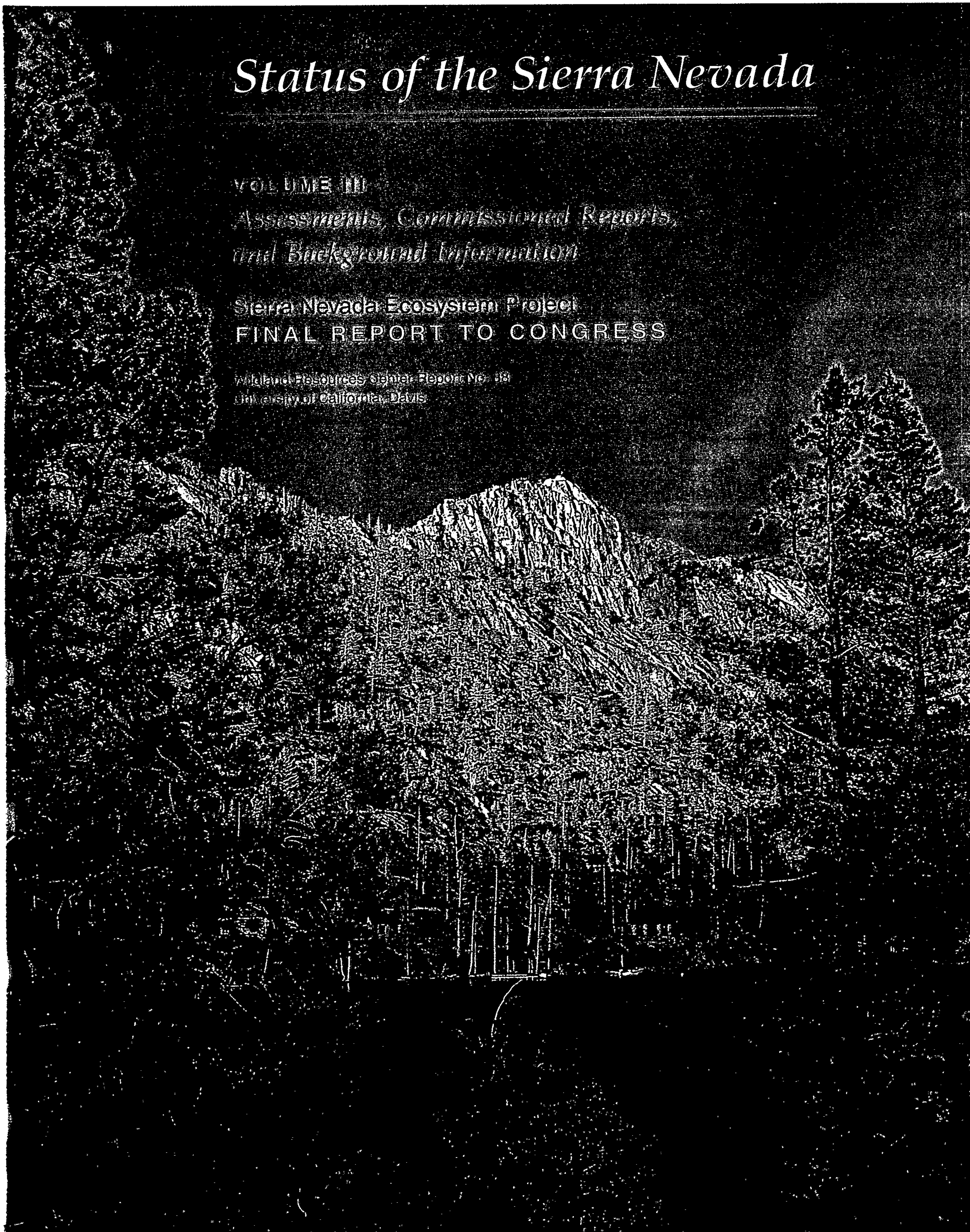

Status of the Sierra Nevada

VOLUME III

Assessments, Commissioned Reports, and Background Information

Sierra Nevada Ecosystem Project
FINAL REPORT TO CONGRESS

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University of California, Davis

SARAH MARVIN
Department of Environmental Science,
Policy, and Management
University of California
Berkeley, California

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Possible Changes in Water Yield and Peak Flows in Response to Forest Management

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ABSTRACT

This chapter is composed of two sections relating to potential hydrologic effects of forest management. The first part concerns total water yield, and the second is about peak flows.

The water-yield section describes a simple method of estimating the trend and magnitude of annual runoff response to changes in amount of forest cover in the Sierra Nevada. The use of this method is strictly limited to reconnaissance level assessments of the potential effects of broad-scale forest management scenarios. A model relating annual runoff response to timber harvest was developed from a simple linear regression of 31 catchment experiment results from the western United States. Correlations of runoff response following timber harvest with mean annual precipitation, mean annual runoff, and the ratio of mean annual runoff to mean annual precipitation indicated that the model would benefit from stratification by one or more of these variables. Because mean annual precipitation data are generally easier to obtain, a model was developed by stratifying the data set to a mean annual precipitation range representative of the Sierra Nevada conifer forest zone.

The simple linear regression indicates that a ten percent increase in timber harvest distributed evenly across the Sierra Nevada conifer forest zone may result in a 0 to 26-mm increase in mean annual runoff. Stratification of the data set to regions of above and below average mean annual precipitation indicated that a ten percent reduction in forest may result in a 10 to 52-mm and a -1 to 18-mm increase in annual runoff, respectively. Furthermore, these results indicate that trend and magnitude of changes in runoff following forest reduction are much more difficult to predict in drier regions. Further analyses were conducted to compare the results obtained from more complex multiple regressions. For the purpose of estimating trend and magnitude of runoff response, the multiple regressions produced results nearly identical to the simple runoff versus forest reduction regression.

The results of the stratified regressions were applied in two examples of projected changes in forest, one forest-wide and one Sierra Nevada-wide. The results indicate that annual runoff would be minimally affected by projected trends in forest reduction alone. However, these results do not include further effects from logging road construction, skid trails, or any other aspect of multiple-use management. Furthermore, the models and results herein are limited to annual runoff, only.

A paired catchment technique was used to assess historical trends in channel-forming peak flows in response to long-term watershed conversion to a logging-based ecosystem in the southern Sierra Nevada. The "treated" watershed, the South Fork Tule River, was subject to cumulative logging and road construction from approximately 1950 to 1989. By 1984, 58% of the forested area and 21% of the entire watershed had been logged. Double-mass plots of the treated and control watersheds over the period 1940-1989 indicated that an inflection point occurred at water years 1967-1969, about the same time as a significant increase in the land-conversion. Separation of the data set at 1967 produced a post-conversion slope twice as steep as the pre-conversion period, implying that channel-forming peak flows increased in response to cumulative canopy reduction and road construction. One possible cause of the increase in peak flows is an increase in snowpack and exposure to latent and sensible heat flux in clearcuts. Two hypothetical scenarios were developed to assess the increase in water available for runoff from the clearcut watershed. Increases of 15% and 11% were found for the forested area and the whole watershed, respectively.

Vegetation-Runoff Relationships for Predicting Water Yield Change

INTRODUCTION

One of the goals of the Sierra Nevada Ecosystem Project is to determine how broad-scale planning scenarios resulting in changes in vegetation cover or density may affect annual runoff from Sierra Nevada watersheds. Complex models have been used to predict changes in runoff from changes in vegetation at the individual watershed level (e.g., McGurk and Davis 1996). These models require watershed specific data for a number of components that affect the water balance. When a region, rather than an individual watershed, is the study area and the desired information is a determination of trend or magnitude, researchers have resorted to simple models based only on percentage of vegetation removed (Bosch and Hewlett 1982; Hibbert 1983; Harr 1983). These models are developed from relationships established by linear regression of multiple paired catchment experiments.

Around the world, hundreds of experiments have been conducted to determine the effect of removing or planting vegetation on streamflow. The primary purpose of these studies has been to determine whether and by how much water supplies can be augmented by removing vegetation from watersheds. These studies usually follow the typical "catchment experiment" design, wherein the mean annual water yield of two similar forested catchments, or small watersheds (10-200-ha) are calibrated to each other (typically 5-10 years). Following calibration, the vegetation on one of the catchments is partly or completely removed by mechanical means, burning, or herbicide application (or a combination of the three) while the second catchment is left untreated as a control. Annual precipitation and streamflow measurements are typically recorded for one to ten years following treatment. Comparisons are then made between the predicted streamflow from the calibrated relationship and the observed, post-treatment streamflow. Statistical analyses are usually employed to determine the significance of measured changes. A common use of the results of these individual experiments is to predict water yield increases from vegetation treatments in other watersheds.

Bosch and Hewlett (1982) used a world-wide sample of catchment experiments to develop a simple linear regression equation between the percentage of forest cover removed and the maximum increase in water yield recorded in the first five years following the treatment. The regressions were stratified by conifer, hardwood, and shrubland vegetation types. The authors estimated a 40 mm increase in runoff per 10 percent reduction in cover for the conifer forest. The equation explained 42% of the variability in water yield change.

The purpose of this study is threefold: 1) to develop a simple model that could be used to determine general trend and magnitude of runoff response across the Sierra Nevada to broad-scale planning scenarios resulting in change in forest density; 2) to compare this relationship to Bosch and Hewlett's (1982) world-wide estimate; and 3) to estimate trend in runoff by applying the models developed in this study to proposed broad-scale scenarios in the Sierra Nevada. An extensive review of the literature is included to explain the concepts involved in predicting changes in runoff from vegetation treatments. Other components of the water balance that have a greater effect on stream ecology and geomorphology as well as on water supply are also affected by vegetation changes. An assessment of annual runoff is only the first step of a watershed analysis. This analysis is restricted to annual runoff, because the effects of change in vegetation on peak and low flows are far more complex.

REVIEW OF WATER YIELD LITERATURE

Due to the fact that most of the experimental studies involve reductions rather than increases in forest cover, the following discussion is necessarily limited to this scenario. The catchment experiments show that, all other hydrologic factors remaining equal and favorable to runoff, water yield may be increased by removing vegetation. The premise of this statement is that vegetation intercepts and evapotranspires precipitation that might otherwise become runoff. 'All factors remaining equal' refers to the fact that there are many environmental factors that complicate this simple premise, some of which are not favorable for increasing water yield.

Many researchers group all runoff factors into three variables:

runoff = precipitation - (evapotranspiration + deep seepage).

Since runoff and precipitation are easy to measure and evapotranspiration is not, this simple relationship is often used to predict evapotranspiration, by substituting runoff and precipitation values and dropping the unmeasurable, but presumed insignificant deep seepage factor:

evapotranspiration = precipitation - runoff.

This simplification is a tempting method to determine evapotranspiration rates that can then be used to predict runoff from removing all or parts of the source of evapotranspiration. While the basic relationship is valid, back-calculating reductions in evapotranspiration this way frequently results in overestimating water yield change from vegetation removal. Furthermore, the method transfers errors in both precipitation and runoff measurements to the evapotranspiration term.

Direction and magnitude of runoff response to changes in vegetation is not always predictable, because the relationship depends on the interaction of physical and biological factors present in the individual watershed. For example, five studies conducted in Arizona on a ponderosa pine forest found varying increases in runoff in response to clearcutting and thinning (U.S. Environmental Protection Agency 1980). The difference between the predicted and measured yields ranged from 16-222%. However, the differences do not correlate well with the percentage of cover reduction. The 100% clearcut watershed increased yield by 35% (~51 mm); the 75% thinned watershed yielded a 222% (~43 mm) increase; and the 50% clearcut and thinned watershed yielded a 103% (~142 mm) increase. Similarly, the results from logging eleven drainages within a Virginia river basin failed to produce a reliable or accurate model to predict hydrologic response to vegetation manipulation within the 148-ha area. The following is a discussion of factors that affect the magnitude of runoff response to vegetation treatment, including the ways in which each may confound the ability to predict amount or direction of water yield change from vegetation treatment.

Climate

The review of catchment studies supports previous findings that the greatest initial water yield increases occur on watersheds with the highest mean annual precipitation (MAP) (Bosch and Hewlett 1982; Ziemer 1986). However, the duration of an increase in runoff may be shorter in regions with high MAP, because revegetation occurs at a faster rate. The magnitude of the increase in runoff varies with annual and seasonal precipitation. Wet years produce higher increases than dry years, which may produce no increase at all (David et al. 1994). Wet seasons produce higher absolute increases than dry seasons. In Mediterranean climates where most precipitation occurs in the dormant season, transpirational draft may not be greatly affected by reducing vegetation.

Detectable increases in runoff are unlikely from watersheds with MAP less than 18 inches (Bosch and Hewlett 1982), and the potential for increasing runoff remains low for watersheds with MAP below 27-31 inches (MacDonald 1985 cited in Kattelmann 1987). Shallow-rooted grasslands can transpire as much as some forested sites when a water deficit exists and soils are shallow (Eagleson and Segarra 1985; MacDonald 1991), or when clearing results in an increase in evaporation that is not counteracted by a decrease in transpiration (Calder 1993).

Vegetation

The amount of vegetation existing prior to treatment may be more important to changes in water yield than the amount of vegetation that is removed. For example, much of subalpine zone in California is already at or close to maximum water yield efficiency (Kattelmann 1987). This efficiency is attributed to the open vegetation cover which optimizes snow retention, evapotranspiration, and runoff to produce the highest water yields. Kattelmann (1987) concludes that vegetation cover below forty percent cannot be effectively managed for increased water yields.

Transpiration varies with differences in vegetation species, vigor, density, and environmental constraints (availability of water and energy). Interception of rain and snow and subsequent ablation also vary by vegetation type (deciduous versus evergreen), canopy cover, and leaf size and shape. The disposition of these factors in both vegetation removed and the remaining or succeeding vegetation affect runoff response. For example, Kauffman et. al. (1987) found that remaining understory vegetation offset expected evapotranspirational savings from clearing an aspen overstory. The remaining understory had no such effect on savings from removal of a spruce-fir overstory.

Location

The effect of evapotranspiration on water yield may be influenced more by the location of the vegetation treatment within the watershed than by any other factor. One study in Arizona found an average increase of 16 mm (40%) when channel-side shrubs on 15% of the chaparral-dominated watershed were chemically treated. A further reduction in cover of 20% on the upper slopes produced no additional increase (Hibbert et al. 1983). Similar results were found in several studies conducted in climates where a soil moisture deficit exists during the growing season (Calder 1993; Greenwood et al. 1985; Hornbeck 1975; Whitehead and Calder 1993). The amount of increased runoff that actually reaches the stream channel is partly determined by potential uptake by other vegetation between the origin of the runoff and the channel (Kattelmann et al. 1984; Eagleson and Segarra 1985). If a goal of management is to increase runoff, location of the treatment is especially important on watersheds that cannot be completely clearcut or that must retain a riparian buffer zone, such as streams in the National Forests.

Topography

Slope aspect and gradient may influence the effectiveness of vegetation removal on runoff, in both amount and timing. Southern exposure, especially combined with steep slope gradient, will increase solar radiation to any snowpack present and accelerate snowmelt. Even nearby rocks and vegetation not covered with snow absorb energy which is re-radiated to the snowpack.

The greater solar radiation received by south-facing slopes often limits vegetation to more drought-tolerant species that use so little water that changes in cover do not significantly affect runoff. Slope may also be important in that steep slopes are less capable of retaining excess soil moisture on site or delaying its movement downhill.

Silvicultural Method

Vegetation cover reduced by a given percentage after thinning may produce a smaller (or non-detectable) yield than the same percentage reduction through clearcutting (depending on the location of the treatments). Most studies have failed to detect changes in runoff from vegetation treatments of less than 20-35% (Bosch and Hewlett 1982; Turner 1993). This is especially true of watersheds with low MAP. It is not known whether this lack of detectable response is due solely to the inability of stream gauges to detect small changes in runoff or if typical watershed characteristics prevent small increases in runoff from reaching the channel.

Several studies have shown that net snow water equivalent (SWE) may be increased by harvesting a watershed in strips or patches through reduced snow interception and subsequent ablation (Troendle and King 1985, Kauffman et al. 1987). The change in SWE is dependent upon the height of the neighboring forest stand and the size and shape of the cut. Maximum SWE frequently fails to translate to maximum annual runoff. Much of the increased runoff may be used by the surrounding forest stand (MacDonald 1989) unless it is melted by warm rain storms before the growing season begins.

Soils

Soil permeability and soil moisture capacity are critical factors that affect both the ability to increase annual water yield and the timing of runoff. Deep soils have been found to produce some of the greatest water yield increases, while shallow soils (especially in Mediterranean climates) produce the smallest yields (Bosch and Hewlett 1982; Kattelmann 1987). Furthermore, shallow soil combined with a steep slope may already efficiently transport runoff to stream channels. Removing vegetation from such sites will have nominal effects on runoff.

Infiltration and runoff rates for a given soil type change with land-use impacts and reduction in cover. Soil compaction from logging equipment and from mineral soil exposure to the force of raindrops decreases infiltration and increases overland flow, which may result in greater annual runoff (Harr 1975; Reid 1993).

Land Use/Cover

The current and historic uses of a watershed may determine whether any increase in water yield is possible. The Mokelumne River basin has undergone logging, grazing, road construction, and development since the 1850's. Euphrat (1992) analyzed stream and precipitation gage data for two branches of the Mokelumne River from 1941 to 1990 and compared runoff to an earlier study covering the period up to 1949. Euphrat concluded that annual water yield had increased at the onset of logging activities and peaked by 1949. Apparently, from 1949 to 1990, the detected peak remained constant, even as the cumulative watershed area affected by logging, grazing, and settlement increased. There may be a point in road-based logging ecosystems at which water yield is maximized, regardless of increasing harvest. Over a large landscape, a balance between reforestation and deforestation, watershed rehabilitation and destruction, and road construction and obliteration may keep long-term mean annual runoff relatively constant. This balance of activities may have the opposite effect on annual runoff in individual years. The Mokelumne River study reported a trend in streams "producing both more water in wet years, and less water in dry years" beginning around 1971 (Euphrat 1992).

In summary, magnitude and in some cases trend, of runoff response to vegetation change may be less related to the amount of vegetation change than another environmental factor. The literature points to the role of climate particularly in the form of seasonal precipitation.

The following analysis attempts to produce general runoff-vegetation treatment relationships tailored to the average range of environmental conditions in the Sierra Nevada conifer forests. As stated previously, the goal of developing these relationships is to provide a method of first approximation of trend and magnitude of runoff response to broad-scale planning scenarios.

RUNOFF-TREATMENT RELATIONSHIPS FOR THE SIERRA NEVADA

Methods

To develop runoff-treatment relationships for the Sierra Nevada region I compiled a database of water yield studies that were similar to Sierra Nevada conditions. Since there are very few studies specific to the Sierra Nevada itself, I started with all studies in the western United States mountain ranges, excluding the coast ranges. While this eliminated the confounding effects of the different precipitation-growing season relationship of the eastern United States, I could not eliminate similar climatic differences existing in western study sites controlled more by a continental than by a marine climate regime. Reducing the study to only marine-influenced climates would have drastically reduced the sample size and biased the results towards a higher range in mean annual precipitation.

Tables 1 and 2 document the attributes of 31 catchment studies, all of which have coniferous forests. The data set includes studies from Arizona, Colorado, Oregon, Washington, and California. Mean annual precipitation ranges from 400 mm in Colorado to 2840 mm in Oregon, mean annual runoff (MAF) ranges from 18 mm in Arizona to 2710 mm in Oregon, mid-area elevation ranges from 500 m in Oregon to 3200 m in Colorado, and drainage area ranges from 9 to 563-ha.

The two main variables used in the following regressions are: the independent variable 'treat', which is the area of the watershed treated (by logging or clearing vegetation), in percent; and the dependent variable 'Qdyr5', which is the corresponding average annual change in water yield (in millimeters) for the first five years following vegetation removal. Most catchment studies reported cover treated as percent of watershed. However, some mixed percent basal area with percent watershed area. This may be a source of error in the following regressions, as the two methods are not equivalent.

The basic question is whether there is a statistically significant, positive relationship between the area of a watershed treated and change in runoff. The null hypothesis is that there is no relationship between these variables (slope = 0) at the 90 percent confidence level ($p=.10$). If a positive, statistically significant slope results, the trend for water yield to increase with vegetation removal will be valid for the data set. Depending on the ability of the regression equation to explain the variability in water yield change, the slope will indicate the magnitude of change that may be expected from a given percentage of watershed area treated.

This first approximation of runoff response to vegetation change is followed by attempts to account for differences from other significant independent variables: mean annual precipitation, vegetation type, and slope aspect. Mean annual runoff is so strongly correlated with mean annual precipitation that inclusion in a model is redundant. The usefulness of these variables is tested in stratified linear regressions and multiple-regressions. The results are compared to the simple runoff versus percent treatment model.

Results and Discussion

Simple Runoff versus Treatment Regression Figure 1 shows the results of the first regression: increase in runoff versus reduction in forest cover for all western U.S. studies in the data set (see table 3 for a complete comparison of model results from this study). The plot shows a non-zero slope, which is statistically significant at the 90% level of probability (p-value=.042; the probability that the estimated change in water yield could be due solely to random variability instead of percent treatment is 4.2%). Presumably, the water yield change due to a 0% change in vegetation would be zero. However, due to a lack of data points at 0% watershed treatment and non-normal data, the equation gives a mean intercept of 12 mm (0 mm falls well within the confidence interval).

To more accurately reflect the variability in the mean runoff-treatment relationships, I report the range in response as the 95% confidence limits. The estimated mean water yield increase associated with a ten percent change in cover for this data set is 12 mm, within a range of 0 to 24-mm. The regression coefficient is extremely low (r^2=0.14), indicating that area treated fails to explain most of the variability in water yield change. For comparison, Bosch and Hewlett's (1982) regression (covering a greater range in climate) produced an r^2 of 0.42. The greatest variation about the regression line is for treatments of 100%. Both the highest (positive) and lowest (negative) residuals occur at 100% treatment. The rest of the data points are fairly well distributed. The lack of a normal distribution for this data can be partly accounted for by two major factors. The first is the variability inherent in the way experiments were conducted and the data were collected by the individual researchers of each sample point. The second is the influence of more dominant independent variables that is magnified as percentage of watershed area treated increases.

Stratification by Mean Annual Precipitation Ideally, the data set used to develop a runoff-treatment equation representative of the forest zone of the Sierra Nevada would consist of results from dormant season precipitation, because 80-90% of precipitation in this zone occurs from October to April. All of the studies included in the data set have a winter precipitation period. However, too few catchment studies reported the differences in seasonal changes in runoff. In addition, to be representative of the Sierra Nevada the data set should correspond to a pattern of high MAP being dominated by snow and lower MAP being dominated by rainfall. Unfortunately, study watersheds with the highest MAPs are located in the Oregon Cascades where precipitation is a mix of rain and snow and the lowest MAPs are located in the snow zones of Arizona. Due to the limited availability of catchment study results, MAP is used as a surrogate for the more complex relationship between precipitation and runoff.

A comparison of correlation coefficients between percent cover treated (r = .38), MAP (r = .82), and MAF (r = .84) shows that both MAP and MAF individually explain a far greater amount of the variability in streamflow change following treatment than does the amount of treatment. The potential for changes in vegetation to affect mean annual runoff is so dependent

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upon the water available to the system that the vegetation change itself is almost insignificant in comparison. These results suggest that a better runoff-treatment relationship should be possible by stratifying the data set by ranges in MAP.

The first stratification by MAP was made by limiting the data set to a range typical of the Sierra Nevada's MAP: 500 mm to 2400 mm (Schoenherr 1992). The goal was to retain sample points while reducing the variability in MAP. Three points below 500 mm and two points above 2400 mm were dropped, leaving 26 sample points. The goodness-of-fit for the new model was unchanged (r^2 = .14) while the regression slope was slightly less significant (p-value=.58). The only difference between the two runoff-treatment models was the elimination of three studies that reported no increase in water yield from treatments of 25% and 100%. The elimination of these points increased the estimated mean change in runoff associated with a ten percent increase in treatment from 12 mm to 13 mm (figure 2). However, the increase is not statistically significant. Because the purpose of developing the runoff-treatment relationships is to determine trend and magnitude, the models are considered identical: a mean increase on the order of 10 mm per 10 percent reduction in forested area may be expected from the average watershed in an average year (average as defined by the data set). An additional assumption is that the treated area is located on an "average site" within the watershed.

Conditions across the Sierra Nevada forest zone are not average. In particular, MAP ranges from relatively low in the southern Sierra to moderate in the northern Sierra to extremely high in the central Sierra. To determine trend and magnitude of annual runoff response in broad regions that are not represented by average MAP, I stratified the data set to these three general regions. Rather than improve the model, further stratification of the data set into high, medium, and low MAP eliminated the statistical significance of the regression for the nine sample points within MAP 400 mm to 610 mm (roughly corresponding to the foothill woodland community in the Sierra Nevada. However, the 400 mm point is for a spruce forest in Colorado). The slope was not statistically significant (r^2=0.14; p-value=0.33), indicating that runoff response to change in vegetation in this low MAP range is considerably less than for the whole data set. This interpretation supports previous findings that regions of lower precipitation are associated with smaller changes in runoff following timber harvest.

The middle MAP range stratification of 630 mm to 960 mm (roughly equal to the mixed conifer forest in the Sierra Nevada) also failed to produce a significant relationship between treatment and runoff (r^2=0.09; p-value=0.37). A significant relationship only emerged when the MAP reached a range of 950 mm to 2400 mm (roughly equal to the Sierra Nevada lodgepole pine - red fir community, but the sample is dominated by Douglas fir). The results of the high MAP regression indicate that a 10 percent increase in treatment may be associated with a 31 mm mean increase in runoff, within a range of 10 to 52-mm. The goodness-of-fit is also relatively high (r^2 =0.64), with treatment explaining 64% of the variation in water yield increase.

The results from stratifying the data set by MAP range show that the simple treatment-runoff model may explain up to 64% of the change in runoff for regions with the highest MAP. For watersheds with MAP falling within the range 400 mm to 1000 mm, percent watershed treatment is a very poor indicator of changes in runoff. Stratification within this range failed to produce any significant relationship. The results of the lower MAP range also indicate that during periods of low precipitation, watershed treatments throughout the Sierra Nevada are unlikely to affect runoff. Similarly, the higher MAP range illustrates that a greater response to treatment will occur in high precipitation years. Watersheds with MAP falling between 900 mm and 1000 mm

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are in a transition zone. If stratified into the higher MAP range, use of the model would probably result in overestimates of runoff associated with percent treatment, as was the case with the southern Sierra Nevada sample point (study number 104).

Stratification by Aspect Aspect is most important in the lower elevations where plant communities may be defined by north and south facing slopes. In higher elevations, aspect will determine the locations and densities of individual tree species. In addition to plant distribution, aspect may be a useful indicator of stomatal activity between and within plant species.

The following treatment-runoff models were derived from the Sierra Nevada MAP data described above. Ten south and one west aspect were grouped into the south-facing data set; nine north and three east aspects were grouped into the north-facing data set. Neither data set benefited from further stratifying into south only and north only groups.

The regression for south-facing slopes produced no significant relationship between treatment and runoff. (r^2=0.07; p-value=0.38). The regression for north-facing slopes produced a higher regression coefficient (r^2=0.28), but the model still explains a small fraction of the variability of runoff response to watershed treatment. The treatment-runoff relationship is statistically significant at the 90% level of confidence (p-value = 0.076). The main difference between the data sets for north and south facing slopes (besides aspect) is the mean treatment, which is 76% for south-facing slopes and 56% for north-facing slopes. MAP and mean change in runoff are virtually equal between the data sets. Stratification by aspect supports the trends revealed by the stratification by MAP: runoff response to vegetation removal is dependent upon greater availability of moisture, whether by higher precipitation or by lower solar radiation.

Stratification by Plant Community In addition to representing broad climatic conditions, stratification by plant community may also substitute for broad differences in edaphic conditions. The data set was stratified into three associations determined by the dominant tree species: mixed conifer (dominated by ponderosa pine); lodgepole pine-spruce-fir; and Douglas fir.

The only statistically significant regression by plant community is for the Douglas fir. The r^2 is 0.56, which is similar to the highest MAP stratified model because both data sets include many of the same sample points. The model indicates that a ten percent reduction in vegetation may be associated with a mean increase in runoff of 27 mm, within a range of 3 to 51 mm.

Stratification by vegetation type is almost the same as stratification by MAP. The Douglas fir data set (8 points, all of which occur in the Oregon Cascades) corresponds to a mean MAP of 1887 mm. Mixed conifer (12 data points, primarily in Arizona) corresponds to a mean MAP of 705 mm. The lodgepole pine - spruce - fir (6 data points, primarily in Colorado) corresponds to MAP 633 mm. The lodgepole pine-spruce-fir subset is not representative of the environment of these species in the Sierra Nevada. A more appropriate surrogate for the Sierra Nevada red and white fir forests would be the Douglas fir type. The problem with this substitution is the precipitation type: the Sierra Nevada red and white fir zones are characterized by deep snowpack, which is not the case of the Douglas fir in the Oregon Cascades.

Multiple Regression The purpose of the following multiple regression analysis is to determine the differences between estimating trend and magnitude of runoff response from the simple runoff-treatment model (with or without stratification) and a more complex model requiring basin-specific characteristics. The data set used is the set of 26 samples fitting the Sierra Nevada MAP range.

The independent variables tested were percent treatment, MAP, MAF, and the ratio of MAF to MAP. The regression with all four variables results in an r^2 of 0.81 and the relationships for all the variables except MAF are significant at the 90% level. Even though the correlation between runoff response and MAF is strongly positive, there is no statistical significance of MAF in the multiple regression the relationship. Despite this result, the model has a better fit with MAF retained. The multiple regression equation is:

$$Y_{fit} = -217 + 1.15X_1 + 0.24X_2 + 323X_3 - 0.25X_4,$$

where X_1 is percent cover reduction, X_2 is MAP, X_3 is MAF/MAP ratio, and X_4 is MAF.

For this data set, holding all other factors equal, a 10% increase in treatment is associated with an 12 mm mean increase in runoff, within a range of 4 mm to 19 mm. As anticipated from the literature review, runoff response to vegetation removal is greater for watersheds with higher MAP, higher MAF/MAP ratio. In terms of trend and magnitude, the change in runoff from change in treatment produced by the multiple regression is virtually identical to the results from the simple runoff-treatment model.

Stratification into south- and north-facing slopes significantly improves the goodness-of-fit for both aspects, but not the significance of the independent variables. For the first time, a model explains most of the variability in runoff response for drier watersheds. For the south-facing aspect, the r^2 is 0.90. However, only the MAF/MAP ratio was significant at the 90% level.

For north-facing slopes, the fit is slightly lower, with an r^2 of 0.87. Treatment is the only variable significant at the 90% level. Holding all other variables equal, a ten percent treatment is associated with an 18 mm mean increase in runoff, within a range of 3 to 32-mm. The multiple-regression resulted in a slight reduction in the effect of treatment.

Stratification by plant community produces the highest fit of any previous model, but the results are inconsistent. The drawback of using the stratification with the multiple regressions is the loss of degrees of freedom. This flaw in methodology is apparent in the failure of two of the models to produce statistically significant relationships between runoff response and all the independent variables.

In the previous analysis of the simple treatment-runoff model, stratification by plant community produced only a weak relationship for the 'mixed conifer' and 'lodgepole pine-spruce-fir' forests (r^2 of 0.18 and 0.01, respectively). With the multiple regression, these two forest types produced r^2 values of 0.58 and 1.0, respectively. Despite the improvement in fit for the models, the relationship between treatment and runoff is not significant at the 90% level. The Douglas fir data set indicates a positive treatment-runoff relationship at the 90% level (p-value=0.075).

To summarize, multiple regression, in this case, does not significantly improve or change the results from the simple runoff-treatment regressions. The primary limitation to using multiple regression on this data set is the small sample size that reduces the power of the analysis. The trends and magnitudes in runoff response to vegetation treatment are the same: greater response to vegetation treatment will occur in wetter environments and no trend can safely be predicted for driest environments. Inclusion of MAP, MAF, and the ratio of the two did not change the magnitude of potential change in runoff from treatment in an average watershed, which is approximately a 0 to 20-mm increase in runoff per 10 percent change in watershed area treated. The multiple regression did increase the statistical significance of this estimated value.

In terms of magnitude, combined with the indications from stratifying by MAP, it may be concluded that treatment of watersheds in drier regions of the Sierra Nevada will probably result in less than 10 mm (as low as 0 mm) change in runoff per 10 percent change in treatment. Regions wetter than the average conditions of this data set may result in a greater than 10 mm change (up to 50 mm for extreme conditions).

APPLICATION OF RUNOFF-TREATMENT MODELS

The following is an application of the runoff-treatment models developed above to broad, generalized areas whose average site characteristics fall within the sample averages. As discussed in the previous section, the tremendous variability in actual watershed conditions render the following examples suitable only for comparisons of runoff response to broad-scale scenarios applied evenly across the range of watershed conditions represented by the data set used to develop the particular model.

The purpose of the following applications is twofold: 1) to compare the results of the models developed in this study to results produced by other methods in the same region; and 2) to assess the maximum potential runoff change from realistic, broad-scale, forest treatments. The proposed forest treatments are projections made in U.S. Forest Service (USFS) and California Department of Forest and Fire Protection (CDF) planning documents.

Methods

The following calculations purposely err on the high side of potential runoff response. In the following applications, a period of fifty years (the period of the typical U.S. Forest Service Land and Resource Management Plan [LRMP]) is used to estimate the maximum cumulative change in runoff that could be produced from projected changes in forest cover or volume. The USFS and the CDF project changes in standing volume rather than changes in forest area. Annual rates of change in forest volume were calculated as the difference between projected rates of regrowth and timber harvest. In order to compare results to USFS estimates of water yield, the long-term annual change in runoff over the entire period had to be calculated as the cumulative sum of each net annual change in runoff, divided by the study period: annual change in runoff x 1275/50. For practical purposes, the resulting "annual change in runoff" is meaningless, because change in runoff will be minimal in the first few years and much greater at the end of the 50 year period. A projected annual net reduction in forest volume of one percent would equal a 50 percent reduction in volume by year 50.

Results and Discussion

Forest-scale Scenario The first example is a comparison of the runoff-treatment equation developed in this study to the USFS estimated water yield from increased timber harvest in the Sequoia National Forest (SQF). The average SQF forest environment is characterized by relatively low precipitation and runoff, shallow soils, sparse forest cover, and a low percentage of forest type associated with high water yields from treatment (Douglas and red fir). Forest-wide mean annual precipitation is 762 mm (U.S. Forest Service 1988). Over 75% of SQF land is composed of rock-outcrop dominated soils. The standing timber strata is dominated by mixed conifer (70%). Based on data provided in the LRMP, 291,320 acre-feet of runoff come from the

364,000 acres of total timber strata.[1] Therefore, unit-area annual runoff from the conifer forest averages 244 mm.

The LRMP projected an average annual decrease in forest volume of 11.5 million board feet (mmbf).[2] Standing volume is 8100 mmbf, therefore the annual reduction in standing timber volume is 0.14%. I stratified the data set for the SQF conifer forest MAP range of 510 to 1230-mm. I used an upper MAP limit that is greater than the actual upper limit for the SQF to make the model average MAP (772 mm) similar to the SQF average MAP (762 mm). The SQF model estimates a mean increase in runoff of 8 mm per 10 percent reduction in forest ($r2=.14$; p-value=.077). Using 95% confidence limits, the range in mean response is -1 to 18-mm. Applying the stratified runoff-treatment model to the projected change in timber volume produced a mean total increase of 143 mm over 50 years, or an annual average increase of 3 mm. The range as defined by the 95% confidence limits is a 0 - 6 mm average annual increase for 50 years. In terms of percentage of existing runoff, the increase is 0 - 1%. The upper estimate is one-third to one-half of the USFS estimate for the same scenario (U.S. Forest Service 1988).

Sierra Nevada Scenario To determine the potential range of runoff response to realistic projections of change in forest standing-volume, I applied the stratified runoff-versus-treatment models to the Forest and Range Resource Assessment Program's (FRRAP) projections (California Department of Forestry and Fire Protection 1993). The FRRAP estimates of both standing timber volume and projected logging volume are lower than the USFS estimates in sample LRMPs. For the three FRRAP regions and the Sierra Nevada as a unit I calculated the possible range in mean change in runoff using the Sierra Nevada runoff-treatment model developed in this study.

The results of the projected changes in timber volume and runoff response are displayed in tables 4 and 5, respectively. The projected change in the rate of forest reduction for the central Sierra Nevada is the greatest, producing 2 to 11-mm of additional annual runoff. Projected change is so low in the southern Sierra Nevada that no detectable change in annual runoff would occur. The northern Sierra Nevada falls in the middle with a projected increase in annual runoff of 1 to 4-mm. The "Sierra Total" is the FRRAP estimate for change across the Sierra Nevada as a whole. The resulting increase in annual runoff is 1 to 6-mm.

Kattelmann et al. (1983), using completely different methods, concluded that water yield could be augmented by one half to two percent from the Sierra Nevada National Forests, or an average increase of 0.6 cm. This estimate is based on a scenario of intensive forest management within the constraints of existing environmental and multiple-use regulations. The authors proposed cutting 25% of well-suited watersheds every 25 years. In terms of total area treated, this would be similar to cutting 1% of the selected watersheds per year for 25 years. It is unknown what percentage of the total National Forest area could be treated in this way, however it is reasonable to assume that the increase in treatment would be well under 1%. If this is the case, Kattelmann et al.'s estimate falls within the 95% confidence interval (1 to 6-mm) generated by the "Sierra Nevada MAP" model, for the 50 year period.

[1] Acres from Table 3.11 (US Forest Service 1988, p. 3-53) were multiplied by water yield coefficients for existing timber species from the SQF water yield method (US Forest Service 1984, p. 2).

[2] Annual logging rate increases from 97 mmbf to 102 mmbf, while regrowth rate decreases from 104 mmbf to 97.5 mmbf, an increase in vegetation loss of 11.5 mmbf (US Forest Service 1988).

DISCUSSION

General Trends in Annual Runoff Response to Forest Treatment

The results of the bivariate and multiple regressions are supported by trends found in the water yield literature. Regional variation in precipitation is the greatest determinant of potential for runoff change from vegetation removal. Across the United States, both total mean annual precipitation and seasonal distribution determine the magnitude of runoff response: catchment studies from the high mean annual precipitation regions of the Pacific Northwest and the eastern states are consistently associated with the greatest increases in runoff resulting from timber harvest. These catchments also recover the most rapidly from timber harvest. High increases in runoff also occur in regions that receive significant precipitation in the growing season.

The Sierra Nevada has a Mediterranean climate: on average, eighty percent of precipitation occurs outside of the growing season, from December through April. Primarily because of its seasonal distribution of precipitation, most regions of the Sierra Nevada (certainly those most in need of augmented streamflow) do not fit Bosch and Hewlett's 1982 estimates of runoff for a percentage reduction in cover. Runoff potential from Sierra Nevada watersheds with exceptionally high MAP and dense forest cover may be comparable to Bosch and Hewlett's estimates, however very little of the increase would occur during the growing season, when additional runoff is most needed. Value of streamflow augmentation is temptingly great in dry regions of the Sierra Nevada, but the most drastic, permanent reductions in forest cover would be required to convert a significant proportion of precipitation to runoff in these areas. As in the rest of the Sierra Nevada, most of the increase would occur in winter or spring snowmelt peaks, when the monetary (which is greatest for hydroelectric power) and ecological values are lowest.

Unless timber harvest is specifically designed to increase water yield (e.g., clear-cutting significant areas near stream channels and treating densely forested sites), total annual runoff is unlikely to change noticeably. Large-scale increases that would be detectable in major rivers will not occur and local changes will not occur when and where they are needed. A significant cumulative change in forest cover and associated roads and landings over the long term (a total ecosystem conversion), as has occurred in parts of the Sierra Nevada since the post-World War II years, may (and probably has) increase total annual runoff. In other parts of the Sierra Nevada, increase in biomass and canopy cover from fire suppression may counteract or bring about the reverse effect on flow.

Application of Treatment Versus Runoff Models

A simple treatment versus runoff relationship stratified to region-wide average conditions appears to be a useful tool for estimating potential trend and magnitude of annual runoff response to very general planning scenarios. Application of the models in a reconnaissance level assessment suggests that the minor increases in rates of timber harvest projected by the USFS and the CDF are unlikely to affect annual runoff in the short term. Over the fifty year planning period, an increase in annual runoff would peak in the last decade, when the greatest amount of forest would have been removed and the evapotranspiration rate of regrowth would not have reached that of mature forest.

For National Forest planning purposes, the biggest source of error in using the treatment versus runoff models will be in extending the use of the model below the 25% treatment limit.

Changes in the rates of vegetation removal on National Forest lands are of a minute magnitude, on the order of 0.1% per year, or 5% total over fifty years. At this level of change, it is arguable whether any change in runoff would occur. Two catchment studies in the Sierra each reported watershed treatments of 25%. The southern Sierra watershed produced no change in runoff (McCammon 1977); the central Sierra watershed produced a first year increase of 40 mm (Rick - please insert cite). Lack of runoff response at low levels of treatment may be due to an inability to detect a real change with available equipment, a change in runoff that falls within the error term (e.g. for USGS gauges, data accuracy ranges from 5-15%), or the existence of a minimum threshold of forest treatment before excess runoff is generated. In any case, extreme caution must be used in applying the models to treatments under 25%.

The model does not predict timing and use of water yield. For water value, timing will determine the cost or benefit of any change in runoff. The drier the location, year, or season, the more valuable the water and the smaller the probability that an increase in water yield will result from treatment. Other potential effects of timber harvest activities include changes in peak and low flows, sediment yield, channel configuration, and related cumulative and secondary effects. These models do not address any effects of vegetation removal other than annual runoff within the first five years of treatment.

Mean values should not be applied to any planning use requiring a specific value of runoff, such as cost benefit analyses and statements of forest outputs. An appropriate use of the models in these types of analyses might be to use the 95% confidence limits, and report all results as a range of possible mean values. Incorporation of the confidence limits is crucial, because they indicate that the mean increase could fall anywhere within that interval.

CONCLUSIONS

The results of linear regression analyses of 31 western United States catchment experiments produced a simple method of estimating the trend and order of magnitude of annual runoff response to changes in amount of forest cover for regions of the Sierra Nevada conifer forest zone. Further multiple regressions produced results nearly identical to the simpler model. However, the multiple regressions were hampered by the small sample size. Because of the strong correlations of runoff response following timber harvest with mean annual precipitation, mean annual runoff, and the ratio of mean annual runoff to mean annual precipitation the models developed herein were stratified to match regional characteristics. Mean annual precipitation data are generally easier to obtain, hence models targeted for Sierra Nevada-wide, above, and below average moisture conditions were developed by stratifying the data set to the appropriate mean annual precipitation ranges. The use of this method is strictly limited to reconnaissance level assessments of the potential effects of broad-scale forest management scenarios.

The regression results indicate that a ten percent increase in timber harvest distributed evenly across the Sierra Nevada conifer forest zone may result in a 0 to 26-mm increase in mean annual runoff. Results targeted for regions of above and below average mean annual precipitation suggest that a ten percent reduction in forest may result in a 10 to 52-mm and a -1 to 18-mm increase in annual runoff, respectively. Thus, runoff response in regions of low mean annual precipitation cannot be expected to produce detectable changes in annual runoff from moderate changes in forest cover or density. Furthermore, these results indicate that trend and magnitude of changes in runoff following forest reduction are much more difficult to predict in drier regions. These findings are supported by the water yield literature which indicates that significant changes in annual runoff are common in wet regions and in wet years, but not in dry regions or dry years.

The stratified models were applied to two scenarios of projected changes in forest, one forest-wide and one Sierra Nevada-wide. The forest-wide scenario, based on U.S. Forest Service projections for the Sequoia National Forest, resulted in a 0 to 6-mm mean increase in annual runoff averaged over a period of 50 years. The Sierra Nevada-wide scenario, based on California Department of Forestry and Fire Protection projections, resulted in a 1 to 6-mm mean increase in annual runoff averaged over a period of 50 years. Thus, the results indicate that annual runoff would probably be minimally affected by projected trends in forest reduction alone. However, these results do not include further effects from logging road construction, skid trails, or any other aspect of multiple-use management. Furthermore, the models and results herein are limited to annual runoff, only. Timing of runoff, peak flows, baseflow and sediment yield may all be affected by the scenarios used in this study.

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Peak Flow Changes with Watershed Conversion to a Logging-based Ecosystem

INTRODUCTION

The purpose of this study was to determine if a change in channel-forming peak flows could be detected from the gradual, long-term conversion of a Sierra Nevada watershed to a logged, multiple-use ecosystem. An increase in channel-forming and larger size peak flows may lead to detrimental effects to many beneficial uses of the watershed, such as fish habitat, riparian vegetation, and reservoir space. A significant increase in peak flows may cause bed scour, channel incision (leading to a lowered water table), downstream aggradation, and bank erosion among other channel changes (see Reid 1994; Meehan 1991; and MacDonald et al. 1991 for thorough reviews of these processes).

There is a paucity of knowledge of the effects of timber harvest activities (vegetation removal, skid trails, road construction and use, and site-preparation) on peak flows in Sierra Nevada streams. Most watersheds in the Sierra timber zone have been altered by multiple-use management since at least the 1940s. Some of these watersheds, such as the National Parks, have been primarily affected by recreational use, fire-suppression policy, and grazing. Others have been altered more by timber harvest. It is this latter category that has the potential to increase peak flow size through reduction of evapotranspiration, decreased infiltration (to deep soils or groundwater), and increased exposure of snowpack to warm rain-dominated storms. In this study, I evaluate the significance of timber harvest activities on channel-forming peak flows in the Sierra Nevada by: 1) assessing the literature from other regions to determine what principles of timber harvest and peak flows may be most relevant to the Sierra Nevada; and 2) applying those principles to a watershed analysis of peak flow response to long-term conversion to a logged, multiple-use ecosystem in the Tule River basin.

BACKGROUND

Channel-Forming Peak Flows

Channel-forming peak flows are those peaks that occur frequently enough to dominate channel geometry and grain size (Dunne and Leopold 1978) or are large enough to cause a sudden but long-lasting change in channel geometry and bed load (Lisle 1981). There is relatively little information on what recurrence interval is the channel-forming flow for different streams (the recurrence interval is the average rate of recurrence of a given annual peak discharge over the period of record). The "bankfull discharge" is generally accepted as the channel-forming flow for most streams (Dunne and Leopold 1978), and tends to correspond to a 1.5- to 2-year (Q1.5 to Q2) recurrence interval. However, this may be an over-generalization when applied to steep mountain drainages, where the 5-year event may be the more significant flow (Washington Forest Practices Board 1994). An increase in the frequency of the Q2 to Q5 flow (depending on the stream) or a volume increase sufficient to raise the Q2 size flow to a Q5 size may have a detrimental effect on the stream ecosystem as the channel adjusts to a new hydrologic regime. Some watershed managers use a rule-of-thumb of a 20% increase to determine whether the Q2 has increased to a Q5 flow (Washington Forest Practices Board 1994). However, it is important

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to note that bed load mobilization may be predicted for flow size, but this determination is not a substitute for depth of scour (Washington Forest Practices Board 1994). The literature search for this report did not uncover published research on channel-forming flows for Sierra Nevada streams.

Most paired catchment experiments testing the effects of timber harvest on peak flows failed to address the relevance of peak flow size to long-term channel stability and consequent long-term changes to aquatic habitat and other sensitive beneficial uses. This is partly because the typical post-harvest study period was from 1 to 8 years. While there are exceptions, these are too few to extrapolate results to Sierra Nevada watersheds without long-term monitoring of peak flows in representative watersheds. The necessary monitoring is just beginning in some regions such as the Sequoia National Forest, under the 1990 Land Management Plan Mediated Settlement Agreement. The most valuable monitoring resource is the USGS stream gauge program. Unfortunately, very few Sierran watersheds have continuous records and many long-term gauges are being terminated (e.g., the South Fork Tule gauge was terminated in 1989).

Flood Flows

The flood-sized peak flows are vivid in the minds of most Californians. One of the significant debates over the establishment of the U.S. Forest Service under the Organic Act was initiated by California legislators who wanted to ensure that the flood-dampening effects of the forests were preserved (Bassman 1974; Steen 1976). The storm events in most western slope Sierra watersheds that cause major downstream flooding tend to occur with a frequency of one in ten years (Kattelmann et al. 1991). The majority of these floods are generated by mid-winter rain-on-snowpack storms. The major storms and flows are capable of mobilizing and carrying massive amounts of sediment from hillslope erosion and channel scour (Dean 1972). Part of the sediment load is transported into reservoirs, resulting in a decrease in storage capacity. Sediment exceeding flow capacity or capability is deposited instream to aggrade the channel. Such aggradation can put the river in a state of disequilibrium for a long time, especially in Mediterranean climates where precipitation is highly variable (Lisle 1981).

Potential Effects of Timber Harvest Activities on Peak Flows

Although there is variability in the effects of timber harvest activities on peak flows, researchers have identified several processes by which peak flows may be altered. Processes that may produce increases in peak flow size include: 1) soil disturbance that results in compaction or in concentration of drainage resulting in decreased infiltration at the site of disturbance; 2) reduced transpiration resulting in increased antecedent soil moisture; 3) reduced canopy interception of precipitation resulting in increased antecedent soil moisture and increased snowpack; 4) increased exposure of the snowpack to sensible and latent heat flux. A process that may increase or decrease peak flows from snowmelt is the downstream desynchronization or synchronization of peak flows from different tributaries due to advancing the peak flow date of harvested watersheds. The effects on peak flows are more complex and variable than the following summary can convey. Furthermore, due to the diverse methods that can activate a long-term change in peak flows, the associated impacts on beneficial uses will vary.

Soil Disturbance The creation of impervious surfaces by soil compaction or fire-caused hydrophobic soils results in decreased infiltration, increased overland flow, and more efficient delivery to the stream. These effects are limited to the area of the watershed disturbance. In the

Kings River, timber harvest activities (mainly skid trails) caused as much as 19% compaction (G. M. Kondolf, University of California, Berkeley, conversation with the author, October 30, 1995). Infiltration is also decreased by loss of detention storage (leaf litter and depressions in the soil that retain runoff and facilitate infiltration). The magnitude of the effect on peak flow size depends upon the amount of area no longer capable of infiltration and the amount of precipitation rerouted. The literature on peak flows is dominated by this consideration. However, unless a significant percentage of the watershed is burned or compacted, the potential increase in peak flow size is not as large as for other mechanisms.

Studies in the Idaho Batholith (Gray and Megahan 1981; Megahan and Molitor 1975) and Washington (Helvey 1980) on the effects of clear-cutting before and after fire demonstrate that the effects of fire on sediment yield are significantly greater with clear-cutting. Unfortunately, these studies did not measure peak flows. However, antecedent soil moisture and increased overland flow were controlling factors in the Idaho and Washington studies, respectively.

Reduced Transpiration A reduction in transpirational draft that increases antecedent soil moisture may increase peak flows generated by summer thunderstorms or by the first fall rains. In order for there to be antecedent soil moisture at the end of the growing season the soil must either be deep enough so that no herbaceous vegetation could tap all the moisture or there must be no vegetative layer whatsoever. In Mediterranean climates, where summers are virtually dry, soil with just herbaceous cover may be as dry as soil with deep-rooted vegetation. In those forests with deep, moisture retaining soils, a clear-cut plot may retain antecedent soil moisture over the growing season. In this case, the clear-cut site will reach saturation earlier than the equivalent forested site and will generate Hortonian or saturation overland flow more readily. The antecedent soil moisture will then augment stormflow. However, the greater stormflow from the clear-cut site will only last as long as it takes the depleted soil beneath the forest canopy to reach saturation. Therefore, antecedent soil moisture is considered significant only in increasing the size of fairly small peak flows, and only for a short time following the growing season.

Reduced Canopy Interception A portion of canopy-intercepted rainfall may be evaporated. The effect of preventing this small amount of rainfall from reaching the ground is also considered minor in its effect on channel-forming peak flows. Canopy interception plays a larger role where precipitation falls as snow. Snowpacks in the highest elevations (coldest winters) of the Sierra Nevada cause the largest peak flows to occur in the springtime, when the longer days increase air temperature. Increased snowpacks in clear-cut patches augment springtime and early summer peak flows (Troendle and King 1987). Increases of 21% to 59% in annual peak flows from spring snowmelt were documented in Colorado, Alberta, and British Columbia (Cheng 1989). Clear-cuts that are small enough to be shaded by nearby forest (1 to 3 tree heights) will melt later and may not contribute to streamflow at all (MacDonald 1989).

Increased Exposure of Snowpack Most paired catchment studies to date conclude that channel-forming peak flows are unaffected by *carefully implemented* timber harvest (Harr et al. 1982; Harr and McCorison 1979; Hibbert and Gottfried 1987; Wright et al. 1990; Ziemer 1981). In the western United States, these conclusions are being revised in light of evidence from studies conducted in watersheds subject to rain-on-snow storms (Berris and Harr 1987; Christner and Harr 1982). The influence of timber harvest on the size and frequency of rain-on-snow events is complex and fairly unpredictable. Researchers generally agree that timber harvest in small clear-cut patches increases snowpack (Troendle and King 1987; MacDonald 1989; Kattelmann 1982) and that, in regions subject to warm winter or spring rainstorms while snow is still on the ground, these increased snowpacks are subject to greater latent and sensible heat flux from warm storms (Berris and Harr 1987; MacDonald and Hoffman 1995). On the other hand, MacDonald and Hoffman (1995) were unable to detect a correlation between size of rain-on-snow generated peak flows and timber harvest. Harr and McCorison (1979) actually detected decreases in rain-on-snow peak flows for one year following timber harvest due to a lack of large warm storms.

Relevance of Peak Flow Change to Sierra Nevada

All the peak flow generating processes described above may be augmented from timber harvest activities in the Sierra Nevada, however I located only two Sierra studies of these effects. One paired catchment experiment studied the effect of timber harvest activities on annual May peak flows in the Kern Plateau (Sequoia National Forest). McCammon (1977) found no effects from timber harvest on May snowmelt peak flows, but he did not monitor the potential effects on winter peak flows. The post-treatment monitoring period lasted only three years. The second study was conducted on the Mokelumne River in the central Sierra Nevada (Euphrat 1992). The results of Euphrat's (1992) study of the Middle and South Forks of the Mokelumne River reflect the reality of long-term multiple-use management dominated by logging on a basin scale. The problem with this study is that effects from vegetation removal cannot be separated from roads, skid trails, or fire. Using USGS stream gauge data , Euphrat detected a statistically significant increase in ten-inch and greater storm residuals (from a regression of rainfall against runoff) that track with time for the period 1960-1990. Furthermore, Euphrat found no similar tracking between climate, and time. The only apparent cause of the increase in storm residuals was the effect of cumulative logging activities.

The role of soil disturbance in the Sierra Nevada is still unknown and should also be researched. Although the greater potential to affect large peak flows appears to be through increased rain-on-snow generated peaks, increases in large peak flows without rain-on-snow have been documented (see examples in Cheng 1989). Research should focus on the combined effects of soil disturbance, roads and landings, and different intensities of fire (e.g., intensities of broadcast burning, prescribed fire, and wildfire).

Virtually no published research has been conducted to determine specifically how peak flows in Sierra Nevada watersheds are affected by timber harvest. Given the magnitude of peak flow increases due to rain-on-snow storms and the fact that much of the Sierra Nevada timber zone is subject to these conditions, it is crucial to develop monitoring specifically to determine the effects of vegetation management on rain-on-snow peak flows. In the absence of this monitoring, historical trend analyses can increase our understanding of how we have affected and may continue to affect peak flows through multiple-use management. The following is such a study for the South Fork Tule River.

STUDY WATERSHED DESCRIPTIONS

The Tule River basin is located on the western slope of southern Sierra Nevada. The South Fork gauge is located at latitude 36° 02' 33", longitude 118° 51' 24", at an elevation of 235 m (770 ft). The North-Middle Fork gauge is located at latitude 36° 10' 29", longitude 118° 41' 41" at an elevation of 890 m (2,920 ft). Drainage areas are 282 km^2 and 102 km^2 (109 mi^2 and

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39.3 mi^2) for the South Fork and North-Middle Fork, respectively. The South Fork drains to the west with timbered slopes facing north, west, and south. The North-Middle Fork drains primarily south, with timbered slopes facing east and west. The South Fork varies in elevation from 235 m (770 ft) at the stream gauge to 2835 m (9300 ft); the North-Middle Fork varies from 890 m (2,920 ft) at the stream gauge to 2926 m (9600 ft) at the headwaters.

Mixed conifer, ponderosa pine, and giant sequoia forest types (including cut-over area) cover the upper one-third of the South Fork (approximately 8,539 ha; 21,100 ac); dense oak stands (2,224 ha; 5,495 ac), rangeland (13,485 ha; 33,322 ac), and grassland (963 ha; 2,380 ac) cover the lower elevations (Tule River Planning Commission 1973). The North-Middle Fork has a similar vegetation distribution, but with a greater percentage of area in mixed conifer, red fir, and giant sequoia forest types. Three-quarters of the South Fork is part of the Tule River Indian Reservation (TRIR), but almost half of the timbered area is owned by the USFS. The TRIR is rural with two, approximately 1 km (0.6 mi) long, sparsely developed, narrow strips along the river. The timbered area is criss-crossed with logging roads. The North-Middle Fork is technically designated as an "unroaded" area; however, a limited amount of recreational development, similar in extent to the TRIR, exists in the lower part of the watershed (see Results Section for more detail).

Precipitation occurs as rain, snow, and rain-on-snow in both watersheds. Mean annual precipitation (MAP) ranges from 460 mm to 1,140+ mm (18 in to 45+ in) on the South Fork; and 760 mm to 1,270+ mm (30 in to 50+ in) on the North-Middle Fork. The higher MAP range in the North-Middle Fork produces a greater annual runoff than on the South Fork, even though the South Fork is a larger watershed. However, except for the two highest recorded peaks, annual peak flows tend to be greater on the South Fork. Snow falls as low as 1520 m (5000 ft), but average snow line elevation is 1980 m (6500 ft). Warm mid-winter storms produce rain as high as 2740 m (9000 ft) in the Tule River basin (California Department of Water Resources 1960). The majority of annual peak flows occur during mid-winter rain-on-snow storms in both watersheds. Smaller annual peaks occur during the spring snowmelt.

Bedrock of the Tule River basin is predominantly Mesozoic granitic intrusives with some pre-Cretaceous metamorphic bedrock in the lower South Fork. Soils are moderately developed granitics, coarse-textured and well-drained (CH2M Hill 1974).

METHODS

Determination of Land-Cover Change

To determine the relationship between peak flow trend and long-term multiple-use management I estimated relative changes in land-cover over the period 1916 to 1989. I documented growth of the road network from maps and aerial photographs; chaparral clearing and permanent woodland thinning from aerial photographs and rangeland management documents; and timber removal from land-use planning and forest management documents. Aerial photographs were available for years 1970 and 1979. Maps spanned the period from 1916 to 1989, in several different scales. Consulted maps were produced by the USGS (7.5 minute quadrangle maps) and the USFS.

Analysis of Peak Flow Data

The purpose of this analysis was to determine whether cumulative changes in land-cover may have produced detectable changes in channel-forming and larger peak flows in a Sierra Nevada watershed. Following traditional practice, the channel-forming peak flow is assumed to be the Q2 flow ("bankfull"). Most similar analyses look for changes sufficient to increase the Q2 flow to Q5 size. Since little is known about effects of long-term changes in peak flows on beneficial uses in the Sierra Nevada, I do not employ any minimum threshold of concern. The purpose is to determine whether or not peak flows have changed detectably.

To control for changes in climate over the study period, I selected two similar watersheds that have been subjected to the same peak flow generating events. Problems with finding appropriate watersheds were the lack of continuous gauge data, both peak flow and precipitation, and the existence of a nearby gauged control watershed that had not already been significantly affected by land-use change or whose records were not affected by flow diversions. I could locate only one pair of watersheds that did not completely violate these conditions: the South Fork Tule River (South Fork) and the North Fork of the Middle Fork Tule River (North-Middle Fork). Only annual peak flows could be included in the analysis, because the records for the North-Middle Fork do not include partial duration flows (all flows above a baseflow). Peak flows were gauged on the South Fork at USGS station South Fork Tule River near Success (no. 11204500) and on the North-Middle Fork at North Fork of Middle Fork Tule River near Springville (no. 11202000).

I determined the Q2 flow by constructing a flood frequency curve from the entire data set available for the South Fork, 1932 through 1989 (water years 1955 and 1956 were missing from the records; 1956 was a major flood for both watersheds). Notwithstanding the data inconsistencies, the Q2 was 22 cms (780 cfs). I matched peak flow events by comparing dates of annual peak flows from the North-Middle Fork and corresponding partial peak flows from the South Fork. If the peaks occurred within one day of each other, I considered them a pair. Use of South Fork partial peaks occurred in only two pairs (i.e. all but two pairs represent the annual peak on both watersheds). I could not use precipitation data to assist the pairing, because the only nearby gauge (Springville Ranger Station) does not cover the necessary period of record. Furthermore, because of the lack of continuous and representative precipitation data, I could not test for peak flow trends with precipitation. I did not stratify the data between rainfall, rain-on-snow, and spring snowmelt generated peaks for two reasons: 1) without climate data, I could not be certain of the distinction between events; and 2) a separation may have resulted in too few data points for analysis.

There were three major limitations to the data from these watersheds. First, the "control" watershed is only relatively unaffected by land-cover change (see results section). However, the change in land-cover in the timber zone of the South Fork is significant enough relative to the North-Middle Fork to make comparisons. Second, the more problematic limitation is the lack of a continuous record of instantaneous peak flows for either watershed. The common period of record begins in 1940 and ends in 1989. Fortunately, this period does contain significant changes in land-cover on the South Fork. Several years of data are missing from both records and when years of non-similar peak flow events are dropped, the data set drops to only thirty pairs. The third problem is that the North-Middle Fork peak flows are affected by diversions for a hydroelectric facility. The maximum average daily diversion is 2 cms (66 cfs) (Woodward-Clyde Consultants 1985). A comparison of mean annual maximum flow between the combined river and conduit and river only indicates that the larger peak flows are not diverted. However, as flow size decreases, the influence of the diversion increases. To reduce the effect of the diversion to an acceptable level, I eliminated all flows for which more than five percent of the annual daily mean flow was diverted. This eliminated seven peak flow pairs, leaving a total of twelve (table 6). The South Fork is also diverted, but the 0.3 cms (10 cfs) (CH2M Hill 1974) is a minuscule percentage of the peak daily flows.

I analyzed the peak flow data by producing double-mass plots in which the cumulative values of peak flows in both watersheds were plotted against each other. From this plot, I looked for inflection points in the slope and compared dates of these to the dates of significant cumulative land-cover change. I separated the data set at a point that was both the most prominent break in slope and corresponded to a period of significant cumulative land-cover change from what had existed in previous years. I conducted linear regressions (least-squares method) of the South Fork (dependent variable) and the North-Middle Fork (independent variable) cumulative values for the two slopes to determine if there was a statistically significant difference between the two periods.

As a second phase of the analysis I conducted a pre- and post-ecosystem conversion analysis of the annual (i.e., not cumulative) peak flow values, based on the break in slope identified in the first analysis. I developed a linear regression for the pre-treatment period (considered the calibration period, even though land-cover change had already begun) and used this to predict South Fork peak flows from North-Middle Fork peak flows. I then plotted South Fork peak flow values with the regression line and visually compared the difference. I did not determine the statistical significance of actual South Fork peak flows compared to the predicted values, because I did not expect to find significance for individual years. The purpose of the study was to detect a change in trend rather than in individual years.

Determination of Change in Water Available for Runoff

The purpose of this assessment was to determine whether the changes in canopy cover were sufficient to increase the size of peak flows from rain-on-snow storms. Again, due to a lack of site specific data, this part of the analysis is only appropriate as an indicator of the potential for long term multiple-use management to affect rain-on-snow peak flows. The major assumptions of this analysis were: 1) the difference in snow water equivalence (SWE) before and after timber harvest equals additional water available for runoff; and 2) seasonal precipitation patterns in the Tule River watershed are similar to those in the Kings and American River watersheds (in terms of the percentage of annual precipitation delivered by a given date).

Only the first assumption is potentially problematic. The method for determining change in water available for runoff (WAR) was drawn from the watershed analysis guidelines used by the state of Washington (Washington Forest Practices Board 1994; hereafter referred to as the Board) and research conducted by Brunengo et al. (1992) in which available water is based upon varying levels of canopy cover. However, WAR only represents the increase in effective precipitation, not the increase in runoff, which is dependent upon soil properties and flow paths. Therefore, the results of this analysis will only indicate the potential change in water available for runoff in rain-on-snow storms.

Brunengo (1992) determined (empirically) that new clear-cuts retain three times as much snow on the ground as mature forest and that the difference in water available for runoff is the same ratio. The Board modified these values, assigning the difference in water available for runoff between a mature stand and a fully stocked young stand a ratio of 2. The ratio of a mature stand to an intermediate stand is 1.5. Smith and Berg (1982) presented ratios of SWE under three different canopy covers to SWE in open adjacent plots at the Central Sierra Snow Lab. For the months of January and February, the ratios for red fir averaged 0.65, meaning the open areas accumulated 1.5 times more SWE than under fir canopy. Based on these results, I assigned WAR modifiers of 0.65 for forested cover and 0.98 for logged areas (to account for minimal regrowth). These ratios reflect percentage of precipitation intercepted by canopy. I divided the watershed into hydrologic units based upon elevation and mean annual precipitation (MAP). Elevations above 1524 m (5000 ft), approximately one-third of the watershed, were demarcated as subject to rain-on-snow peaks. These elevations also coincide with most of the timber stand. WAR from the remaining watershed area was considered unchanged. The rain-on-snow zone includes four hydrologic zones ranging in MAP from 762 mm to >1,143 mm (30 in to 45 in). These zones are based on an isohyetal map produced by CH2M Hill (1974). Table 7 lists hydrologic units and associated changes in forested area.

To estimate the potential magnitude of changes in WAR from long-term logging in the upper watershed I developed two plausible scenarios of snowpack and snowmelt. Snowpack, precipitation, and temperature data were not available for the South Fork Tule watershed, so I constructed scenarios based on observations of the South Fork Tule combined with normal conditions in other Sierra Nevada watersheds within the rain-on-snow zone. I determined the potential SWE for each month based on monthly distributions of MAP in the Kings (G. M. Kondolf, University of California, Berkeley, conversation with the author, October 30, 1995) and American River watersheds (Smith and Berg 1982). For both watersheds, in an average year 25% of seasonal precipitation has fallen by mid-December. However, the 25% mark may occur as early as late-October and as late as mid-February. The average date for 50% of precipitation is late-January, with extremes of early-December and mid-March (Smith and Berg 1982). The significance of these dates is that warm rainstorms throughout the Sierra are most frequent November through January (McGurk et al. 1993) and there is a greater chance of snowpack for melting later in the season. The potential for a significant change in WAR from a rain-on-snow storm will be greatest after canopy-intercepted snow has melted and accumulation of snow in openings is greatest.

I developed a rain-on-snow scenario based on reasonable SWE values for the Tule River watershed. I determined change in WAR for each hydrologic unit and calculated a weighted total for the forest zone and for the whole watershed (table 8). The scenario assumes that the maximum SWE available for runoff equals the maximum amount of SWE that could be melted by an average, 2-year 24-hour rainstorm, which is approximately 5 cm (R.C. Kattelmann, written communication, 19 December 1995). SWE amounts for before and after logging periods were adjusted by the appropriate canopy cover ratios. I did not construct a maximum potential change in WAR scenario, because there were too many unknown variables for this watershed.

RESULTS

Land-Cover History of the South Fork Tule River Watershed

The South Fork Tule has undergone a continuous increase in cumulative land-cover change in three general spurts, all primarily within the timber zone: 1950, pre-1966, and pre-1972.

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Maps and historical documents indicate that the South Fork was virtually undeveloped and unlogged from the turn-of-the-century until approximately 1950, shortly after a lumber mill was constructed on the TRIR. Conversion of the conifer forest to a logged ecosystem began at this time. Over the period 1950 to 1972, ~140 million board feet (mmbf) were logged from 4,000 ha, 46 percent of the conifer forest (Tule River Planning Commission 1973). Also by 1970, at least 540 ha of dense oak woodland had been converted to grassland. Between 1952 and 1966 area in roads more than doubled, all in the conifer forest. By 1972, there were 165 ha of roadways on the TRIR (Tule River Planning Commission 1973), primarily improved dirt and jeep trails, judging from map designations. An additional 20 to 25-km of improved roads on USFS land appear on maps between 1972 and 1984. Assuming road widths and surfaces based on USFS classifications, the 1972-1984 additional area in roads equals 13 ha.

Records of logging in the USFS section of the South Fork begin in 1961, with pieces of larger salvage cuts on neighboring watersheds occurring in 1961 and 1962. Light timber harvest continued through 1972. Between 1984 and 1989, 550 ha were clear-cut. A second boom in road construction in the conifer forest occurred between 1972 and 1984, when logging increased on the USFS land (between 1972 and 1984, these timber stands changed ownership from private inholdings to USFS). Apparently, a modest amount of timber (12 mmbf) was thinned from TRIR land from 1977 to 1987. Aerial photographs show that woodland area converted to grassland doubled by 1979. A range management plan called for a continuation of type conversion, but with an emphasis on thinning rather than clearing. By 1984, 12 to 34 years of regeneration had occurred on timber stands that had been harvested between 1950 and 1972. Not all stands had regenerated successfully (U.S. Soil Conservation Service 1979).

A conservative estimate of timber harvest over the period 1950 to 1972 is 146 mmbf on 4,210 ha, or ~50% of the conifer forest. From 1972 to 1989, approximately 18 mmbf of additional timber was harvested on 590 ha, for a total of ~56% of the forest. Road area in the entire watershed increased at minimum 170 ha between 1950 and 1984. Most of the road construction occurred in the upper watershed. This brings the altered area to ~58% of the forest zone and ~21% of the entire watershed (see table 7). These estimates do not include landings and only include roads that have been recorded on published maps.

Range reports state that the primary grazing sites were overgrazed and compaction occurred at watering sites. There is no indication as to whether grazing area and intensity increased significantly over the period of study. The oak woodland thinning and chaparral conversion that were recommended in range documents were intended to alleviate existing grazing problems and perhaps increase the herd. Compared to the harvest of over half of the timber zone, hydrologic changes from this scale of grazing management are expected to be minimal. A similar conclusion applies to rural development within the TRIR. The sources used here indicate that no significant expansion took place between 1940 and 1988.

Due to the diversity of the data sources and the patchy coverage over the study period, the estimates of land cover change are approximate. Percentages should be viewed as the magnitude of change rather than precise values. The greatest uncertainty lies in the rate of logging that occurred between 1950 and 1970. This point is important in determining the amount and age of regrowth that occurred by the end of the study period.

Peak Flows

The double-mass plot of cumulative peak flow showed a definite break in slope occurring sometime after 1950 (figure 3). The points for years 1967 and 1969 fall where the break in slope begins and could go with either slope. Because the land-cover change was cumulative, it is likely that the change became significant enough to affect a detectable change in peak flows by 1967, around seventeen years after timber harvest began. By 1966, road area in the timber zone had doubled. Hence, I separated the pre- and post-periods at water year 1967: the period before significant land-cover change is 1940 to 1963 (5 flows); the significantly altered land-cover period is 1967 to 1988 (7 flows) (see table 6 for Q2 and larger size flows in each period).

The results of the linear regressions for South Fork versus North-Middle Fork cumulative peak flows for each period are shown in figure 4. The slope of the double-mass plots for the before and after periods are 0.62 and 1.25, respectively. The fit is very high for both slopes, with the North-Middle Fork explaining 98% and 99% of variation in the South Fork for the before and after periods, respectively. Most importantly, there is no overlap in slope between the two periods (the 95% confidence intervals for each slope do not overlap with each other), indicating a statistically significant difference in trend between the two periods.

A second method of viewing the results was to generate a pre-conversion relationship of individual peak flows (i.e. non-cumulative), predict the post-conversion South Fork values, and plot the calibration slope with the observed values. Figure 5 shows that five of the seven post-conversion peak flows fall above the regression line, meaning that the pre-conversion relationship underestimates these post-change peak flows. No statistical significance is implied from this plot.

Change in Water Available for Runoff (WAR) in Rain-on-Snow Zone

The hypothetical SWE and storms produced only slight increases in WAR between the pre- and post-logging periods (table 8). Increases of 10% or more were only produced on the headwaters. The lack of change in the lower part of the watershed masked the increases in WAR from the upper watershed. The scenario resulted in increases of WAR of 6 to 15-mm , with the highest increase generated from the hydrologic unit with the highest precipitation and greatest area logged. The area-weighted increase in WAR was 9 mm (5%) across the forest zone and 3 mm (5%) for the whole watershed. Although I did not determine a test for the statistical significance of the changes in WAR, these values would be within the margin of error of USGS stream gauge data.

DISCUSSION

Peak Flows

These results indicate the primary factors altering conditions in the South Fork Tule watershed are timber harvest and road construction. Although the effects of each factor cannot be conclusively separated, the more drastic factor in terms of watershed area is the amount of forest removed from logging. Results also suggest that logging dominated multiple-use management may be associated with increased peak flows on the South Fork Tule River. The effects of fire-suppression in the North-Middle Fork may also reduce peak flows in that watershed, accounting for the perceived increase in the South Fork. However, the 40% of the

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South Fork timber zone that was not logged has also been managed under a fire-suppression policy since the 1900s. It is unlikely that the forest canopy of the North-Middle Fork could have increased nearly as much as forest canopy has been reduced on the South Fork. Competition for water, light, and soil nutrients would put a limit on the amount increased density, even without fire.

The hypothetical WAR results indicate that the amount of timber harvest documented for the South Fork may be sufficient to increase WAR, hence peak flows. However, the method used to estimate changes in WAR from timber harvest probably underestimates potential increases. The method accounts for reduced canopy interception from clear-cutting, but does not incorporate the greater potential for snowmelt in the openings. Because I did not develop a relationship between increase in WAR and increase in peak flow (primarily due to the fact that WAR is more a factor of wind speed than storm size), I cannot conclude the magnitude of an increase in peak flows, nor can I determine the recurrence interval in question. If the watershed soils were previously saturated from prior snowmelt one could assume that any increase in WAR (especially from a cleared area) would translate to stormflow. This assumption would also be valid due to the extremely permeable soils underlain by unfractured bedrock. If one assumes that the 2-year storm typically generates a 2-year peak flow, a rough analysis of the effect of increased WAR on a potential channel-forming flow may be made. Under these conditions, the increase in WAR of 5% across the watershed would not increase the Q2 flow to Q5 size for this hypothetical example. Increases in peak flows could still be significant to channel geomorphology in headwater streams within the forested zone. Furthermore, without monitoring of streamflow and beneficial uses specific to this and similar Sierra watersheds, one cannot conclude that no negative effects will occur from these increases in peak flow.

A weakness of this study is the small data set. Although the period of record covers years 1940 to 1989 (with a few missing years), only twelve pairs of Q2 and larger annual peak flows could be matched. Since climate data were not readily available for the two watersheds, I could not completely rule out the possibility that climate change has affected the records of either watershed. Some researchers have documented a decrease in April to July runoff relative to total annual runoff from Sierran watersheds (Roos 1991). This trend may instead be viewed as an increase in total annual runoff concentrated in winter runoff (Wahl 1991). This trend would indicate an increase in rain-dominated winter storms or in winter and early spring snowmelt due to increasing temperatures (Pupacko 1993). If there has been a change in climate exposing snowpack to warm storms, the effect on peak flows would be greater in a watershed that had been extensively logged.

<u>The Roles of Historical Trend Studies and Controlled Experiments in Determining the Effects of Multiple-use</u>

The only non-modeling investigations of the long-term effects of "ecosystem conversion" on peak flows in the Sierra Nevada are post-watershed change assessments. Because these studies are conducted after land-use and land-cover change have occurred and do not conform to the requirements of a controlled catchment experiment, many researchers are reluctant to accept the results. However, these studies provide information that the controlled catchment experiments are incapable of providing: a case study of watershed management conducted with the complexities and problems of multiple-use policies. Controlled experiments are essential to tease out the hydrological effects of specific actions, such as removing vegetation, while holding all other factors equal. However, the typical short-term controlled experiment cannot capture the hydrological effects of long-term interacting changes in natural factors such as climate, fire, and insect populations. Nor can controlled experiments simulate the individual and cumulative effects of a commercial timber harvest conducted under a variety of constraints; residential development patterns; or political and economic pressure to protect or exploit a variety of natural resources within the watershed. The results of controlled experiments may be used to develop comprehensive models, calibrated by real data, capable of simulating past or future hydrologic change, but the accuracy of the results and conclusions are dependent upon the factors used to develop the model. Calibration does not make up for missing components or gaps in theory.

Post-treatment research is invaluable in that it checks the assumptions and results of controlled experiments and modeling simulations. Vegetation management in actual practice will rarely approximate the "treatment watershed" in a controlled experiment. Typically, there will be other practices occurring upstream or downstream in the watershed, prescribed Best Management Practices (BMPs) will have to be altered to fit the budget of the project, as will "programmed" watershed restoration projects. The effects of past management choices will unexpectedly crop up (e.g. sediment wedges accumulating behind rotting culverts). Also, hydrological theory is not completely developed, and modeling simulations may fit a data set while masking effects. For example, a study on the effects of timber harvest on peak flows in an Oregon watershed concluded that peaks were unaffected by harvest. Although the test was statistically correct, the experiment method masked the changes in peak flows caused by rain-on-snow storms (Harr 1986).

Long-term monitoring of land-cover change and hydrologic response would both demonstrate the usefulness of controlled experiments for predicting the important consequences of land-use choices and call attention to the potential gaps in theory. USGS gauge data is a potential source of this long-term monitoring. Preferably, USGS monitoring would have been conducted with ecological assessments in mind, from implementation of gauges, through changes in land use, to the present. However, historical reconstructions are possible and wherever continuous gauge data exists, there is a potential to discover what really happens to a hydrologic system when its watershed is progressively converted to a full-fledged human ecosystem. Then, supplemented with findings from controlled experiments and modeling, the complex webs of cause and effect may be unraveled.

CONCLUSIONS

Analyses of land-cover change, potential increase in water available for runoff, and channel-forming (annual series) peak flows were conducted to determine the long-term effects of watershed conversion to a logged ecosystem. Over the period 1940 to 1989, land-cover had changed significantly on the South Fork Tule, primarily in the form of timber harvest and new road construction. Beginning around 1950, cumulative land-conversion progressed slowly until sometime prior to 1966, at which point the rate of conversion increased. The forest zone canopy was reduced by at least 58%. Across the watershed, the forest and woodland was reduced by at least 21%.

The significant cumulative change in land-cover corresponded to an inflection point found in a double-mass plot of South Fork (dependent variable) and North-Middle Fork (independent variable) peak flows. Separation of the slope at the inflection point, between water years 1963 and 1967, produced two slopes without overlapping confidence intervals (95%). The slope of the post-conversion period peaks was double the slope of the pre-conversion period. Thus, the increase in peak flows tracked with time and cumulative logging and road construction. The analysis did not determine the size of the increase.

Two hypothetical rain-on-snow storms with varying amounts of snowpack indicated that the decrease in canopy cover resulting in increased snowpack subject to latent and sensible heat flux may be responsible for at least part of the increased peak flows. The hypothetical snowpack and storm scenarios were insufficient to increase the Q2 to the Q5 peak flow size.

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Table 1. Western United States water yield experiments used in regression analysis

Location	Study site	Type of study	Percentage of watershed treated	Mean Annual Precipitation MAP (mm)	Mean Annual Flow MAF (mm)	MAF/ MAP Ratio	Increase in Flow (mm)	References	Study No.
Beaver Creek, AZ	WS 1	paired catchment	100%	457	20	0.04	0	Brown (1971); Clary et al. (1974); Hibbert (1979)	10
Beaver Creek, AZ	WS 3	paired catchment	83%	457	18	0.04	11.4	Brown (1971); Clary et al. (1974); Hibbert (1979)	11
Beaver Creek, AZ	WS 6	paired catchment	100%	508	67	0.13	11.3	Brown (1971); Clary et al. (1974)	12
Beaver Creek, AZ	WS 12	paired catchment	100%	621	152	0.24	68.7	Brown (1971)	13
Beaver Creek, AZ	WS 9	paired catchment	33%	686	172	0.25	72.9	Brown (1971)	15
Castle Creek, AZ	West Fork	paired catchment	100%	639	71	0.11	16.5	Rich (1968, 1972); Rich and Thompson (1974)	16
Coyote Creek, OR	1	paired catchment	50%	1229	627	0.51	60	Harr (1976, 1983); Harr et al. (1979)	40
Coyote Creek, OR	2	paired catchment	30%	1229	643	0.52	90	Harr (1976, 1983); Harr et al. (1979)	41
Coyote Creek, OR	3	paired catchment	100%	1229	674	0.55	290	Harr (1976, 1983); Harr et al. (1979)	42
Deadhorse Creek, CO	North Fork	paired catchment	36%	648	147	0.23	75	Alexander and Watkins (1977); Troendle (1983); Troendle and King (1987)	43
Entiat, WA	McCree	uncontrolled for climate	100%	579	112	0.19	91	Helvey (1973, 1980)	45
Entiat, WA	Burns	uncontrolled for climate	100%	597	155	0.26	74	Helvey (1973, 1980)	46
Entiat, WA	Fox	uncontrolled for climate	100%	-	175	-	112	Helvey (1973, 1980)	47
Fox Creek, OR	FC-1	paired catchment	25%	2790	2710	.97	0	Harr (1976, 1980); Harr and Fredriksen (1988)	60
Fox Creek, OR	FC-3	paired catchment	25%	2840	2350	0.83	0	Harr (1976, 1980); Harr and Fredriksen (1988)	61
Frazer, CO	Fool Creek	paired catchment	40%	762	283	0.37	115	Alexander and Watkins (1977); Troendle and King (1985)	62
H.J. Andrews, OR	WS 1	paired catchment	100%	2388	1376	0.58	418	Rothacher (1970, 1973); Harr (1976, 1986); Harr et al. (1979) Hicks, Beschta, and Harr (1991)	64

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Table 1 (Continued)

Location	Study site	Type of study	Percentage of watershed treated	Mean annual precipitation MAP (mm)	Mean annual flow MAF (mm)	MAF/ MAP ratio	Increase in flow (mm)	References	Study No.
H.J. Andrews, OR	WS 3	paired catchment	25%	2388	1346	0.56	218	Rothacher (1970); Harr (1976, 1986); Harr et al. (1979); Hicks, Beschta, and Harr (1991)	65
H.J. Andrews, OR	WS 6	paired catchment	100%	2150	1290	0.60	322	Rothacher (1970); Harr (1976); Harr et al. (1979)	66
H.J. Andrews, OR	WS 7	paired catchment	60%	2150	1290	0.60	176	Rothacher (1970); Harr (1976); Harr et al. (1979)	67
H.J. Andrews, OR	WS 10	paired catchment	100%	2330	1650	0.71	243	Rothacher (1970); Harr (1976, 1986); Harr et al. (1979)	68
Meeker, CO	White River	uncontrolled for climate	30%	400	261	0.65	39	Love (1955)	92
Salmon Creek, CA	Burton	paired catchment	25%	953	157	0.16	0	McCammon (1977)	104
Sierra Ancha, AZ	North Fork, Workman Creek (a)	paired catchment	32%	813	86	0.11	31.4	Rich et al. (1961); Ingebo and Hibbert (1974); Rich and Gottfried (1976); Hibbert (1979)	108
Sierra Ancha, AZ	North Fork, Workman Creek (b)	paired catchment	73%	813	86	0.11	76.6	Rich et al. (1961); Rich and Gottfried (1976); Hibbert (1979)	109
Sierra Ancha, AZ	South Fork, Workman Creek (a)	paired catchment	45%	813	87	0.11	0	Rich et al. (1961); Rich and Gottfried (1976); Hibbert (1979)	111
Sierra Ancha, AZ	South Fork, Workman Creek (b)	paired catchment	83%	813	87	0.11	93	Rich et al. (1961); Ingebo and Hibbert (1974); Rich and Gottfried (1976); Hibbert (1979)	300
Wagon Wheel Gap, CO	B	paired catchment	100%	536	157	0.30	28.2	Bates and Henry (1928); Reinhart et al. (1963); Van Haveren (1981)	123
Deadhorse Creek, CO	Inter-basin area	paired catchment	28%	-	-	-	0	Alexander and Watkins (1977); Troendle (1983); Troendle and King (1987)	210
Deadhorse Creek, CO	North Slope (8)	paired catchment	40%	-	-	-	0	Alexander and Watkins (1977); Troendle (1983); Troendle and King (1987)	211
Thomas Creek, AZ	South Fork	paired catchment	34%	768	82	0.11	44	Gottfried (1991)	301

Table 2. Site features of water yield experiments used in regression analysis

Location	Study Site	Drainage Area (ha)	Mid-area Elevation (m)	Aspect	Percent Slope	Vegetation	Soils	Soil Depth (cm)	Treatment	Study No.
Beaver Creek, AZ	WS 1	124	1700	W	21%	Utah juniper-pinyon forest	volcanic rock, soils stoney clay	<60	cleared by cabling and burning	10
Beaver Creek, AZ	WS 3	146	1600	W	7%	Utah juniper-pinyon forest	volcanic rock, soils stoney clay	<60	herbicide application to overstory, no vegetation removal	11
Beaver Creek, AZ	WS 6	42	1977	SW	5%	alligator and Utah juniper-ponderosa pine forest	silty clay	<76	clear-cut	12
Beaver Creek, AZ	WS 12	184	2157	SW	7%	ponderosa pine, gambel oak, alligator juniper	silty clay	<60	clear-cut	13
Beaver Creek, AZ	WS 9	452	2246	W	6%	ponderosa pine and gambel oak	silty clay loam	<60	clear-cut in strips	15
Castle Creek, AZ	West Fork	364	2500	SE	-	ponderosa pine	igneous origin	-	clear-cut and thinned	16
Coyote Creek, OR	1	69	900	NE	23-36% average	Douglas fir, mixed conifer	well-drained gravely loam, altered volcaniclistic parent material	50-150	shelterwood cut by tractor	40
Coyote Creek, OR	2	68	900	NE	23-36% average	Douglas fir, mixed conifer	well-drained gravely loam, altered volcaniclistic parent material	50-150	patch-cut; 14% by tractor, 16% by high-lead	41
Coyote Creek, OR	3	50	900	NE	23-36% average	Douglas fir, mixed conifer	well-drained gravely loam, altered volcaniclistic parent material	50-150	clear-cut; 23% by tractor, 77% by high lead	42
Deadhorse Creek, CO	North Fork	41	-	S	~40%	old-growth lodgepole pine	angular gravel and stone derived from schist and gneiss rocks	-	commercial clear-cut (2450 cu m or 168 cu m/ha) downhill skidding	43
Entiat, WA	McCree	514	1348	SE	-	Ponderosa pine and Douglas fir	sandy loam	-	burned	45
Entiat, WA	Burns	563	1403	-	-	Ponderosa pine and Douglas fir	sandy loam	-	burned	46
Entiat, WA	Fox	473	1495	-	-	Ponderosa pine and Douglas fir	sandy loam	-	burned	47

Table 2 (Continued)

Location	Study Site	Drainage Area (ha)	Mid-area Elevation (m)	Aspect	Percent Slope	Vegetation	Soils	Soil Depth (cm)	Treatment	Study No.
Fox Creek, OR	FC-1	59	895	WNW	5-9% average	Pacific silver fir, overmature western hemlock and Douglas-fir	silt loams or stony, cobbly loams	100-300	clear-cut by high-lead (1969)	60
Fox Creek, OR	FC-3	71	920	W	5-9% average	Douglas fir, western hemlock	silt loams or stony, cobbly loams	100-300	clear-cut by tractor (6%)and high-lead (19%) (1971-1972)	61
Frazer, CO	Fool Creek	289	3200	N	-	77% subalpine forest (lodgepole pine, spruce-fir); 23% alpine forest	angular gravel and stone derived from schist and gneiss rocks	-	commercial cut in strips perpendicular to contour	62
H.J. Andrews, OR	WS 1	96	700	NW	53-63%	Douglas-fir, western hemlock	gravely loams and clay loams, altered volcaniclistic parent material	-	commercial clear-cut by skyline suspension	64
H.J. Andrews, OR	WS 3	101	760	NW	53-63%	Douglas-fir, western hemlock	gravely loams and clay loams, altered volcaniclistic parent material	-	patch-cut by high-lead cable	65
H.J. Andrews, OR	WS 6	13	900	S	27-31%	Douglas-fir	relatively unaltered volcaniclastic parent material	-	clear-cut, 93% by high-lead cable, 7% by tractor	66
H.J. Andrews, OR	WS 7	21	900	S	27-31%	Douglas-fir	relatively unaltered volcaniclastic parent material	-	shelterwood cut, 40% by high-lead cable, 60% by tractor	67
H.J. Andrews, OR	WS 10	9	500	SW	65-70%	Douglas-fir, western hemlock	altered volcaniclastic parent material	-	clear-cut by high-lead cable	68
Meeker, CO	White River	308	-	-	-	spruce		-	80% killed by insect infestation	92
Salmon Creek, CA	Burton	119	2490	N	30-50%	montane chaparral and ponderosa pine-red fir forest	gravely sandy loam to loamy sand	-	commercial selection harvest	104
Sierra Ancha, AZ	North Fork, Workman Creek (a)	100	2225	SW	-	ponderosa pine	clay loam	up to 5	moist site cleared	108
Sierra Ancha, AZ	North Fork, Workman Creek (b)	100	2225	SW	-	ponderosa pine	clay loam	up to 5	dry site cleared	109

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Table 2 (Continued)

Location	Study Site	Drainage Area (ha)	Mid-area Elevation (m)	Aspect	Percent Slope	Vegetation	Soils	Soil Depth (cm)	Treatment	Study No.
Sierra Ancha, AZ	South Fork, Workman Creek (a)	129	2165	NW	-	ponderosa pine	clay loam	up to 5	clear-cut and thinned	111
Sierra Ancha, AZ	South Fork, Workman Creek (b)	78	~2250	E	~40%	spruce-fir, lodgepole pine	angular gravel and stone derived from schist and gneiss rocks	-	Partial cut	300
Wagon Wheel Gap, CO	B	81	3110	NE	-	84% aspen and conifer	augite, quartzite, rocky clay loam	-	clear-cut	123
Deadhorse Creek, CO	Inter-basin area	141	~3200	E	~40%	lodgepole pine-spruce-fir	angular gravel and stone derived from schist and gneiss rocks	-	treatment of North Fork (15 ha) and North Slope (24 ha)	210
Deadhorse Creek, CO	North Slope (8)	41	-	N	~40%	spruce-fir	angular gravel and stone derived from schist and gneiss rocks	-	selection cut	211
Thomas Creek, AZ	South Fork	227	2667	N and S	22%	old-growth southwestern mixed conifer	loamy-skeletal Alfisols formed from basalt material and alluvial deposits	51-102+	patch clear-cutting, group selection, and single-tree selection	301

Table 3. Summary of runoff versus treatment results

Model Description	Mean runoff per 10% change in treatment	95% confidence limits	R^2	Statistical level of confidence	N	Reference
World-wide, treatment-runoff	~40 mm	not reported	0.42	not reported	94	Bosch and Hewlett, 1982
Western U.S. mountains, treatment-runoff	12 mm	0-24 mm	0.14	95%	31	this paper
Sierra MAP range (500-2400 mm), treatment-runoff	13 mm	0-26 mm	0.14	90%	26	this paper
MAP 400 - 610 mm, treatment-runoff	4 mm	-5-12 mm	0.14	not significant (67%)	9	this paper
MAP 630 - 960 mm, treatment-runoff	5 mm	-6-15 mm	0.09	not significant (63%)	11	this paper
MAP 950 - 2400 mm, treatment-runoff	31 mm	10-52 mm	0.64	95%	9	this paper
Sequoia National Forest MAP range (510-1230 mm), treatment-runoff	8 mm	-1-18 mm	0.16	90%	20	this paper
Southern aspect, MAP 500-2400 mm, treatment-runoff	9 mm	-15-32 mm	0.07	not significant (56%)	11	this paper
Northern aspect, MAP 500-2400 mm, treatment-runoff	23 mm	-3-49 mm	0.28	90%	12	this paper
Mixed conifer, treatment-runoff	5 mm	-2-12 mm	0.18	not significant (83%)	12	this paper
Lodgepole pine-spruce-fir, treatment-runoff	2 mm	-21-25 mm	0.01	not significant (18%)	6	this paper
Douglas fir, treatment-runoff	27 mm	3-51 mm	0.56	95%	8	this paper
Western U.S. mountains, multiple regression (see text)	14 mm	8-20 mm	0.80	99%	31	this paper
MAP 500-2400 mm, multiple regression	12 mm	4-19 mm	0.81	95%	26	this paper
MAP 400 - 610 mm, multiple regression	6 mm	-5-17 mm	0.78	not significant (80%)	9	this paper
MAP 630 - 960 mm, multiple regression	7 mm	-3-16 mm	0.68	not significant (86%)	11	this paper
MAP 950 - 2400 mm, multiple regression	30 mm	12-48 mm	0.93	99%	9	this paper
Sequoia National Forest MAP range (510-1230 mm), multiple regression	8 mm	0-16 mm	0.57	95%	20	this paper
Southern aspect, MAP 500-2400 mm, multiple regression	8 mm	-5-21 mm	0.90	not significant (80%)	11	this paper
Northern aspect, MAP 500-2400 mm, multiple regression	18 mm	3-32 mm	0.87	95%	12	this paper
Mixed conifer, multiple regression	3 mm	-8-14 mm	0.58	not significant (43%)	12	this paper
Lodgepole pine-spruce-fir, multiple regression	-5 mm	-22-13 mm	1.00	not significant (83%)	6	this paper
Douglas fir, multiple regression	27 mm	-5-59 mm	0.91	90%	8	this paper

Table 4. Projected change in forest cover by Sierra Nevada region

FRRAP Region	Productive Available Timberland (acres)	1980-1990 Inventory (mbf)	1980-1990 Average Annual Harvest (mbf)	(%)	1990-2000 Average Annual Harvest (mbf)	(%)	Average Annual Change in Harvest (mbf)	(%)	1980-1990 Average Annual Growth (mbf)	1990-2000 Average Annual Growth (mbf)	Average Annual Change in Growth (mbf)	(%)
Sacramento (Northern Sierra)	1,778,000	29,587,200	394,476	1.33%	430,214	1.45%	35,738	0.12%	393,850	406,308	12,458	0.04%
Central Sierra	1,211,000	30,296,320	469,295	1.55%	496,233	1.64%	26,938	0.09%	441,069	402,401	-38,668	-0.13%
San Joaquin (Southern Sierra)	948,000	9,013,802	99,951	1.11%	112,382	1.25%	12,431	0.14%	105,929	117,207	11,278	0.13%
Sierra Total	3,937,000	68,897,322	963,722	1.40%	1,038,829	1.51%	75,107	0.11%	940,848	925,916	-14,932	-0.02%

Table 5. Range in annual runoff increases from projected changes in forest cover

FRRAP Region	Average Annual Change in Timber Volume (mbf)	(%)	Average Annual 50 yr Min. (mm)	Average Annual 50 yr Max. (mm)
Sacramento (Northern Sierra)	-23,280	-0.08%	1	4
Central Sierra	-65,606	-0.22%	2	11
San Joaquin (Southern Sierra)	- 1,153	-0.01%	0	0
Sierra Total	-90,039	-0.13%	1	6

Table 6. Peak flow pairs used in analysis.

year	month	South Fork (cms)	North-Middle Fork (cms)
1943	3	176	62
1945	2	55	34
1951	11	201	311
1957	5	32	53
1963	2	50	155
1967	12	405	478
1969	1	149	144
1970	1	96	69
1980	1	186	178
1982	4	114	73
1983	12	59	26
1984	11	66	38

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Table 7. Hydrologic units in the South Fork Tule Watershed

Hydrologic Unit	Mean Annual Precipitation (mm)	Pre-logging vegetated area (ha)	Area logged (ha)	Percentage logged (%)	Post-logging vegetated area (ha)	Post-logging vegetated area (%)
Forest Zone						
A	>1143	1253	1183	94	70	6
B	1016 - 1143	2723	1062	39	1661	61
C	889 - 1015	2334	715	31	1619	69
D	762 - 888	2230	2006	90	224	10
total forest zone		**8540**	**4966**	**58**	**3574**	**42**
Woodland, Chaparral, and Grassland Zone						
E	457 - 761	19660	1000	5	18660	95
total watershed area		**28200**	**5966**	**21**	**22234**	**79**

Table 8. Water available for runoff

Hydrologic Unit	Pre-logging SWE (mm)	Post-logging SWE (mm)	Change in SWE (mm)	Estimated 2-yr, 24-hr rainfall (mm)*	Pre-logging WAR (mm)	Post-logging WAR (mm)	Percentage change in WAR
A	33	48	15	102	135	150	11%
B	33	39	6	89	122	128	5%
C	26	32	6	76	102	108	6%
D	26	38	12	64	90	102	13%
Total Forest						**9**	**5%**
E	0	0	0	38	38	38	0%
Total Watershed						**3**	**5%**

*Adapted from Dunne and Leopold 1978.

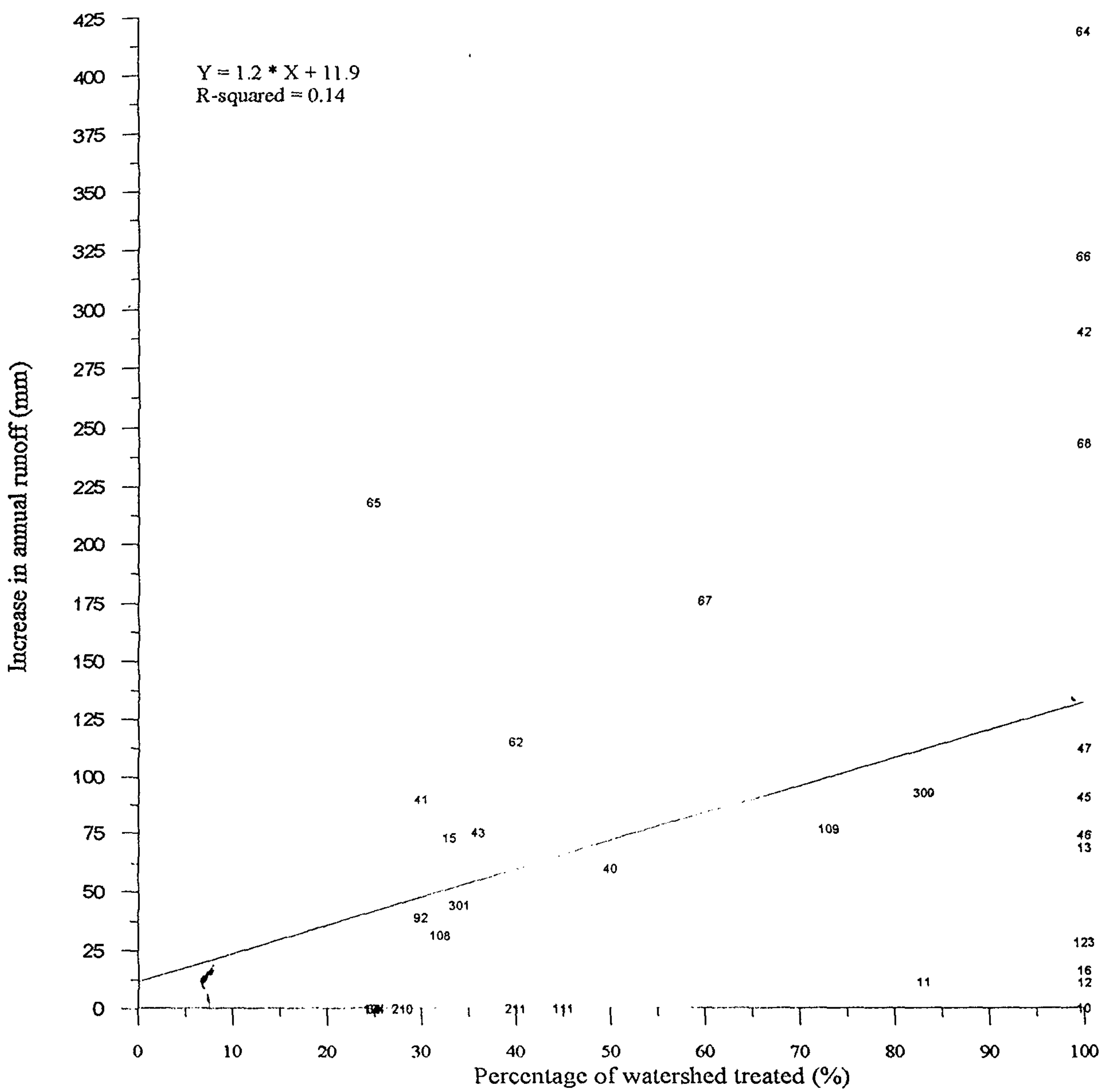

Figure 1. Regression results of increase in runoff versus percentage of watershed treated for the western United States data set. Symbols correspond to study numbers in tables 1 and 2.

D-049064

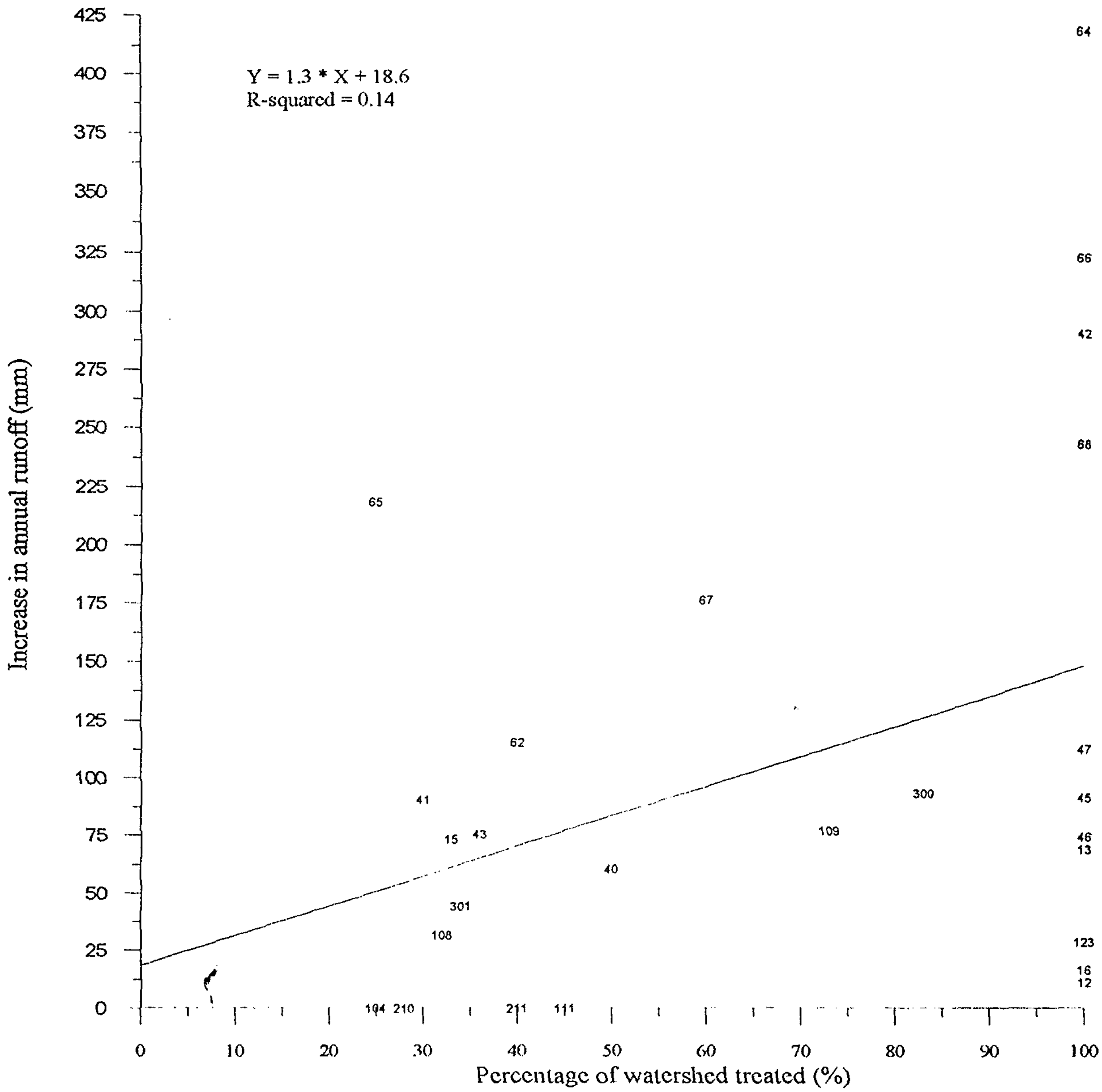

Figure 2. Regression results of increase in runoff versus percentage of watershed treated after restricting mean annual precipitation to a range typical of the Sierra Nevada. Symbols correspond to study numbers in tables 1 and 2.

D-049065

D-049065

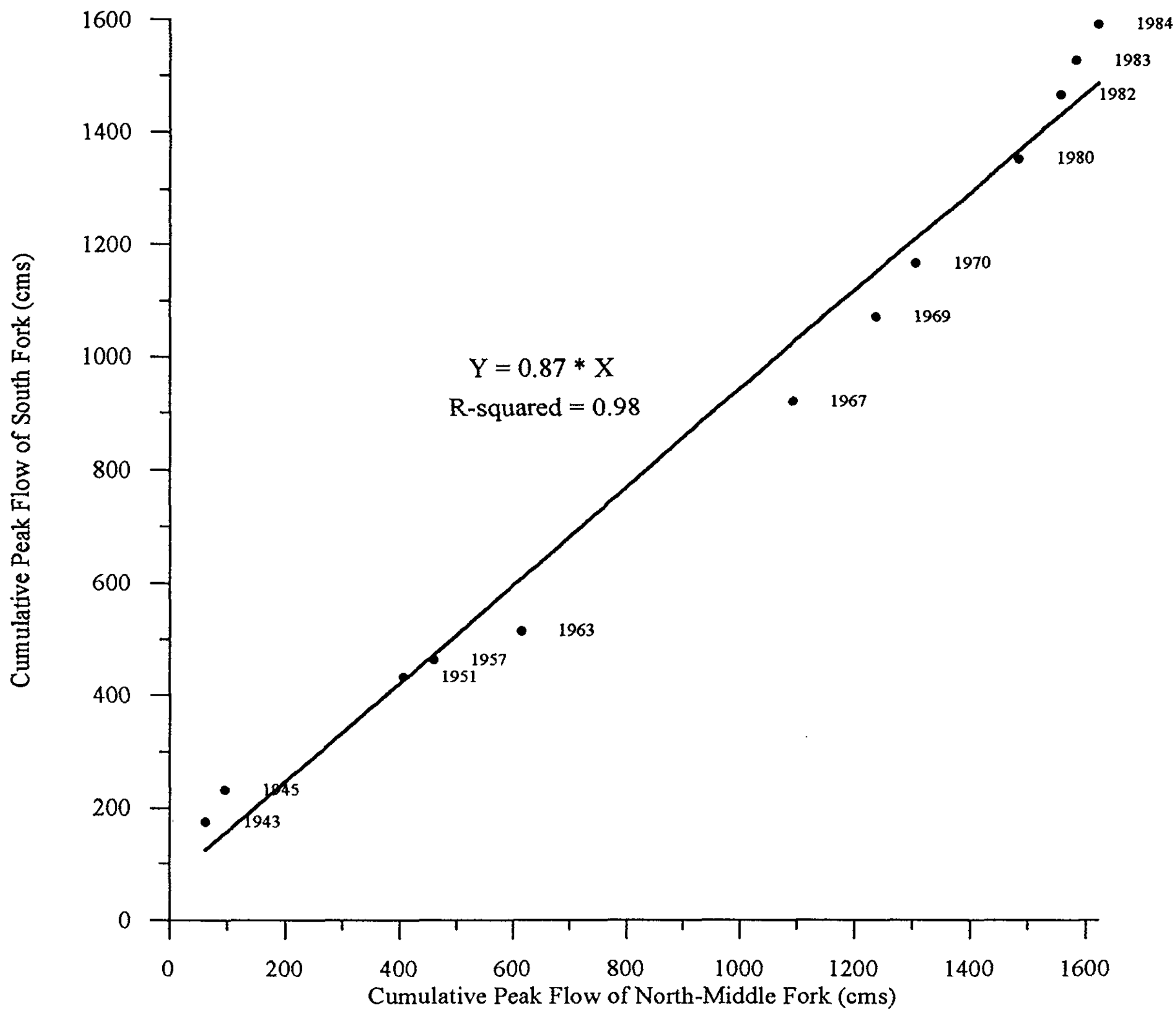

Figure . Double-mass plot of cumulative peak flows of the South Fork and North-Middle Fork Tule River. Curve was fitted by least-squares regression.

D-049066

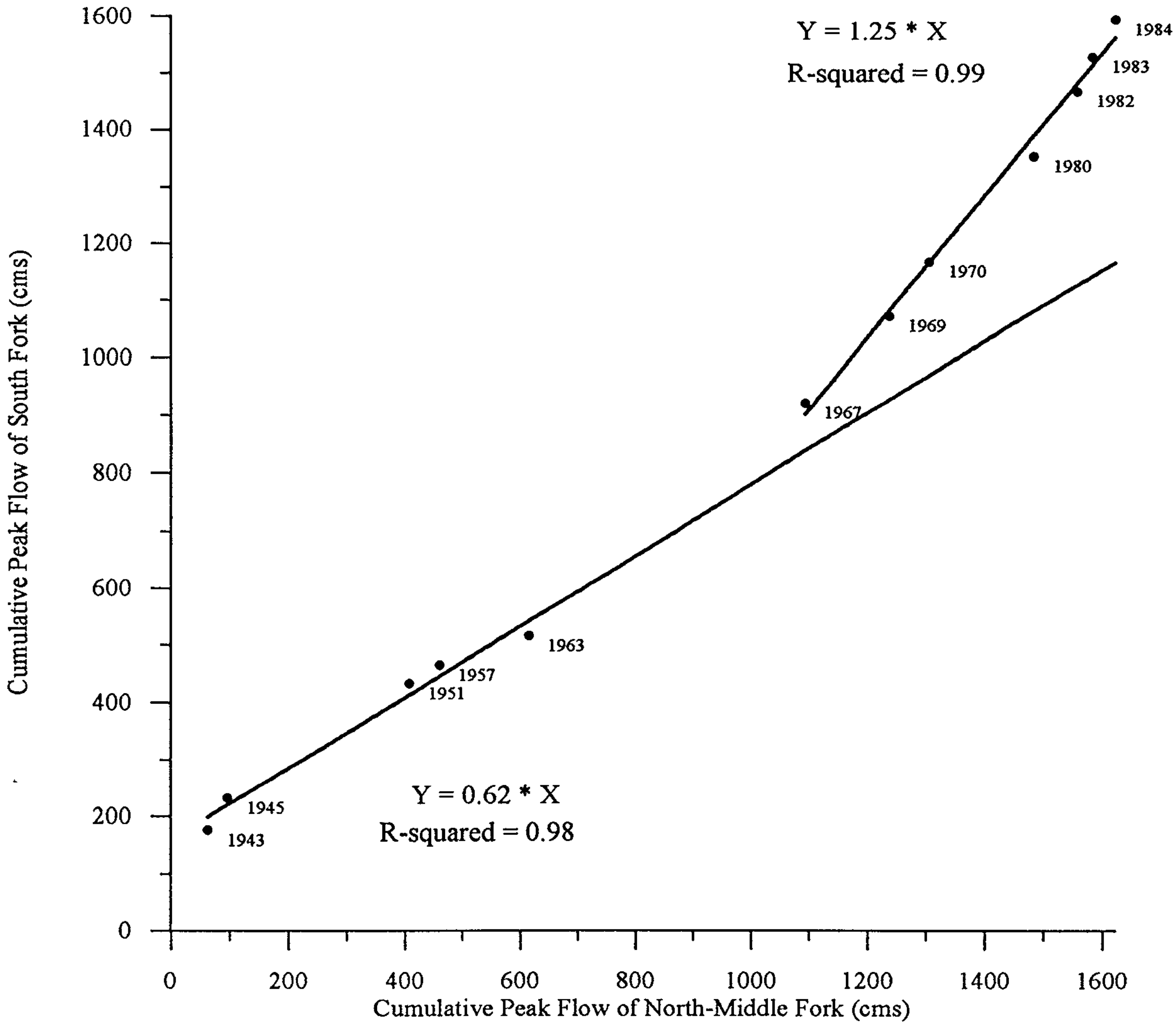

Figure . Double-mass plot of cumulative peak flows of the South Fork and North-Middle Fork Tule River for periods 1943-1963 and 1967-1984. Curves were fitted by least-squares regression.

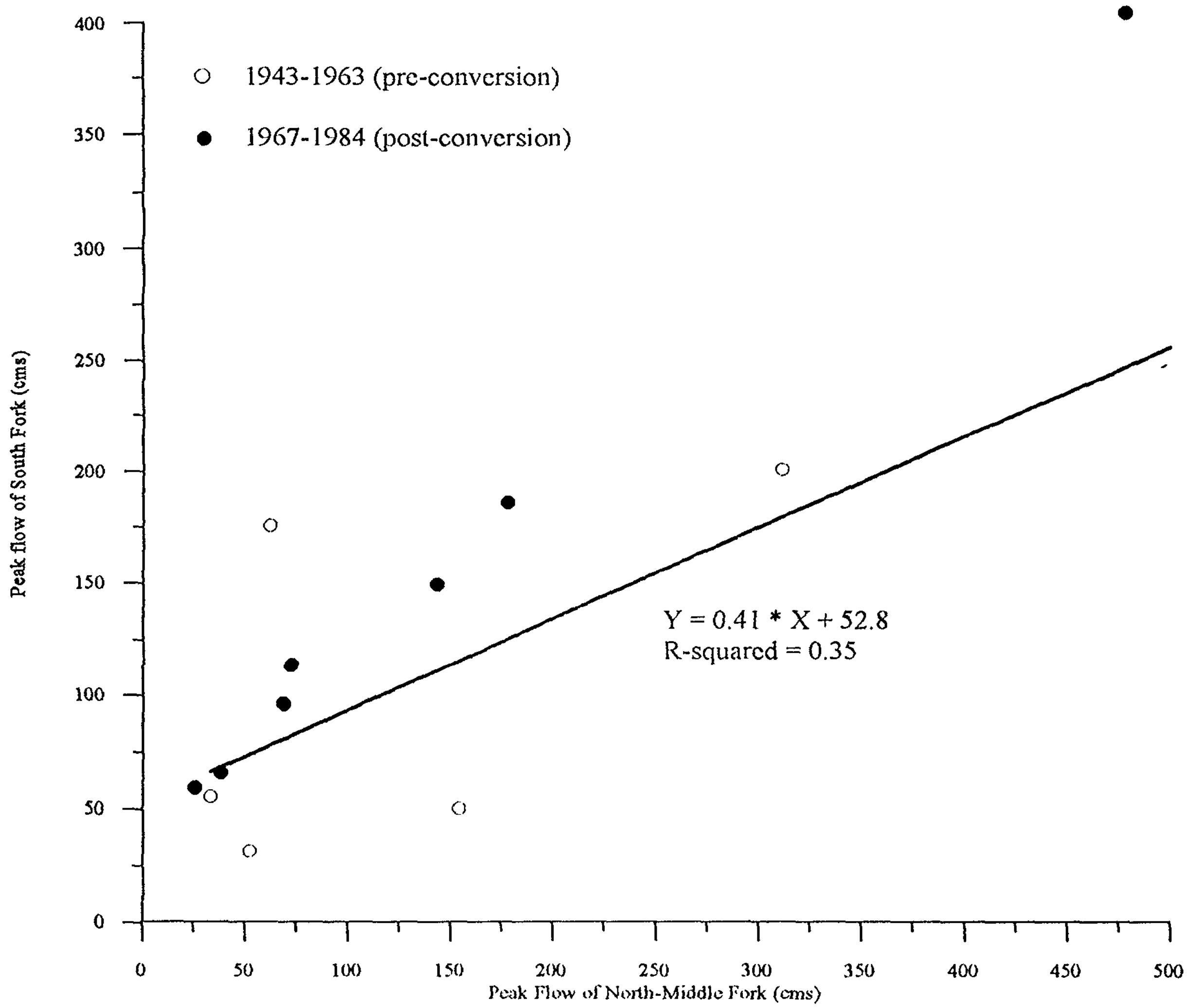

Figure . Relationship between annual peak flows on the South Fork and North-Middle Fork Tule River during the pre- and post-conversion periods. See text for explanation.