Water Yields Resulting From Treatments on the Workman Creek Experimental Watersheds in Central Arizona

LOWELL R. RICH AND GERALD J. GOTTFRIED

USDA Forest Service, Rocky Mountain Forest and Range Experiment Station, Forest Hydrology Laboratory, Tempe, Arizona 85281

The three Workman Creek watersheds were instrumented to determine the hydrology of mixed conifer forests and to determine the changes in streamflow and sedimentation as a result of manipulating the forest vegetation. A small riparian cut on North Fork did not increase water yields. A selection timber harvest, improvement cut, and fire which removed 45% of the basal area on South Fork increased yields slightly. In contrast, converting 32.4 ha (80 acres) of moist site forest to grass significantly increased water yields on the 100.4-ha (248 acre) North Fork watershed. Water yields were increased even more after 40.5 ha (100 acres) of dry site pine forest were converted to grass. An increase of 69 mm (2.70 in.), or 84%, of expected runoff resulted from the combined treatment. Clearing 83% of the South Fork watershed preparatory to planting ponderosa pine significantly increased water yields by 93 mm (3.67 in.), or by 111%.

INTRODUCTION

Mixed conifer stands cover approximately 121,500 ha (300,000 acres) in Arizona. They are an important source of water. Under Arizona conditions, water yielded as streamflow is usually a small percent of the precipitation, around 10–15% for mixed conifer sites. This report summarizes the changes in water yields resulting from the most recent treatments applied at Workman Creek.

DESCRIPTION OF WORKMAN CREEK WATERSHEDS

General Characteristics

The Workman Creek experimental watersheds are located within the Salt River drainage in central Arizona, about 48 airline km (30 mi) north of Globe. They are part of the Sierra Ancha experimental forest. The three watersheds (Figure 1), North Fork with 100.4 ha (248 acres), Middle Fork with 210.9 ha (521 acres), and South Fork with 128.7 ha (318 acres), drain into Salome Creek and then into Roosevelt Reservoir. Perennial streamflow has been measured continuously since gaging stations were established in 1938.

Climate

The Workman Creek climate is characterized by cold moist winters, dry warm springs, and hot moist summers [*Pase and Johnson,* 1968]. There are two distinct rainy seasons. Annual precipitation measured at the recording rain gage in Middle Fork of Workman Creek has averaged (with standard error) 835 ± 41 mm (32.89 ± 1.60 in.) from 1938 through 1973. Highest annual precipitation, 1,547 mm (60.92 in.), occurred during the 1972–1973 water year (October–September), following the lowest annual precipitation, 428 mm (16.85 in.), during the 1971–1972 water year. Precipitation during the eight winter months, October–May, has averaged 559 ± 42 mm (22.01 ± 1.64 in.), or 67%, of the annual total. Summer precipitation has averaged 276 ± 16 mm (10.88 ± 0.61 in.).

Annual temperatures at the Workman Creek climatic station averaged about 8.9°C (48°F), varying from −0.6°C (31°F) in January to 18.3°C (65°F) during July and August.

Geology and Soils

The Workman Creek watersheds are underlain by Dripping Springs quartzite that has been intruded by diabase and basalt plugs and sills. Troy sandstone outcrops are found on the upper part of the watersheds. Most of the formations are nearly level but with a low westward dip. Elevations vary from 2,010 to 2,356 m (6,590 to 7,724 ft) [*Rich et al.,* 1961].

Surface soils are of loam to clay loam texture, with granular or crumb structure. Subsoils are mostly layered and vary in texture from clay loams to clay. Soil depths vary from a few centimeters to more than 5 m (15 ft). Infiltration rates on the three watersheds are high in the surface soils, averaging 151 ± 34 mm/h (5.94 ± 1.33 in./h) but decrease with depth to an average of 2.0 ± 0.8 mm/h (0.08 ± 0.03 in./h) at about 97 cm (38 in.) (T. W. Barret, unpublished report, 1970).

Vegetation

Sites for plant growth within the Workman Creek watershed vary from the dry southern exposures of North Fork to the moist sites on the northern exposures of South Fork. Middle Fork, with its westerly aspect, is intermediate.

Ponderosa pine (*Pinus ponderosa*) is the most abundant tree on the area. On the more moist sites, Douglas fir (*Pseudotsuga menziesii*) and white fir (*Abies concolor*) are important. Gambel oak (*Quercus gambelii*) and New Mexican locust (*Robinia neomexicana*) are common as understory. Bigtooth maple (*Acer grandidentatum*), Arizona alder (*Alnus oblongifolia*), Arizona walnut (*Juglans major*), and aspen (*Populus tremuloides*) are found sparingly along stream channels.

The average tree composition of the original stands in 1953 on the three watersheds was ponderosa pine, 53%; white fir, 22%; Douglas fir, 7%; Gambel oak, 17%; and other species, 1%. Average basal area per hectare for all trees 2.5 cm (1 in.) dbh and over was 40.0 m² (174 ft²/acre) on North Fork, 44.3 m² (193 ft²/acre) on Middle Fork, and 46.2 m² (201 ft²/acre) on South Fork.

Less than 1% of the ground surface under the dense forest canopy is covered by grasses or herbaceous species. Herbaceous plants are abundant in the 8.1-ha (20 acre) meadow on Middle Fork and in the 0.8-ha (2 acre) meadow on South Fork.

Streamflow

Perennial streamflow is recorded continuously at 90°V-notch weirs on North Fork and South Fork and a combination 90°V-notch and 7-ft Cipolletti weir at Main Dam on the main watershed below the confluence of the three catchments.

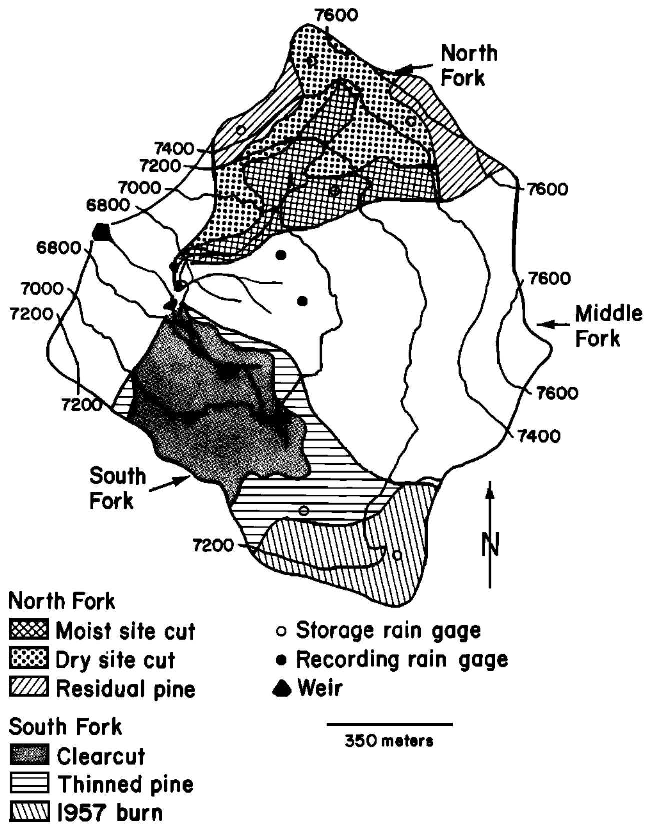

Fig. 1. The Workman Creek experimental watersheds including the main treatment areas. Middle Fork, the control watershed, also includes the area between the confluence of the three forks and the Main Dam.

The difference in flow between Main Dam and the two other stations determines the Middle Fork annual streamflow. Sediments are trapped in the weir ponds for measurement. Average annual streamflow from October 1938 to September 1953, before treatments, was 81 ± 21 mm (3.20 ± 0.82 in.) for Middle Fork, 86 ± 18 mm (3.38 ± 0.71 in.) for North Fork, 87 ± 12 mm (3.41 ± 0.47 in.) for South Fork and 84 ± 18 mm (3.30 ± 0.69 in.) for Main Dam.

The method of calculating Middle Fork runoff is a weakness in the experiments; however, we do not feel that it compromises the results. Workman Creek is not losing appreciable amounts of runoff in the reach between the confluence and the Main Dam. Deep seepage and interflow are not a problem, since the channel is underlain by impervious bedrock. The Main Dam cutoff wall is secured to this formation. Fluctuations in bank storage or in flood plain groundwater levels should be minimal, since Workman Creek is perennial and the flood plain is narrow. Any losses would be the result of increased consumptive use by riparian vegetation in July and August. North Fork results (which will be discussed later) indicate this use will have little effect on annual streamflows. A high-velocity trapezoidal flume was constructed in 1952 on Middle Fork above the confluence, but data were summarized for only a few years; none of these data were used in the following analyses.

Eighty percent of the annual streamflows in the 35 years of record on Middle Fork have been below 102 mm (4 in.). The 35-year average is 78 ± 14 mm (3.07 ± 0.55 in.). A plot of annual precipitation versus annual runoff for the watershed (Figure 2) indicates that the watershed runoff coefficient (the ratio of annual runoff to annual precipitation) increases during high-precipitation years. The largest runoff events occur when snowmelt or precipitation coincide with saturated soil conditions. The average annual runoff coefficient on Middle Fork during the 35 years was 0.08 ± 0.01. The highest annual coefficients, about 0.25, were measured in 1941 and 1973. Higher short-term coefficients have been recorded during prolonged storms and snowmelt seasons. Average annual runoff coefficients during the 15-year pretreatment period were close to 0.10 for all watersheds.

Rich et al. [1961] report that an average of about 77% of the streamflow is derived from snowmelt and comes between December and April. Approximately 87% of the average annual streamflow from the three forks during pretreatment occurred during the eight winter months. Monthly runoff peaks in March. South Fork streamflows normally remain high into April. Base flow, derived from winter precipitation, is an important component of summer streamflow. Most summer precipitation, with the exception of high-intensity convectional rains, is used on site.

Average evapotranspiration during the pretreatment period, based on the simplified water budget formula

$$\text{evapotranspiration} = \text{precipitation} - \text{runoff}$$

was approximately 716 ± 20 mm (28.2 ± 0.8 in.) for the three areas. The Middle Fork recording rain gage collected an average of 800 ± 53 mm (31.5 ± 2.1 in.) during this time.

The estimated runoff coefficients and calculated evapotrans-

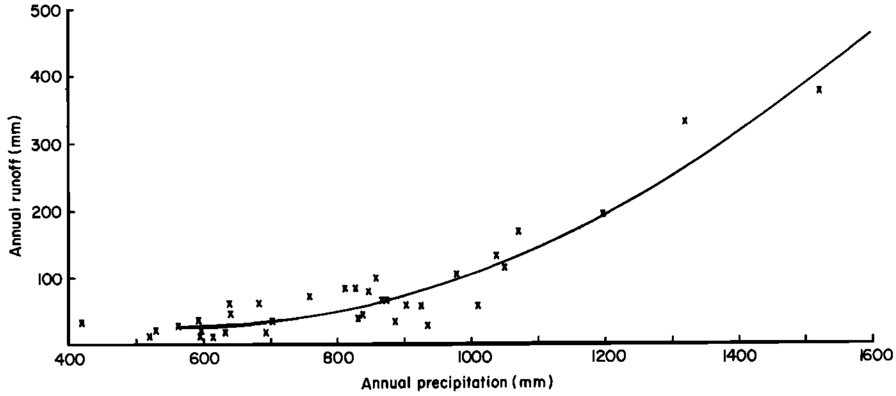

Fig. 2. The relationship between precipitation and runoff for the Middle Fork virgin mixed conifer watershed (based on 35 years of record).

piration are affected by the universal problems of measuring precipitation, especially snow. It is probable that snow moisture has been underestimated. However, we feel that our comparisons are valid, since the problem is common to both pretreatment and posttreatment periods.

RESEARCH DESIGN

The Workman Creek watersheds were instrumented to determine the hydrology of mixed conifer forests and to determine the changes in streamflow and sedimentation as a result of manipulating the forest vegetation. The objective on North Fork is to increase water yields by removing the forest vegetation in a series of steps and converting to grass cover. The objective on South Fork is to evaluate water and sediment yields resulting from forest management activities. Middle Fork is reserved as the control watershed. Table 1 summarizes the type and the time sequence of the Workman Creek treatments. The treatments are experimental and were selected to cover the range of yields possible through manipulation or removal of forest vegetation. We do not mean to imply or recommend the actual application of these treatments.

The Workman Creek experiments were designed as paired watershed studies. Pretreatment regressions of streamflow were developed between the watersheds to be treated and the control watershed. Similar regressions were developed after treatment. The pretreatment and posttreatment regressions were compared by covariance analysis to determine significance of the changes in streamflow due to treatment. The method of analysis did not require that the watershed regression coefficients be equal [*Walker and Lev,* 1953].

Although linear regressions are most commonly used, analysis of new treatments plus reevaluation of previous ones has indicated significant curvilinearity for many of the relationships, especially under the influence of extreme years (1941, 1966, 1973) which have occurred during all treatment periods. We decided to use the second-order polynomial regression model, of the form $Y = a + bx + cx^2$, where x is Middle Fork runoff, in the analyses to be consistent and to facilitate the calculations. All curvilinear regressions were highly significant. Pretreatment streamflow correlation coefficients were 0.99 between South Fork and Middle Fork and 0.98 between North Fork and Middle Fork.

Linear regression models were used in the analysis of the effects of treatment on seasonal and on monthly runoff. A separate analysis was conducted for each month.

Long-term mean annual runoff from Middle Fork was used as our average regression x value for calculating percent changes in water yields. This made the analysis less sensitive to extreme high and low streamflows. The 28-year mean, 70 mm (2.76 in.), was used for analyses involving the first set of treatments because of limitations in the range of data, and the 35-year mean, 78 mm (3.07 in.), was used for those involving only the second set. Appropriate long-term means were also used for other analyses, e.g., seasonal runoff and estimated evapotranspiration. Long-term means should give the land manager a better idea of average changes that can be expected from a treatment. It is better to plan for the average than for the larger runoffs which may occur once every 12 years. Statistical significance is indicated by values above the 5% level, although values above the 1% level were not uncommon. Means derived from covariance analyses are shown with the associated confidence limits.

TABLE 1. Schedule of Treatments for the Workman Creek Watersheds

Year	Treatment		
	North Fork	Middle Fork	South Fork
1938–1952	calibration	calibration	calibration
1953	riparian cut of broadleaf species	control	start of single tree selection harvest
1958	convert moist site (mostly Douglas fir and white fir) to grassland	control	
1966	convert dry site (mostly ponderosa pine) to grassland	control	convert to a pure ponderosa pine stand with a basal area of 9.2 m^2/ha (40 ft^2/acre)

NORTH FORK TREATMENTS

Previous Treatments

Riparian cut of broad-leaved trees. The Arizona alder and bigtooth maple adjacent to streams, springs, and seeps were cut during August 1953, and the stumps were treated to prevent sprouting. The cut removed 0.6% of the total basal area of all trees on the 100.4-ha (248 acre) watershed.

Conversion of moist site forest vegetation to grassland. Thirty-two hectares (80 acres) of moist site forest, predominantly white fir and Douglas fir (32% of the watershed), were cleared during September and October 1958 (Figure 1). The boundaries of the cleared area were determined by the topographic break between the steeper, moist slopes, extending along the channel, and the flatter, dry slopes (Figure 3). Where topographic boundaries were not clear, forest composi-

Fig. 3. View of the Workman Creek watersheds looking northeast from Carr Peak. The North Fork watershed is shown on the left, Middle Fork in the center, and South Fork on the right. The moist site treatment was applied to the cleared area adjacent to the North Fork channels. The 1957 burn is at the upper end of South Fork. The photograph was taken in November 1970 (U.S. Forest Service photo).

tion was used. In moist site areas, 50% of the trees were Douglas fir and white fir.

Trees larger than 25.4 cm (10 in.) were harvested. Smaller trees and unmerchantable material were windrowed by bulldozer and burned. The cleared ground was seeded with a mixture of 40% slender wheatgrass (*Agropyron trachycaulum*), 40% Kentucky bluegrass (*Poa pratensis*), and 20% orchard grass (*Dactylis glomerata*) at a rate of 11.2 kg/ha (10 lb/acre). Redtop (*Agrostis alba*) was seeded in the stream channels at the same rate.

Current Treatments

The next step after converting the moist site forest to a grass cover was to convert the adjacent dry site merchantable ponderosa pine forest to grass (Figure 3). The 40.5-ha (100 acre) stand was predominantly ponderosa pine, but with a good representation of white fir and Douglas fir, some of very large diameter. The basal area was 50.3 m^2/ha (219 ft^2/acre), a very dense stand; gross volume was 154 m^3/ha (11,000 board ft/acre), 79% pine. Southwest aspects and 20% slopes were most common. Twenty-five percent of the area had slopes of 40% or steeper.

The timber harvest was conducted in the fall of 1966. An attempt was made to windrow the slash and residual trees with a bulldozer, but the work was too costly. In December 1969, much of the residual stand was destroyed by a prescribed burn. Surviving trees in the treatment area were treated with silvicide, thus essentially eradicating the stand. Approximately 6,270-m^3 (1.1 million board ft) gross volume was harvested or eliminated.

In June 1970 the dry site was seeded with the same formulation and rate of wheatgrass, Kentucky bluegrass, and orchard grass that was used in the previous treatment. A 1971 range inventory indicated the area produced 1,780 ± 305 kg/ha (1,588 ± 272 lb/acre) of grasses, forbs, and grasslike species. Grasses made up 39% of the composition. New Mexican locust invaded many of the treated areas. About 27.5 ha (68 acres) of unmerchantable pine remain on the steeper areas of the watershed.

SOUTH FORK TREATMENTS

Previous Treatment

The watershed was marked by the single-tree selection method. The timber was cut from June 1953 until November 1955. The harvest removed 46% of the merchantable timber, 17,100 m^3 (3 million board ft), and reduced basal area of trees 2.5 cm (1 in.) dbh and over by 24%. Logging damage, access roads, and skid trails reduced the basal area by an additional 6%. Stand improvement work, designed to control dwarf mistletoe (*Arceuthobium vaginatum* subsp. *cryptopodum*) and to reduce competition with pine reproduction by fir, Gambel oak, and New Mexican locust, reduced basal area on the watershed by another 6%. On July 6, 1957, a wildfire burned 24.3 ha (60 acres) in the upper southeast portion of South Fork (Figure 1). The fire destroyed an additional 9% of the original basal area on the watershed. Thus total basal area was reduced 45% by all activities.

Current Treatment

The objective for the second treatment was to convert the pine-fir stand into a pure ponderosa pine stand, and to maintain the stand at a density of 9.2 m^2/ha (40 ft^2/acre). This density should optimize overall production of timber and water. Ponderosa pine was favored partially because of its high commercial value.

The average basal area of the stand, including the 1957 burn, was 27.1 m^2/ha (118 ft^2/acre) at the beginning of the second treatment. It averaged about 32.1 m^2/ha (140 ft^2/acre) in the timbered areas. Fifty percent of the merchantable trees were white fir and Douglas fir. Gross volume was approximately 140 m^3/ha (10,000 board ft/acre). Slopes of 5–10% with north and northwest aspects were most common.

The timber harvest on South Fork began in September 1966. A total gross volume of 16,530 m^3 (2.9 million board ft) was removed or eliminated from the watershed. All merchantable timber was removed from the pine areas and the residual trees were thinned to 9.2 m^2/ha (40 ft^2/acre). Areas of white fir and Douglas fir, as well as areas of ponderosa pine heavily infested with dwarf mistletoe, were cleared and the slash windrowed (Figure 3).

The cleared areas and the 1957 burn area required artificial reforestation to reach the desired density level. Planting the burn with 2-0 ponderosa pine seedlings met with limited success in 1967. A 1972 planting had to be postponed because of a total lack of winter moisture. The watershed was planted in 1973 and 1974, but it is too early to ascertain success. Plant competition and a large pocket gopher (*Thomomys bottae*) population have frustrated reforestation activities in spite of control attempts. The transition to a ponderosa pine watershed has not yet been achieved.

Except for about 22.3 ha (55 acres) of thinned pine, the watershed is largely cleared, with reinvading natural vegetation, especially bracken fern (*Pteridium aquilinum*) and New Mexican locust. Range inventories indicate herbaceous vegetation on South Fork can range from 2580 ± 424 kg/ha (2,302 ± 378 lb/acre) in a wet year to 974 ± 138 kg/ha (869 ± 123 lb/acre) in a relatively dry one.

WATER YIELD RESULTS

North Fork

Riparian cut. The removal of the broad-leaved riparian trees did not have a statistically significant effect on the annual or growing season streamflow or on diurnal streamflow fluctuations. Since the riparian cut did not significantly affect streamflow, the 5 years of data from 1954–1958 were included in the calibration or pretreatment regression for evaluating the next treatment (Figure 4).

Moist site conversion. The moist site treatment resulted in statistically significant water yield increases, as indicated by the differences between the pretreatment and the post-treatment regression curves, $\hat{Y}_2 - \hat{Y}_1 = 0.82 + 0.34X - 0.03X^2$ (Figure 4). However, this relationship is only valid for Middle Fork values of less than 203 mm (8 in.) of runoff, the maximum during the period. Covariance analysis for average conditions indicated an increase of 42 ± 10%, or of 32 ± 7 mm (1.26 ± 0.29 in.). Increases varied from 95% when flow on Middle Fork was 25 mm (1 in.) to 36% when flow was 102 mm (4 in.). All calculated water yield increases equal to or greater than 21 mm (0.82 in.) are significant. Monthly analyses indicate significant water yield increases occurred in all months except December, January, and April. Streamflow volume increases resulting from the treatment have been greatest during the 8-month winter period (L. R. Rich, unpublished report, 1967).

Dry site conversion. Streamflow measurements after converting the dry site merchantable ponderosa pine stand to grass also indicate a significant increase in water yield (Figure 4).

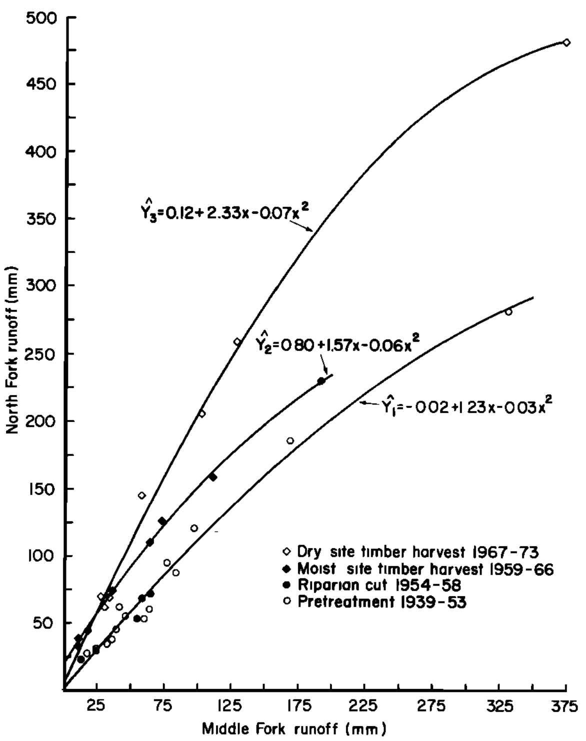

Fig. 4. Pretreatment and posttreatment regressions for North Fork show treatment effects on annual runoff (differences among curves). The region of statistical significance along the X axis, above which all values are significant, is 0 mm (0.00 in.) for moist site treatment and 2.3 mm (0.09 in.) for the dry site treatment.

The increases in water yields, above those produced by the moist site treatment, are described by the equation $\hat{Y}_3 - \hat{Y}_2 = -0.68 + 0.76X - 0.01X^2$. The increase amounts to 31 ± 9% greater flow, for average conditions, than was obtained after the moist site treatment. The average increase is 34 ± 9 mm (1.32 ± 0.37 in.).

The increases produced by the combined moist and dry site treatments can be described by the equation $\hat{Y}_3 - \hat{Y}_1 = 0.14 + 1.10X - 0.04X^2$. Combined increases vary from 102% at 25 mm (1 in.) to 87% at 102-mm (4 in.) yield from the control watershed. Any increase of 6 mm (0.24 in.) or more is statistically significant. The combination of the two treatments results in a 84 ± 11% total increase when compared with original conditions. This is equal to an increase of 69 ± 9 mm (2.70 ± 0.35 in.). The yearly differences between expected and observed annual runoff for the combined treatment is presented in Figure 5.

The runoff changes can also be described in terms of runoff coefficient and calculated evapotranspiration. The average annual runoff coefficient was 0.18 ± 0.03 during the combined moist site and dry site cut; an increase of 82 ± 12% over pretreatment period. The changes in the precipitation-runoff relationship can also be illustrated graphically (Figure 6). The base curve describing undisturbed forest conditions was derived from data from all three Workman Creek watersheds. Calculated evapotranspiration during the combined period was 752 ± 91 mm (29.6 ± 3.6 in.). A covariance analysis indicates that this is a significant decrease of 10 ± 3%. We assume that most evapotranspiration decreases occurred during the summer but the influence on soil moisture storage helped produce major water yield increases in winter. Peak monthly flow is in March, but all months except December showed significant increases in runoff. Regressions for July and August, however, were relatively weak for both catchments. Runoff during the eight winter months increased by 76 ± 20% and during the summer period by 129 ± 47%. The winter increases are more important for water yields because of the volumes of water involved.

South Fork

Single-tree selection harvest. The timber harvest resulted in small annual water yield increases (Figure 7). Actual water yields were slightly (but usually not significantly) higher than expected without treatment for 10 out of 13 years. Changes were insignificant from a practical point of view; however, they were statistically significant, primarily because of the 1966 water year, the third highest on record. The analysis indicates increases of 7 ± 6%, or of 6 ± 5 mm (0.23 ± 0.20 in.), for average conditions. The two regressions are almost the same at average and low values. The water yield increases are described by the equation $\hat{Y}_2 - \hat{Y}_1 = 0.18 - 0.14X + 0.03X^2$. This equation is also based on data to 203 mm (8 in.) maximum annual runoff. Increases of 5 mm (0.18 in.) or greater are significant; only 1966 meets this requirement. March was the only month to have significant increases in runoff (L. R. Rich, unpublished report, 1967). The 1957 wildfire did not significantly increase annual water yields, although it did result in increased flood peaks during the first two summers [*Rich*, 1962].

Clearing for 9.2-m²/ha basal area. The timber harvest and thinning significantly increased water yields (Figure 7). The results parallel the results from the combined moist and dry site cuts on North Fork. Water yields from South Fork since the clearing indicate increases of between 78 and 121% of those expected. Water yield increases are described by $\hat{Y}_3 - \hat{Y}_1 = 0.20 + 1.35X - 0.03X^2$. Values equal to or greater than 9 mm (0.35 in.) are significant. Covariance analysis at average conditions indicated an increase of 111 ± 16%, which compares favorably with the 84 ± 11% increase for North Fork. The South Fork average increase was 93 ± 13 mm (3.67 ± 0.52 in.). The relationship between expected and observed annual runoff for the last South Fork treatment is presented in Figure 8.

The South Fork average annual runoff coefficient was 0.22 ± 0.03 following treatment, an increase of 99 ± 17%. The precipitation-runoff changes are also described in Figure 6. Calculated annual average evapotranspiration was 721 ± 89 mm (28.4 ± 3.5 in.) during the start toward 9.2 m²/ha (40 ft²/acre), representing a significant decrease of 14 ± 4%. As

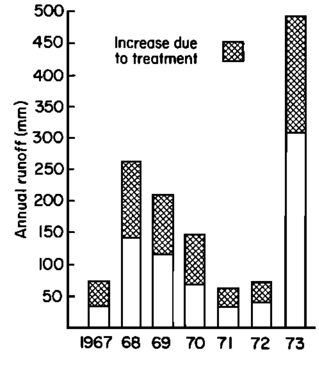

Fig. 5. Difference between observed and expected water yields from the combined treatment when compared with pretreatment conditions, North Fork Workman Creek.

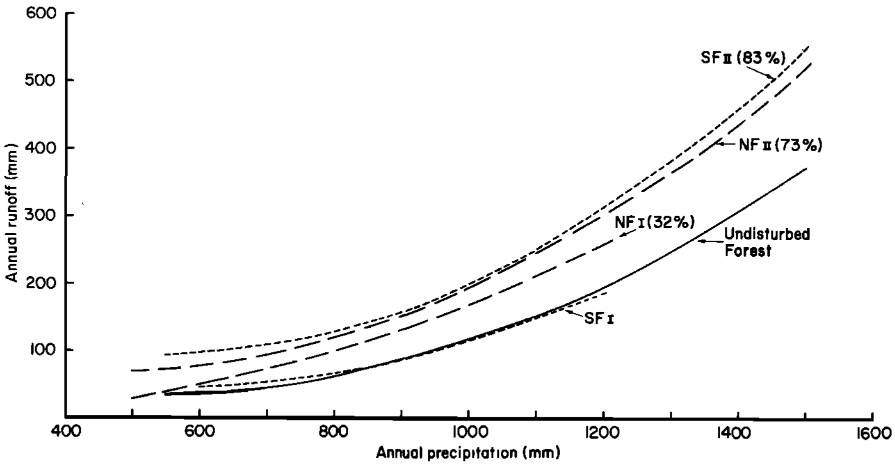

Fig. 6. Precipitation-runoff curves for the main Workman Creek treatments: South Fork selection harvest (SFI); North Fork moist site cut (NFI); North Fork dry site cut (NFII); South Fork clearing (SFII); and for undisturbed conditions. The percentages following the treatment code represent the percent of the watershed cleared.

with North Fork, all months except December showed significant increases in streamflow, with the greatest flows and the largest increases usually occurring in March. There was an average water yield increase of 106 ± 21% in winter and an average increase of 147 ± 64% in summer.

The earlier treatments and resultant water yield increases are discussed more thoroughly by *Rich et al.* [1961] and *Rich* [1962, 1965].

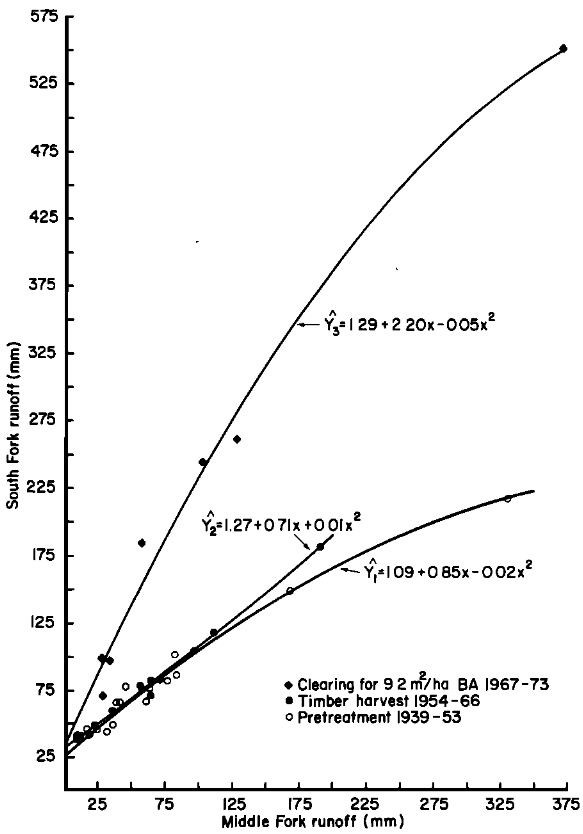

Fig. 7. Pretreatment and posttreatment regressions for South Fork show treatment effects on annual runoff (differences among curves). The region of statistical significance along the *X* axis, above which all values are significant, is 0 mm (0.00 in.) for the timber harvest and 3.0 mm (0.12 in.) for the vegetation conversion.

SEDIMENTATION RESULTS

North Fork

Trapped sediment measured at the weir pond indicated an average pretreatment erosion rate of 0.03 m^3/ha/yr (0.4 ft^3/acre/yr). *Rich et al.* [1961] report 0.16 m^3/ha (2.3 ft^3/acre) and 0.43 m^3/ha (6.2 ft^3/acre) for the first 2 years after the moist site treatment, which are relatively low sedimentation rates.

The average sedimentation rate for the 7 years since the dry site treatment has been 0.14 m^3/ha/yr (2.0 ft^3/acre/yr). Sediment is usually moved only during high-volume stormflows. However, the storm of September 5, 1970, which produced 290 mm (11.40 in.) of rain in 24 hours, did not cause serious damage to treated areas on either watershed. Observations indicate that the channel and main logging road are the major contributory areas.

South Fork

Rich [1962] indicates that South Fork produced an average of 0.01 m^3/ha/yr (0.1 ft^3/acre/yr) of sediment until the 1957 wildfire. The selection timber harvest had little effect on soil movement. The sedimentation rate rose sharply during the summer after the fire to 0.18 m^3/ha (2.57 ft^3/acre) for the

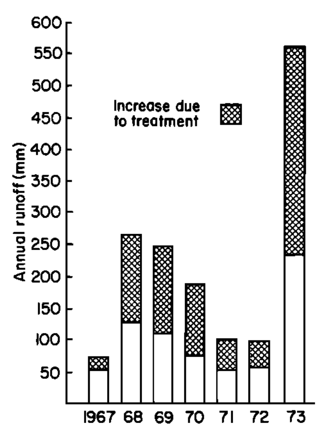

Fig. 8. Difference between observed and expected water yields from the clearing and start to 9.2 m^2/ha (40 ft^2/acre) when compared with pretreatment conditions, South Fork Workman Creek.

watershed. At that rate it would be 0.95 m^3/ha (13.63 ft^3/acre) for the 24.3-ha (60 acre) burn, the presumed source of the sediment. Approximately 1,234 m^3 (1 ac ft) were eroded from the burn, but only 2% was sampled at the weir. The rest was redeposited on the area or in the channel or was washed over the weir in suspension. The rate receded to an average of 0.03 m^3/ha/yr (0.4 ft^3/acre/yr) within $2\frac{1}{2}$ years.

During the October 1966 to September 1973 period the erosion rate was 0.05 m^3/ha/yr (0.7 ft^3/acre/yr).

Middle Fork

The sedimentation rate on Middle Fork, upstream from the flume, was about 0.002 m^3/ha/yr (0.03 ft^3/acre/yr) during the same period. The Main Dam measured a sedimentation rate of 0.10 m^3/ha/yr (1.4 ft^3/acre/yr). Most of this originated on Middle Fork, since flumes usually are designed for flows which will transport most sediments through them. The relatively high Middle Fork sedimentation rate is influenced by the main access road to the watersheds, which passes through its lower end, adjacent to the channel. It is also probable that the Main Dam traps some sediments that have escaped the upstream weir ponds.

DISCUSSION

The Workman Creek experiments have bracketed the water yield increases possible through a range of forest treatments. The increases have been achieved by converting the vegetation from deep-rooted old growth conifers into shallow-rooted grasses, forbs, brush, or pine seedlings. The shallower-rooted vegetation utilizes less soil moisture during the growing season, as indicated by the increase in summer runoff. Consequently, less precipitation is needed to recharge the soil during the water-yielding winter period, and there is an earlier and more efficient movement of water into the stream channels. Redistribution of snow probably contributes to the water yield increases also, but this factor was not studied.

It is necessary to remove significant numbers of trees or clear areas of significant size to increase water yields. The removal of a small quantity of deciduous riparian trees on North Fork did not increase water yields. The relatively small effect of individual tree removal was further demonstrated by the single-tree selection harvest on South Fork. Although the harvest removed one third of the merchantable timber and almost half of the basal area, water yield increases were significant only after unusually high precipitation. In contrast, the heavy removals on the moist and dry sites of North Fork and the clearcutting on South Fork significantly increased water yields.

The relationships between increased runoff and percent of a watershed treated is illustrated by the series of precipitation-runoff curves in Figure 6. The selection harvest curve and the undisturbed forest curve are almost identical. At the upper level the South Fork second treatment curve and the North Fork dry site curve are close together. These represent 83% and 73% of the respective watershed under treatment. The North Fork moist site cut, with 32% of the area treated, is intermediate.

We cannot accurately draw a curve representing a 100% clearing of a watershed. From our experience on Workman Creek, however, the curve should not be very far above the dry site or the South Fork clearing curves. Removing the remaining 27.5 ha (68 acres) of pine on North Fork or the thinned pine on South Fork should not result in a large increase in annual runoff over that already achieved, although there could be increases in quick flows from individual storms. Runoff is not generated uniformly over a watershed, and the remaining trees are growing on shallow soils at relatively long distances from the channel. Effective movement of additional moisture would depend on soil moisture conditions in adjacent areas. These may also be the reasons why the 24.3-ha (60 acre) wildfire never significantly increased water yield. It is probable that the moist site cut approached maximum water yield with minimum loss of desirable forest.

Watershed experiments from throughout the western United States (Table 2), representing a wide range of climatic, physiographic, and vegetation conditions, confirm that clearing large areas of forest results in increased water yields. The findings from the H. J. Andrews and the Beaver Creek watersheds also confirm that the greater the degree of clearing, the greater the increase in runoff.

Workman Creek mean pretreatment runoff was lower than any reported above in spite of higher mean annual precipitation than most. This indicates higher evapotranspiration and soil moisture recharge demands in relation to precipitation on Workman Creek. This is also true for other Arizona mixed conifer areas. The greater relative runoff increases from Work-

TABLE 2. Annual Water Yield Increases Reported From Selected High Forest Experimental Watersheds in the Western United States

Area	Treatment	Mean Precipitation		Untreated Mean Runoff		Forest Type	Increase, %	Reference
		mm	in.	mm	in.			
Wagon Wheel Gap, Colo.	100% clearcut	536	21	157	6.18	Douglas fir Engelmann spruce	22	*Leaf* [1975] *Hibbert* [1967]
Fool Creek, Fraser, Colo.	40% clearcut strips	762	30	283	11.14	Lodgepole pine Engelmann spruce Subalpine fir	25	*Leaf* [1975] *Hibbert* [1967]
H. J. Andrews, Ore.								
Watershed 1	100% progressive clear-cut	2388	94	1376	54.18	Douglas fir	34*	*Rothacher et al.* [1967] *Rothacher* [1970]
Watershed 3	33% patch cut	2388	94	1339	52.70	Douglas fir	13	
Beaver Creek, Ariz.†								
Watershed 12	100% clearcut	635	25	153	6.04	Ponderosa pine	34	*Brown et al.* [1974]
Watershed 9	32% clearcut strips	635	25	170	6.70	Ponderosa pine	16	

*Approximation.
†Only winter streamflow.

man Creek are the result of the greater treatment influence on the high evapotranspiration demand. High evapotranspiration demands also characterize the Arizona chaparral type. *Hibbert et al.* [1974] report that increases averaged 96 ± 64 mm (3.8 ± 2.5 in.), a threefold increase, when the shrub cover was eradicated on six experimental watersheds. Evapotranspiration reduction was important in the other forest studies, but the initial demands were less in proportion to precipitation because of short, cool growing seasons (Colorado), excessive moisture (Oregon), or because of relatively shallow soils and low stand densities (Beaver Creek).

The results suggest even-aged forest management as a possible way of both maintaining the timber supply and increasing streamflow. Even-aged management implies that the forest would be harvested in a series of patch cuttings; in this instance they could be scheduled on a 20-year cutting cycle over a 120-year tree rotation. The removal of patches of mature timber would reduce evapotranspiration until new trees become established. The patches could be designed to increase snow accumulation and at the same time allow for natural reseeding from the adjacent forest. Sites with a high water yield potential could be scheduled in the harvesting sequence so continued runoff increases would be insured, or they could be converted and maintained in grass or other shallow-rooted herbaceous cover for even larger increases.

A study described as a possible start toward even-aged management, involving the clearcutting of small blocks or patches on one sixth of a watershed, has been initiated on the Castle Creek experimental watersheds of eastern Arizona. The blocks are distributed throughout the area and are located according to timber stand conditions. *Rich* [1972] reports that the treatment resulted in significant water yield increases of approximately 29% based on pretreatment conditions.

Summary

Removing the dry site merchantable ponderosa pine and converting the area to grass on North Fork of Workman Creek increased water yields 31%. An increase of 84% resulted from the combined moist and dry site treatments which affected 73% of the watershed. Only the unmerchantable pine areas of North Fork remained untreated.

The South Fork treatment was designed to convert the watershed to ponderosa pine with a reduced density of 9.2 m^2 of basal area per hectare (40 ft^2/acre); 83% of the watershed was cleared in preparation for planting pine, and the remaining 17% of the area was thinned. This treatment resulted in average water yield increases of 111%.

Results to date from Workman Creek indicate that removal of forest vegetation in significant areas and amounts will substantially increase water yields. The problem now is to develop a system of timber management that will increase water yields while maintaining a favorable and adequate tree cover for economic and esthetic needs.

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