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# Changes in Streamflow in an Herbicide-Treated Pinyon-Juniper Watershed in Arizona

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A 147-ha pinyon-juniper watershed in north-central Arizona was sprayed with a herbicide mixture to kill all overstory vegetation. After 8 years of postherbicide evaluation, the dead trees were removed. The herbicide treatment induced an increase in annual streamflow of about 157%. There is an indication that after the dead trees were removed, streamflow was reduced to near-pretreatment levels.

## INTRODUCTION

The pinyon-juniper woodland type occupies over $24 \times 10^6$ ha between altitudes of 1220 and 1980 m above sea level in the western and southwestern United States [*U.S. Department of Agriculture, Forest Service*, 1958] with about $21 \times 10^6$ ha in Arizona, New Mexico, Colorado, and Utah [*Dortignac*, 1960]. The area and numbers of trees in this woodland type have increased since the early 1900's because of increased livestock grazing and the reduction in number of forest fires [*Arnold and Schroeder*, 1955; *Barr*, 1956].

*Barr* [1956] estimated a probable increase in annual water yield of 13 to 25 mm from the removal of pinyon-juniper in Arizona (about $5.5 \times 10^6$ ha) if the land were reseeded with grasses. A study of pinyon-juniper removal by *Collings and Myrick* [1966], however, found no significant change in water yield. *Skau* [1964*a*, *b*] reported that any change in water yield from pinyon-juniper removal would probably result from reduced interception and evapotranspiration losses. *Clary et al.* [1974], after reviewing all documented hydrologic results from the southwestern pinyon-juniper type, stated that the possibility of increasing water yield through overstory removal was only marginal.

The Beaver Creek research watersheds in north-central Arizona were established in the mid 1950's to quantify vegetation effects on water yield from pinyon-juniper woodlands on volcanic-derived soils. In Arizona and southwestern New Mexico, about one third of the pinyon-juniper type woodland is on soils derived from volcanic rocks. Two types of vegetation manipulation in the woodland type have been studied: clearing the overstory and killing the overstory with herbicides. Preliminary results of the herbicide treatment have previously been reported by *Clary et al.* [1974]. This paper documents changes in water yield in the 8-year period following an herbicide application and in the subsequent 6-year period following removal of the dead trees.

## STUDY AREA

The two adjacent watersheds used in this study are 80 km south of Flagstaff, Arizona, in the pinyon-juniper woodland type of the Beaver Creek drainage. The watershed which had the herbicide treatment is 147 ha in area; the control watershed is 51 ha in size (Table 1).

Soil, developed from volcanic basalt parent material, is predominately a Springerville very stony clay, about 110 cm deep with a clay texture throughout [*Williams and Anderson*, 1967]. Most of the clay is montmorillonite, which swells and shrinks during each wet and dry cycle, forming cracks as much as 5 cm wide and 1 m deep.

Mean annual precipitation on the treated watershed is 463 mm (1958–1982), with a high of 691 mm and a low of 210 mm (Figure 1). Two major precipitation seasons characterize this area [*Baker*, 1982*a*]. Mean precipitation during the seven winter months, October through April, is 296 mm, or 64% of the annual total. Most of the remaining precipitation falls during July, August, and September.

Continuous streamflow records on each watershed were obtained from a precalibrated concrete trapezoidal flume [*Clary et al.*, 1974]. Mean annual streamflow from the herbicide-treated and control watersheds are presented in Table 1. Annual streamflow on the treated watershed has varied from zero in 1959, 1963, and 1974 to 149 mm in 1973 (Figure 2).

Most of the water yield produced on the Beaver Creek experimental watersheds is in the winter. In 21 of the 25 years of this study that streamflow was produced, 15 years had 100% of the annual discharge produced during the winter season. The soil mantle begins to recharge during the winter, when water from rain or snowmelt is available and evapotranspiration demands are low. Most streamflow appears as snowmelt runoff in March and April. The stream channels in these headwater basins become dry before the onset of summer rains.

Much of the streamflow from these upland or headwater basins is the product of direct flow that consists of overland flow and a substantial portion of interflow. *Baker* [1982*b*] found that more than 80% of the streamflow originates as direct flow both before and after treatment. The shallow *A* horizon covers a relatively impermeable soil layer with hydraulic conductivities of less than 1 mm $h^{-1}$ [*Williams and Anderson*, 1967]. This shallow soil horizon is quickly recharged by winter snowmelt or rain events. Winter rainfall and snowmelt events with intensities greater than 1 mm $h^{-1}$ are common on Beaver Creek [*U.S. Department of Commerce*, 1967; *Ffolliott and Hansen*, 1968].

## TREATMENT AND ANALYSES

A foliage spray application of 2.8 kg acid equivalent of picloram and 5.6 kg acid equivalent of 2, 4-*D* [(2, 4-dichlorophenoxy) acetic acid] as triisopropolamine salts in 94 L of water per hectare were made onto 114 ha of the treated watershed in August 1968. The remaining 33 ha were either left untreated or individual trees were treated with the same herbicide using a backpack mist blower.



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TABLE 1. Physical Characteristics for Two Experimental Watersheds on Beaver Creek

| Characteristic | Herbicide Watershed | Control Watershed |
|---|---|---|
| Size, ha | 147 | 51 |
| Aspect | west | northwest |
| Midarea elevation, m | 1573 | 1591 |
| Basal area, $m^2\ ha^{-1}$ | 13 | 12 |
| Annual precipitation | | |
| pretreatment | 453 | 466 |
| postherbicide | 426 | 425 |
| post-tree removal | 518 | 524 |
| Annual streamflow | | |
| pretreatment | 22 | 25 |
| Postherbicide | 28 | 20 |
| post-tree removal | 60 | 62 |
| Peak discharge (maximum recorded), $m^3\ s^{-1}\ km^{-2}$ | 7.7* | 9.3 |
| Soil water holding capacity, mm | >460 | >460 |

*Storm event occurred in August 1964, prior to herbicide treatment.

In 1976, after 8 years of postherbicide evaluation, a commercial firewood sale was used to remove all merchantable firewood. The residual slash was piled and mostly burned in 1977.

Analysis of covariance was employed to compare streamflow observed during the two treatment periods to streamflow during the pretreatment period. Streamflow during the two treatment periods was also compared. Scheffe's method was used to conduct pairwise comparisons of covariate adjusted means with significance assessed at $\alpha = 0.10$. Streamflow on the control watershed was employed as the covariate.

Because of the variation in precipitation, and therefore streamflow, during the experiment, the analysis was unduly influenced by a few years of large streamflow amounts, especially during the postherbicide period. Therefore a $\log_e (x + c)$ transformation was employed to more equitably distribute the influence of these larger streamflow years throughout the range of data. A constant $c$ was needed as part of the transformation because zero streamflow was observed in a few years. Because the choice of the constant value can sometimes affect analysis results [*Mielke*, 1979], the covariance analysis was conducted for several values of $c$ ranging from 0.001 to 1.0. The effect of varying $c$ is reported in the results section. Adjusted means were retransformed to original units using a smearing estimate [*Duan*, 1983].

## EFFECTS OF HERBICIDE APPLICATION

### *Vegetation*

On the entire watershed, 83% of the Utah junipers were killed by herbicide treatment, including 96% killed on the broadcast area, 70% on the individual tree buffer area, and very little damage on the untreated areas [*Clary et al.*, 1974]. Shrub live oak and pinyon pine were severely damaged initially but showed marked recovery after 2 or 3 years. Cliffrose was moderately damaged but recovered quickly. Side-oats grama and other established perennial grasses were undamaged.

Numerous annual forbs and grasses invaded the watershed after the herbicide treatment. However, 4 years after treatment, perennial grasses were becoming more apparent over much of the watershed. Some of the annual forbs grew exceptionally large during the initial two years after treatment. This unusual growth may have been due to increased available soil water and possibly to the result of nutrients released by the dead vegatation. The estimated annual increase in understory vegetation yield following the herbicide treatment was 663 kg $ha^{-1}$. This figure includes production from 1970 through 1975. The first posttreatment year (1969) was eliminated due to possible carry-over effects of the herbicide treatment.

### *Annual Streamflow*

The 11 years of pretreatment data (1958–1968) define the regression used in determining posttreatment effects on annual water yield (Figure 3). Regardless of the constant $c$ employed in transforming the streamflow data, hypothesis of equal regression coëfficients and equal variances among the pre- and postherbicide and post-tree removal periods were not rejected ($p > 0.70$ and $p > 0.10$, respectively). The hypothesis of equal covariate adjusted streamflow among treatment periods was rejected ($p < 0.001$). Subsequent Scheffe's pairwise comparison indicates a significant increase in streamflow of 157% during the postherbicide period (retransformed adjusted means at $c = 0.001$ were 2.8 mm versus 7.2 mm for the pretreatment and postherbicide periods). Comparison of the postherbicide and post-tree removal periods was inconclusive with a decrease in streamflow (retransformed adjusted mean at $c = 0.001$ was 3.8 mm or only 36% larger than the pretreatment estimate) which was significant at $p$ ranging from 0.10 to 0.15 depending on the value of $c$ employed. Comparison of the post-tree removal period with the pretreatment period was nonsignificant regardless of the value of $c$ employed.

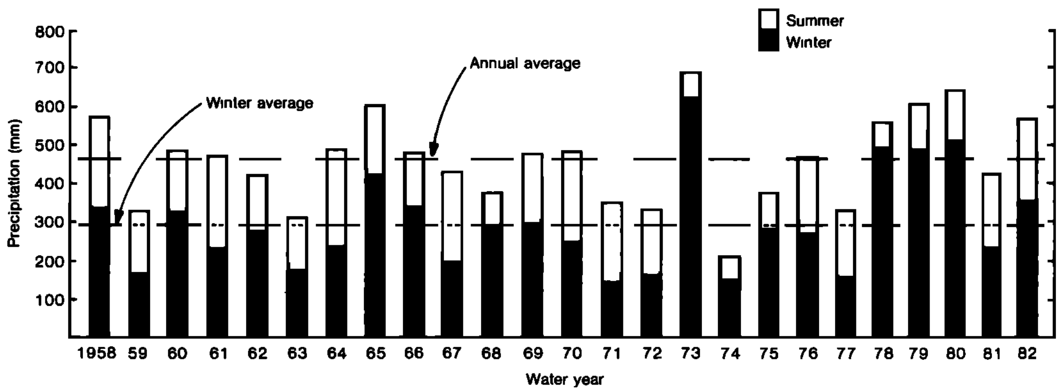


Fig. 1. Average winter (October–April) and summer precipitation on the herbicide-treated watershed.

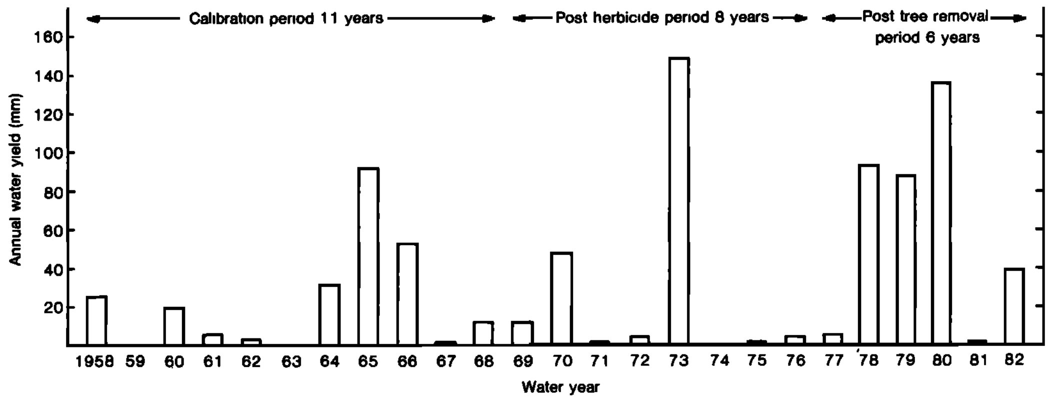


Fig. 2. Annual water yield from the herbicide-treated watershed.

*Johnsen* [1980] gravimetrically measured soil water content on the study areas and found that the soil mantle below 30 cm on the treated watershed did not dry down to $-15$ bars of atmospheric pressure for 7 years after the trees were killed. Similar soil in untreated areas, however, dried to wilting point each spring. Killing the overstory trees apparently resulted in reduced evapotranspiration losses.

Treatment of the pinyon-juniper watershed with an herbicide induced an increase in annual streamflow of 157%. This increase was still apparent 8 years after treatment at which time the residual dead trees were removed. Although the analysis is somewhat inconclusive ($p = 0.10$–$0.15$), there is an indication that subsequent streamflow was reduced to near pretreatment levels.

### *Major Storm Event*

An opportunity to assess the influence of the 2-year-old herbicide treatment on storm runoff was provided on September 5, 1970 [*Clary et al.*, 1974; *Thorud and Ffolliott*, 1973]. This storm produced peak rates of streamflow that correspond approximately to the 20- and 50-year recurrence events estimated from regionalized peak flood flow frequency curves for the control and treated watersheds, respectively (H. M. Babcock, unpublished data, 1971). Total precipitation on the herbicide-treated watershed was 97 mm (Table 2), with a maximum 60-minute rainfall intensity of 34 mm $h^{-1}$. Peak discharge on the treated watershed was about 25% greater than expected [*Clary et al.*, 1974]. The storm produced 26 mm of streamflow on the treated watershed, 1.3 times the amount from the control, even though the control watershed received more precipitation (Table 2). Basin recharge (precipitation minus streamflow) was 1.2 times greater on the control watershed.

The 2-year-old herbicide-treated watershed had lower evapotranspiration losses as indicated by the additional 13 mm of basin recharge on its control watershed (Table 2). The greater peak discharge and nearly equal time to peak from the larger treated watershed also indicate treatment effects attributed to reduced evapotranspiration losses and to more efficient water transport to the channel system. The increase in water transport efficiency is even more significant, since the treated watershed was nearly three times larger in size. Runoff efficiencies (storm flow/storm precipitation) for the treated and control basins were 0.26 and 0.19, respectively.

## DISCUSSION

The hydrologic regimes of the woodland areas on volcanic-derived soils on Beaver Creek are different from those of many other areas. The relatively shallow soil depth, the high clay content, and the predominately short spring streamflow period limit the effect that vegetation manipulation has upon the streamflow regimes from these upland pinyon-juniper watersheds. Most forested areas have a higher portion of their streamflow produced by the base flow component. From hydrograph analysis of streamflow on Beaver Creek, it appears that much of the streamflow from these woodland watersheds results from direct flow.

Pinyon pine and Utah juniper, being evergreen species, can transpire in the winter if the soil mantle is recharged, but the rate is usually low because of the cool temperatures. Summer precipitation characteristically follows an early May to mid-July dry period during which high evapotranspiration rates deplete available soil water. Summer rains are seldom concentrated enough or of sufficient quantity to recharge the soil mantle. Soil water continues to be depleted during the dry fall months when evapotranspiration potential is still high. Early winter precipitation is used to recharge the soil mantle.

The herbicide treatment did reduce evapotranspiration losses, as shown by the increase in annual and storm water

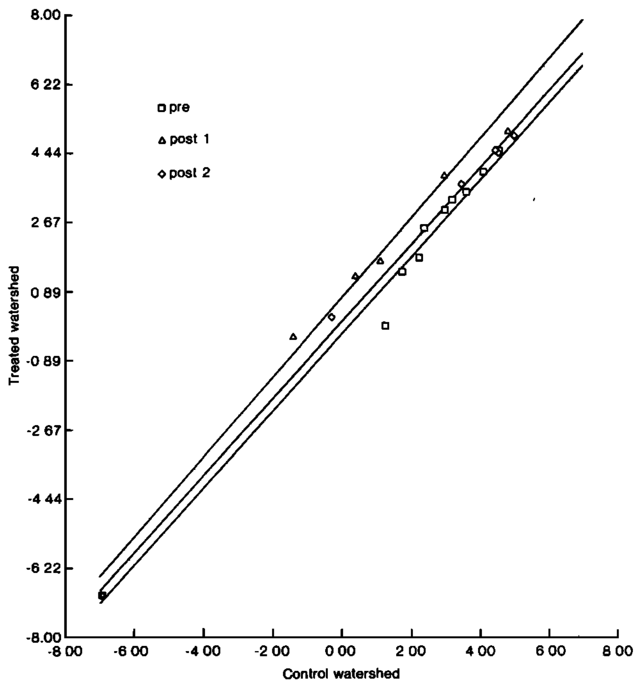


Fig. 3. Pretreatment, postherbicide, and post–tree removal regressions of annual water yield using a $\log_e (x + 0.001)$ transformation.

TABLE 2. Statistics for the Single Storm Event of September 5, 1970

| | Herbicide Watershed | Control Watershed |
|---|---|---|
| Precipitation, mm | 97 | 104 |
| Streamflow, mm | 26 | 20 |
| Approximate peak flow recurrence interval, yr* | 50 | 20 |
| Peak discharge, $m^3\ s^{-1}\ km^{-2}$ | 5.1 | 4.1 |
| Flow duration, h | 22.8 | 17.1 |
| Basin recharge (precipitation minus streamflow), mm | 71 | 84 |
| Time to peak, h | 1.6 | 1.5 |

*H. M. Babcock (unpublished data, 1971).

yields and by the decrease in soil water loss. The increase in water yield was achieved by killing the overstory trees and leaving them in place. These dead trees apparently provided enough shade and wind resistance to create a microclimate that reduced evaporation and enabled much of the soil mantle to remain above its soil moisture wilting point. With reduced soil water loss, less precipitation was needed to recharge the soil mantle; consequently, more precipitation became available for streamflow.

## Conclusions

Although the increase in annual streamflow is statistically significant on the treated watershed, these increases in many years may not be of practical importance from a management view point. To justify and to make this treatment economically feasible, a land manager might need to consider the additional increases in other resources, such as additional grazing (caused by increased herbage production) or increased benefits for wildlife.

Most water yield increases resulting from a herbicide treatment would be added to the normal spring streamflow. Therefore any increase in water yield, or a significant portion of that increase, is less likely to be lost in transmission from the headwater basins to the lower reservoir system.

The results indicate that water yields can be increased on basins with volcanic soil by chemically killing the pinyon-juniper overstory and leaving the dead trees standing. This increase can be expected about 1 out of every 2 years when precipitation equals or exceeds the winter average. Therefore a management system may be devised where dispersed upland pinyon-juniper basins could be chemically treated to provide some additional water yield. Managers, however, must recognize that these treated areas may not be esthetically pleasing to much of the public and that the use of chemicals is opposed by many people.

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