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Effects of Ponderosa Pine Treatments on Water Yield in Arizona

MALCHUS B. BAKER, JR.

Rocky Mountain Forest and Range Experiment Station, Tempe, Arizona

Annual water yields were determined for three levels of overstory removal and three levels of strip cut with thinning applied on ponderosa pine watersheds. Water yield increases from a completely cleared watershed were statistically significant for 7 years, losing significance after recovery and growth of Gambel oak and herbaceous vegetation. Water yield increases were maintained 6 years after a light overstory removal and 10 years following a heavy overstory removal cut. Significant increases were obtained for 3–4 years following two levels of strip cut with thinning, but were then lost on watersheds with a high percentage of southern exposure or low slopes. Water yield increase remained at a 15% level during the first 6 years on a strip-cut watershed with 60% of its area on northern aspects.

INTRODUCTION

Ponderosa pine grows at elevations of 1700–2600 m in the Southwest [*Schubert*, 1974] where it occupies about 1.7 million ha in Arizona and 1.9 million ha in New Mexico [*Spencer*, 1966; *Choate*, 1966]. Although ponderosa pine occupies only about 0.7 million ha in the Salt-Verde River Basin in Arizona, or 20% of the watershed, nearly 50% of the total water yield in this basin originates from the pine type [*Barr*, 1956].

Ponderosa pine occurs primarily on soils developed from granite, schist, and shale. Local areas, with soils developed from igneous rocks, limestone, and sandstone, are scattered throughout the vegetation type [*Love*, 1960]. In the Salt-Verde River Basin, 57% of the ponderosa pine occurs on soils derived from igneous rocks and 43% on sedimentary-derived soils.

Hydrologists have conducted extensive studies of the effects of removing forest overstory, concluding that forest clearing generally increases water yield in all regions of the United States [*Douglass*, 1983; *Troendle*, 1983; *Hibbert*, 1983; *Harr*, 1983; and *Kattelmann et al.*, 1983] and in many other regions of the world [*Bosch and Hewlett*, 1982]. Where a major portion of water yield is from melting snow, the effect of forest manipulation on streamflow depends, in part, on how these activities influence both accumulation and melting characteristics of the snowpack. Clear-cutting in patches, strips, or blocks increases snow accumulation in these areas and thus increases the amount of water available for streamflow [*Gary*, 1975; *Leaf*, 1975]. Greater water yields can be expected from cleared stands as the result of reduced interception and evapotranspiration losses, of greater source-area concentration of snowmelt water, and of greater year-to-year carryover of soil water [*Gary*, 1979].

Snow regimes are affected by aspect. *Haupt* [1951, 1979] found that aspect affected snow accumulation and melt rates in conifer forests in Idaho; snow accumulation on north, east, and west aspects was 35, 30, and 24% greater than on south-facing slopes. In California, *Anderson and West* [1965] observed that northfacing slopes accumulated and retained more snow than on southfacing slopes. *Ffolliott and Hansen* [1968] and *Ffolliott and Thorud* [1969] also found snow accumulation to be greater on "cool" than on "warm" sites in Arizona. *Hansen and Ffolliott* [1968] also observed that throughout the winter, a large portion of the snowpack would melt from southerly aspects.

Evaporation losses from snowpack, under forested conditions, may be relatively small, with most snowpack water equivalent appearing as melt at the bottom of the snowpack. However, as openings are created by various harvesting practices, evaporation losses may become more significant, especially for openings on sites exposed to wind [*Ffolliott and Thorud*, 1975; *Cline et al.*, 1977]. *Ashton* [1966] measured average daytime evaporation rate of approximately 0.8 mm from December to early May in a ponderosa pine stand in eastern Arizona. During the same period, daytime evaporation losses in an opening were nearly twice as large.

Water yield response to clearcutting is also affected by slopes [*Cline et al.*, 1977]. On a north slope in Idaho, substantial gain (270–350 mm) in potential water yield per year resulted from removal of transpiring plant cover, elimination of snow interception by a closed-canopied forest, and gradual reoccupation by herbaceous plants. On a south slope, small to moderate increases (40–110 mm) in water yield resulted from clearcutting. Invading shrub species on the south slope rapidly reoccupied the soil mantle and after 4 years extracted more water from the soil during the extremely dry summer than did the original tree overstory and shrub understory.

The USDA Forest Service established the Beaver Creek research watersheds, within the Salt-Verde River Basin in north-central Arizona, to study the potential for increasing water yield in several vegetation zones on volcanic-derived soils. Results from this research in the ponderosa pine type are presented in this report.

STUDY AREA

The watersheds are located about 80 km south of Flagstaff, Arizona, in the ponderosa pine type of the Beaver Creek drainage (Figure 1). Physical characteristics of the experimental watersheds are shown in Table 1.

Soils are developed from volcanic basalt and cinder parent materials, and are predominantely a Brolliar stony clay loam, and a Sponseller or a Siesta stony silt loam, respectively. Soil depth is generally less than 1 m [*Williams and Anderson*, 1967]. The shallow A horizon of the soils in the Beaver Creek drainage covers a relatively impermeable soil layer with permeability rates of 1–5 mm hr^{-1} [*Williams and Anderson*, 1967]. Rainfall and snowmelt intensities greater than the range of permeability rates are common on Beaver Creek [*U.S. Department of Commerce*, 1967; *Ffolliott and Hansen*, 1968].

Before treatment, all study basins were stocked with

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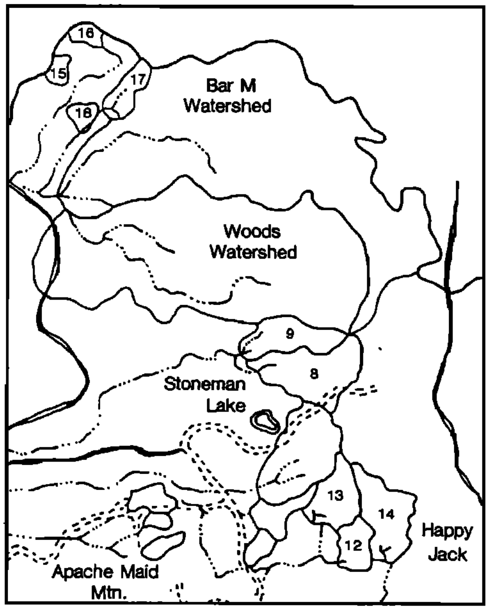

Fig. 1. Location of study watersheds in the Beaver Creek drainage area.

uneven-aged stands of ponderosa pine (*Pinus ponderosa* Laws.) interspersed with Gambel oak (*Quercus gambelii* Nutt.) and alligator juniper (*Juniperus deppeana* Steud.). Overstory basal area ranged from 21 to 32 m^2 ha^{-1} (Table 1).

Mean annual temperature in the ponderosa pine on Beaver Creek is 7.2°C, and average monthly temperature ranges from −2.2°C in January to 17.8°C in July [*Baker*, 1982]. Mean annual precipitation has ranged from about 550 to 785 mm (Table 1). Two major precipitation seasons characterize this area. Average winter precipitation ranges from about 360 to 510 mm, or about 60% of the annual total (Figure 2). Most of the remaining precipitation falls during July, August, and September.

Ninety-seven percent of the annual water yield (Figure 2) is produced in the winter (October through April). The water year is defined as the period from October 1 through September 30. Essentially, all May water yield is residual from the spring runoff period. The soil mantle is recharged during the winter when rain or snowmelt is available and evapotranspiration demands are low. Most streamflow is from snowmelt in March and April, terminating in early May, and most stream channels become dry before the onset of summer rains which produce 3% of the water yield (Figure 2).

TREATMENTS AND ANALYSES

Two types of vegetation manipulation have been studied on Beaver Creek: reduction of the forest overstory and creation of cleared openings [*Brown et al.*, 1974]. Preliminary results of these treatments have been reported by *Brown et al.* [1974]. This paper documents water yield response from six watershed treatments during the 15-year period (1968–1982) of research.

On the completely cleared watershed (no. 12) (Figure 1), all merchantable poles and sawtimber were removed and the remaining nonmerchantable timber felled in 1966–1967. All slash and debris were machine windrowed to trap and retain snow, reduce evapotranspiration losses, and increase surface drainage efficiency of the watershed. Tree species (predominantely oak and some juniper) were allowed to sprout and grow after the initial clearing treatment. Because the hydrologic changes caused by timber harvesting cannot be separated from those caused by slash windrows, the "treatment" consists of timber cutting; soil disturbance associated with felling, yarding, slash windrowing; and the presence of windrows.

The windrows were at least 1.5 m high and spaced approximately 30 m apart. Windrow orientation was either east to west or northwest to southeast, depending on which alignment best served to direct surface flow into existing stream channels. It was hypothesized that east-west alignment would provide maximum shade and thus encourage retention of snow and reduction of evaporation losses, and that northwest-southeast alignment, which is perpendicular to the prevailing winds, would provide maximum trapping of snow behind windrows and reduce the amount of snow blown off the watershed. The windrows were removed by burning in the fall of 1977.

On watersheds 8 and 17 (Figure 1), 33 and 77% of the

TABLE 1. Physical Characteristics for Experimental Watersheds on Beaver Creek

	Overstory Removal						Strip-Cut With Thinning					
	100%		77%		33%		68%		57%		31%	
Characteristics	Treated	Control	Treated	Control	Treated	Control	Treated	Control	Treated	Control	Treated	Control
Watershed number	12	13	17	18	8	13	16	15	14	13	9	8
Size, ha	184	369	121	98	730	369	102	66	546	369	454	730
Aspect												
channel orientation	SW	SW	SW	S	W	SW	SE	S	S	SW	W	W
warm*, %	87	74	69	99	58	74	43	71	84	74	40	58
cool, %	13	26	31	1	42	26	57	29	16	26	60	42
Midarea elevation, m	2150	2195	2115	2054	2225	2195	2164	2103	2194	2195	2194	2225
Basal area, m^2 ha^{-1}												
initial	24	29	30	32	30	29	22	21	28	29	29	30
residual	0	29	7	32	20	29	7	21	12	29	20	30
Annual precipitation, mean												
before treatment, mm	617	609	726	728	679	606	703	685	650	609	645	658
after treatment, mm	552	592	717	733	808	695	748	785	709	654	663	681
Annual streamflow, mean												
before treatment, mm	150	93	206	180	174	97	135	99	117	94	155	160
after treatment, mm	186	94	256	197	337	166	236	161	180	143	211	188

Treatments for watershed pairs refer to average level of basal area reductions by the two harvesting methods.
*Warm aspects = 113°–292°.

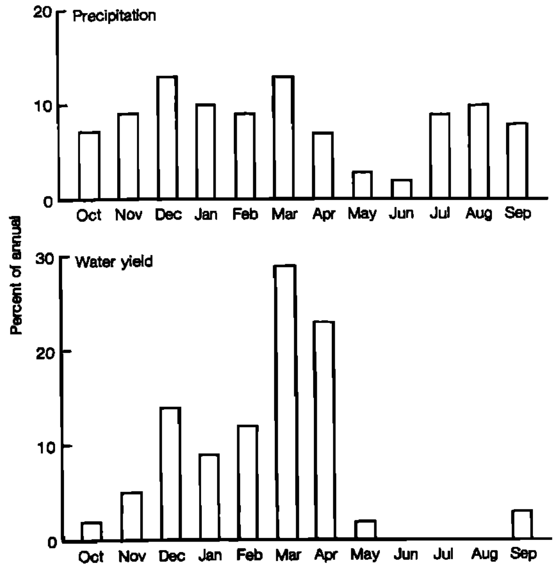

Fig. 2. Mean monthly precipitation and water yield in ponderosa pine as percent of annual.

initial overstory basal area were removed, respectively. On lightly cut watershed 8, stands of trees less than 30 cm diameter breast high (dbh) were reduced to a growing stock level of 14 m^2 ha^{-1} of basal area, while stands of trees 30 cm dbh and larger were reduced to an actual basal area of 16 m^2 ha^{-1}. Growing stock levels are numerical indices representing future basal area levels when the average tree diameter reaches 25 cm or more. Slash was either lopped and scattered or piled and burned, depending on its density.

On heavily cut watershed 17, 77% of the initial 30 m^2 ha^{-1} of basal area was removed, leaving even-aged groups of trees with an average basal area of 7 m^2 ha^{-1}. All slash was windrowed.

On the three strip-cut watersheds (nos. 9, 14, and 16) (Figure 1), all merchantable pulpwood and sawtimber were removed within strips and the remaining nonmerchantable trees felled. Cut strips on watershed 9 were 18 m wide, running perpendicular to the stream channel system. The intervening 37-m uncut strips were undisturbed. This treatment removed 31% of the watershed basal area. All slash was piled and burned in the cleared strips.

One third of the timber on watershed 14 was cleared in irregular cut strips averaging 18 m wide. Forest overstory in the intervening leave strips, which averaged 37 m wide, was reduced (24%) to 18 m^2 ha^{-1} of basal area. The overall treatment resulted in a 57% reduction in watershed basal area. Slash was piled and burned in the cleared strips.

Fifty percent of the overstory on watershed 16 was removed in irregular strips averaging 18 m wide. The forest overstory of the intervening leave strips was reduced to 18 m^2 ha^{-1} of basal area. Overall, 68% of the watershed basal area was removed. Slash was piled and burned in the cleared strips.

In reality, the residual basal area on the one half strip-cut and thinned watershed was the same as that remaining on the heavily cut watershed. Because the posttreatment basal area was so light, it is difficult to define the leave strips, either on the ground or from aerial photographs. Therefore any influence of the strips upon the snowpack, and subsequent streamflow, is questionable because of the heavy reduction in basal area.

A paired watershed method was used to evaluate changes in annual water yield resulting from overstory removal. A streamflow relationship was developed between two similar watersheds over a range of climatic conditions. After one watershed was treated, streamflow from the control watershed was used to predict what flow would have been on the other watershed had it not been treated. Differences between measured streamflow from the treated watershed and streamflow predicted by the pretreatment relationship were then attributed to the treatment activities. This procedure provides a graphical display of the water yield response and shows the variation that can be obtained on these watersheds (Figure 3). However, there is no statistical method that can be applied to analyze the significance of the overall response as presented.

Water yield response is generally observed to decrease with time after treatment [*Douglass*, 1983; *Harr*, 1983; *Troendle*, 1983] and is often influenced by the amount or intensity of precipitation. Because snowmelt is the major source of water yield on Beaver Creek, the influence of precipitation is better reflected through streamflow from the control watershed. Flow on the control watershed is used to account for much of the variation in annual precipitation regimes caused by rain-on-snow events, precipitation distribution, and differences in snowmelt patterns. The following model was fit to the years of postharvest data:

$$Q_{\text{treated}} = a + bQ_{\text{control}} + cQ_{\text{control}}t$$

where

Q_{treated} annual flow on treated watershed in mm;
Q_{control} annual flow on control watershed in mm;
t time in years since treatment;
a, b, c coefficients of regression.

This model provided the best fit for all but the 100% clearing treatment where the interaction term between time and flow on the control watershed was replaced with only the time factor (see appendix). An analysis of covariance can be used to adjust treatment means of a dependent variable for differences in sets of values of corresponding independent variables. An analysis of covariance, however, assumes that a treatment response remains constant with time. Since a vegetation treatment on a watershed is not expected to remain constant, an evaluation of the difference between the pretreatment and posttreatment regressions at a particular value in the middle of the data was used for assessment of overall treatment effect [*Rogosa*, 1980]. Pretreatment and posttreatment regressions were evaluated at the annual flow mean on the control watershed for each of the years after treatment to determine expected water yield increases under an average situation. Significance of the water response for the individual years was then assessed at α/n, where n is the number of years of record after treatment [*Miller*, 1966], an α level of 0.10 was adopted.

RESULTS

Effect of Overstory Reduction on Water Yield

Annual streamflow deviations from the pretreatment regression for 23 years on the 100% cleared watershed are shown in Figure 3*a*. In the first complete year (1968) after clearing, streamflow increased 99 mm or 63% above the flow expected had the forest not been cut. The clearing treatment was not completed until June 1967; therefore 1967 was not included in the analysis. However, it is obvious from Figure 3*a* that the clearing treatment had an influence on its water yield. Most of the 101-mm (128%) response in 1967 resulted from intense summer rains on this newly treated watershed. Water yield

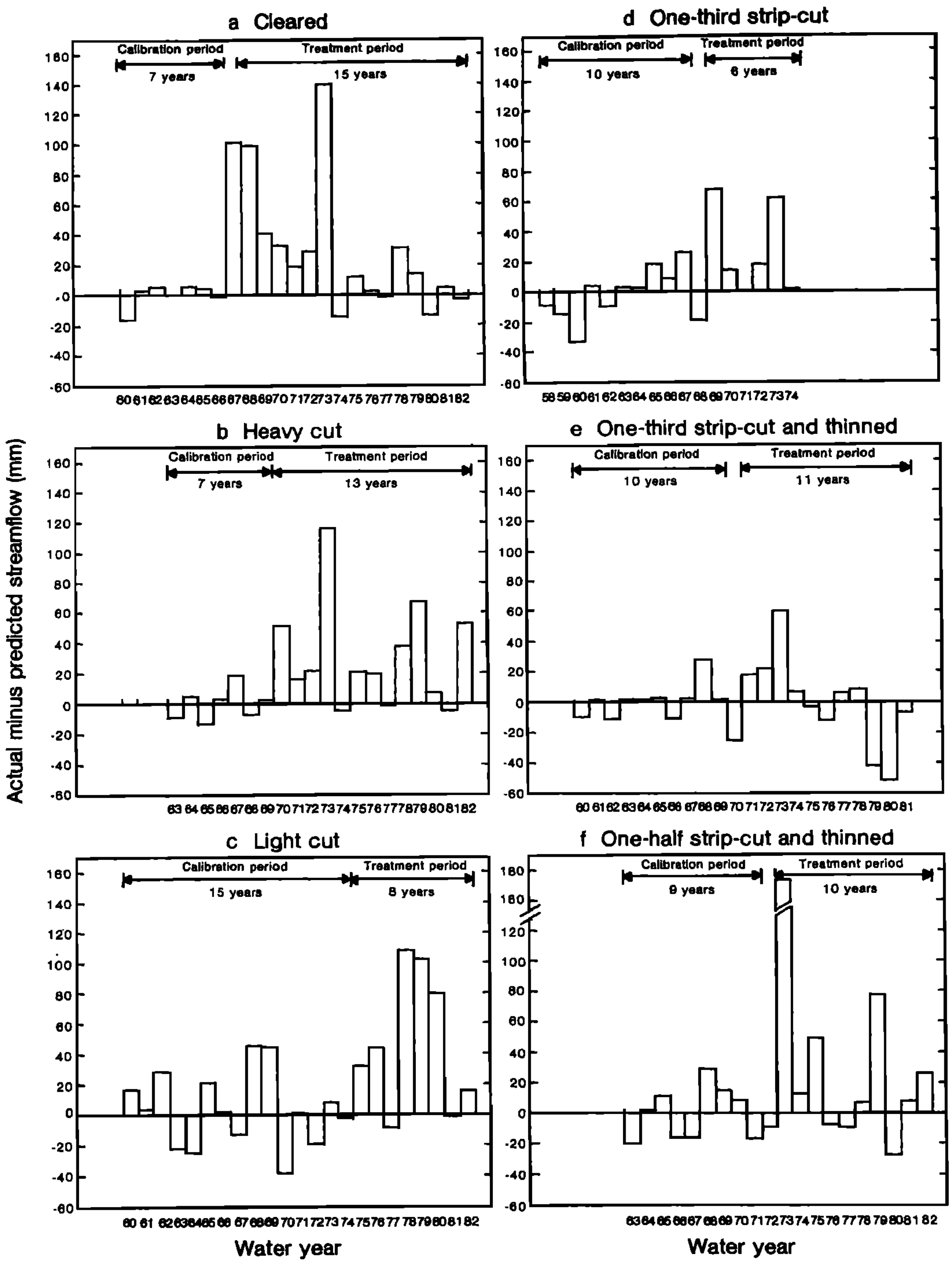

Fig. 3. Annual streamflow deviations from pretreatment regressions.

response is quite variable in the Southwest and is heavily influenced by the highly variable precipitation regime. Water year 1973, the highest ranked year for both annual and winter precipitation amounts, produced the largest response of 140 mm (25%). After 1974, one of the lowest precipitation years during the study period, the water response was generally reduced. The 31- and 14-mm responses in 1978 and 1979, which had the fourth and third highest winter precipitation totals, respectively, clearly reflect a reduced treatment effect. The continuing decline appears to be confirmed by the lack of response in 1980, which had the second highest precipitation amount on record.

The first year response on the heavily cut (77%) watershed (Figure 3*b*) was 52 mm (35%), which resulted essentially from one summer rainstorm that produced 130 mm of precipitation. Water year 1973 again produced the largest response of 116 mm (22%). Increases of 38 and 67 mm in water years 1978 and 1979, respectively, show the influence of these wet years. The response of 7 mm in 1980 seems unusually low considering that it is the second highest precipitation year on record, while the response of 53 mm in 1982 seems high for this relatively dry winter.

The first 2 years of streamflow response on the lightly cut watershed (Figure 3*c*) were 32 mm (20%) and 44 mm (28%),

TABLE 2. Significant Increases in Annual Predicted Water Yield for Various Levels of Basal Area Reductions by the Two Harvesting Methods

Years After Treatment	Overstory Removal						Strip-Cut With Thinning					
	100%		77%		33%		68%		57%		31%	
	Millimeters	Percent	Millimeters	Percent	Millimeters	Percent	Millimeters	Percent	Millimeters	Percent	Millimeters	Percent
1	62	41	63	29	70	35	72	45	33	24	25	15
2	56	37	58	27	61	30	62	38	27	20	25	15
3	50	33	53	24	52	25	51	32	22	16	25	15
4	44	29	48	22	42	21	n.s.	···	17	12	25	15
5	38	26	43	20	32	16	n.s.	···	n.s.	···	25	15
6	32	22	38	17	23	11	n.s.	···	n.s.	···	25	15*
7	27	18	33	15	n.s.	···	n.s.	···	n.s.	···		
8	n.s.	···	28	13	n.s.	···	n.s.	···	n.s.	···		
9	n.s.	···	23	10			n.s.	···	n.s.	···		
10	n.s.	···	18	8			n.s.	···	n.s.	···		

*Analysis terminated because control watershed was treated.

respectively. Responses in these years appear comparable in relative magnitude to the previously discussed treated watersheds and are followed by larger responses of 108, 102, and 80 mm in 1978, 1979, and 1980, respectively, which were much wetter years. The 1980 response of 80 mm is different from the negative or low responses observed on the two previously discussed watersheds. Water year 1980 had major streamflow production in January and February which amounted to 70% or more of the annual streamflow total on all but the lightly cut watershed. On this watershed only 40% of the annual total occurred in January and February and another 40% occurred in April. This is a prime example of how streamflow timing or distribution can influence the annual streamflow total.

Effect of Strip Cutting With Thinning on Water Yield

Streamflow for the three strip-cut watersheds are shown in Figures 3*d*–3*f*. Initial response on the one third strip-cut watershed was 68 mm or 24% and occurs just before the low response during 1970 through 1972 (Figure 3*d*). Response in 1973 is 62 mm and precedes one of the driest winters on record which only produced a 2-mm increase in streamflow. The control for this watershed pair was treated in 1975; therefore no further estimates of streamflow increase can be made.

Treatment on the one third strip-cut and thinned watershed was completed in 1970, and the initial streamflow response of 18 mm occurred in the second lowest winter precipitation year (1971) (Figure 3*e*). Streamflow response in 1973 was 60 mm, while the remaining years of record showed a low or negative response.

The first posttreatment year on the one half strip-cut and thinned watershed was 1973, the highest precipitation year during the study (Figure 3*f*). This resulted in the largest response of 174 mm or 51% that was observed on any of the treated watersheds. Of the other 3 high precipitation years 1978 through 1980, only 1979 showed an appreciable response of 78 mm. Water year 1982, one of the drier winters on record, showed a 26-mm increase in streamflow.

Duration of Water Yield Response

Analysis of the pretreatment and posttreatment regressions at a point indicates a reduction in streamflow over time caused by vegetation recovery for all but the one third strip-cut watershed (Table 2). A time trend for this treatment would probably have developed if additional years of data had been available. The predicted duration and amount of water yield increases were determined at the long-term water yield mean for the control watershed. The equations and statistics for these relationships are in the appendix. Predicted water yield increases on the completely cleared watershed ranged from 62 to 27 mm (41 to 18%) in the seventh year, when statistical significance was lost. Results of this analysis for the other treatments are also presented in Table 2.

No clear relationship can be shown between the degree of timber reduction and water yield increase. With the strong relationship of water yield increase to precipitation and time after treatment, significant differences in treatment responses, particularly for the initial year, can be expected when initiated in different water years (Figure 3). Use of the long-term water yield mean on the control watershed is an attempt to account for some of these differences in the prediction models.

DISCUSSION

Water yield increases on the 100% cleared watershed are attributed primarily to reduced evapotranspiration, including lower interception losses, and to a more efficient source-area concentration of snowmelt and storm runoff water resulting from the windrowed slash. Surface disturbance associated with the clearing operation and windrowing of the slash apparently caused the unusual amount of surface storm runoff in the summer of 1967, immediately after the treatment was completed in June. Thereafter the increases in yield were mostly from snowmelt.

Except for the unusually wet winter of 1973, the streamflow increases on the 100% cleared watershed were largest in the first posttreatment year (October 1967 to September 1968) and declined thereafter until they disappeared or became nonsignificant (Figure 3*a*). Decline of the treatment effect is attributed to posttreatment recovery of native herbaceous and shrubby plants, which by 1973 were producing 564 kg ha^{-1} of biomass. By 1975, the total basal area of recovering vegetation, mostly Gambel oak, was 2.7 m^2 ha^{-1}. While this is not much basal area compared with the pretreatment pine cover (24 m^2 ha^{-1}), the oak sprouts produced numerous stems and considerable transpiring surfaces. The leaf area index was 6.3 [*Whittaker and Woodwell*, 1967] with a canopy density of 15–20%. This compares to a leaf area index of 5.2 for the untreated ponderosa pine with a canopy density of 80–85% (C. C. Grier, personal communication, 1980).

Thus it appears that the vegetation was recovered sufficiently after 7 years (Table 2) for soil water depletion in this relatively shallow profile to be about the same at the end of the growing season as it would be under an original pine cover. While these increases may seem short-lived for a completely cleared watershed, they persisted longer than cleared areas in Utah where Gambel oak sprouts were allowed to reclaim the sites [*Tew*, 1969].

Water yield increases from the two partial overstory reduction treatments are also attributed mainly to reduced evapotranspiration losses. On both watersheds, the wetter years (1973, 1978, 1979, and 1980) often had higher water yield increases than the initial treatment years (Figures 3*b* and 3*c*).

Losses of treatment response are attributed to the ability of the residual forest stands [*Schubert*, 1971] and the increased shrub and herbaceous vegetation [*Curtis*, 1964; *Tew*, 1969] to utilize similar amounts of soil water as the original forest overstory. Similar results were found in Oregon where heavy thinning of ponderosa pine only reduced summer soil water during the first 3 years after treatment [*Helvey*, 1975]. The extended length of treatment response on the heavily cut watershed (10 years versus 7 years on the completely cleared basin) is believed a function of the shorter surface flow lengths on this narrow watershed.

Water responses on the three strip-cut watersheds are attributed to reduction in evapotranspiration and to more efficient source-area concentration of snowmelt and storm runoff in the cleared strips. These watersheds all responded to the wet winter of 1973 (Figures 3*d*, 3*e*, and 3*f*). This is dramatically shown on the one half strip-cut and thinned watershed where 1973 was the first posttreatment year and resulted in the largest water yield response obtained during the entire study. Although the record on the one third strip-cut watershed was prematurely terminated, the water responses on the strip-cut watersheds generally appear to be smaller and more variable than those on the other treated watersheds. One possible factor responsible for this variation and rapid decline in water response is the watershed physiography.

The lightly cut watershed (Figure 3*c*) has 42% of its area classified as cool aspects and showed a significant increase in water yield for 6 years (Table 2). Although the heavily cut watershed (Figure 3*b*) has only 31% cool aspects, it is long and narrow. Therefore flow lengths to the channel system are relatively short and increase water transport efficiency, resulting in a longer response period. The one third strip-cut watershed (Figure 3*d*) has 60% of its strips located on cool aspects which could have contributed to the longer response period of at least 6 years, while the one third strip-cut and thinned watershed (Figure 3*e*) has only 16% of its area on cool aspects and lost its response after 4 years. Although the one half strip-cut and thinned watershed (Figure 3*f*) has 57% of its area on cool aspects, it also has 65% of its area with slope of 5% or less. This large area of relatively flat terrain would reduce runoff efficiency from this watershed and helps explain the loss of response after 3 years. Watersheds with warm or southerly aspects are also exposed to the prevailing southwesterly winds. When the overstory vegetation on these basins is reduced, soil and snow surfaces become more exposed to the prevailing wind and to the incoming solar radiation. These two factors could increase stress on the soil moisture and snowpack, reducing or quickly negating streamflow increases obtained by decreases in transpiration.

Additional solar radiation on the more open, southerly exposed watersheds can initiate snowmelt earlier in the season with smaller increases in energy supplied to the snowpack. These early snowmelt events are often initiated and terminated (because of a reduction in energy load) without completely depleting the snowpack. This snowmelt pattern can occur a number of times in a winter season and reduces the efficiency of runoff delivery to the stream channels. More snow is also expected to be lost to evaporation and sublimation because of increased exposure to the prevailing southwest winds and solar radiation. These factors could combine to utilize or even exceed initial savings in evapotranspiration within a short time after treatment application, particularly on watersheds with predominately southern exposure.

CONCLUSIONS

The potential for increasing water yield in ponderosa pine is less than from other commercial forest types because pine forest inherently occurs on drier sites. Water yield from pine watersheds in the southwest is derived mostly from snowmelt and is greatly influenced by the amount and distribution of precipitation, basin physiography, and soil type. The soil type is similar on all the watersheds used in the study, but mean annual precipitation ranges from 580 to 740 mm and the composition of warm and cool aspect varys considerably. Variation in first year water response of 20–170 mm shows the importance of precipitation timing and amount on water yield and its apparent dominance over the percent of overstory removal.

Water yield increases can be realized through management of ponderosa pine overstory from forested watersheds with basal area in excess of 23 m^2/ha. Although large variation in response can be expected, initial mean increases of 15–45% are realistic from pine forest on shallow, basalt-derived soils with basal area reductions of 30–100%.

On southern aspects, water yield response will generally be lost after 6–10 years using a uniform overstory reduction treatment and possibly as quickly as 3 years when using a strip-cut and thinning harvesting procedure. There are indications that water yield response on watersheds with northern exposure will persist for a longer time period and that increases may be realized with relatively small reductions in basal area (possibly as low as 30%).

APPENDIX

The significance of the treatment effect was assessed by comparing the following pretreatment and posttreatment regressions at the mean annual water yield observed for the control watershed during the period of record. These regressions were used to develop the residuals in Figure 3 and the predicted water yield increases in Table 2.

100% clearing

$$Q_{\text{pre}} = 4.73 + 1.55Q_{\text{control}} \qquad Syx = 18.65 \text{ mm} \qquad r^2 = 0.995 \qquad n = 7$$

$$Q_{\text{post}} = 38.86 + 1.91Q_{\text{control}} - 5.84t \qquad Syx = 22.37 \qquad r^2 = 0.991 \qquad n = 10$$

$$Q_{\text{control}}\bar{X} = 93.4 \text{ mm}$$

Heavy cut

$$Q_{\text{pre}} = 20.03 + 1.04Q_{\text{control}} \qquad Syx = 11.37 \text{ mm} \qquad r^2 = 0.992 \qquad n = 7$$

$$Q_{\text{post}} = 21.39 + (1.39\text{–}0.027t)Q_{\text{control}} \qquad Syx = 15.72 \qquad r^2 = 0.996 \qquad n = 11$$

$$Q_{\text{control}}\bar{X} = 190.6 \text{ mm}$$

Light cut

$$Q_{\text{pre}} = 20.97 + 1.55Q_{\text{control}} \qquad Syx = 28.35 \text{ mm} \qquad r^2 = 0.965 \qquad n = 15$$

$$Q_{post} = 5.10 + (2.37\text{–}0.081t)Q_{control} \qquad Syx = 11.17$$

$$r^2 = 0.998 \qquad n = 8$$

$$Q_{control}\bar{X} = 116.8 \text{ mm}$$

One third strip-cut

$$Q_{pre} = -5.97 + 1.01Q_{control} \qquad Syx = 18.03 \text{ mm}$$

$$r^2 = 0.982 \qquad n = 10$$

$$Q_{post} = -17.62 + 1.22Q_{control} \qquad Syx = 26.61$$

$$r^2 = 0.988 \qquad n = 7$$

$$Q_{control}\bar{X} = 170.27 \text{ mm}$$

One third strip-cut and thinned

$$Q_{pre} = -6.71 + 1.30Q_{control} \qquad Syx = 11.85 \text{ mm}$$

$$r^2 = 0.982 \qquad n = 11$$

$$Q_{post} = -1.64 + (1.59\text{–}0.048t)Q_{control} \qquad Syx = 13.44$$

$$r^2 = 0.995 \qquad n = 10$$

$$Q_{control}\bar{X} = 111.8 \text{ mm}$$

One half strip-cut and thinned

$$Q_{pre} = 27.41 + 1.08Q_{control} \qquad Syx = 18.61 \text{ mm}$$

$$r^2 = 0.963 \qquad n = 9$$

$$Q_{post} = 27.76 + (1.75\text{–}0.086t)Q_{control} \qquad Syx = 39.93$$

$$r^2 = 0.965 \qquad n = 8$$

$$Q_{control}\bar{X} = 122.7 \text{ mm}$$

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M. B. Baker, Rocky Mountain Forest and Range Experiment Station, Forestry Science Laboratory, Arizona State University, Tempe, AZ 85287.

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