IMPACTS OF VEGETATIVE TREATMENTS ON SEDIMENT CONCENTRATIONS FROM THE BEAVER CREEK WATERSHEDS IN NORTH-CENTRAL ARIZONA

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Estimating sediment production and export from watersheds is helpful in predicting on-site and off-site environmental impacts of vegetative treatments. Besides causing siltation in downstream reaches and depositions in reservoirs (Grenney and Heyse 1985), sediment in itself is a major pollutant and a carrier of plant nutrients, pesticides, and other chemicals (Glymph 1972; Osterkamp and Parker 1991; Duff et al. 1996). Although *sediment load* is an important parameter for estimating sediment buildup in reservoirs, *sediment concentration* is a primary factor of environmental concern to land managers (Wetzel 1983; Grenney and Heyse 1985).

One method of analyzing the effects of vegetative treatments on sediment concentrations is through interpretation of sediment rating curves that relate sediment concentration to streamflow discharge (Lopes and Ffolliott 1993; Lopes et al. 1996). A sediment rating curve reflects the pattern of soil erosion and sediment delivery operating on a watershed, and provides a readily accessible starting point for investigating the impacts of vegetative treatments on sediment discharge. This paper discusses the derivation of sediment rating curves to estimate impacts of vegetative treatments on sediment concentrations from the Beaver Creek watersheds in north-central Arizona. Improvement in developing these sediment rating curves by partitioning the data set into streamflow-generating mechanism and hydrograph stage is also discussed.

Study Area

The Beaver Creek watersheds, located about 80 km south of Flagstaff, are situated in the Salt and Verde River Basin of north-central Arizona. These watersheds are representative of the extensive areas of ponderosa pine forests and pinyon-juniper woodlands found in the southwestern United States. Descriptions of vegetative characteristics, physiological features, and precipitation-streamflow regimes of these watersheds have been presented by Brown et al. (1974), Clary et al. (1974), and Baker (1982) and will therefore not be detailed here.

The most important precipitation from a streamflow-generation standpoint is that originating from frontal storms during October through April, when about 60 percent of the annual precipitation falls. A second precipitation season is July through early September, when high-intensity, short-duration, localized convectional storms are common. Most annual runoff is produced from melting snowpacks in March or April. Winter runoff accounts for 85 percent of the annual water yield (Baker 1982). Suspended sediment discharges are 75–80 percent of the total sediment discharge from the watersheds studied.

Vegetative Treatments Evaluated

The vegetative treatments evaluated on ponderosa pine watersheds consisted of creating cleared openings in the forest overstories and reducing forest overstory densities. WS 12 (184 ha) was completely cleared. All merchantable timber was removed and the remaining nonmerchantable wood, and all intermingling Gambel oak and alligator juniper, were felled in 1966–67. Residual slash and debris was machine windrowed to trap and retain snow, reduce evapotranspiration losses, and increase surface drainage efficiency. The windrows were burned in 1977 to determine whether their removal would influence water yield (Baker 1983). Ponderosa pine, Gambel oak, and alligator juniper

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were allowed to seed themselves or sprout and grow following the clearing treatment. Because hydrologic changes caused by the treatment cannot be separated from those caused by the windrows, the evaluated treatment consists of complete forest clearing, soil disturbances due to timber harvesting operations, and soil disturbances due to the presence of windrows. The treatment resulted in an average increase in annual water yield of about 30 percent (44.5 cm) for 7 years after treatment, at which time the post-treatment response became insignificant.

On WS 14 (546 ha), one-third of the ponderosa pine forest was cleared in irregular strips averaging 18 m wide in 1970. Slash was piled and burned in the cut strips. The forest overstory in the intervening leave strips, which averaged 37 m wide, was reduced by thinning to about 25 percent or 18 m^2 ha^{-1} of basal area, a density level thought optimal for subsequent growth. Slash and debris were piled and burned in the cleared strips. This treatment resulted in a 57 percent reduction in basal area on the watershed. Gambel oak was retained throughout the watershed for mast and browse production, which is important to indigenous wildlife. Annual water yield increased about 20 percent (24 cm) in the first 4 post-treatment years, after which the response was insignificantly low or negative.

WS 13 (369 ha) served as a control against which the completely cleared and strip-cut treatments were evaluated. Although some commercial timber had been harvested in the early 1950s, conditions on this watershed at the time of this study represented those obtained through minimal managerial inputs.

Treatments on the pinyon-juniper watersheds consisted of converting the woodland overstories to covers of less water-consuming herbaceous plants. On WS 1 (131 ha), a cabling treatment was applied in 1963. Larger trees were uprooted by a heavy cable pulled between two bulldozers. Smaller trees missed by cabling were hand-chopped, slash was burned, and the watershed was seeded with a mixture of forage species. This treatment did not result in significant increases in annual water yields.

On WS 3 (147 ha), a mixture of picloram (2.8 kg ha^{-1}) and 2,4-D (5.6 kg ha^{-1}) was applied by helicopter to 114 ha in 1968; the remaining 33 ha were either not treated or the trees were sprayed with a backpack mist-blower. This treatment resulted in a significant increase in annual water yields of about 160 percent (11.4 mm) for 8 post-treatment years, after which the residual dead trees were removed in a firewood sale.

WS 2 (51 ha) was a control against which the cabling and herbicide treatments were evaluated. Conditions on this watershed represented those obtained through minimal managerial inputs.

Acquisition of Data Sets

Suspended sediment concentration and streamflow data obtained from 1974 through 1982 were the source data for this study. Data sets reflecting immediate impacts of the vegetative treatments were excluded from the analysis to better describe long-term impacts of the treatments on sediment concentrations. Either grab samples, integrated samples obtained with a DH-48 hand sampler, or pumping samples were analyzed by filtration to determine sediment concentrations. Streamflow was measured in concrete trapezoidal flumes. When a sample of suspended sediment was collected, the time was indicated on a digital tape on the continuous water-level recorders at the gauging stations. Sediment data were collected for streamflow discharges in excess of 0.05 m^3 s^{-1} and at time intervals greater than 1 hr to reduce possible effects of serial correlation.

Three types of events served as the basis for studying the effects of streamflow-generation mechanisms on sediment concentrations:

Type 1: Snowmelt-runoff events not preceded by precipitation; relatively slow response time to peak streamflow discharge; streamflow duration of several days or weeks; occurs in late winter–early spring.

Type 2: Mostly convectional rainfall events of high intensity and short duration; rapid response time to peak streamflow discharge; streamflow duration of hours or a few days; occurs in late summer–early fall.

Type 3: Essentially frontal rainfall events of low intensity and relatively long duration, mostly in late fall and winter months; insignificant snow accumulations on the ground; moderate response time to peak streamflow discharge.

Event types 1 and 3 generated most of the streamflow events studied in the ponderosa pine forests, whereas event types 1 and 2 resulted in streamflow events studied in the pinyon-juniper woodlands. Rain-on-snow events, which were major events when they occurred, represented less than 10 percent of the individual streamflow-generation mechanisms on the watersheds studied and were therefore excluded from this analysis.

Derivation of Sediment Rating Curves

Sediment rating curves are frequently expressed in terms of a power function form, such as $C = aQ^b$, where C = suspended sediment concentration (mg/L), Q = streamflow discharge (m^3/s), and a, b = regression coefficients for a particular stream. Sediment rating curves to be derived in a power function form are often approximated by least-square linear regressions of logarithmic-transformed data (Walling 1977); this transformation was used in this study. The procedure to overcome the possibility of bias when the regression estimates were detransformed and to minimize spurious conditions has been outlined by Duan (1983).

The coefficient of determination, R^2, was used to compare goodness-of-fits of the derived sediment rating curves. An adjusted coefficient of determination, Ra^2, was used to correct for the dependence of goodness-of-fit on degrees of freedom:

$$Ra^2 = R^2 - \frac{P\left(1 - R^2\right)}{N - P - 1}$$

where N = number of observations and P = number of independent variables = 1.

Analysis of the derived sediment rating curves began with the complete data sets from each of the watersheds studied. These data sets were subsequently partitioned into the types of streamflow-generation mechanism (snowmelt runoff or convectional rainfall) and then into the hydrograph stage. Suspended sediment samples collected in periods of high streamflow discharges were assigned the same weight as measurements made during low streamflow discharges in deriving the sediment rating curves. Parameters a and b of the sediment rating curves for the ponderosa pine watersheds, with the 95 percent confidence limits, fitted standard errors, coefficients of determination, and F statistics, are presented in Table 1. Similar statistics for the pinyon-juniper watersheds are shown in Table 2.

Comparative Analysis and Discussion

A hierarchical test was made to determine the statistical significance of changes in explained variations of sediment concentrations, expressed in terms of R^2, at the watershed, streamflow generation, and hydrograph stage levels. The null hypothesis at each level was that the parameters a and b of two sediment rating curves had not changed when the data sets were disaggregated. This null hypothesis was formulated as

$$H_0 : a_1 = a_2 = \ldots = a_m, b_1 = b_2 = \ldots = b_m$$

where m = number of equations tested. At each level, the Chow test (Kmenta 1986) was performed in a pairwise fashion to test the null hypothesis that the parameters (a and b) of two sediment rating curves had not changed significantly (at the 95% level of significance) due to partitioning. Test results are shown in Tables 1 and 2, and the comparative analysis and the accompanying discussion are presented below.

Ponderosa Pine Watersheds

There were significant differences in sediment rating curves among the treated ponderosa pine watersheds and control watershed at the watershed level. These differences indicated that for a similar streamflow discharge, sediment concentrations from the completely cleared watershed (WS 12) were significantly higher than those from the strip-cut watershed (WS 14), and that sediment concentrations from the strip-cut watershed were higher than those from the control watershed.

WS 12 experienced watershed-wide soil disturbance from the complete clearing treatment, simultaneous breaking up of the herbaceous ground cover by the clearing operation, and follow-up pushing of the residual slash and debris into windrows. Soil disturbance on WS 14 was less extensive and more localized than what took place on WS 12. The most destructive portion of the disturbance on WS 14 occurred on the third of the watershed that was cut into irregular strips, where much of the protective herbaceous plant cover was disturbed, and where the residual slash and debris were piled and burned. Larger snowpack accumulations occurred in the strip-cuts in comparison to those in intervening leave strips. These strip-cuts had up-down slope orientations, causing increased overland water flows originating from the larger snowpack buildups concentrated in the strips, where most of the sediment production on WS 14 took place.

Streamflow-generation mechanisms on the ponderosa pine watersheds were snowmelt runoff (type 1) and frontal rainfall (type 3). Although sediment rating curves derived at the

Table 1. Sediment rating curve parameters, with 95% confidence limits, standard errors, coefficients of determination, and F statistics for ponderosa pine watersheds.

Watershed	Event Type	N	a	95% Confidence Intervals		b	95% Confidence Intervals		Standard Error SE	r_a^2	F Statistics	Significance
12	all	353	154.579	121.667	196.413	1.042	0.947	1.137	125.97	0.57	468.54	**
	1	326	155.234	120.370	200.224	1.066	0.964	1.167	125.39	0.57	426.87	**
	1r	148	170.847	114.559	254.700	1.027	0.877	1.177	169.38	0.55	182.82	**
	1f	131	141.415	99.093	201.393	1.198	1.058	1.399	64.91	0.69	282.32	**
	3	26	162.577	83.813	315.726	0.865	0.634	1.097	135.65	0.70	59.38	**
	3r	12	175.942	46.664	663.722	0.880	0.693	1.267	182.39	0.69	25.69	**
	3f	14	127.938	14.280	14.280	0.746	0.287	1.205	98.82	0.47	12.55	**
13	all	204	28.679	21.804	37.717	0.677	0.579	0.776	61.40	0.47	183.40	**
	1	179	26.272	19.909	34.678	0.665	0.560	0.770	64.44	0.47	156.44	**
	1r	44	39.853	15.288	103.837	1.030	0.745	1.315	94.37	0.55	53.35	**
	1f	71	21.670	12.754	36.782	0.608	0.425	0.790	56.86	0.38	44.01	**
	3	25										N/S
	3r	8	76.552	10.800	121.456	0.537	0.512	1.164	24.14	0.46	6.94	**
	3f	12	36.196	44.945	70.906	0.938	0.886	1.062	73.24	0.74	32.77	**
14	all	473	56.590	43.335	68.681	0.974	0.919	1.097	74.94	0.50	475.87	**
	1	432	74.788	75.944	112.071	1.008	1.019	1.294	97.63	0.53	494.69	**
	1r	140	44.905	30.817	65.431	1.156	0.740	1.018	46.72	0.66	276.26	**
	1f	154	80.902	42.763	153.134	0.879	0.314	0.815	50.12	0.50	156.45	**
	3	41	112.158	54.425	231.101	0.578	0.245	0.746	55.15	0.37	24.31	**
	3r	20										N/S
	3f	9										N/S

N = sample size
F statistics = equation significant at 0.05
Significance = regression significance (**) at $\alpha = 0.05$.
all = sediment rating curve using all measurements
1, 2, 3 = event types 1, 2, 3, respectively
r = rising stage of event hydrograph
f = falling stage of event hydrograph
N/S = not significant

Table 2. Sediment rating curve parameters, with 95% confidence limits, standard errors, coefficients of determination, and F statistics for pinyon-juniper watersheds.

Watershed	Event Type	N	a	95% Confidence Intervals		b	95% Confidence Intervals		Standard Error SE	r_a^2	F Statistics	Significance
1	all	525	7.362	5.297	10.257	0.233	0.143	0.324	7.03	0.05	39.33	**
	1	429	6.982	4.831	10.069	0.216	0.114	0.318	7.37	0.04	17.26	**
	1r	93	66.222	26.122	105.925	0.779	0.632	0.956	9.79	0.54	11.01	**
	1f	333										N/S
	2	90	6.668	3.013	14.757	0.231	0.025	0.438	4.17	0.04	4.94	**
	2r	20	38.905	10.116	149.624	0.529	0.190	0.868	2.92	0.34	10.77	**
	2f	70										N/S
2	all	519	5.129	3.664	7.161	0.193	0.112	0.274	2.98	0.04	22.01	**
	1	448	4.335	3.013	6.237	0.168	0.081	0.256	3.13	0.03	14.24	**
	1r	153	13.772	6.730	28.119	0.438	0.253	0.625	4.23	0.12	21.82	**
	1f	288										N/S
	2	65	14.125	6.124	32.509	0.363	0.157	0.568	2.74	0.15	12.37	**
	2r	12	16.672	10.789	25.763	0.172	0.073	0.270	1.22	0.51	15.16	**
	2f	53	29.923			0.613				0.46	45.88	**
3	all	611	8.091	5.916	11.066	0.245	0.168	0.321	4.67	0.06	25.76	**
	1	572	8.147	5.984	11.092	0.244	0.168	0.320	4.95	0.06	40.13	**
	1r	203	29.174	17.179	49.431	0.547	0.408	0.685	6.66	0.23	60.46	**
	1f	362	4.457	3.097	6.412	0.120	0.034	0.206	2.31	0.02	7.48	**
	2	33										N/S
	2r	9										N/S
	2f	23										N/S

N = sample size
F statistics = equation significant at 0.05
Significance = regression significance (**) at $\alpha = 0.05$.
all = sediment rating curve using all measurements
1, 2, 3 = event types 1, 2, 3, respectively
r = rising stage of event hydrograph
f = falling stage of event hydrograph
N/S = not significant

watershed level were not significantly different from those derived for frontal rainfall events for WS 13, they were different for WS 12 and WS 14. This result was not surprising, as the process of dislodging and transporting soil particles by low-intensity, relatively long duration, frontal rainfall events (type 3) would be less effective on watersheds with more vegetative cover (WS 13). It follows that estimates of sediment concentrations from sediment rating curves for the ponderosa pine watersheds would be improved by separating sediment data derived from snowmelt runoff from those derived from the complete data sets.

Hydrographs were partitioned into rising and falling stages to evaluate the commonly observed statement that the rising stage of a hydrograph is generally associated with higher rates of suspended sediment transport than the falling stage (Elliott and DeFeyter 1986; Glysson 1987; Brooks et al. 1997). The results indicated a greater difference between sediment rating curves derived after the data sets were partitioned into rising and falling stage hydrographs. Sediment concentrations for the rising stage of a hydrograph were generally higher than those for the falling stage. This finding reinforced the previous findings that higher rates of sediment transport during stormflow events are found with the rising limb of a hydrograph.

Pinyon-Juniper Watersheds

There were differences in sediment rating curves among the treated pinyon-juniper watersheds and the control watershed at the watershed level (Lopes et al. 1996). The main difference was higher sediment concentrations from the cabled watershed (WS 1) than the control watershed for similar streamflow discharges. Higher concentrations of suspended sediment on WS 1 were likely a reflection of the soil disturbances caused by uprooting trees in the cabling treatment.

There was also a difference between sediment rating curves derived for the watershed treated with herbicides (WS 3), which experienced little soil disturbance as a result of treatment, and the control watershed. However, soil disturbance caused by the follow-up removal of merchantable firewood, and piling and burning the residual slash 8 years after the herbicide treatment, was apparently significant in terms of affecting suspended sediment discharge.

There were significant differences in sediment rating curves derived from the total data sets and the curves derived from the data sets after they had been partitioned by streamflow-generation mechanisms for WS 1 and WS 2. However, there was no significant difference in sediment concentration when streamflow-generation mechanisms were considered on WS 3. Similar to the situation observed on the ponderosa pine watersheds, a large portion (85%) of the total data sets was associated with snowmelt runoff events; therefore, these latter events dominated the statistical properties.

Sediment rating curves derived from data sets partitioned into rising and falling stage hydrographs were different from those derived at the streamflow-generation levels of analysis for convectional rainfall events (type 2) on WS 2 and snowmelt-runoff events (type 1) on WS 3. There were no differences in suspended sediment concentration for the rising and falling limbs of the hydrograph for the other cases. Therefore, with the exception of hydrographs generated by convectional rainfall events (type 2) on WS 2 and by snowmelt-runoff events (type 1) on WS 3, results from the pinyon-juniper watersheds do not support the statement that higher rates of sediment transport are found with the rising limb of a hydrograph.

Conclusions

Soil disturbances caused by vegetative treatments on Beaver Creek watersheds in both vegetative types generally increased sediment concentrations significantly above those of control watersheds. This response is reflected by their respective sediment rating curves. Completely cleared and strip-cut ponderosa pine watersheds produced higher suspended sediment concentrations than did the control watershed. Likewise, cabled and herbicide-treated pinyon-juniper watersheds yielded higher sediment-laden streamflows than did the control. It is important to emphasize, however, that the elevated suspended sediment concentrations observed following the treatments in both of the vegetative types were still low relative to water-quality standards.

Although more than 85 percent of the data analyzed represented snowmelt-runoff events in both vegetative types, derivation of sediment rating curves based on streamflow-generation mechanism improved the sensitivity of the analysis. This improvement was particularly true for watersheds that had higher levels of disturbance.

Sediment concentrations were generally higher in the rising stage than in the falling stage for ponderosa pine watersheds. However, there was no clear evidence of higher sediment concentrations in the rising stage of the hydrograph as compared to the falling stage in the pinyon-juniper watersheds.

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