"REVIEWED"

WINTER OROGRAPHIC CLOUD SEEDING NORTHEAST OF BEAR LAKE, UTAH

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Abstract. A wintertime operational cloud seeding program was conducted in portions of the Bear Lake watershed of Utah, Wyoming, and Idaho for a 15 year period. Seeding operations were curtailed in 1970 but initiated again in 1979. This sequence of events provides the opportunity to examine possible seeding effects over the 18 year period as well as studying the natural precipitation regime that fell between the two seeded periods. Results of this analysis indicate approximately an 11 percent increase in April 1 snowpack water content based upon a target/control evaluation. A double mass plot of the target/control April 1 snowpack water content indicates breaks in slope coincident with the years of project initiation, termination, and re-initiation. This double mass plot lends considerable credence to the interpretation that the indicated 11 percent difference in snowpack can be attributed to the cloud seeding activities.

1. INTRODUCTION

North American Weather Consultants (NAWC) has conducted a winter orographic cloud seeding program in the Bear Lake drainage of Utah, Wyoming, and Idaho for a number of years. The project, sponsored by Utah Power and Light Co. (UP&L) was initiated in 1954 and continued on an annual basis until 1970 except for one not seeded year (1965-66). The program was re-initiated during the 1979-80 winter season and continued during the 1980-81 and 1981-82 winter seasons.

This snowfall augmentation program was initiated in the mid-1950's in hopes of increasing streamflow in the Bear River Drainage in order to generate additional hydroelectric power through UP&L's facilities. The program was terminated in 1970 because benefit-cost ratios declined due to rising project costs. The rapidly escalating costs of fossil fuel production of electricity in the 1970's led to re-establishment of the program in a portion of the former target area in 1979.

NAWC has performed several evaluations of the effectiveness of the earlier as well as the more recent seeding program. These evaluations are based upon the target-control concept frequently utilized to evaluate operational seeding programs.

2. BACKGROUND

The Bear Lake drainage target areas have changed over the years as have seeding criteria, but the basic concept guiding operations has remained essentially unchanged. This concept, simply stated, is that naturally occurring winter storms in mountainous regions of the west are often inefficient in producing precipitation for lack of an adequate number of ice nuclei to initiate the Bergeron ice crystal growth process. This deficiency is frequently exhibited in these storms by the presence of supercooled water droplets, which cause aircraft icing. Silver iodide particles, demonstrated to be very effective ice nuclei by Vonnegut, can be released into these storms to improve their precipitation efficiency.

The Bear Lake Drainage seeding program has consistently employed NAWC ground-based seeding generators to disperse silver iodide nuclei, at 6 grams of silver iodide per hour from each generator. These generators are operated by local residents as instructed by NAWC's project meteorologists. Silver iodide - sodium iodide solutions were used 1954-70, silver iodide - ammonium iodide solutions since 1979.

In 1954 the original target area was the entire Bear Lake watershed Fig. 2). The target was reduced to cover only the Smith and Thomas Fork portions of this watershed in 1963 (Fig. 1). A research area in which Utah State University (USU) conducted weather modification research (1969-1976) also is shown in Figure 2.

The seeding program in 1954-1970 usually ran from October to May. When the program was re- established in 1979 the period was shortened to mid-November through mid-April.

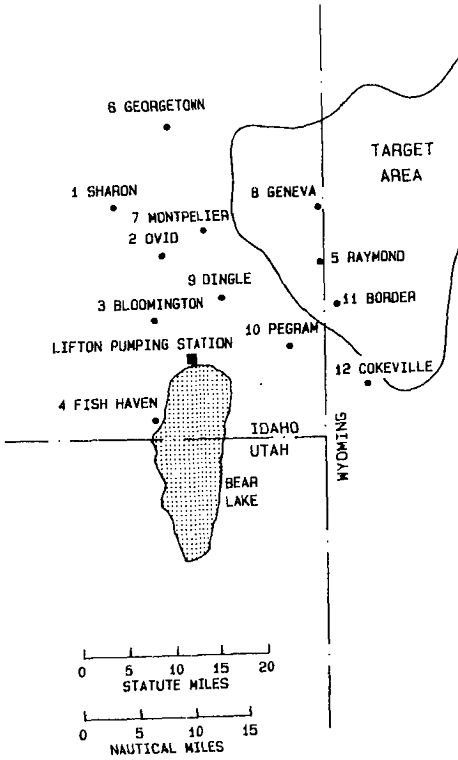

FIG. 1 GENERATOR SITES (SOLID CIRCLES) AND 1981-82 TARGET AREAS.

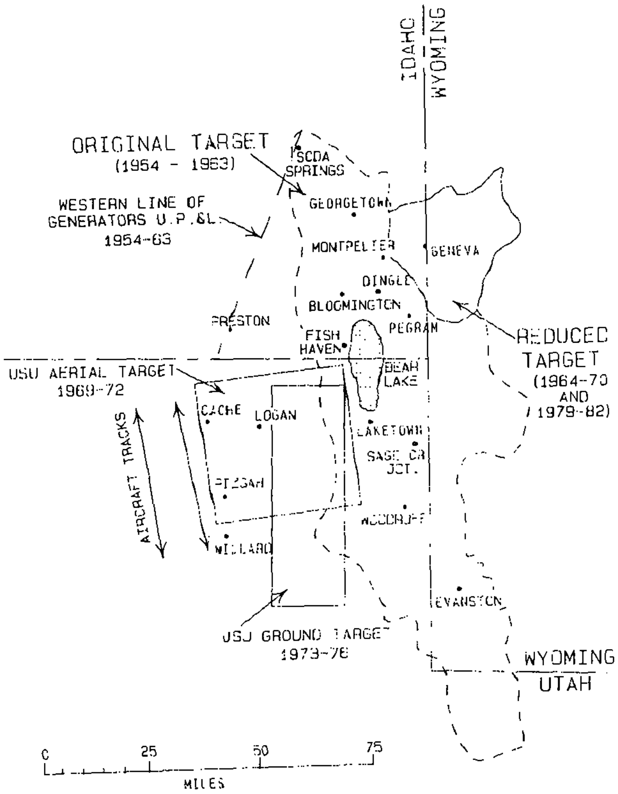

FIG. 2 ORIGINAL TARGET (1954-63), PRESENT REDUCED TARGET AREA, AND EARLIER UTAH STATE UNIVERSITY TARGET AREAS.

3. EARLIER EVALUATIONS

Evaluations of the earlier seeding program (1954-1970) were based upon SCS snow survey April 1 water content data. Target and control groupings were selected and linear regressions developed from the historical period of 1937-1954. Two snowcourses represented the north target, the Smith and Thomas Fork areas. To correlate with this north target, two control areas were selected: control north (three stations) and control west (two stations). Correlation coefficients of .887 were found between control west and north target and .922 between control north and north target. The control west relation was useful in evaluating the program only after its size was decreased in 1963, since this area was part of the earlier larger target area (i.e., the Bear Lake watershed).

For the 15 years of seeding (1954-70 except 1965-66) the actual snowpack water content averaged approximately 12 percent higher in the north target compared with north control regression estimates, using a linear relation based on data for 18 years (1937-54) (NAWC, 1970). The one-tailed Student's t statistic indicated a significance of .0133. Using control west versus target north gave an average increase of approximately 10 percent for the six seeded years after target area size reduction (1963-1970) with a significance of .007 (NAWC, 1970).

4. CURRENT EVALUATIONS

The lapse in seeding in this project area from 1970-79 provides an interesting opportunity to compare results from the earlier seeded period with the nine year unseeded period, and also with the more recent three years of renewed seeding (1979-82). An evaluation of the first year of renewed seeding activities (1969-70) revealed, however, two rather significant changes that prohibited the direct adoption of the previously established target-control evaluation: the 1969-76 weather modification research program at USU, and elimination of one of the two north target snowcourses (Number 10G10, Piney Lebarge). Some of the control west snowcourses were either within or downwind of USU's experimentation. Dropping the Piney Lebarge snowcourse is an even more serious problem since only two snowcourses were available for the earlier evaluations, thus only one snowcourse now represented the target area. These problems forced selection of new target and control stations.

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The original concept of a target-control type evaluation was maintained. Two sources of data were considered: SCS April 1 water content snowcourse data and NWS cooperative precipitation measurements. In the snowcourse assessment the unseeded period was selected to cover the years 1948-54, 1966, and 1971-79, since one of the three possible target snowcourses began in 1948. Control snowcourses were selected outside the earlier seeded areas of both NAWC's Bear Lake drainage pre-1964 program (Fig. 3) and USU's experimental areas. Three control and three target stations were finally selected (Fig. 4). Linear regression equations for an average of the three target versus an average of the three control stations gave a correlation coefficient of .843 for the 16 historical year sample of .843 (Table 1). One historical not-seeded year (1977-78) was deleted from these calculations because of an apparent discrepancy between published snowcourse data and actual runoff generated from the basin (personal communication with UP&L hydrologist).

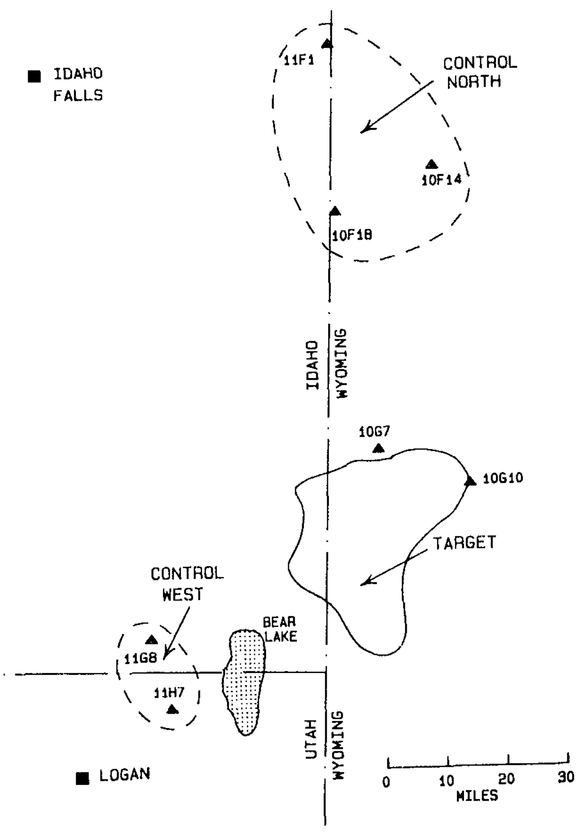

FIG. 3 TARGET AND CONTROL AREAS

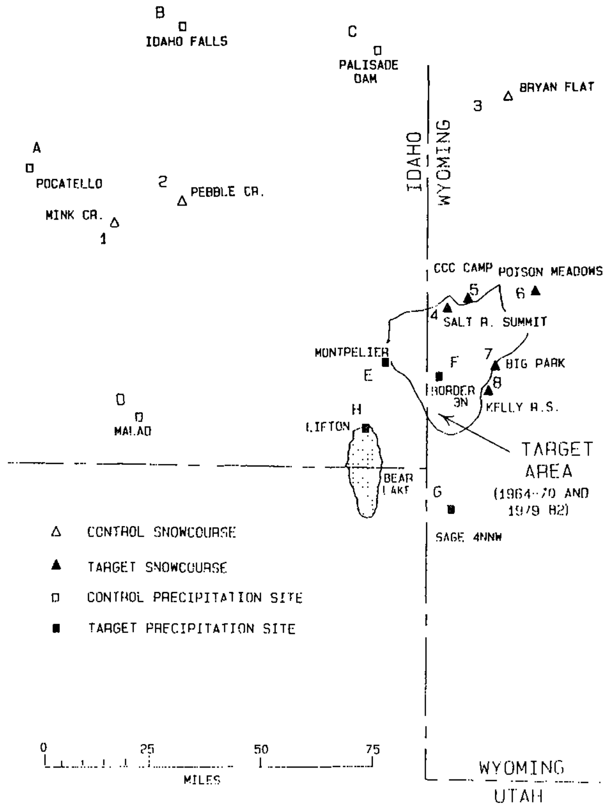

FIG. 4 LOCATIONS OF TARGET AND CONTROL SNOW COURSES AND PRECIPITATION GAGES IN RELATION TO PRESENT CLOUD SEEDING TARGET AREAS.

The regression equation developed for the snowcourse data was then used to predict the expected average snowpack water content for each seeded year. All seeded years were included since the Smith-Thomas Fork area was consistently seeded during the entire project. An indication of approximately a 11 percent increase was indicated by comparison of actual versus predicted water contents for 18 years of seeding (1955-70 except 1965-66, and 1980-82); Student's t one-tailed significance was .055.

Another technique to depict changes in meteorological or hydrological data is the double mass plot. Such a presentation consists of plots of accumulated values of one variable versus the accumulated values of another variable. If the two variables are related in a systematic fashion, then a straight line plot is the result. A change in this relation with time will be indicated by a change in slope of a line drawn through the points. Such a break can occur when one measurement station is relocated, or in our situation when a cloud seeding program begins or ends. A double mass plot of the snowcourse data for the period 1948-1982 (excluding 1978) shows an upward break

Table 1 Snowcourse and precipitation target and control data

	Snowcourse April 1 Water Content Data (inches) $y_c = 1.02x + 3.52$				December-March Precipitation Data (inches) $y_c = .72x + 1.31$			
Year	Avg. Control x	Avg. Target y_o	Regression Estimate y_c	Ratio of y_o/y_c	Avg. Control Precip x	Avg. Target Precip y_o	Regression Estimate y_c	Ratio of y_o/y_c
Not Seeded								
1947-48	13.0	14.7	16.8	.88	---	---	---	---
1948-49	18.9	18.4	22.8	.81	5.74	4.65	5.44	.88
1949-50	20.4	24.1	24.3	.99	5.96	7.28	5.60	1.30
1950-51	16.1	23.9	19.9	1.20	5.06	4.77	4.95	.96
1951-52	24.1	22.4	28.1	.80	6.23	6.07	5.80	1.05
1952-53	15.3	16.7	19.1	.87	5.11	5.09	4.99	1.02
1953-54	15.9	21.1	19.7	1.07	4.46	4.96	4.52	1.10
1965-66	10.1	13.6	13.8	.99	2.57	3.73	3.16	1.18
1970-71	20.6	30.1	24.5	1.23	5.64	5.83	5.37	1.09
1971-72	19.7	26.5	23.6	1.12	4.78	4.84	4.75	1.02
1972-73	13.3	15.9	17.1	.93	5.31	4.34	5.13	.85
1973-74	17.3	22.7	21.2	1.07	5.82	4.03	5.50	.73
1974-75	18.2	21.4	22.7	.97	5.91	5.77	5.57	1.04
1975-76	19.4	25.0	23.3	1.07	4.64	4.85	4.65	1.04
1976-77	5.7	9.0	9.3	.97	1.91	2.32	2.69	.86
1977-78	---	---	---	---	7.29	6.55	6.56	1.00
1978-79	16.0	19.3	19.8	.97	5.02	4.56	4.92	.93
Mean	16.5	20.3			5.09	4.98		
Std. Dev.	4.3	5.2			1.28	1.14		
Variance	18.8	27.3			1.63	1.29		
Seeded								
1954-55	9.9	15.4	13.6	1.13	3.72	4.24	3.99	1.06
1955-56	14.2	26.0	18.0	1.44	7.10	5.72	6.42	.89
1956-57	12.3	21.2	16.1	1.32	4.47	5.56	4.53	1.23
1957-58	16.8	20.2	20.7	.98	4.97	5.60	4.89	1.15
1958-59	12.9	17.6	16.7	1.05	4.05	3.17	4.23	.75
1959-60	10.4	15.2	14.1	1.08	3.96	5.15	4.16	1.24
1960-61	11.4	13.3	15.1	.88	3.09	2.03	3.53	.58
1961-62	16.7	23.3	20.6	1.13	5.63	6.75	5.36	1.26
1962-63	6.1	15.3	9.7	1.58	4.48	4.36	4.54	.96
1963-64	14.7	18.7	18.5	1.01	4.30	4.13	4.41	.94
1964-65	16.6	26.4	20.4	1.29	5.39	7.03	5.19	1.35
1966-67	15.6	21.4	19.4	1.10	4.36	5.33	4.45	1.20
1967-68	12.7	16.6	16.4	1.01	4.93	4.53	4.86	.93
1968-69	16.7	21.0	20.4	1.03	5.15	5.64	5.02	1.12
1969-70	14.5	19.3	18.2	1.06	5.05	3.65	4.95	.74
1979-80	17.0	19.9	20.7	.96	6.16	6.97	5.75	1.21
1980-81	7.7	10.7	11.4	.94	3.61	3.70	3.91	.95
1981-82	19.5	25.9	23.4	1.11	7.54	7.96	6.74	1.18
Mean	13.7	19.3	17.4	1.11	4.89	5.08	4.83	1.05
Std. Dev.	3.45	4.32			1.14	1.47		
Variance	11.89	18.64			1.29	2.17		

in slope coincident with the year seeding began (1955), a downward break when seeding ended (1970), and an indication of another upward break in slope coincident when seeding began again in 1980.

Even though the primary goal of the seeding program has been to increase high elevation snowpack, a supplemental evaluation was performed with lower elevation precipitation data. Again, historical data were sparse in the Smith and Thomas Fork target area. Two stations had daily data back to 1948 and four control stations, located in Southeastern Idaho, also have similar historical records (Fig. 4). Since this target area has consistently been seeded from December to March, precipitation data for those four months were averaged for the control and target stations. A linear regression equation gave a correlation coefficient of .80 (Table 1).

Precipitation data (December-March) for the 18 seeded years were in like manner utilized to compare predicted target area precipitation with observed precipitation. The indicated increase in precipitation, using the control area predictions, was approximately five percent. The Student's t significance was .181.

5. SUMMARY

Target and control evaluations of a long-term operational winter snowpack augmentation program conducted in the Bear Lake drainage indicate a 11 percent increase in April 1 snowpack water content in the target area,

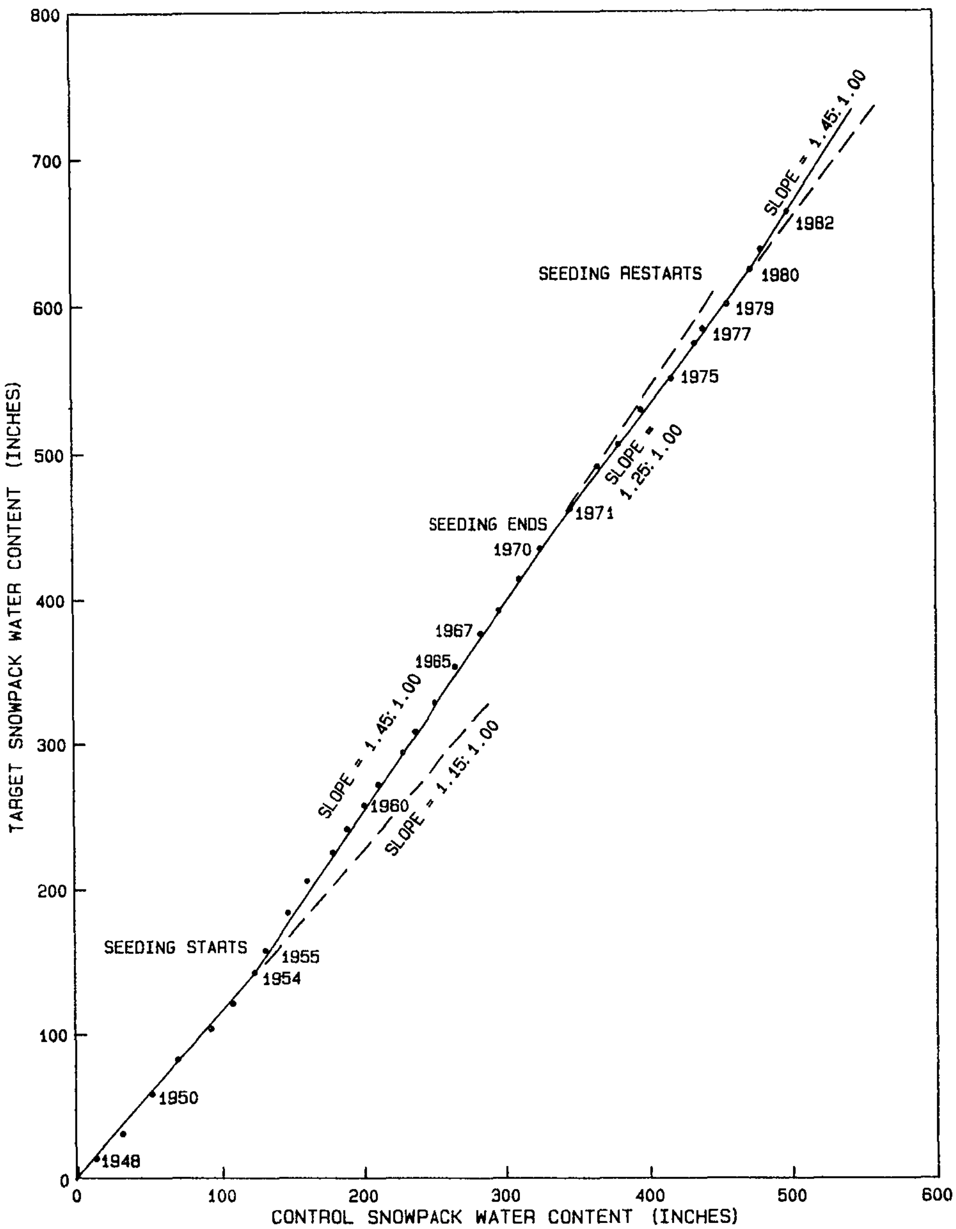

FIG. 5 DOUBLE MASS CURVE, UP&L PROJECT, SNOWCOURSE DATA, 3 TARGET AND 3 CONTROL STATION.

with a one-tailed Student's t significance of .055. A double mass plot of the accumulated snowpack water content values for the control versus target areas has breaks coinciding with initiation and suspension of seeding activities. A similar evaluation of the potential impact of seeding on lower elevation precipitation in the target area indicates a five percent increase but with lower statistical significance (.181). These results are in agreement with 1) the basic goal of the program - enhanced snowpack in the higher elevations and 2) the basic conceptual model of the seedability of winter orographic storms, i.e, supercooled liquid water is formed on the windward slopes of mountain barriers and release of ground generated seeding material upwind of these barriers can successfully convert this excess liquid water into enhanced snowfall on the mountain barrier.

REFERENCES

NAWC Report No. 109, 1970: Evaluation of an artificial nucleation program in the Bear Lake drainage.