

ESTIMATIONS OF DOWNWIND CLOUD SEEDING EFFECTS IN UTAH

Mark E. Solak, David P. Yorty and Don A. Griffith
North American Weather Consultants, Inc.
Sandy, Utah, U.S.A.

Abstract. Estimations of effects on precipitation downwind of a long-standing operational snowpack augmentation project in Utah are made, using an adaptation of the historical target/control regression technique which has been used to estimate the seasonal effects over more than twenty seasons within the project's target area. Target area analyses of December-March high elevation precipitation data for this project indicate an overall season-average increase of about 14%. Estimations of downwind effects are made for distance bands downwind as far as 150 miles. The downwind analyses indicate increases of similar magnitude to those for the target, expressed as percentages or ratio values, extending to about 100 miles downwind. Beyond 100 miles the ratio values decay, reaching 1.0 at about 125 miles. Expressed as average-depth precipitation amounts, the target area precipitation difference is about 1.4 inches of additional water, while the values within downwind distance bands range from 0.4 to 0.25 inches, reaching zero at about 125 miles.

1. INTRODUCTION

Prominent among the most commonly posed questions regarding cloud seeding projects, especially those projects with the stated goal of precipitation increase, is that of effects downwind of a given project's intended target area. The question occasionally carries the connotation of "stealing" someone else's water, sometimes referred to as robbing Peter (the downwind folks) to pay Paul (those who benefit from the seeding project). This question, among others, must be answered as forthrightly and factually as possible when it is posed. The most succinct, and probably accurate, answer to the question is "no." However, this curt response should be accompanied by some substantiation, with summary comments reflecting the conventional wisdom in the weather modification community, or better yet, reference to some quantitative estimates from similar projects, if available.

The conventional wisdom in the community suggests that, rather than decreases in precipitation downwind of target areas, increases are indicated for substantial distances, extending downwind in some instances more than one hundred miles. Quantitative or semi-quantitative estimates have been published by others. A rather comprehensive review of downwind effects of precipitation enhancement is presented by Long (2001). The analysis and results shown in this current article address this issue in the State of Utah, where snowpack augmentation projects have been conducted nearly continuously for

almost three decades. The intent in this work is to provide additional, at least semi-quantitative, evidence to address the downwind area issue, and to shed some light on the effects of seeding as a function of downwind distance.

2. BACKGROUND

Utah is the second driest state in the nation. Substantial ranching and agricultural activity, coupled with ongoing population growth, have sustained a supportive environment for attempts to augment water supplies. Winter cloud seeding projects have been conducted for several of the mountain ranges within the state. One project in particular lends itself favorably to investigation of downwind effects. This is the Central/Southern Utah project which has been operated for 25 winter seasons during the period from 1974 through the present. A few seasons during the mid-1980's were not seeded due to adequate water supplies. The mountain ranges in central and southern Utah are oriented basically north-south. Barrier crest heights average approximately 9000 feet in elevation, with many peaks above 10,000 feet and a few above 12,000 feet msl.

This project involves ground-based seeding with silver iodide from 70-75 sites and has been subject to historical target/control regression evaluation spanning its entire operational lifetime. Seasonal evaluations for December-March precipitation at higher elevations indicate an overall area average seasonal increase over many

seeded seasons of 11-15%, as reported in Griffith *et al.* (1991) and Griffith *et al.* (1997). Most recently, an evaluation covering 25 seeded seasons (Solak *et al.*, 2002) reported a 14% increase. The indicated 14% average seasonal increase corresponds to an average 1.39 inches of additional snowpack water content across the approximately 10,000 square mile target area. Independent analyses of the project conducted by the State of Utah Division of Water Resources (Stauffer and Williams, 2000) and (Stauffer, 2001) provided similar estimates of percentage increases and also addressed the resultant increase in augmented streamflow. Stauffer estimates the average annual increased runoff from the Central/Southern seeding project alone at about 142,500 acre feet. Thus, plausible/credible, if not precise, estimates for the magnitude of the seeding effects within the high elevation target area, and the resultant runoff, have been established.

The terrain downwind of the seeding project target area is relatively flat for a distance of about 150 miles, with only isolated mountains. This lack of substantial orographic influences is considered a simplifying factor in the analysis. A reasonable array of reporting stations is available in the downwind region, with adequately long periods of record for establishment of historical relationships. In an earlier article (Griffith *et al.*, 1991), average-value downwind effects for this seeding project were investigated over thirteen seeded seasons for a single downwind group of sites. That analysis indicated an average 15% increase in precipitation for the seven-site group extending a maximum of 75 miles downwind. In the current work, we capitalize on the fact that the array of downwind sites is sufficiently dense for assessment of the estimated effects as a function of downwind distance (as far as 150 miles) and enjoy the benefit of a larger number of seeded seasons.

3. METHODOLOGY

A total of 17 NWS cooperative observer reporting sites were selected downwind of the seeding target area (Table 1). Figure 1 shows the location of these sites relative to the target area. Precipitation records for the months of December through March were analyzed, the same period as the target area analyses, comparing a not-seeded base period with the years when seeding was conducted. All downwind area sites with adequate period of record and data quality were used.

Table 1. Downwind Reporting Stations

Reporting Station	Elevation (ft)
Price, UT	5700
Castledale, UT	5620
Ferron, UT	5940
Capitol Reef NP, UT	5500
Boulder, UT	6700
Kanab, UT	4950
Hanksville, UT	4310
Green River, UT	4070
Moab, UT	4020
Monticello, UT	6820
Blanding, UT	6040
Bluff, UT	4320
Mexican Hat, UT	4130
Altenbern, CO	5690
Grand Junction, CO	4840
Gateway, CO	4550
Northdale, CO	6680

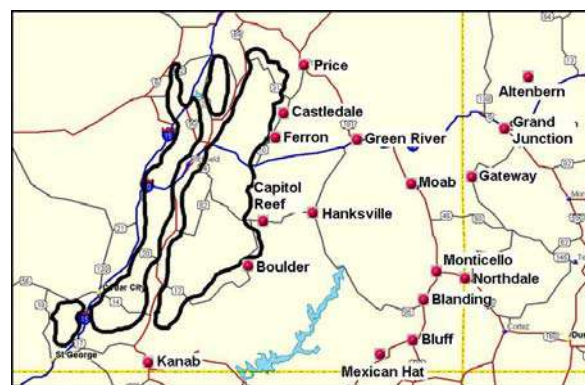


Figure 1. Map of Seeding Target Area and Downwind Sites

The base period for this study included the years 1956-1973, and 1984, when no seeding was conducted in the Utah project area, and for which adequate precipitation records are available. The

seeded period consists of the water years 1974-2002, excluding 1984-1987 when little or no seeding occurred.

A group of control sites was selected that provided the highest correlation of seasonal average precipitation values with the downwind reporting sites. The control group used in this study consists of ten National Weather Service cooperative observer reporting sites assumed to be unaffected by any seeding, one located in Utah, four in Nevada, and five in Arizona (Table 2). Figure 2 shows the locations of these sites. The control site elevations range from 4,330 to 7,000 feet, with a mean elevation of 5,977 feet.

Table 2. Control Stations

Reporting Station	Elevation (ft)
Ruby Lake, NV	6010
Callao, UT	4330
McGill, NV	6300
Ely, NV	6250
Pioche, NV	6180
Grand Canyon NP, AZ	6790
Wupatki NM, AZ	4910
Seligman, AZ	5250
Williams, AZ	6750
Flagstaff, AZ	7000



Figure 2. Control Sites for Downwind Study

The downwind sites are located in the arid regions of southeastern Utah and adjacent border region of western Colorado. All of these sites are considered downwind of the seeding target area shown in Figure 1, based on a mean westerly wind flow sector during storm periods. The sites begin immediately downwind (east) of the seeding target area in Utah, with the eastern extent of the downwind sites limited by the numerous significant mountain ranges in western Colorado and the potential effects on precipitation by other seeding projects in Colorado. The downwind site elevations range from 4,020 to 6,820 feet, with a mean elevation of 5,287 feet.

A linear regression equation describing the relationship between the control group and each downwind site was developed, based on the 19-season base period. Similarly, equations were developed relating the control group to various distance groupings of the downwind sites. These equations were then used to predict the natural precipitation at the downwind area sites and groupings of those sites, allowing comparisons between the observed and predicted precipitation amounts in various combinations during seeded seasons.

4. RESULTS

Figure 3 shows the ratio values of observed over predicted precipitation amounts for 25 seeded seasons for each downwind site. The downwind sites are identified according to their degree of correlation with the control sites during the base period, as described in the figure caption. Comparison of the observed versus predicted precipitation for the individual downwind sites yields rough estimates of the apparent effects of seeding at each site over the 25-season analysis period. These site-specific ratios are quite variable, and probably not very meaningful individually. Much of the variation is likely due to the scarcity of winter precipitation in this downwind region, making the results highly sensitive to individual storm or season outliers. However, the single site data do suggest an interesting gradient of decreasing ratios with increasing distance downwind from the seeding target. The full 17-site group average observed/predicted (O/P) ratio is 1.08, suggesting average precipitation increases of about 8%.

The first partition of the data by downwind distance was made at 75 miles, to allow comparison with the earlier downwind effects

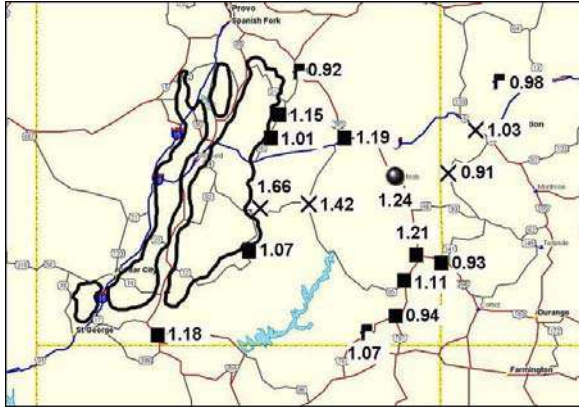


Figure 3. Individual site ratios for seeded seasons. Symbols show degree of correlation with control: Square: $R = 0.80$ or greater; Flag: $R = 0.70 - 0.79$; Ball: $R = 0.60 - 0.69$; X: $R < 0.60$.

reported by Griffith *et al.*, 1991. That study indicated, for 13 seeded seasons, a 15% average increase for a group of sites with a downwind limit of approximately 75 miles. The current study which includes 25 (an additional 12) seeded seasons indicates a 14% average increase out to 75 miles and an increase of about 5% from 75-150 miles downwind.

To investigate the apparent gradient in downwind seeding effects, the downwind precipitation sites were grouped into three distance bands: a) those approximately 0 - 50 miles downwind of the target, b) 50-100 miles downwind and c) 100-150 miles downwind. With this grouping, 7 sites were included in the first group, 3 in the second and 7 in the third. The differences between the group sizes in this lightly populated region are due to the fact the most of the downwind data are located either immediately adjacent to the seeding target area, or in the Utah/Colorado border region. However, the results from this 50-mile grouping seem believable, as shown in Table 3. The data are plotted in Figure 4. These results imply that seeding contributed to increases in wintertime precipitation for ~100 miles downwind of the target, with the indicated increases declining rather quickly beyond 100 miles. Target site data are from a previously published regression analysis of seeding effects on the target area (Solak, 2002), and are obtained using a different set of control sites which are better correlated with the seeding target sites.

Table 3. Results of grouping data into 50-mile-wide downwind distance bands

Distance From Target	No. of Sites	Ratio Obs/Pred	Precip. Diff. (in.)	Correlation (r)
Seeding Target	27	1.14	1.39"	0.97
0-50 miles	7	1.14	0.38"	0.91
50-100 miles	3	1.17	0.34"	0.82
100-150 miles	7	1.03	0.10"	0.91

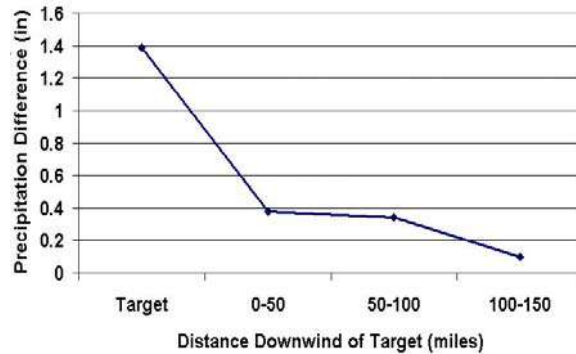
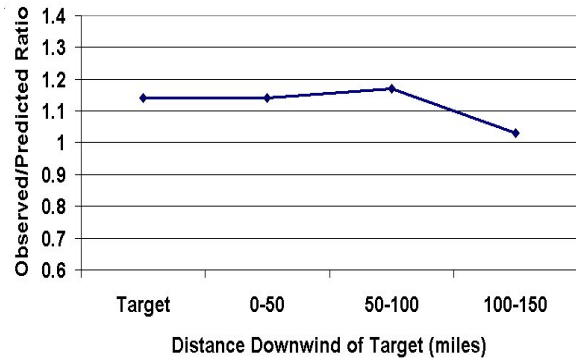


Figure 4. Ratios (upper) and seasonal precipitation difference plots for target and downwind sites

To investigate even finer spatial resolution of the apparent downwind seeding effects, the downwind region was subdivided into a total of six groups, each covering a distance band approximately 25 miles in width. Table 4 shows the results of this grouping, which are plotted in Figure 5. These 25-mile results are similar to the

analysis using 50-mile distance groupings, with the exception of the second group, which consists of only one site that appears to be an outlier. The results again suggest increases in precipitation in the first ~100 miles downwind of the seeding target, with seeded/non-seeded ratios decaying to unity about 125 miles downwind.

The results within the various downwind distance partitions are consolidated in Table 5 for ease of comparison. In each cell (downwind distance band) of the table, the following data are shown: the observed/predicted (O/P) ratio, the resultant difference in precipitation (dp), the correlation coefficient (r), and the number of sites in the distance band (n). A distance scale is shown at the bottom of the table for identification of the various downwind distance groups.

Table 4. Results of grouping data into 25-mile-wide downwind distance bands

Distance From Target	No. of Sites	Ratio Obs/Pred	Precip. Diff. (in.)	Correlation (r)
Target	27	1.14	1.39"	0.97
0-25 miles	6	1.12	0.35"	0.90
25-50 miles	1	1.42	0.49"	0.59
50-75 miles	1	1.19	0.32"	0.82
75-100 miles	2	1.16	0.35"	0.75
100-125 miles	4	1.06	0.25"	0.88
125-150 miles	3	0.98	-0.09"	0.83

5. DISCUSSION, CONCLUSIONS AND SPECULATIONS

This work is a-posteriori, the analysis method being a simple adaptation of the commonly used historical target/control regression approach to evaluations of non-randomized operational projects (Dennis, 1980). The results pertain to ground-based seeding with pure (non-chlorinated) silver iodide (AgI) formulations using

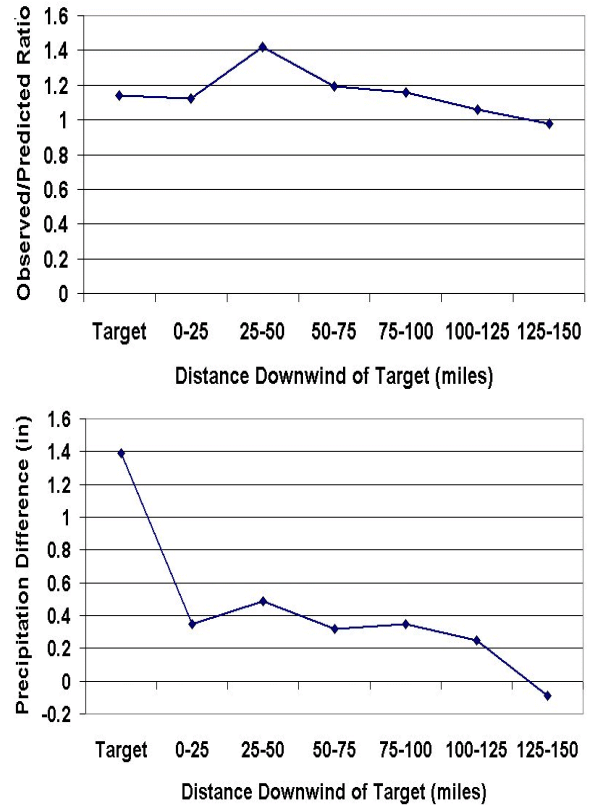


Figure 5. Ratios (upper) and seasonal precipitation difference plots for target and downwind sites

ammonium iodide (NH_4I) as the acetone solution solubilizer. Use of NH_4I is thought to greatly reduce, if not eliminate, photolytic deactivation of the ice nuclei (Super et al, 1975). Use of a four-month season as the evaluation unit yields bulk index estimates appropriate to addressing the basic downwind effects questions, while helping to minimize the impact of dominant storms or outliers.

Recognizing the limitations of the methodology and especially the statistical uncertainties involved, we nonetheless consider the indicated results to be useful and likely approximating reality. The results appear to support the statements that a) there is little evidence that precipitation increases in a target area lead to reductions in precipitation downwind, and b) that the better quality statistical analyses suggest that precipitation changes in extra (downwind) areas tend to be of the same sign and magnitude as the effects in a primary target area (Long, 2001).

TABLE 5
Summary of Downwind Indications

All Downwind Sites: O/P = 1.08 , dp = 0.26", r = 0.95, n = 17					
O/P = 1.14 , dp = 0.36", r = 0.91, n = 8			O/P = 1.05 , dp = 0.16", r = 0.89, n = 9		
O/P = 1.14 , dp = 0.38" r = 0.91, n = 7		O/P = 1.17 , dp = 0.34" r = 0.82, n = 3		O/P = 1.03 , dp = 0.10" r = 0.91, n = 7	
O/P = 1.12 dp = 0.35" r = 0.90 n = 6	O/P = 1.42 dp = 0.49" r = 0.59 n = 1	O/P = 1.19 dp = 0.32" r = 0.82 n = 1	O/P = 1.16 dp = 0.35" r = 0.75 n = 2	O/P = 1.06 dp = 0.25" r = 0.88 n = 4	O/P = 0.98 dp = -0.09" r = 0.83 n = 3
0	25	50	75	100	125
Downwind Distance (miles)					

Beyond the indication of downwind increases (rather than decreases) in precipitation, perhaps one of the more useful indications is the apparent 100-125 mile limit of the downwind increases. The magnitudes and downwind extent of the indicated precipitation increases are consistent with the concept of simple downwind transport of the pure AgI ice forming nuclei. At the seeding rates involved in this project, 8 g/hr from each ground generator, it is difficult to imagine that the ice nuclei concentrations produced by the cloud seeding would remain adequate for any discernible precipitation enhancement effects beyond the 100-125 mile downwind limit indicated by this study. No appreciable dynamic seeding effects are expected, given the low seeding rates and the types of storms involved.

In the case of this evaluation, even though the observed/predicted precipitation ratios are similar for the target and downwind areas, the estimated amounts of additional precipitation in the downwind areas are considerably less than in the target, as seen in Tables 3-5. This is because of the dry climate in this downwind "rain shadow" area, which on average receives only a small fraction of the precipitation observed in the target.

An apparent west-east axis of elevated individual downwind site ratios, which can be seen in Figure 3, may reflect the influences of a) the fact that the higher ratio sites are more centrally located downwind of the target area and are, thus, most often under the seeded plumes under a wide variety of wind flow situations, b) terrain-induced nuclei concentration and channeling, or c) anomalous values due to imperfect statistical correlation.

A recent change to the use of chlorinated, so-called faster acting, seeding formulations for this project provides a distinct operational break point and may eventually yield an opportunity for comparison of the apparent downwind effects between the two seeding formulations once a sufficient number of seasons using the new formulation have accumulated.

6. REFERENCES

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