AN EVALUATION OF THE SAN JOAQUIN OPERATIONAL CLOUD SEEDING PROGRAM USING MONTE CARLO PERMUTATION STATISTICS

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Abstract. An independent target-control statistical evaluation of the Southern California Edison (SCE) Upper San Joaquin River Basin Weather Modification Program, also known as the Big Creek Cloud Seeding Project, was conducted using Monte Carlo permutation statistics. The cumulative effect of seeding over the entire history of the project through water year 2006 was calculated in terms of confidence intervals because they provide information on the strength of the seeding effect and, thereby, allows informed judgments to be made about its cost-effectiveness and societal value. The effect of seeding on several targets in the Upper San Joaquin River Basin was evaluated using the control(s) that gives the most precise evaluation results possible with the available data. Evidence for positive, statistically significant and cost-effective increases in streamflow after 56 years of seeding was found for Mono Creek and Pitman Creek, but the results for Bear Creek were not statistically significant. Physical studies that help explain the statistical results and that could lead to more cost-effective seeding operations are suggested.

1. INTRODUCTION

The Upper San Joaquin River Basin Weather Modification Program, also known as the Big Creek Cloud Seeding Project, is an operational cloud seeding program sponsored by the Southern California Edison Company (SCE). The objectives of the cloud seeding program include enhancing streamflow for increased hydroelectric power generation with additional benefits to downstream agriculture and reservoir recreation. It is arguably the longest continuously operated cloud seeding program in the world. Operational cloud seeding began during water year 1951 and has been conducted every year since then. North American Weather Consultants (hereafter referred to as NAWC) conducted the cloud seeding operations during water years 1951-1987 and 1991-1992, and Atmospherics Incorporated (hereafter referred to as AI) conducted the cloud seeding operations during water years 1988-1990 and 1993-present. Although designed primarily to enhance snowpack and subsequent streamflow, both summer and winter storms have been seeded with silver iodide ground generators, airborne silver iodide generators, airborne silver iodide flares, and/or airborne hygroscopic flares.

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SCE and its seeding contractors conducted evaluations of the effectiveness of the Upper San Joaquin River Basin Weather Modification Program for individual years and for several blocks of years (see, for example, NAWC, 1966; NAWC, 1978; AI, 1991). The evaluations were primarily based on streamflow analysis using the historical regression method although evaluations for some of the years included radar and precipitation analyses as well. NAWC used various sites at various times as the target streamflow station (e.g., San Joaquin River below Hooper Creek, San Joaquin River at Miller Crossing, San Joaquin River near Florence Lake, and Bear Creek), and used the Merced River at Pohono Bridge streamflow station and various precipitation sites, usually in combination, as control stations. AI consistently used Bear Creek as the target streamflow station and the Merced River at Pohono Bridge and Cottonwood Creek in combination as the control. For some of the early years, NAWC and SCE also used double mass analysis of target and control streamflows to detect seeding effects and estimate their magnitude (see, e.g., NAWC, 1978). The results of the various analyses by the seeding contractors based on target-control comparisons suggested a positive effect of seeding ranging from 7%-9% depending on the period of evaluation and the choice of target-control sites. The Panel on Weather and Climate Modification to the Committee on Atmospheric Sciences, National Academy of Sciences conducted an evaluation of the first 14 years of the San Joaquin River Basin Operational Cloud Seeding Program (National Academy of Science,

1966) using an unspecified statistical method with streamflow as the test variable and reported a 7% increase at a significance level of 0.04. In his evaluation of the Kern River operational cloud seeding program, Silverman (2008) included for comparison and pooling an evaluation of the first 56 years of the San Joaquin operational cloud seeding program at Pitman Creek using the bias-adjusted regression ratio and found evidence for a positive, statistically significant and cost effective seeding effect.

The success of any cloud seeding activity requires (1) statistical evidence of a significant increase in the response variable (water year streamflow in this case) presumably due to seeding, and (2) physical evidence that establishes the plausibility that the effects suggested by the statistical evidence could have been caused by the seeding intervention (AMS, 1998). This study is primarily concerned with assessing the statistical evidence in support of the San Joaquin operational cloud seeding program. The purpose of this study is to conduct an independent statistical evaluation of the Upper San Joaquin River Basin Weather Modification Program in order to determine if the requisite statistical evidence exists. The objectives of the evaluation are (1) to evaluate the program over its 56 years of operation from water years 1951 to 2006 and, thereby, take advantage of the longevity of the data base, (2) to evaluate the operational seeding program using Monte Carlo permutation statistics, (3) to provide information on the strength of the seeding effect and its confidence interval to allow informed judgments to be made about its societal value and cost-effectiveness, and (4) to identify follow-up physical studies that will help explain and support the plausibility of the statistical results obtained thus far, and lead to the optimization of the cost-effectiveness of the seeding operations.

2. EVALUATION PROCEDURES

Permutation analysis, also known as re-randomization analysis, is a non-parametric method of analysis that is based solely on the experimental data itself. It does not depend on any assumptions about the distribution shape and its associated properties or about independence of the data from one time to another. Re-randomization (permutation) analysis involves the calculation of all permutations of the observed data to determine how unusual the observed experimental outcome is. Tukey *et al.* (1978) stated that re-randomization (permutation) analysis offers the most secure basis for drawing statistical conclusions and advocated its use in evaluating weather modification experiments, especially confirmatory experiments. This was emphasized by Gabriel (1979), who discussed some of the advantages of re-randomization tests over classical parametric tests.

A drawback to the application of permutation analysis by exact methods is they are computationally exorbitant. By the use of re-randomization inference, Gabriel (1999, 2002) developed the ratio statistics methodology for randomized experiments that is computationally practical and yields results that approximate those from re-randomization analysis. Silverman (2007) extended the ratio statistics methodology to non-randomized operational cloud seeding programs by introducing an empirical adjustment factor to account for biases that can occur when non-randomized, operational data are compared to historical records.

Monte Carlo permutation analysis will be the statistical basis for the evaluation presented in this study. The Monte Carlo permutation test is an asymptotically equivalent permutation test that is useful when there are too many permutations to practically allow for complete enumeration. This is done by generating a reference set of possible experimental outcomes by random Monte Carlo sampling, which consists of a small (relative to the total number of possible permutations) random sample of the possible experimental outcomes. However, the number of Monte Carlo random samples must be large enough to achieve the required accuracy of the test. In this study the Monte Carlo permutation test will be applied to the regression ratio (Gabriel, 1999) test statistic using a random Monte Carlo sample of 30,000 permutations. For an observed P-value of 0.05, the accuracy from 30,000 random permutations is, with 99% confidence, ±0.004. For larger values of the observed P-value, the use of 30,000 random Monte Carlo samples yields even more accurate test results.

The regression ratio (RR) is given by the relationship, $RR = SR / SR_{PRED}$ where the single ratio (SR) is the ratio of the average target streamflow during the operational period (TS_O) to the average streamflow for the seeding target during the historical period (TS_H), i.e., $SR=TS_O/TS_H$, and SR_{PRED}

is the ratio of TS_O and TS_H that are predicted by the target-control regression relationship for the data over the entire period of analysis (Gabriel, 1999). By dividing the SR by SR_{PRED}, the SR is adjusted for effects due to natural differences in streamflow between TS_O and TS_H, and thereby improves the precision in the estimate of the target streamflow. By taking advantage of the high correlation between the target and control streamflows over the entire period of analysis, the variance of the regression ratio is reduced with respect to the variance of the single ratio for the target. This enables the detection of smaller effects due to seeding with greater probability.

The main emphasis in the presentation of the results is on confidence intervals because they infer a range within which the true seeding effect lies whereas null hypothesis significance tests infer only whether there is any effect at all (Gabriel, 2002; Nicholls, 2001). Use of confidence intervals provides information on the strength of the seeding effect to allow informed judgments to be made about its cost-effectiveness and societal value. The method of Fletcher and Steffens (1996) is used to calculate the confidence limits estimated by the Monte Carlo permutation test.

3. SELECTION OF THE TARGETS AND CONTROLS

The evaluation of the Upper San Joaquin River Basin Weather Modification Program was evaluated using unregulated "natural" or full natural flow (FNF) streamflow data. In particular, the water year (October-September) streamflow expressed in Acre-Feet (AF) served as the response variable in the evaluations. There is an intrinsic and unavoidable error of about ± 5% in the streamflow measurements. Since the measurement errors are random variables and apply to both the target and control data alike, they should not bias the evaluations and should not interfere with the detection of a seeding effect if one exists.

It is emphasized at the outset that the selection of target stations in the San Joaquin River Basin was limited to those streamflow gauging sites for which full natural flow (FNF) data was available in the public domain. This included FNF data that was available directly or could be derived from data available in the public domain. Thus, the target stations available for use in this study were limited to Bear Creek near Lake T.A. Edison (USGS site #11230500, hereafter referred to as BCK), Pitman Creek (USGS site #11237500, hereafter referred to as PIT) and Mono Creek (USGS site #11231500, hereafter referred to as MNO). The unregulated streamflow data for BCK and PIT were obtained from the USGS through their web site online at http://waterdata.usgs.gov/ca/nwis/nwis. The FNF data for MNO were obtained by making the appropriate storage and evaporation adjustments to the regulated streamflow data reported on the USGS web site using the reservoir storage data for Lake Thomas A. Edison Reservoir reported on the CDEC web site online at http://cdec.water.ca.gov and the evaporation rates suggested by Longacre and Blaney (1961).

Silverman (2007) showed that it is imperative to use as the control or controls, to the extent that available data permits, the streamflow station or stations that yield the most precise results. The control or combination of controls that has the highest correlation with the target and the lowest standard deviation of the residuals (differences between the observed and predicted values) will yield the most precise evaluation results. A potential control is a streamflow station that has not been seeded, is highly correlated with the target, and has a long enough record of full natural flow data during the historical and operational period to support a meaningful evaluation. There are four (4) potential control stations: the Merced River at Pohono Bridge (USGS site #11266500, hereafter referred to as MDP) and the Merced River at Happy Isles Bridge near Yosemite (USGS site # 11264500, hereafter referred to as MHI) in the Merced watershed, the Stanislaus River at Goodwin (hereafter referred to as SNS in the Stanislaus watershed), and Cottonwood Creek (hereafter referred to as CCR in the Eastern Sierra watershed).

The geographical characteristics, data record lengths and average water year streamflow for the target stations are given in Table 1. The geographical location of the seeding targets is shown on the streamflow map of the San Joaquin River Basin in Fig. 1. Fig. 2 is a map of the region that shows the relative locations of all the targets and all the potential controls.

Table 1. Geographical characteristics, average water year streamflow and data record lengths of the selected target and potential control stations used in this study

Station Name	Sta. ID	USGS No (1)	Latitude (° N)	Longitude (° W)	Elevation (feet)	Avg FNF (AF) (4)	Record Water Yrs
Targets							
Bear Creek	BCK	11230500	37.339	118.973	7,367	70,957	1922-2006
Mono Creek	MNO	11231500	37.361	118.991	7,380	117,547	1922-2006
Pitman Creek	PIT	11237500	37.199	119.213	7,020	31,068	1929-2006
Potential Controls							
Stanislaus R - Goodwin	SNS	(2)	37.852	120.637	252	1,155,497	1901-2006
Merced R at Pohono Bridge	MDP	11266500	37.717	119.665	3,862	475,832	1917-2006
Merced R at Happy Isles Br	MHI	11264500	37.732	119.558	4,017	270,314	1916-2006
Cottonwood Creek	CCR	(3)	36.439	118.080	3,779	17,472	1935-2006

(1) Data obtained from the United States Geological Survey (USGS) website online at http://waterdata.usgs.gov/nwis/nwis
(2) Data obtained from the California Data Exchange Center (CDEC) website online at http://cdec.water.ca.gov
(3) Data obtained from the Los Angeles Department of Water and Power (Personal Communication)
(4) Average water year full natural flow (FNF) in Acre-Feet during the historical period 1935-1950

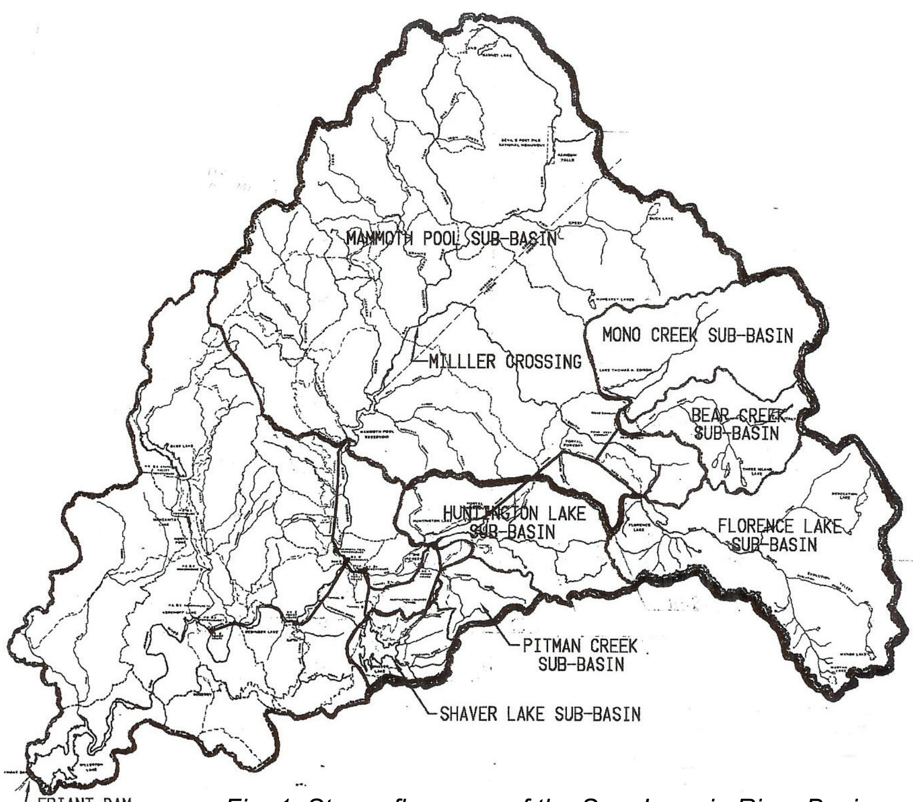

Fig. 1. Streamflow map of the San Joaquin River Basin

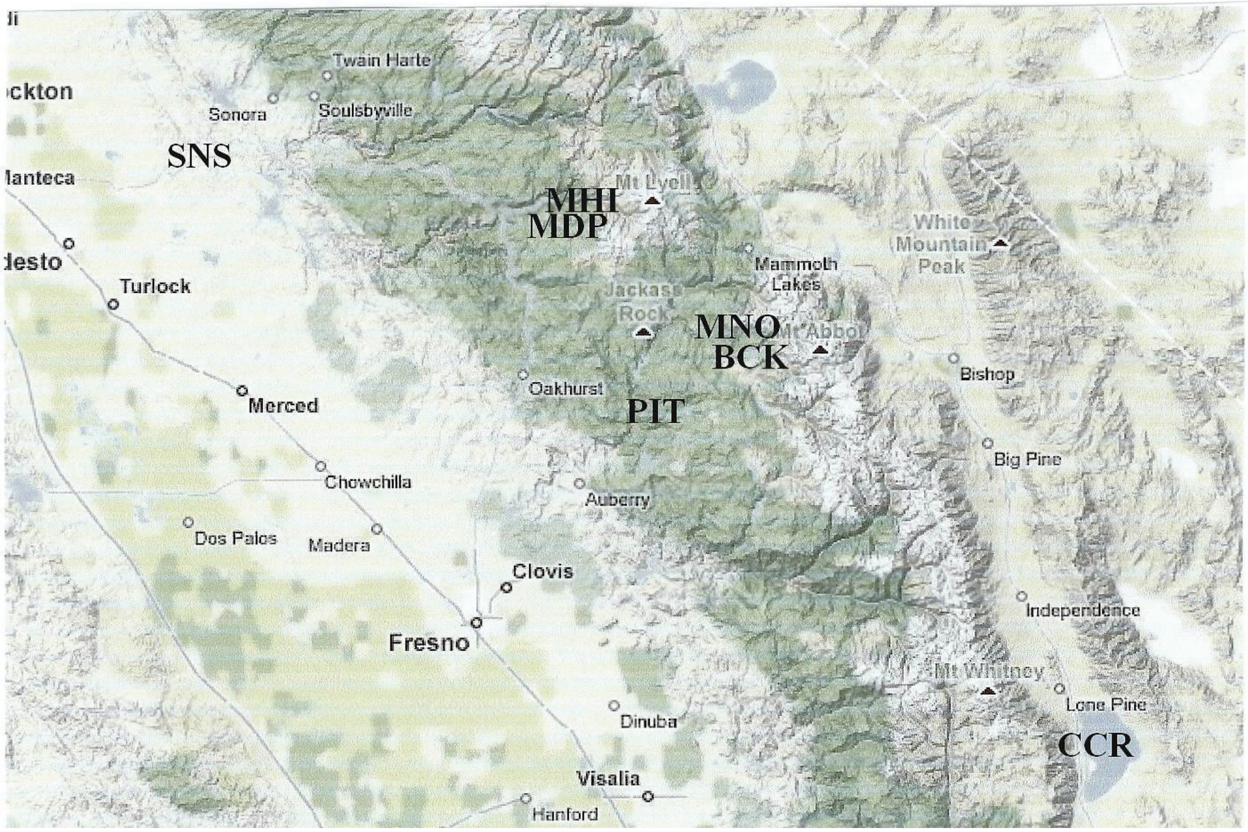

Fig. 2. Map showing the relative locations of all the targets and all the potential controls.

4. EVALUATION OF BEAR CREEK

At the outset it was decided to use BCK as the first target to evaluate because it was used by NAWC and AI as the target in their evaluations of seeding effects and, therefore, it afforded the opportunity to compare the results produced here with those of previous evaluations.

The four potential control stations were investigated by themselves and in physically reasonable combinations. The resulting linear and multiple correlation coefficients, ρ, and standard deviations of the residuals (differences between the observed and predicted values), s_o, are given in Table 2. It was found that the control having the highest correlation with BCK was the combination of MHI and CCR that yielded a multiple correlation coefficient of 0.984. In accordance with the regression ratio method, a multiple regression equation was derived for the 72-year period (1935-2006) that predicts the streamflow at the target station (BCK) as a function of the streamflow at the control station combination of MHI and CCR. The following equation for the water year streamflow at the target was obtained:

$$BCK(AF) = 0.19284 * MHI(AF) + 0.72487 * CCR(AF) + 7806.99\ AF$$

The regression equation was obtained using the least squares method. The regression results should be accurate and robust since there were no outliers in the data and the regression residuals exhibited homoscedacity (constant variance). This equation enabled the calculation of SR_{PRED} and, in turn, the calculation of RR as outlined in section 2. Applying the Monte Carlo permutation test as described in section 2, it was found with 90% confidence that the true effect of seeding lies somewhere between -1.18% and +3.00%. Thus, the null hypothesis can not be rejected and the result is not statistically significant.

Table 2. Linear and multiple regression analysis results for BCK against each potential control alone and the indicated combination of controls, respectively, for the entire period of analysis (including both the historical and operational periods).

Control	Corr. Coeff. δ	Std Dev Res s_o (AF)
MDP	0.972	6,861
MHI	0.974	6,654
SNS	0.945	9,615
CCR	0.882	13,806
MDP, CCR	0.983	5,462
MHI, CCR	**0.984**	**5,276**
SNS, CCR	0.973	6,862

5. EVALUATION OF ALL SELECTED TARGETS

The three (3) selected targets in the San Joaquin River Basin were examined in an effort to determine the area extent and magnitude of the seeding effects. The process of choosing the control site combination that yields the most precise results, as described in Section 4 for BCK, was repeated for the other 2 targets. While it was found that the combination of MHI and CCR was best for BCK, the combination of MDP and CCR was best for MNO and PIT. Therefore, the evaluation of the seeding effects on MNO and PIT was carried out with the combination of MDP and CCR, as described in section 4.

The results of the evaluation of seeding effects on the 3 target stations are shown in Table 3. The multiple correlation coefficients between the data for each of the target sites with their respective controls are also shown in Table 3. It can be seen in Table 3 that the seeding effect for MNO and PIT are positive and statistically significant at a 2-sided level of significance of 0.10. The observed experimental outcome for BCK is considerably weaker and not statistically significant. It is particularly important to note that the evaluation results based on Monte Carlo permutation analyses shown here confirms and reinforces the evaluation results based on the bias-adjusted regression ratio. It confirms that ratio statistics results approximate those from re-randomization analyses extremely well.

It is beyond the scope of this study to determine the physical cause(s) for the different levels of seeding effectiveness. One can, however, speculate that it is likely that targeting and seeding coverage of such a large drainage area as the Upper San Joaquin River Basin was not very uniform and that any increase in streamflow that may have been produced by seeding in some locations was diluted by the streamflow from those areas not efficiently seeded or not targeted for seeding.

The poorer seeding effectiveness at Bear Creek is consistent with the results of the silver-in-snow tracer study reported by McGurty (1999). Only silver iodide seeding chemicals released by aircraft were found in the Bear Creek sub-basin while none were found that were released by the ground generators. Thus, the increase in streamflow at Bear Creek appears to be the result of the aircraft seeding alone, supplemental seeding that did not start until 1975. In the Mono Creek sub-basin, tracers indicated that the source of the silver iodide was from both the aircraft and ground generators, with the majority coming from the ground generators.

Table 3. Water year seeding effects on the selected San Joaquin River Basin targets. The proportional effect of seeding is δ(%) = 100*(RR-1), where RR is the Regression Ratio, and LB and UB are the lower and upper bound of the Monte Carlo permutation test 90% confidence interval, respectively

	Bear Creek	Mono Creek	Pitman Creek
Correlation with Controls	0.984	0.975	0.980
90% Conf. Interval			
LB (%)	-1.18	+1.99	+1.53
UB (%)	+3.00	+8.80	+9.26

6. SUMMARY AND CONCLUSIONS

An independent statistical evaluation of the Upper San Joaquin River Basin Weather Modification Program over its period of operations from 1951 to 2006 was conducted using Monte Carlo permutation analyses. The stated objectives of the evaluation were achieved. Additional results obtained were insightful and enhanced the stated objectives. The following is a summary of the main findings of this evaluation study:

(1) The Monte Carlo permutation analysis of water year streamflow for Bear Creek, the target chosen for the first evaluation, indicated with 90% confidence that the true effect of seeding lies somewhere between –1.18% and +3.00%, a statistically non-significant result.

(2) Three (3) streamflow stations in the San Joaquin River Basin were examined to determine the area extent and magnitude of the seeding effects. Evidence for positive, statistically significant and cost-effective increases in streamflow after 56 years of seeding was found for MNO and PIT, but the results for BCK were not statistically significant.

(3) The evaluation results based on Monte Carlo permutation analyses shown here confirms and reinforces the evaluation results based on the bias-adjusted regression ratio. It confirms that ratio statistics results approximate those from rerandomization analyses extremely well.

It is emphasized that this study is an *a posteriori* evaluation of a non-randomized seeding operation. In addition, this evaluation is an exploratory study that involves consideration of a multiplicity of hypotheses/analyses, some of which are suggested by the results of previous analyses. In view of these considerations, the results should be interpreted as measures of the strength of the suggested seeding effect and not as measures of statistical significance. Nevertheless, the estimated effects of seeding should be of considerable value to SCE in determining the past, present and future value of their cloud seeding operations according to risk criteria used in their business operations. As Boe *et al.* (2004) state, "… if a potential sponsor of a cloud seeding program, following careful deliberation, decided they had an 80% likelihood of obtaining a 10% increase in precipitation that would yield a benefit/cost ratio of 10:1, they would probably choose to support the program." According to Henderson (2003) an increase in streamflow of only 1.5% in the Sierra Nevada Mountain watersheds would yield a benefit/cost ratio of 10:1 where the benefits include both non-consumptive hydroelectric power generation and other downstream consumptive uses such as agricultural irrigation.

7. REMARKS

Additional studies are needed to clarify and extend the results of this evaluation, and to resolve the uncertainties and deficiencies in the statistical and physical evidence obtained thus far. Progress in physical understanding comes from noting the unexpected and following it up as well as from confirming the expected. Scientists should be mindful that the results from *a posteriori* analyses might evince a physically interesting result that in fact might only reflect chance. Nevertheless, strong statistical support for a result alerts the physical scientist even though there is no ready theory to explain the results or the findings run counter to the postulated seeding conceptual model or the findings appear to be inconsistent with the findings of previous physical studies. Physical understanding is clarified and advanced through follow-up statistical and physical studies and experiments prompted by such findings.

Follow-up physical studies that are needed to help explain the statistical results obtained thus far include, but are not limited to, analyses aimed at understanding:

(1) why Cottonwood Creek, as an additional control, captures an important part of the target variability, especially during the past 10 years,

(2) why there is a difference in seeding effect among the various targets, and

(3) what are the relative roles of ground and aircraft seeding.

Acknowledgments - The author is grateful to the Weather Modification Association for its support in the publication of this paper. The author offers a special thanks to Paul Scantlin of the Los Angeles Department of Water and Power for providing the Cottonwood Creek streamflow data that contributed greatly to the precision of the evaluation.

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