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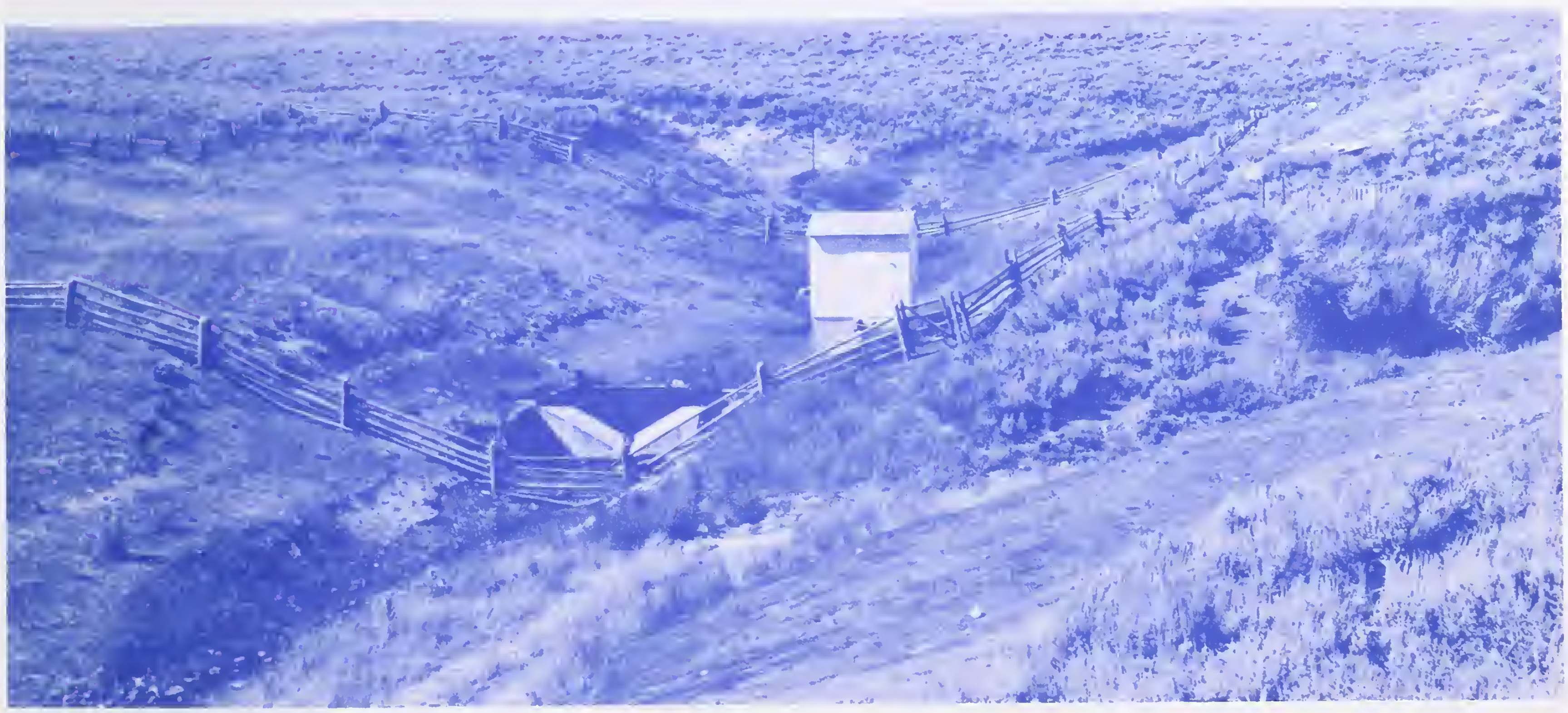
High-Elevation Watershed Response to Sagebrush Control

in Southcentral Wyoming

David L. Sturges



Abstract

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Hydrologic and vegetative changes induced by controlling sagebrush with the herbicide 2,4-D were evaluated over a 23-year study using paired watersheds. Annual water yield increased 20% for 11 years after sagebrush control, but then returned to a pretreatment level. Two-thirds of the increase came as snowmelt discharge and one-third as increased groundwater discharge through the remainder of the year. Treatment did not change the date or the magnitude of peak snowmelt discharge, but snowmelt duration was lengthened 22% (p=0.19). Total sediment transport averaged 3.44 and 0.59 tonnes/km^2/y on the untreated and treated watershed. Coarse sediment transport was not affected by treatment. Grass production more than doubled in the 5 years after spraying and was 1.5 times greater in the ninth and tenth years. Eleven years after treatment, sagebrush on the treated watershed had returned to a pretreatment density.

Keywords: Water yield improvement, streamflow, rangeland hydrology, sediment transport, sagebrush control, range improvement, forage production, range management

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INTRODUCTION

Extensive control of big sagebrush (*Artemisia tridentata*) to increase forage production for livestock became practical after World War II with the development of phenoxy herbicides that could be aerially applied. In Wyoming alone, 788,000 ha were sprayed between 1952 and 1976 (Freeburn 1979). Since then, the concern over environmental side effects from herbicides has greatly reduced their use. In recent years, burning sagebrush rangeland in the spring or fall has gained favor as a control method (Beardall and Sylvester 1976, Nimir and Payne 1978, Ralphs and Busby 1979).

Forage available to livestock commonly doubles or triples after spraying or burning sagebrush on sites with an adequate stocking of herbaceous species (Pechanec et al. 1954, Hyder and Sneva 1956, Hedrick et al. 1966, Sturges 1977a, Miller et al. 1980). Even larger production responses are possible by plowing and reseeding sagebrush stands on sites where desirable plants comprise less than 20% of total plant cover (Pechanec et al. 1965). Desirable species to seed and methods of establishment were reviewed by Keller (1979).

Vegetative and hydrologic responses to sagebrush eradication vary with the control method. Maximum surface disturbance occurs when sagebrush stands are plowed. Spraying with herbicides such as 2,4-D is least destructive to litter and residual vegetation because there is no surface disturbance and grasses are unaffected by the herbicide. Burning destroys vegetation and litter indiscriminately. Prescribed burns conducted in the spring before herbaceous vegetation initiates growth are less destructive to watershed cover values than summer or fall burning. Vegetation quickly develops following a spring burn, but burning after vegetation growth is complete leaves soil unprotected through the winter and early spring.

The hydrologic changes that result from sagebrush control have received much less attention than the vegetation responses. Several investigators have looked at the effects of various cultural treatments on water infiltration, overland flow, and sediment movement by applying simulated rainfall to small plots and measuring the runoff (Gifford and Skau 1967, Gifford 1972, Gifford and Busby 1974, Gifford 1979, Gifford 1982, Hart 1984).

Snow accumulation characteristics can be affected by sagebrush control until vegetation is covered by snow. At a windswept mountain big sagebrush (*A. t.* ssp. *vaseyana*) site, the rate of snow accumulation in sprayed areas was slightly less than in untreated sagebrush stands early in the winter, but maximum snow accumulation was similar for both areas because topographic features, not vegetation height, controlled snow accumulation (Sturges 1977b). Sonder and Alley (1961) found that snow depths were similar for sprayed and unsprayed stands in a location where sagebrush was less than 15 cm tall and drifting was common. Hutchison (1965) showed that the rate of snow accumulation in a sagebrush stand was greater than in adjacent grass vegetation during the time sagebrush crowns were above the snow surface. Minimal differences exist in snowmelt rates over sagebrush, grass, and bare soil as long as snow depths exceed vegetation height (Connaughton 1935, Hutchison 1965, Sturges 1977b).

Sagebrush soil water studies were reviewed by Sturges (1977a). Once residual vegetation responds to release from sagebrush competition, reduced water use can occur on sites where water recharge extends below 1 m. About a 15% reduction in water use was found within the surface 1.8 m of soil the second year after treatment (Tabler 1968, Sturges 1977a) even though water use by vegetation for spray and nonspray treatments was similar in the surface 0.9 m of soil. Seasonal depletion differences averaged 9% in the 20 years after spraying, which equaled 2.4

cm of water (Sturges 1993). This study was conducted in Wyoming and was the only soil water investigation to extend more than 3 years after sagebrush control.

Lusby (1979) conducted the only watershed-based study to evaluate the effects of sagebrush conversion on water and sediment yields. The mountain big sagebrush stand was plowed and beardless wheatgrass (*Agropyron inerme*) was planted. Herbaceous production was about 110 kg/ha before beardless wheatgrass was planted, but increased to about 450 kg/ha after grass establishment. Treatment greatly reduced the area of bare soil (Shown et al. 1972). Water yield decreased about 20% on treated watersheds, but sediment transport decreased about 80%, because of a reduction in summer rainstorm runoff.

The objective of this study was to evaluate the hydrologic and vegetative effects of controlling sagebrush with a herbicide. Treatment evaluations were based on total annual water yield, annual water yield attributable to snowmelt and groundwater discharge, and midwinter discharge. Hydrograph components relating to the timing and magnitude of snowmelt discharge were also examined in addition to the effects of treatment on maximum snow-water accumulation, coarse sediment deposition, and vegetation characteristics. Investigations used a paired watershed approach that involved measurements on two drainage basins. Both watersheds had perennial flow. Water discharge information was collected for 8 years before sagebrush control and for 14 years after treatment. The study provides one of the few long-term hydrologic data sets that exist for sagebrush rangeland at a watershed scale.

STUDY AREA AND METHODS

The study was conducted between 1968 and 1990 at the Stratton Sagebrush Hydrology Study area, 32 km west of Saratoga in southcentral Wyoming. Two adjacent basins, Loco Creek 663 ha, and Sane Creek 238 ha, were used (fig. 1). Watershed elevations range from 2,340 m to 2,470 m. The Sane Creek drainage was aerially sprayed with 2,4-D in 1976 after completion of an 8-year calibration period and the study continued until 1990. Loco Creek watershed remained in an undisturbed state throughout the study. Details of herbicide application were provided by Sturges (1986).

Streamflow originates in springs located 1.6 km above the Loco Creek streamgage and 33 m above the Sane Creek streamgage. Gaging stations consist of a 120° V-notch weir blade seated in a concrete cut-

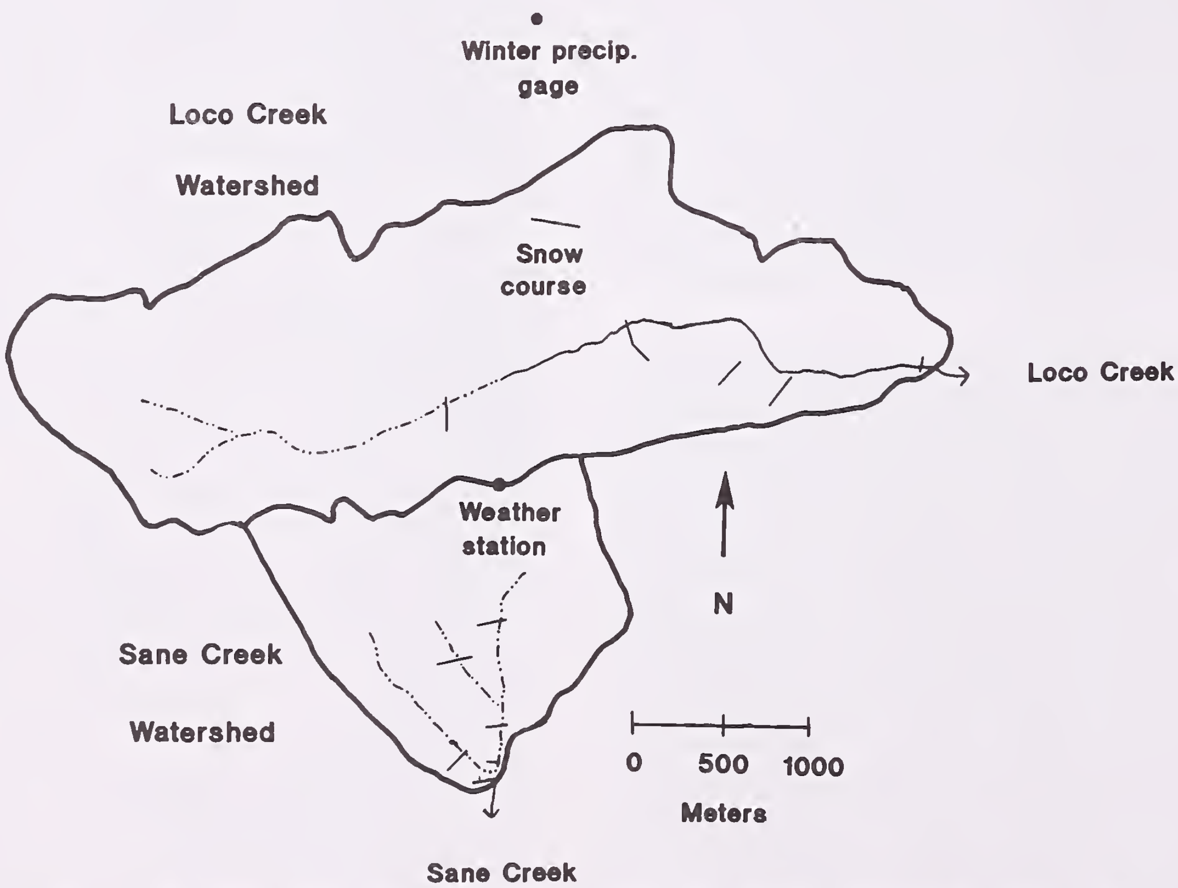

Figure 1. — The Loco Creek and Sane Creek watersheds, Stratton Sagebrush Hydrology Study area. The Sane Creek watershed was aerially sprayed with 2,4-D to control sagebrush.

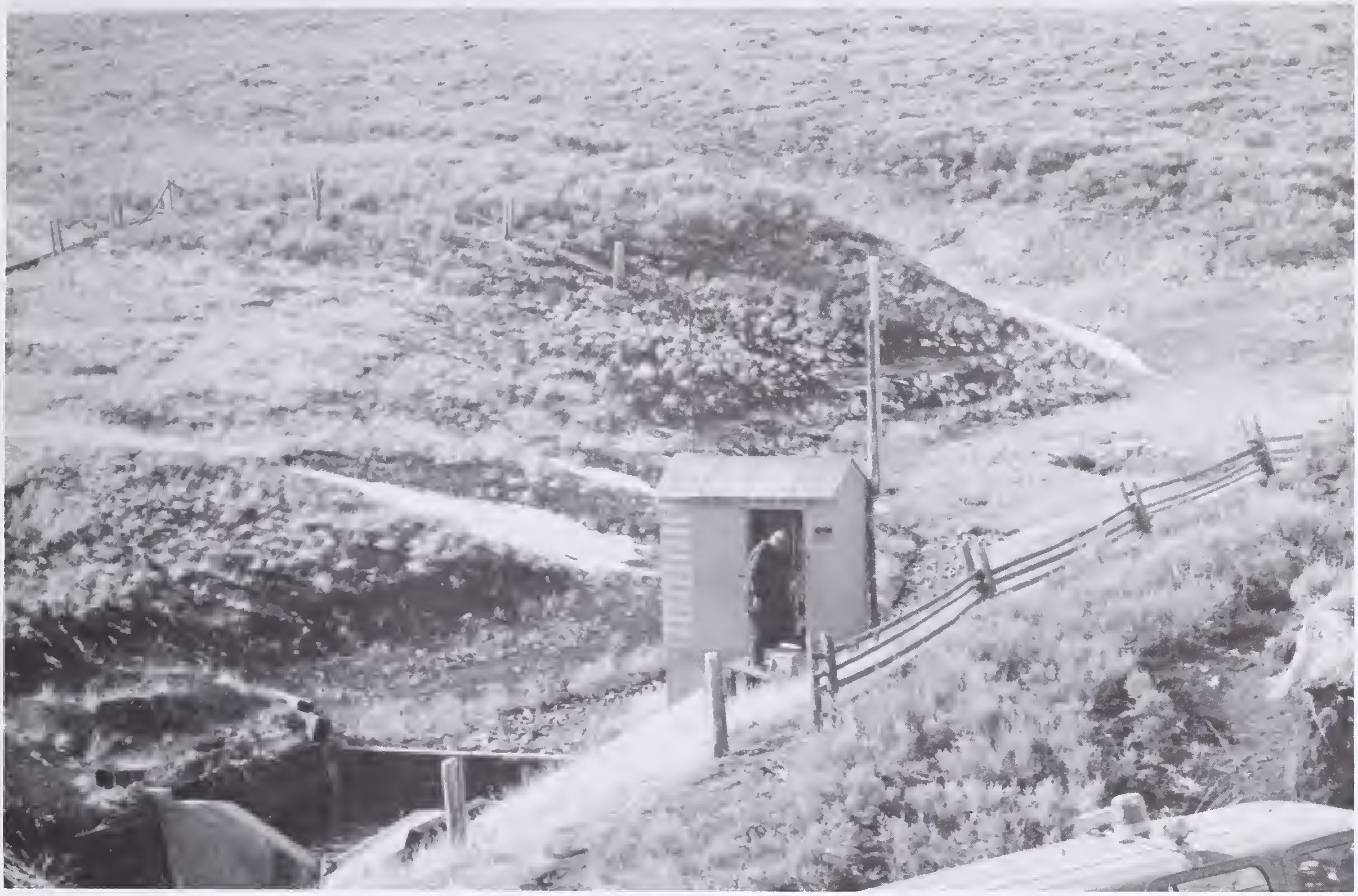

Figure 2a. — The Sane Creek streamgage (March 31, 1981) showing the cutoff wall, V-notch, and stilling basin in a winter with no snow accumulation. The metal culvert provided access to the V-notch when drifted snow covered the gaging station.

off wall resting on sandstone (fig. 2). A stilling basin was located on the upstream side of the cutoff wall. The Loco Creek basin was 6.9 m wide and 9.1 m long and the stilling basin at Sane Creek was 4.7 m wide and 5.5 m long. Water stage was continuously recorded on a strip chart. The entire Loco Creek gaging station was covered with a multiplate arch to prevent burial by drifting snow. Sane Creek water was warm enough to melt a cavern in the snowpack so that snow did not obstruct the V-notch and covering was not necessary (fig. 2).

Climatological data were collected at a weather station located near the divide between Loco Creek and Sane Creek watersheds (fig. 1). Daily rainfall totals were corrected to interval precipitation measured in an adjacent pit gage. From October to May, precipitation was measured by a recording gage located in an aspen (*Populus tremuloides*) grove 800 m north of the Loco Creek watershed boundary (fig. 1). This location provided shelter from the wind allowing a more accurate measurement of precipitation received as snow than is possible in exposed locations (Tabler et al. 1990).

Soils developed in place from sandstone of the Brown's Park Formation and belong to the Mollisol or Aridisol order. Soil developmental processes were strongly influenced by snow accumulation patterns. Mollisols soils occupy drainages and snow depositional areas and are members of the Argic Cryoborall subgroup. These soils have a loam texture in the A and B horizon and the B horizon extends more than 1 m deep. Aridisol soils are characteristic of upland areas where most of the winter snowfall is removed by the wind. They are a member of the Borollic Haplargids subgroup. The B horizon is sometimes lacking in Aridisol soils and the A horizon may be less than 15 cm thick.

Mountain big sagebrush is found on well-developed soils along with grasses such as Idaho fescue (*Festuca idahoensis*), blue grasses (*Poa* spp.), and

Figure 2b. — Appearance of the Sane Creek streamgage (February 26, 1980) in a normal winter at the time drifted snow covered the V-notch and stilling basin and was about to extend over the building housing the water level recorder and pumping sediment sampler.

needlegrasses (*Stipa* spp.). Soils are less developed on the drier windward slopes and ridges. Wyoming big sagebrush (*A. t.* ssp. *wyomingensis*) and black sagebrush (*A. nova*), in addition to June grass (*Koeleria macrantha*), bluebunch wheatgrass (*A. spicatum*) and bottlebrush squirreltail (*Sitanion hystrix*) are found in these locations. Forbs comprise less than 25% of annual herbaceous production. Burke (1989) and Burke et al. (1989) quantified the relation between topographic position and distribution of plant species, soil temperature, and nitrogen mineralization at the Stratton site. Differences are a consequence of snow redistribution.

The Stratton Sagebrush Hydrology study area comprised about half of a grazing allotment administered by the U. S. Department of the Interior Bureau of Land Management, and had been grazed by sheep for many years. It was not possible to exclude grazing from the study area. Sheep typically lambed on the Stratton site in late May, grazed for a month, and then returned in late summer before leaving by October. Sheep usage patterns from 1968 to 1973 were reasonably similar to grazing patterns existing before study initiation. The watersheds were lightly grazed between 1973 and 1983 and were ungrazed from 1984 to 1986. In 1987 the allotment was converted from sheep use to cattle use. Watersheds were grazed by cattle during September in 1987 and 1988 and during July and August in 1989 and 1990. Upland portions of the watersheds received reasonable use under both sheep and cattle grazing regimes, but cattle utilized vegetation along Loco Creek much more heavily than did sheep. Sane Creek watershed was deferred from grazing the year that sagebrush was sprayed and in the succeeding 2 years.

Vegetation Productivity and Sagebrush Density on Watersheds

Total herbaceous production was measured annually on Loco and Sane Creek watersheds from 1968 to 1981 and again in 1985 and 1986, the ninth and tenth year after sagebrush control. A double sampling system was employed to collect information about vegetation production and composition. An electronic capacitance meter (Morris et al. 1976) that sampled a 30 x 61-cm area provided information about total herbaceous production. Information from a smaller number of clipped plots that were also 30 x 61 cm in size provided data to relate readings by the capacitance meter to herbage weight. Beginning in 1972, herbage from clipped plots was separated into sagebrush, grass, and forb categories to provide information about composition. Sturges (1986) fully described sampling procedures used to measure vegetation production and sagebrush density.

The density of sagebrush on Loco and Sane Creek watersheds was determined 2 years before treatment of Sane Creek watershed. Density measurements were repeated on Sane Creek watershed 1 and 10 years after spraying to evaluate sagebrush mortality and reestablishment. In 1977 and in 1987, individual sagebrush plants were categorized as seedlings (plants less than 3 cm tall with a herbaceous stem) or as plants that established before or after spraying.

Streamflow

Daily water discharge through the year was calculated from the continuous record of stage. Annual flow from each watershed was separated into groundwater (base flow) and snowmelt components. Snowmelt runoff was defined to start when average daily discharge exceeded 0.001 $m^3/sec/km^2$ and to end when discharge fell below 0.002 $m^3/sec/km^2$, a broad inflection point on the recession hydrograph (fig. 3). Groundwater discharge during the snowmelt interval was assumed to increase linearly between these discharge values. Snowmelt discharge was that portion of daily flow exceeding groundwater discharge. Annual groundwater discharge was the sum of groundwater flow during snowmelt plus all discharge in the remainder of the year. Midwinter discharge was defined as accumulated flow from December 1 to February 28, a period in which discharge was sustained solely by groundwater.

Daily streamflow information made it possible to assess the effects of treatment on the date and magnitude of peak snowmelt discharge, length of the snowmelt period, and the minimum number of days required to accumulate the annual half-flow volume of snowmelt discharge (50% of snowmelt runoff). Court (1962) discussed advantages of using half-flow dates to characterize streamflow timing, rather than the use of single criterion such as the date or the magnitude of maximum yearly discharge. The occurrence of a single event is often influenced by short-term weather patterns that do not necessarily reflect hydrograph changes attributable to land management practices.

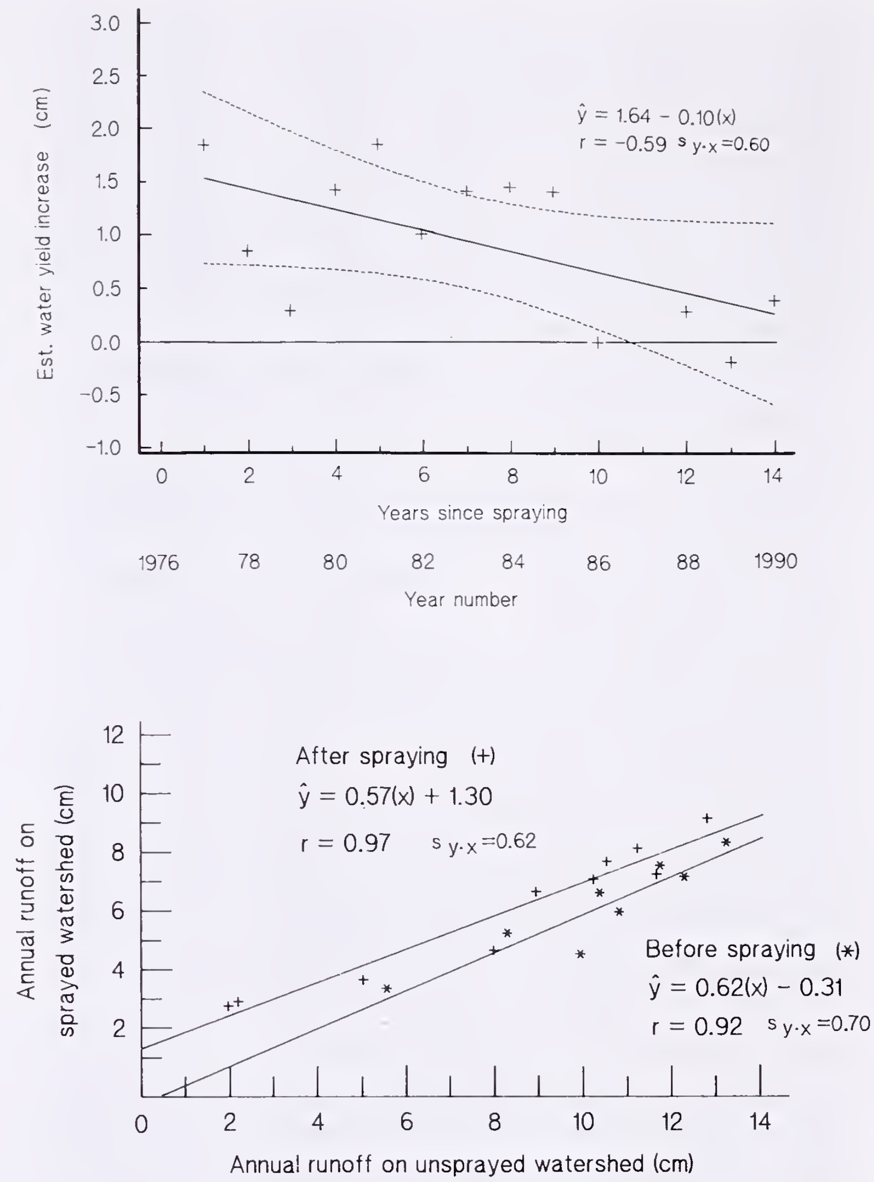

Figure 3. — *Top:* The relation between the increase in water yield on Sane Creek watershed and elapsed time since the watershed was sprayed. *Bottom:* Pretreatment and posttreatment relations between annual water yield on the unsprayed watershed (Loco Creek) and the sprayed watershed (Sane Creek).

Sediment Transport

The stilling basin at each streamgage permitted larger sized sediment particles to settle and collect at the bottom of the basin. Sediment that remained in suspension passed through the gage with water flowing over the V-notch. The residence time of water in stilling basins, and thus the time available for settlement, was a function of flow volume, which continually changed. Sediment transport was classified as either coarse or filtrable in this study. Coarse sediment was material deposited in stilling basins and filtrable sediment was that portion of the sediment load discharged through the V-notch.

The volume of coarse sediment deposited annually in stilling basins was measured between 1971 and 1990 by a rod and level survey. Measurements were made after cessation of snowmelt runoff using a 0.61-m grid placed over the basin. The composition of Loco Creek coarse sediment was measured in 1976 and 1978. Samples of coarse sediment were collected at three locations along transects that crossed the stilling basin at distances of 1.2, 3.7, and 6.1 m from the cutoff wall. Sediment was obtained from depths of 2.5 to 10.2 cm and 15.2 to 22.9 cm at each sampling location. The samples were ashed at 475°C for 48 h to determine organic content and the texture of residual mineral matter less than 2 mm in diameter was determined by mechanical analysis.

Information about the export of filtrable sediment from Loco and Sane Creek watersheds was provided by samplers that pumped water from stilling basins (Models PS–67 and PS–69 developed by the Federal Interagency Sedimentation Committee). The sediment sampler intake pipe in the Loco Creek stilling basin was located 0.4 m upstream of the cutoff wall and 3 m from the center of the V-notch; at Sane Creek, it was located 2.3 m upstream of the cutoff wall and 1.7 m from the center of the V-notch. Collection of filtrable sediment information began in 1973 before initiation of snowmelt runoff and continued through 1989. The Loco Creek sampler was operated year-round. Data collection was discontinued in winter months at Sane Creek between 1973 and 1980; thereafter the sampler was operated year-round. Water samples were collected at 0600 and 1800 h during the snowmelt period to coincide with minimum and maximum daily discharge, respectively, and at 1800 h during the remainder of the year. Each sample consisted of about 400 ml of water. Filtrable sediment content of water was determined by standard analysis procedures using filters with pores 45 microns in diameter (APHA 1985).

The concentration of filtrable sediment in water collected from the Loco Creek stilling basin was corrected to concentration of sediment in water flowing over the V-notch by a regression relation developed each year. Data were obtained for the relation by manually collecting a 400-ml water sample at the V-notch just before collection of a water sample by the pumping sampler. Similar measurements at Sane Creek indicated that a correction was unnecessary. Filtrable sediment levels were less than 10 mg/l most of the year and there was not a significant relation between sediment concentration in water pumped from the stilling basin and collected at the V-notch.

The volume of filtrable sediment discharged each day was estimated by multiplying average water discharge by filtrable sediment concentration. This calculation assumes that sediment and water have the same bulk density, a reasonable approximation for the low filtrable sediment levels present in Loco and Sane Creek water. Daily filtrable sediment discharge was summed on each watershed to provide estimates of filtrable sediment discharge during the snowmelt period and for the year. Estimates were not made if more than a few days of sediment information were missing while snowmelt runoff was high because the majority of filtrable sediment discharge in a year occurs at this time. Filtrable sediment discharge for Sane Creek in winter months from 1974 to 1980 was estimated by multiplying daily water discharge by average monthly sediment concentration determined in years that data were collected.

Snow Accumulation

The depth of snow deposited in topographic catchments was measured at or near maximum accumulation from 1968 to 1989. Seven index snow courses were located within Loco Creek watershed and six index snow courses were located in Sane Creek watershed (fig. 1). Individual snow courses ranged from 61 m to 290 m long. Depending upon length, depth measurements were taken at 15.2 or 30.5 m intervals along a snow course. Snow was probed with an aluminum rod to determine depth (Jairell 1975), or when too deep to probe (about 6 m), a rod and level survey provided an indirect measurement of depth. The relation developed by Tabler (1985) between the depth and the density of wind-deposited snow was employed to estimate snow water content. A southwest wind direction prevailed in winter months so that drifting patterns were similar each year. The volume of snow accumulating in topographic catchments was sensitive to winter precipitation and to snow retention characteristics of vegetation on the fetch zone.

Statistical Analysis of Data

Inspection of water yield data from Loco and Sane Creek watersheds revealed an obvious increase in flow for about 10 years following sagebrush control. An assessment of the duration of significant flow increase was made by constructing a data set based on the difference between actual and expected water yield through the 14-year posttreatment period. Expected Sane Creek water yield was that which would have occurred if sagebrush had not been sprayed and was estimated from Loco Creek discharge using the pretreatment streamflow regression relation. The yearly increase in water yield was regressed against elapsed time since spraying and confidence bands were constructed about the regression line. The point at which the lower confidence band crossed the point of zero flow increase identified the number of years that water yield significantly increased (Rogosa 1980). Troendle and King (1985) followed a similar procedure to estimate the hydrologic recovery rate following timber harvest on Fool Creek watershed located in Colorado on the Fraser Experimental Forest.

Covariance analysis could be used to determine if spraying significantly changed a hydrologic or vegetation characteristic when the correlation coefficient in pretreatment and posttreatment regression relations was significantly different from zero (Steel and Torrie 1980). If these requirements were not met, a two factor analysis of variance (Green 1979) was used to test watershed data for significant differences. The two factor analysis provided a comparison between watersheds and a comparison between pretreatment and posttreatment time periods. A significant interaction between watershed and time period indicated that spraying altered the posttreatment average value on Sane Creek watershed compared to the average value on Loco Creek watershed.

Vegetation production and composition data were tested for statistical significance by the two factor analysis of variance. Percentage composition data were first transformed by arcsin transformation. To provide information about the persistence of changes in herbaceous production, data collected before spraying were compared with data collected 9 and 10 years after spraying. A comparison was also made between herbaceous production levels in the first 5 years after spraying and production levels 9 and 10 years after spraying. The significance of mean differences between time periods was identified using the *t* test.

The following hydrologic variables could be tested by covariance analysis: annual runoff, snowmelt discharge, groundwater discharge, maximum snowmelt runoff rate, and snow accumulation. These hydrologic variables were tested by two factor analysis of variance: midwinter discharge, the date of maximum snowmelt runoff, the duration of snowmelt runoff, the minimum number of days required to accumulate 50% of yearly snowmelt discharge, and coarse sediment transport. A *t* test was used to determine if coarse sediment deposition in Loco and Sane Creek stilling basins was significantly different in pretreatment and posttreatment periods. A 0.05 probability was used to indicate statistical significance throughout this paper unless a lower probability level was specified.

The impact of sagebrush control on filtrable sediment export from Sane Creek watershed could not be statistically evaluated because of a lack of data in pretreatment years. Filtrable sediment measurements began 3 years before Sane Creek watershed was sprayed, but only 1 year of information was available in the pretreatment period because of malfunctions in sampler operation. Nevertheless, data provide important insights about the mode and magnitude of sediment transport on the two watersheds.

RESULTS

The climatic regime at the Stratton Hydrology Study area favored redistribution of snow by wind, which in turn strongly affected hydrologic processes. Maximum daily temperatures were below freezing from mid-November through March when the majority of yearly snowfall was received. Average monthly wind speeds exceeded 5.8 m/sec between November and March and reached a yearly maximum of 7.7 m/sec in January. Yearly wind speeds were minimal in July and August at about 3 m/sec and the direction was more variable than in winter months. Average annual temperature was 2.7°C

Information about precipitation, snow-water accumulation on index snow courses, and water yield, is tabulated in table 1 for all years of study. Precipitation averaged 51.8 cm/y, and about 75% of the total fell as snow. Summer rainfall, June through September, was 11.7 cm. Precipitation and runoff data are indicative of the wide range in annual values that characterize higher elevation, windswept sagebrush rangeland. There was no snow accumulation in the 1980–81 winter (fig. 2); a complete snow cover was present on slopes normally swept free of snow in winters with high precipitation such as in 1978–79 and 1983–84. Effective winter precipitation for Loco and Sane Creek watersheds is unknown because of snow relocation.

Vegetation Response

Sagebrush density was about 36,000 plants/ha on Loco and Sane Creek watersheds before treatment (table 2). Herbicide application resulted in a 77% reduction in sagebrush canopy cover on Sane Creek watershed the year after spraying and a 62% reduction in the number of live plants (Sturges 1986). Sagebrush density increased sharply in subsequent years (table 2). The combined density of sagebrush seedlings and established plants 11 years after spraying was similar to the density of sagebrush on Sane Creek

Table 1. — Precipitation and snow-water accumulation on index transects, and water yield for Loco Creek and Sane Creek watersheds (n = number of years).

	Precipitation		Date max. snow accum.	Snow-water accumulation		Water yield: Snowmelt		Water yield: Groundwater		Water yield: Total	
Year	Annual	Winter		Loco	Sane	Loco	Sane	Loco	Sane	Loco	Sane
	cm			cm		cm					
Before treatment											
1968	NA	NA	404	112.5	63.3	5.51	2.15	2.74	3.09	8.25	5.24
1969	51.2	23.3	409	71.7	34.9	3.05	0.35	2.46	3.00	5.51	3.35
1970	59.2	25.7	430	86.4	47.4	7.03	3.27	3.31	3.34	10.34	6.61
1971	60.8	29.9	331	105.0	60.5	8.30	4.01	3.96	3.14	12.26	7.15
1972	62.4	30.7	316	110.2	58.5	6.54	1.57	3.36	2.95	9.90	4.52
1973	64.1	25.1	405	102.2	64.3	9.50	4.73	3.71	3.60	13.21	8.33
1974	43.7	27.5	320	127.2	60.7	7.54	3.44	4.17	4.10	11.71	7.54
1975	58.8	29.8	425	108.3	58.8	6.78	2.17	3.99	3.79	10.77	5.96
n	(7)			(8)		(8)		(8)		(8)	
Avg.	57.2	27.4		102.9	56.1	6.78	2.71	3.46	3.38	10.24	6.09
Treatment year											
1976	37.3	28.0	413	112.9	67.8	6.93	2.12	3.93	3.66	10.86	5.78
After treatment (Significant increase in water yield)											
1977	48.8	14.4	407	19.7	15.3	[a]	[a]	1.93	2.75	1.93	2.75
1978	51.5	18.0	302	67.0	37.9	2.42	.52	2.56	3.13	4.98	3.65
1979	46.5	34.1	419	158.5	85.0	8.27	3.59	3.36	3.65	11.63	7.24
1980	48.5	27.2	327	128.2	81.8	7.29	4.01	3.91	4.12	11.20	8.13
1981	52.8	12.0	402	0.5	0.0	[a]	[a]	2.16	2.90	2.16	2.90
1982	50.1	23.3	325	108.2	53.1	6.92	3.49	3.28	3.58	10.20	7.07
1983	63.3	15.2	310	75.7	45.1	6.75	3.58	3.75	4.10	10.50	7.68
1984	62.4	35.9	412	131.4	82.0	8.54	4.49	4.25	4.65	12.79	9.14
1985	46.5	21.7	402	95.6	50.5	4.65	2.59	4.25	4.06	8.90	6.65
1986	55.1	19.6	227	88.7	53.2	3.96	1.09	3.98	3.56	7.94	4.65
1987	41.7	17.8	331	19.9	8.5	2.50	2.77	3.12	3.10	5.62	5.87
n	(11)			(10[b])		(8[b])		(10[b])		(10[b])	
Avg.	51.6	21.7		87.4	50.4	6.10	2.92	3.34	3.65	7.94	5.99
(Nonsignificant increase in water yield)											
1988	41.2	21.2	322	90.5	54.2	3.40	.73	3.23	3.39	6.63	4.12
1989	37.6	21.9	315	78.6	38.5	2.07	[a]	2.99	2.67	5.06	2.67
1990	NA	17.1	320	NA	NA	0.89	[a]	2.48	2.18	3.37	2.18
n	(2)	(3)		(2)		(3)	(1)	(3)		(3)	
Avg.	39.4	20.1		84.6	46.4	2.12	.73	2.90	2.75	5.02	2.99
All years of study											
n	(21)			(22)		(21)		(19)	(23)	(23)	
Avg.	51.8	23.6		90.9	51.0	5.66	2.67	3.34	3.41	8.51	5.62

[a] *No snowmelt runoff during year*
[b] *1987 data omitted from average*
NA - Not available

watershed before treatment. Established plants were about equally divided between ones that survived treatment and those that established after the watershed was sprayed.

Treatment of Sane Creek watershed did not significantly affect total herbaceous production in the 5 years after spraying (Sturges 1986) or in the ninth and tenth year (table 3). However, treatment greatly changed vegetation composition. There was a significant increase in grass production that compensated for a significant decrease in sagebrush production. Grass production averaged 199 kg/ha before treatment, 409 kg/ha the first 5 years after treatment, and 286 kg/ha in the ninth and tenth year after treatment. The reduction in grass production with time in posttreatment years was significant at the 0.10 level of probability. Differences between the percentage composition of sagebrush and of grass on the two watersheds was significant in the 5 years after treatment and differences remained significant in the

Table 2. — Sagebrush density and 95% confidence interval for Loco and Sane Creek watersheds 2 years before treatment and for Sane Creek watershed in the first and eleventh year after treatment.

Years after spraying	Plants ha: Sane Creek Plants	Sane Creek Seedlings	Loco Creek Plants
–2	35,681 ± 10,971		36,867 ± 7,413
1	14,925 ± 4,991	1,977 ± 1,334	
11	29,306 ± 11,762	8,649 ± 7,759	

Table 3. — Total herbaceous production on Loco and Sane Creek watersheds, and composition and productivity by sagebrush, grass, and forb herbage categories. Total production data were collected with an electronic capacitance meter and herbage composition and production data are based on data from clipped plots.

	Total production		Composition						Production					
			Sagebrush		Grass		Forb		Sage		Grass		Forb	
Years	Loco Creek (kg/ha)	Sane Creek (kg/ha)	Loco (%)	Sane (%)	Loco (%)	Sane (%)	Loco (%)	Sane (%)	Loco (kg/ha)	Sane (kg/ha)	Loco (kg/ha)	Sane (kg/ha)	Loco (kg/ha)	Sane (kg/ha)
Before treatment														
1968	1017	680												
1969	699	827												
1970	772	790												
1971	1085	1174												
1972	1033	568	75	49	19	38	6	13	645	245	168	193	49	63
1973	960	765	56	60	18	19	26	21	528	507	174	157	245	174
1974	814	921	67	73	24	20	9	7	515	818	188	230	73	82
1975	1024	1044	52	56	29	22	19	22	521	543	289	215	194	215
	n = 8								n = 4					
Avg.	926	846	63	60	22	25	15	15	552	528	205	199	140	134
Treatment year														
1976	907	591	64	26	26	10	14	550	142	232	318	84	74	
After treatment														
1977	691	519	64	18	27	74	9	8	400	78	166	315	55	36
1978	782	831	65	12	30	82	5	6	408	87	192	585	29	45
1979	880	668	67	21	24	70	9	10	515	110	180	370	72	50
1980	905	663	75	40	16	48	9	12	609	244	130	293	69	74
1981	923	859	69	27	25	66	6	7	556	199	204	484	48	55
	n = 5								n = 5					
Avg.	836	708	68	23[a]	24	68[a]	8	9	498	144[a]	174	409[a]	55	52
1985	907	781	67	29	26	61	7	10	478	155	193	321	50	55
1986	921	745	66	45	23	47	11	8	562	202	195	250	98	41
	n = 2								n = 2					
Avg.	914	763	67	37[a]	24	54[a]	9	9	520	179[a]	194	286[a, b]	74	48

[a] *Sane Creek mean significantly different from Loco Creek mean*

[b] *Mean grass production for Sane Creek in posttreatment intervals significantly different at 0.10 probability level*

ninth and tenth year as well (table 3). Productivity of forbs was not affected by treatment.

Although subject to considerable yearly variation, vegetation composition and production information from Sane Creek watershed indicated that with time, sagebrush increased and grasses decreased in importance. Average grass production on the Sane Creek watershed was 2.4 times as large as on Loco Creek watershed in the 5 years after treatment, but only 1.5 times as large in the ninth and tenth years (table 3).

Water-Yield

Winter precipitation influenced water yield characteristics in pretreatment and posttreatment intervals (table 1). Later years of the study encompassed winter drought conditions that began in the late 1980s in the western United States. Average winter precipitation in the 8 years preceding treatment was 5.7 cm greater than in the first 11 years after treatment and 7.3 cm greater than that received 12–14 years after treatment. Discharge rates were not great enough to meet snowmelt runoff criteria in four of the fourteen posttreatment years on one or both watersheds (table 1).

An increase of at least 1 cm in annual water yield from Sane Creek watershed was normal in the 9 years after spraying, but then annual discharge appeared to revert to a pretreatment level (fig. 3). The lower confidence band about the regression relation between water yield increase and elapsed time since spraying intersected the point of zero flow increase 11 years after treatment. Therefore, all statistical analyses of treatment effects were based on the 11-year period from 1977 to 1987. However, 1987 data were omitted from analyses because of the unusual nature of flow that was unrelated to the effects of sagebrush control. An unusual sequence of events beginning in the fall of 1986 produced the highest instantaneous discharge rates ever measured on the Stratton watersheds during 1987 snowmelt, and snowmelt delivery efficiency was also extremely high. Surface soil was rewet before freezing in the fall of 1986 because of above normal precipitation. Winter precipitation was low, and extremely warm temperatures in April 1987 caused the shallow snowpack to rapidly melt. Because infiltration rates were impaired during the early stages of snowmelt, water quickly reached drainage channels and was transported off the watershed.

Average annual water yield for Sane Creek was 5.50 cm in pretreatment years and 6.58 cm in the 11-years after spraying, a 20% flow increase that was statistically significant (table 4). The increase of 1.08 cm in water yield provided an additional 25,656 m^3 of water each year. Pretreatment and posttreatment regression relations are shown in figure 3. The posttreatment relation was displaced upward from the pretreatment relation, but remained somewhat parallel to it. The parallelism suggests that the increase in flow was of similar magnitude each year rather than being proportionally greater in wet years. This interpretation of treatment effect was supported by regression coefficients that were not significantly different at the 0.05 probability level. However, at the 0.18 probability level, the hypothesis of similar sized flow increases each year would be rejected. The intercept value of the posttreatment relation was significantly greater than the intercept value of the pretreatment relation, accounting for the upward displacement of the posttreatment regression line.

Analysis of snowmelt and groundwater discharge components indicates that control of sagebrush on Sane Creek watershed significantly increased both discharge components (table 4). Snowmelt discharge increased from an average of 2.49 cm before treatment to 3.14 cm after treatment, a 26% increase in flow. Groundwater discharge increased from 3.34 cm before treatment to 3.69 cm after treatment, a 10% increase in flow. Absolute increases in snowmelt and groundwater discharge were 0.65 and 0.35 cm/y, which provided 1.00 cm additional water per year. This sum differs somewhat from the 1.08 cm increase in water yield provided by the analysis based on total annual runoff. The discrepancy arose because 2 years fewer data were available in the posttreatment period for the snowmelt analysis than for analyses based on total and groundwater discharge.

Before spraying, midwinter discharge in the December-February period was sometimes greater on Loco Creek watershed and sometimes greater on Sane Creek watershed, but after spraying, Sane Creek discharge was numerically greater in all but 2 years. Average midwinter flows were 0.60 and 0.71 cm before and after treatment, but the 18% increase in flow was not large enough for significance because of the inconsistent response (table 4).

Control of sagebrush on Sane Creek watershed had no discernable effect on the date of maximum snowmelt runoff, maximum snowmelt discharge, the minimum number of days required to accumulate 50% of yearly snowmelt discharge, or the duration of snowmelt runoff (table 4). The date of maximum snowmelt discharge was May 11 (Julian Day 131) in pre-

Table 4. — Pretreatment and posttreatment regression equations, correlation coefficients, and adjusted mean values from covariance analysis based on four water discharge characteristics, four snowmelt hydrograph parameters, and snow water accumulation on index transects.

Variable	Period	Regression equation	Correlation coeff.	Adjusted mean value: Loco	Adjusted mean value: Sane	Significance level	Mean change: Absolute	Mean change: %
Water discharge								
Total discharge (cm)	Before treatment	$\hat{Y}$ = 0.624 (Loco) – 0.307	0.92*	9.12	5.50			
	After treatment	$\hat{Y}$ = 0.570 (Loco) + 1.301	.97*		6.58	0.004	+ 1.08	+ 20
Snowmelt discharge (cm)	Before treatment	$\hat{Y}$ = 0.692 (Loco) – 1.983	.94*	6.44	2.49			
	After treatment	$\hat{Y}$ = 0.620 (Loco) – 0.862	.95*		3.14	.019	+ 0.65	+ 26
Groundwater discharge (cm)	Before treatment	$\hat{Y}$ = 0.491 (Loco) + 1.675	.73*	3.40	3.34			
	After treatment	$\hat{Y}$ = 0.647 (Loco) + 1.486	.92*		3.69	.018	+ 0.35	+ 10
Midwinter discharge (cm)	Before treatment	$\hat{Y}$ = 0.380 (Loco) + 0.375	.54	.59	.60			
	After treatment	$\hat{Y}$ = 0.543 (Loco) + 0.391	.87*		.71	.350	+ 0.11	+ 18
Snowmelt parameters								
Snowmelt duration (No. days)	Before treatment	$\hat{Y}$ = 0.629 (Loco) – 14.33	.87*	111.9	56.2			
	After treatment	$\hat{Y}$ = 0.540 (Loco) + 7.84	.32		68.5	.185	+ 12.3	+ 22
Date maximum discharge (Julian day no.)	Before treatment	$\hat{Y}$ = 0.683 (Loco) + 35.6	.54	139.4	130.8			
	After treatment	$\hat{Y}$ = 0.608 (Loco) + 43.4	.51		128.2	.742	– 2.6	– 2
Yearly maximum discharge (m^3/s/day)	Before treatment	$\hat{Y}$ = 0.968 (Loco) – 0.0064	.87*	.025	.018			
	After treatment	$\hat{Y}$ = 0.677 (Loco) + 0.0018	.78*		.019	.902	+ 0.001	+ 6
Minimum time required to accumulate 50% of snowmelt discharge (No. days)	Before treatment	$\hat{Y}$ = 0.428 (Loco) + 3.945	.66	23.5	14.0			
	After treatment	$\hat{Y}$ = 0.358 (Loco) + 7.209	.26		15.6	.593	+ 1.6	+ 11
Snow accumulation								
Snow-water content (cm)	Before treatment	$\hat{Y}$ = 0.507 (Loco) + 3.88	.86*	94.3	51.7			
	After treatment	$\hat{Y}$ = 0.560 (Loco) + 1.71	.98*		54.9	.249	+ 3.2	+ 6

** Correlation coefficient significantly different from zero at the 0.05 level of probability.*

treatment years and 2.6 days earlier in posttreatment years. Maximum snowmelt runoff averaged 0.018 and 0.019 $m^3/sec/km^2$ in years before and after treatment. The minimum length of time required to accumulate half of snowmelt discharge was 14.0 days in years before treatment and 15.6 days in years after treatment. These intervals comprised 25 and 23% of the snowmelt period in pretreatment and posttreatment years. Thus, the increase in snowmelt discharge was uniformly distributed through the snowmelt period rather than appearing as additional flow during the time of maximum discharge. Average duration of snowmelt runoff was 56.2 days before treatment and 68.5 days after treatment, a 22% increase in length that was significant at a 0.19 probability level.

Sediment Transport

Coarse sediment transport from Loco Creek watershed usually exceeded transport from Sane Creek watershed (table 5). Both watersheds showed a wide range in yearly transport rates. Two occurrences of extreme snowmelt runoff on Sane Creek greatly elevated yearly sediment deposition in the stilling basin compared to deposition in the Loco Creek stilling basin. These were over-snow runoff in 1973 (Sturges 1975) and a debris flow that originated immediately above the streamgage in 1987. Coarse sediment transport values for Sane Creek in these years greatly exceeded transport measured in other years of study.

Coarse sediment transport on the two watersheds was significantly different in pretreatment and posttreatment time periods because of reduced sediment transport on Loco Creek watershed in posttreatment years compared to pretreatment years. Transport rates for Sane Creek were not significantly different in the two time periods. Loco Creek transport averaged 1.99 and 0.76 tonnes/km^2/y in pretreatment and posttreatment years, which was almost a three-fold

Table 5. — Total annual runoff and coarse filtrable sediment discharge for Loco Creek and Sane Creek watersheds.

Year	Annual runoff		Sediment discharge: Coarse		Filtrable: Snowmelt		Filtrable: Annual		Total		Filtrable discharge during snowmelt	
	Loco	Sane	Loco	Sane	Loco	Sane	Loco	Sane	Loco	Sane	Loco	Sane
	(cm)		tons/km²/y								(%)	
Before treatment												
1968	8.25	5.24										
1969	5.51	5.35										
1970	10.34	6.61										
1971	12.26	7.15	2.20	0.26								
1972	9.90	4.52	1.79	.10								
1973	13.21	8.33	2.51	1.10	NA	NA	NA	NA	NA	NA	NA	NA
1974	11.71	7.54	1.30	.16	3.86	0.15	4.03	0.29	5.33	0.45	96	51
1975	10.77	5.96	2.37	.10	NA	.17	NA	.35	NA	.45	NA	47
n	(8)		(4)									
Avg.	10.24	6.09	1.99	.37								
Treatment year												
1976	10.86	5.78	0.52	.05	3.95	.21	4.15	.37	4.67	.42	95	55
After treatment (Significant increase in water yield)												
1977	1.93[a]	2.75[a]	.13	.55	[a]	[a]	.32	.12	0.45	.67	[a]	[a]
1978	4.98	3.65	.49	.23	1.70	.06	1.89	.17	2.38	.40	90	35
1979	11.63	7.24	1.33	.19	4.21	.33	4.45	NA	5.78	NA	95	NA
1980	11.20	8.13	1.48	.07	3.70	.31	3.99	.43	5.47	.50	93	71
1981	2.16[a]	2.90[a]	.32	.00	[a]	[a]	1.15	.21	1.47	.21	[a]	[a]
1982	10.20	7.07	.98	.13	3.06	.26	3.38	.41	4.36	.54	91	64
1983	10.50	7.68	.75	.26	2.35	.34	2.71	.48	3.46	.74	87	72
1984	12.79	9.14	1.16	.13	4.13	.52	4.41	.83	5.57	.96	94	62
1985	8.90	6.65	.30	.13	1.42	.19	1.67	.30	1.97	.43	85	65
1986	7.94	4.65	.64	.16	1.43	.10	1.75	.22	2.39	.38	82	43
1987	5.62	5.87	.80	1.04	2.51	1.05	2.77	1.19	3.57	2.23	91	88
n	(10[b])		(10[b])		(8[b])		(10[b])	(9[b])	(10[b])	(9[b])	(8[b])	(7[b])
Avg.	7.94	5.99	.76	.19	2.75	.26	2.57	.35	3.33	.54	90	59
(Nonsignificant increase in water yield)												
1988	6.63	4.12	.19	.23	0.91	.08	1.16	.18	1.35	.41	79	43
1989	5.06	2.67[a]	.02	.13	NA	[a]	NA	.12	NA	.12	NA	[a]
1990	3.37	2.18[a]	.22	.03	NA	NA	NA	NA	NA	NA	NA	NA
n	(3)		(3)		(1)	(1)	(1)	(2)	(1)	(2)	1	1
Avg.	5.72	3.90	.13	.04	.91	.08	1.166	.15	1.35	.27	79	43
All years of study												
n	(23)		(19)		(12)	(14)	(14)	(15)	(14)	(15)	(12)	(12)
Avg.	8.51	5.62	.91	.24	2.77	.50	2.70	.38	3.44	.59	90	58

[a] *No snowmelt runoff during year*
[b] *1987 data omitted from average*
NA = Not available

reduction. Transport rates for Sane Creek were lower than those for Loco Creek, averaging 0.37 and 0.19 tonnes/km²/y in years before and after treatment.

Characteristics of sediment taken from the Loco Creek stilling pond in 1976 and 1978 (table 6) were similar although the flow regime in years preceding sampling was quite different. Water yields in 1975 and 1976 were above average whereas water yields in 1977 and 1978 were well below average. Sediment contained less than 5% organic matter. Less than 1%

Table 6. — Selected physical characteristics of coarse sediment deposited in the Loco Creek stilling basin.

Distance from cutoff wall	Sample depth	Year	Bulk density	Ignition weight loss	Rock (2 mm)	Inorganic composition[a]			Texture
						Sand	Silt	Clay	
— m —	— cm —		— g/cm³ —			%			
1.2	2.5–10.2	1976	0.90	5.8	0	62	37	1	Sandy loam
		1978	1.10	2.5	0	76	22	2	Sandy loam
	15.2–22.9	1976	.88	5.9	0	63	35	2	Sandy loam
		1978	1.47	1.3	0	88	10	2	Sandy loam
3.7	2.5–10.2	1976	1.14	3.4	0	69	30	1	Sandy loam
		1978	.95	3.8	0	69	30	1	Sandy loam
	15.2–22.9	1976	1.11	3.4	0	68	31	1	Sandy loam
		1978	1.29	2.6	0	77	22	1	Loamy sand
6.1	2.5–10.2	1976	1.12	3.2	1	76	23	1	Loamy sand
		1978	1.13	2.9	2	79	19	2	Loamy sand
	15.2–22.9	1976	1.06	4.0	1	70	28	2	Loamy sand
		1978	1.35	2.1	0	84	14	2	Loamy sand
Avg.			1.13	3.4	0	73	25	2	

[a] *After ignition and rock removal*

of inorganic matter was composed of rocks greater than 2 mm in diameter. Sand and silt particles composed about 98% of inorganic matter and the sand fraction was more than twice as large as the silt fraction. Clay-sized materials apparently remained in suspension and were carried from the pond with water flowing over the V-notch; virtually no clay was detected in pond sediment.

Filtrable sediment data collected during the study indicate that transport from Loco Creek watershed exceeded transport from Sane Creek watershed before and after Sane Creek watershed was sprayed. Pretreatment data were limited so that a statistical analysis of treatment effect could not be performed. Average filtrable discharge from Loco and Sane Creek watersheds was 2.70 and 0.38 tonnes/km^2/y, based on all years of record (table 5). Transport of filtrable sediment was concentrated during the snowmelt runoff interval. Nearly 60% of annual filtrable sediment transport was yielded during snowmelt for Sane Creek watershed and 90% for Loco Creek watershed.

Snow Accumulation

Control of sagebrush on Sane Creek watershed did not affect snow deposition in topographic catchments. Snow water content of index snow courses was 51.7 cm before treatment and 54.9 cm after treatment (table 4). The lack of significant change is unsurprising. Winds are so strong and persistent at the study site that a major change in effective height of vegetation would have been necessary to change snow retention characteristics.

DISCUSSION

Water Yield

The 1.08-cm increase in water yield on Sane Creek watershed was less than half of the potential 2.4-cm water yield increase implied by the results of a soil water plot study conducted at the Stratton study area (Sturges 1993). The study extended over a 22-year period and results provide a basis for interpreting how control of sagebrush affected vegetation and hydrologic processes on Sane Creek watershed. The plot study was located in a moderate snow depositional area with well developed soils that were rewet each year to at least a 2-m depth. Soil water use patterns in the surface 0.9 m of soil were similar for treated and untreated sagebrush stands, but substantially less water was withdrawn by grass-dominated vegetation from soil at depths of 0.9 to 1.8 m. Seasonal differences in withdrawal averaged 2.4 cm in the 20 years following sagebrush control. Similar changes in water use patterns were observed by Tabler (1968) in a study that also measured soil water content to a 1.8-m depth. Sagebrush roots extended through the soil water measurement zone (Tabler 1964), and sufficient precipitation was received to recharge soil water.

Results from the plot study probably represent the maximum reduction in seasonal water use that can occur following sagebrush control. Because windward slopes within Sane Creek watershed retained little snow and soils were shallow, these portions of the watershed did not contribute to the increase in streamflow. Other segments of the watershed contributed marginally to the flow increase. Thus, the average increase of 1.08 cm in water yield for the entire watershed is consistent with changes in soil water depletion observed in the plot study.

The 11-year period of increased water yield for Sane Creek was considerably less than the potential duration of a treatment effect based on results of the plot study. The deterioration in treatment effect is particularly evident in streamflow data for 1977 and 1990, the first and fourteenth year after spraying (fig. 3). Winter precipitation was low in both years and snow accumulation was insufficient to generate snowmelt discharge. However, the increase in water yield in 1977 was the second largest in the 11-year posttreatment period even though annual runoff on Loco and Sane Creek watersheds was extremely low. In contrast, Sane Creek discharge in 1990 was about that predicted to occur before treatment. Data for 1981 and 1989 provide similar comparisons because of low winter snowfall and a lack of snowmelt runoff. The increase in flow in 1981 was the largest of any year after spraying, and water yield 13 years after spraying in 1989 was slightly below that predicted to occur before treatment.

The change in soil water dynamics that lead to increased water yield from Sane Creek watershed is similar to the mechanism that causes water yield to increase following chaparral control in Arizona and California (Hill and Rice 1963, Hibbert 1971). Rowe and Reimann (1961) outlined three conditions that must be satisfied before chaparral to grass conversion could increase streamflow. First, soils must be deeper than 0.9 m. Second, there must be sufficient precipitation to recharge the soil mantle. Third, grass stands must remain free of weeds. Water withdrawal from the surface 0.9 m of soil is not affected by chaparral conversion, but water content of soil below 0.9 m under grass vegetation remains higher than under chaparral vegetation. Consequently, less precipitation is required to replenish soil water after conversion and the difference becomes available for streamflow.

Two-thirds of the increase in annual water yield from Sane Creek watershed was realized as snowmelt discharge and one-third as groundwater discharge. However, separation of annual discharge into snowmelt and groundwater components did not explicitly identify the time of year when groundwater discharge increased. At least a portion of the increase was realized during snowmelt because the snowmelt runoff period was lengthened ($p = 0.19$). Discharge between December and February, when flow originates entirely from groundwater depletion, was also examined. Flows during this period increased from 0.60 cm in pretreatment years to 0.71 cm after treatment ($p = 0.35$) suggesting that treatment increased groundwater discharge throughout the year, rather than only during snowmelt.

The results of this study combined with those of a watershed-based study in Colorado (Lusby 1979) represent a spectrum of hydrologic responses that can be expected following sagebrush control. The Colorado study site received about 20 cm less precipitation than the Stratton site, and bedrock was about 1 m below the soil surface. A dense stand of mountain big sagebrush was present, but only a remnant stand of herbaceous species remained in the understory. The watershed was plowed and grass was seeded. Total annual water yield was reduced 20% after grass established because of a 75% reduction in summer rainfall runoff. Sediment transport was reduced 80% in response to decreased rainfall runoff. In contrast, sagebrush was controlled with a herbicide in the Stratton study because herbaceous species were still a productive component of the vegetation stand. At Stratton, the reduction in evapotranspiration losses from sagebrush control resulted in a 20% increase in water yield. Peak snowmelt rates and course sediment transport were unaffected by treatment.

Sagebrush-dominated lands are low water producers compared to forested lands. However, the flow regime for sagebrush watersheds at the Stratton site was similar in some respects to that of Fool Creek, a 289 ha subalpine watershed. Fool Creek, located on the Fraser Experimental Forest in Colorado, is representative of subalpine forested lands in the central Rocky Mountains (Troendle and Kaufmann 1987). Average daily discharges for Fool Creek and Loco Creek are shown on figure 4. The majority of yearly discharge for both vegetation types occurred during snowmelt. Snowmelt occurred about a month earlier in the sagebrush zone. Annual water yield from the forested watershed equaled about 50% of precipitation and about 16% of precipitation from the sagebrush watershed.

Vegetation management on forest and rangelands has been proposed to increase water supplies in the West. Hibbert (1979) provided estimates of potential increases in water yield for major vegetation types in the Colorado River basin. Increases from sagebrush lands were believed to be restricted to higher elevation land inhabited by mountain big sagebrush. Con-

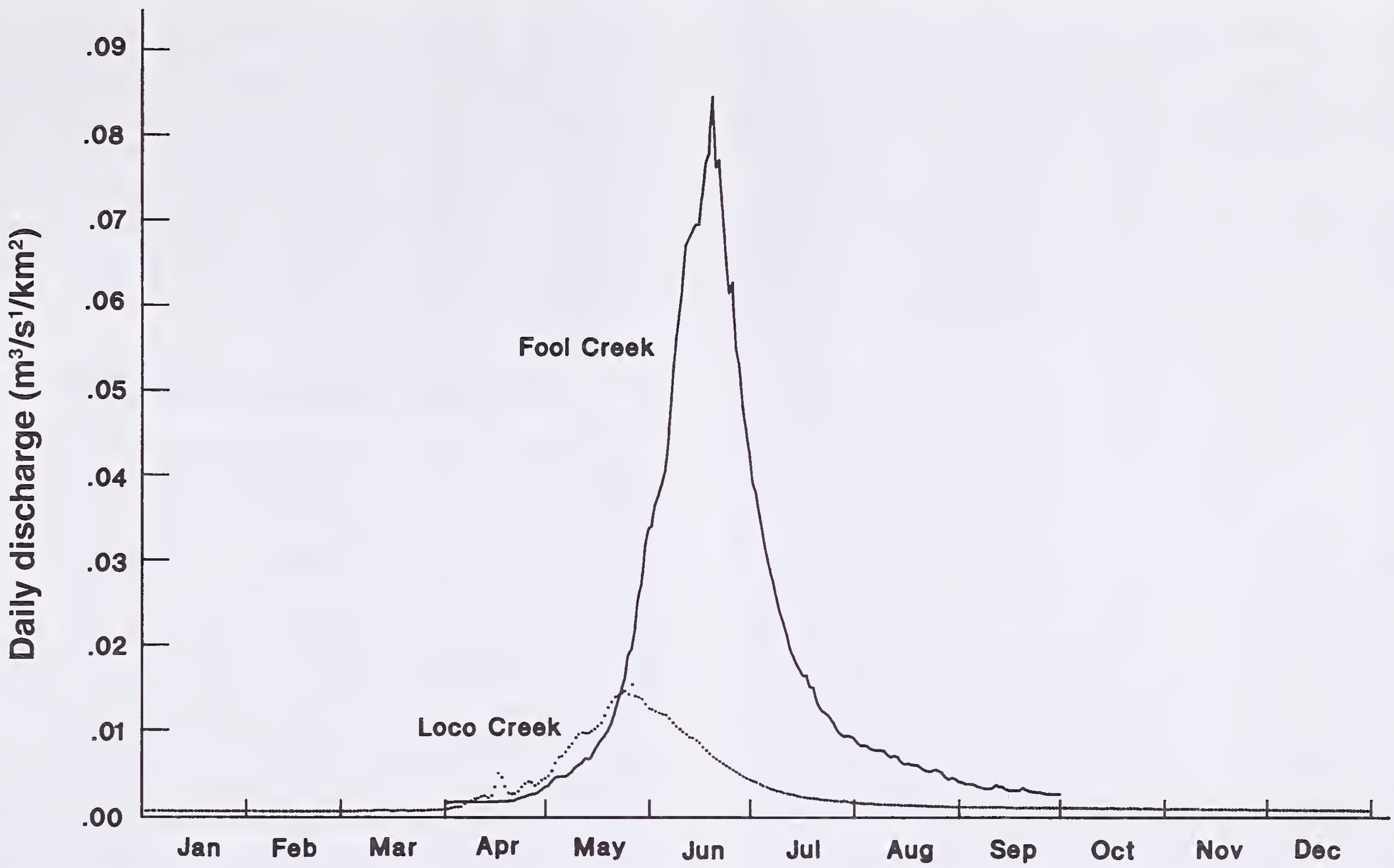

Figure 4. — Comparison of the flow regime for the sagebrush-covered Loco Creek watershed with Fool Creek, a subalpine forested watershed located on the Fraser Experimental Forest in Colorado. Snowmelt discharge on Loco Creek watershed was defined to start when average daily flow exceeded 0.001 $m^3/sec/km^2$ and to end when daily flow fell below 0.002 $m^3/sec/km^2$.

version of sagebrush to herbaceous vegetation in this situation was estimated to yield no more than 1.25 cm of additional water. Rechard (1973) presented three watershed management techniques for water supply development in Wyoming. Sagebrush conversion was included on the basis of published soil water studies showing that evapotranspirational losses were reduced after conversion, which might be realized as increased streamflow.

Sediment Movement

Coarse sediment movement was very low on both Loco and Sane Creek watersheds before Sane Creek was sprayed and further decreased after treatment. The effects of sagebrush control, however, cannot be isolated from the effects of reduced runoff and a reduction in grazing pressure in later years of the study. The latter two factors probably contributed to the reduction in sediment transport. Water yield from Loco Creek watershed was about 20% less in the 11-year posttreatment period compared to the pretreatment period, and coarse sediment transport was about 60% less. Sane Creek flows were about the same in pretreatment and posttreatment periods because increased water yield compensated for reduced precipitation. Coarse sediment transport from Sane Creek watershed in the posttreatment period was about half as large as in the pretreatment period. Changes in ground cover on Sane Creek watershed in the 5 years after spraying did favor greater soil stability. Hydrologic cover values significantly increased and there was a significant decrease in bare ground (Sturges 1986). Hydrologic cover (ground cover provided by vegetation and litter) is an indicator of the potential for surface runoff.

Control of sagebrush and planting of beardless wheatgrass had a major effect on sediment transport from two small (2–4 ha) watersheds in Colorado (Lusby 1979). Sediment transport was reduced about 80% after the grass stand established, primarily because of decreased rainfall runoff in summer months. Sediment transport in the Colorado study was determined from annual measurements of sediment accumulation in detention reservoirs and was expressed in volume units rather than in weight units. Assuming that reservoir sediments had a bulk density of 1.2 g/cm^3, sediment transport averaged about 620 $tonnes/km^2/y$.

Quantitative information on sediment transport from rangeland watersheds is limited, but rates at the Stratton study site apparently represent minimal levels for the sagebrush type. Total sediment discharge from Loco and Sane Creek watersheds averaged 3.44 and 0.59 tonnes/km^2/y, based on about 15 years of record (table 5). Sagebrush-covered watersheds within the Reynolds Creek Experimental area in southwest Idaho (Johnson and Smith 1978) had much higher sediment transport rates than Stratton watersheds. At Reynolds Creek, sediment transport from a large watershed (54.5 km^2) averaged 2,600 tonnes/km^2/y. Sediment yield averaged 95 tonnes/km^2/y from a steep, 83-ha watershed where annual precipitation was about 25 cm and most runoff was generated by intense thunderstorms. A watershed 40 ha in size receiving about 40 cm of precipitation annually had a sediment yield of about 30 tonnes/km^2/y as did a 26-ha watershed receiving 100 cm of precipitation. Runoff from both of these watersheds was generated by rain-on-snow events or by snowmelt.

Sediment transport from sagebrush-covered watersheds in Colorado (Lusby 1979) also greatly exceeded sediment transport at the Stratton study site.

Vegetation Characteristics

Herbaceous production by grasses and forbs tripled the first 3 years after spraying on the plot study conducted at the Stratton site (Sturges 1993). Production remained twice as large as for untreated sagebrush vegetation 10 to 17 years after spraying. On Sane Creek watershed, herbaceous production more than doubled the first 5 years after treatment and still exceeded production on the unsprayed watershed 9 and 10 years after treatment. The increase in herbaceous production was caused by grasses, because forbs are of minor importance at the Stratton site. Herbaceous production measurements on Loco and Sane Creek watersheds were not continued beyond the tenth posttreatment year because of the change in livestock class. An unknown amount of variation was introduced into watershed herbaceous production data because of yearly differences in sheep grazing patterns. However, study results are believed representative of changes in vegetation production that occur following sagebrush control because of the similarity in results of this study with those of the plot study where grazing was excluded.

Results from the watershed and plot studies do differ in the rapidity with which sagebrush established on treated areas subsequent to spraying. Sagebrush was virtually eliminated by 2,4-D application in the plot study and remained an extremely minor vegetation component in the twentieth year after spraying (Sturges 1993). Sagebrush density on Sane Creek watershed 11 years after spraying was about the same as before treatment. The rapid return was attributable to not achieving near-total control of sagebrush in the treatment year.

SUMMARY AND CONCLUSIONS

Results of the Stratton study support the belief that sagebrush conversion can increase water yield (Hibbert 1979, Rechard 1973). Annual water yield increased 20% in the 11 years after sagebrush was controlled. The increase would occur only in locations where soils exceed 0.9 m in depth and precipitation is sufficient to fully recharge soil water, and would persist only as long as sagebrush remains a minor component of vegetation. Two-thirds of the increase in streamflow came during the snowmelt period and the remaining flow increase was attributable to increased groundwater discharge that appeared to be distributed through the year. Treatment had no effect on the date of maximum snowmelt discharge or upon the maximum rate of snowmelt discharge. The snowmelt interval was lengthened 22% ($p = 0.19$). Water yield returned to a pretreatment level after 11 years when sagebrush again became an important vegetation component.

Filtrable sediment transport accounted for about 80% of total sediment discharge on Loco Creek watershed and 70% of transport on Sane Creek watershed. Coarse sediment transport decreased after treatment but this effect appeared to be in response to decreased streamflow because of lower precipitation as well as in response to control of sagebrush. Coarse sediment transport averaged 0.91 and 0.24 tonnes/km^2/y from Loco and Sane Creek watersheds, which is low in comparison to data from two other locations in the sagebrush zone. The effects of sagebrush control on filtrable sediment transport could not be assessed because of the lack of data in pretreatment years.

Vegetation responses on Sane Creek watershed were typical of those expected from sagebrush control. Total herbaceous production was not affected by spraying, but grass production more than doubled in the 5 years after spraying and remained 1.5 times greater in the ninth and tenth years. Sagebrush increased in importance in years after treatment because of an incomplete kill at the time of spraying and establishment of new plants from seed.

The results of the Stratton study combined with those of a watershed-based study in Colorado (Lusby 1979) represent a spectrum of hydrologic responses that can be expected following sagebrush control. A dense stand of mountain sagebrush was present at the Colorado study site, with only a remnent stand of herbaceous species. Consequently, the sagebrush stand was plowed and grass was seeded. Sagebrush was controlled with a herbicide in the Stratton study because herbaceous species were still a productive component of the vegetation stand. Annual water yield was reduced 20% in the Colorado study because of a 75% reduction in summer rainfall runoff and sediment transport was reduced 80%. Control of sagebrush at the Stratton site lead to a 20% increase in water yield as reduced evapotranspirational losses were translated into increased flow. Peak snowmelt runoff rates, the date of maximum snowmelt discharge, and coarse sediment transport, were unaffected by treatment. Livestock forage production was significantly increased at the Colorado and Stratton study sites. Replacement of a sagebrush-dominated vegetation system with a grass-dominated system increased litter cover and reduced the extent of bare ground at both locations both of which were desirable hydrologic changes. Thus, studies support the belief that sagebrush control can improve the hydrologic performance of treated lands.

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