

A WINTER CLOUD SEEDING PROGRAM IN UTAH

**Don A. Griffith, John R. Thompson,
and Dan A. Risch**

**North American Weather Consultants
Salt Lake City, Utah**

Abstract: A winter orographic cloud seeding program has been conducted over the higher elevation areas of central and southern Utah for 13 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 11 percent increase in precipitation in the target area over that predicted from the control area precipitation. A similar evaluation of precipitation falling in a lower elevation region downwind of the intended target area indicates an average excess of approximately 15 percent.

1.0 INTRODUCTION

A cloud seeding program has been conducted in portions of Utah every winter season since the 1973-74 season, except for 1983-84. The goal of this program has been to augment naturally occurring snowpack in the higher elevation regions. The augmented snowpack is intended to augment surface streamflow used for irrigation. This program has been administered by a non-profit organization known as the Utah Water Resources Development Corporation. This program was initiated at the county level for the first two years that cloud seeding was conducted. 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 Board of Supervisors or County Water Conservancy Districts. North American Weather Consultants (NAWC) has been the contractor selected to conduct this program by the Utah Water Resources Development Corporation each winter of operation.

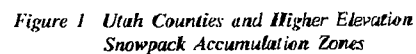
2.0 BACKGROUND

The Utah winter cloud seeding program originated in the central and southern portions of the State, partially in response to drought conditions that affected the State in the early 1970's. Several organizational meetings were conducted with county officials in the summer and fall of 1973. Methods of financing an operational cloud seeding program were discussed and a formula established which allocated the proposed contract costs to the participating counties on the basis of county assessed valuation. Seeding first began in January of 1974. The next seeding program started in December the following winter season of 1974. The normal period of operation after these first two years has been November 15 through April 15. This period was selected to concentrate on the primary period of snowpack accumulation.

The number of counties that have participated in this program has fluctuated from year to year. Typically more counties have been involved in the

Even though cloud seeding operations have been conducted in several different portions of the State, this paper will summarize operations conducted in the central and southern Utah counties. Figure 2 provides a map of this area with the highest elevation snowpack accumulation zones delineated by shading. The locations of the ground generators utilized to seed for this area for the 1989-90 program are also provided on Figure 2 for reference.

The design of the Utah seeding program has been based upon the results of previously conducted research programs. Three general hypotheses can be stated concerning this program which are as follows:



Participants - Winter Cloud Seeding Program

NOTE: Normal Operational Periods - November 15-April 15

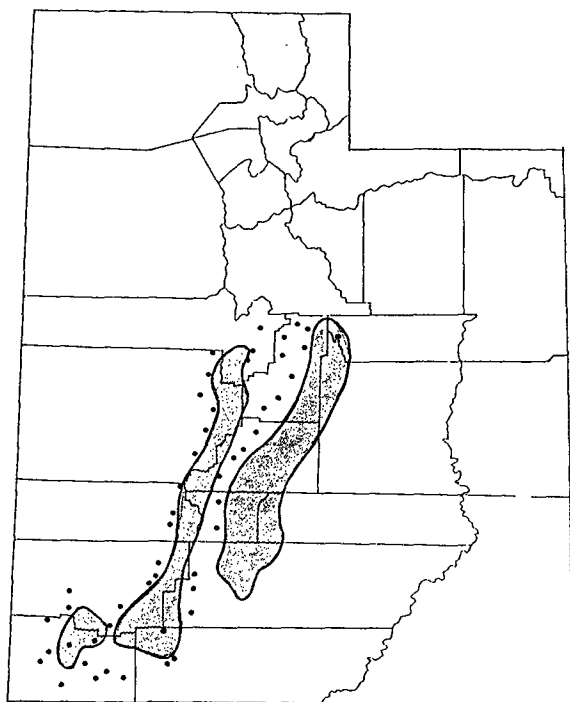


Figure 2 Central and Southern Utah Cloud Seeding Areas with 1989-90 Generator Locations.

- o Sufficient supercooled water is present in storms over Utah to permit seeding material to nucleate and grow additional precipitation.
- o Seeding material released from ground generators can reach seedable locations in sufficiently dilute but wide-spread concentrations to affect a significant portion of a storm.
- o Growth times and trajectories of natural and augmented precipitation are appropriate to intercept the intended target area.

NAWC personnel, along with a number of other groups, developed an effective means of generating minute crystalline particles of silver iodide in the early 1950's. Such particles had been demonstrated to be effective ice nuclei in research conducted in the late 1940's. The basic "generator" consists of a stainless steel tank that contains a solution of silver iodide dissolved in acetone, using ammonium iodide as a solubilizing agent, with a 2 percent by weight concentration of silver iodide.

This solution is pressurized by a propane tank that forces the silver iodide - acetone-ammonium iodide solution through a spray nozzle. The generator is also vented through the spray nozzle. The propane is lit by a local operator. This operator also adjusts the flow of seeding solution into the propane flame.

Silver iodide particles produced by this generator have been tested at the Colorado State University Cloud Simulation Laboratory (Finnegan, 1982). Garvey, 1975 provides a discussion of the procedures used in testing silver iodide generators at this facility. Figure 3 provides an effectiveness plot for this generator. Numbers of ice crystals produced in an isothermal and water saturated cloud through combustion of one gram of silver iodide as a function of cloud temperature are plotted in this figure for a cloud liquid water content of 0.5gm^3 . This generator is typically operated to dispense 6 g per hour of silver iodide when burning .1 gallon per hour of seeding solution with 0.5 gallon per hour of propane consumption.

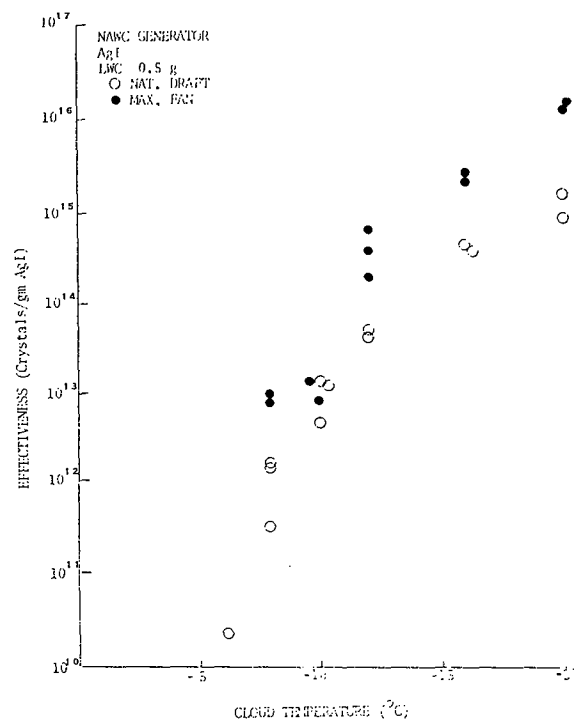


Figure 3 CSU Effectiveness Plots for NAWC Silver Iodide Generator

A network of these manually operated generators has been utilized in the Utah cloud seeding program. Generators have typically been located upwind (west) of the major mountain barriers which comprise the target area. Local residents are trained in the operation of the generators and turn them on or off as instructed by the project meteorologists. Generator sites have normally been at lower elevation valley or foothill locations. The number of generators installed are a function of the size of the target area(s). Typically 50-60 ground generators have been utilized each season in the central and southern Utah seeding program.

Up to four higher elevation, remotely controlled silver iodide-acetone ground generators were utilized in the program in the early 1980's. Aircraft seeding, using up to four aircraft, was utilized in the late 1970's and early 1980's. These seeding modes were utilized in recognition that certain "seedable" storm periods were probably unseedable using lower elevation generators due to atmospheric stability conditions. These seeding modes have not been used in more recent years due to budget constraints.

Seeding criteria have been utilized in the conduct of the Utah cloud seeding program. These criteria were adopted from the analysis by Vardiman and Moore (1978) and that of Shaffer (1983). These criteria are summarized in Table 2.

Table 2
Utah Seeding Criteria

-
- | | |
|---|--|
| o | Cloud Top Temperature $\leq -10^{\circ}\text{C} \leq -30^{\circ}\text{C}$ |
| o | No Low-level Trapping Inversions |
| o | Cloud Base Mixing Ratios $\geq 3 \text{ g Kg}^{-1}$ |
| o | Height of the -5°C Level at or Below Mountain Crest Height |
-

Analysis of data collected from past seasons of the conduct of National Oceanic and Atmospheric Research sponsored research programs in Utah in the 1983, 1985, and 1987 winter seasons have indicated that supercooled liquid water (observed by a microwave radiometer) was present 88 percent of the time when these seeding criteria were satisfied (Risch, et al., 1988).

A weather forecast laboratory, normally located in Salt Lake City, has served as the operations center for the conduct of the cloud seeding program. This laboratory has been equipped to receive standard National Weather Service observation and forecast products as well as weather satellite observations (GOES). The project meteorologists utilize this information to determine whether portions of naturally occurring storms meet the seeding criteria (Table 2) and also to determine which generators should be activated or de-activated in an attempt to target the seeding effects based upon windflow and stability considerations.

4.0 EVALUATION OF SEEDING EFFECTIVENESS

Evaluating the results of an operational cloud seeding program are unfortunately rather difficult. 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 easier 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. 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 years required to establish these results (often five years or more).

In spite of the difficulties involved, there are techniques 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 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. Any resulting difference can be tested for its significance through statistical tests. This target and control technique works well where a good correlation can be found between target and control area precipitation. Generally, the closer the two areas are together, the higher will be the correlation. 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 of 0.90 or better would be considered excellent and correlations around 0.85 would be very good. A correlation of 0.90 would indicate that over 80 percent 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. Correlations less than about 0.80 are still acceptable, but it would likely take much longer to attach any statistical significance to the apparent seeding results.

Additional mathematical tests can be made to determine how significant the excess (or deficit) is, but unless the difference is very large it usually requires several episodes (in this case, seasons) to achieve a meaningful level of significance. In the evaluations which follow two independent statistical tests were employed. One was the student's t-test (one tailed) as developed by Thom (1957) for multiple events and the other was the non-parametric Wilcoxon, Mann-Whitney ranking U-test (one tailed) as described in Siegel (1956). The application of statistical tests is actually intended to be applied to randomly collected data sets. This approach is used in weather modification research programs where the seed, no-seed decision is determined randomly. This randomization approach is typically not used on operational programs in an attempt to maximize the cloud seeding results. Dennis (1980) describes some of the difficulties of applying statistics to non-randomized operational programs. Consequently, statistical test results reported here can only be considered as an indicator of validity of the result and not absolute proof.

Precipitation data have routinely been used in assessing the effectiveness of the Utah cloud seeding program. These data have been obtained from official U.S. Soil Conservation Service (SCS) and National Weather Service (NWS) gages. Utah is fortunate in that the SCS has maintained a network of higher elevation storage precipitation gage sites. These data are rendered especially useful for our purposes since the SCS has typically obtained approximately monthly readings from this network. Lower elevation NWS cooperative observer gage sites have also been utilized in these evaluations. An earlier evaluation (Thompson and Griffith, 1981), covering seven years of seeding in central and southern Utah indicated increases in target area precipitation from 8-14 percent.

We have utilized NWS cooperative gage sites in eastern Nevada and western Utah as a "control" area since the late 1970's. "Target" SCS high elevation storage gages have included all available sites within the higher elevation areas of the target. Figure 4 provides the locations of the control and target stations used in the current evaluation. Seven stations comprise the control group and 33 stations comprise the target group. Table 3 provides the name, location, and elevation of these stations.

TABLE 3
Precipitation Control/Target Station Locations

Name	Latitude (N)	Longitude (W)	Elevation (ft)
Control (C7)			
Callao, UT	39°54'	113°43'	4330
Elko, NV	40°50'	115°47'	5075
Ely, NV	39°17'	114°51'	6257
McGill, NV	39°24'	114°46'	6340
Pioche, NV	37°56'	114°27'	6165
Ruby Lake, NV	40°12'	115°30'	6012
Wendover, UT	40°44'	114°02'	4237
Primary Target			
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
Blowhard Mtn. Radar	37°35'	112°51'	10694
*Box Creek	38°30'	112°02'	9300
*Buck Flat	39°08'	111°27'	9800
Bryce Can. NP Hdq.	37°39'	112°10'	7915
*Castle Valley	37°40'	112°44'	9580
*Clear Ck. Rdg. No. 1	39°52'	111°17'	9200
*Clear Ck. Rdg. No. 2	39°53'	111°16'	8300
Duck Creek Village	37°31'	112°40'	8400
*Ephraim-Alp. Mead.	39°18'	111°27'	10000
*Ephraim-Headquarters	39°18'	111°29'	8700
*Farnsworth Lake	38°46'	111°40'	9600
*Fish Lake	38°33'	111°43'	8700
*Gooseberry R.S.	38°48'	111°41'	8000
*Gooseberry Res.	39°41'	111°19'	8700
Hatch	37°39'	112°26'	6910
Hiawatha	39°29'	111°01'	7284
*Indian Canyon	39°54'	110°45'	9100
*Kimberly Mine	38°29'	112°23'	9300
*Little Grassy Ck.	37°29'	113°51'	6100
*Long Flat	37°30'	113°25'	8000
*Mount Baldy R.S.	39°08'	111°30'	9500
*Panguitch Lake RS	37°43'	112°38'	8200
*Picky Keg Spring	39°02'	111°35'	9600
*Pine Creek	38°53'	112°15'	8800
*Red Pine Ridge	39°27'	111°16'	9200
*Tall Poles	37°43'	112°51'	8800
*Webster Flat	37°35'	112°54'	9200
*White River No. 1	39°53'	110°59'	8550
*Wildsoe-Esc. No. 3	37°50'	111°53'	9500

*Storage Gage

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 last 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).

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, and 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 $r^2 = .865$. The linear equation relating the two areas is: $Y_c = 2.72 + 2.53x$ where Y_c is the calculated average target precipitation and x is the observed average control area precipitation.

A cloud seeding program was conducted to affect the entire central and southern Utah target area for the water years of 1974-1983. As mentioned previously, no cloud seeding was conducted in the 1984 water year. A restricted program was operated in 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 1988-1990 water years. Consequently, there are 13 water years in which seeding has been conducted to affect the central and southern Utah target area.

The linear equation developed in the not seeded historical period was utilized to predict the target area average precipitation for each of the 13 seeded seasons. These predicted precipitation amounts were divided into the observed target area precipitation amounts. The values of the average control area precipitation (x observed), the observed target area precipitation (y observed), the calculated target area precipitation (y calculated), the ratio of y observed to y calculated, the difference between y observed and calculated, and the single tailed U and t test statistics are provided in Table 4. An examination of the ratios in Table 4 indicates that every seeded year but one (1978) 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 the 13 seeded years is 1.114 or an excess of +11.4%. The average difference between the observed and

calculated target area precipitation is 1.23 inches. Probability tests yielded very low values: the one tailed and test statistic was .0012 and the one tailed u test was .0003.

In the past few years there have been questions about possible downwind effects of the Utah cloud seeding program. We have performed a separate evaluation of possible downwind effects in east central Utah. The same target/control area approach has been utilized. Figure 4 provides the locations of the NWS cooperative gages that have been used in this evaluation. Table 5 provides the names of the target and control stations. A linear regression equation was developed for the same historical period (1956-1973, and 1984 water years) for the average December-March precipitation. This equation was : $Y_c = -0.16 + .51(x)$ which had an $r^2 = .72$. This equation was used to calculate the downwind area precipitation for the 13 seeded seasons. The results are provided in Table 6.

The average observed to predicted target area ratio for the 13 seeded years was 1.152 or an indicated excess of 15.2 percent. The U test statistic was less than commonly accepted significance levels, but the t statistic would be considered statistically significant if the data had been drawn from a randomized data set.

Table 4

Results of Target/Control Evaluation -
Primary Target Area

YEAR	XOBS	YOBS	YCALC	RATIO
<u>Historical Seasons</u>				
1956	4.02	11.12	12.89	.86
1957	3.39	11.80	11.31	1.04
1958	4.15	13.13	13.23	.99
1959	2.30	8.72	8.53	1.02
1960	3.41	11.62	11.36	1.02
1961	1.82	7.53	7.33	1.00
1962	3.86	13.76	12.50	1.10
1963	2.31	8.49	8.55	.99
1964	2.11	7.86	8.07	.97
1965	3.45	11.66	11.45	1.02
1966	2.08	8.17	7.98	1.02
1967	4.52	11.79	14.15	.83
1968	3.30	11.81	11.07	1.07
1969	4.85	16.81	14.99	1.12
1970	2.56	9.53	9.19	1.04
1971	2.29	8.74	8.52	1.03
1972	2.09	6.93	8.00	.87
1973	4.06	12.85	12.98	.99
1984	3.74	12.19	12.20	1.00
<u>Seeded Seasons</u>				
1974	2.36	11.18	8.68	1.29
1975	3.39	12.51	11.29	1.11
1976	2.10	8.87	8.04	1.10
1977	1.08	5.97	5.44	1.10
1978	6.06	17.31	18.07	.96
1979	3.89	16.05	12.56	1.28
1980	5.16	18.45	15.79	1.17
1981	2.20	8.55	8.29	1.03
1982	4.12	14.54	13.14	1.11
1983	4.56	15.76	14.25	1.11
1988	2.10	9.55	8.04	1.19
1989	2.56	9.70	9.21	1.05
1990	2.38	9.14	8.74	1.05

Mean Seed 3.23 12.12 10.89 1.12
Historical Correlation Coefficient .930 $Y = 2.72 + 2.53(X)$

Standard error of the estimate for Y is .97
For the 13 seeded years, percent excess = 11.4 T = 3.53
Probability = .0012 and the Odds are 841.9:1

YOBS/YCALC Ratio for 13 Seeded Years = 1.114
U = 33.0 Z = -3.47 Probability = .0003 Right Way

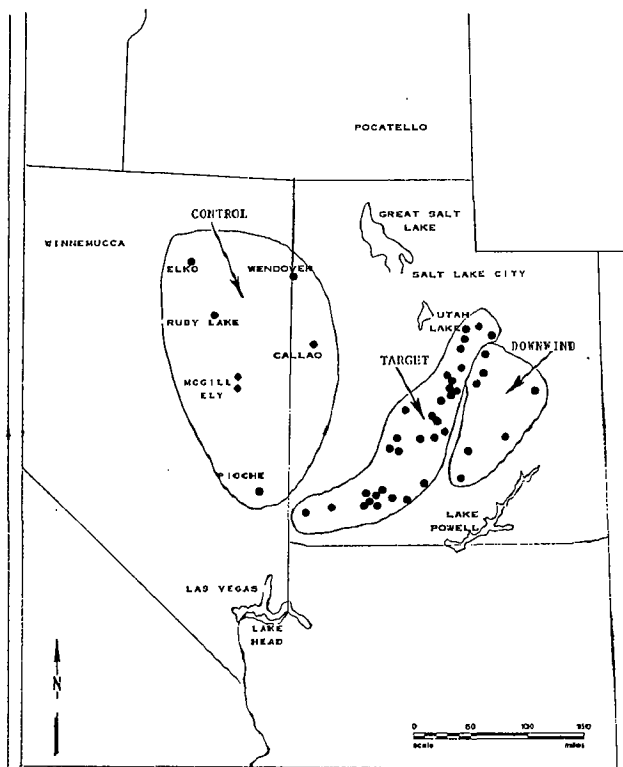


Figure 4 Control, Target, and Downwind Station Locations

Table 5

Downwind Precipitation Station Locations

Name	Latitude (N)	Longitude (W)	Elev. (Ft)
Boulder	37° 55'	111° 25'	6700
Capitol Reef NP	38° 17'	111° 16'	5500
Castle Dale	39° 12'	111° 1'	5620
Ferron	39° 5'	111° 8'	5930
Green River AVN	39° 0'	110° 10'	4070
Hanksville	38° 22'	110° 43'	4308
Hiawatha	39° 29'	111° 1'	7280

Table 6

Results of Target/Control Evaluation -
Downwind Area

YEAR	XOBS	YOBS	YCALC	RATIO
Historical Seasons				
1956	3.34	1.16	1.56	.75
1957	5.00	1.71	2.41	.71
1958	5.13	2.06	2.48	.83
1959	2.69	1.10	1.23	.90
1960	5.09	2.85	2.46	1.16
1961	2.89	1.40	1.33	1.06
1962	5.57	2.45	2.71	.91
1963	2.74	1.15	1.25	.92
1964	2.43	.93	1.09	.86
1965	5.09	2.75	2.46	1.12
1966	4.33	2.36	2.07	1.14
1967	5.13	2.17	2.48	.87
1968	5.36	3.03	2.60	1.17
1969	6.83	4.59	3.36	1.37
1970	4.18	1.35	1.99	.68
1971	2.27	1.47	1.01	1.46
1972	2.16	1.07	.95	1.12
1973	7.29	2.90	3.59	.81
1984	3.41	2.10	1.60	1.31
Seeded Seasons				
1974	2.99	1.41	1.38	1.02
1975	4.17	2.29	1.99	1.15
1976	3.82	1.22	1.81	.68
1977	1.81	.50	.77	.64
1978	8.63	4.45	4.28	1.04
1979	6.62	5.26	3.25	1.62
1980	8.84	5.56	4.39	1.27
1981	3.54	2.02	1.66	1.21
1982	5.92	2.77	2.88	.96
1983	6.79	3.51	3.34	1.05
1988	3.31	2.54	1.55	1.65
1989	3.20	2.06	1.49	1.38
1990	4.24	1.91	2.03	.94
MEAN SEED	4.91	2.73	2.37	1.12

Historical Correlation Coefficient .846
Standard Error of the estimate for Y is .51
For the 13 seeded years, percent excess = 15.2
T = 1.89
Probability = .0378 and the odds are 26.4:1
YOBS/YCALC Ratio for 13 Seeded Years = 1.152
U = 95.0 Z = -1.09 Probability = .144 Right Way

5.0 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 was utilized to predict the target area precipitation during the 13 seeded seasons an excess of +11.4 percent with an average difference of 1.23 inches was determined for the seeded period of December-March. Standard statistical tests indicate these values would be highly significant (i.e., on the order of 1 chance in 1000 that the results could be due to chance) had the data been drawn from a randomized data set. 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.

Even though the data were not drawn from a randomized data set, because of the extremely low probability values, we feel the evaluation is highly indicative of a positive cloud seeding effect. An examination of data provided in Table 4 suggests that the seasonal percentage excess is not related to the total amount of precipitation that fell in the target area. Consequently, it could be inferred that the effects of cloud seeding on a percentage basis are similar in dry, normal, and wet seasons. When comparing excess amounts of precipitation, however, larger absolute amounts result in the wetter years even though percentage increases may be similar.

In an attempt to quantify the potential significance of a 1.23 inch seasonal increase in precipitation, a simple calculation indicates this would equal 603,520 acre feet of water if the 1.23 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 evapotranspiration losses. If only 10 percent of the 603, 520 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.

The apparent effects of the Utah seeding program in a region downwind of the target area indicates precipitation increases of approximately 15 percent. This result is contrary to a commonly held concern about cloud seeding programs that they will decrease the amount of precipitation in downwind areas. This result is in agreement with an earlier National Science Foundation Study (Brown, et al., 1978) which concluded that the better quality evidence available from mostly a-posteriori analyses of past randomized seeding programs suggests that precipitation changes in extended areas tend to be of the same sign (increases or decreases) and roughly the

same magnitude as the primary target area effects and that there is currently little evidence available to support the Robbing Peter to pay Paul hypothesis that seeding to increase rain in one area will deprive some other area of its normal rainfall. However, the data base is inadequate to rule out the possibility that such a combination might occur".

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