SEVEN YEARS OF WEATHER MODIFICATION IN CENTRAL AND SOUTHERN UTAH[1]

by

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INTRODUCTION

There exists in many areas of the State of Utah a need for additional water, primarily for agricultural purposes. There has been and continues to be considerable emphasis placed on water conservation and development projects such as construction of dams and reservoirs, sprinkler irrigation systems, concrete lined canals and upgraded culinary water systems. Such projects are aimed at conserving and utilizing the natural supply of water. However, this supply of water often falls far short of the amount required to fulfill all desired needs. This is the basic reason weather modification or cloud seeding as a technology to increase precipitation was considered in the early 1950's and again in 1973 in the State of Utah.

Beginning with the winter season of 1973-74, North American Weather Consultants (NAWC) has, under permit from the Division of Water Resources, conducted an operational weather modification program designed to enhance winter snowfall in the mountainous sections of central and southern Utah. Sponsors of the program have included the Utah Water Resources Development Corporation (formerly Southern Utah Water Resources Development Corporation) and the State of Utah, Division of Water Resources. The latter has been an active participant since 1975. The Department of Interior, Water and Power Resources Service, has been indirectly involved with the program through the provision of funds for rawinsonde and radar observations to the State of Utah. Initially only ground generators were used, but beginning with the 1975-76 winter season seeding has also been conducted with the aid of aircraft (aerial seeding). Ground generator locations and aerial seeding tracks have varied throughout the duration of the project, but in general, operational efforts have been directed at the high elevation portions of the watersheds.

BACKGROUND

Whenever cloud seeding is discussed the question of evaluation always arises. Many attempts have been made to evaluate the progress of the winter snowpack augmentation project; however, because of a lack of data these evaluations were never statistically significant. The results of an operational project are much more difficult to determine than those of a research project. Operationally, the sponsor's objective is to increase the precipitation to the maximum amount possible, thus all seedable storms are treated. On the other hand, the research objective is knowledge; therefore, techniques such as randomization can be used to determine the effects.

The Utah Water Research Laboratory (UWRL) conducted an evaluation (Hill 1977) of the first two years of the seeding program (1973-74 and 1975-75 seasons) utilizing a technique based on predicting expected amounts of precipitation in the target and comparing the predicted values to amounts actually observed. The predicted precipitation amounts for the two seeded

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years were established utilizing several meteorological parameters as predictors based on the unseeded period 1966-73. Dr. Hill concluded that "any increase in precipitation from seeding has not yet been detected".

A second evaluation of the project's results was performed by NAWC following the third season of operations (Griffith et al., 1976). Both precipitation and snowpack water content were evaluated in this study. Seven target areas were identified and a series of multiple linear regression equations were developed for each of the target areas using precipitation observed in four control areas in the adjacent states of Arizona and Nevada. The control areas were selected outside of Utah in order to minimize any possibility of contamination from the seeding operations.

The NAWC three-year evaluation of the observed versus the calculated precipitation as determined from the regression equations for the period November through March generally showed either no increase or slight increases up to about ten percent above predicted. None of the seven target analyses indicated statistical significance as great as the ten percent level. This evaluation appeared to be significantly impacted by the large distances involved between the target and control areas.

Because of the general lack of convincing evidence, the Division of Water Resources contracted with the UWRL to continue the development of an evaluation method. The results of this work are expected by May 1981. NAWC, acting on its own initiative, conducted a second in-house evaluation of the Southern Winter Project. This evaluation covered five years of seeding (1974-1978). This report is published and available for public distribution.

The Utah Division of Water Resources has responsibility for reviewing documents relating to evaluation published by a contractor operating in the State of Utah under an approved permit. NAWC's report was reviewed by the State Weather Modification Technical Advisory Committee. This committee determined that the conclusion of the report appeared valid and that a thorough review of the data by the Division of Water Resources staff should be completed. This review was completed with the general conclusion reached that the weather modification program in Central and Southern Utah was producing cost effective results. NAWC has recently updated the evaluation to cover seven years of seeding on the program (1974-80) which is the primary topic of this paper.

PROGRAM DESCRIPTION

The intended target areas of the program, as defined in an earlier design study (Thompson et al., 1978), encompasses some 31,000 sq km (12,000 sq mi) of mountains in central and southern Utah. Commissioners or water conservancy districts of counties potentially involved in the program vote annually whether to participate. The DWR then shares the cost of the program. On the average, 12 counties have particpated annually since the state involvement began in 1975 (Figure 1).

Both silver iodide (AgI) ground generators and seeding aircraft were used in selected storm periods until 1979, after which only ground generators were used. Manually operated units are supplemented by remotely controlled units at higher elevations. For the current 1980-81 season, 75 manual and 4 remote generators were installed. Table 1 summarizes the operational aspects of the program since 1973. Rawinsonde data (balloon-borne instrumentation providing temperature, humidity, and upper-level wind) were collected specifically for the seeding program beginning in 1977. These data are utilized as input to making decisions on whether certain storm situations should be seeded or not.

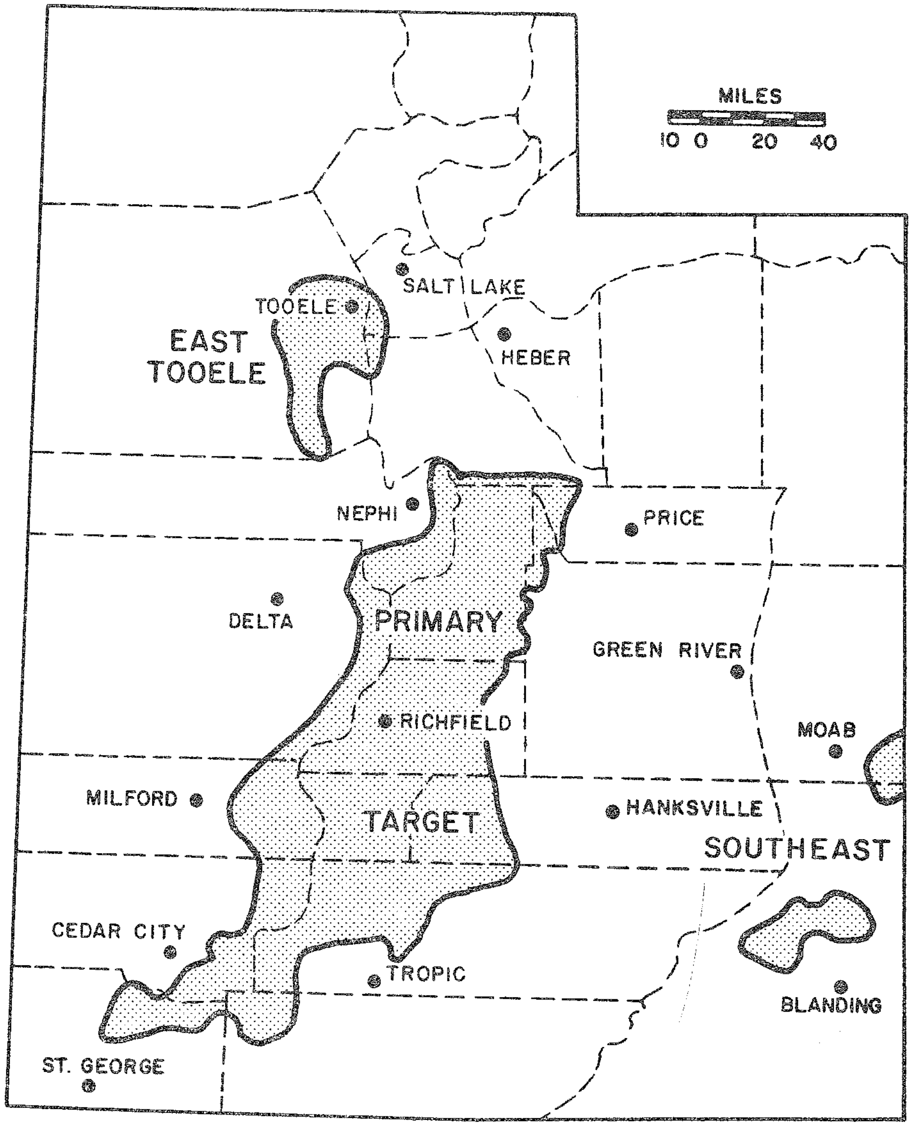

Fig. 1. County seats of Utah counties involved in weather modification program and project target areas (hatched), 1974-1980.

EVALUATION BACKGROUND

The program is strictly an operational program designed to optimize any benefits, without any randomization. Portions of naturally occurring storms deemed seedable by established seedability criteria (Thompson **et al.**, 1978) are seeded. Consequently, evaluation has relied upon comparisons of target and control precipitation.

The earlier evaluation of five years of seeding (Thompson, 1979) also was based upon comparisons of target control precipitation, but only from January to March. This was the only period consistently seeded during the five years. This five-year evaluation work was independently verified by the Division of Water Resources (Div. of Water Resources, 1981).

Thompson (1979) found that the 1974-78 January-March precipitation in the Primary Target was greater than that predicted by the regression equations. Some differences between observed and calculated values were highly significant, particularly in the southern half of the target. For

Table 1. Utah winter seeding project summary.

Season	No. of Counties	Project Period	Number of Ground Generators	Generator Hours	Days	Aircraft	Aerial Hours	Rawinsonde Sites
1973-74	12	1 Jan-31 Mar	53	7,567	29	-	-	-
1974-75	12	1 Dec-31 Mar	58	21,413	59	-	-	-
1975-76	14	15 Nov-15 Apr	75	15,445	55	1	46	-
1976-77	13	15 Nov-30 May	70					
	4	15 Jan-30 May	13					
	5	1 Mar-30 May	26					
	22		109	19,619	67	1	193	-
1977-78*	17	15 Nov-15 Apr	102	16,653	62	3	393**	Milford Roosevelt
1978-79***	13	15 Nov-15 Apr	72	5,902	24	2	149**	Blanding Beaver
1979-80***	13	15 Nov-15 Apr	72	5,368	41	-	-	Blanding Beaver Nephi Richfield

* Radar sites at Milford and Roosevelt
** Includes observation flight time
*** Early suspensions

Project control from Salt Lake City except first two years.

the total target, the indicated increase due to seeding was approximately 18 percent, highly significant at the .018 level by the Wilcoxon-Mann-Whitney rank test.

Both this evaluation and that of the DWR were reviewed by a Technical Advisory Board organized by the DWR to provide guidance and expertise. Dr. Ruben Gabriel, Univ. of Rochester statistician, reviewed the five-year evaluation as part of a National Oceanic and Atmospheric Administration (NOAA) program to design a comprehensive evaluation of both the Utah and North Dakota state/local seeding programs.

The major recommendation of both the Technical Advisory Board and Dr. Gabriel was for additional analyses using other stations as control areas, since the evaluation used control stations selected **post hoc**. The new analyses were suggested to confirm that comparable results could be achieved with different controls. In addition, Dr. Gabriel recommended elimination of four of the stations in the original ten station control due to their proximity to the target.

These recommendations have been followed; the results of the evaluation, updated to cover seven years of seeding, 1974-1980 follows.

EVALUATION APPROACH

To cover seven years of seeding the evaluation approach is the same as that of the five-year evaluation; e.g., statistical, using the correlation between a control area and a target area to determine the apparent effectiveness of seeding. Like the previous five-year evaluation, the basic data consist of January through March precipitation.

The control in the five-year evaluation consisted of ten precipitation measuring stations in west-central Utah (one station was actually just over the state line in Nevada). As suggested by Dr. Gabriel, four stations in the eastern part of the control, near the western edge of the target, were eliminated, leaving a six station control (C_1 in Fig. 2). A second control (C_2) included six precipitation stations located in Nevada, Arizona, and Utah. Few stations in eastern Nevada and northern Arizona have long-term stable records of precipitation so Lehman Cave National Monument, Nevada was included in both controls. Otherwise, C_2 stations were much farther removed from the target than C_1. Combining the average precipitation at each of the 11 individual stations of C_1 and C_2 produced yet another control (C_3) extending from eastern Nevada and western Utah to northwestern Arizona. All three of the controls were used to develop regression equations for the various targets (Table 2); ratios of observed target precipitation to calculated precipitation were determined for each target-control relationship (Table 3).

Four target areas, e.g., Central, South Central, Dixie and the east Tooele County target area (not included in the five-year evaluation), and two supplemental areas (Eastern and North Central) were used. The Eastern area is not in the intended target area, but was included to investigate potential extra area effects. The North Central area was selected to seek seeding effects in an area not expected to be directly affected by the seeding. In this manner, some assessment could be made of whether there was some bias in the seeded years favoring the likelihood of detecting a "seeding effect".

The isolated target areas in southeastern Utah were not evaluated in the five-year evaluation and have also been excluded from this evaluation due to lack of long-term precipitation stations. Precipitation gage locations are indicated in Fig. 2 by a circle and storage gage locations are shown by an "X". Most precipitation gages are in valleys at lower elevations, with storage gages at elevations above 3360 m (8000 ft MSL). Seeding in the east Tooele area did not begin until 1975-76, so the evaluation for that section is for January-March, 1976-1980.

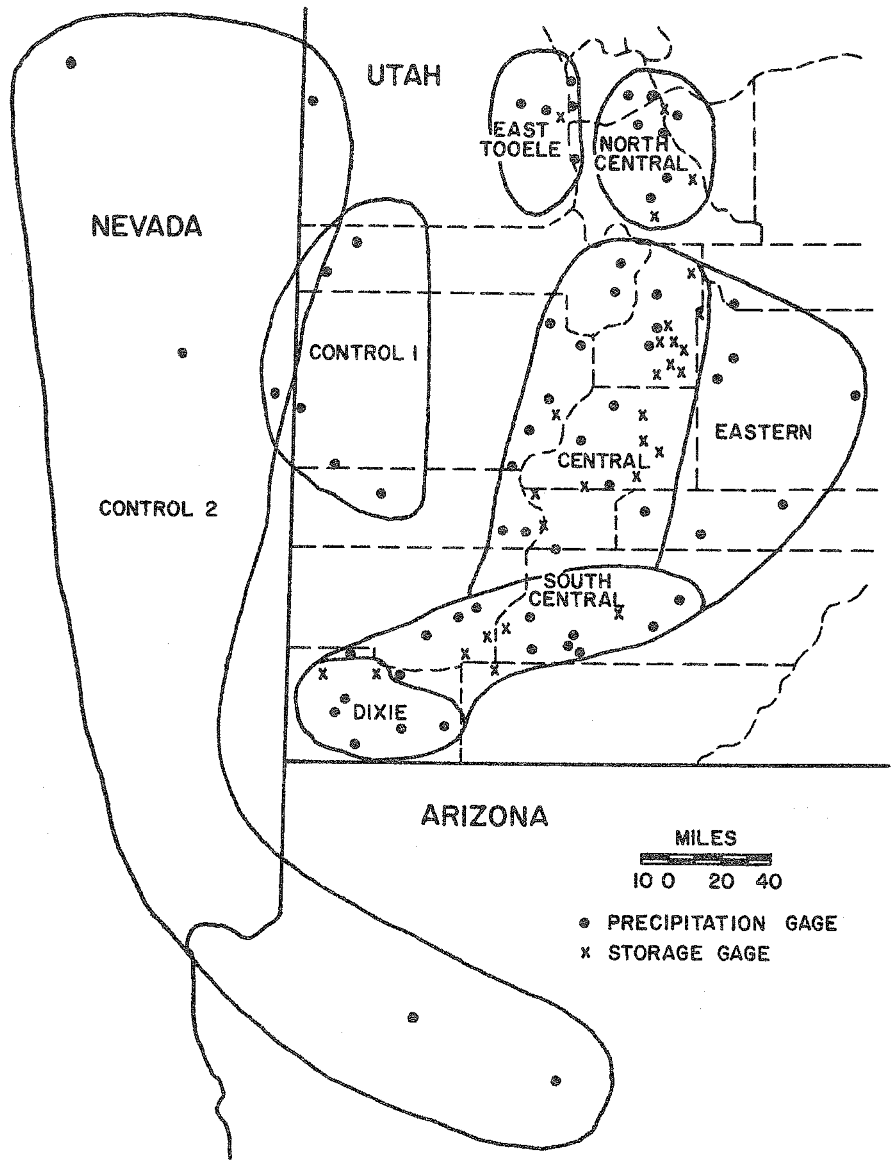

Fig. 2. Control, target, and supplemental areas.

Precipitation stations with reliable long-term records were sought in the Climatological Data for Arizona, Nevada and Utah, published by the National Climatic Center, NOAA, Storage-Gage Precipitation Data for western United States, also published by the National Climatic Center, and the Water Supply Outlook for Utah, published by the Soil Conservation Service, USDA. Except for some storage gages, data were available back to about 1950. However, another seeding project had been conducted in southern Utah from 1951 to 1955 (Hales et al, 1955). To eliminate any possible effect from that seeding these years were excluded and the historical data base was formed from January-March precipitation 1956-1973.

Data Quality

The control area stations had consistent data, although occasional monthly totals were reported as estimated. Precipitation data were available in the Central target for 17 low elevation stations and 17 storage gages at higher elevations. Less than five percent of the data were missing but,

Table 2. Linear regression equations developed for target areas.

Target Group	Linear Regression Equations		
1) Central			
Low elevation	$Yc=1.2\ C_1 + 1.19$	$Yc= .78\ C_2 + .8$	$Yc=1.08\ C_3 + .78$
High elevation	$Yc=2.56\ C_1 + 5.28$	$Yc=1.69\ C_2 + 4.41$	$Yc=2.3\ C_3 + 4.40$
Combined	$Yc=1.88\ C_1 + 3.24$	$Yc=1.24\ C_2 + 2.61$	$Yc=1.69\ C_3 + 2.59$
2) South Central			
Low elevation	$Yc=1.86\ C_1 - .02$	$Yc=1.18\ C_2 - .48$	$Yc=1.61\ C_3 - .99$
High elevation	$Yc=4.21\ C_1 + 1.55$	$Yc=2.66\ C_2 + .46$	$Yc=3.64\ C_3 + .41$
Combined	$Yc=2.55\ C_1 + .47$	$Yc=1.62\ C_2 - .21$	$Yc=2.21\ C_3 - .22$
3) Dixie	$Yc=3.28\ C_1 - .30$	$Yc=2.03\ C_2 - 1.07$	$Yc=2.8\ C_3 - 1.12$
4) Primary Target (Σ1,2,3)			
Low elevation	$Yc=1.84\ C_1 + .48$	$Yc=1.17\ C_2 - .02$	$Yc=1.61\ C_3 - .04$
High elevation	$Yc=2.93\ C_1 + 4.44$	$Yc=1.91\ C_2 + 3.52$	$Yc=2.61\ C_3 + 3.50$
Combined	$Yc=2.26\ C_1 + 1.98$	$Yc=1.45\ C_2 + 1.32$	$Yc=1.99\ C_3 + 1.30$
5) Eastern Tooele	$Yc=1.11\ C_1 + 3.10$	$Yc= .65\ C_2 + 2.94$	$Yc=1.00\ C_3 + 2.72$
6) Eastern Supplemental	$Yc= .74\ C_1 + .21$	$Yc= .48\ C_2 - .01$	$Yc= .64\ C_3$
7) North Central Supplemental	$Yc=2.07\ C_1 + 5.20$	$Yc=1.26\ C_2 + 4.77$	$Yc=1.75\ C_3 + 4.71$

where:

Yc = Target group calculated precipitation (inches)

C_1 = Revised control group precipitation (inches)

C_2 = Expanded control group precipitation (inches)

C_3 = Combined (C_1+C_2) control group precipitation (inches)

on those occasions when they were, estimates were made from surrounding locations by plotting the available data on charts and drawing isohyetals around the missing data areas. For the eight storage gages installed during 1956 and the one in 1957, data were estimated from surrounding data in a similar manner. The storage gages normally were read at or near the end of each month. When two or more months were combined, an interpolated value for the desired period was computed from the known percentage of precipitation which fell at the surrounding sites.

In the South Central target area, the 12 low elevation precipitation gages all have consistent records. Data were available from five storage gages, although 1956 data were estimated at two. Less than three percent of the historical data were missing from the storage gages, and all was available in the seeded years.

Table 3. Summary of correlations, ratios and significance for various sub-sectors of target.

Target Group	Correlation Coefficient (r)			Ratio (Yo/Yc)			Statistical Significance (P)		
	C_1	C_2	C_3	C_1	C_2	C_3	C_1	C_2	C_3
1) Central									
Low elevation	.760	.829	.832	1.178	1.113	1.132	.234	.194	.122
High elevation	.730	.804	.798	1.135	1.083	1.106	.070	.078	.055
Combined	.755	.829	.825	1.144	1.086	1.113	.079	.110	.079
2) South Central									
Low elevation	.846	.896	.889	1.360	1.235	1.282	.028	.010	.017
High elevation	.891	.937	.935	1.262	1.173	1.213	.007	.004	.002
Combined	.874	.922	.918	1.303	1.202	1.244	.012	.007	.002
3) Dixie	.885	.917	.918	1.329	1.228	1.268	.089	.028	.055
4) Primary Target (Σ1,2,3)									
Low elevation	.883	.935	.934	1.272	1.176	1.210	.055	.032	.015
High elevation	.799	.867	.862	1.162	1.102	1.125	.032	.062	.024
Combined	.852	.913	.913	1.204	1.132	1.161	.028	.024	.010
5) Eastern Tooele	.813	.796	.806	1.175*	1.175*	1.155*	.055	.055	.049
6) Eastern (supplemental)	.785	.847	.830	1.522	1.399	1.476	.163	.070	.070
7) North Central (supplemental	.758	.774	.780	1.137	1.103	1.117	.314	.273	.272

* Eastern Tooele for five-year period, 1976-80.

The Dixie target area has five lower elevation precipitation stations, and two storage gages, at lower elevations than the ones in the Central and South Central target areas. These sites were not activated until 1959 and the data for the first three years have been estimated from surrounding locations.

The six precipitation gages in the Eastern supplementary area, just east of the Wasatch Plateau all had good data. The North Central supplemental area had ten stations at both low and high elevations, three of which were storage gage sites at intermediate levels between 2250 and 2450 meters. To select stations less likely to be affected by the seeding generator sites to the west and northwest (i.e., generator locations used to seed the Stansbury and Oquirrh Mountains in east Tooele County), precipitation gages in the Salt Lake and Provo areas were not chosen.

Data Compilation

Precipitation for each station within a group (either the controls or the various target groups) was summed for three months, January through March, for each individual year. These three monthly totals were then summed for all the stations within the group and averaged to obtain a "yearly" average.

Station histories of the precipitation gages indicate that many have been moved from a few to several hundred meters; elevation changes were generally less than 30 meters, but occasionally as much as 120 meters. A few gages have been moved one to as much as five kilometers, but records at the nearest gages suggest no appreciable changes have occurred.

The storage gages' histories indicate a more stable pattern with little movement. Minor elevation changes (generally less than 60 meters) occurred at about half the sites. None of the moves was significant enough to change the station precipitation pattern and thereby affect the regression computations.

RESULTS

Separate linear regressions were developed relating average January-March precipitation, (1956-1973), in each of the target areas to that in the three control groups (C_1, C_2, and C_3). These equations were then applied to 1974-1980 control area precipitation to estimate the target area precipitation if it had not been seeded.

Ratios of the observed target precipitation (Yo) to the calculated precipitation (Yc) were computed and tested by the Wilcoxon-Mann-Whitney ranking test (one-tailed). Where appropriate, target groups were stratified by elevation (valley precipitation gages and mountain storage gages).

In general, the correlation coefficients (Table 3) were good to very good (> .80) for most of the target/control relationships, although a few were .73 to .79. They were poorest with the six station control in western Utah (C_1) and improved with both the expanded six station control (C_2) and the combined eleven station control (C_3).

Differences between observed and predicted precipitation increased from north to south in the three sections of the Primary Target area (i.e., Central, South Central and Dixie), and become correspondingly more significant statistically in the southern regions. In general, C_1 provides the greatest and C_2 the least indication of differences. C_3 (the combined control) typically provides an estimate between these two controls, and often provides the highest statistical significance of the three.

While the indicated results of seeding for each of the sub-sections are important, perhaps the most important aspect is the apparent effect of seeding for the total Primary Target (Table 3, Group 4). The ratio of seeded precipitation to that calculated using C_1 indicates an increase of approximately 20% during the seeded seven year period (January-March from 1974-80). Results could be attributed to chance alone in less than 3 cases out of 100. The ratio determined from C_2 indicates approximately a 13% increase, but the level of significance remains high (.032). The results from the combined eleven station control (C_3) indicate a 16% increase significant at the .01 level.

In eastern Tooele county results of five years of seeding were very similar for each control. Computations from both C_1 and C_2 indicated a precipitation increase of approximately 17% in the target during the seeded period, while the results utilizing C_3 were 15%. The significance levels were .04 to .055.

In the Eastern supplemental area ratios of observed to calculated precipitation were high, with reasonably high statistical significance, suggesting a rather strong possibility of a positive extra-area effect in an area normally "downwind" of the primary target area during storm periods. Although indicated seeding effects yield large percentages in this Eastern region, the absolute magnitudes are relatively small since the normal wintertime precipitation is low.

In the North Central supplemental area ratios of observed to calculated precipitation are greater than one, although they do not approach statistical significance. This region could be affected intermittently by the seeding in either the Eastern Tooele County or northern portion of the Primary Target area.

As indicated in Fig. 3, most of the apparent effects of seeding seem to have occurred during the last three years, although a sizable increase in observed over calculated precipitation is indicated also in 1974. In all, five of the seven seeded years indicate increases over expected values. Little seeding effect is suggested in the drought years of 1976 and 1977, which had few seeding opportunities due to lack of storminess. The year 1975 also indicates that little seeding effect, for reasons that are not as apparent.

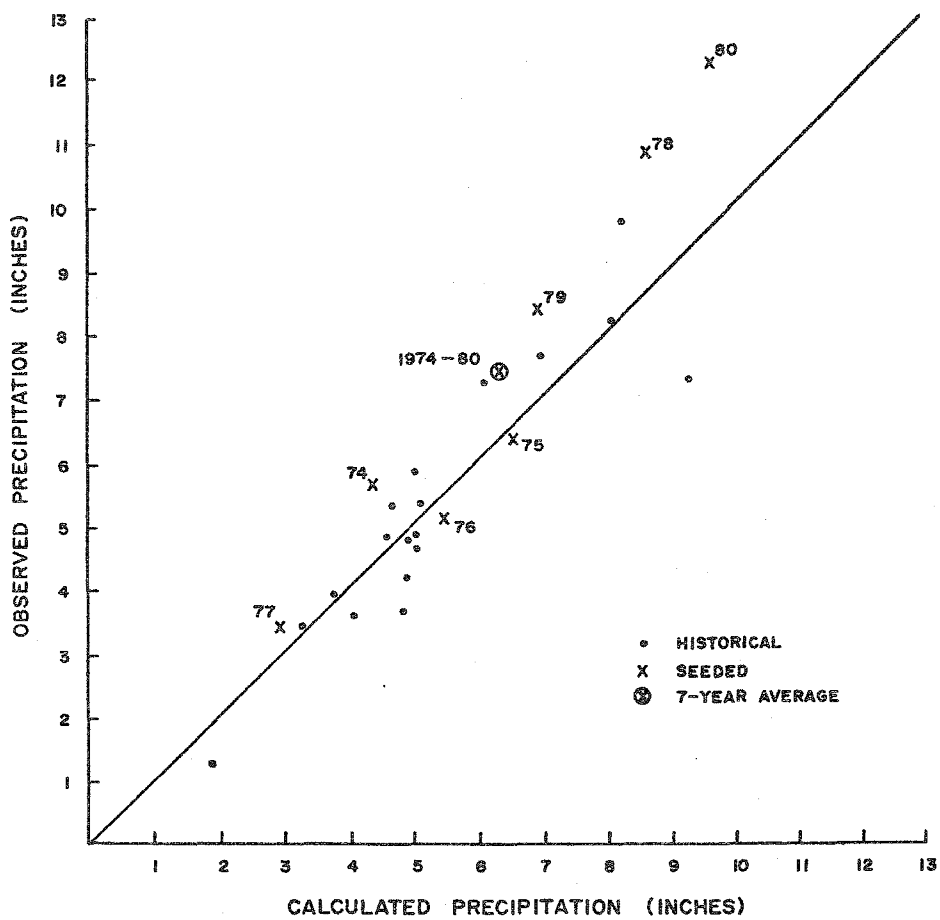

Fig. 3. Comparison of calculated precipitation (based on combined controls, C_1 and C_2) vs. observed January-March precipitation for unseeded and seeded periods, primary target area (low and high elevations combined).

CONCLUSIONS

Post hoc analyses using three separate controls to predict target precipitation from three sets of regression equations, while differing in indicated percentage increase, generally agree qualitatively. All indicate that the January-March target area precipitation, 1974-1980 (1976-80 for East Tooele), was greater than that predicted by the regression equations. Some differences between observed and calculated (expected) values were highly significant. In the five-year evaluation, Thompson (1979) noted that the southern portion of the Primary Target had higher ratios which achieved greater significance than those in the northern portion. This trend has continued through the seven-year evaluation; the indicated increases in the south are about twice those in the north. The southern area indicates statistical significance about one order of magnitude greater than the northern portion, except for Dixie where several seeding suspensions during the last two years, might account for the lower significance level.

Evidence of positive extra area effects continues to appear to the east of the target, but the results are not highly significant. North of the target, an indication of a minor seeding effect, is even less statistically significant than east of the target where carryover effects could be occurring for the last five years, from seeding in Tooele County.

The five-year evaluation (Thompson, 1979) concluded that seeding had increased January-March precipitation within the intended target area of the Utah seeding program. This seven-year evaluation utilizing the revised control and extended area controls corroborates the previous results.

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