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MODERATE TIMBER HARVESTING INCREASES WATER YIELDS FROM AN ARIZONA MIXED CONIFER WATERSHED[1]

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ABSTRACT: A paired watershed design was used to evaluate the effects of a management prescription which included patch clearcutting, group selection, and single-tree selection harvesting on water yield improvement. The harvest created 63 openings, averaging 0.5 ha in size over 13 percent of the watershed area. Stand density was reduced by 34 percent to 30 m^2/ha. Average annual streamflow for the initial eight-year period since treatment increased significantly by about 45 percent, or 44 mm, mostly because of increased winter runoff. A greater proportion of the snowmelt-generated streamflow occurred earlier in the spring, while annual peak flows were increased by an average of 65 percent, or about 28.42 l/s/km^2. Maximum snow water equivalents remained unchanged. The primary causes of the increases were reduced evapotranspiration and increased snow accumulation in the openings; however, it appears that the partially cut stand contributed to the increases.

(KEY TERMS: water yield improvement; peak flows; patch clearcutting; partial harvesting; mixed conifer forests; Arizona.)

INTRODUCTION

The southwestern mixed conifer and associated aspen and spruce-fir forests cover approximately 1.0 million ha of high elevation lands in Arizona and New Mexico. These forests are found on about 132,300 ha in Arizona, about 0.4 percent of the state (Spencer, 1966), while approximately 3 percent of New Mexico supports these moist-site forests (Choate, 1966).

Although the mixed conifer and associate forest types only cover a small area, they produce a wide range of commercial and noncommercial products. These forests occupy watersheds which receive high amounts of precipitation, especially as snow, and have relatively lower evapotranspiration demands than most other vegetation types in the Southwest. Water, which is not used on site, runs off and becomes the source for most of the region's major rivers. In Arizona, 6 percent of the state's surface water supply originates from the relatively small area occupied by mixed conifer watersheds (Rich and Thompson, 1974). Water management in this zone can contribute to regional and local water requirements.

Managers must consider alternative management strategies to arrive at a prescription which will produce the most beneficial mix of products. Prescriptions can be designed which will favor water yield improvement and still be beneficial for continued timber production and for maintaining or improving wildlife habitats. For example, periodic harvesting of trees in small groups and clearcuts is compatible with recommended silvicultural methods for mixed conifers (Alexander, 1974; Jones, 1974) as well as with water and wildlife objectives. However, such a prescription has never been tested fully in the Southwest. Previous water yield experiments in southwestern mixed conifer forests (Rich, 1972; Rich and Gottfried, 1976), as well as in ponderosa pine forests (Baker, 1986), have utilized relatively large clearcuts and stand density reductions to achieve increased streamflow. These prescriptions generally have been beneficial for wildlife (Patton, 1976), but not for sustained conifer production (Gottfried, 1983; Jones, 1974; Rich and Gottfried, 1976).

In the mid-1970s, the two Thomas Creek watersheds of eastern Arizona were selected as the site of a mixed conifer resource evaluation project. The project was designed to demonstrate and evaluate the most current knowledge of mixed conifer management. One of the primary objectives was to develop an operational resource allocation and utilization procedure which could be used to develop sound management prescriptions for a 120-year rotation period. The results of the allocation, which were developed and described by Brown (1976), indicated that a prescription using patch clearcutting in conjunction with

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other silvicultural methods should produce the highest level of return. The objective of the current study is to evaluate the effects of the initial entry under the proposed multiresource prescription on water yield improvement and on the hydrology of an Arizona mixed conifer watershed.

STUDY AREA

The Thomas Creek watersheds (Table 1) are located within the White Mountains of east-central Arizona, about 24 km south of Alpine. They are in the headwater region of the Salt River, a main tributary of the Gila River, and are administered by the Apache-Sitgreaves National Forests.

TABLE 1. Watershed and Pre-Treatment Hydrological Characteristics.

Characteristic	South Fork	North Fork
Size (hectares)		
Total	227.4	189.0
South-Facing Slope	125.9	132.3
North-Facing Slope	101.5	56.7
Elevation (meters)	2,545-2.789	2,545-2.819
Slope, Average (percent)	22	27
Basal Area (m^2/ha) in 1974	45.8 (sale area)	41.0
Runoff (mm) ± Standard Error		
Annual	82 ± 31	69 ± 29
Winter	75 ± 30	66 ± 28
Summer	7 ± 2	3 ± 1
Peak Flows (l/s/km^2) ± Standard Error		
Annual	36.93 ± 16.79	31.78 ± 15.40
Winter	35.60 ± 16.81	28.55 ± 15.55
Summer	9.06 ± 4.38	10.52 ± 3.87
Largest Peak (1973)	206.71	193.88

Geology-Soils

The White Mountains are at the eastern edge of the Central Highlands Province in Arizona. The surface geology is attributed to Tertiary and Quaternary basaltic eruptions which produced extensive flows (Wilson, 1962).

Two-thirds of the soils on the watersheds have been classified as Mollic Eutroboralf loamy-skeletal, mixed, while most of the other soils have been classified as Mollic Cryoboralf loamy-skeletal mixed. Sandy loam textures are common to all of the nonalluvial surface soils. Soil depths vary from 51 to over 102 cm. The deepest soils, over 152 cm, are found in the stream bottom, where they developed from alluvial deposits of basalt material.

Climate

The Southwest is characterized by two precipitation seasons. Winter storms originating in the Pacific generally occur from October through May, with the most intense storms occurring from mid-November through mid-April. The late spring and early summer are characterized by dry conditions. The second rainy or monsoon season generally begins at the end of June or beginning of July when moisture enters Arizona from the Gulf of Mexico. Arizona also occasionally will be affected in autumn by eastern North Pacific tropical cyclones which push moisture into the state.

Precipitation has been measured continuously on a recording gage located near the South Fork weir. The record contains almost 24 years. The October 1 to September 30 water year is used in all of the Thomas Creek climatic and hydrologic evaluations. It allows for the entire winter season and corresponding runoff to be evaluated as one period. Annual precipitation for the 23 complete years of record, from 1964 to 1986 (Figure 1), averaged 768 ± 36 mm (with standard error). Approximately 56 percent of the annual precipitation (Figure 1) occurs during the October through May winter period, generally as snow which can remain on the watersheds into May. Precipitation amounts fluctuate throughout the year (Figure 2); May receives the least precipitation while July and August receive the most rainfall. The period from 1979 through 1986 was wetter than the previous 15-year period (1964-1978), with an annual average precipitation of 878 ± 61 mm compared to 709 ± 38 mm. This difference is attributed to heavier winter precipitation.

Maximum temperatures range from an average of 5.6°C in January to 23.9°C in June. Minimum temperatures for the two months are –7.8°C and 5.6°C, respectively.

Hydrology

Streamflow (Table 1) has been recorded continuously on South Fork since the 1963 water year, and on North Fork since the 1966 water year. Each stream is measured at a 120° V-notch weir, which is constructed into impervious clay or bedrock strata. The two streams are ephemeral; dry periods can occur in both winter and summer, depending on the distribution of precipitation. South Fork and North Fork annual runoff volumes during the common pre-treatment period (1966-1977) were similar (Table 1) and well correlated with a coefficient of determination (r^2) of 0.992 and a standard error of ± 10 mm (Figure 3).

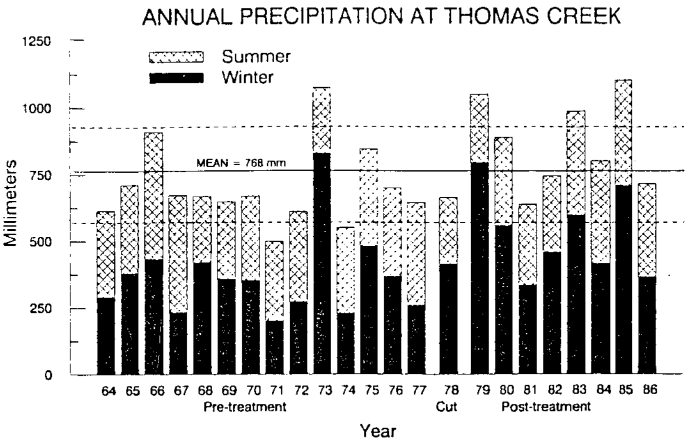

Figure 1. Annual Precipitation for the Thomas Creek Recording Rain Gage Can Be Divided Into Winter and Summer Seasons. The annual mean is presented with the one standard deviation band.

Two-thirds of the annual pre-treatment streamflows, from both areas, were less than 102 mm, and many years were less than 25 mm. The greatest volumes on record were measured in 1973 when South Fork produced 362 mm of runoff and North Fork produced 339 mm. Average annual flow rates during the common pre-treatment period were 3.06 $l/s/km^2$ for South Fork and 2.58 $l/s/km^2$ for North Fork.

Approximately 80 percent of the annual runoff occurs during March, April, and May (Figure 2), with April having the greatest flows. North Fork tends to start its winter runoff increases earlier, possibly because of the higher proportions of south-facing slopes where snow melts earlier. During the pre-treatment period, South Fork runoff volumes averaged 10 percent of the annual precipitation while North Fork averaged 8 percent. Higher short-term runoff coefficients have occurred during prolonged storms or snowmelt seasons.

Mean annual and seasonal peak flows during the common pre-treatment period, in $l/s/km^2$, were not significantly different between North Fork and South Fork (Table 1).

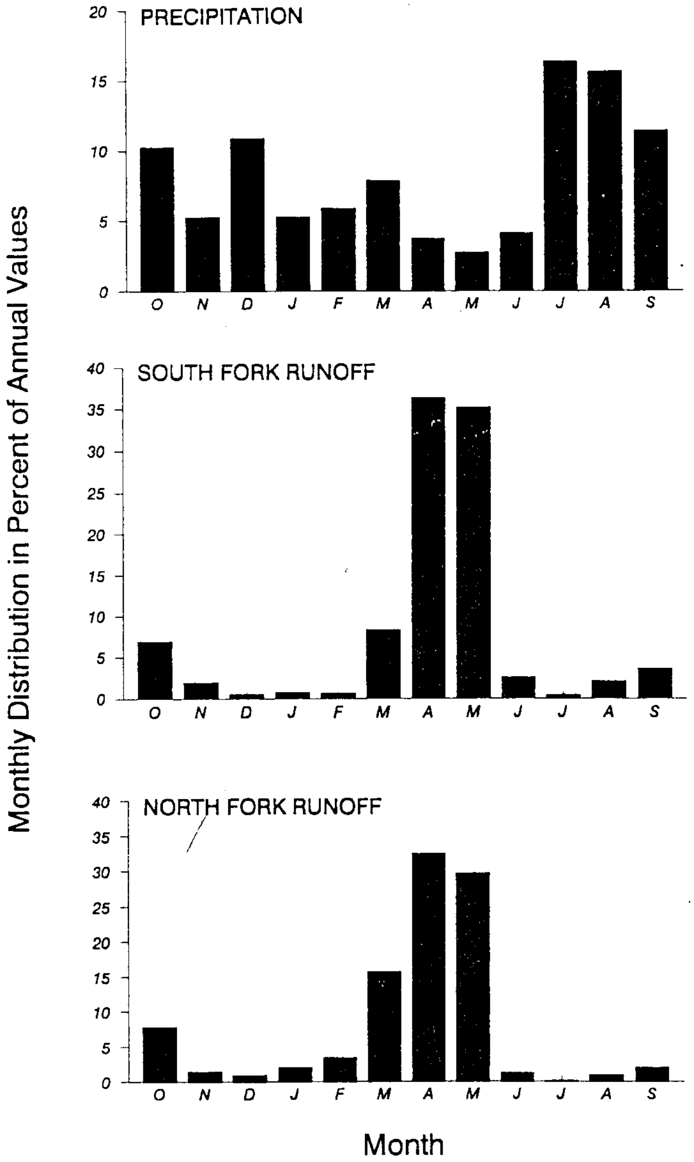

Figure 2. Mean Monthly Precipitation and Runoff as a Percent of Mean Annual Values During the 12-Year Pre-Treatment Period (1966-1977).

Forest Stand Characteristics

The Thomas Creek watersheds supported an undisturbed, multistoried old-growth southwestern mixed conifer stand (Table 1). The stand consisted of a mosaic of groups and patches of varying sizes. Patch structure could be single-storied or multistoried, but the overall effect was of a multistoried stand (Jones, 1974). Composition also was variable with some areas containing a single species, such as ponderosa pine (*Pinus ponderosa*) or aspen (*Populus tremuloides*), while others contained all eight of the main tree species. The major tree species are Engelmann spruce (*Picea engelmannii*), blue spruce (*P. pungens*), Douglas-fir (*Pseudotsuga menziesii* var. *glauca*), white fir (*Abies concolor*), corkbark fir (*A. lasiocarpa* var. *arizonica*), ponderosa pine, southwestern white pine (*P. strobiformis*), and quaking aspen. Gambel oak (*Quercus gambelii*) is an important understory species. Most Thomas Creek stands have been classified as belonging to the *Picea engelmannii*/*Senecio cardamine* habitat type (PIEN/SECA), *Abies concolor* phase by Fitzhugh *et al.* (1987).

THE TREATMENT

South Fork was divided into land response units (LRU's) to facilitate the operational resource allocation and utilization procedures of Brown (1976). The land response units were divided on the basis of slope, aspect, or unique features such as the stream bottom.

The silvicultural prescription for Unit 5 (11.3 ha in the upper channel bottom) called for a 30 percent reduction in basal area of sawtimber trees using single-tree selection. The removal was designed to harvest poor quality and overmature trees. The prescription for Unit 3 (94.3 ha on the south-facing slope) was for a group selection resulting in a 30 percent basal area reduction. The prescription for LRU 4 (64.4 ha on the north-facing slope) called for patch cutting over one-third of the area. Single-tree selection was practiced in the areas between groups or patches in both large units. A 0.8 ha meadow within the sale area was left undisturbed. Approximately 56.6 ha in the downstream part of the watershed were not included in the timber sale because of the locally steep slopes. The timber sale area then was planned for 170.8 ha, or 75 percent of South Fork, although not all of the area was harvested.

The main harvesting activities began in May 1978 and continued through January 1979, removing 13,924 m^3 net volume. Most of the activity after October 1, 1978, was intermittent and involved normal skidding and hauling, and some salvage of windthrown trees. The harvest resulted in a 34 percent reduction the total basal area of the treated area from 45.8 to 30.2 m^2/ha. The reduction was 30 percent, to 32.1 m^2/ha on areas that remained stocked following the harvest.

Analysis of aerial photographs from the post-harvest period indicated 63 openings 0.2 ha or larger on Thomas Creek. These openings were in both LRU 3 and LRU 4. The average opening was 0.5 ha and openings ranged from 0.2 to 1.7 ha. Approximately 84 percent of the openings were smaller than 0.6 ha. The total area in the 63 openings was 30.5 ha. This accounted for 18 percent of the harvesting area and 13 percent of the total watershed area.

RESEARCH DESIGN

The Thomas Creek experiment was designed as a paired watershed study with South Fork receiving the treatment and North Fork serving as the hydrologic control. The 21 years of common record were divided into a 12-year pre-treatment period (1966-1977) and an eight-year post-treatment period (1979-1986). The 1978 water year, when most of the logging was conducted, was considered a transitional year and not included in the analysis. However, 1979 is considered a post-treatment water year since little cutting occurred between October and January.

Linear regressions were used in the statistical analyses between treatment periods. Pre-treatment and post-treatment regressions were developed between South Fork and North Fork for the particular attribute being studied. The two regressions were compared by covariance analysis to determine significance of changes due to treatment. Covariance allows for adjusting for the effects of an uncontrollable variable, such as precipitation. The method of analysis did not require that the watershed regression coefficients be equal (Rogosa, 1980; Walker and Lev, 1953). The assumption of normality was verified by analyzing normal and detrended normal probability plots of residual values from the covariance analysis. Cook D and Lever tests were run to locate extreme values. Residual values adjusted for the North Fork flow were compared in some of the monthly streamflow evaluations where the assumptions of normality and homogeneity were not strong. Since many watershed studies have shown a decline of treatment effects with time (Hibbert, 1967), the post-treatment relationship for annual flows was checked for changes over time using a technique which evaluates the interaction of time, in years, with annual flow on the control watershed (Baker, 1986), but no significant influence was detected.

Long-term mean annual runoff values from North Fork were used as the average regression independent variable for calculating percent changes in water yields. Similar long-term means were used in other analyses. This made the analysis less sensitive to extreme high or low streamflows. Long-term means should give the land manager a better idea of average changes that can be expected from treatment. Student t-tests were used to compare individual watershed or climatic factors within and between treatment periods. Means appear with their standard errors, except where noted, while average increases derived from covariance analyses appear with their confidence limits. A Type I error of $\alpha = 0.05$ was used in all analyses, except where noted.

Snowmelt is the primary source for streamflow on Thomas Creek. Snow measurements began in 1974 and continued through 1986. Measurements of snow depth and of snow water equivalent, the primary parameter used in the current evaluation, were made using a Federal snow tube throughout the winter. The statistical analysis compared the annual maximum accumulation measured on permanent snow course lines within the treated area on South Fork and the adjacent areas of North Fork. Maximum values may not necessarily be the seasonal peak, but the highest values measured for the year.

RESULTS

Water Yield Improvement

The South Fork harvest resulted in a 34 percent reduction in total stand basal area and in the clearing of 18 percent of the unit in small groups and patch clearcuts. The treatment produced statistically significant annual water yield increases, as indicated by the differences between the pre-treatment and post-treatment regressions: $Y_2–Y_1 = 33.234 + 0.125\ X$ (Figure 3). The regression elevations are highly significantly different (1 percent level), while the slopes are significantly different. The increases are both additive and multiplicative. The post-treatment regression had a r^2 of 0.988 and a standard error of ± 14 mm. Covariance analysis for average conditions indicated an increase of 44 ± 11 mm (44.8 percent ± 11.7 percent). The comparison of the estimated annual runoff for the two periods ($Y_2–Y_1$) indicated that runoff increases were significant for each of the eight post-treatment years. The yearly differences between expected and observed annual runoff are presented in Figure 4; relative increases ranged from 23 mm (146 percent) in 1981, a dry year, to 41 mm (16 percent) in 1985, a wet year. The greatest difference occurred in 1979, when the increase was 70 mm or 25 percent. Streamflow increases were greater for the four wettest years of the post-treatment period relative to the other years. The mean increase is equivalent to 99,362 m^3 from the 227.4 ha watershed. The average daily discharge rose by 1.64 ± 0.44 $l/s/km^2$.

The Thomas Creeks are ephemeral streams; prior to treatment, South Fork averaged 58 no-flow days and North Fork averaged 35 no-flow days a year. These differences were not significantly different. The regression relationship between the number of days a year without flow on South Fork in relation to North Fork changed after treatment, with South Fork showing a significant average decrease relative to North Fork. South Fork had an average of 11 days without flow while North Fork had a 33-day average.

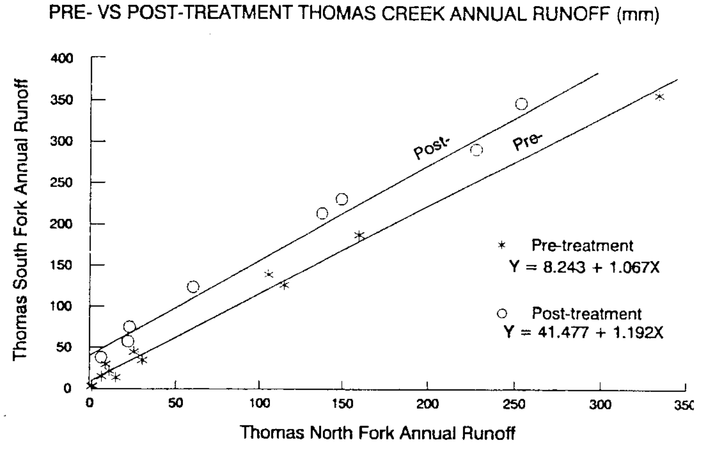

Figure 3. The Relationship Between Watersheds Changed After Treatment, Indicating Significant Annual Streamflow Increases.

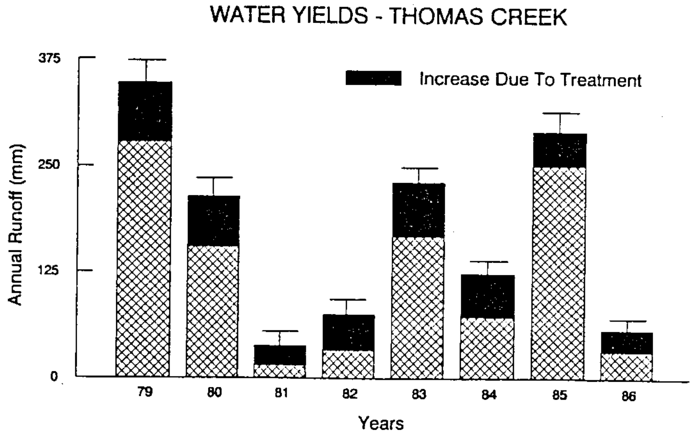

Figure 4. Differences Between Observed and Expected Annual Runoff Following the Harvest are Shown With the Positive Confidence Line of the Observed Runoff.

The yearly streamflow increases which occurred during the post-treatment period were generated by winter snowmelt or rain storms. Winter streamflow increases were similar to the annual responses, significantly increasing by 43 ± 10 mm or 47.3 percent ± 11.0 percent. Summer runoff also increased (43.2 percent ± 51.3 percent), but the total added volume was only 3 ± 3 mm and the covariance analysis did not show significant differences following harvesting. Monthly runoff values changed on both watersheds. The regression and covariance analyses showed significant South Fork runoff (Figure 5) increases for the months of: October, February, March, April, and July. No increases were found for December, June, or September while the evaluations for the remaining months were less conclusive showing increases at probability levels of between 0.06 and 0.08. Close to 80 percent of the annual runoff still occurs in March, April, and May (Figure 5); the mean adjusted increases for the three months are:

Month	Percent Increase	Increased Volume (mm)
March	82 ± 56	8 ± 5
April	50 ± 27	19 ± 10
May	19 ± 19	6 ± 6

The apparent increase in December flows, although not significant, was due to the storms of December 1979.

The relationship between mean annual runoff efficiencies also changed following treatment. The average runoff coefficient for South Fork was 0.096 between 1966 and 1977, but almost doubled to 0.183 during the post-treatment period. The North Fork runoff coefficient also increased by 0.033 to 0.113 during the recent wet regime. The covariance analysis indicates that the relationship between the watersheds for mean annual runoff coefficient has changed significantly, with an average increase of 0.050 ± 0.013 (46.4 percent ± 12.3 percent).

Peak Flows

All post-treatment annual peaks occurred in winter and, except for 1984 when a large September-October storm passed through Arizona, all were generated at least in part, by snowmelt. Seven of the annual peaks occurred on the same day on both watersheds.

Harvesting and other vegetation manipulations influence soil moisture and impact the magnitude of peak flows. Covariance analyses of both annual and winter peak flows indicate that the South Fork harvest resulted in significant additive increases in peak flow rates. The annual increases, which are represented by the equation: $Y_2 - Y_1 = 28.274 + 0.004 X$ (Figure 6), were 28.42 ± 22.63 l/s/km^2, equivalent to 64.7 percent ± 51.5 percent. The pre- and post-treatment regressions had respective r^2 values of 0.98 and 0.67, and standard errors of ± 9.09 and ± 34.68 l/s/km^2. The pre-treatment regressions are influenced by the record 1973 peak flow; similar record flows were recorded from throughout Arizona during that year (Baker, 1986; Rich and Gottfried, 1976). The wide confidence band for the second period is partially due to the rapid and large response of South Fork to the September 1984 storm. Winter peaks on South Fork increased by 26.32 ± 22.85 l/s/km^2 or by 59.8 percent ± 51.9 percent. Mean peak flows were apparently higher on North Fork during the post-treatment winter period while mean summer peaks were lower, but these changes were not statistically significant. Covariance analysis of the summer peaks showed no significant changes on South Fork due to treatment.

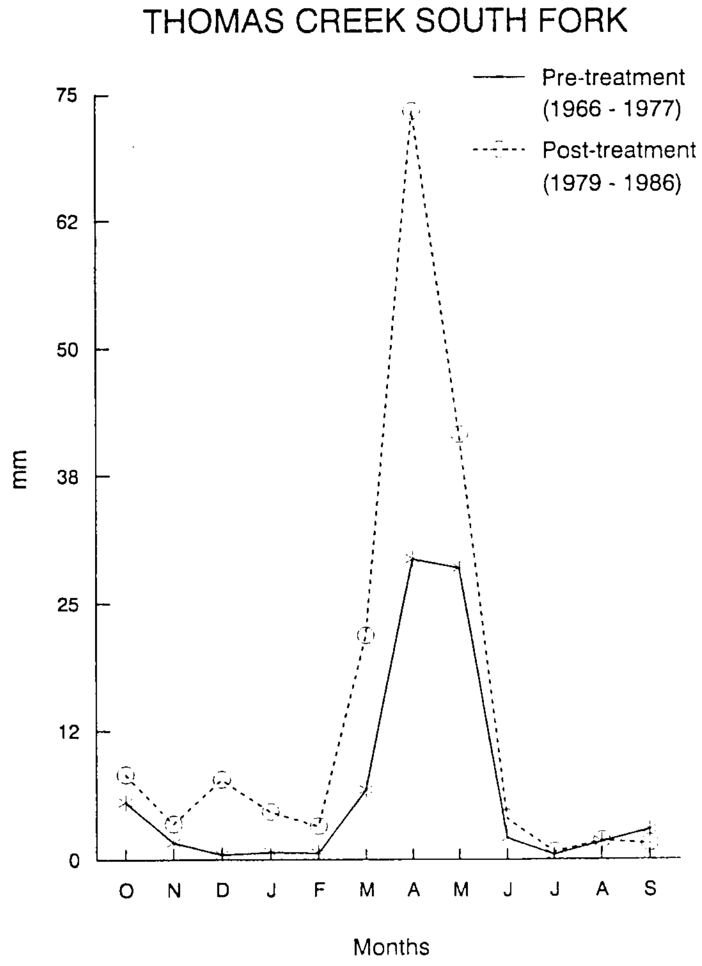

Figure 5. Monthly Runoff Increased Significantly for Five Months of the Year.

Snow Water Equivalents

Snowmelt was the prime source of augmented streamflow for six of the eight post-treatment years, and rain-on-snow was a factor in another year.

Increases in snow water equivalent accumulations on the treated watershed would account for some of the runoff increases. Prior to harvest, the maximum snow water equivalent on South Fork was 100 ± 16 mm, while it was 78 ± 16 mm on North Fork. Following treatment, the respective means were 195 ± 39 mm and 156 ± 34 mm. However, the covariance analysis did not show any significant changes in the relationship due to treatment. Analyses of the effects of treatment on maximum snow water accumulations on north-facing and south-facing slopes also did not show any significant difference.

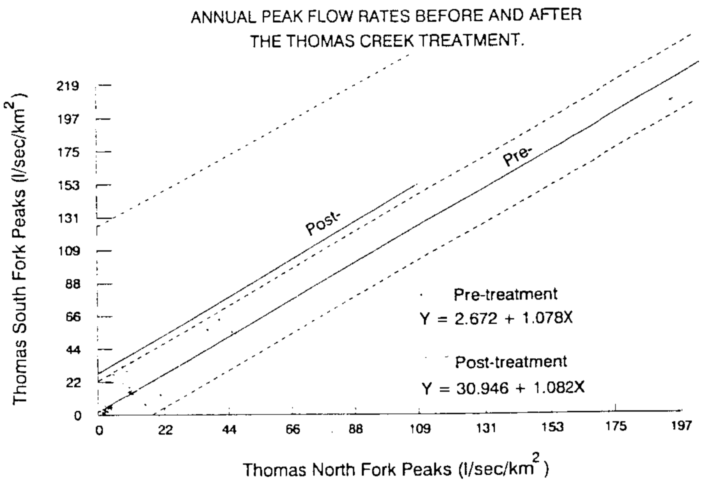

Figure 6. Treatment Resulted in an Increase in the Annual Peak Flow Discharge Rates.

DISCUSSION

Water Yields

The harvest on the South Fork of Thomas Creek resulted in highly significant increases in average annual runoff of 44 ± 11 mm (44.8 percent ± 11.7 percent). If all of the increases are assumed to come from the 170.8 ha harvested area, the increase would be 58 mm. If, however, the increases were all attributed to the 63 openings (30.5 ha or 13 percent of South Fork), the increase would be 326 mm. Water yield increases from small openings generally have been attributed to lower evapotranspiration and greater snow accumulations and melt rates than in the original forest (Rich and Thompson, 1974; Troendle and King, 1987). The importance of winter increases at Thomas Creek agrees with results reported for other experimental forested watersheds in Arizona (Baker, 1986; Rich, 1972; Rich and Gottfried, 1976) and Colorado (Troendle and King, 1985, 1987).

The Thomas Creek runoff increases can be compared to estimates derived from a simple model proposed by Rich and Thompson (1974) for Arizona mixed conifer forests. The model estimated increased runoff amounts from a knowledge of the percent of watershed in openings and the expected pre-treatment runoff. Using 82 mm of pre-treatment streamflow and 13 percent of the watershed in openings, the current results (44 mm) would plot above the predicted levels of approximately 13 mm.

The current results can also be compared to similar experimental results from other mixed conifer or subalpine forested watersheds in Arizona and Colorado (Table 2). The table shows the total increases in annual streamflow for the entire watersheds and the increase if all changes were attributed to the cleared areas. The Colorado data for cleared areas range from 25 mm to 205 mm while the Arizona data range from 75 mm to 156 mm. Hibbert (1979) indicates that there may be a 127 to 190 mm water increase on Colorado clearcuts. None of these values is close to the 326 mm reported at Thomas Creek.

Watersheds respond differently to similar treatments because of physiographic, channel, or soil physical characteristics (Baker, 1986; Rich and Gottfried, 1976). However, another explanation for the larger increases in mean streamflow volumes is that the partially cut areas are also contributing to the increased flows, especially during wet years. These areas represent 82 percent of the timber sale area or 62 percent of the entire watershed area. Rich and Gottfried (1976) and the literature reviewed by Troendle and King (1987) indicate that uniformly reducing stand density by single-tree selection or by thinning generally should not produce large runoff increases. The explanation was that the neighboring residual trees would utilize any of the extra soil moisture that had previously been used by the harvested trees. Researchers and managers felt that to increase runoff, stand densities had to be reduced heavily to basal areas of 6.9 m^2/ha as was done on Watershed 17 of Beaver Creek (Baker, 1986) or to 9.2 m^2/ha as was proposed for the South Fork of Workman Creek (Rich and Gottfried, 1976).

The Workman Creek South Fork results for the single-tree selection did indicate small but significant average increases, especially following the wet 1966 water year, but this was considered unusual (Rich and Gottfried, 1976). Baker (1986) reported significant water yield increases when density in a ponderosa pine stand was reduced 33 percent. Troendle and King (1987) recently indicated that a 40 percent reduction in basal area apparently increased annual runoff, although this was not validated statistically.

Increases from partially cut stands during average and wet years can be attributed to the fact that

TABLE 2. Average Annual Water Yield Increases Reported for Other Mixed Conifer and Subalpine Forests in Arizona and Colorado.

Watershed	Treatment	Annual Ppt. (mm)	WS Area (ha)	Percent WS in Openings	Average Annual Water Yield Increase			Forest Type	Reference
					Watershed (%)	(mm)	Opening (mm)		
WORKMAN CREEK, ARIZONA									
North Fork	moist site	833	100	32	42	32	101	mixed conifer	Hibbert and Gottfried (1987)
	dry site			40	37	45	112	ponderosa pine, mixed conifer	
	moist-dry site			73	72	67	93	mixed conifer, ponderosa pine	
South Fork	clearing for 9.2 m^2/ha		129	83	110	107	129	mixed conifer	
CASTLE CREEK, ARIZONA									
West Fork	1/6 patch cut	681	364	17	29	13	75	ponderosa pine, mixed conifer	Rich (1972)
WILLOW CREEK, ARIZONA									
East Fork	selection and diameter limit cut	749	198	62	54	96	156	mixed conifer	Gottfried (1983)
DEADHORSE CREEK, COLORADO									
North Fork	5H circular openings	762	41	36	29	60	166	subalpine	Troendle and King (1987)
WAGON WHEEL GAP, COLORADO									
	clearcut	544	81	100	15	25	25	subalpine, mixed conifer	Van Haveren (1981)
FOOL CREEK, COLORADO									
	alternating strip cut	635	289	40	40	82	205	subalpine	Troendle and King (1985)

residual trees are not utilizing all of the available soil water. It takes less additional precipitation to recharge the soil mantle, and any further increments of moisture then are available for movement into the stream system. Trees use most of the available water during dry years and more precipitation is needed to recharge the soil. Troendle (1987) studied soil moisture depletion under several basal area densities of lodgepole pine (*P. contorta*). He found that basal area was not related to daily soil moisture depletion during dry years; however, during average and wet years, daily soil moisture depletion increased as basal area increased. Results from Thomas Creek also have demonstrated increased evapotranspiration from relatively undisturbed dense stands during wetter summers than during similar drier periods (Gottfried, 1989). In wet years, a reduction in basal area would result in a proportional reduction in soil moisture depletion. These findings tend to support the earlier explanation for increased flows. The lack of a significant relationship during dry years possibly could indicate that the trees have adjusted to the drought conditions; however, at low densities, fewer trees are using about the same amount of water as more trees at the higher densities. This would be beneficial for growth of the residual stand.

Increased snowpack accumulations would also contribute to increased streamflow (Ffolliott *et al.*, 1989). Troendle and King (1987) and Troendle (1987) found a significant 16 percent increase in peak snow water equivalents after the partial harvest in Colorado, which would have augmented the impacts of reduced soil moisture depletions on water yields. Strip harvesting at Fool Creek, Colorado, also resulted in a 9 percent increase in peak snow water equivalents over the watershed (Troendle and King, 1985). However, the patch clearcutting on the North Fork of Deadhorse Creek did not result in a significant increase in snow water equivalents on the watershed (Troendle and King, 1987). The Thomas Creek snow surveys also did not indicate any significant changes in watershed snow water equivalents following the harvest, in spite of the fact that Plasencia (1988) found more snow in representative openings than in the adjacent partially harvested forest on the watershed.

More snow was deposited in the small forest openings than in the adjacent stand (Plasencia, 1988). Snow trapped in the open is subject to increased solar and thermal radiation from the surrounding trees. This results in more rapid and earlier snowmelt. Even under undisturbed conditions, streamflow will increase within one to two days of the start of snowmelt on the slopes (Gottfried and Ffolliott, 1980). Troendle and King (1985) illustrated how harvesting at Fool Creek and at Deadhorse Creek advanced the timing of spring runoff. Most of the increased flow occurred in the rising side of the annual hydrograph. A similar evaluation was not conducted for Thomas Creek, but a change in timing was observed. The March through May period still accounts for approximately 80 percent of the runoff; however, 55 percent of the annual flow now occurs in March and April compared to 45 percent prior to the timber sale. The difference is significant. May flow is now a smaller proportion, by approximately 11 percent, of the annual flow. These data tend to support the Colorado data that cutting openings tends to result in an earlier rise in snowmelt-generated runoff.

Annual peak flows, as well as winter peaks, increased significantly following the South Fork treatment. Annual peaks increased by about 65 percent (28.42 l/s/km^2) while winter peaks were 60 percent higher. Higher soil moisture levels will result in more rapid movement of water into the stream, and in a sharper and greater rise in the hydrograph. Although the harvest had a minimal effect on overland flow and erosion, increased streamflow volumes and peak flows have accelerated natural channel erosion processes within the study area (Heede and King, 1990). The effects of increased peaks and sedimentation on downstream sites is unknown. However, Hibbert and Gottfried (1987) indicate that peak discharges generally have little impact outside of the immediate watershed area. In addition, watershed treatments appear to have little impact on peak flows during major storm events when the soil reaches a point of saturation.

Significant increases in peak discharge have been noted in other watershed studies which have involved clearing or heavy harvests. Troendle and King (1987), for example, found a 50 percent increase in mean peak discharge on the North Fork of Deadhorse Creek. Mean peak flows rose from 26.6 to 39.6 l/s, which is equivalent to a 31.7 l/s/km^2 increase. The neighboring Fool Creek Watershed had a 23 percent increase in peak flow rate, about 55 l/s, after strip clearcutting (Troendle and King, 1985) and Wagon Wheel Gap showed a 50 percent increase (Van Haveren, 1981). The 65 percent change at Thomas Creek is similar in magnitude to the Colorado findings.

Regional Implications

The hydrological data from Thomas Creek were used to simulate water yield increases from 25,367 ha of mixed conifer forest within the Upper Black River Basin of the Salt River of Arizona (Gottfried, 1989). A patch cutting system applied using a 120-year rotation eventually could produce about 18.5 million m^3 of increased runoff annually. Some of the additional water would be lost in transmission; and, since largest water yield increases from vegetation manipulation generally occur in wet years, some will be lost through evaporation and releases from downstream reservoirs (Brown and Fogel, 1987). However, water will be held for downstream use, and even released water will contribute to ground water recharge. The Thomas Creek prescription could be beneficial on smaller municipal watersheds which contain southwestern mixed conifer forests.

CONCLUSIONS

The Thomas Creek treatment, after eight years of evaluation, has resulted in significant water yield increases. The study demonstrates that large clearings or removing large numbers of trees, as cited earlier, is not necessary to increase runoff from forested watersheds. Increases can be obtained with less severe treatments. Harvesting of more, or larger, openings could have produced more runoff but at the expense of long-term forest productivity, wildlife habitat, and of other multiple benefits. In fact, other studies (Ffolliott and Gottfried, 1989; Gottfried, 1989) have demonstrated that the small clearings and selection harvesting at Thomas Creek benefitted the timber and some wildlife-range resources. Prescriptions which are similar to the one at Thomas Creek could provide compromise alternatives for the management of the southwestern mixed conifer forests. The fact that the partially harvested areas appear to have contributed to the water yield increases also provides another possible benefit to be considered when evaluating the potential for uneven-aged management in these forests. In addition, uneven-aged silvicultural methods can be used to maintain biodiversity and old-growth attributes within a stand. However, additional research, on both watersheds and research plots, is necessary before more definite conclusions can be drawn about the hydrological impacts of partial harvesting.

Although numerous factors must be considered when preparing a forest management prescription, the Thomas Creek prescription is an option which should be considered for application in similar southwestern mixed conifer stands.

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