precipitation, and general climatic norms. From this set, 15 of the most promising variables were selected for further analysis (Table 2).

An all-possible-subsets regression procedure was used to examine possible regression models and identify "good" models. No single statistical criteria was solely relied upon in choosing the "best" model. Test criteria included Mallow's Cp [*Daniel and Wood,* 1971], the adjusted coefficient of multiple determination R_a^2, the overall F test for the existence of a regression relation, the partial F test for the marginal reduction in variance associated with each additional variable, and graphical analysis of residuals [*Neter et al.,* 1983]. The correlation matrix derived earlier was also used to check for interdependencies among included independent variables. In addition, the signs of the regression coefficients were considered in relation to the simple correlation coefficient of that variable to the dependent streamflow variable and in relation to the expected directional influence of that variable. By this both objective and subjective process the preferred descriptive regression model was chosen for each of the streamflow ratio variables examined.

RESULTS

Effects of Logging on Streamflow Parameters

The simple linear regressions for the calibration period of the six South Fork basic streamflow variables on those of the North Fork yielded significant relationships at the 0.005 significance level or smaller (Table 3).

For the postlogging period the relationships between the North Fork and South Fork streamflow variables were more variable. Five of these regressions were significant at the 0.025 significance level or smaller (Table 3). No significant relationship could be detected between the North and South Forks for the number of low-flow days (LOFLOZ) after logging.

Posttreatment South Fork observations that fell outside of the prediction limits calculated for the pretreatment calibration regression (at 0.05 significance level) were judged to be significantly different than the expected value (Figures 2-7). While a lack of consistently significant alterations of the streamflow response is apparent, the figures provide some evidence of enhanced streamflow beginning in 1972.

The total annual flow volume (TOTVOL) measured at the South Fork weir (Figure 2) increased during the period from 1973 to 1982, ranging from an additional 7 to 34% of the expected flow. In absolute terms this increase in volume amounted to an additional 2.3 x 10^5 to 9.9 x 10^5 m^3 of water each year (an average of 4 x 10^5 m^3 per year or a 15% increase).

The volume of streamflow recorded at the South Fork weir during the low-flow (summer) season (SUMVOL) ranged from 14 to 55% greater than the predicted value for the

TABLE 2. Independent Variables Developed for Use in the Multiple Regression Analysis

Name	Definition
	Logging Variables
%AC	percent of watershed area compacted; includes road, landing, and skid trail areas
%ADF2	cumulative percent of area harvested by selection method, employing an exponential decay function to model recovery of vegetation water use with time after logging; half-life of recovery estimated at 3.5 years
	Precipitation Variables
PPTSEAS	total measured precipitation for the low-flow season, cm
TRD/TD	number of days with recorded precipitation during the API year divided by the length of the API year in days*
SRD/SD	number of days with recorded precipitation during the low-flow season divided by the length of the low-flow season in days
SRD/TRD	number of days with recorded precipitation during the low-flow season divided by the total number of days with recorded precipitation
	Antecedent Precipitation Variables
LENYR	length of the API year, days
LENSEAS	length of the low-flow season, days
APIYR	cumulative daily antecedent precipitation index for the API year, cm
APISEAS	cumulative daily antecedent precipitation index for the low-flow season, cm
MINAPI	minimum one-day antecedent precipitation index for the low-flow season (and API year), cm
MAXAPI	maximum one-day antecedent precipitation index for the API year, cm
PREAPI	cumulative daily antecedent precipitation index for the preceding API year, cm
	Solar Radiation Variables
HRLIT	estimated total possible daylight for the low-flow season based on times of sunrise and sunset at 39°N latitude, hours†
MLYDAY	estimated normal mean daily incoming radiation for the low-flow season. Total estimated normal incoming radiation for the low-flow season divided by the length of the low-flow season, langleys/day

*The API year begins at the end of the preceding low-flow period and continues through the final day of the current low-flow period. Thus it includes the "winter" or "rainy" season as well as the low-flow season.

†*U.S. Naval Observatory* [1946].

period 1972-1978. The increases during the 1972, 1974, 1975, and 1978 seasons were statistically significant (Figure 3). The greatest percent increase occurred in 1978, although in absolute terms the largest increase, 9 x $10^4 m^3$, occurred in 1974. For the 7-year postlogging period from 1972 through 1978, SUMVOL increased an average of 29%, or an additional 5 x $10^5 m^3$ per low-flow season, compared to the prelogging period. During the 1981 season a statistically significant decrease, 27% in summer flow was detected. A 19% decrease was observed in 1983, but this was not found to be significant.

To investigate change in the seasonal distribution of streamflow volume on the South Fork following logging, the variable PARTVOL (SUMVOL/TOTVOL) was analyzed (Figure 4). The proportionate summer flow volume relative to annual flow volume exceeded the predicted value for the years 1972-1975 and 1978, with 1972 being significantly greater. For the years 1976 and 1979-1983 the observed value fell below the predicted value, with 1981 being significantly lower.

The number of low-flow days (LOFLOZ), days with mean daily flow rates of less than 5.66 L s^{-1}, was consistently fewer than predicted following logging (Figure 5). From 1972 through 1978, LOFLOZ averaged 43 fewer days than predicted, a 40% decrease. Between 1979 and 1983 the number of low-flow days returned to that observed before logging.

The rate of flow at the onset of the low-flow season (START) generally increased after logging the South Fork, with the increases significant for the years 1973-1976, 1982, and 1983 (Figure 6). The maximum increase occurred in 1974 when the flow rate was 46% (13 L s^{-1}) higher than predicted. From 1973 to 1983 the observed rate of flow averaged 25% above the predicted rate.

Beginning in 1973 and continuing through the end of the study period, the observed end-of-season flow rate (END) was greater than the predicted value, but only for the years

TABLE 3. Calibration and Posttreatment Regression Coefficients

	Calibration			Posttreatment		
Variable	b_0	b_1	F	b_0	b_1	F
TOTVOL	120.70	0.85	287*	423.20	0.85	323*
SUMVOL	-39.43	1.51	64*	11.20	1.25	8‡
PARTVOL	0.01	1.12	31†	0.02	0.94	21†
LOFLOZ	-43.20	1.22	63*	10.34	0.57	3 ns
START	8.11	0.53	50*	4.08	0.83	36"
END	-8.02	1.61	1032*	-39.98	3.09	48*

Regression not statistically significant at the minimum 0.050 significance level, ns.
*Regression significant at the 0.001 significance level.
†Regression significant at the 0.005 significance level.
*Regression significant at the 0.025 significance level.

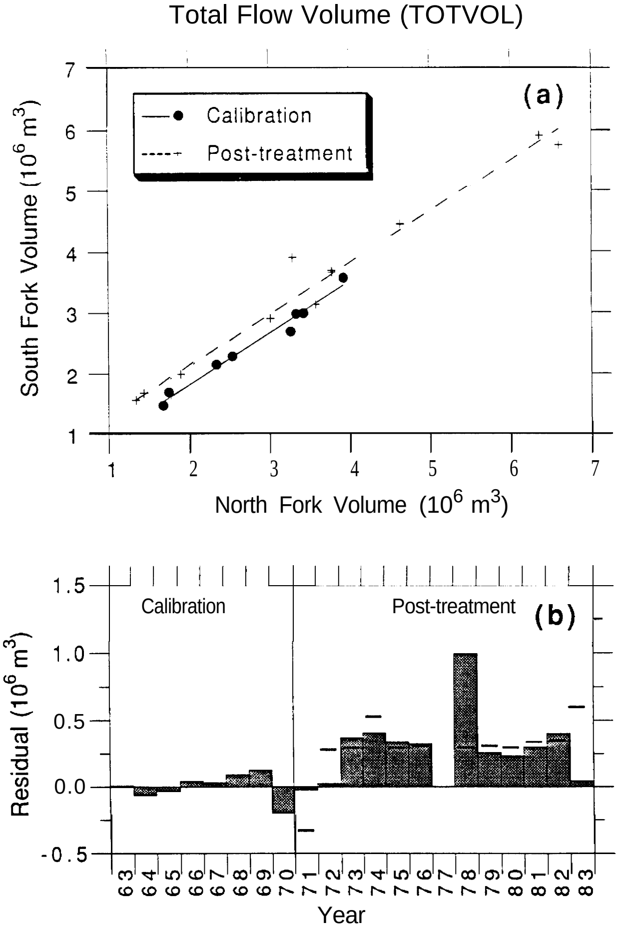

Fig. 2. Results of linear regression for North Fork and South Fork total annual flow volumes: the low-flow season plus the preceding rainy season (TOTVOL). *(a)* Calibration and posttreatment periods. *(b)* Residuals for calibration period and deviations from calibration regression for posttreatment period. Horizontal bars indicate the 95% prediction limits for posttreatment years.

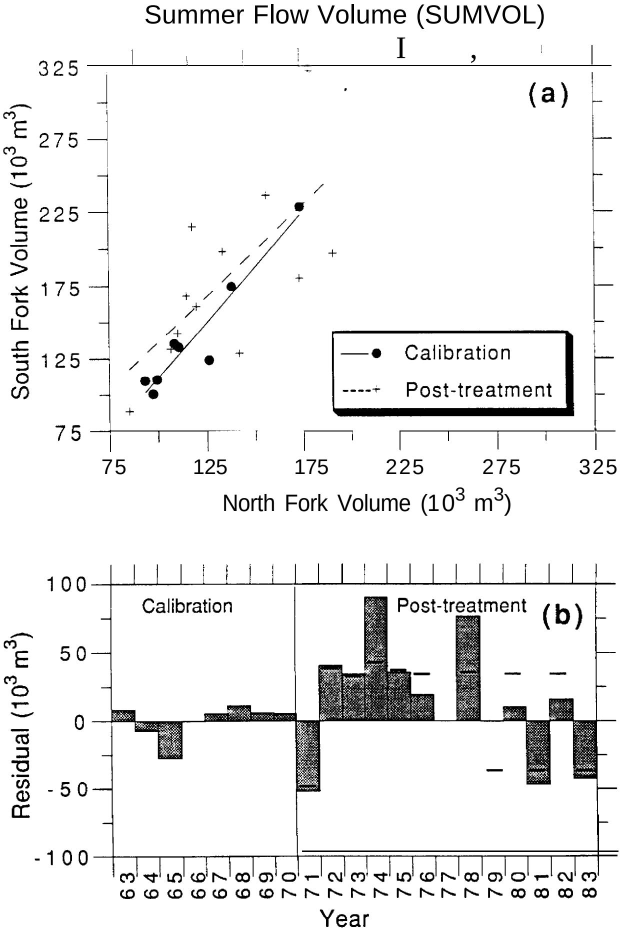

Fig. 3. Results of linear regression for North Fork and South Fork total low-flow season volumes (SUMVOL). *(a)* Calibration and posttreatment periods. *(b)* Residuals for calibration period and deviations from calibration regression for posttreatment period. Horizontal bars indicate the 95% prediction limits for posttreatment years.

1974, 1975, 1977, and 1978 was this increase significant at the 0.05 significance level (Figure 7). The final day of the season occurs when the daily API again exceeds the low-flow season API threshold, that is, substantial precipitation triggers the end of the low-flow season. The increase averaged 87% and ranged from 6% (1979) to 178% (1976). In absolute terms the maximum increase occurred in 1974 when the observed flow rate was 382 L s^{-1} greater than predicted by the prelogging calibration regression. During other years this increase varied from 2 L s^{-1} in 1979 to 250 L s^{-1} in 1978 and averaged 63 L s^{-1}.

Factors Associated With Variations in the Streamflow Response

Multiple linear regression analysis was used to further examine the alteration of the streamflow pattern after timber harvest and to identify factors that were significant in determining differences between the South Fork and North Fork streamflow response. The 0.05 significance level was used for testing the significance of each additional variable (Table 4).

The logging variable, cumulative percent of area logged (%ADF2), was the most significant independent variable associated with five of the six dependent variables. For the sixth dependent variable, annual flow volume differences (TOTVOLSN), the percent of the South Fork watershed area compacted by roads, landings, and skid trails (%AC) was the most significant independent variable. These variables indicated that an enhancement of the South Fork flow was associated with forest harvesting operations.

The antecedent precipitation variables significantly improved the prediction of relative differences between the two streams. High antecedent moisture conditions preceding (PREAPI) and during (APIYR) the hydrologic year were related to an increase in the South Fork flow relative to the North Fork.

When seasonal precipitation (PPTSEAS) during the low-flow season was high, the South Fork flow level was enhanced relative to the North Fork. However, as the proportion of the season's days having recorded precipitation (SRD/SD) increased, which may be viewed as an index of cloud cover, the two streams responded more similarly.

Roads, Landings, and Skid Trails

By the completion of timber harvest operations in 1973, 15% of the South Fork watershed was occupied by roads, landings, and skid trails.

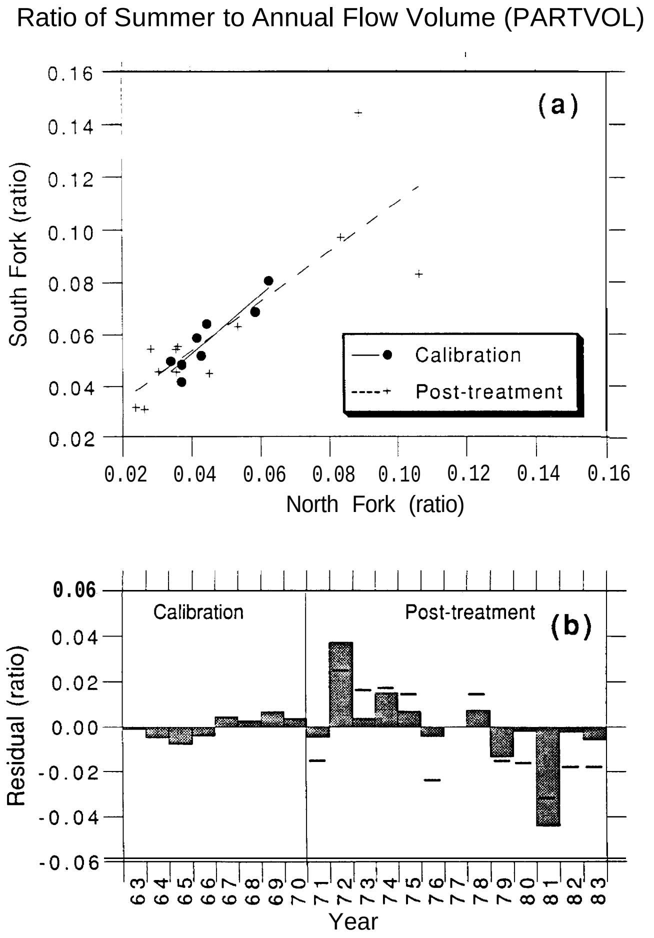

Fig. 4. Results of linear regression for North Fork and South Fork ratios of total low-flow season flow volume to total annual flow volume (PARTVOL). *(a)* Calibration and posttreatment periods. *(b)* Residuals for calibration period and deviations from calibration regression for posttreatment period. Horizontal bars indicate the 95% prediction limits for posttreatment years.

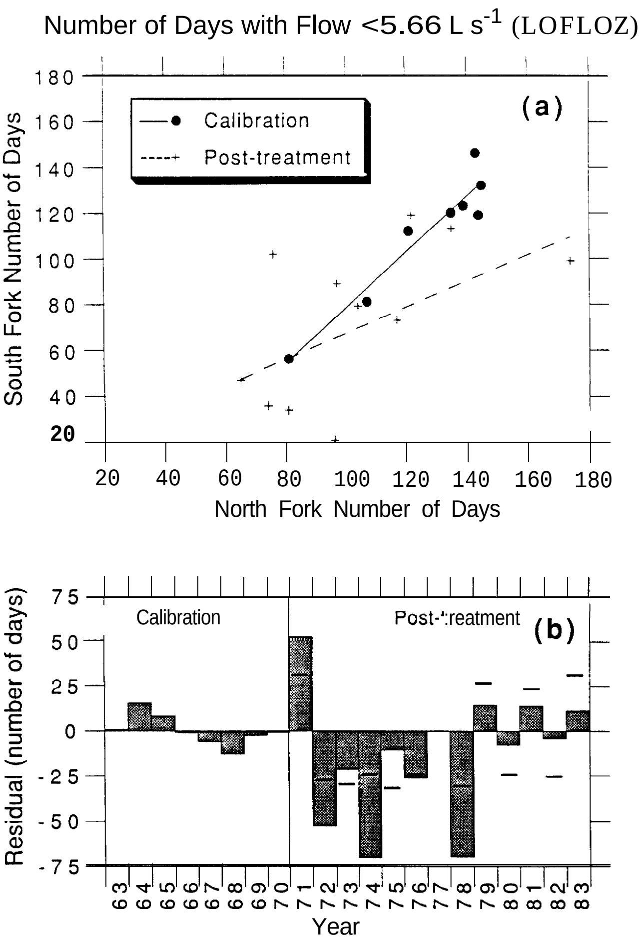

Fig. 5. Results of linear regression for North Fork and South Fork number of low-flow days when the mean daily flow was less than 5.66 L s^{-1} (LOFLOZ). *(a)* Calibration and posttreatment periods. *(b)* Residuals for calibration period and deviations from calibration regression for posttreatment period. Horizontal bars indicate the 95% prediction limits for posttreatment years.

High rates of infiltration, typical of forest soils in the coastal Pacific Northwest, generally preclude the occurrence of overland flow except for areas of bare rock or extremely shallow soil and intermittent channels [*Harr*, 1979]. This condition seems to be characteristic of the Caspar Creek site. Finding no consistent increase in winter storm peak flows, *Ziemer* [1981] reasoned that precipitation continued to infiltrate and supply subsurface flow and that compaction from the construction of the transportation network at Caspar Creek did not result in significantly reduced infiltration for the overall watershed.

Subsequently, *Sendek* [1985] reported evidence that streamflow response to precipitation at Caspar Creek became quicker and more efficient after logging. We found that an increase in annual flow volume, which averaged 15% above the predicted volume, was correlated with the percent of the watershed area converted to roads, landings, and skid trails. Variables representing removal of forest vegetation were modelled to decrease as a function of time since logging. If the increase in rainy season flow volume had been closely associated with a decrease in evapotranspiration as a result of the reduction in forest vegetation, one of the alternate logging factors that represented such forest influences should have correlated more highly with this change. A probable explanation is that the increase in annual flow volume associated with the winter season was mainly the result of a reduction in interception losses from the roads, landings, and skid trails accompanied by a minimal reduction in soil moisture storage.

Alteration of Forest Vegetation

Timber harvest operations selectively removed 67% of the South Fork timber volume between 1971 and 1973. Removal of forest vegetation reduces evapotranspiration and canopy interception losses, thereby increasing soil moisture storage. During the growing season, substantial differences in soil moisture can develop between a logged and unlogged watershed. Although lower evapotranspiration rates characterize the winter period, it is possible for an “interstorm” difference in soil moisture to develop between a logged and an unlogged watershed during the winter. Such dissimilarity may be indicated by differences in base flow recession. The enhancement of streamflow at Caspar Creek can be explained in light of these principles.

Proportionately larger increases in mean daily flow rate relative to prelogging predicted rates occurred from the first day of the low-flow season to the final day of the low-flow

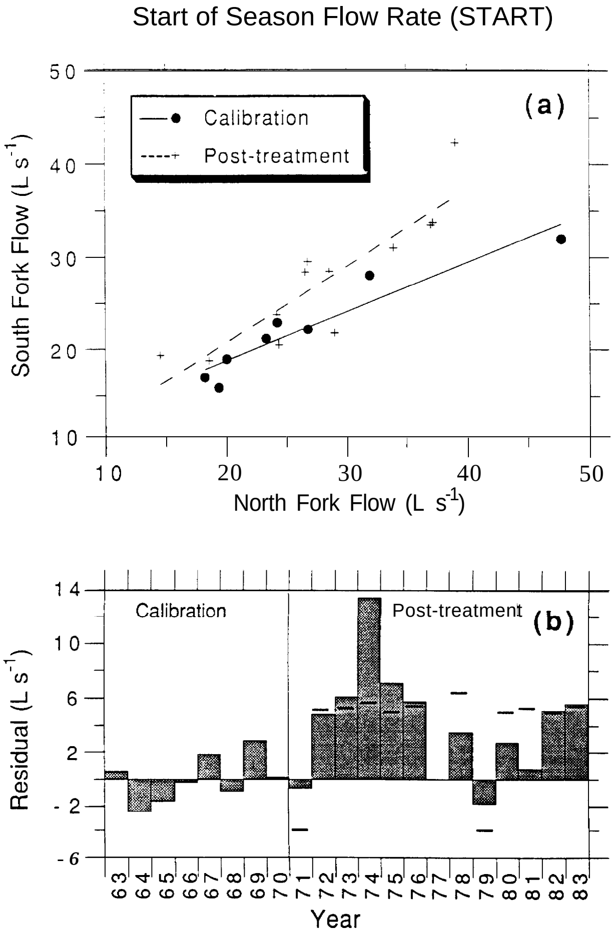

Fig. 6. Results of linear regression for North Fork and South Fork mean daily flow on the first day of the low-flow season (START). *(a)* Calibration and posttreatment periods. *(b)* Residuals for calibration period and deviations from calibration regression for posttreatment period. Horizontal bars indicate the 95% prediction limits for posttreatment years.

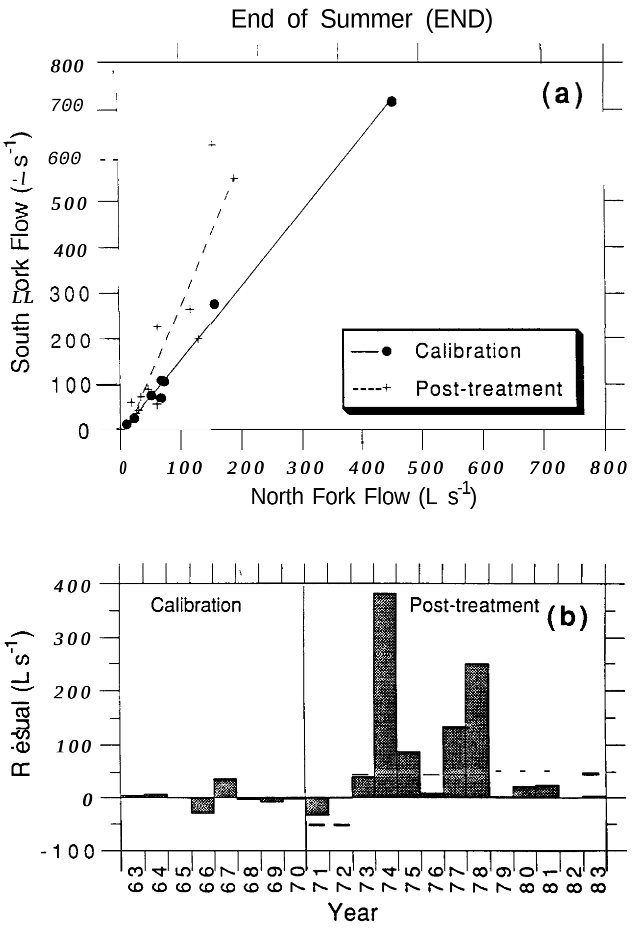

Fig. 7. Results of linear regression for North Fork and South Fork mean daily flow on the final day of the low-flow season (END). *(a)* Calibration and posttreatment periods. *(b)* Residuals for calibration period and deviations from calibration regression for posttreatment period. Horizontal bars indicate the 95% prediction limits for posttreatment years.

season. This trend suggests that soil moisture differences were developing between the two Caspar Creek watersheds as the growing season progressed.

Canopy interception is determined by total leaf area and the amount and intensity of precipitation. During a major winter storm the proportion of intercepted precipitation is probably inconsequential. However, during a light rain or fog, a considerable proportion of the total can be intercepted by a dense coniferous forest [*Dunne and Leopold,* 1978]. Along California's north coast, numerous small storms occur, each separated by a prolonged rainless interval. During such low-intensity precipitation events, interception loss on the North Fork was probably substantially greater than that on the South Fork after logging, and differences in interception between the two watersheds may have contributed to the increase in water yields detected in the logged area.

As seasonal precipitation (PPTSEAS) increased, summer flows on the South Fork increased significantly in comparison to those on the North Fork. This difference suggests that a greater proportion of summer precipitation reached the soil surface and was available to offset evapotranspiration by the remaining vegetation on the logged watershed. On the control watershed, more of this precipitation was probably intercepted and evaporated directly from leaf surfaces.

Regrowth

After 1978, increases in South Fork flow were detected only for the variables directly related to winter streamflow processes and meteorological conditions (TOTVOL and START). A significant increase was not detected for those variables reflecting summer conditions. In 1981 and 1983 there was a significant decrease in total summer season flow (SUMVOL).

The removal of mature timber by selective harvest operations was designed to improve the growth potential of the younger trees. By creating openings in the canopy and reducing competition for sunlight and water, the growth and water use of the remaining vegetation and invading trees, brush, and forbs may have been accelerated, as has been documented in other forest environments [*Bogatyrev and Vasil'eva,* 1985; *Jarvis,* 1985; *Greenwood et al.,* 1985]. This mechanism would explain the rapid reduction of summer flow enhancements and the possibility of decreased summer flows after growth has been stimulated in the remaining vegetation.

Antecedent Moisture Influences

Multiple regression analysis indicated that antecedent moisture conditions, represented by antecedent precipita-

TABLE 4. Standardized Coefficients and Statistics for Six Multiple Regression Models

Independent Variables and Statistics	Dependent Variables					
	TOTVOLSN	SUMVOLSN	PARTVOLSN	LOFLOZSN	STARTSN	ENDSN
%ADF2		0.886	0.999	-0.562	0.651	0.803
%AC	0.821		-0.822			
PREAPI	-0.416	-0.334			-0.390	-0.446
APIYR	-0.630		0.527			
APISEAS						0.215
PPTSEAS		0.350		-0.460		
SRD/SD				0.591		
R^2	0.766	0.692	0.608	0.476	0.463	0.847
Overall *F*	16.3*	11.2*	8.3†	8.9†	6.9‡	27.7*
Standard Error	0.055	0.157	0.169	0.180	0.113	0.372

*Regression significant at the 0.001 significance level.
†Regression significant at the 0.005 significance level.
‡Regression significant at the 0.025 significance level.

tion (API), significantly influenced the magnitude of flow differences between the two Caspar Creek watersheds (Table 4). During years with high cumulative API values or preceded by years with high values, the logging effects on streamflow were reduced. A logical explanation is that during these wetter years, soil moisture deficits are small for much of the year, and thus both basins show similar summer recession characteristics. In contrast, during drier years, extensive differences in soil moisture may develop between the basins, owing to reduced evapotranspiration on the logged watershed.

The cumulative API for the preceding year (PREAPI) was a significant variable in four of the six regressions (Table 4). This suggests that the carryover effect of past antecedent moisture regimes may be substantial. The adequacy of soil moisture during critical growth periods can influence subsequent transpiration and growth rates depending on nutrient conditions and other growth requirements, but the extent of this effect is unclear [*Russell*, 1973]. The carryover effect of the antecedent moisture conditions of the preceding year possibly is an indirect reflection of variations in vegetation vigor and overall efficiency of water use rather than a direct indication of persistent soil moisture differences.

Additional Climatic Factors

The proportion of rainy days variables (SRD/SD, SRD/TRD, and TRD/TD) were screened as gross indicators of cloud cover. The variable SRD/SD contributed significantly to variance reduction in the regression between the South and North Fork watersheds for the number of low-flow days (LOFLOZSN). This variable suggests that cloud cover and light summer rainfall or fog reduced evaporative demand that, in turn, caused a minor reduction in flow difference between the two streams.

Management Implications

This research indicates that the potential exists for increasing water yield from a second-growth Douglas fir and redwood forest by selective harvest operations. On the average a 15% increase in annual water yield would be expected for the first decade after logging. However, several important characteristics of this expected increase lessen its utility to water managers. First, the timing of the augmented yield is displaced from the time of peak demand. At Caspar Creek, 90% of the flow increase was realized during the rainy high-flow season. Water demand is usually greatest during low-flow periods in the summer. In addition, that portion of the flow increase that occurred during the low-flow season diminished rapidly in the years following logging. Beyond 5 years after the completion of logging, no significant flow increases were detected, and a possible decline in summer flows relative to prelogging levels was noted. Persistent summer flow augmentation would not be expected without continued vegetation reduction in the logged watershed. Also, the sizeable variation in flow enhancements detected in the postlogging years at Caspar Creek suggests that water yield increases could not be depended upon by planners and managers to meet specific water demand levels. This lack of certainty would reduce the utility of flow increases. The potential side effect of increased sediment yields accompanying streamflow enhancements realized in logged watersheds would counter the possible benefits. At Caspar Creek, *Rice et al.* [1979] found that stream sediment increased by 80% with road building and 275% with logging.

In the Pacific Northwest a large proportion of the forest land is managed for timber production. As a result, it appears probable that forest management decisions involving cutting cycle, volume harvested, and postharvest silvicultural practices will continue to be based on timber management objectives. Forest practices that encourage the rapid regrowth of trees are not likely to result in prolonged water yield increases related to harvesting. In contrast, forest operations designed to maximize water yield augmentations by inhibiting regrowth may pose problems related to slope stability, sedimentation impacts, and timber growth and yield.

We found some indication of a reduction in summer flows beyond 5 years after logging. This reduction might be the result of accelerated transpiration and growth by the residual vegetation. Reduced summer flows may, in turn, affect the aquatic ecosystem by reducing in-stream habitat capacity for fish.

CONCLUSIONS

Selective logging of an 85-year-old second-growth Douglas fir and redwood forest at the Caspar Creek watershed resulted in the alteration of the amount and seasonal distribution of streamflow. Streamflow was augmented both for the low-flow season and the annual period. Increases were greatest in the year after logging was completed, 1974, and diminished irregularly thereafter. Increases in summer flow volume were detected between 1972 and 1978, although not all of these increases were considered statistically significant. Enhancement of the summer flow volume was less persistent than annual flow increases.

The prospects of increasing water yield by selective harvesting of second-growth forest along California's north coast are not promising for two important reasons. First, the difficulty of reliably predicting the timing and extent of streamflow increases resulting from logging would make this supply undependable. Second, although the quantity of available water may be increased, the quality of the supply could be adversely affected by increases in suspended sediment and turbidity. This study suggests that water yield increases resulting from selection harvesting along the northern coast of California will be of minimal importance when compared to other forest management and production goals.

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