Stormflow Responses to Forest Treatments on Two Arizona Mixed Conifer Watersheds

Alden R. Hibbert and Gerald J. Gottfried[1]

Abstract--Forty years of hydrological records from the North and South Forks of Workman Creek were analyzed to estimate the effects of several treatments on stormflow volumes and peaks. Summer stormflows and peaks increased exponentially with size of storm after each treatment. Although percent changes were large, actual increases were very small. Winter stormflow increases were smaller on a percent basis but were larger in volume.

Water yield improvement has been the major emphasis of forest hydrology in the arid Southwest, where the demand is great for water. However, precipitation varies greatly from year to year and large amounts of runoff may be generated by individual storms. In recent years, several large winter storms have generated damaging floods which have raised fears of dam failures in the main valley population centers.

These events have created an interest in the effects of forest management practices on both winter and summer stormflow volumes and peak flow rates. It is well known that water yields can be increased by reducing forest cover (Rich and Gottfried 1976, Brown and et al. 1974, Baker 1986). However, it is not known if stormflows are increased proportionately to nonstorm (base) flows, since little work has been done on individual stormflows.

Mixed-conifer forests occupy 322,500 acres in Arizona, and approximately 2 million acres in the entire Southwest, including southwestern Colorado. The 40-year hydrological record on the Workman Creek watersheds provides an excellent opportunity to describe and analyze the effects of several forest management treatments on stormflow volumes and peak flow rates.

STUDY AREA

Workman Creek is within the Sierra Ancha Experimental Forest, approximately 30 miles north of Globe in central Arizona. The three experimental watersheds are North Fork (248 acres), Middle Fork (521 acres), and South Fork (318 acres). Elevations range from 6645 to 7789 ft.

The climate at Workman Creek is characterized by cold, moist winters; warm, dry springs and falls; and by warm, moist summers. The average annual precipitation at the recording rain gage in Middle Fork was (with standard error) 32.8 ± 1.5 inches from 1938 through 1981. Approximately two-thirds of the precipitation falls during the October to May winter period, usually as snow. Numerous, intense thunderstorms occur in a rainy season from July through September.

Perennial streamflow was recorded continuously at 90° V-notch weirs on North Fork and on South Fork and at a combination 90° V-notch and 7-foot Cipoletti weir at Main Dam on the main watershed below the confluence of the three watersheds. Control watershed (Middle Fork) streamflow was not gaged separately, but is calculated by substracting the South and North Fork values from the Main Dam streamflow (Rich and Gottfried 1976). Average annual runoff for the entire watershed at Main Dam prior to treatment in 1953, was 3.30 ± 0.69 inches. Mean runoff values for all three sub-watersheds were within 3% of the average for Main Dam.

Mixed-conifer stands of Douglas-fir *(Pseudotsuga menziesii)*, white fir *(Abies concolor)*, and ponderosa pine *(Pinus ponderosa)* originally occupied the more moist site, while almost pure ponderosa pine stands were found on drier sites. New Mexico locust *(Robinia neomexicana)* and Gambel oak *(Quercus gambelii)* were common understory trees. Average basal area was about 189 ft² per acre for all trees 1 inch d.b.h. and larger.

WORKMAN CREEK TREATMENTS

The Workman Creek watersheds were established in 1939 to determine the hydrology of mixed conifer forests and

[1]Principal Hydrologist and Research Forester, Rocky Mountain Forest and Range Experiment Station's Research Work Unit in Tempe, Arizona. Gottfried is currently at the Rocky Mountain Forest and Range Experiment Station's Research Work Unit in Flagstaff, Arizona. Station headquarters is in Fort Collins, in cooperation with Colorado State University.

changes in streamflow and sedimentation caused by land management treatments. The objective on North Fork was to determine the potential for water yield improvement by removing the vegetation in a series of steps, and converting to a grass cover. The South Fork objective was to evaluate changes resulting from forest management activities. The sequence of treatments is presented in table 1. The treatments and their effects on annual and seasonal water yields are summarized below from Rich and Gottfried (1976).

South Fork

The first treatment in 1953 was a single-tree selection harvest, which, with roads, skid trails, and stand improvement work, reduced watershed basal area by 36%. In July 1957, a 60-acre wildfire in the upper end of South Fork destroyed another 9% of the original basal area. The harvest and burn (1954-66) resulted in a statistically significant water yield increase of 0.24 ± 0.20 inch (7 ± 6%); however, the increase was so small that it was considered insignificant from a practical point of view. No detectable water yield changes occurred after the 1957 wildfire, but Rich (1962) reported that all flood peaks for the first two summers were higher than expected; the largest storm peaked to 157 csm, twice the value of the previous high event.

A commercial harvest in 1966 removed most merchantable trees and thinned the remainder in an effort to convert the mixed conifer stand to ponderosa pine with a proposed final stand density of 40 ft^2/acre, considered optimum for combined timber and water production. Unstocked areas were planted with ponderosa pine seedlings. This treatment, which affected 83% of watershed, resulted in an average annual water yield increase of 4.20 ± 1.08 inches (110 ± 29%) from 1967 through 1979.

North Fork

The first treatment in August 1953 was a riparian cut of broadleaved trees consisting of Arizona alder (*Alnus oblongifolia*) and big tooth maple (*Acer grandidentatum*) along streams, springs, and seeps. This treatment, which removed 0.6% of watershed basal area, did not produce a detectable increase in seasonal or annual runoff.

Nearly one-third (80 acres) of the watershed adjacent to the channel was cleared of its moist site forest of predominantly Douglas-fir and white fir by a timber harvest in 1958. The cleared area was seeded to grass. The moist site treatment (1959-66) increased water yields by 1.28 ± 0.28 inches (42 ± 10%), most of the increases occurring during the 8-month winter period.

The final North Fork treatment in 1966 converted 100 acres (40%) of dry-site merchantable ponderosa pine, upslope from the moist-site area, to grassland. Grasses were seeded, and New Mexico locust invaded the cleared sites, as occurred on the moist-site clearing. Streamflows from 1967 through 1979 increased 1.77 ± 2.99 inches (37 ± 45%) above those produced by the moist-site treatment. The combined moist- and dry-site treatments (1959-79) increased streamflow by 2.65 ± 0.80 inches (72 ± 22%).

DATA ANALYSIS

The hydrographs from 40 years of records (1940-1979) were reviewed for rain-generated-stormflow events 0.001 inch and larger, which occurred simultaneously on all three watersheds. Stormflow hydrographs were partitioned into stormflow and delayed flow components using the hydro-

Table 1.--Schedule of treatments for the Workman Creek watersheds.

Water years	Treatments				
	North Fork	No. of years	Middle Fork	South Fork	No. of years
1939-53	Calibration	15	Calibration	Calibration	15
1954-58	Riparian cut of broadleaf species	5	Control		
1954-56				Start of single-tree selection harvest	3
1957-58				Wildfire	2
1959-66	Convert moist site to grassland	8	Control	Interim period	8
1967-79	Convert dry site to grassland	13	Control	Commercial clearcut to convert to a pure ponderosa pine stand with a basal area of 40 ft./acre	13

graph separation technique developed by Hewlett and Hibbert (1967). Separation was arbitrarily determined by projecting a line of 0.05 csm/hr slope from the storm hydrograph rise to the recession limb. Peak flow rate is maximum hydrograph peak minus initial flow rate at rise of storm hydrograph.

The data were analyzed by winter (October-May) and summer (June-September) periods. Different techniques were used to evaluate the two periods. Changes in summer stormflows and peaks were determined by comparing the relationship between stormflow volume or peak and storm rainfall. Increases were calculated by comparing the regression coefficients of the pre- and posttreatment relationships. Exponential regression relationships were developed for each treatment period using log-transformed data to control variance. Regressions of the transformed data were significant ($P \leq .05$), with the r^2 values ranging from 0.27 to 0.54. The pre- and posttreatment regressions were compared in a covariance analysis using dummy values to separate treatment periods.

Winter events could not be analyzed by the runoff-precipitation relationship because of the variability caused by rain on snow, where the actual daily inputs of snowmelt into the channels were unknown. Winter stormflow volumes were analyzed by comparing before- and after-treatment linear regressions developed from paired events on treated and control watersheds. Regressions had r^2 values between 0.82 and 0.93. Two sets of regressions were developed: one for stormflow volumes up to 2.5 inches (2 large snowmelt-dominated stormflows between 4 and 8 inches were rejected as outliers), and the other for smaller stormflows of less than 0.5 inch. Posttreatment regressions were compared with the respective pretreatment regression, and a combined regression was then developed to describe the differences between the two relationships. Covariance analysis was used to compare the slope and intercept coefficients of the pre- and posttreatment regressions. The differential slope and intercept coefficients of the combined regression reflect this comparison. Differences in the slope coefficient indicate that a treatment has a multiplicative effect, where the dependent variable increases more rapidly than does the independent variable.

No analysis was made on winter peaks. The arrangement of weirs on Workman Creek, and the need to calculate Middle Fork (control watershed) values, makes it difficult to separate peak flows on Middle Fork from the peaks on the other two watersheds.

RESULTS

Summer Storms

Summer stormflows and peaks increased after each treatment compared with pretreatment levels, when storm rainfall is used as the independent variable in a log-transformed regression analysis (table 2). The increases were exponentially related to storm size (fig. 1) for storm rainfalls between 0.5 and 2.5 inches. Small storms of less than 0.5 inch were excluded from the analysis because of the large variability attributed to the spotty nature of storm coverage on the watersheds. Peak flow response curves are not shown, but were very similar to the stormflow curves in figure 1.

South Fork

The largest increases in summer stormflows and peaks over pretreatment conditions occurred on South Fork during the two summers after the 60-acre burn. Stormflow volumes increased from 2.5 to 3 times, and peaks increased from 5 to

Table 2.--Changes in summer stormflows and peaks after various treatments on Workman Creek watersheds.

Treatment	N	Stormflows				Peaks			
		At Ppt = 1 in.		At Ppt = 2 in.		At Ppt = 1 in.		At Ppt = 2 in.	
		Inches	%	*Inches*	%	*csm*	%	*csm*	%
South Fork									
Pretreatment	54	0.0023[1]	--	0.0079[1]	--	1.47[1]	--	3.97[1]	--
Single tree	26	0.0018	78	0.0177	223	0.7	49	4.0	102
60-acre burn	12	0.0062	264	0.0450	564	3.8	264	33.8	848
Postburn interim	52	-0.0003	-12	0.0039	49	-0.3	-22	0.4	10
Commercial	69	0.0021	90	0.0103	130	0.8	54	3.6	91
North Fork									
Pretreatment	54	0.0008[1]	--	0.0033[1]	--	0.51[1]	--	1.54[1]	--
Riparian	37	0.0007	92	0.0093	280	0.3	51	2.3	149
Moist site	52	0.0026	322	0.0150	442	1.6	304	6.4	411
Dry Site	69	0.0030	378	0.0125	378	1.5	299	4.8	307

[1]These are pretreatment means which are the basis for computing percent changes after treatment.

10 times above values recorded during the previous three years following the single-tree selection harvest. The harvest, however, also showed a substantial percentage increase of 223% over pretreatment level for 2 inches of rain (table 2, fig. 1), although the increase was only 0.018 inch of flow volume. After the first two postfire summers, stormflows and peaks returned to near pretreatment levels, and became nonsignificant for the next eight summers of the interim period (1959-66). Stormflows and peaks during the commercial harvest period (1967-1979) were less responsive to summer storms than during either the selection harvest or wildfire. An exception was for storms of less than 1.5 inches of rainfall, when the response was essentially the same as for single-tree selection harvest (fig. 1).

North Fork

The riparian cut increased summer stormflows and peaks during the 5-year posttreatment period by up to 280% (0.009 inch) at 2 inches of rainfall, even though no annual or seasonal runoff increases were detected for this treatment by previous investigators (Rich and Gottfried 1976). The moist-site cut, on 32% of the watershed next to the channel, increased summer stormflows and peaks from 322% to 442% (0.003 to 0.015 inch) over pretreatment levels for rains of 1 to 2 inches, or roughly twice as much as was caused by the riparian cut. After the dry-site cut on the upper slopes of North Fork, increases in stormflows and peaks dropped back slightly for storms greater than 1.5 inches, although they were still four or more times larger than expected without treatment (table 2, fig. 1).

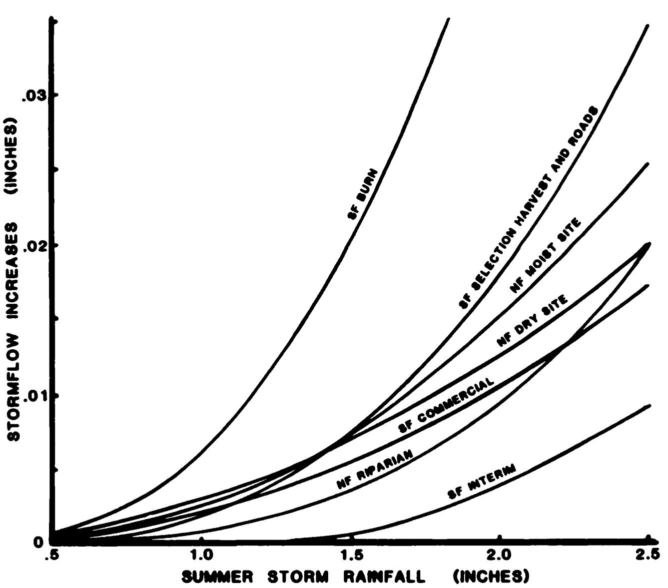

Figure 1.--Summer treatment response curves developed from differences between posttreatment and pretreatment stormflow regressions on storm rainfall.

Winter Storms

Winter stormflows responded less to treatment in terms of percent increase than did summer stormflows, although the actual flow volume increases were larger. Linear regressions using all data except 2 outliers indicated statistically significant increases in the differential slope coefficients for each treatment period (rows 1, 2, 5, 6 in table 3). Additional regressions were run on small storms only by limiting the range of control watershed stormflows to less than 0.5 inch (rows 3, 4, 7, 8 in table 3). The reason for classifying the data in this way was to examine the possibility of the increases being larger for small storms than for large storms, a trend indicated by a regression analysis of log transformed data.

The results were mixed: the largest increases in regression slope change for North Fork treatments were in the $\leq$0.5-inch stormflow range (rows 7 and 8, table 3). For the South Fork, a small nonsignificant decrease was indicated for the combined selection cut, burn, and interim period (row 3, table 3), and a marginally significant ($P = 0.06$) increase was shown for the commercial cut (row 4, table 3). The results are heavily influenced by small events because 75 to 87% of the stormflows were smaller than 0.5 inch. The lack of stormflow response in the first treatment period on South Fork (row 3, table 3) is consistent with earlier evaluations, which showed very little annual or seasonal increase from these treatments (Rich and Gottfried 1976). However, this lack of small stormflow response for the first treatment period on South Fork changes to a strong response when seven larger storms (0.5-2.5 inches) are added to the analysis (row 1, table 3). It is possible that, after treatment, South Fork was more responsive to larger storms than was North Fork. Predictions based on the 0-2.5 inches data set must be made with caution because of the disproportionate influence of the small number of storm events larger than 0.5 inch.

Winter stormflow volume increases (last columns in table 3) were calculated by taking the difference between posttreatment and pretreatment regressions evaluated at control watershed stormflow levels of 0.5 inch for the $\leq$0.5 inch data set, and 2 inches for the larger stormflow range. It is apparent that, while the percent increases are much less than for summer storms, the actual increases in stormflow volumes are much larger.

SUMMARY AND CONCLUSIONS

The changes in summer stormflows and peaks, which increased exponentially with storm rainfall after various treatments, indicate the sensitivity of the channels and channel-side environments to vegetation removal and soil disturbance. These increases in stormflows and peaks are largely attributed to decreased interception of rainfall caused by removal of the vegetation along the channels, and to more direct runoff into the channels from roads, skid trails, and from other disturbance, such as the wildfire.

Table 3.--Increases in winter stormflows after treatments on Workman Creek Watersheds.

Row	Treatment period	Number of paired events	Range in control watershed stormflow	Linear Regression Coefficients						Calculated increase[1]	
				Differential intercept			Differential slope				
			Inches	Inches	%	P value	Slope	%	P value	Inches	%
	South Fork										
1	Selection cut, burn, interim	44	0.0-2.5	-0.28	-86	ns	0.303	69	0.0001	0.58	63
2	Commercial	44	0.0-2.5	-.005	16	ns	.423	96	.001	.85	92
3	Selection cut, burn, interim	37	0.0-0.5	.002	75	ns	-.118	-13	ns	0	0
4	Commercial	39	0.0-0.5	.012	382	ns	.186	20	.06	.11	22
	North Fork										
5	Moist site	25	0.0-2.5	-.005	-17	ns	.262	32	.0001	.52	31
6	Dry site	44	0.0-2.5	.032	119	ns	.121	15	.02	.27	16
7	Moist site	20	0.0-0.5	.002	37	ns	.400	33	.02	.20	33
8	Dry site	39	0.0-0.5	.022	548	ns	.310	26	.02	.18	29

[1]Increases in winter stormflow were calculated at 0.5 inch of control flow using the regressions for the 0-0.5 inch data range, and at 2.0 inches using the regression for the 0-2.5 inches data range.

However dramatic the percentage changes appear to be, they are modest in terms of actual flow volumes and peak rates. The greatest changes were produced by the wildfire on South Fork, where an increase of 564% was equivalent to a 0.045-inch runoff from a 2-inch storm, or about 2% of the rainfall. The 858% change in peak flow was equivalent to an increase of 34 csm. However, except for very localized impacts on the watershed and in the channel, the actual increases were too small to be of significance from a land management standpoint. Even the wildfire related increases were readily absorbed in the channel system within a mile or so downstream, although a larger burned area would have had a greater impact downstream.

Winter stormflow increases were readily detectable only for treatments that affected vegetation on one-third or more of the watershed. The increases are primarily attributed to lower growing-season evapotranspiration, which results in quicker soil recharge and more efficient moisture movement. Summer storms contributed little to streamflow other than rain falling directly onto the channel surfaces and streamside areas. Therefore, the potential for downstream flow rates to be materially affected by treatment is greater in winter than in summer. This is anticipated, since most of the water yield increases detected in the annual streamflow analyses, up to 110% on South Fork, must be accounted for in the wet season flows. However, we looked at less than one-third of the total streamflow in our analyses because snowmelt, which dominates the runoff process at Workman Creek, was not included. Water yield studies in Colorado have suggested that the effects of forest treatments on snow accumulation and on snowmelt account for a major part of the increased runoff (Troendle 1983).

There is evidence from studies in Oregon and California, for example, Ziemer (1981), that large stormflows are not greatly affected by forest treatments. We were unable to verify similar trends at Workman Creek because of the small number of large storms, although observation during a few large rain on snow events suggest little or no difference between treated and untreated responses from the three catchments. Therefore, we generally agree with the concept that upstream treatment effects tend to become negligible once the soil mantle is fully charged. At that point, the amount of precipitation or snowmelt entering the system determines streamflow volumes.

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