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PRELIMINARY ESTIMATES OF INCREASED RUNOFF FROM ADDITIONAL HIGH ELEVATION SNOWFALL IN THE UPPER COLORADO RIVER BASIN

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Abstract. Evaluations of winter orographic cloud seeding projects often have been based on precipitation because of difficulties associated with evaluation by streamflow at many locations. But most sponsors are primarily interested in the amount of additional streamflow that might be expected from successful cloud seeding. Preliminary estimates have been made of the percentage increases in streamflow that might result from increased snow water equivalent in the Upper Colorado River Basin. This was done by fitting linear regression equations to paired streamflow and snow water equivalent observations from several mountain watersheds for which streamflow was not significantly affected by transbasin diversions or upstream regulation of flows. The regression equations were used to predict percentage seasonal and annual streamflow enhancements for a 10 pct increase in mean April 1 snow water equivalent.

Predicted seasonal streamflow increases ranged from 6 to 21 pct, with most drainages estimated to have 10 pct or more additional runoff. Possible reasons for differences in predicted streamflow are discussed. The reasons include snow water equivalent measurements that are unrepresentative of the watersheds, variations in geology and vegetation, and drainage slope and aspect which affect incoming solar radiation. It is suggested that as cloud seeding technology improves, more attention should be given to targeting areas that maximize streamflow enhancement.

1. INTRODUCTION

The drought of the past several years has produced renewed interest in winter orographic cloud seeding in the West. The most common purpose of seeding is to attempt to enhance the streamflow (runoff). While ski areas are interested in more snowfall **per se**, most weather modification sponsors want additional streamflow for purposes including electrical power generation and agricultural, municipal and industrial uses.

The percentage increase in seasonal snowpack achievable by a properly designed and conducted seeding program is still an open question. However, statistical analyses of some projects have suggested seasonal precipitation increases on the order of 10 pct (American Meteorological Society 1992). But water user groups and agencies are more interested in how much additional runoff would be produced by increasing the high elevation snowpack. This paper is a limited and simplified attempt to estimate runoff increases that might be expected from seasonal snowpack enhancement in the Upper Colorado River Basin.

The volume of runoff following the annual mountain snowpack accumulation and depletion cycle is primarily related to the total water equivalent of the season's snowpack. However, other important factors include:

- infiltration characteristics of the soil and underlying bedrock,
- antecedent soil water,
- slope and aspect of the watershed,
- amount, distribution and types of vegetative cover,
- spatial distribution of the snowpack,
- amount and timing of spring and summer rain, and
- evapotranspiration, which is related to solar radiation, wind, air temperature, humidity and vegetation.

Numerical models are evolving that handle the above noted physical factors in a realistic manner. For example, sophisticated models are currently being adapted to the Gunnison River Basin of Colorado as part of Bureau of Reclamation and Geological Survey (GS) investigations into the effects of climate change. Once these models are adequately tested and calibrated, they will offer an excellent means of exploring streamflow responses to simulated increases in snowfall. However, the modeling approach is beyond the scope of the present "first look" study.

2. OBSERVATIONS AND EVALUATION PROCEDURES

The Soil Conservation Service (SCS) operates a large network of snow courses and snow pillows throughout western mountains for the purpose of forecasting runoff. Snowpack water equivalent (SWE) observations from this network were used with GS stream gauge measurements to develop snowpack-runoff relationships for selected watersheds (drainage basins). These resulting relationships were used to estimate the percentage increase in runoff associated with a given percentage increase in SWE near the end of the accumulation season. A similar approach was used by Frank (1973) on a small experimental watershed in western Colorado.

This approach is admittedly a simplified procedure for dealing with complex and interrelated physical processes. However, reasonably long-term historic data should provide "first-approximation" estimates of the amount of additional runoff that could be expected with a given percentage increase in SWE. This estimate can be made by simply observing how runoff increased in years wetter than some baseline (e.g., mean snowpack season) during the period of record. This estimate was not made on a year-by-year basis. Rather, a linear regression equation was fitted to all the runoff-snowpack data for a given watershed, and that equation was used to predict the consequences of increased SWE.

The beginning of snowpack depletion approximately coincides with April 1 observations at many SCS snow course and snow pillow sites in the Upper Colorado River Basin (hereafter Basin). Furthermore, the effectiveness of ground-based seeding with the commonly used silver iodide (AgI) aerosol likely decreases after about April 1 because the lower atmosphere becomes too warm for nucleation with AgI. For these reasons, a hypothetical seeding project was assumed which terminated the end of each March, after having achieved a 10 pct increase in the seasonal snowpack. Percentage snowpack increases caused by seeding probably would differ from season to season. However, this simple model is adequate for the purpose of this study.

The GS Water Resources Data publications for 1990 (most recent available) were used to examine all high elevation drainages that have streamflow observations in the Basin. The stream gauge observations selected were not significantly affected by upstream transmountain or transbasin diversions, and were not regulated by upstream reservoirs. Drainages with less than 15 yr of record were also eliminated from further consideration. Observations had to be rated by the GS as "good" or "fair," although a few sites were accepted with "poor" stream gauge ratings during the low runoff winter months. Only 15 gauged drainages in the Basin met the stated criteria.

The resulting stream gauge locations were superimposed on SCS snow course and snow pillow location maps. Snow courses or pillows were identified to compare with each stream gauge using the criteria that each snow measuring site had to:

- be at a higher elevation than the stream gauge;
- be located within the gauged drainage or an adjoining drainage,
- have at least 15 yr of record coinciding with the stream gauge record; and
- have above zero SWE values on April 1 for each year of record.

Fourteen basins–7 in Colorado, 5 in Utah, and 2 in Wyoming–met all the above criteria. Areas of gauged drainage basins ranged from 8 to 132 mi^2. These small drainages were all above 7000 ft elevation because lower stream gauges were affected by reservoir storage, irrigation diversion, or other regulation. Records exist for many other high elevation gauges which, however, were affected by transbasin diversions.

The linear correlation coefficient (R) was calculated between April 1 SWE observations and both seasonal (April through July), and water year (October through September), total runoff volumes. Where drainages had more than one snow course available, R was calculated for each individual snow course and the means of all possible combinations of snow courses. The R-values were higher with seasonal runoff volumes than with water year volumes. These higher values might have been expected because half the water year is past when the snow course observations are made. Of course, most of each water year's runoff is concentrated in the April through July snowmelt period. Second order polynomial equations were also fitted to the data sets, but variance explained was only slightly more than explained by a first order equation (linear regression equation).

No more than four snow courses existed that met the above criteria for any individual stream gauge, and in some cases only a single snow course was available. The final choice of snow course(s) for each basin was based on a combination of attempting to maximize the variance explained (R^2) while averaging as many snow courses as possible. The combination which used the most courses was used as long as R was not reduced by more than 0.01 from that calculated between April through July runoff and some other individual snow course or combination of snow courses.

3. RESULTS AND DISCUSSION

3.1 Seasonal Runoff Relationships

Table 1 lists the individual stream gauges and associated snow courses selected for relating runoff and SWE. Drainage areas and the number of winters of record are also noted. In all cases, the last year of record was 1990, the most recent available runoff data. The linear correlation coefficient between April through July runoff and April 1 SWE is listed for each individual snow course and for mean snow course values. The highest coefficients for individual basins range between 0.70 and 0.92 with a mean value of 0.81. This range indicates that the snow course observations explained between about 50 to 85 pct of the variance in seasonal runoff.

Table 1 also shows the coefficients A and B of the linear regression equation $Y = A + BX$ where Y is the total seasonal runoff in acre-ft and X is the April 1 SWE in inches. Finally, the same coefficients are given between water year runoff and April 1 SWE. They will be discussed later.

Table 1. - Listing of stream gauges and snow courses used in this study. Drainage areas, years of data, correlation coefficients (*R*), and regression equation coefficients (streamflow = *A* + *B* x April 1 SWE) are included.

STREAM GAUGE	AREA Mi^2	SNOW COURSE	NO. OF WINTERS	APRIL THRU JULY *R*	*A*	*B*	WATER YEAR *R*	*A*	*B*
Darling Creek near Leal CO	8	Jones Pass	25	.73	-588	353	.71	318	398
		Middle Fork Cmpg.	25	.77	-269	551	.75	600	628
		Mean	25	.77	-743	452	.74	109	511
Dolores River below Rico CO	105	Lizard Head	30	.84	-2376	4671	.79	12813	4930
		Trout Lake	23	.85	5433	4869	.82	19815	5161
		Mean	23	.87	-4964	5056	.83	10120	5279
South Fork of Williams Fork near Leal CO	27	Jones Pass	25	.87	417	1040	.83	3158	1223
		Middle Fork Cmpg.	25	.87	2151	1543	.84	4832	1850
		Mean	25	.89	318	1302	.85	2878	1543
Castle Creek above Aspen CO	32	Lift	20	.76	-729	1194	.72	3691	1461
Turkey Creek near Red Cliff CO	24	Shrine Pass	27	.76	-5743	1048	.74	-4185	1114
Wearyman Creek above Aspen CO	9	Pando	26	.61	913	426	.59	1752	473
		Shrine Pass	26	.71	-891	315	.68	-230	349
		Mean	26	.70	-545	393	.67	146	435
East Fork San Juan R. above Sand Cr. near Pagosa Springs CO	64	Hiway	29	.92	-8951	2245	.88	713	2380
		Wolf Creek Pass	26	.91	-4147	1912	.86	6860	1987
		Wolf Creek Summit	30	.90	-8473	1904	.87	339	2043
		Mean	26	.92	-8771	2075	.88	1463	2176
East Fork River near Sandy WY	79	Pocket Creek	30	.82	19126	3874	.81	23568	4239
		Big Sandy Opening	30	.79	17400	3583	.77	22804	3843
		Mean	30	.82	15885	3895	.81	20604	4220
Pine Cr. above Fremont Lake WY	76	Elkhart Park	30	.86	41503	4500	.82	54066	5451
Lake Fork River above Moon Lake near Mt.Home UT	78	Lakefork # 1	26	.69	24467	3188	.66	38306	3905
		Lakefork Basin	16	.86	7278	2887	.75	22894	3261
		Mean	16	.86	11069	3324	.78	24755	3916
Yellowstone River near Altonah UT	132	Lakefork # 1	29	.74	15772	4275	.68	42732	5337
		Five Points Lake	18	.72	18244	2560	.63	34639	2934
		Mean	18	.75	15646	3565	.67	43264	4463
Whiterocks River near Whiterocks UT	113	Paradise Park	29	.56	25076	2379	.54	48042	2728
		Mosby Mtn.	30	.64	23885	2998	.61	46175	3465
		Chepeta	20	.64	14575	2986	.59	35837	3465
		Chepeta-Whiterock	19	.69	15388	2779	.66	36092	3292
		Mean	19	.74	13387	3253	.71	33977	3834
White R. below Tabbyune Creek near Soldier Summit UT	76	White River # 1	22	.85	-13660	2299	.84	-12908	2493
		Clear Creek # 2	22	.80	-16996	2411	.78	-15284	2532
		Mean	22	.84	-16742	2453	.83	-15680	2621
7 Mile Cr. near Fish Lake UT	24	Farnsworth Lake	26	.83	-7543	723	.77	-6706	887

Table 2 provides predicted percentage increases in seasonal runoff, based on the regression equations of Table 1, for an assumed 10 pct increase in the mean snowpack value for the period of record. Similar predicted percentage increases are given for the entire water year runoff. Predicted percentage runoff values could be higher or lower during dry or wet years, depending upon the individual regression equations. Values were calculated for 10 and 90 percentile snowpack amounts to approximate dry and wet winters, respectively. The majority of these values were within 1 to 2 pct of the percentage runoff values shown for the mean snowpack. For example, the predicted runoff increase for a 10 pct increase in mean SWE was 11.4 pct for Darling Creek, Colorado. The predicted runoff increases for 10 pct increases in the 10 and 90 percentile SWE values for the same drainage were 12.3 and 10.9 pct, respectively. Only the runoff values associated with mean SWE increases of 10 pct will be discussed further.

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Table 2. - List of stream gauges, elevations and estimated pct runoff increases for 10 pct increases in mean April 1 SWE.

STREAM GAUGE	GAUGE ELEVATION (FT MSL)	SNOW COURSE ELEVATION RANGE (FT MSL)	HIGHEST PT. IN DRAINAGE (FT MSL)	Pct RUNOFF INCREASE APRIL-JULY	WATER YEAR
Darling Creek - CO	9,090	9,000 - 10,400	12,500	11	10
Dolores River - CO	8,422	9,780 - 10,200	14,246	11	9
Williams Fork River - CO	8,950	9,000 - 10,400	12,500	10	9
Castle Creek - CO	9,100	11,250	14,265	10	9
Turkey Creek - CO	8,918	10,700	11,800	14	13
Wearyman Creek - CO	9,158	9,500 - 10,700	11,800	11	10
San Juan River - CO	8,900	10,320 - 11,000	13,300	12	10
East Fork River - WY	7,800	9,080 - 9,350	12,378	8	7
Pine Creek - WY	7,540	9,400	13,745	6	6
Lake Fork River - UT	8,180	10,100 - 10,900	13,219	8	7
Yellowstone River - UT	7,430	10,100 - 10,900	13,512	8	6
White Rocks River - UT	7,160	9,500 - 10,350	12,425	8	6
White River - UT	7,230	8,330 - 8,550	9,150	19	17
Seven Mile Creek - UT	9,200	9,600	11,610	21	16

Elevations above m.s.l. (mean sea level) are listed in Table 2 for each stream gauge, the associated snow course (elevation range where two or more snow courses were used), and the highest point in the drainage.

The results for April through July seasonal runoff will be examined first. Table 2 reveals that predicted runoff increases for the assumed 10 pct increase in the mean snowpack range from a low of 6 pct to a high of 21 pct. Nine of the 14 drainages indicated runoff increases of 10 pct or more, 4 drainages indicated 8 pct, and the predicted runoff for one basin was 6 pct.

3.2 Snow Course and Pillow Representativeness

Every spring and summer, certain water losses must be at least partially satisfied by the melting snowpack at the expense of seasonal runoff. These losses include infiltration into the soil and evapotranspiration into the atmosphere. Therefore, a 10 pct increase in mean snowpack might be expected to cause a greater percentage increase in streamflow. That is, the efficiency of conversion of snowpack to runoff might be expected to increase as the snowpack increased above the minimum required to satisfy infiltration, evapotranspiration, and other losses. But Table 2 indicates that only half the watersheds had a greater than 10 pct increase in seasonal runoff for a 10 pct increase in mean SWE, and 5 watersheds had a calculated runoff increase less than 10 pct.

Less than 10 pct runoff increases might well be expected from individual winters. For example, the previous fall might have had low antecedent water moisture, or the melt season might have been hot, windy, and dry. However, as noted earlier, the predicted runoff percentages are based not on individual seasons, but on regression equations fitted to populations of 16 to 30 seasons. So other physical reasons must be sought to explain the low runoff yields of some basins.

Figure 1 is a plot of observed April through July runoff at Seven Mile Creek in Utah vs observed April 1 SWE for the Farnsworth Lake snow pillow. The regression line shown predicts a 21 pct increase in runoff for a 10 pct increase in mean snowpack. Extrapolating the regression equation to zero runoff suggests that over 10 in of April 1 SWE are required to produce any runoff. The pillow is only 400 ft higher than the stream gauge, so its snowpack measurement should be representative of the lower basin. Higher elevations presumably have higher SWE. Thus, the data suggest that a

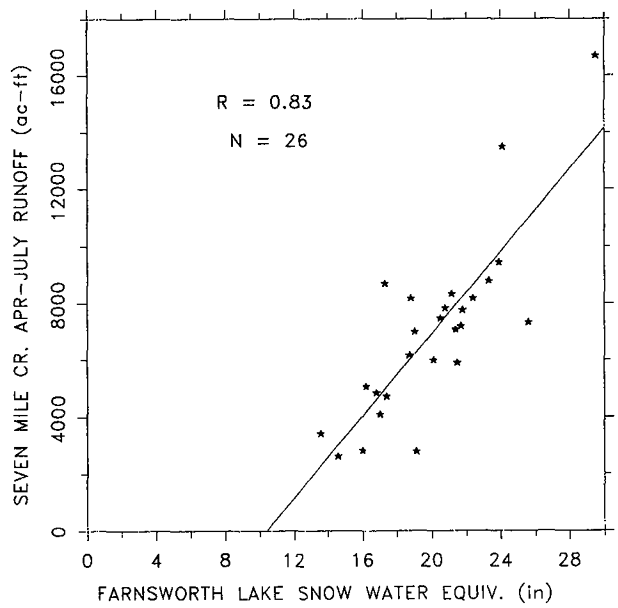

Fig. 1. April through July runoff at Seven Mile Creek UT vs April 1 snow water equivalent at the Farnsworth Lake UT snow pillow. R is the linear correlation coefficient and N is the number of data pairs.

significant amount of snowmelt is needed to satisfy losses before this drainage produces any runoff.

In contrast, Fig. 2 is a similar plot for Pine Creek in Wyoming. Extrapolation to zero SWE suggests that runoff would be over a quarter of the maximum observed during the 30 yr of record, even if the Elkhart Park snow course had no snow on April 1. This extrapolation raises the suspicion that Elkhart Park may poorly represent the basin's snow cover, even though a high degree of association exists (R=0.83), and the course is 1900 ft above the stream gauge. In fact, examination of a detailed topographical map showing the basin boundaries, and gauge and snow course locations, revealed that the large majority of the basin was much higher than the snow course. The entire basin is in a wilderness area and the snow course is just outside the basin at an elevation 4300 ft below the basin crest. Even with no April 1 snowpack at Elkhart Park, a considerable amount of snow would be expected at higher elevations. In contrast, the snow course in Fig. 1 is only 2000 ft below the highest terrain in the basin. The Fig. 1 snow course probably represents the actual snow water volume within its basin better than the Fig. 2 snow course. However, both snow courses probably have significantly less SWE than the mean values within their drainages.

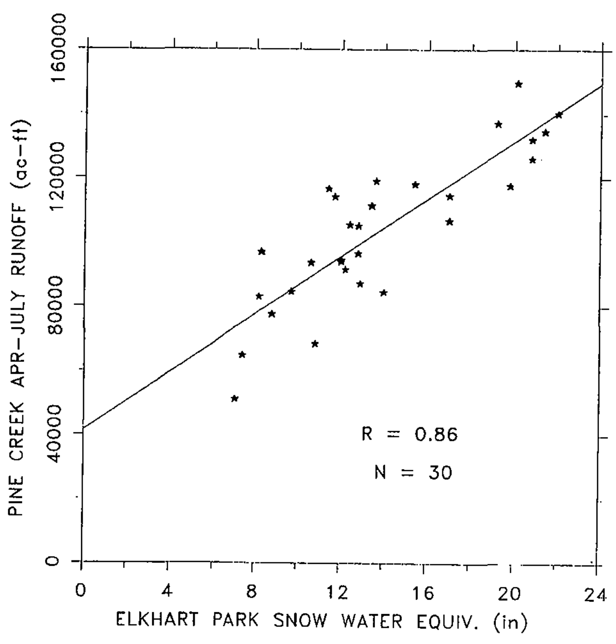

Fig. 2. Similar to Fig. 1 except April through July runoff at Pine Creek WY vs April 1 snow water equivalent at the Elkhart Park WY snow pillow.

Because of ease of access and protection from wind afforded by conifer tree cover, most snow courses tend to be located in the lower portions of mountain watersheds. No known accurate method exists to directly measure SWE at the higher elevations, usually well above treeline, where drifting and scouring of the snowpack are common. Yet the higher elevations generally receive greater precipitation amounts.

For example, Super and Reynolds (1991) indicated that almost half the variance in April 1 SWE was explained by elevation in the Sevier River Basin of central Utah, with greater SWE at higher elevations. On the other hand, the snowpack above timberline may experience considerable sublimation losses caused by strong winds and low humidity periods between storms. Losses on south-facing slopes can be especially severe because of high received amounts of solar radiation. Conversely, north-facing slopes may store deep snowpacks well into the melt season. So most snow courses probably do not represent the mean SWE within their drainage, even when their SWE measurements correlate highly with runoff. The lack of representative SWE observations is a shortcoming of the approach used herein.

Plots similar to Figs. 1 and 2, but with less extreme regression equation intercepts, were found for all other combinations of stream gauges vs snow courses. Ordinate (y-axis) intercepts were negative for all cases which had a predicted runoff more than 10 pct (Fig. 1), and positive when the predicted runoff was less than 10 pct (Fig. 2). Regression equations for the latter cases suggest that even if the snow courses had no snow on April 1, the approximate beginning of the melt season, significant runoff would still take place. Spring rains may be a significant factor in some watersheds, but much of the runoff must come from elevations higher than the snow courses, known to accumulate more snow during the winter.

To examine the suspected effect of snow course elevation further, linear regression equations were calculated between runoff and each available snow course as listed in Table 1. The higher elevation courses predicted higher percentage runoff increases in 7 of the 10 basins that had more than one snow course. The three exceptions indicated no marked elevation effect likely because they had little difference in both snow course elevations and predicted runoff.

Figure 3 presents a more typical plot for the 14 basins examined. The figure shows the April through July runoff in the east fork of the San Juan River of Colorado, measured at 8900 ft, vs mean April 1 SWE for three high elevation courses, ranging from 10,300 to 11,000 ft. The highest point in the basin is at 13,300 ft. Therefore, these courses might be representative of the basin. The degree of association was the highest of any basin with an R-value of 0.92. The regression equation predicts a 12 pct runoff increase associated with a 10 pct increase in mean April 1 SWE.

3.3 Similarities and Differences Among Drainages

All the Colorado basins had predicted seasonal runoff values between 10 to 14 pct. Two of the Utah basin runoff values were near 20 pct; both on the Wasatch Plateau of central Utah. The other three Utah basins, all with values of 8 pct, are on the Uinta Mountains. The two remaining basins, with runoff values of 6 and 8 pct, are on the Wind River Range of

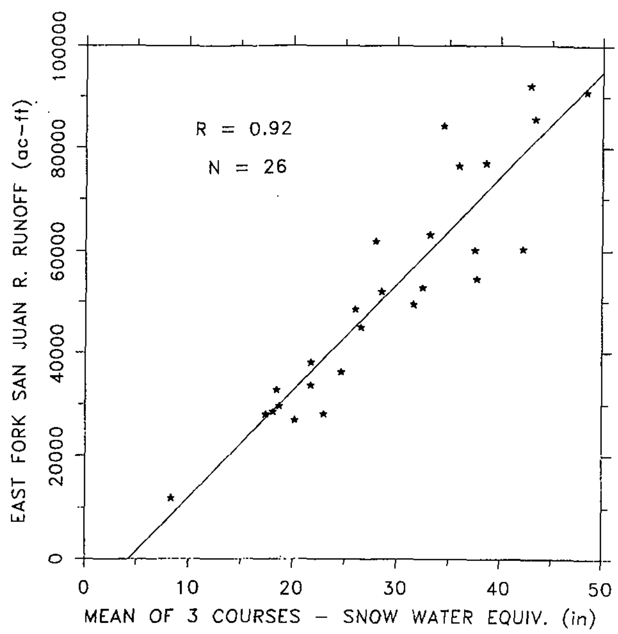

Fig. 3. Similar to Fig. 1 except April through July runoff at East Fork of the San Juan River CO vs mean April 1 snow water equivalent from three high elevation snow courses.

Wyoming. The Wyoming drainages are wholly or mostly within wilderness areas and the snow courses are at relatively low elevations outside the wilderness areas. Therefore, the SWE observations are presumed to poorly represent the Wyoming drainages.

The five watersheds in Table 2 with seasonal runoff predictions less than 10 pct all had steep slopes facing south or southwest. Such slopes would be expected to have high snowpack losses caused by sublimation, and melt water losses caused by evapotranspiration. These losses may have been partially responsible for the relatively low runoff predictions from these basins.

At least two, and possibly all three of the drainages on the Uinta Mountains have considerable limestone and numerous sinkholes in their lower portions according to a Forest Service hydrologist (Roland Leiby, personal communication). Thus, significant runoff may be diverted from the gauged drainages because of the porous geology, perhaps appearing later below the stream gauges or even in other drainages. Geology may also be an important factor in reducing the runoff in the other drainages that had predicted runoff increases less than 10 pct. Geology may also partially explain exceptionally high runoff predictions. For example, the White River, Utah drainage, predicted to have 19 pct additional seasonal runoff (Table 2), is known to have clay soils that swell when wet, making them practically impermeable to infiltration losses. While geology is known to be an important factor in evaluation of drainage runoff characteristics, further consideration of the geology of the drainages of Table 1 is beyond the scope of this study.

Another potentially important factor beyond the scope of this study is vegetation cover which can affect evapotranspiration. Further, snowfall interception by forest canopy, and subsequent sublimation of the snow, can represent a significant moisture loss. Therefore, vegetation cover differences may partially explain some of the variations in runoff response among the basins investigated.

3.4 Annual Runoff Relationships

The water year correlation coefficients of Table 1 are all less than the corresponding values for seasonal runoff. This difference might be expected because precipitation (usually rain) between August 1 and the beginning of the seasonal snowpack in early winter would contribute variance to the water year runoff in addition to that found in the April through July runoff. However, the water year correlation coefficients are not markedly lower in most cases, reflecting the fact that the seasonal runoff contributes most of the water year runoff. For example, the mean seasonal runoff values of Figs. 1, 2, and 3 represent 63, 80, and 80 pct, respectively, of the mean water year runoff values for the same gauges.

Predictions of water year runoff increases, again based on mean April 1 SWE data, are given in Table 2. Most percentage values are only 1 to 2 pct less than the seasonal runoff predictions. These values again reflect the predominance of the spring-summer runoff period in the annual flow from these mountain watersheds.

4. RUNOFF PREDICTIONS FROM ADDITIONAL WATERSHEDS

4.1 Predictions from Two Small Uinta Mountain Watersheds

After work was completed with the stream gauge observations noted in Table 1, a search was made for additional watersheds with more representative data. Two adjoining drainages on the south-facing slopes of the Unita Mountains had been used by the Forest Service to investigate timber harvesting effects on runoff. The drainages, both 12 mi^2 in area, are believed to be above most of the limestone and sinkhole geology noted in section 3.3 (Roland Leiby, personal communication). The drainages are about 10 mi northeast of the Whiterocks River gauge noted in Table 1. The stream gauges have been discontinued, but earlier observations are published by the GS as North Fork of Dry Fork (8284 ft) and East Fork of Dry Fork (8150 ft).

Pre-forest treatment (by clear cutting) stream gauge observations are available from the East Fork drainage from 1947-1958. The approach discussed in section 2 was applied to April 1 SWE data from the nearest snow course (Paradise Park, 10,100 ft), located in an adjoining drainage, to estimate runoff enhancement. The *R*-value between seasonal runoff and SWE was

0.66. A 10 pct runoff increase was predicted for a 10 pct increase in the mean SWE.

Similarly, 14 yr of pre-treatment data are available from the North Fork drainage and a snow course in the highest portion of the drainage (Ashley-Twin Lakes, 10,500 ft). These data were obtained from 1962-1985, but April 1 SWE observations were not made in several of these years. The available runoff and SWE data resulted in an *R*-value of 0.89. The predicted seasonal runoff increase was again 10 pct.

The runoff predictions from these two small, high altitude watersheds are higher than the predicted 8 pct seasonal runoff values from each of the three larger Uinta drainages of Table 1 (Lake Fork, Yellowstone, White Rocks). This finding lends support to the hypothesis that porous geology in the lower portions of the three larger drainages reduces runoff.

4.2 Predictions from Two Small Colorado Experimental Watersheds

Snow course and runoff measurements were presented by Frank (1973) for the since discontinued Black Mesa Experimental Range between Montrose and Gunnison, Colorado, at elevations near 9800 ft. Near-peak SWE data came from 5 snow courses on or very near a small (about 0.5 mi^2) experimental watershed which was gauged for runoff. The snowpack data should be quite representative of the small area. About half the area is open grassland and the rest has aspen, spruce, and fir cover. Slope is limited over the watershed.

The *R*-value exceeded 0.94 for the 13 yr of data presented by Frank (1973), higher than any of the values in Table 1. Using the procedures described above, a 20 pct increase in seasonal runoff was predicted from a 10 pct increase in mean SWE. It is suspected that the high runoff enhancement is because the Black Mesa is underlain by relatively impervious volcanic rhyolite and andesite (Paulsen 1962). While water will infiltrate the loamy surface soils, their thickness ranges from a few inches to a few feet. Once the soil is at water-holding capacity, additional snowmelt should largely result in runoff.

Different results were obtained using data from another 0.5 mi^2 Colorado watershed. Annual runoff and SWE observations were obtained for 1967-1990 from Lexen Creek in the Fraser Experimental Forest 50 miles west of Denver (Charles Troendle, personal communication). Drainage elevations range from 9850 to 11,600 ft and the watershed has not been disturbed by forest cutting or other activities. About 70 snow sampling sites around the watershed were measured on most years, but the specific sites sampled varied considerably from year to year. Snow sampling dates varied from March 20 to April 8. The highest *R*-value (0.85) was obtained with a common set of 24 snow sampling sites that were measured each of 17 yr. The approach used with all previous watersheds resulted in a prediction of 8 pct more annual runoff for a 10 pct increase in mean SWE. This increase is lower than any of the Colorado watersheds previously discussed.

A description of the watershed's geology is presented by Alexander et al. (1985). It shows that Lexen Creek flows down a narrow, steep-sided valley filled with alluvium and glacial outwash. The material is very permeable. It appears probable that a large fraction of the snowmelt moves as groundwater below the stream gauge. The presumed groundwater flow could eventually add to the runoff further downstream, but obviously not at the stream gauge used for Lexen Creek.

5. SUMMARY

This study estimated the percentage increases in runoff that might be expected from 10 pct snowpack increases in unregulated mountain watersheds in the Upper Colorado River Basin. April 1 SWE data collected by the SCS were used together with GS stream gauge observations to develop snowpack-runoff relationships for 16 individual drainages. Observations from two small experimental watersheds were also used to develop linear regression equations between streamflow and near-maximum SWE. These relationships were used to estimate the percentage increase in runoff predicted for a 10 pct increase in snow accumulation during a mean season.

This approach suggested that April through July total runoff would increase at least 10 pct in most watersheds for a 10 pct increase in the mean snowpack. However, some basins indicated increases of only 6-8 pct. Closer examination suggested that snow courses in or near some watersheds, though well correlated with runoff, poorly represented actual snowpack conditions throughout the watershed. These snow courses tended to be low elevation courses for which the calculated linear regression equations predicted substantial flow even with zero SWE on April 1. In general, the higher the snow course elevation, the greater was the prediction of percentage increase in runoff.

About 20 pct runoff enhancements were predicted for 2 of the basins in Table 2 and for 1 small experimental watershed with representative SWE observations and limited slope. Two of these 3 basins are known to have relatively impervious base material. Only 8 pct runoff enhancement was predicted for a second small experimental watershed with very permeable base material. It seems probable that subsurface flow reduced the measured runoff in that drainage.

Other important factors believed to influence the snowpack-runoff relationships are those that cause variability in sublimation and evapotranspiration losses (slope, aspect, vegetation). All five drainages listed in Tables 1 and 2 with predicted runoff increases less that 10 pct had steep south-facing or southwest-facing slopes which would maximize such losses. The geology of at least two of these drainages could reduce runoff.

A given percentage snowpack increase at higher elevations probably will result in a larger runoff increment than the same percentage increase in the lower elevation snowpack of the basin. The evidence in this paper supports that concept, and higher elevations usually have greater SWE, which suggests that cloud seeding projects should emphasize targeting of the higher elevations in mountain watersheds. However, slopes exposed to strong solar radiation and/or sustained winds may lose much of their snowfall. As the technology of winter weather modification improves, more attention should be given to targeting areas which maximize runoff.

The conversion of snowpack to runoff is a complex, nonlinear process. Observations from well-instrumented watersheds, coupled with physically-based numerical models, could be used to provide accurate and reliable estimates of runoff responses to enhanced snowpack. In the meantime, the estimates made by this simpler approach are probably reasonable, conservative first approximations. These estimates indicate that in most mountain locations in the Upper Colorado River Basin, a 10 pct increase in SWE should result in at least a 10 pct increase in spring and summer runoff. Runoff increases up to 20 pct may be expected from some drainages. Conversely, drainages with high evapotranspiration losses or very permeable soils may produce less than 10 pct runoff increases.

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