A Statistical Evaluation of the Kern River Operational Cloud Seeding Program

Bernard A. Silverman, PhD
Consulting Meteorologist
Centennial, CO, USA

Abstract

A target-control statistical evaluation of the Kern River Basin operational cloud seeding program was conducted using ratio statistics. The cumulative effect of seeding from water year 1977 through water year 2006 was calculated in terms of confidence intervals because they provide information on the strength of the seeding effect whereas null hypothesis significance tests infer only whether there is any seeding effect at all. The effect of seeding on several targets in the Kern River Basin was evaluated using the controls that give the most precise evaluation results possible with the available data. Evidence for positive, statistically significant and cost effective seeding effects was found at all 3 target sites in the Kern River Basin that were evaluated with estimated increases in streamflow due to seeding ranging from +8.4% to +12.2%, depending on the target location. Physical studies that help explain the statistical results and that could lead to more cost-effective seeding operations are indicated.

Pooling of the estimates of the seeding effects for the Kern River, Kings River and San Joaquin River Basin operational cloud seeding programs indicated that the common effect of seeding on the three River Basins is +6.4% with 90% confidence that the true effect of seeding is somewhere between +3.9% and +9.0%. The probability that the seeding effect is greater than 0% and 1% (threshold of cost-effectiveness) are both 100%. Thus, there is strong statistical evidence in support of the hypothesis that cloud seeding in the watersheds of the Southern Sierra Nevada Mountains is a cost-effective technology for increasing streamflow by significant and societally important quantities.

1. INTRODUCTION

There are operational (non-randomized) cloud seeding programs being conducted in almost all of the major watersheds of the Sierra Nevada Mountains of California aimed at increasing precipitation in order to enhance streamflow for increased hydroelectric power generation, for downstream agriculture and/or reservoir recreation. The Kern River Basin is the southern-most major western slope watershed in the Sierra Nevada Mountains. The Kern River operational cloud seeding program is sponsored by the North Kern Water Storage District (NKWSD). According to Solak *et al.* (1987), operational cloud seeding began during water year 1951 and was carried out sporadically until 1970. Brown (1971) reported that a cloud seeding program was carried out by Precipitation Control Company in the Kern River Basin during the period 1950-1963 but no description of the program or its results are given in the scientific literature. No seeding was done from 1971 through 1976. Seeding operations were resumed in water year 1977 in response to a rather severe drought. Seeding operations have been conducted by Atmospherics Incorporated (AI) every year since 1977 on a steady and regular basis except for several extremely wet years when seeding was suspended.

Winter storms are seeded from November through April each year. Airborne seeding with silver iodide pyrotechnics and more recently with hygroscopic chemicals has been carried out since the seeding program began. Seeding operations were expanded in the 1992-1993 operational year to include silver iodide dispensed from ground generators.

Solak *et al.* (1987) conducted an evaluation of the Kern River operational cloud seeding program that covered operations through water year 1986. The evaluation was based on streamflow analysis using the historical regression method with support from double mass analyses and radar data comparisons. The results of the target-control, historical regression evaluation of the 8-year seeding period from 1977 to 1986 (no seeding was done in 1979 and 1980 because they were extremely high precipitation years) indicated a slightly more than 15% increase in streamflow with a 99.5% probability of a positive effect. This result was supported by the double mass analysis which also suggested an increase of about 5% during the seeding period from 1951 to 1970.

The purpose of this study is to conduct an independent statistical evaluation of the Kern River operational cloud seeding program from water year 1977 through water year 2006. The objectives of the evaluation are (1) to determine if cloud seeding enhanced streamflow in the Kern River Basin, (2) to provide information on the strength of the seeding effect and its confidence interval to allow informed judgments to be made about its cost-effectiveness, and (3) to identify physical studies that help explain the statistical results and lead to an improvement in the cost-effectiveness of the seeding operations.

2. EVALUATION PROCEDURES

The bias-adjusted regression ratio was used in a target-control evaluation of the effect of seeding on streamflow in the Kern River Basin. Silverman (2007a) described and demonstrated the capability and merits of using ratio statistics and the bias-adjusted regression ratio, in particular, in evaluating the effectiveness of operational (non-randomized) cloud seeding programs. He showed that the bias-adjusted regression ratio is a more precise and more reliable method for evaluating operational (non-randomized) seeding programs than the traditional historical regression methodology used heretofore. He also showed that the bias-adjusted regression ratio results for the Kings River operational cloud seeding program were statistically comparable to those from the re-randomization analysis. Following is a summary of the major concepts about the bias-adjusted regression ratio methodology and its application to the evaluation of operational cloud seeding programs. See Gabriel (1999) for a description of the ratio statistics methodology, and Silverman (2007a) for a more complete description of its application to operational (non-randomized) cloud seeding programs.

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 (including both the historical and operational periods). 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.

The RR results are adjusted for biases that can occur when operational data are compared to historical records in an *a posteriori* evaluation of non-randomized seeding programs. An adjustment is made to the RR results based on multiplying its computed P-value by an adjustment factor. For this study, the adjustment factor was found to be equal to 2 just as it was for the Kings River evaluation (Silverman, 2007a). At various stages in the evaluation, the results using the regression ratio that were adjusted for bias in this way, hereafter called RR_A, were compared to those from re-randomization to verify their accuracy for the sample sizes involved.

The main emphasis in the presentation of the results is on confidence intervals because they infer a range within which the true 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 significance.

3. SELECTION OF THE TARGET AND CONTROL

The Kern River Basin operational cloud seeding program was evaluated using unregulated “natural” or full natural flow (FNF) streamflow data that was obtained from the California Data Exchange Center (CDEC) web site (http://cdec.water.ca.gov). At the outset it was decided to use Kern River below Isabella (CDEC ID: KRI) as the target. KRI was selected to represent the Kern River Basin instead of Kern River near Kernville (CDEC ID: KRK), as was used by Solak *et al.* (1987), because it had a longer period of record during the operational period. However, KRK was also evaluated as one of the additional targets (see Section 5) and those results will be compared to the results obtained by Solak *et al.* (1987).

Silverman (2007a) 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, Merced River at Pohono Bridge (USGS site #11266500, hereafter referred to as MDP), Merced River at Happy Isles Bridge near Yosemite (USGS site # 11264500, hereafter referred to as MHI), Success Dam (Tulare Lake) (CDEC ID: SCC), and Cottonwood Creek (hereafter referred to as CCR). Suitably long records of FNF data were available for each of these control stations. Solak *et al.* (1987) used MDP as their control because it had the highest single-station correlation of the controls they considered. The 4 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 1. Based on the results given in Table 1, SCC and CCR were chosen as the best control site combination for the evaluation of KRI.

4. RESULTS

4.1 Evaluation by Water Year

In accordance with the regression ratio evaluation method, a multiple regression equation was derived for the data over the entire period of analysis (including both the historical and operational periods) that predicts the streamflow at the target station (KRI) as a function of the streamflow at the control stations (SCC&CCR). The following equation for the predicted water year streamflow at the target was obtained:

KRI (AF) = 1.82 * SCC (AF) + 23.99 * CCR (AF) + 62019.88

This equation enabled the calculation of SR_{PRED} and, in turn, the calculation of RR_A as outlined in Section 2. That coupled with the standard error of estimate permitted the calculation of the confidence statements as prescribed by Gabriel (2002).

Table 1. Linear and multiple regression analysis results for KRI 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	Data Source	Record Length	Corr. Coeff. ρ	Std Dev Res s_o
MDP	1	1930-2006	0.901	189,044
MHI	1	1930-2006	0.899	190,818
SCC	2	1931-2006	0.945	143,258
CCR	3	1935-2006	0.941	148,868
MDP&CCR	-	1935-2006	0.963	119,619
MHI&CCR	-	1935-2006	0.961	123,234
SCC&CCR	**-**	**1935-2006**	**0.981**	**87,230**
MDP&SCC	-	1931-2006	0.968	111,428
MHI&SCC	-	1931-2006	0.969	108,270

1. Available from the United States Geological Survey (USGS) web site online at http://waterdata.usgs.gov/ca/nwis/nwis
2. Available from the California Data Exchange Center at the CDEC web site online http://cdec.water.ca.gov
3. Obtained from the Los Angeles Department of Water and Power (Personal Communication)

Because of the lack of information about seeding operations during the period 1951-1970, the evaluation is focused on the operational period 1977-2006 (not including those years in which seeding was suspended) when steady and regular seeding operations were systematically conducted. The non-seeded water years that were used in the evaluation included the periods 1935-1950 and 1971-1976. The 1951-1970 period of seeding uncertainty was not included in the evaluation at all. The results of the evaluation of the effect of seeding on KRI streamflow are given in Table 2. In addition to the 90% confidence interval, the level of confidence that the seeding effect was positive (≥ 0%) is shown. The level of confidence that the annual average seeding effect is ≥ 1% is also shown. Since the annual cost of the seeding operations is somewhat less than the benefit derived from a 1% increase in streamflow, the level of confidence that the annual average seeding effect is ≥ 1% is taken as a conservative indicator of the cost-effectiveness of the seeding operations. Henderson (2003) has shown that the benefit-to-cost ratio of increasing streamflow by 1% through the snowpack augmentation programs in the Sierra Nevada mountain watersheds is about 6.8:1, so a threshold of cost effectiveness of 1% is very conservative indeed.

It can be seen from Table 2 that the results of the evaluation suggest a strong positive effect of seeding. There is 100.0% probability that the seeding effect is ≥ 0% and 99.9 % probability that the seeding effect is ≥ 1% (the threshold of cost effectiveness). It is estimated there is an increase in streamflow due to seeding at KRI of +12.2% with 90% confidence that the true effect of seeding is somewhere between +6.1% and +18.6%. This result is statistically comparable to the 90% confidence limits estimated by re-randomization analysis that, using the method of Fletcher and Steffens (1996), were +5.4% and +15.3%.

Table 2. Results are given for the evaluation of KRI water year streamflow. Results are presented for the proportional effect of seeding, δ(%) = 100*(RR_A-1), where RR_A is the bias-adjusted regression ratio, P_0 is the probability (%) that δ ≥ 0%, and P_1 is the probability (%) that δ ≥ 1% (the threshold of cost effectiveness).

Evaluation Statistic	1976-2006
δ(%)	+12.2
90% Confidence Interval	
Lower Bound (LB) (%)	+ 6.1
Upper Bound (UB) (%)	+18.6
P_0	100.0
P_1	99.9

A second evaluation was done for the operational period 1951-1970 (with known non-seeded years excluded) assuming some seeding, however sporadically, was done in every seeded year. It is estimated there is an increase in streamflow due to seeding at KRI of +8.2% with 90% confidence that the true effect of seeding is somewhere between +3.1% and +13.6%. Apparently seeding was not quite as effective during the period 1951-1970 as it was during the period 1976-2006 but it is still impressively positive. Thus, if the period 1935-1976 was used as the historical period for the evaluation of seeding during 1977-2006, the estimate of the seeding effects shown in Table 2 would have been undoubtedly less positive.

4.2. Evaluation by Season

Of the many ways this data could be stratified for further analysis, an operational partition of the streamflow data by season was indicated. An analysis was conducted to determine the effect of seeding on the streamflow during the winter months when all of the seeding operations are carried out and the effect of seeding on the streamflow during the summer months when the runoff is primarily due to the melting of the snowpack that accumulated during the winter months. Consequently, the October-September (O2S) water year data was divided into an October-March (O2M) period and an April-September (A2S) period for the seasonally stratified analysis. The results of the stratified analyses were obtained following the evaluation procedures outlined in section 2 and are given in Table 3.

It can be seen from Table 3 that the percentage increase in streamflow due to seeding in the winter season (O2M) is impressively greater than it is for the summer season (A2S). Although the natural streamflow during the winter season is only about 25% of the water year total, the absolute increase in streamflow due to seeding accounts for 75% of the total water year increase in streamflow. The observed increase in streamflow during the winter season (O2M period) was not expected since the seeding during the O2M period was *intended* to mainly increase high elevation snowpack and the increase in streamflow due to seeding was expected to manifest

Table 3. Results are given for the evaluation of KRI during October-March (O2M) and April-September (A2S) seasons for the operational period 1977-2006. The results for the whole water year (O2S) are also shown. Results are given for the proportional effect of seeding, δ(%) = 100*(RR_A -1), P_0 is the probability (%) that δ ≥ 0%, and P_1 is the probability (%) that δ ≥ 1%.

	O2M	A2S	O2S
Avg Target Flow-Seed (AF)	227,486	534,981	762,467
Avg Target Flow-NoSeed (AF)	162,466	494,105	656,571
δ(%)	+32.2	+5.3	+12.2
90% Confidence Interval			
Lower Bound (LB) (%)	+18.5	-0.4	+ 6.1
Upper Bound (UB) (%)	+47.4	+11.3	+18.6
P_0	100.0	93.3	100.0
P_1	100.0	88.9	99.9

itself primarily in the summer season (A2S period) when the accumulated snowpack melted. The physical basis for this result is worthy of further study.

5. ADDITIONAL TARGETS IN THE KERN RIVER BASIN

Three (3) streamflow stations in the Kern River Basin were examined in an effort to determine the area extent and magnitude of the seeding effects. The 3 target stations included Kern River-Bakersfield (CDEC ID: KRB) and Kern River Near Kernville (CDEC ID: KRK) in addition to Kern River Below Isabella (CDEC ID: KRI). The geographical characteristics and data record lengths for the target stations are given in Table 4.

The process of choosing the control site combination that yields the most precise results, as described in Section 3 for KRI, was repeated for the other 2 targets. It was found that SCC& CCR was best for all of them. Therefore, the evaluation of the seeding effects on KRK and KRB was carried out with controls SCC&CCR using the following regression equations:

KRK (AF) = 1.31 * SCC (AF) + 17.29 * CCR (AF) + 101825.90

KRB (AF) = 2.01 * SCC (AF) + 25.11 * CCR (AF) + 56415.35

The estimated seeding effects on the 3 target stations are shown in Table 5. The multiple correlation coefficients between the data for each of the target sites with the controls are also shown in Table 5. In examining and comparing the results among the target stations, it is important to note that the end year of the evaluation is not the same for all the target stations.

The first and, perhaps, most important thing to notice about the results shown in Table 5 is that the seeding effect for all the targets was positive and statistically significant at a 1-sided level of significance of 0.05. The results for KRK, KRI and KRB

Table 4. Geographical characteristics and data record lengths of the selected target stations used in this study.

Station Name	Sta. ID	Latitude (^{o} N)	Longitude (^{o} W)	Elevation (feet)	Drainage (mi^2)	Record Water Yrs
Kern R Nr Kernville	KRK[1]	35.945	118.477	3,620	846	1930-1995
Kern R Blw Isabella	KRI[1]	35.639	118.484	2,435	2,074	1930-2006
Kern R-Bakersfield	KRB[1]	35.432	118.945	~ 680	2,407	1930-2006

[1] Full natural flows as reported by the CDEC

Table 5. Water year seeding effects are shown for each of the selected Kern River Basin targets. The proportional effect of seeding is $\delta(\%) = 100*(RR_A-1)$, where RR_A is the bias-adjusted Regression Ratio, LB and UB are the lower and upper bound of the 90% confidence interval, respectively, P_0 is the probability (%) that $\delta \geq 0\%$ and P_1 is the probability (%) that $\delta \geq 1\%$ (the threshold of cost effectiveness).

Evaluation Dimensions	KRK	KRI	KRB
End Evaluation Water Year	1995	2006	2006
Correlation with Controls	0.979	0.981	0.987
Std Dev of Residuals	67,449	87,230	77,434
δ (%)	+9.0	+12.2	+8.4
90% Conf. Interval			
LB (%)	+2.5	+ 6.1	+3.4
UB (%)	+15.9	+18.6	+13.5
P_0	99.0	100.0	99.8
P_1	98.1	99.9	99.3

indicate a strong positive seeding effect ranging from +8.4% to +12.2%. It is beyond the scope of this study to determine the physical cause(s) for the different effects of seeding at the various targets but one can speculate it is probably, at least in part, the result of the spatial coverage of the seeding. It is very likely that some areas in the Kern River Basin were seeded more effectively than other areas, and some areas in the drainage system may not have been seeded at all.

As mentioned earlier, Solak et al. (1987) conducted an evaluation of the Kern River operational cloud seeding program based on streamflow analysis using the historical regression method. They used USGS data for the Kern River near Kernville (KRK) plus No. 3 Canal as the target and the Merced River at Pohono Bridge (MDP) as the control. The results of the target-control, historical regression evaluation of the 8-year seeding period from 1977 to 1986 (1979 and 1980 were not seeded) indicated a slightly more than 15% increase in streamflow with a 99.5% probability of a positive effect. The target (KRK)-control (SCC&CCR) evaluation using the regression ratio methodology for the same 8-year period indicated a +10.3% increase in streamflow with a 99.1% probability of a positive effect. Here, as in the evaluation of the Kings River operational cloud seeding program (Silverman, 2007a), the historical regression evaluation overestimated the seeding effect relative to the regression ratio evaluation, at least for operational periods less than 25 years in duration.

6. TIME EVOLUTION OF SEEDING EFFECTIVENESS

An analysis of the strength and consistency of the seeding effect over time and space was investigated in the next step of the evaluation. A progressive statistical evaluation using ratio statistics, called the cumulative year statistical evaluation or time evolution analysis, was conducted. Using this method the seeding effect was evaluated as a function of the cumulative number of years of seeding operations (initially the first 5 operational years, then the first 6 operational years, then the first 7 operational years, ..., and finally all operational years). Although 5 operational years was used as the starting point for the time evolution analysis, it is estimated that about 10 operational years is needed to obtain a stable statistical estimate of the seeding effect against the natural variability of the streamflow. The seeding effect calculated for each water year is the value that would have been obtained if the evaluation were done for all operational years up to and including that water year. A significant change in trend in the plot of the cumulative year seeding effect vs water year is indicative of a significant change in some aspect of the meteorology and/or seeding procedure that affects seeding effectiveness.

Fig. 1 shows how the estimated effect of seeding on water year streamflow evolved over time for the 3 targets selected for evaluation in the Kern River Basin. For clarity of presentation, the 90 percent confidence limits are not shown. Suffice it to say that the 90 percent confidence limits for all the estimated seeding effects shown in Fig. 1 are positive, indicating that the true effect of seeding on the 3 targets was always positive and statistically significant at a 1-sided level of significance of 0.05. For each of the targets the 90 percent confidence limit lines follow the pattern of their point value plot and narrow with time as the standard error of estimate decreases with increasing sample size.

Note that the time evolution of the seeding effect at the 3 targets are very similar, each target responding to the seeding in a similar manner, albeit at different levels of effect. The long-term trend is characterized by an initial increase in seeding effectiveness that reaches its peak of about +16% at KRI after 11 seeded years (water year 1989), then steadily decreases to about +11% after 23 years of seeding (water year 2001) and then starts increasing again to about +12% after 28 years of seeding (water year 2006). Superimposed on the long-term trend are numerous short-term fluctuations in seeding effectiveness. It is speculated that the short-term fluctuations in seeding effectiveness are likely due to the natural variability in seeding opportunities. The causes of the decrease in seeding effectiveness that started in 1990 and the increase that started in 2002 are not readily apparent. Also, the introduction of ground generator seeding in water year 1993 does not appear to have had any noticeable impact on seeding effectiveness.

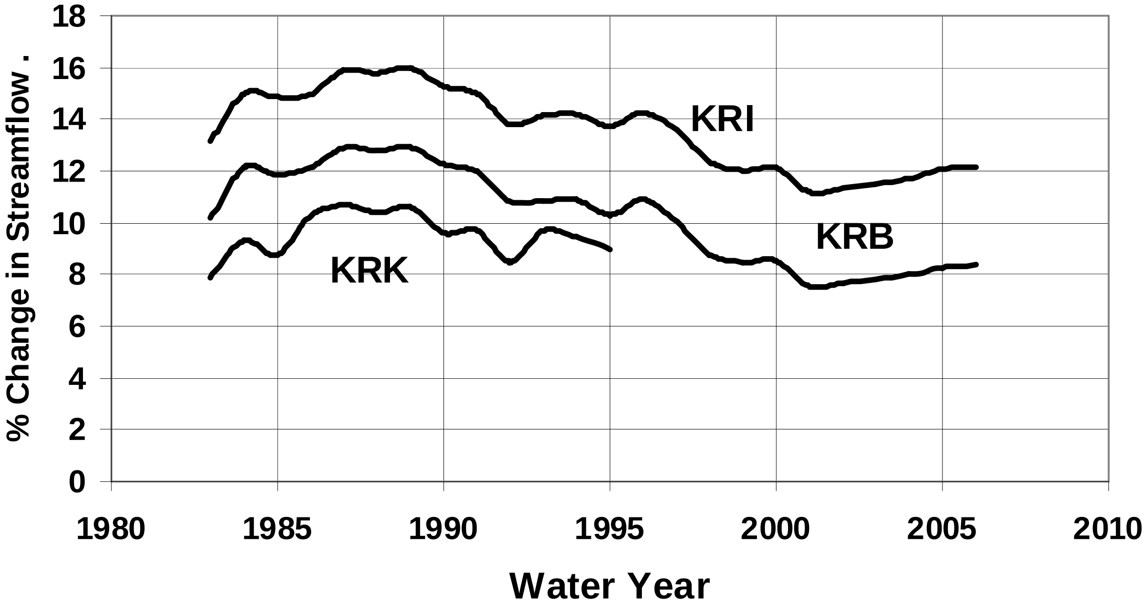

Fig.1. The proportional effect of seeding, $\delta(\%) = 100*(RR_A-1)$, for the indicated targets is plotted as a function of the cumulative number of seeded years. The seeding effect calculated for each water year is the value that would have been obtained if the evaluation were done for all operational years up to and including that water year.

7. SUMMARY AND CONCLUSIONS

An independent statistical evaluation of the Kern River Basin operational cloud seeding program was conducted using ratio statistics and, in particular, the bias-adjusted regression ratio. The stated objectives of the evaluation were achieved. The following is a summary of the main findings of this evaluation study:

(1) The ratio statistics evaluation of water year streamflow for KRI, the target chosen *a priori* for evaluation, indicated that there is a +12.2% increase in streamflow with 90% confidence that the true effect of seeding lies somewhere between +6.1% and +18.6%. The probability that the effect of seeding is equal to or greater than 0% and 1% (the threshold of cost-effective operations) is 100.0 and 99.9, respectively.

(2) When the KRI water year streamflow data was stratified into 2 periods, it was found that both the percentage increase and absolute increase in streamflow due to seeding are greater in the October-March period (winter season) than they are in the April-September period (summer season). Although the natural streamflow during the winter season is only about 25% of the water year total, the percentage increase in streamflow due to seeding is considerably greater in the winter season than it is in the summer season and results in an absolute increase in streamflow due to seeding that accounts for 75% of the total water year increase in streamflow.

(3) Three (3) streamflow stations in the Kern River Basin were examined to determine the area extent and magnitude of the seeding effects. Evidence for positive, statistically significant and cost-effective seeding effects were found for all the selected targets with estimated increases in streamflow after 28 years of seeding ranging from +8.4 to +12.2%, depending on target location.

(4) The time evolution of seeding effectiveness revealed that there was an increase in seeding effectiveness from 1977 to 1989, fol-

> lowed by a slow decrease in seeding effectiveness from 1990 until 2001 which then increased until 2006. The physical causes of these changes in the trend of seeding effectiveness are not immediately apparent.

Reiterating what Silverman (2007a) stated, it is emphasized that this study is an *a posteriori* evaluation of a non-randomized seeding operation. Therefore, 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 the North Kern Water Storage District in determining the past, present and future value of their cloud seeding operations according to risk criteria used in their business operations. 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.

8. DISCUSSION

As mentioned earlier, the Kern River operational cloud seeding program is one of the operational cloud seeding programs being conducted in a major watershed of the Sierra Nevada Mountains of California that has been evaluated using ratio statistics. The Kings River and San Joaquin operational cloud seeding programs were also evaluated using ratio statistics (Silverman, 2007a and Silverman, 2007b, respectively). It is useful to compare the evaluation results of these operational cloud seeding programs in order to highlight differences and similarities in seeding effectiveness and, by learning from each other's seeding operational procedures, to gain insights on how to optimize future cloud seeding operations. Since the three operational cloud seeding programs in the Sierras were evaluated using the same evaluation method (ratio statistics), the comparison of results will not be confounded by differences caused by the use of different statistical evaluation methods.

Whereas the Kern River Basin is the southernmost major western slope watershed in the Sierra Nevada Mountains, the Kings River Basin is the second major watershed north-northwest of the Kern River Basin with the Kaweah River Basin between them. The San Joaquin River Basin is the next major watershed north-northwest of the Kings River Basin. For the purpose of comparing the evaluation results, the Kern River Basin targets will be limited to KRB and KRI because of their substantially longer seeding records. The Kings River operational cloud seeding program is represented by Kings R-Pine Flat Dam (KGF) in accordance with Silverman (2007a). Of the several seeding targets in the San Joaquin River Basin that were evaluated (Silverman, 2007b), Pitman Creek (USGS Station No. 11237500, herein referred to as PIT) was chosen to represent the seeding results primarily because the streamflow data for this target is in the public domain. The evaluations for both KGF and PIT were updated to include water years 2005 and 2006 so as to be comparable with the evaluations of KRB and KRI. The updated evaluation of KGF indicated that there is a +4.6% increase in streamflow with 90% confidence that the true effect of seeding lies somewhere between +1.1% and +8.2%. The updated evaluation of PIT indicated that there is a +8.1% increase in streamflow with 90% confidence that the true effect of seeding lies somewhere between +3.5% and +13.0%.

The distance between the Kern River targets (KRB and KRI) and the Kings River target (KGF) is about 95-100 miles and the distance between the Kings River target (KGF) and the San Joaquin target (PIT) is only about 25 miles. Given that, it is noteworthy that the estimated effect of seeding over the Kern River Basin (KRB and KRI in Table 5) is considerably greater than it is over the Kings River Basin (KGF). It is also somewhat greater than it is over the San Joaquin River Basin (PIT) which, in turn, is considerably greater than it is over the very nearby Kings River Basin (KGF). It is not obvious why this should be the case since all three programs seeded with both aircraft and ground generators, and the seeding in all three programs was, for the most part, carried out by the same seeding contractor in accordance with the same seeding conceptual model. Additional information concerning, for example, possible differences in their seeding operations, differences in their ability to achieve the desired seeding spatial coverage, and differences in the quantity and quality of seeding opportunities are needed to determine the physical cause(s) of the differences in seeding effectiveness.

The estimates of seeding effectiveness on the Kern River, Kings River and San Joaquin River Basins were pooled to obtain an estimate of the common effect of seeding over the three Basins. KRB was chosen to represent the Kern River Basin in the pooling because it yielded the most conservative increase in streamflow due to seeding. Pooling of the estimates was done according to the method of Gabriel (2002). The weight assigned to the statistical result for each target was directly proportional to the number of years that target was seeded and inversely proportional to that target's standard error of estimate. The results of pooling the results for KRB, KGF and PIT are given in Table 6 along with the results for each of individual targets. It can be seen that the common effect of seeding on the three River Basins is +6.4% with 90% confidence that the true effect of seeding is somewhere between +3.9% and +9.0%. The probability that the seeding effect is greater than 0% and 1% (threshold of cost-effectiveness) are both 100%. Thus, there is strong statistical evidence in support of the hypothesis that cloud seeding in the watersheds of the Southern Sierra Nevada Mountains is a cost-effective technology for increasing streamflow by significant and societally important quantities.

There are 8 other operational cloud seeding programs being conducted in the major watersheds of the Sierra Nevada Mountains, i.e., in the Kaweah River Basin, the Eastern Sierra, the Tuolumne River Basin, the Carson-Walker River Basins, the Upper Mokelumne River Basin, the Upper American River Basin, the Tahoe-Truckee River Basins, and the Lake Almanor watershed. An evaluation of the seeding effectiveness of these programs and a comparison of their results should provide a wealth of information that would undoubtedly lead to the optimization of all of them. In addition, the differences in seeding effectiveness between programs in the northern Sierra and Southern Sierra Mountains that have a substantially different topography, and the difference in seeding effectiveness between the western slope and eastern slope watersheds could be explored.

9. REMARKS

Physical understanding is clarified and advanced through follow-up physical studies and experiments prompted by both expected and unexpected statistical findings such as those found in this study. 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 the seeding effect is greater in winter than summer,
2. why Cottonwood Creek, as an additional control, captures an important part of the target variability,
3. why there is a difference in seeding effect among the various targets,
4. what are the physical causes of the significant changes in trend in the time evolution of seeding effectiveness,
5. what are the relative roles of ground and aircraft seeding, and
6. why seeding is more effective in the Kern River than in the San Joaquin River Basins which, in turn, is greater than it is in the Kings River Basin.

The answers to these questions will help establish the physical plausibility that the statistical changes in streamflow were caused by the cloud seeding and should provide insights on how to improve the cost-effectiveness of the seeding operations.

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Table 6. Water year seeding effects are shown for each of the targets in the three watersheds, the Kern (KRB), Kings (KGF) and San Joaquin (PIT) River Basins, and for the common effect of seeding based on pooling (POOL) these results. Definition of the evaluation dimensions are the same as those in Table 5.

Evaluation Dimensions	KRB	KGF	PIT	POOL
Number of Seeded Years	28	45	56	
δ (%)	+8.4	+4.6	+8.1	+6.4
90% Conf. Interval				
LB (%)	+3.4	+1.1	+3.5	+3.9
UB (%)	+13.5	+8.2	+13.0	+9.0
P_0	99.8	98.5	99.8	100.0
P_1	99.3	95.2	99.4	100.0

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