

AN UPDATE ON A WINTER CLOUD SEEDING PROGRAM IN UTAH

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Abstract: A winter orographic cloud seeding program has been conducted over the higher elevation areas of central and southern Utah for 19 winter seasons. The primary seeding mode has been ground-based, manually operated silver iodide generators located in valley and foothill locations upwind of the intended higher elevation target areas. The goal of this program is to augment naturally occurring snowfall in these higher elevation areas. Resulting augmented spring and summer streamflow is utilized for irrigation.

A target/control evaluation of this program indicates approximately an average 14.6 percent increase in precipitation in the target area over that predicted from the control area precipitation. A Monte Carlo test consisting of 1,000 random draws indicates these results are significant at the 5% confidence level.

1. INTRODUCTION

Previous papers have described the winter cloud seeding program being conducted in Utah (Thompson and Griffith, 1981) (Griffith, et. al, 1991). This paper provides an update on this long term winter cloud seeding program conducted in the central and southern mountainous areas of Utah. Figure 1 provides a map of the intended target. This cloud seeding program has been conducted in portions of Utah every winter season since the 1973-74 season, except for 1983-84 when natural precipitation was abundant over all of the State and the various clients did not request a seeding program. The goal of this program has been to augment naturally occurring snowpack in the higher elevation regions. The augmented snowpack is intended to increase surface streamflow used for irrigation. This program was initiated at the county level for the first two years that cloud seeding was conducted. Since that time, it has been administered by a non-profit organization known as the Utah Water Resources Development Corporation. The State of Utah, through the Division of Water Resources, has provided financial cost sharing assistance to the participating counties since the 1975-76 winter season. County participation in the cloud seeding program has been determined each fall through either the County Boards of Supervisors or County Water Conservancy Districts. TRC North American Weather Consultants (TRC NAWC) has been

the contractor selected to conduct this program by the Utah Water Resources Development Corporation each winter of operation. The referenced papers provide additional detail on the background and design of the program.

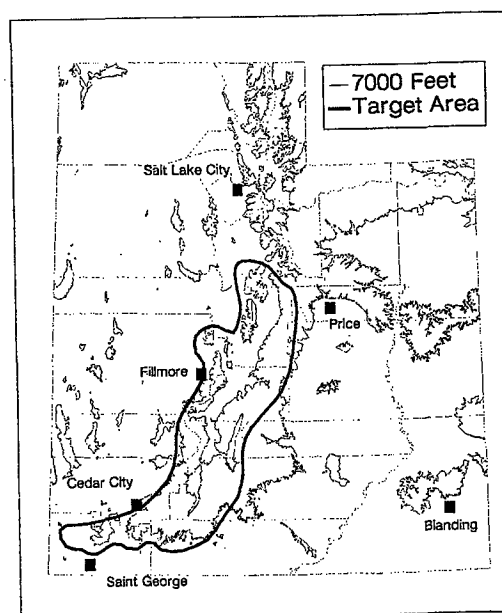


Figure 1: Central and Southern Utah Target Area

2. EVALUATION OF SEEDING EFFECTIVENESS

Evaluating the results of an operational cloud seeding program are unfortunately rather difficult (WMO Statement on Weather Modification, 1993). The seemingly simple problem of determining the effects of cloud seeding has received considerable attention over the years. The primary reason for the difficulty stems from the large natural variability in the amounts of precipitation that occur in a given area. Since cloud seeding is only feasible when there are clouds and usually only when there are clouds that are near to or are already producing precipitation naturally, the question then becomes, "Did the seeding increase (or decrease) the precipitation that was observed, and if so, by how much"? The ability to detect a seeding effect becomes a function of the size of the seeding increase compared to the natural variability in the precipitation pattern. Larger seeding effects can be detected more easily and with a smaller number of seeded cases than are required to detect small increases.

Historically, the most significant seeding results have been observed in wintertime seeding programs in mountainous areas (WMO, 1993). The apparent differences due to seeding are relatively small, however, being on the order of a 5-15 percent seasonal increase. The relatively small percent increase, in part, accounts for the significant number of operational years required to establish these results (often five years or more).

In spite of the difficulties involved, techniques are available to evaluate the effects of operational seeding programs. The techniques are not as rigorous or scientifically acceptable as is the randomization technique used in research, where roughly one half the sample of storm periods is randomly not seeded. They do, however, offer the potential of at least establishing an indication of the effects of seeding on operational programs.

Probably the most commonly employed evaluation technique, and the one that TRC NAWC has utilized, is the "target" and "control" comparison. This technique is based on the selection of a variable that would be affected by seeding (such as liquid precipitation or snow). Records of the variable to be tested are acquired for an historical period of several years duration (20 or more if possible). These records are divided into those that lie within the designated target area of the project and those in a nearby control area. Ideally the control area should be selected in an area which would be unaffected by the seeding. All the historical data, e.g., precipitation, in both the target and

control areas are taken from a period that has not been subject to cloud seeding activities, since past seeding could affect the development of a relationship between the two areas. These two sets of data are analyzed mathematically to develop a regression equation which predicts the amount of target area precipitation, based on observed precipitation in the control area. This equation is then used during the seeded period to estimate what the target area precipitation should have been based on that observed in the control area. A comparison can then be made between the predicted target area precipitation and that which actually occurred. This target and control technique works well where a good historical correlation can be found between target and control area precipitation. Generally, the closer the two areas are together, the higher the correlation will be. Areas selected too close together, however, can be subject to contamination of the control area by the seeding activities. This can result in an underestimate of the seeding effect. For precipitation and snowpack assessments, correlations (r) of 0.90 or better would be considered excellent and indicate that over 80 percent (r^2) of the variance (random variability) in the historical data set would be explained by the regression equation used to predict the expected precipitation or snowpack in the seeded years.

Precipitation data have routinely been used in assessing the effectiveness of the Utah cloud seeding program. These data have been obtained from the Natural Resources Conservation Service (NRCS) and National Weather Service (NWS) gages. Utah is fortunate in that the NRCS has maintained a network of higher elevation storage precipitation gage sites. These data are especially useful for our purposes since the NRCS has typically obtained approximately monthly readings from this network. Lower elevation NWS cooperative observer gage sites have also been utilized in these evaluations.

Precipitation stations in eastern Nevada and western Utah were used as a control area in some of the earlier evaluations of this program. Some of these stations have been discontinued in recent years. As a consequence a new control area has been established. This new control area is composed of NWS and NRCS cooperative gage sites in eastern Nevada and northern Arizona. "Target" NRCS high elevation storage gages included all available sites within the higher elevation areas of the target. Figure 2 provides the locations of the control and target stations used in the current evaluation. Thirteen stations comprise the control group and 31 stations comprise the target group. Table 1 provides the name, location, and elevation of these stations.

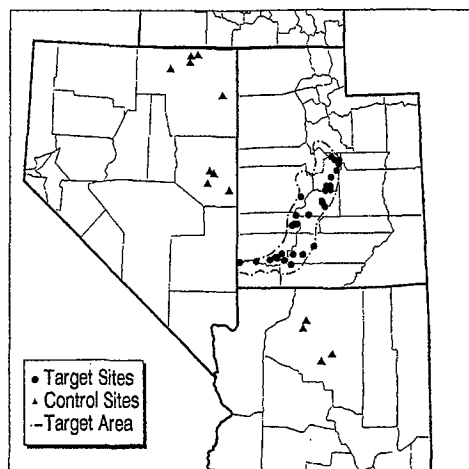


Figure 2: Location of Target and Control Sites

Data from these stations were acquired for the typical seeded period of December-March. These months were routinely seeded throughout their entirety whereas only the latter half of November and first half of April were routinely seeded. We have not made any attempt to evaluate the seeding effects in these latter time periods due to the temporal resolution of the higher elevation gages (i.e. monthly). Due to missing information, some data estimation was required at some of the stations in the early portion of the historical period.

A historical period where no cloud seeding operations were conducted in or upwind of the central and southern Utah target area was determined. This period included the water years of 1956-1973, plus 1984 (19 years). The average December-March precipitation in the "control" area was related to that in the "target" area utilizing the linear correlation technique. The control and target areas were highly correlated with an $r^2 = .933$. The linear equation relating the two areas is: $Y_c = -2.69 + 1.38x$ where Y_c is the calculated average target precipitation (inches) and x is the observed average control area precipitation (inches).

A cloud seeding program was conducted to affect the entire central and southern Utah target area for the water years of 1974-1983. No cloud seeding was conducted in the 1984 water year. A restricted program was operated in only the extreme southwestern portion of the State during the 1985-1987 water years. The entire central and southern Utah target area was again seeded in the 1988-1996 water years. Consequently, there are 19 water years in which seeding has been conducted to affect the entire central and southern Utah target area.

Table 1: Precipitation Control/Target Station Locations

Site Name	PRIMARY TARGET		
	Lat(N)	Long(W)	Elev.(Ft)
Control Sites			
Bright Angel, Az	36°13'	112°04'	8400
Grand Canyon N.P.2, Az	36°03'	112°09'	6785
Snowslide Canyon1, Az	35°21'	111°39'	9750
Wupatki, NM, Az	35°31'	111°22'	4908
Bear Creek, Nv	41°50'	115°27'	8040
Berry Creek, Nv	39°21'	114°39'	9100
Great Basin N.P., Nv	39°00'	114°13'	6830
Jacks Peak1, NV	41°32'	116°01'	8420
McGill, Nv	39°24'	114°46'	6340
Oasis, Nv	41°02'	114°30'	5830
Pole Creek RS, Nv	41°52'	115°15'	8330
Seventy-Six Ck, Nv	41°42'	115°28'	7100
Ward Mountain, No 2 Nv	39°08'	114°49'	9200
Target Sites			
Beaver Canyon PH	38°16'	112°29'	7277
Beaver Dams	39°08'	111°33'	8000
Big Flat	38°18'	112°21'	10290
Black Fl. UM Ck.	38°41'	111°36'	9400
Box Creek	38°30'	112°02'	9300
Buck Flat	39°08'	111°27'	9800
Dills Camp	39°02'	111°28'	9200
Electric Lake UP&L	39°36'	111°13'	8380
Fairview 8N	39°45'	111°25'	6750
Farnsworth Lake	38°46'	111°40'	9600
Gooseberry R.S.	38°48'	111°41'	7920
Kimberly Mine	38°29'	112°23'	9300
Mammoth-Cottonwood	39°41'	111°19'	8800
Merchant Valley	38°18'	112°26'	8750
Pickle Keg Spring	39°02'	111°35'	9600
Pine Creek	38°53'	112°15'	8800
Red Pine Ridge	39°27'	111°16'	9200
Scofield-Skyland Mine	39°41'	111°12'	8710
Seelye Ck. R.S.	39°19'	111°26'	10000
Alton	37°26'	112°29'	7040
Blowhard Mtn. Radar	37°35'	112°51'	10694
Bryce Can. NP Hdq.	37°39'	112°10'	7915
Castle Valley	37°40'	112°44'	9580
Duck Creek Village	37°31'	112°40'	8400
Hatch	37°39'	112°26'	6910
Kolob	37°32'	113°03'	9250
Little Grassy Ck.	37°29'	113°51'	6100
Long Flat	37°30'	113°25'	8000
Midway Valley	37°34'	112°50'	9800
Webster Flat	37°35'	112°54'	9200
Widtsoe-Esc. No. 3	37°50'	111°53'	9500

The linear equation developed in the not seeded historical period was utilized to predict the target area average precipitation for each of the 19 seeded seasons. The values of the average observed control area precipitation (XOBS), the average observed target area precipitation (YOBS), the average calculated target area precipitation (YCALL), the ratio of y observed to y calculated (ratio), are provided in Table 2. An examination of the ratios in Table 2 indicates that every seeded year had a ratio greater than 1.0. This indicates more precipitation fell in the target area than predicted by the control area precipitation. The average ratio for

Table 2: Linear Regression Information

Historical Data				
Year	XOBS	YOBS	YCALC	RATIO
1957	10.90	12.14	12.38	.98
1958	11.34	13.31	12.99	1.02
1959	7.34	8.26	7.47	1.11
1960	11.08	12.09	12.63	.96
1961	7.89	7.76	8.22	.94
1962	12.18	14.14	14.15	1.00
1963	7.86	8.35	8.18	1.02
1964	7.77	7.84	8.05	.97
1965	10.88	12.24	12.35	.99
1966	8.15	9.05	8.59	1.05
1967	11.09	11.78	12.64	.93
1968	9.90	12.36	11.00	1.12
1969	13.94	17.73	16.59	1.07
1970	9.18	9.73	10.01	.97
1971	8.33	9.03	8.83	1.02
1972	8.00	7.26	8.38	.87
1973	13.01	13.90	15.29	.91
1984	11.26	13.65	12.88	1.06
Mean Unseeded	10.00	11.15	11.15	1.00
Seeded Data				
Year	XOBS	YOBS	YCALC	RATIO
1974	9.04	10.44	9.81	1.06
1975	10.46	11.99	11.78	1.02
1976	8.25	9.46	8.72	1.08
1977	4.96	5.92	4.18	1.42
1978	14.04	19.04	16.72	1.14
1979	12.72	15.94	14.91	1.07
1980	14.38	19.52	17.19	1.14
1981	7.05	8.74	7.06	1.24
1982	12.77	15.91	14.97	1.06
1983	12.30	16.67	14.32	1.16
1988	6.74	9.28	6.64	1.40
1989	8.79	9.64	9.47	1.02
1990	7.01	8.80	7.00	1.26
1991	8.01	10.33	8.38	1.23
1992	7.04	9.82	7.05	1.39
1993	13.77	18.75	16.35	1.15
1994	6.43	8.28	6.21	1.33
1995	10.84	13.39	12.30	1.09
1996	10.07	12.14	11.24	1.08
Mean Seed	9.72	12.32	10.75	1.15
Historical Correlation Coefficient, $r = .966$, $r^2 = .933$ $Y = -2.69 + 1.38(x)$				

the 19 seeded years is 1.146 or an excess of +14.6%. The average difference between the observed and calculated target area precipitation is 1.57 inches. Figure 3 provides a plot of the ranked seed/no seed ratios for the entire data set.

A Monte Carlo test was applied to these data. For the Monte Carlo test, 19 random draws were made by a computer program from the 38 water years of the database. These were designated as "seeded" with the remaining 19 being designated "unseeded". A regression equation was computed from the December through March precipitation for the "historical" years and from this equation "Y calculated" was computed for the "seeded" years and a Y observed/calculated ratio obtained for this random selection. This process was repeated 1,000 times. A 90 percent randomization interval estimate of the ratios was used. This is the closed interval of randomly obtained ratio values (denoted by $[R_{0.05}, R_{0.95}]$ which contains the middle 90 percent of the values. The 1,000 synthetic ratios were placed in rank order and the 51st and the 950th values were taken as the limits of a 90% confidence interval for the ratios computed from the actual seeded and not-seeded years.

The null hypothesis that seeding does not change naturally occurring precipitation amounts would be rejected for a two-sided randomization test if an observed value of the ratio (R) is either less than $R_{0.05}$ or greater than $R_{0.95}$. Similarly, the null hypothesis that seeding does not increase naturally occurring precipitation amounts would be rejected for a one-sided randomization test if an observed value of R is greater than $R_{0.95}$.

When this randomization test was conducted using the precipitation data for the December through March period in each of the 38 water years, the limits of the 90 percent confidence interval were $R_{0.95}$ of 1.06 and $R_{0.05}$ of 0.95. Over the entire 1,000 random draws the ratio ranking ranged from 1.146 at the top to 0.899 at the bottom. The ratio of the 19 water years that were actually seeded was 1.146 ($R_{0.999}$ level) which ranked well above the $R_{0.95} = 1.06$ level.

From this randomization test the null hypothesis that seeding does not change naturally occurring precipitation amounts would be rejected and the randomization test strongly verifies the indications that cloud seeding has produced more precipitation in the target area during the seeded seasons.

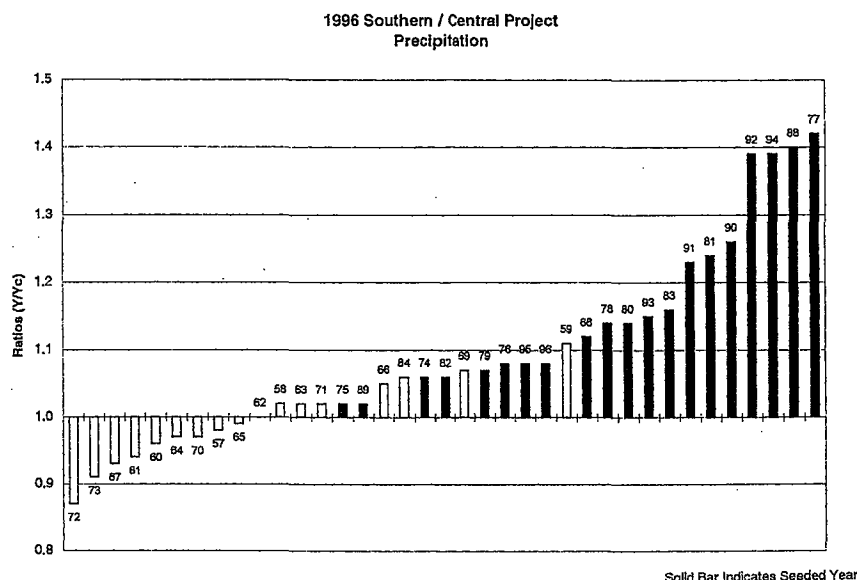


Figure 3: Photo of Ranked Ratios, Historical and Seeded Seasons

3. DISCUSSION

A target/control evaluation of a long-term winter Utah cloud seeding program has been conducted. A historical 19 year period without cloud seeding was utilized to establish a linear regression relationship between the target and control areas. When this regression equation was utilized to predict the target area precipitation during the 19 seeded seasons, an excess of +14.6 percent with an average difference of 1.57 inches was determined for the seeded period of December-March. A Monte Carlo test consisting of 1,000 random draws indicate these results are significant at greater than the 5% level. The results of this evaluation of the Utah cloud seeding program agree with frequently cited increases of 10-15 percent from properly conducted winter orographic cloud seeding programs (WMO, 1993).

In an attempt to quantify the potential significance of an average 1.57 inch seasonal increase in precipitation, a simple calculation indicates this would equal 770,346 acre feet of water if the 1.57 inches was equally distributed over the approximately 9200 square mile target area. Obviously, even if such an effect is being realized, the actual amount of surface runoff that would be generated from this area would be much lower due to evaporation, evapotranspiration, and ground-water recharge losses. If only 10 percent of the 770,346 acre feet were realized as additional surface runoff, the costs of conducting the program are such that the cost of

this additional runoff would be a few dollars per acre foot.

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