INDICATIONS OF DOWNWIND CLOUD SEEDING EFFECTS IN UTAH

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Abstract. Estimation of effects on precipitation downwind (or “extra-area effects”) of a long-standing winter operational snowpack augmentation project in central and southern Utah mountainous areas was originally conducted in a 2003 study. The study utilized a target/control linear regression technique, which has been used to estimate the seasonal effects of cloud seeding within the program’s intended target area. The results of the original study have been updated through the 2018 water year. Seeded target area analyses of December-March high elevation (NRCS SNOTEL) precipitation data for this program indicate an overall season-average increase of about 12% for 41 seeded seasons. Estimations of downwind seeding effects were made for individual stations and various distance bands downwind as far as 100+ miles. The analyses suggest increases of similar percentages to those for the target, expressed as ratio values to the natural precipitation amounts, extending as far as 100 miles downwind (approximately the Utah/Colorado border area). At approximately 100 miles downwind, the area-averaged ratio values (observed divided by predicted values) approach 1.0, suggesting a lack of any significant seeding effect at these distances. Expressed as average-depth precipitation amounts, the target area precipitation increase from seeding is likely about 1.3” of additional water, with much lesser total precipitation increases in the much drier downwind area within 100 miles, trending to 0 beyond this distance. Although variability of the individual downwind station results remains high, the updated results are in good overall agreement with those of the original (2003) study.

1. INTRODUCTION

One of the most frequently asked questions regarding cloud seeding projects, particularly projects with the stated goal of precipitation increase, is that of any effects downwind of a given project’s intended target area. Usually, the concern is over any potential decreases in precipitation downwind of a cloud seeding program. This topic must be dealt with in a straightforward and factual way. While general indications from studies of this topic suggest that decreases downwind of seeding programs do not occur, this study was conducted with the goal of contributing to the knowledge base with regard to this topic.

Several studies of quantitative or semi-quantitative extra-area seeding effects have been published. Some rather comprehensive reviews of downwind effects of precipitation enhancement are presented by Long

(2001) and DeFelice et al. (2014). The analyses 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 over four decades. The intent of this study is to provide additional quantitative evidence to address the downwind precipitation question and the effects of a cloud seeding program as a function of downwind distance. The current analysis is an update of the original, study that included data through the 2002 water year (Solak et al., 2003). An update of the data through the 2011 water year was presented at the Weather Modification Association (WMA) Extra Area Effects Workshop in April 2012. The current paper contains updated data through the 2018 water year.

2. BACKGROUND

Utah is the second driest state in the nation. Substantial ranching and agricultural activity, coupled with significant population growth, have sustained a supportive environment for attempts to augment water supplies. Winter cloud seeding projects have been conducted over several of the mountain ranges within the state. One project in particular lends itself favorably to investigation of downwind effects. This is the geographically extensive central and southern Utah project, which has been operated for over 40 winter seasons during the period from 1974 through the present. A few seasons during the mid-1980's were not seeded, because water supplies were adequate in those years. The mountain ranges in central and southern Utah are oriented primarily 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 generator sites and has been subject to historical target/control regression evaluation spanning its entire operational lifetime. Ongoing evaluations by North American Weather Consultants (NAWC), covering 41 seeded seasons, have indicated an average 12% December to March precipitation increase in the target areas over the life of the program. The indicated 12% average seasonal increase (to the natural December – March mean precipitation or snow water equivalent of 11-12 inches for the target areas) corresponds to an indicated average 1.3 inches of additional snowpack water content across the approximately 10,000 square mile target. This mean value of roughly 11-12” of precipitation in the seeding target areas during December – March compares to just over 3” of precipitation on average for the entire set of downwind sites. The set of control sites as a whole averages between 4 and 5” during this season. However, there is significant climatological variability between stations within each of the data sets.

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. Thus, credible estimates for the magnitude of the seeding effects within the high elevation target area, and the resultant runoff, have long been established.

The terrain downwind, i.e. generally to the east, of the central and southern Utah seeding target areas is relatively flat (when considered on a large scale) for a distance of about 150 miles. Only some isolated high mountain barriers exist in this region. A reasonable array of reporting stations is available in the downwind region, with adequately long periods of record for establishment of historical relationships. A prior analysis (Griffith et al., 1991), investigated average-value downwind effects for this seeding project over thirteen seeded seasons for a single downwind group of sites. That analysis indicated an average 15% increase in precipitation for a seven-site group of gauges extending a maximum of 75 miles downwind. In the more recent analyses, an array of downwind sites is used that is sufficiently dense for a basic estimate of seeding effects as a function of downwind distance (as far as 150 miles), with the benefit of a much larger number of seeded seasons.

3. METHODOLOGY

This work is *a-posteriori*, the analysis method being a simple adaptation of the commonly used historical target/control regression approach for evaluating non-randomized operational projects (Dennis, 1980). The results pertain to ground-based silver iodide (AgI) seeding. Use of a four-month season (December – March) as the evaluation unit yields results corresponding to the most consistently seeded seasonal period, and appropriate to addressing the basic downwind effects questions.

A total of 17 NWS cooperative observer reporting sites were selected downwind of the seeding target area for the 2003 study (Table 1). Three of these sites no longer have current data available and so are not included in the updated evaluation, while another site (Cortez, Colorado) was not included in the original study but was added to the array for this updated analysis. Figure 1 shows the location of these sites relative to the seeding target areas. Precipitation data were totaled for the months of December through March, the same period as for the target area analyses, comparing a non-seeded historical period with the seeded seasons. As with the original analysis, a few estimates were conducted at some sites to fill in data gaps, utilizing data from the closest and/or most climatologically similar sites available.

The base period for this study includes the water years 1956-1973, and 1984, when no seeding was conducted, and for which adequate precipitation records are available. The seeded period consists of the water years 1974-2018, excluding 1984-1987 when little or no seeding occurred.

Table 1. Downwind Reporting Stations

Reporting Station	Elev (ft)	Mean Dec-Mar precip (in) for data in study
Price, UT	5700	2.84
Castledale, UT	5620	2.06
Ferron, UT	5940	2.34
Capitol Reef NP, UT	5500	1.64
Boulder, UT	6700	3.45
Kanab, UT	4950	5.82
Hanksville, UT	4310	1.39
Green River, UT*	4070	1.84
Moab, UT	4020	2.55
Monticello, UT*	6820	5.15
Blanding, UT	6040	4.60
Bluff, UT	4320	2.64
Mexican Hat, UT	4130	2.12
Altenbern, CO	5690	5.04
Grand Junction, CO	4840	2.52
Gateway, CO	4550	3.20
Northdale, CO*	6680	3.39
Cortez, CO	6210	4.00

* Denotes downwind sites in the original study that no longer have current data

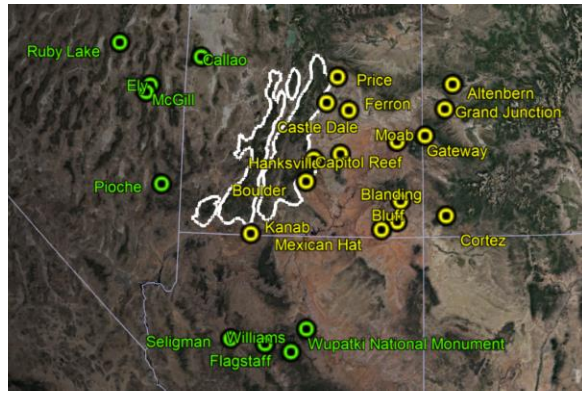

Figure 1. Map of seeding target area (white outline) with control (green) and target (downwind, yellow) sites

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 nine National Weather Service cooperative observer reporting sites assumed to be unaffected by any seeding, one located in Utah, four in Nevada, and four in Arizona (Table 2). One site in the original study control group, Grand Canyon, apparently does not maintain a current data record and was dropped from this group for the updated analysis. The control site elevations range from 4,330 to 7,000 feet, with a mean elevation of about 5,900 feet MSL. It was noted that data from the Ruby Lake, NV station could include some seeding effects due to the historic Nevada State Seeding Program.

Table 2. Control Stations

Reporting Station	Elev (ft)	Mean Dec-Mar precip (in) for data in study
Ruby Lake, NV	6010	5.63
Callao, UT	4330	1.52
McGill, NV	6300	2.45
Ely, NV	6250	3.13
Pioche, NV	6180	5.61
Wupatki NM, AZ	4910	2.14
Seligman, AZ	5250	5.30
Williams, AZ	6750	8.08
Flagstaff, AZ	7000	11.20

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 just over 5,200 feet MSL.

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.

As part of the update for the downwind effects study, various multiple regression analyses were explored. These utilize individual sites and/or groups of control sites as independent control variables, which are analyzed against individual (or groups of) target, e.g. downwind, sites. The linear regression equation contains a multiplication coefficient (or “slope”) for the entire control group, plus an offset term. A multiple regression equation contains a multiplication coefficient for each control site or group of sites, plus an offset term. If a multiple regression is properly developed so that a mathematically stable equation is obtained, it can potentially reduce the natural background noise due to highly variable precipitation patterns, and thus provide more reliable results. Although the R-value given for an equation is always the same or higher for a multiple regression equation than the corresponding linear regression that uses the same data, a multiple linear equation that reduces the season-to-season variability of the observed/predicted ratios (variability due largely to various in natural precipitation patterns) is desirable.

For this updated analysis of downwind effects, several potential multiple regressions were examined but generally failed to provide any significant improvements in the high site-to-site and season-to-season variability of the existing linear regression results for these downwind sites. The most promising of these utilized two control groups, one of which is the average of the northern (Nevada, Utah) upwind control sites and the other an average of the Arizona control sites. This type of geographic grouping of control sites is typically the most successful in producing a useful multiple linear equation, although other variations (such as groups of wetter and drier control sites) were explored. The overall long-term results obtained for these sites were very similar in the multiple linear regressions to those in the respective linear regression equations, helping to confirm the linear regression results despite the high amount of seasonal and site-to-site variability that exists regardless of which equation is used.

4. RESULTS

Figure 2 shows the ratio values of observed over predicted precipitation amounts for 41 seeded seasons for each downwind site. Comparison of the observed versus predicted precipitation for the individual downwind sites yields estimates of the apparent effects of seeding at each site for the entire analyzed (seeded) period. These site-specific ratios are quite variable, and do not carry much statistical significance on an individual basis. 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. Correlation between the control group and individual downwind sites was fair to good, with r values ranging from about 0.50 to 0.86, the majority being greater than 0.70. The single site observed/predicted ratios do suggest a gradient of decreasing ratios with increasing distance downwind from the seeding target. The full 15-site group average observed/predicted (O/P) ratio for all the seeded seasons is 1.06, suggesting average precipitation increases of about 6% in these downwind areas as a whole. For this equation (which utilizes a group average of all the downwind sites), Figure 3 shows the seeded and non-seeded data points and regression line. In this figure, the regression line is based on the historical, non-seeded season data points plotted in blue. The seeded season data points are plotted in red. It is apparent in this figure that there is a considerable amount of variability in the data, which is characteristic of the season to season variability in this naturally dry region. Data points above/left of the regression line represent seasons with observed/predicted ratios above 1.0, and those below/right of the line are associated with ratios less than 1.0.

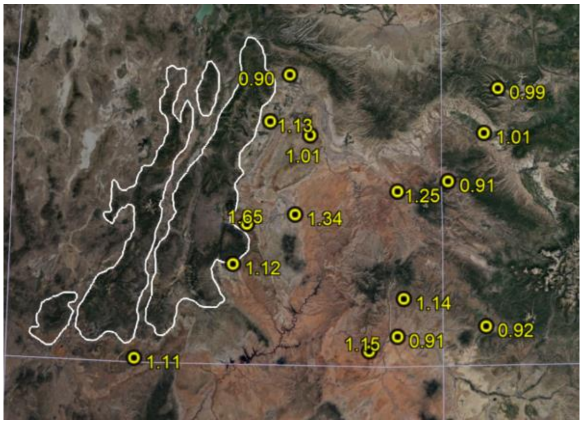

Figure 2. Individual downwind site results (observed/predicted ratios)

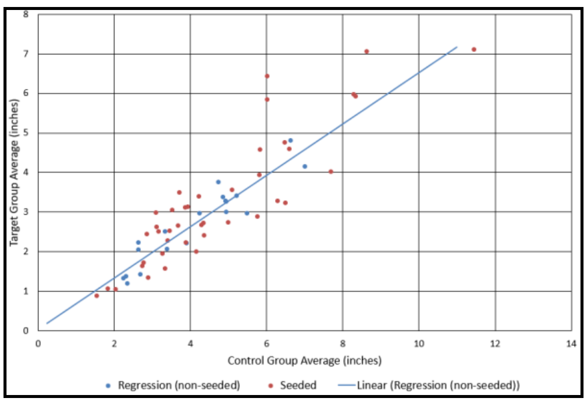

Figure 3. Regression line with data points for non-seeded seasons (blue) and seeded seasons (red)

To investigate the apparent gradient in downwind seeding effects as seen in Figure 2, 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+ miles downwind. With this grouping, 7 sites were included in the first group, 2 in the second and 6 in the third. The large differences between the group sample sizes in this lightly populated region are due to the fact that most of the downwind sites are located either immediately adjacent to the seeding target area, or in the Utah/Colorado border region as well as a little further into western Colorado. The main weakness in this distance grouping is the 50-100 mile group which includes only two sites (Moab and Mexican Hat), which yields a fairly high ratio of 1.20. The results are shown in Table 3. For a quick comparison with earlier studies, a partition of 0 to 75 miles downwind of the target area was made. This partition includes the same initial set (e.g. the 7 sites within 50 miles of the target area), with another partition for sites greater than 75 miles consisting of the remaining 8 sites (e.g. those in both the 50-100 and 100+ distance categories). These ratios suggest that seeding increased wintertime precipitation out to approximately 100 miles downwind of the target. There were no apparent differences beyond about 100 miles.

Table 3. Results of grouping data into various downwind distance bands; two grouping schemes are shown (50-mile and 75-mile intervals)

Distance From Target	No. Sites	Ratio Obs/ Predicted	Precip Diff. (in.)	Correlation (r)
Seeding Target	25	1.12	1.32"	0.96
0-50 miles	7	1.11	0.29"	0.91
50-100 miles	2	1.20	0.43"	0.74
100+ miles	6	0.98	-0.06"	0.84
0-75 miles	7	1.11	0.29"	0.91
75+ miles	8	1.02	0.06"	0.84

5. DISCUSSION AND CONCLUSIONS

The results continue to support the statements that a) no evidence of downwind precipitation decreases due to seeding has been observed, and b) that the better quality statistical analyses suggest that precipitation changes in downwind areas tend to be of the same sign, (i.e. positive) as the effects in a primary target area (Long, 2001).

An apparent west-east axis of elevated individual downwind site ratios, suggested by the distribution of the higher ratios in Figure 2, may reflect the influences of a more central location downwind of the target areas. Beyond the basic indication of downwind increases (rather than decreases) to the natural precipitation, perhaps one of the more useful indications is the suggested ~100 mile extent of downwind increases, which trend toward a neutral result at about that distance. The magnitudes and downwind extent of the indicated precipitation increases are consistent with the concept of the simple downwind transport of AgI ice-forming nuclei. No appreciable dynamic seeding effects are expected, given the relatively low seeding rates and the types of storms seeded.

Although the observed/predicted precipitation ratios appear similar for the target and adjacent downwind areas, the estimated amounts of additional precipitation in the downwind areas in this study are considerably less than in the target, as seen in Table 3. This result is as expected, due to the dry climate in this downwind "rain shadow" area, which on average receives only a small fraction of the precipitation observed in the target areas.

6. REFERENCES

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